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