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Sydney Opera House at night
(Photo: Max Dupain)

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Cast node at Lee House
(Photo: Peter Mackinven)

Sydney revisited

Jack Zunz

This lecture, illustrated by many more slides than can be reproduced here, was given at the Royal College of Art, London, on 17 December 1987, in association with the College's 150th Anniversary 'Great Engineers' exhibition.

The title of my talk tonight is 'Sydney Revisited'. To start with I want to disclaim all responsibility for the choice of subject.

When Derek Walker* asked whether I would talk in this series, I was of course flattered, but I also dithered in that I wasn't sure whether I would be here — and what is there to say that hasn't been said umpteen times before anyway? When pressed I said 'yes, probably' and that was that. I hadn't bargained for Derek's drive, initiative and enterprise. Not only did he take the decision for me but he also decided what I was going to say — no doubt artistic licence allowed by this distinguished college.

He decided on 'Sydney Revisited'. He was probably reminded of the old story of the zoology student who had enjoyed himself at university so much, that when it came to his examination, he had only learnt about the life of the flea. He thought, in fact he knew, that he was bound to be examined on the flea.

1. Michael Lewis, Ove Arup and Jack Zunz at the Opera House site, 1966
(Photo: Harry Sowden)

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* Professor of Architecture and Design, Royal College of Art;
Principal, Derek Walker Associates, Architects.

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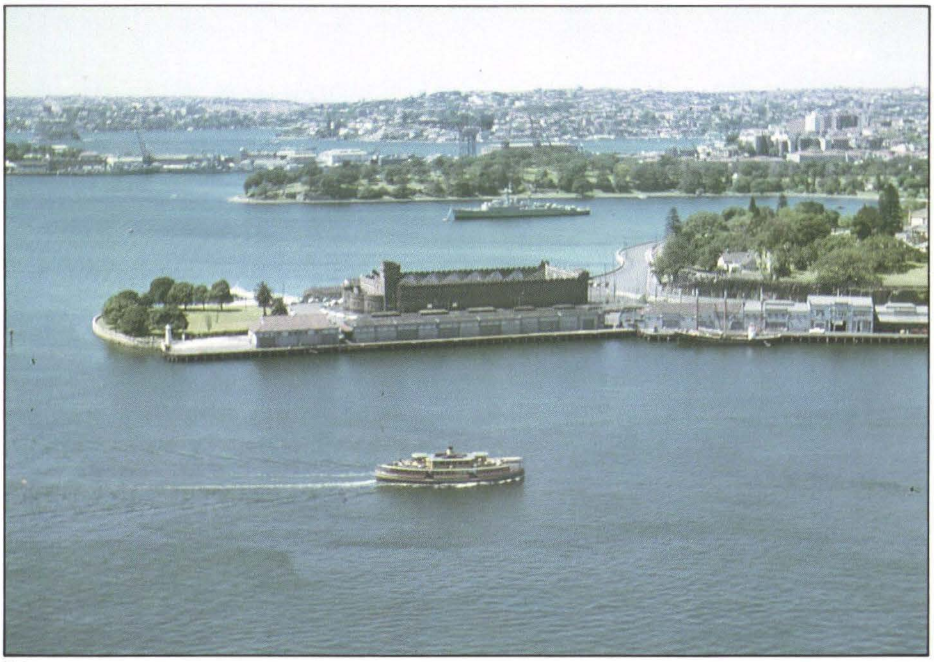

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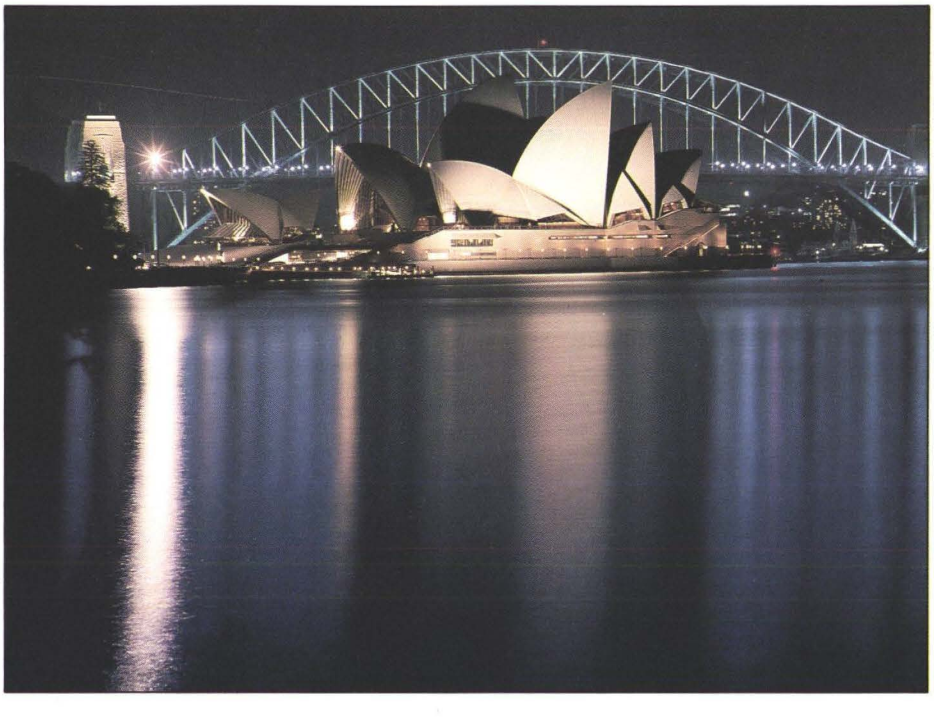


Photo: Max Dupain

In the event he was asked to write about the elephant. Not at all daunted, he began: 'The elephant is a large grey animal with four legs. It has a tail. It has a trunk and two eyes. The eyes can see very well, very well indeed. In fact they can see so well that they can see things that are small, very small indeed. They can even spot a flea. Fleas are small wingless insects of the order *Siphonoptera* ranging in size from $\frac{1}{32}$ in. to $\frac{1}{16}$ in. . . .' and so on.

Derek Walker thought that whatever happened I would talk about Sydney Opera House.

Actually he was wrong. Time had dimmed the memory and when I remonstrated with him, he said 'never mind, you can talk about anything you like — just talk about Arups and their work'. But the invitation cards had been printed and when I started to think on what to base my address, the idea of reflecting on Sydney Opera House some decades on became rather beguiling.

It is quite sobering to reflect that the competition for the Opera House was held 30 years ago and that, despite all the fuss, it has been functioning for nearly 15 years (4).

So what I shall do in the next half hour or so is to reflect on some issues associated with the Opera House. I will then refer to two other, quite well-known buildings — Centre Pompidou and the Hongkong Bank — and make some comparisons.

The Opera House, Centre Pompidou and the Bank in their very different ways were all landmarks of engineering in architecture. I shall concentrate my reflections on the Opera House and I will touch on technical and other issues concerning all three.

So, firstly and in particular for those of you too young to remember, a short Night at the Opera.

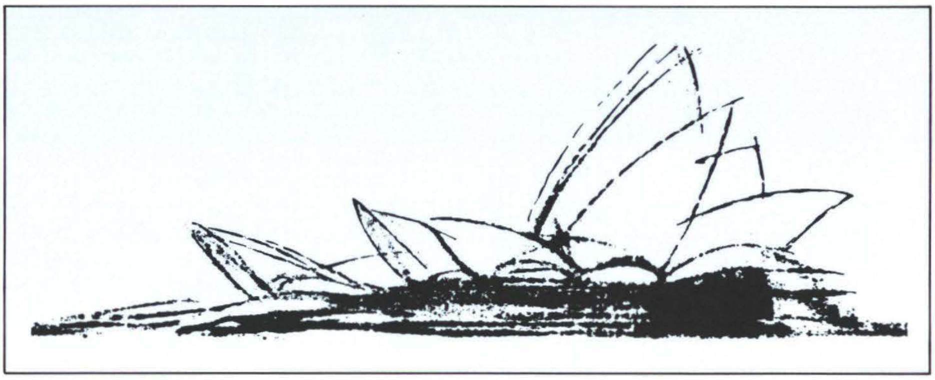
Sydney in the '50s and early '60s was still steeped in its post-Imperial past and very much at the end of the line. But it possessed human and natural resources which, like many of its Asian neighbours in the space of 20 to 30 years, stimulated unprecedented growth that has transformed a very ordinary city into a bustling international centre. It now stands as one of the major and most attractive cities in the world (2).

It also has one of the most beautiful and exciting harbours which, with its dozens of creeks and bays, results in hundreds of miles of coastline — always full of surprises. Those of you fortunate enough to have visited Sydney will have marvelled at this coastline which forms the essential framework for the city.

It was against this beautiful, but then rather provincial, backdrop that in the late '40s Eugene Goossens, a member of the illustrious musical family and a conductor with a substantial international reputation, first suggested the idea of a modern concert hall with facilities for operatic productions. The City Hall, a typical Victorian edifice (now considered to be charming, historic and so on), but totally unsuitable for proper enjoyment of orchestral music, had been the home of the Sydney Symphony, an excellent orchestra sponsored by the Australian Broadcasting Commission.

The site was chosen in the mid 1950s. It was the promontory called Bennelong Point (3) adjacent to Sydney Harbour Bridge. On it stood the by then disused tramsheds.

Sydney Harbour Bridge, completed in 1932 under the direction of Sir Ralph Freeman, is still one of the world's great bridges and as well as being the 'kite mark' of Sydney Harbour, it also marked the scale for anything to be built on Bennelong Point. For reference, its span is 1650 ft. and the deck is 172 ft. above water level (4).



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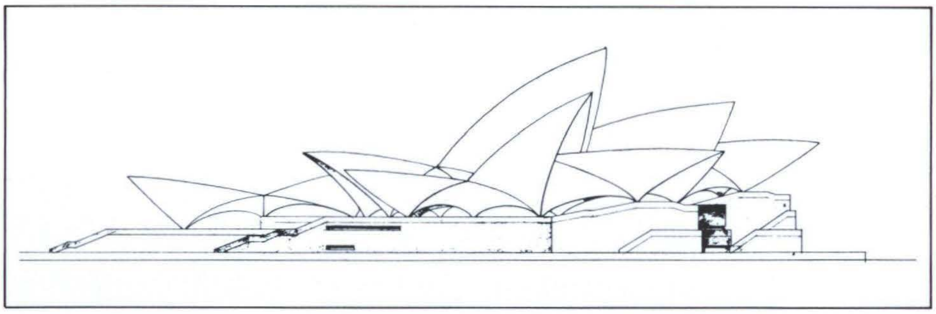

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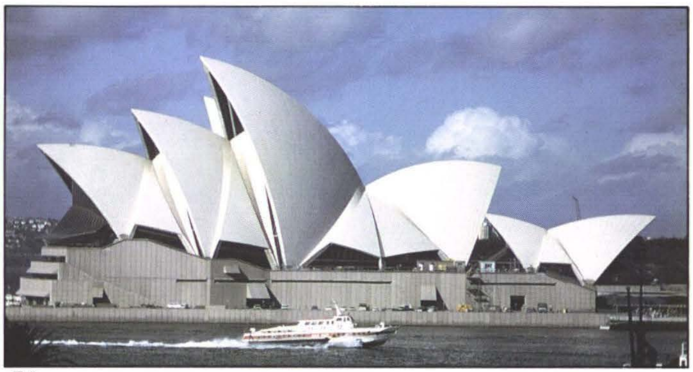

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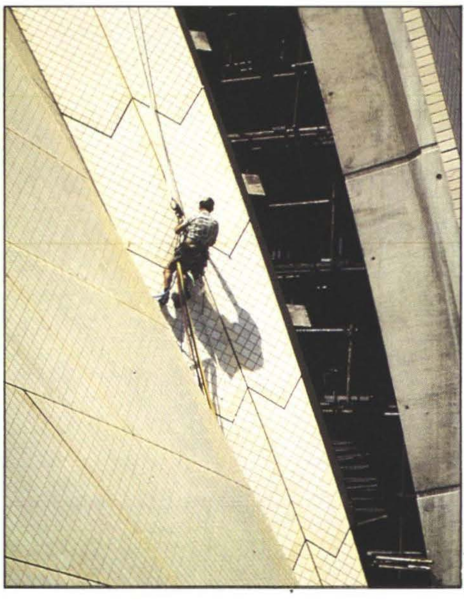

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The Royal Australian Institute of Architects offered its services to the New South Wales Government which, under the leadership of its Socialist Premier Joe Cahill, was to be the sponsor of the Opera House. It was decided to hold an international competition for the design of a complex of buildings to provide facilities for the musical and dramatic arts.

I want to draw your attention to two issues.

Firstly, you will note that so far I have said nothing about engineering. And that is simply because the engineering aspects of the Opera House, or for that of any building or artifact, have no value in themselves. They are of interest in the context of the services they render to whatever they serve — a building, a bridge, a dam or whatever. By itself the structure of Sydney Opera House may have some virtuoso-like qualities — it may even be an engineering cadenza — but in itself it serves no purpose. Its contribution to the whole is important only in so far as the whole has some value. I will, therefore, spend some time on the description of the context — the whole.

The second issue is that from the very early days one spoke about 'the Opera House' — a total and unfortunate misnomer. The International Competition which was launched in 1957 stipulated a schedule of accommodation which included two main hall — one to seat 3000 to 3500 people and the other 1200 to 1500.

The functional requirements were explicit and no function was to be compromised by one of lower priority:

Large Hall

(a) Symphony concerts
(b) Large-scale opera
(c) Ballet and dance
(d) Choral works
(e) Pageants and mass meetings

Small Hall

(a) Dramatic presentations
(b) Intimate opera
(c) Chamber music
(d) Concerts and recitals
(e) Lectures

There was to be additional accommodation for chamber music and drama as well as for rehearsal but with more modest seating capacity. The important point to note is that the primary function is, and always was, to be that of a philharmonic hall with opera playing second fiddle, as it were. Yet the term 'Opera House' stuck — one wonders whether calling it, say 'The Sydney Centre for the Performing Arts', which would have been more accurate, would have changed its image or indeed its history.

Anyway, the four assessors of the competition, who were all eminent architects — Dr. Cobden Parkes, the New South Wales State Architect, Professor Harry Ashworth, the Dean of Architecture at Sydney University, Professor Sir Leslie Martin, the then head of the Architectural School at Cambridge and Eero Saarinen, the distinguished American/Finnish architect — adjudicated the entries. There were 222 submissions, of which 221 complied with the competition rules. One did not. It was prepared by a relatively young and unknown Danish architect, Jørn Utzon, but his proposals prompted the assessors to say, *inter alia,* 'the drawings submitted for the scheme were simple to the point of being diagrammatic (5). Nevertheless, we have returned again and again to the study of these drawings and we are convinced that they present a concept of an opera house which is capable of becoming one of the great buildings of the world. We consider this scheme to be the most creative and original submission. Because of its very originality it is clearly a controversial design. We are, however, absolutely convinced about its merits . . .'

30 years on it is interesting to reflect on the prescience of the assessors. I wonder whether, for all their wisdom, they could have foreseen the degree to which their forecast was realised. Remember, they used the phrase 'great buildings of the world', as well as the words 'originality' and 'controversy'.

Jørn Utzon (6) was awarded the first prize, despite having broken the rules, particularly by ignoring the site boundaries. Most competitors had found it necessary to place the two halls 'head to toe' in order to accommodate the seating requirements as well as providing enough back-stage, and particularly side-stage, accommodation. Utzon placed the halls side by side. If the site wasn't wide enough he would make it wider — a simple jetty-like piece of engineering called the Broadwalk, which became a major feature for the enjoyment of the public to promenade around the complex. But it also meant that, despite widening the site, side and back-stage space was restricted — a cause for much subsequent debate and indeed controversy.

Utzon conceived the scheme for the competition unaided by engineering advice. This is possibly just as well, because the distinctive sculptural quality of the building with its roof structure (7), often likened to billowing sails, was an essential, if not *the* essential part of his first proposals. Sound engineering advice might have persuaded him not to pursue these proposals because of the obvious difficulties and the possibility that the assessors might take fright. His proposals had no geometric definition. From a technical point of view, whether or not there was any geometric definition, his forms were to say the least extravagant. His pointed, ogival arches were, contrary to his expectations, unable to sustain by membrane action alone the forces to which they would be subjected — they had to be stiffened to sustain the very large bending moments which these pointed forms attracted.

But man does not live by bread alone and it was probably just as well that Utzon's romantic concept flew ignorantly in the face of current engineering dogma. When we were appointed as consulting engineers for the project shortly after he received the commission for the job, we told him the technical facts of life. But other suggestions all tended to destroy the basic sculptural quality and all our efforts were then directed towards solving the enormous problems which gradually emerged.

We were appointed in the middle of 1957. We optimistically decided that it could be built; we had some untested ideas, but no proof or knowledge of what materials should be used or how it could be constructed. Yet, despite the sketchiness of the information available about the scheme and particularly its cost, and against our advice, the State Premier Joe Cahill, a man with a mission though little artistic understanding and pretension, bulldozed an Act of Parliament, The Sydney Opera House Act, through the State Legislature in the face of substantial opposition from both inside and outside Parliament.

If he had waited for all the difficulties which subsequently emerged it is doubtful whether any democratic institution would ever have launched the project. The stage was set for one of the most accidental, random and astonishing acts of architectural patronage of modern times.

If I can digress for a moment, we have heard a great deal about the iniquities of the architectural and its associated professions from a person up high. This exercise of power without responsibility, by using tendentious and evocative hyperbole, is supposed to make us ashamed of our contribution to society. Not so — if there *is* a single reason for our urban blight, it is not the misdeed of the planner, the architect or the engineer, but of the promoter or rather the lack of proper patronage or leadership. Being a civil engineer I have always likened the role of the client, whether public or private, to that of the foundations of a structure. If these are faulty they affect the whole edifice. And so it is with the promoters of architecture or engineering — those who are our clients and who should be our patrons. They, and therefore society generally, get the buildings and structures they deserve. Perhaps we should have a college for training promoters and patrons.

Back to the Opera House — the New South Wales Government through its elected politicians and civil servants wanted the best building possible, and Premier Cahill thought that once a start had been made on site there would be no turning back. In that he was, of course, right, but it is doubtful whether he realised that his and successive governments were now riding a tiger which refused to be tamed.

The start was made in the context of the classical construction disaster scenario — a well-meaning but dispersed, unco-ordinated and non-professional client, a brilliant, if wilful architect, no cost plans or limits, no drawings and above all a scheme which was possibly buildable, but nobody yet knew how. Out of these ashes arose Sydney Opera House by sheer chance. Utzon, brilliant and wayward, was the catalyst and the inspiration, Premier Cahill was the driving force and our role I suppose was to make it all possible.

Utzon was considerably influenced by Aztec and Mayan architecture where temples were built on large platforms which formed not only an entity in themselves but also a visible base for the building above. Sydney Opera House has such a platform (8) which, when it was completed, was a massive sculpture in itself. The concourse forms the approach, either on foot or by vehicle. After ascending the steps one circulates around the stage areas towards the auditoria, while remaining all the time in visual contact with the harbour through extensive glass walls in the side and end foyers. This unusual circulation arrangement obviated having tall fly towers over the stage at the end of the peninsula (9) where they would have been aesthetically undesirable. The base platform houses three smaller halls, numerous rehearsal rooms, dressing rooms, workshops, studios, kitchens, bars and restaurants. The total complex caters for about 6000 people for symphony concerts, opera, ballet, drama, chamber music, film shows or conventions.

In engineering terms the base is a reinforced concrete monolith surrounded on the east, north and west by the Broadwalk (10) and approached from the south by a large concourse. This concourse (11) is probably the most interesting engineering structure in the base. It is about 100 m wide and spans up to about 50 m. It is of prestressed concrete and the geometry, like that of the roof structure, was the result of much development and rationalization. It is shaped as it is in order to make maximum use of the compressive strength of concrete. Hence it is T-shaped where the compression is greatest at the top surface, and trough-shaped where the maximum compression is at the bottom, the resulting twisted surfaces intersecting in sine curves.

But the most challenging aspect was the design of the roof structure (12,13). The architect's competition scheme had four main pairs of curved surfaces for each hall. These surfaces, or shells as they were incorrectly called, were geometrically undefined and were connected to each other by a further series of surfaces called side shells, again incorrectly.

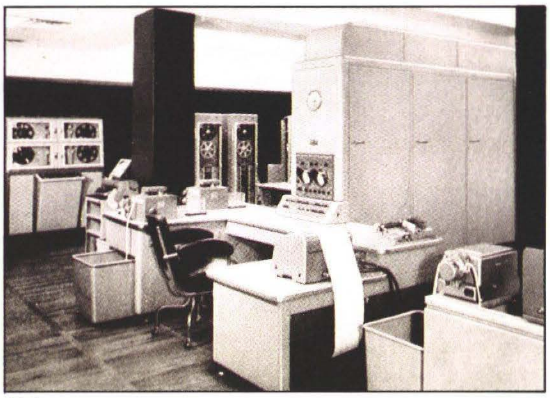
There were a number of factors which made it difficult to comprehend the problem — the interplay of surfaces made a normal back-of-the-envelope assessment of dubious value. The scale of the structure was misleading (it is big, but the scale tended to be diminished by the site and its relationship to the bridge), and above all, there was no geometric definition; nor were acoustic or auditoria ceilings or finishes to the building yet defined.

Over a period of five years, analytical and model tests resulted in the now-familiar structure. It is generally made of precast concrete, with some in situ bits, particularly the pedestals. The elements were stressed together.

There were all sorts of firsts. The application of computers was extensive and quite new. Ferranti, Orion and Pegasus computers driven with thermionic valves (do you remember them?) occupied the kind of space associated now with the major air-conditioning plant of a modern building. Fig. 14 shows a Pegasus computer of the type used for the Opera House while the other one (15) is an Apricot computer, a desk top we use today. Although without computers we would have found some difficulty in building the Sydney Opera House the way we did, the two machines illustrate the dramatic progress made in 25 years. The one cost £1M in today's money (and we couldn't afford it then — we hired time). The other costs £2500 — we now own 150 plus much other hardware. The Pegasus took about 12-14 hours to do a three-dimensional framework analysis which would take two minutes on the Apricot — which incidentally was used in the latter stages of the Hongkong Bank. In each case, cost and time, the ratio is 400:1. But, the Pegasus computer *was* available, which was a dramatic change from the old calculating machines, that made the solution of simultaneous equations with more than dozen unknowns a near-impossible exercise.

The precasting of large segments with matching surfaces glued together with a two-part epoxy was an innovation, although we subsequently discovered that a bridge was being built in France using a similar technique about the same time. Computer print-out setting-out schedules issued to site were a first, as were computerized surveying procedures. The application of laminated glass was the result of much detailed research. There were numerous other developments which were outside our normal experience. The structure was substantially completed in 1966/67 and the total complex fitted out and opened by the Queen in October 1973 (22). Perhaps it was appropriate that the first operatic production was Prokofiev's *War and Peace,* produced by Sam Wanamaker.

There was much relief and rejoicing as well as some pain and unanswered questions.



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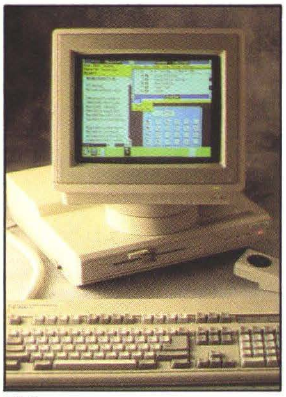

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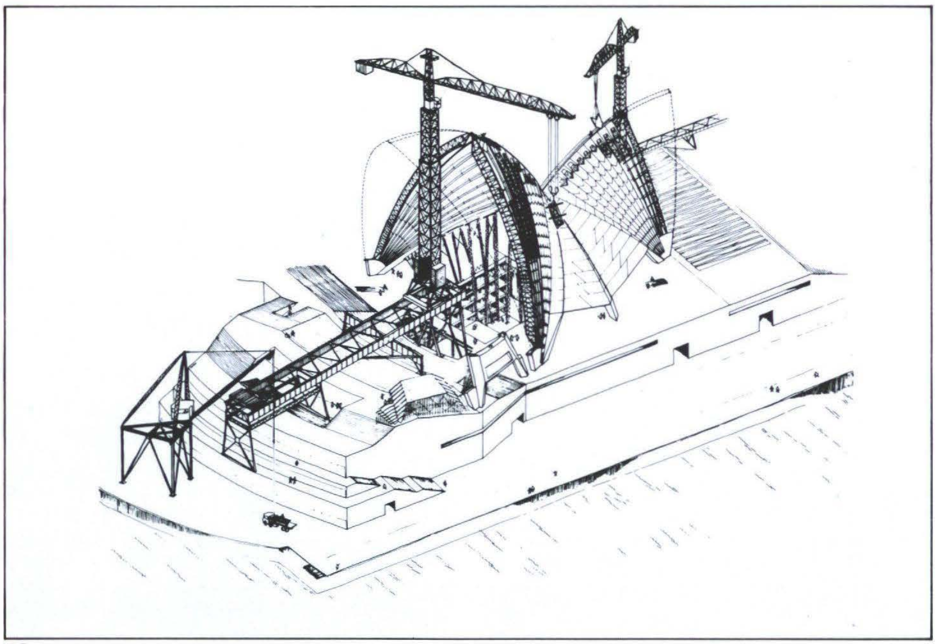

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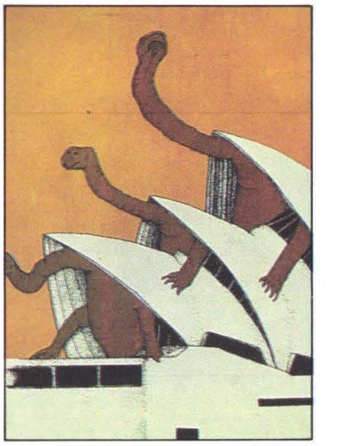

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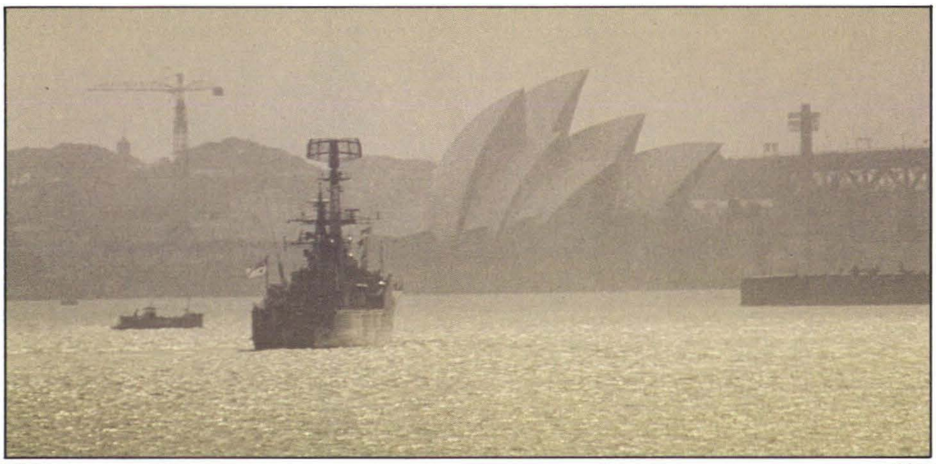

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Architecture, engineering and construction had become integrated into an indivisible whole when the roof design and construction evolved. Boundaries between professions and constructors became blurred.

Everyone felt he or she was working on something unique — a once-in-a-lifetime experience. There was a dedication to the whole, not just the part — it seemed as if perfection was within our grasp. But there were problems — escalating costs and lack of definition for the finishing of the building became a hot political issue and helped to bring about a change of government. Utzon couldn't, wouldn't, in any case didn't produce the kind of information his new political masters asked for. He resigned in 1966 — a complicated and at times acrimonious story. He left the job, he let down many of his friends and closest allies, he split not only the architectural profession but also the community as a whole and he left the project itself in chaos. The roof was substantially complete, and some people felt it should be left in all its glory as a testament to man's folly (17,18).

There had not been much progress on schemes for the auditoria acceptable to the client, nor were there any credible designs for the external enclosures and finishes. There was much emotion, passion and acrimony. What was clear was that whoever took on the daunting task of completing the project, whatever the result, it was a thankless one — the glory would go to Utzon and the criticism to his successors and others. Life without this extraordinary character was bound to be more predictable, plannable and orderly, but the magic was lost — maybe it was never attainable; probably not; but we were all infected by it in the early days.

In the event Sydney was very lucky. The government appointed three architects — two principals from established architectural practices; the third, Peter Hall, one of the principal architects working for the New South Wales Government Architects Department — a department which, though very big, had over the years established an enviable portfolio of well-designed buildings.

Hall, Todd and Littlemore, as the trio's firm became known, set about trying to implement some of Utzon's schemes and ideas. They found little of value — indeed the large hall whose primary function had always been that of a philharmonic hall had been planned as an Opera House, with inappropriate seating and acoustic qualities for a concert hall. They set about trying to fit the requirements of a very sober client into the now completed envelope.

The result is what is now being enjoyed by thousands of people. It is not what we dreamt it might have been, but it is pretty good by any standards, possibly as good as could realistically have been achieved. This is largely the work of Peter Hall, the design partner of the architects who took over.

Reflecting on the whole saga from the comfort of time is interesting. It was of course an extremely controversial project. The design was strange — people had no idea of the consequences of erecting these strange shapes in the middle of this beautiful harbour (19). Newspapers had a field day: if there was a shortage of copy, print something about the Opera House, real or imaginary. We even had predictions of its imminent collapse. One journalist likened it to a set of copulating terrapins (20), and this was before the lurid descriptions of our townscape by HRH.

But one of the most consistent and promising lines of attack was of course its cost. Early estimates based on a quantity surveyors' evaluation were wildly out. The roof was naturally blamed for much of the extravagance. Actually, of a final cost of just in excess of A$100M, just under 20% accounted for the completed structure, including all the roof tiles and the waterproofing. The cost per seat was really not that extravagant, but whatever the cost, does it really matter — that is if you can afford it in the first place? On one of my visits to Sydney in the mid '60s I was taken sailing on Sydney Harbour by a friend, and quite by accident I took this rather intriguing slide (21). Both artifacts have the same value — in money terms that is. One is a frigate recently purchased by the Australian Government for its Navy from the USA, the other the Opera House.

I said earlier that man does not live by bread alone. I have always been fascinated by Vitruvius's definition of the great qualities of architecture — *firmitas, utilitas, venustas* — which has more recently been recast in Henry Wootton's aphorism 'Commodity, Firmness and Delight'. Nothing has changed since Vitruvius or for that matter since Wootton's day — these are the criteria by which all our work as engineers or as architects is finally judged. With our newly acquired technical expertise we have advanced to a stage where we can write computer programs to encompass most if not all aspects of commodity and firmness — almost to a fault. In fact we are in danger of believing all the reams of paper spewed out rather than our reason and intuition, often forgetting the wobbly assumption on which so much of our analytical or financial work is based. But the point at issue is not that we should not ensure that commodity and firmness are both optimized for the problem in question but that we *cannot* write computer programs for delight. Accountants with their balance sheets; analysts with the cost benefit studies or the latest gimmick 'value engineering': none of these can quantify delight, can evaluate how much we, as the public, benefit from what may well be a folly — in financial terms at any rate. How can we even begin to estimate the enrichment when we enjoy something which defies a rigorous arithmetical cost analysis? I don't for one moment believe that anyone can begin to estimate the benefit which Australia and in particular Sydney has derived from the construction of the Opera House. One only has to wander to the peninsula almost any time, day or night, and one finds scores of people — not theatre- or concert- or opera-goers, but ordinary people who just go there because it is such a marvellous place to visit.

So for me looking back, not only has all the pain and suffering been worthwhile, it has brought a greater understanding of some of the issues associated with major projects which are likely to affect many people for many years. We are rightly appreciative of much which has been bequeathed to us from former eras, but we are not yet very good at producing things of value for our successors.

Another matter for reflection has been the effect on the people working on the Opera House. It was like climbing a new peak: Difficult, strenuous, would you make it or wouldn't you? and the tremendous exhilaration when you got to the top. But when you returned to base, what next? It was probably like a post-natal depression — I wouldn't know, I can only surmise.

But it did leave you with a feeling of achievement to play a part in such a major enterprise and the important consequence was that it made all subsequent projects so much easier, at least until the next equivalent challenges came along.

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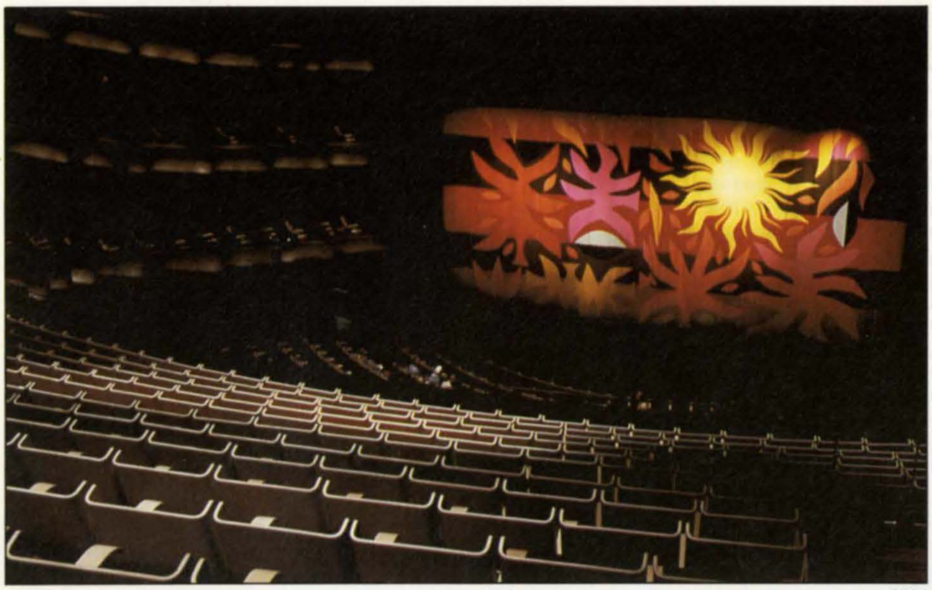

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There were some casualties en route, but those who saw it through, or at least saw through their particular task which they had made their own, were the better for it. Having been tested has enabled them to treat engineering problems, particularly ordinary everyday ones, with newly-acquired confidence, so that the indirect benefits, as a consequence of the talents and expertise being applied to other projects, are incalculable. And just think of the countless children here, in Australia and elsewhere who are spreading the gospel by telling all and sundry 'My Daddy built the Opera House'. They don't say singlehanded — that's inferred!

I was recently interviewed robustly by an eminent architectural critic* who tried to squeeze out of me a guide as to what constituted good engineering in the context of architecture. Was there some kind of natural order which made nonsense out of some of the more extrovert architectural engineering which creates some fun for us as well as some targets for the critics? Fortunately, engineers have not yet fallen into the trap of current architectural criticism where every artifact has to be pigeonholded into some predetermined style — Modern, Late Modern, Post-Modern, Classic, Contextual, and many more. But unfortunately engineers go too far the other way. They usually indulge in no more than implied criticism wrapped up in the most polite language. When papers are presented to our learned institutions, delegates will more often than not congratulate the authors on an excellent paper describing a most outstanding project when what they really mean is something quite different. Critical appraisal of one's work should be the order of the day, but while direct and open it should also be couched in language comprehensible to the average practitioner and not be thickly laced with the critic's own preconceptions and personal prejudices.

Is, then, the Opera House good engineering? There is in my opinion no clear answer. In purely technical terms, as I hinted earlier, there is a lack of logic in the way the forces are transmitted to the ground. And since the structure is on a very large scale, the lack of logic could be said to have similar proportions. But the structure of course is of no use by itself — a more rational structure would have created a fundamentally different building. Whether such a building would have yielded as much delight is doubtful.

Engineering is an art and a science — a cliché which is obvious but often forgotten. Architecture is primarily an art — some say the mother of the arts — a cliché which is also obvious. However, good, even outstanding, engineering does not always result in good architecture. Conversely, good and even great architecture can be created even though the engineering is indifferent. However, when engineering or more accurately, technology is harnessed deliberately as a tool in the service of architecture, the frontiers become blurred. Engineering and architecture become a whole and the result should be judged as such.

Sydney Opera House is the result of a total integration of technology in architecture. While a number of detailed innovations and techniques have served us and the industry well over succeeding years, the engineering whole can only be judged in the context of its architecture.

There remains the question as to whether it is a good building. We know only too well that architectural landmarks, and even masterpieces, don't necessarily make good buildings. I mean here that they may look good, they may even be worth experiencing as magnificent spaces, but as functional buildings they may be flawed. I am on thinnish ice here because there are clearly critics more qualified than I to comment. Some of us felt the Opera House should have been more perfect than it turned out to be. The volume required for the philharmonic hall had to be squeezed into what was available and certainly some of the great vaulted spaces which one should have experienced on circulating around the building, have been diminished in size and scale. Opera was relegated to the smaller hall, and while it is perfectly satisfactory for most of the operatic repertoire, the elephants and camels appropriate for a production of *Aida*, would have some difficulty in passing through the front door, let alone finding parking space on stage between acts.

However, taken as a whole it functions pretty well. The orchestral hall (23) is a splendid space in which to enjoy one's music and the accoustics have turned out to be more than satisfactory. The opera hall itself (24), as well is functional, particularly since the orchestra pit, which was too small initially, has been enlarged. There is a repertory theatre, a cinema, a chamber music room (25) recording hall (26) and several rehearsal rooms, all of which are fine. But of course the building has its critics — tell me one that hasn't.

With these views of the complex, functioning and very much a part as well as a symbol of the city life, if not the country, let's leave the Antipodes. Sydney Opera House was our job number 1112 — one that is the title of a movie but which is also forever imprinted on the minds of many of us who worked on it. Centre Pompidou was number 4123 and Hongkong and Shanghai Bank 9933. These numbers are of no interest to you, except to illustrate that in between these well-known high profile projects we do carry out hundreds of other often much more modest tasks as either civil or building engineers, most of which don't reach the headlines.

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*JENCKS, C. The aesthetics of engineering: Charles Jencks interviews Jack Zunz. *Architectural Design*, 57 (11/12), pp.37-48.

Sydney Opera House (30), Centre Pompidou (27,31) and the Bank (32) happened at roughly 10-year intervals. Each in its very own way has attracted much attention both during construction and after completion. Each project has its own idiosyncratic visual imagery. There are some interesting similarities as well as some striking differences.

All three projects were the subject of international competitions. Sydney Opera House and Centre Pompidou were open international competitions, while Hongkong Bank was a limited invited competition, so clearly the odds were shorter. It is interesting to note that Utzon was listed as being one of the assessors for Centre Pompidou, but did not take part in the adjudication. Pompidou and the Opera House competitions had defined briefs while the object of the Hongkong Bank was to select an architect. All three competitions were won by relatively unknown architects — this is probably more true of Utzon and Piano and Rogers (Pompidou) than in the case of Norman Foster who had received some acclaim for two or three projects, although these were considerably smaller in scale than the Bank. All three buildings turned out to be milestones of engineering in architecture. In each case, in very different ways, the technology of the building was used explicitly to give it its own unique aesthetic quality.

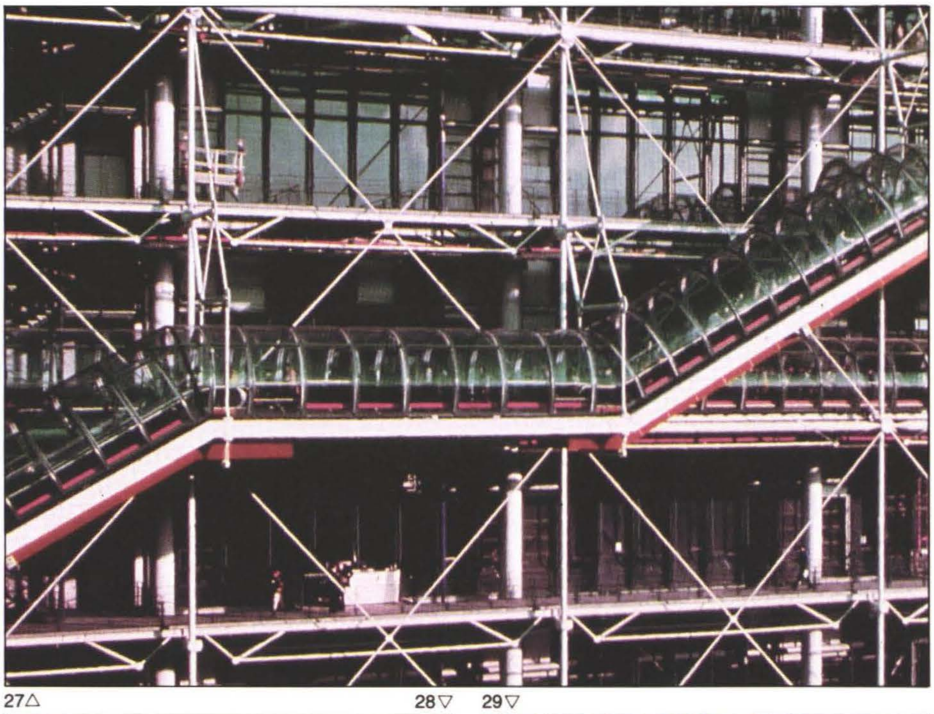
Also, in each case, in order to achieve this distinctive aesthetic quality we worked at the limits of the technology of the day. In some instances the frontiers were extended by some innovations. I have already mentioned the use of epoxy glued joints and prestressing on the Opera House, the essential role of computers, and developments in glass technology. There was also the development of non-ferrous metals for certain fixings (we even used titanium), as well as in the surveying techniques which were complex as a consequence of the geometry of the building. But above all, while the basic sculptural composition was an architectural or artistic concept, the subsequent geometric discipline to which we subjected the building resulted in a clear expression of the underlying engineering forms.

Centre Pompidou, 10 or so years later, was of course built in steel. While the Opera House exploited concrete, prestressed and ordinary, to its limits, Pompidou and subsequently the Bank used the technology of structural steel. Pompidou is particularly interesting in that there is a theme to the exposed structure in that all tension members are solid steel, all compression members are hollow tubes, while joints and nodes are cast steel. This language was created deliberately in order that the structure could be read explicitly. To achieve these objectives meant using cast steel on a scale and of a quality not experienced in contemporary building technology. Use of fracture mechanics technology made the predictability of the performance of large weldable castings possible. The structure being externally unclad meant that the building's susceptibility to fire had to be scientifically investigated. Codes of practice, rules of thumb and normal building regulations were not helpful. An innovative analysis showing which members of the structure were expendable without catastrophic collapse made it possible to design the building in such a way that no fireproofing of the external structure was required, with the exception of the columns. These were liquid-filled and, without the possibility of natural flow in the event of the liquid being heated beyond normal temperatures (28), they were designed to operate like kettles. There were also some innovative features about the foundations to the main columns known as barettes.

On the Bank (32), while the structure again generally gives the building its distinctive architectural expression, the steel structure is actually clad in a sophisticated aluminium system — early attempts to design a liquid-cooled system proved to be unsuccessful. However, for the first time technology developed for the oil industry for their offshore platforms was applied to a building on a major scale (29). The corrosion protection, a cement polymer mixture sprayed onto the steel, was uniquely developed for the project. The major innovations were more in the way the technology was applied rather than the technology itself. Wind studies probably were the most comprehensive ever undertaken for a building project. Full-scale prototype testing of structural members was carried out to verify the extensive computer modelling and the disposition of vierendeel frames to resist windloads were but some of the more unusual technical features of this building.

It is interesting to reflect that in the 20 or so years between the time when we designed the structure of Sydney Opera House to when we were designing the Bank, advances in concrete technology were far outstripped by those in steel — largely as a consequence of much research and development on offshore structures, the rise in strength of the Japanese steel industry, and market forces which had left steel structures for buildings out in the cold for 10 to 20 years after World War Two. But what is worth noting is that all three projects produced technical expertise and fallout which was of direct use on subsequent, often much less high profile, projects.

There were similarities, too, in the construction of the three projects. There was the usual initial euphoria, followed by panic — but in all three cases there was a midlife crisis which placed the very completion of each project in jeopardy. In Sydney, despite a number of minicrises (major ones on any normal project) the balloon really went up when Utzon resigned. If we had at that time walked out too I sometimes wonder what would have happened. In Paris there was also a crisis where the project was in danger of being abandoned about half way through, while on the Bank confidence (or lack of it) in the future of Hong Kong at a time when there appeared to be disagreement in the client's camp as to how much the building should cost led some of the Bank's board members to suggest abandoning its construction. It was a very close run thing.



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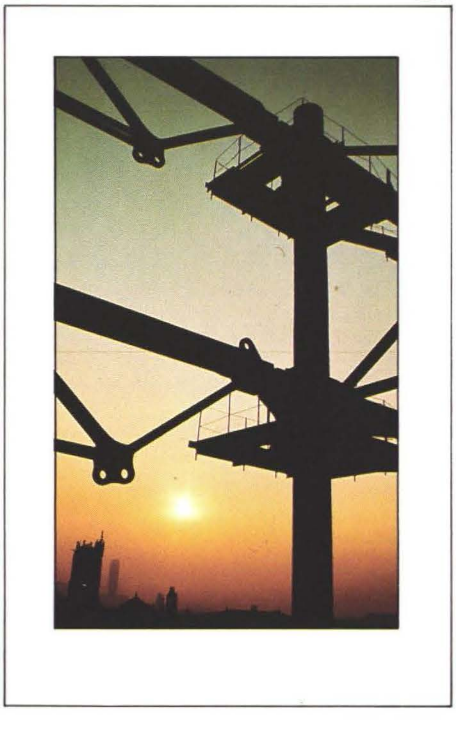

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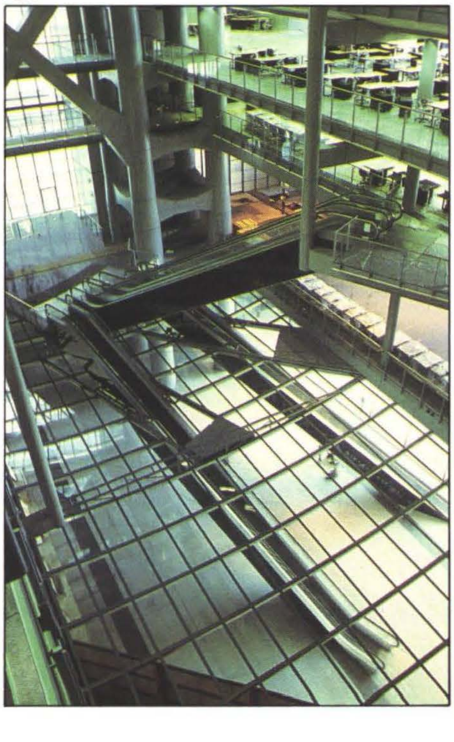

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Photo: Ian Lambot

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Photo: Ian Lambot

All three projects had architects who were or rather are exceptional talents and who, like all exceptional talents, create difficulties, albeit unwittingly, in their search for excellence. Whatever one may feel about the architecture of the three buildings, none would deny that all three are real and exceptional architects in the sense that they are willing to use their talents unsparingly to achieve as near perfection as they see it. And of course in all three buildings we were around at least as willing accomplices.

There were also some significant differences. In the New South Wales Government there was a well-meaning, patient client who didn't really know what he wanted, except that he wanted the best. In France, with typical logic and radicalism, a very powerful client body was erected which proved to be a pivot around which the project was completed within strict time constraints and within cost limits set by the client — an example of the essential function of the client mentioned earlier. The Bank simply wanted the best building in the world — the brief was worked out as we went along, which caused the architect, and all of us, untold difficulties. And despite these and other unforeseen problems in the ground, the building was completed on time — which was astonishingly short. Cost limits were set as we went along, so it is difficult to make comparisons.

Again, Norman Foster, Richard Rogers and Renzo Piano stuck to their guns and have gone from strength to strength acquiring international fame. Utzon, possibly for personal reasons, no-one knows, has done very little: a church in Copenhagen, a building in Kuwait (this was completed by others) — an incredible waste of a massive talent.

One last reflection. I said earlier that it has become progressively more difficult to find enlightened patronage, which is a prerequisite for the creation of anything of lasting value. This is made more difficult by the media where it is now everybody's right to know everything immediately — which is all very well, provided the information is relayed accurately. It isn't usually, so that these projects which have a high profile become very political often before they have even been designed, a process which more often than not threatens their very realization.

That's really all I want to say tonight — it's enough anyway. What I have spoken about is engineering in the service of architecture.

It is an activity that can of course have its frustrations — I suppose all human endeavour has its trials as well as its tribulations. And in these days of specializations, it is more important than ever to concentrate on human qualities as much as on technical ones. However brilliant the engineer and architect, if they cannot or will not communicate or work together effectively, the building will suffer. We must learn to understand the problems of our collaborators and when we do and they understand ours, engineering is or should be a creative and challenging activity. And when it is associated with interesting, or even better, great architecture, it can be exciting and very rewarding.

Engineering in the service of or as part of architecture is an activity which is much discussed. I use the words 'in the service of' deliberately, because it is commonly accepted that the architect is, or on most building projects should be, 'Primus inter pares'; not to make too fine a point, he is supposed to be the leader. By the same token, much of our built environment is the result of projects designed by engineers. They are in the lead — so I leave you with the thought that perhaps more exposure and debate should concern itself with architecture in the service of engineering.

The cast steel nodes for Lee House

Architect: Terry Farrell Partnership

Christopher McCarthy

Introduction

The reasons for the use of a gigantic transfer structure to carry part of the Lee House replacement building over London Wall, and a brief description of it, have already been given in a previous *Arup Journal*[1]. The present article describes the reasoning leading to the selection of cast nodal connections for the transfer structure, as well as examining the development of an innovative design from a conventional one. It also relates the important stages in the production of the cast steel nodes.

Apart from supplying the necessary structural support for the building, the design of the transfer structure also had to take into consideration the architectural and planning requirements of the public space into which it was to be positioned; this was the podium level. The final solution consists of four cable-stayed trusses in the centre of the building, with two bowstring arches at either end.

The design of the truss and arch structure came about in answer to the City Engineer's brief which forbade the closure of London Wall during the working week. In order to reduce the risk of ill fit during construction, the primary ties of the arches and the trusses became adjustable lengths of bars, these being fixed to the steelwork through the means of cast steel nodal connections. In order to reduce the size of the latter to a minimum the bars are fixed at the back face of the nodes.

Each truss has two joints consisting of octagonal cast steel nodes about 2.2m long by 1.4m across, weighing about 17.5 tonnes each. The arches also have two joints each, consisting of cylindrical cast steel nodes about 1.6m long, 0.9m in diameter, and weighing some 5 tonnes each.

Design development of the truss node

The diagonal and horizontal bars of the truss are continued through the node and secured on the outer surface by steel nuts. This arrangement maintains the bottom node in compression and keeps its size to a minimum. The octagonal section provides a plane surface through which the bars pierce the node and a plane surface on its opposite side to which the bars are fixed. The overall size of the node (1.5m × 1.5m × 2.5m) was determined from the 200mm and 300mm spacing of the bars.

Originally an octagonal fabricated steel hollow section filled with grout was envisaged. Grout-filled tubular connections are becoming common practice in the offshore industry, but the design team felt that such a structural solution for this project would require a period of laboratory testing to establish the long-term effects of creep and shrinkage of the grout with respect to the outer steel casing. Due to the lack of sufficient time for testing, however, the grout was replaced by four diaphragms.

A number of fabricators were approached to discuss the fabrication of the diaphragm steel nodes, and to provide costings. They suggested a number of different shapes instead of the octagon to reduce the amount

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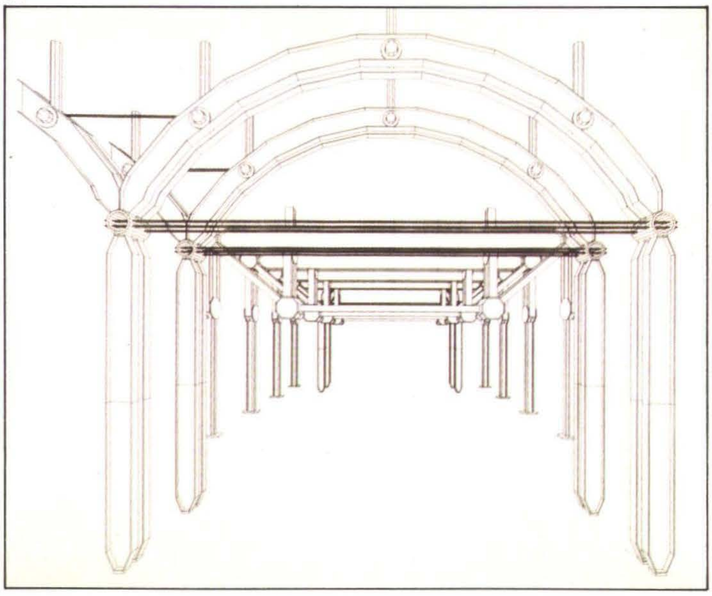

1. Model of air rights building over London Wall (Photo: The architects)

2. Model of transfer structure supporting air rights building frame (Photo: Peter Mackinven)

3. Computer graphic of the transfer structure (Graphics: Terence Haslett)

4. Preliminary model of truss node (Photo: Harry Sowden)

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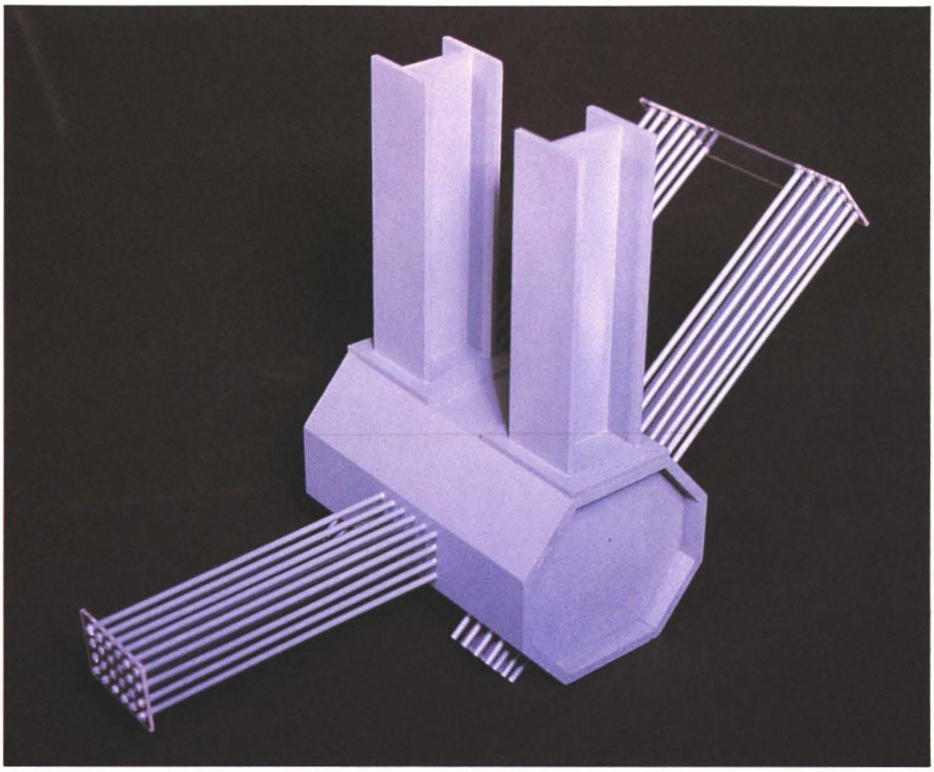

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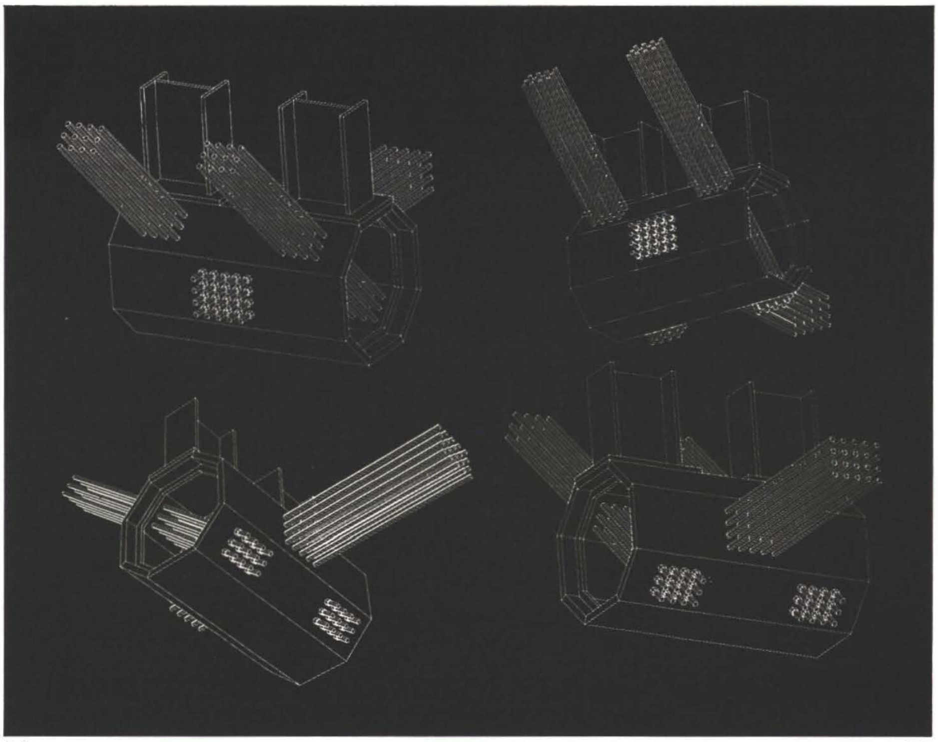

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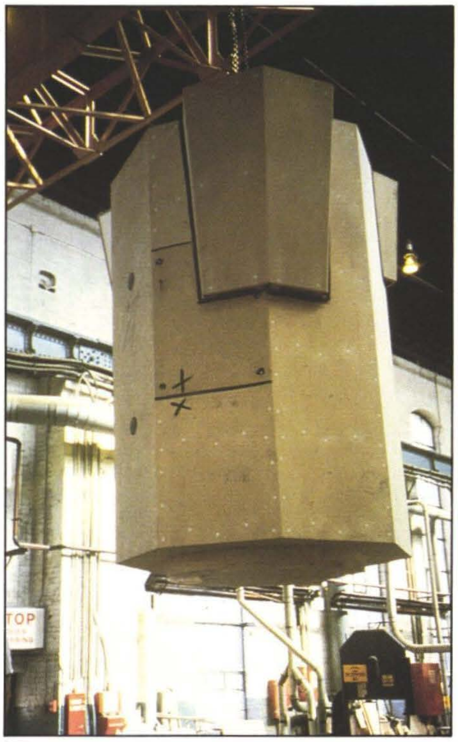

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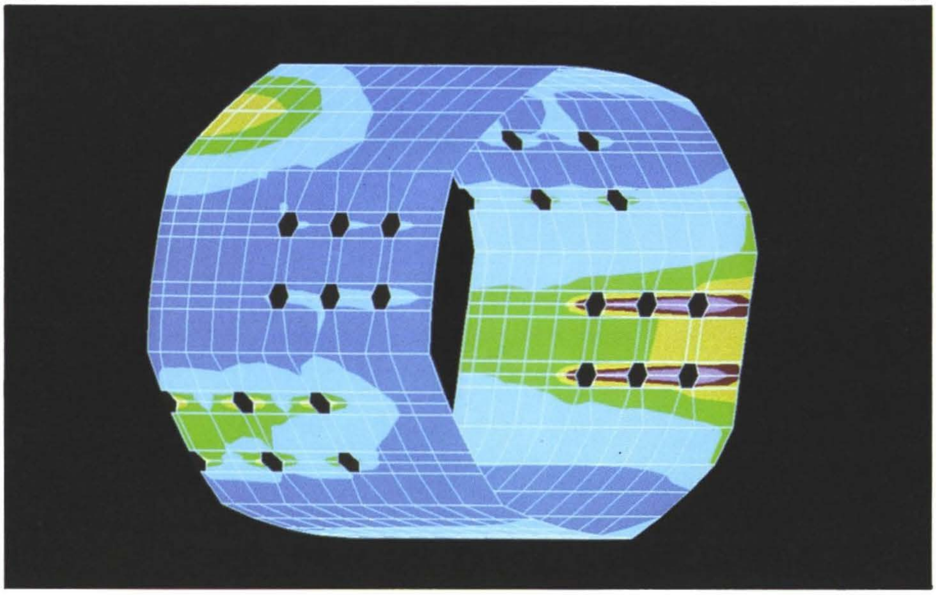

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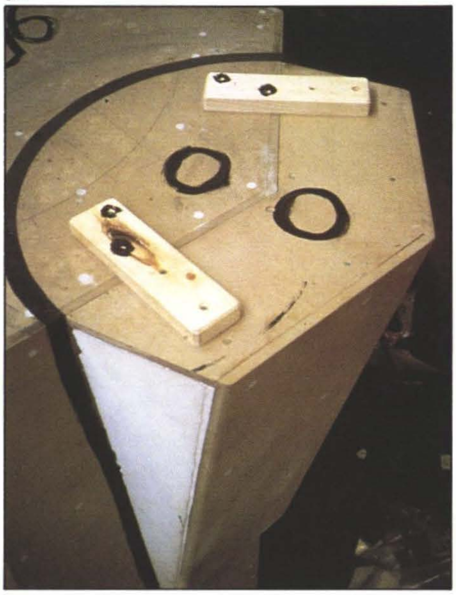

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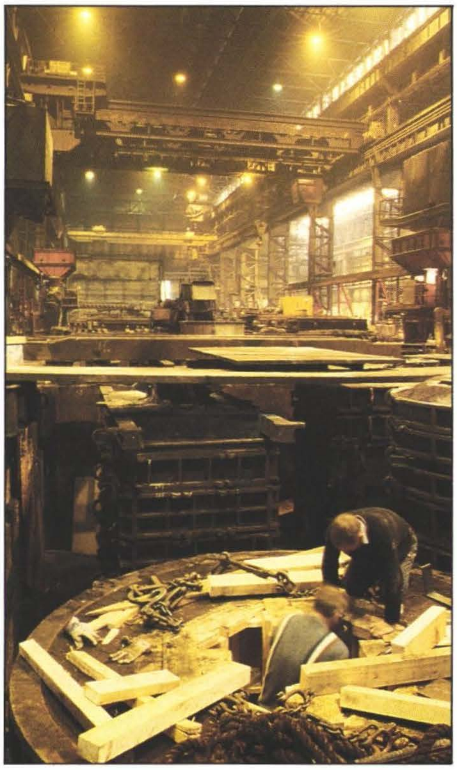

5. Preliminary computer graphics of truss node

6. Preliminary computer graphic of loaded truss node stress pattern

7. Wooden pattern of truss node
(Photo: Christopher McCarthy)

8. Detail of wooden pattern for feeder to truss node
(Photo: Christopher McCarthy)

9. Dismantling wooden pattern from sand model
(Photo: Peter Mackinven)

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of welding, amongst them a rolled tube with cast end plates and a rolled tube with machined ends. These were investigated but the wall thickness of the tube (100mm) was considered too much to roll on a 600mm radius. Also, the circular diaphragms were difficult to fit.

At this time the feasibility of casting the nodes was investigated. Unfortunately the development of castings in the building industry is hindered by a number of misconceptions with respect to both materials and casting procedure. These are:

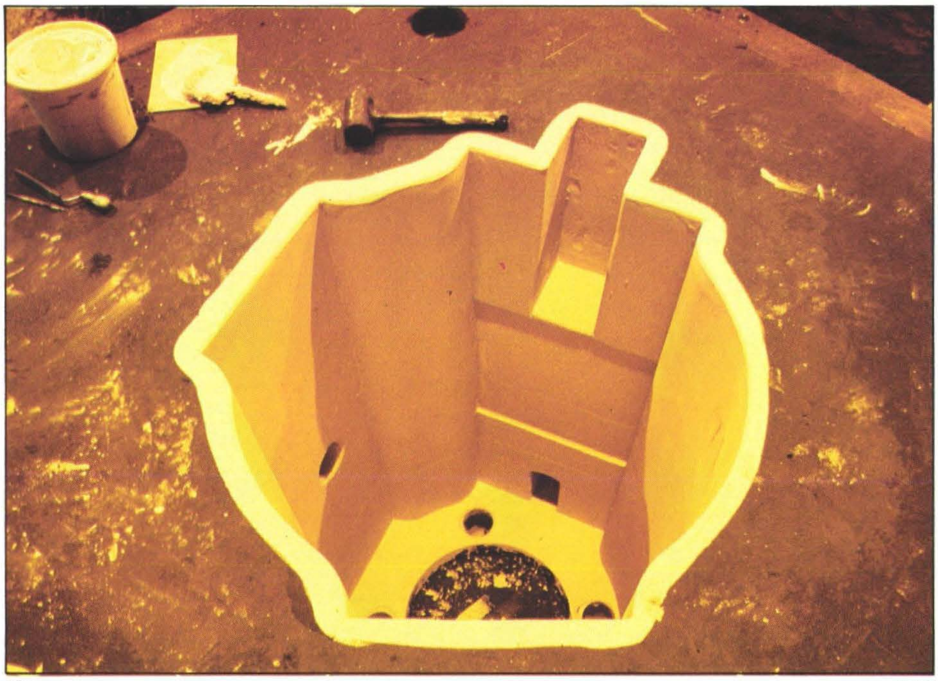
Materials
Castings are thought brittle and unweldable. This is not so. Cast steel can have similar physical properties to grade 50D steel.

Manufacture
Castings are often thought to contain unacceptable cavities. However, structurally sound castings can be achieved by high integrity foundries, though not necessarily by the type which produces ornamental metalwork.

Testing
Cavities in castings are considered impossible to detect. This is not so. Facilities such as ultrasonic testing and radiography can detect satisfactorily cavities and impurities in castings.

It was agreed that a thick-wall cast node without any internal diaphragms would be worth pursuing.

Final design of the nodes
The cast nodes were designed with the assistance of Arup Research & Development and the Industrial Engineering Group using a finite element program to analyze the stress distribution through elements and deformation of elements generated by imposed loads. The results of the analysis were drawn on a VDU screen. Three-dimensional colour plots of the stress distribution through the node instantly illustrate where the node is working the hardest. From this information its shape was modified accordingly.



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10. Sand mould with wooden pattern removed, preparatory to pouring of molten steel (n.b. mould for cylindrical node for arches illustrated). The resin-impregnated sand is hand-compacted to the hardness of sandstone around the pattern; after removal of the latter the mould is coated with a sealant and hardener. (Photo: Peter Mackinven)

11. Pouring molten steel into mould
(Photo: Christopher McCarthy)

12. Finished cast nodes in the foreground, with heat treating in process at the rear left.
(Photo: Christopher McCarthy)

13. Machined node under load test from C-shaped cast steel rig
(Photo: Peter Mackinven)

14. Truss erected with nodes. Diagonal bars yet to be installed.
(Photo: Peter Mackinven)

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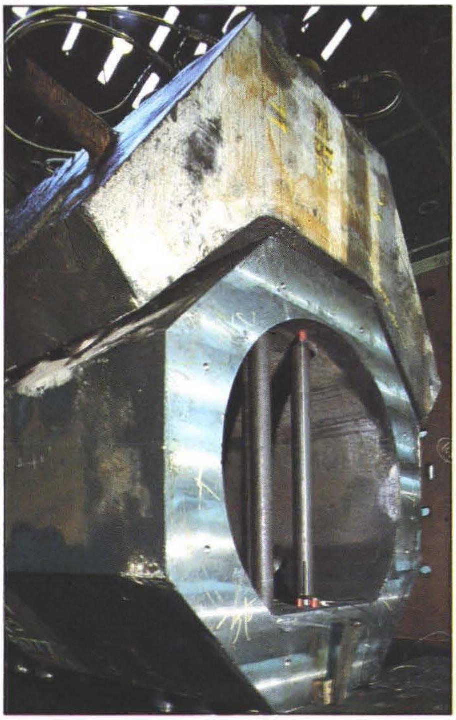

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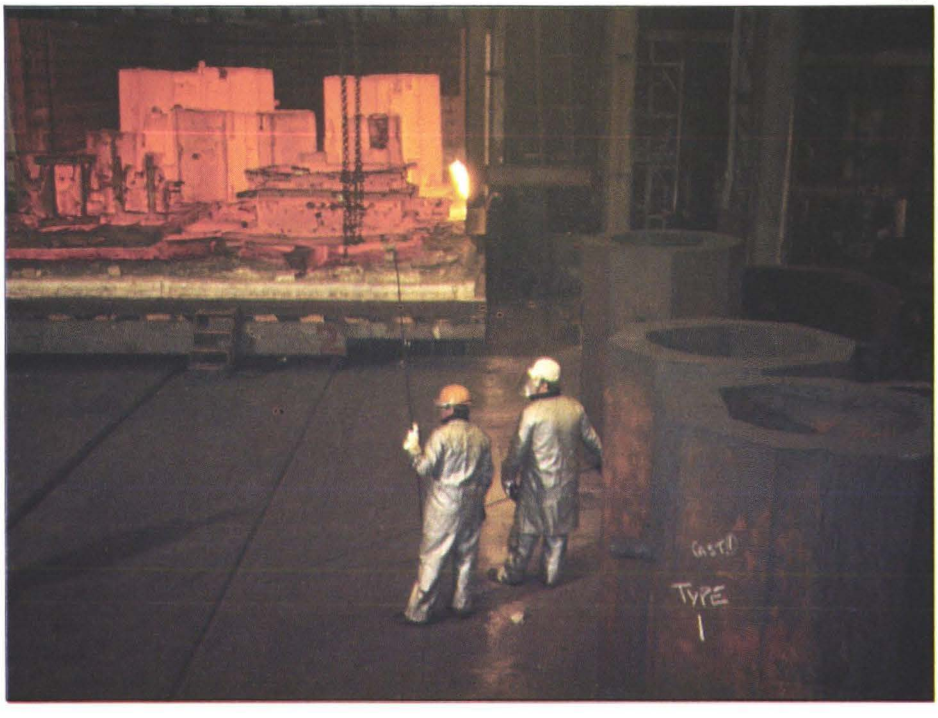

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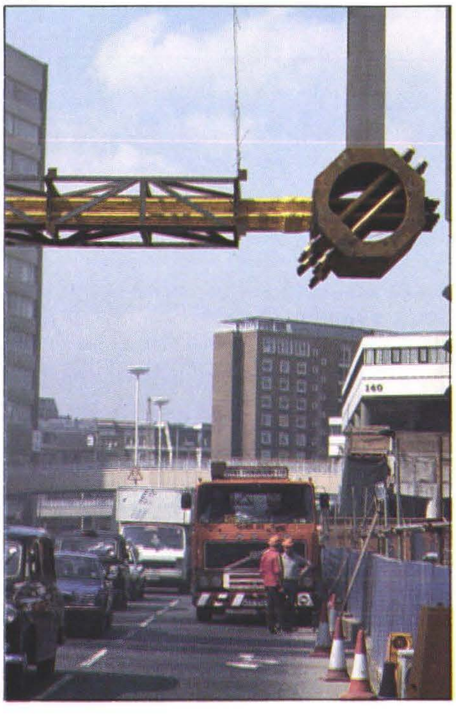


Subsequent to this, River Don Castings of Sheffield were invited to discuss the form of the nodes and to provide a budget price to cast them. Even though the cast nodes were heavier than those with fabricated diaphragms (17 vs. 12 tonnes), the cost was significantly less.

Price, design and technical advantages all favoured the cast solution, and the fabricated diaphragm idea was not developed further.

Choice of supplier

To avoid becoming totally dependent on River Don Castings as a single supplier, Lloyds (Burton), Edgar Allen, Stanton, David Brown, North British Steel Group, Folkes Group and Hoesch of Germany were also invited to submit their cost estimates. Some of the foundries did not have the capacity and others proposed to forge the nodes as opposed to casting them. But forged nodes were more expensive. In August two foundries were asked to tender for the node contract and River Don Castings were subsequently successful.

Since 1982 this firm has produced over 300 high-integrity steel castings weighing between one and 300 tonnes. They have been responsible for supplying 60% of the world market in offshore structural castings.

Production of the cast nodes

Cast iron connectors were commonly used by Victorian engineers. With the advent of welding since the turn of the century, connections could be formed from plates of steel welded together. At that time fabricated connections had a number of advantages over cast connections. They could take tension, were simpler to design, checking and rectifying fabrication were simpler processes and they used less material.

Today, steel sections are commonly welded together or bolted in the absence of cast connectors, but with foundries such as River Don Castings who have a progressive policy towards producing high integrity structural castings, cast connections are becoming a competitive alternative to fabricated options. Since the early '70s this firm has maintained an extensive research and development programme, and has satisfied the needs of the service industry with particular reference to offshore oil and gas installations.

North Sea technology may seem out of place in the building industry but, considering the magnitude of forces that the transfer structure of the air rights building is expected to support (2500 tonnes per truss — the weight of a cross-Channel ferry), it seemed a natural course to follow.

These are the first cast steel nodes that River Don Castings have supplied for a building and as far as they are aware are the largest castings ever to be used in a building.

The cast steel was supplied to an ultimate tensile strength specification of 490 N/m^2 minimum and 640 N/m^2 maximum, with a Charpy V Notch together of 40 joules at $-15°C$. These specifications give similar properties to grade 50D rolled steel.

The nodes were cast during August-November 1987. The casting sequence was as follows:

(1) Workshop drawings
(2) Patterns
(3) Sand moulding
(4) Casting
(5) Removal of risers and abrasive blasting
(6) Heat treatment
(7) Rough machining and/or grinding
(8) Magnetic particle and ultrasonic testing (where applicable)
(9) Weld repair
(10) Magnetic particle test of weld repairs
(11) Radiographic testing
(12) Weld repair
(13) Magnetic particle and radiographic testing (where applicable) of repairs
(14) 400°C stress relief treatment for 24 hours
(15) Hydrostatic testing
(16) Final machining
(17) Magnetic particle testing
(18) Minor repairs (up to the lesser of 9.5mm or 10% wall thickness in depth)
(19) Magnetic particle test of repairs
(20) Load test
(21) Corrosion protection.

Important stages in production

Casting of the nodes did not simply consist of pouring molten steel into a mould and leaving it to solidify. This would produce a shape whose dimensions and general quality would be quite unacceptable. Each cast node was produced by box moulding and wooden pattern assembly techniques, which were carried out under a quality control and quality assurance system. This includes chemical and physical tests and ultrasonic and radiographic inspection of each cast node.

Preparation of the moulds

On receiving the drawings of the nodes, River Don Casting prepared the mould drawings. The moulds are not a simple negative of the casting, but allow for the flow of molten steel, as well as its contraction as it cools and solidifies. Each foundry has its own approach to casting and individual methods are very much a trade secret.

From the mould drawings their respective negative pattern drawings are prepared at 1:1 scale. From these drawings the wooden patterns were made in the pattern shop.

Assembly of the mould with wooden patterns

The patterns were mounted vertically on flat bases and enclosed by a rectangular box. Moulding sand was the packed inside the frame so that it took up the shape of the pattern, which was then withdrawn from the sand, leaving a smooth mould. This was 2% larger than the final casting to allow for thermal contraction of the solidifying molten metal.

Casting

Molten steel was then poured into the mould. This only took a few minutes, but about three days were needed for cooling before the sand mould could be stripped, and the sand sent back to the moulding yard to be re-used.

To compensate for the contraction when the molten metal solidified, feeders were incorporated which acted as a reservoir of liquid metal. This had to remain molten until the cast node had completely solidified. When cooled, the feeders were cut off and sent back for remelting.

Inspection and testing

Each cast node was then cleaned for the first visual inspection. To detect defects beneath the surface of the casting, ultrasonic inspection was carried out over the whole surface of the node. This test depends on the reflection of the sound waves from an interface within the material. It is possible to detect cracks and two-dimensional faults as well as three-dimensional defects greater than about 1mm.

Radiographic inspection was also carried out where necessary. This is much more expensive than ultrasonic inspection, and it can only detect three-dimensional faults and not hair-line cracks, but it does provide hard copy evidence.

Preparation

When surface or internal faults (air voids or lumps of entrapped sand) were detected, they were removed by cutting out with an arc-air lance. The cavity was then filled with sound metal by welding, compatible with the original cast steel. It is normal practice for castings to be repaired in this way. After repair, heat treatment was carried out to refine the grain structure and eliminate residual stresses introduced by welding operations.

The size of defects (6mm + holes or lumps of entrapped sand in or beneath the surface of the cast node) may seem alarming to anyone unfamiliar with steel castings, but this should be regarded in the light of the thickness of the steel, which is usually between 150mm and 430mm. Such voids are commonly detected in ingots for rolled steel plate and they also have to undergo a similar inspection and repair process where necessary.

Mechanical and chemical test data were obtained from small protuberances, known as 'coupons', which are made as an integral part of the node. The coupons accompanied the node through all the stages of manufacture, eventually being cut off and tested when the casting was ready for despatch to the machine shop. River Don Castings subcontracted the machining of the nodes (planing of surfaces and drilling of holes).

The levelling of the bearing plates and the alignment of the holes were crucial activities and had to be executed to within ±0.1% tolerances. Once the machining was completed and tolerances checked, each node was load tested.

Testing

River Don Castings were commissioned to provide test rigs: a C-shaped rig for the octagonal truss nodes and an A-shaped rig for the cylindrical arch nodes. Each node was to be loaded by jacks to 1.25 times its design load. During the loading sequence a number of strain gauges positioned around the node measured and recorded the deformation under loading. From the measurements taken, we were able to determine that the node was behaving elastically. All the nodes have proved to be satisfactory.

It is important to emphasize that the primary purpose of the load test was *not* to prove the design, but to ensure that the manufactured product was fit for use as a primary structural element in the building.

Once each node had passed its test it was sand blasted and painted. They were then stored off site until March 1988, at which time each node became an integral part of the eight transfer structures.

Conclusion

It is advisable to place the need for the casting option for the nodes in perspective. Many a client, consultant or contractor warns against innovation for its own sake. There is little to be gained from introducing new ideas if they cannot be justified on economic grounds. However, on this project the cast nodes have provided the client with a most economical solution, as well as being technically and visually most appropriate for the purpose they are required to meet in the structure.

Credits

Client:
MEPC
Architect:
Terry Farrell Partnership Ltd.
Engineer:
Ove Arup & Partners
Management contractors:
Mowlem Management Ltd.
Castings sub-contractor:
River Don Castings Ltd.
Steel erection sub-contractor:
RDL Ltd.

Reference

(1) SANDERSON, C. Lee House redevelopment transfer structure: a painting by Ben Johnson. *The Arup Journal, 22*(2) , pp.15-18, Summer 1987.

Linn Products Eaglesham, Glasgow

Architect:
The Richard Rogers Partnership Ltd.

Peter Evans
Jane Wernick

Introduction

Linn Products manufacture hi-fi and computer equipment and write and develop software. Discerning music lovers with all kinds of taste aspire to ownership of their hi-fi equipment, in particular the turntable. This is considered to be the most fundamental and important component in a hi-fi system and the Linn *Sondek LP12* turntable, while engineered to the highest standards of design and precision, is in outward appearance, simple and free of gadgetry.

Their requirements for a new building reflected a similar principle. It was their wish, having acquired a green field site, to establish a prestigious and attractive headquarters and manufacturing complex which would enhance their reputation, but which would not be ostentatious or out of character with its surroundings. However, inside, the factory would use the most modern manufacturing equipment, CAD/CAM techniques, and computerized and automated systems for the distribution of materials around the building. The scheme also had to allow for future expansion.

The site, to the south of Glasgow, in rolling and wooded countryside overlooking the Clyde valley, was sensitive and planning permission had been obtained on appeal to the Secretary of State, subject to reserved matters concerning massing and colour.

The site

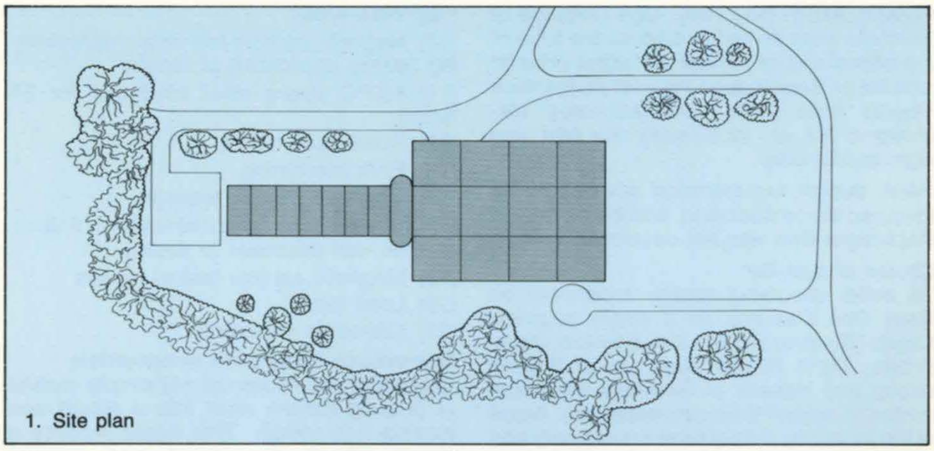
The hill top site (Fig. 1), is sheltered by mature trees to the south and west but is exposed to the north and east, with long views overlooking fields. A previous borehole site investigation, supplemented by later trial pits, showed a general succession of fill and topsoil overlying glacial till overlying basalt, which had weathered on its top surface. No groundwater was observed, except for slight seepages in the rock in wet weather. The site slopes from west to east, fairly gently at first then becoming steeper. The basalt is nearer the surface to the west, covered by only about 0.5m of topsoil and glacial till, while to the east the bedrock is very much deeper, overlain by about 3m of glacial till and fill (Fig. 5).

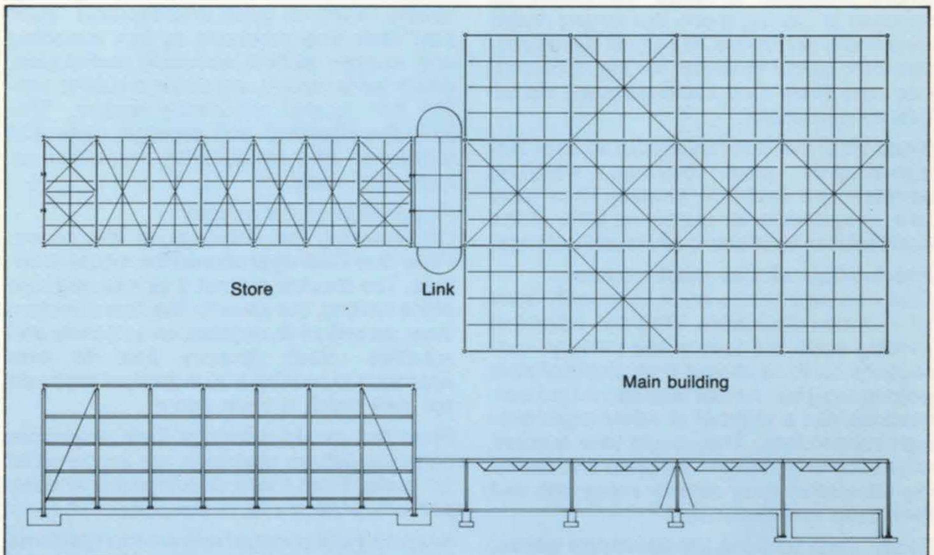
The site was occupied by a derelict house, outbuildings and hardstandings used by vehicle repairers, and a neglected formal garden surrounded by a high stone wall.

The development

One of the most important considerations in the development of the brief was the part that automation was to play. The manufacturing work-stations would be supplied with materials and components from an automated store, using computerized retrieval systems and automatic guided vehicles. This system would also deal with the receipt of incoming materials and the despatch of finished products.

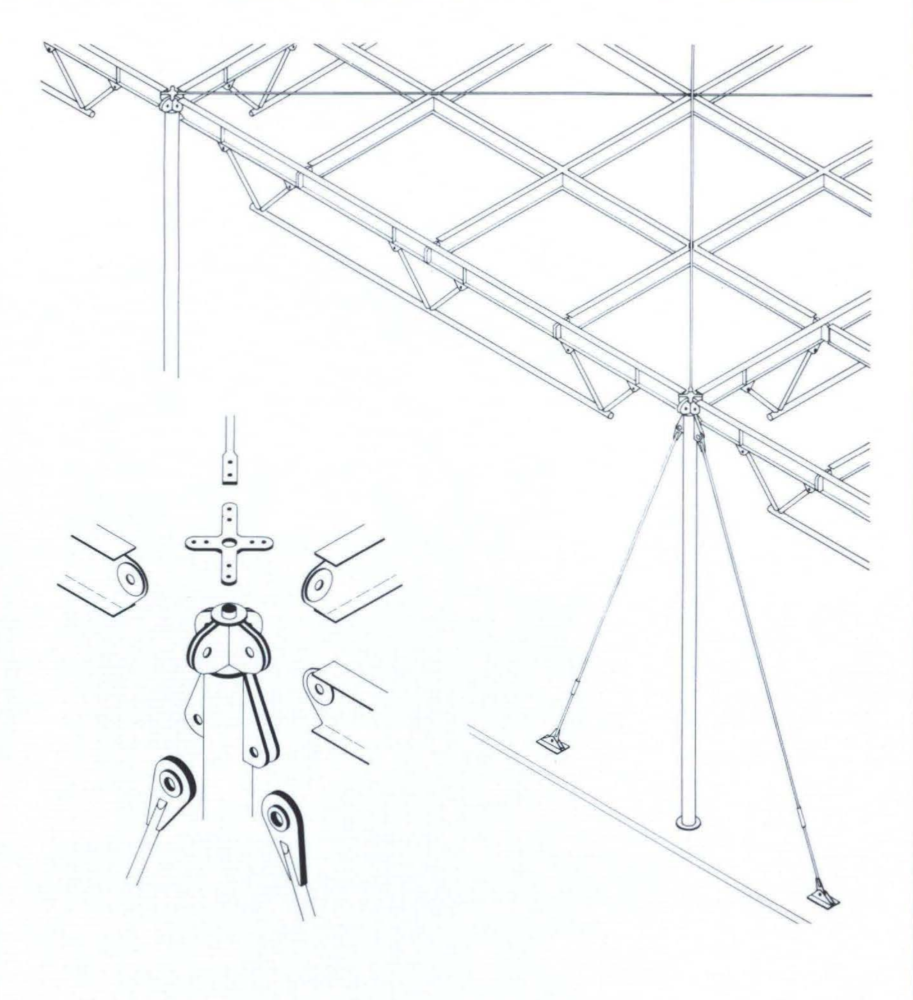
The development comprises a main building linked to the store. The former is used as the head office and also houses areas for demonstration rooms, research and development, manufacture and quality control. The store contains racks to either side of the main aisles, along each of which a vertical crane travels. This runs on a floor-mounted rail and is secured by a top rail, fixed to the racking. The cranes receive instructions and automatically pick the goods on their pallets from the racks. To work to the best efficiencies there are rules concerning optimum aisle lengths and heights, based on the horizontal and vertical speeds and accelerations of the cranes. In general the higher the store, the more efficient. The size and shape of the store then depends on the storage capacity required, the numbers of cranes needed to service the factory and, at the detailed level, the aisle widths and racking dimensions, which vary between manufacturers. Such equipment is subject to continuing technical advancement and change, as well as being expensive. The correct choice by the client is thus crucial to the future success of his firm's business. Inevitably, such decisions are left to the last moment, and probably a little beyond, to ensure that the best and most advantageous arrangements have been made.


1. Site plan

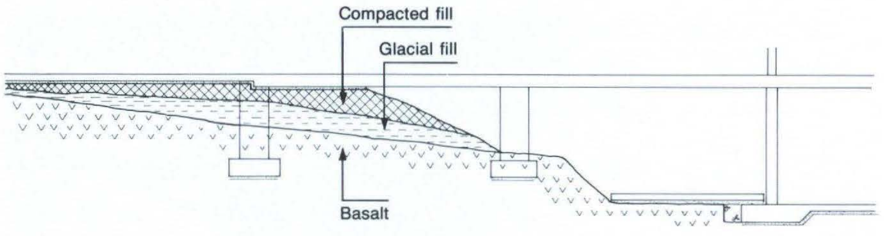


2. Framing arrangements

3. The main building



4. Steelwork details of main building



5. Part section through main building

6. Main building and store

The store and main building are joined by the link, where goods are transferred from the cranes to the automatic guided vehicle by means of a conveyor system.

Clearly, in planning terms, a building like the store presents a challenge, especially on a site in the country, because it is required to be tall and since it is uninhabited it does not need windows and is, therefore, no more than a simple box. The impact of such a building has been lessened by compromising on the height and by locating it against a backdrop of surrounding trees.

This position is also advantageous in relation to the ground conditions, where the basalt is closest to the ground surface, providing a solid foundation for the ground slab that supports the substantial loads from the feet of the racking system.

The main building

In contrast to the more basic requirements for the store, the design options for the main building were greater, although the proximity of one to the other was an influence. The scheme designs ranged from the very simple, in the manner almost of agricultural buildings, to solutions deriving from the style of previous projects by The Richards Rogers Partnership — Fleetguard and Patscenter with their masts and ties. However, the latter types did not seem appropriate, nor was it believed they could be sustained by the budget. Therefore, a simple form evolved owing more to the influence of Mies van der Rohe than their recent works.

For the main building and the store a 14.4m module was established (Fig. 2). In the main building there was the desire for this module to be seen to build up in squares and this, together with the economic considerations, led to the two-way spanning grillage solution, made up from standard universal beams, brought to site semi-assembled where they were finally welded together. These universal beams are repeated in the top boom of the trusses that bound each module, which have a tubular steel bottom boom and diagonals to provide extra strength. The trusses are supported on tubular steel columns 6.5m high. The building is four modules long (57.6m) by three wide (43.2m) giving a plan area of approximately 2,500m^2.

Stability in the plane of the roof is achieved by rows of horizontal diagonal bracing in each direction, fixed to the column tops. To provide lateral stability each elevation has a pair of ties from the tops of the columns to the foundations (Fig. 4).

At the east of the site, advantage has been taken of the natural slope of the ground and underlying rock to provide a lower ground floor level, founded directly on the basalt.

To avoid expensive retaining wall construction around the lower ground, an undercroft was created with the soil battered back under the ground floor (Fig. 5). The main ground floor is, therefore, suspended over the undercroft and the lower ground floor level where, since no manufacturing space would be interrupted, the grid underneath was halved to reduce spans. Half-way along towards the store the main factory floor becomes ground-bearing on compacted fill on the glacial till.

The foundations are however consistent on piers and pads taken down to the basalt. The automatic guided vehicles follow wires set into grooves cut into the concrete cover and, to achieve the required finish, the concrete was power-trowelled.

Along the south side of the main building a mezzanine level has been introduced of loadbearing blockwork, stack-bonded, and reinforced concrete slab construction. This is supported by additional ground beams at ground floor level.

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The sloping ground that provided the split levels allowed the opportunity to create a full double-height entrance foyer, with access to the ground and mezzanine provided by a featured steel staircase. The roof is covered by profiled steel sheeting and the elevations have steel panels with some glazing.

The store

The store operates automatically and people only need to enter for maintenance and repair work; the service requirements are minimal. The plan of the store is one 14.4m module wide, but longitudinally this was halved to give 7.2m bays of which seven were required to give a length of 50m.

The height was eventually settled at some 16m, and while a higher store would have been more efficient there were the planning considerations which this choice recognizes.

The structure is a series of steel portal frames at the 7.2m centres, spanning 14.4m across the store. These frames are linked by horizontal members that act as rails to support the profiled steel sheet cladding. The cranes and racking systems are independent of the store superstructure. The windloads on the side walls are shared between the column footings and the roof, which acts as a horizontal truss spanning between the two end walls. The end walls are then braced and are each founded on a substantial concrete base with sufficient mass to prevent overturning.

The stability in the long direction is provided by ties in the end bays.

The foundations for the store and the heavily loaded ground slab are founded directly on the basalt and differences in levels were made up with lean mix concrete.

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7. The store
8. View down into entrance foyer
9. Entrance
10. The foyer
11. Main building, entrance and escape stair
12. Entrance
13 & 14. Inside the main building

Programme

The design team was appointed in early 1985 and in anticipation of full planning permission being obtained, the management contract was tendered concurrently with the planning application and an award was made in August 1985. The substructure package started on site in October 1985 after the completion of the demolition and site access roads. The erection of the structural steelwork commenced in early 1986.

The project was essentially complete in January 1987 but Linn Products phased their moves to coincide with holiday periods. Their research and development department moved in first during the Easter holiday and the rest of the factory followed during the Glasgow Fairs holiday in August.

Credits

Client:
Linn Products Ltd.
Architect:
The Richard Rogers Partnership Ltd.
Services engineer:
YRM Engineers
Quantity surveyor:
Hanscomb Partnership
Management contractors:
Balfour Beatty Construction Ltd.
Structural steelwork:
Tubeworkers Ltd.
Photos:
Guthrie Photography
Drawings:
Derek Woodcraft

Princes Square

Architect: Hugh Martin & Partners

Brian Veitch

Princes Square was completed in 1841 for James Campbell, a wealthy clothier, who in the Square's opening year was Lord Provost of Glasgow. For his services to the city he received a knighthood from Queen Victoria and in return he named his new buildings after her eldest son Prince Edward. The Square was built as a central open courtyard, 30m wide by 50m long, surrounded on all sides by dignified four-storey merchants' buildings. Throughout the 19th and early 20th centuries textiles, shirting and thread manufacturing flourished within. With changing times the fortunes of the Square waned. In 1984, partly vacant and in need of repair and renovation, it was put up for sale.

Our clients saw and grasped the opportunity which these old buildings offered to create Scotland's first true speciality shopping centre. With first-hand knowledge of Covent Garden behind them, and after thorough local market research and a study tour of the US, they finalized plans to glaze over and enclose the central courtyard and reconstruct the interiors of the surrounding buildings to present-day retail standards. From the start no concessions were made in preserving and enhancing the special qualities of the Square.

1. View from management suite (Level 3). The original stone-built square is now covered in with a glass roof supported on a new steel structure which also supports the new shopping access galleries at each level. Vertical circulation for shoppers is achieved by dramatic glass lifts and escalators at each level.

2. Carefully designed individual retail units open into the square.

3. Decorative projecting canopies adorn each of the three arcade entrances from Glasgow's premier shopping precinct, Buchanan Street.

4. At the east elevation of the square a decorative spiral stairway links the three lower retail floors.

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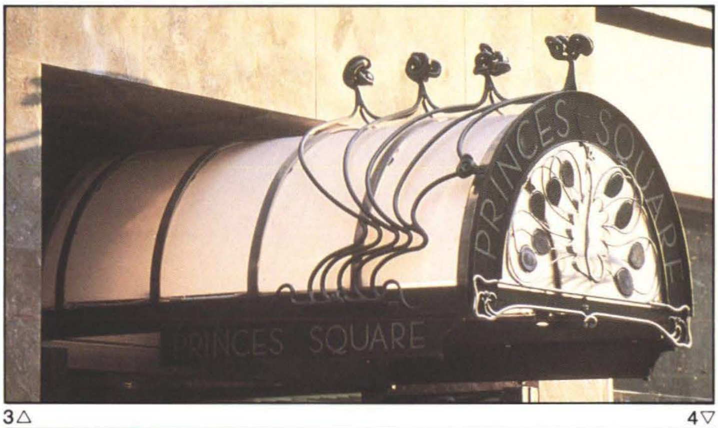

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The Victorian facades were retained and restored while behind and hidden from view a modern steel-framed replacement structure was inserted. The soaring new steel roof structure over the central courtyard was designed carefully using modern techniques and materials to sit comfortably alongside and draw the eye upwards to the four levels of trading above.

These photographs were taken at the end of last year when already the centre was popular as a place to eat. Shopfitters worked hard behind the scenes to complete the 62 retail units and restaurants for the formal opening on 29 April this year by Prince Charles.

Credits

Client:
Guardian Royal Exchange Properties and Teesland Development Co.

Project management:
Precept Development & Project Control

Architect:
Hugh Martin & Partners

Structural engineer:
Ove Arup & Partners Scotland

M&E engineer:
Wallace, Whittle & Partners

Quantity surveyor:
c b a Chartered Quantity Surveyors

Interior design:
The Design Solution

Lighting consultants:
Lighting Design Partnership

Main contractor:
Sir Robert McAlpine & Sons Ltd.

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5. Glass lifts serve each level and offer dramatic views into the square.

6. Food court level, showing security cameras and theatre lighting units.

7-9. Carefully designed ornamental metalwork, etched glass balustrades and coloured glass lamps maintain the high quality of the speciality shopping centre.

10 & 11. Up and down escalators serve each level and give a good view of each shopping level to the visitor.

Photos: Scott Lee & Stuart Campbell

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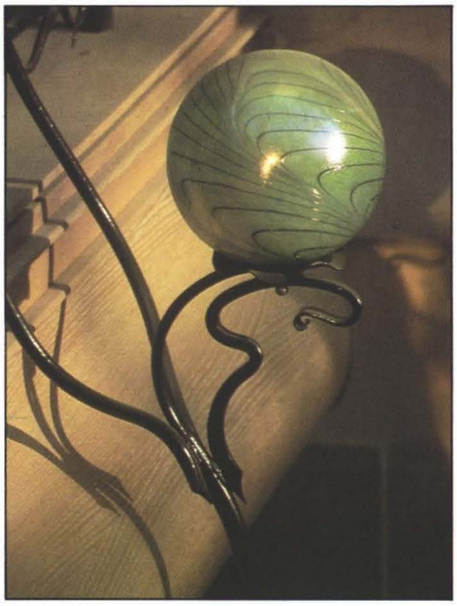

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G-Mex Exhibition Centre, Manchester

Architect: EGS Design, Manchester

John McGrath

Manchester's new G-Mex Centre, formerly the derelict Central Railway Station (Fig. 1), has now been open for nearly two years.

The sensitive conversion of the grade II listed building has proved a commercial success and provided a fine venue for many sporting and musical events. The recently televised G-Mex Soccer Six competition has proved a big hit with soccer teams like Arsenal, Manchester United, Nottingham Forest and Spurs all competing. Other sell-out events include big name pop concerts which have attracted the likes of Spandau Ballet, Simply Red, Bryan Adams and the Pet Shop Boys. Classical music lovers have not been left out. A season of pop classics performed by the Hallé Orchestra have become an annual event, and the sounds of the *1812 Overture* have proved exciting when matched to an in-built lighting effects controller (Fig. 3).

On the exhibition front, success has also been achieved (Fig. 4). The Northern Motor Show, Ideal Homes Exhibition and the Fast Food Fair are just a few of the exhibitions that have become an annual event. The Centre has bookings up to three years in advance.

The site and the building

The 10.5ha site provided opportunities for ample car parking, both underneath the exhibition halls and by conversion of the viaducts at the rear of the centre, thus creating a total of 5000 car parking spaces.

The exhibition hall, formerly known as the train hall, has retained its Victorian splendour with the existing single 65m span arches and the train hall walls being repaired and restored. A new roof with Paxton roof lights has been provided to simulate the original roof construction.


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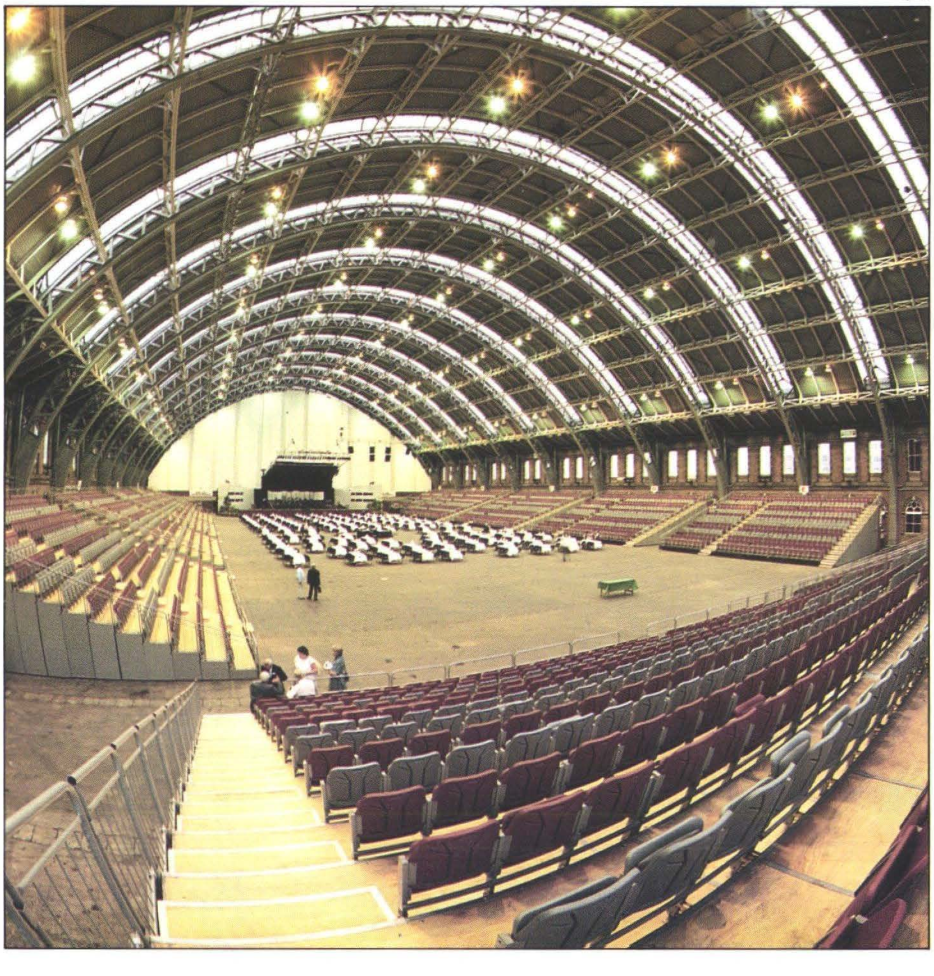

1. Central Station was closed by British Rail in 1969 (Photo: Barry Tyler)

2. General view of the conversion (Photo: Paul Francis)

3. G-Mex gets ready for a pop classic (Photo: courtesy of GEC)

Car parking in the arches underneath the halls has effectively been doubled with the introduction of a mezzanine floor which required the removal of some 2m of fill to expose the existing Victorian arches (Fig. 5).

The services

G-Mex has an electrical load of 4200kVa and can consume up to 700kW of gas. Energy management and environmental control have proved key factors in the success of the centre.

Five systems of lighting provide a flexible and energy-saving facility which allows the differing lighting requirements of exhibitors and event organizers to be achieved. A microprocessor controls 360kW of arena lighting. The system also incorporates a special effects package.

Heat is generated via two undercroft plantrooms using full condensing gas boilers.

Hot water is provided by a central system of direct acting, gas-fired water heaters.

The chilled water requirements of the exhibition halls are provided by two machines located in the Great Bridgewater Street plantrooms (Fig. 6). These are automatically controlled via temperatures devices located within the halls.

A building management system is connected to all plantrooms giving the operator a monitoring and control facility from a central control room for all mechanical and electrical systems.

To satisfy the strict requirements of the City of Manchester Act and to obtain necessary licences for music and dance, a maintained emergency lighting system has been installed in all public areas.

Mechanical and electrical services have been designed to be as unobtrusive as possible and not obscure, in any way, the original structure of the hall.

To provide services for exhibition stands a central walk through subway duct runs longitudinally below exhibition hall floor (Fig. 7).

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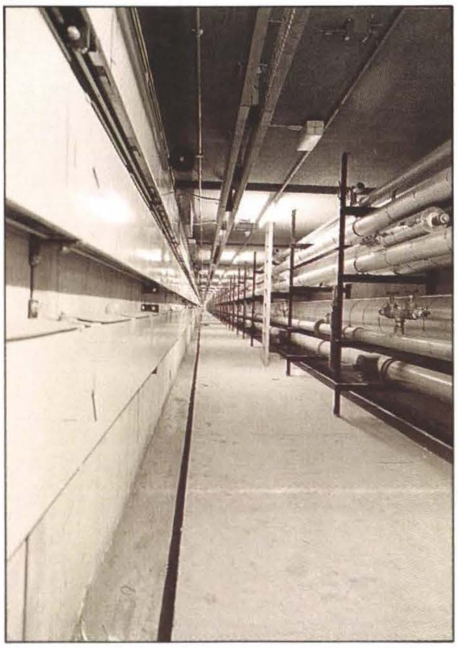

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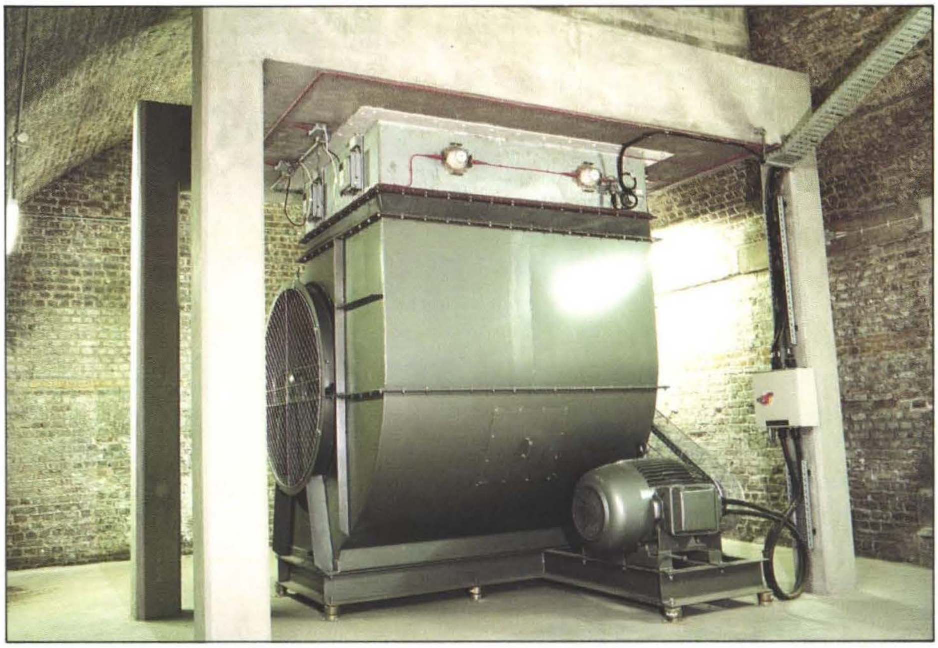


The subway is connected to open top trenches branching off at 6m intervals throughout the length of the exhibition halls, and these trenches allow connection of services to exhibition stands.

The subway contains all necessary services, e.g. gas, compressed air, mains cold water, power and drainage. Valued connections in the subway allow temporary exhibition stand services to be made.

The electrical power requirements for the halls are provided by three busbars which run down the length of the walkthrough duct. The busbar systems provide an electrical load facility within the exhibition spaces in excess of 150 W/m^2.

Integration of services into existing structures

One of the major tasks undertaken by Ove Arup and Partners, Manchester, was the integration of services into the existing structures without spoiling the natural beauty of the roof and the train hall walls.

In effect, our brief was to provide an environment to meet modern-day standards and overcome the physical constraints provided by the building.

Care was taken to disguise or hide pipes, conduits, and trunking within the train hall roof.

Plantrooms were positioned in existing arches and builderswork ducts where built into and hidden in new gables at the front and rear of the train hall.

Two large, roof-mounted parapet ducts were cleverly hidden behind the train hall walls and deliver temperature-controlled air via steel spigots through the train hall roof.

Conclusions

G-Mex was awarded a Civic Trust Award for 1987. The scheme has received much praise from the press and the general public both in Manchester and throughout the UK.

Much assistance was provided by many parts of the firm and the general concensus is that all involved enjoyed a very exciting and challenging project.

4. The Centre showing an exhibition in progress (Photo: Paul Tomlin)

5. Victorian arches underneath the walls

6. One of the Great Bridgewater Street undercroft plantrooms

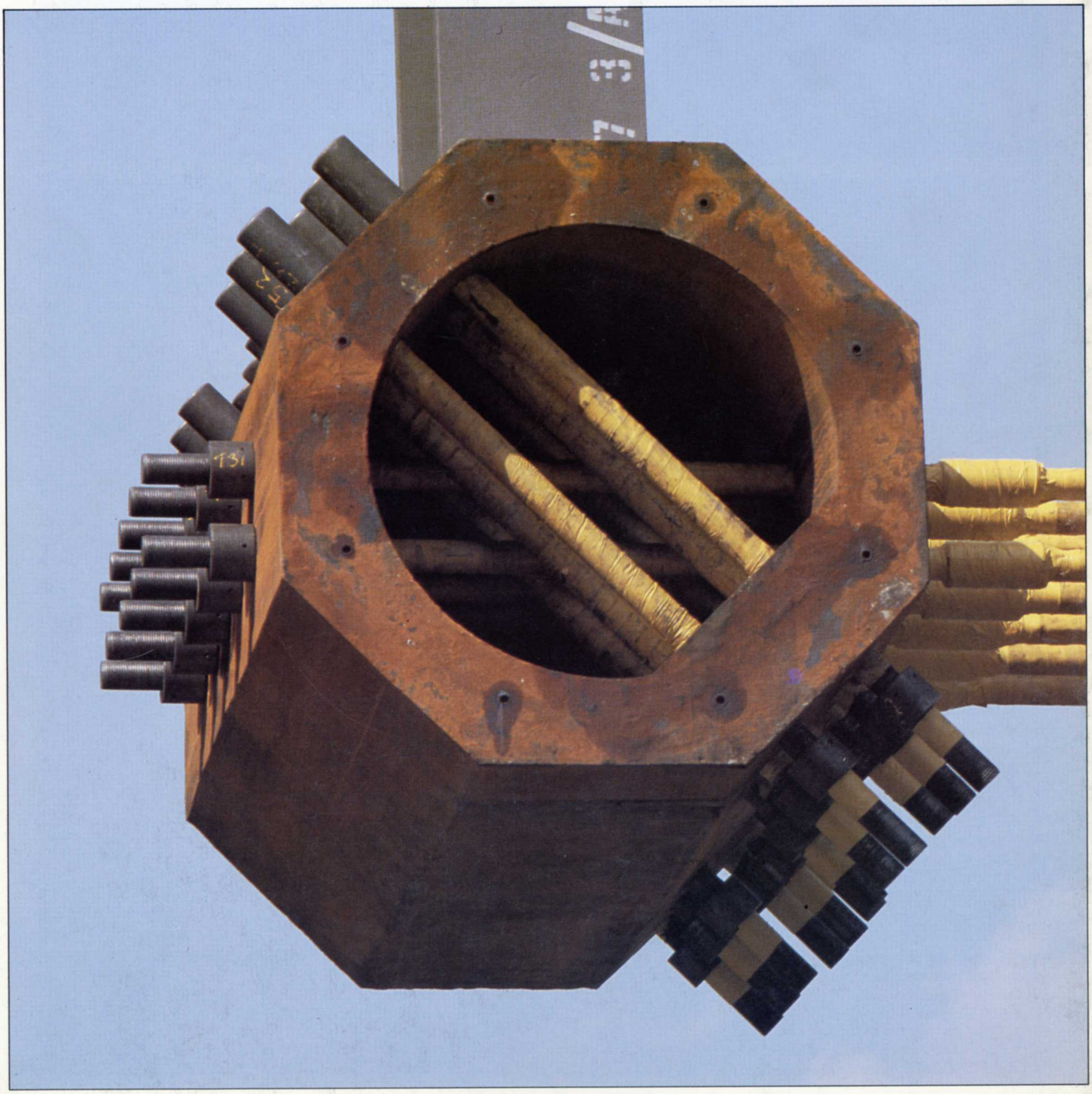
7. Subway duct provides services to exhibition stands

8. New plenum chamber formed from existing arches

(Photos: 5 to 8, Kay Photographic)

Credits

Architect:
EGS Design, Manchester
Client:
Central Station Properties Ltd, Manchester
Services engineers:
Ove Arup & Partners
Structural engineers:
Brian Colquhoun & Partners



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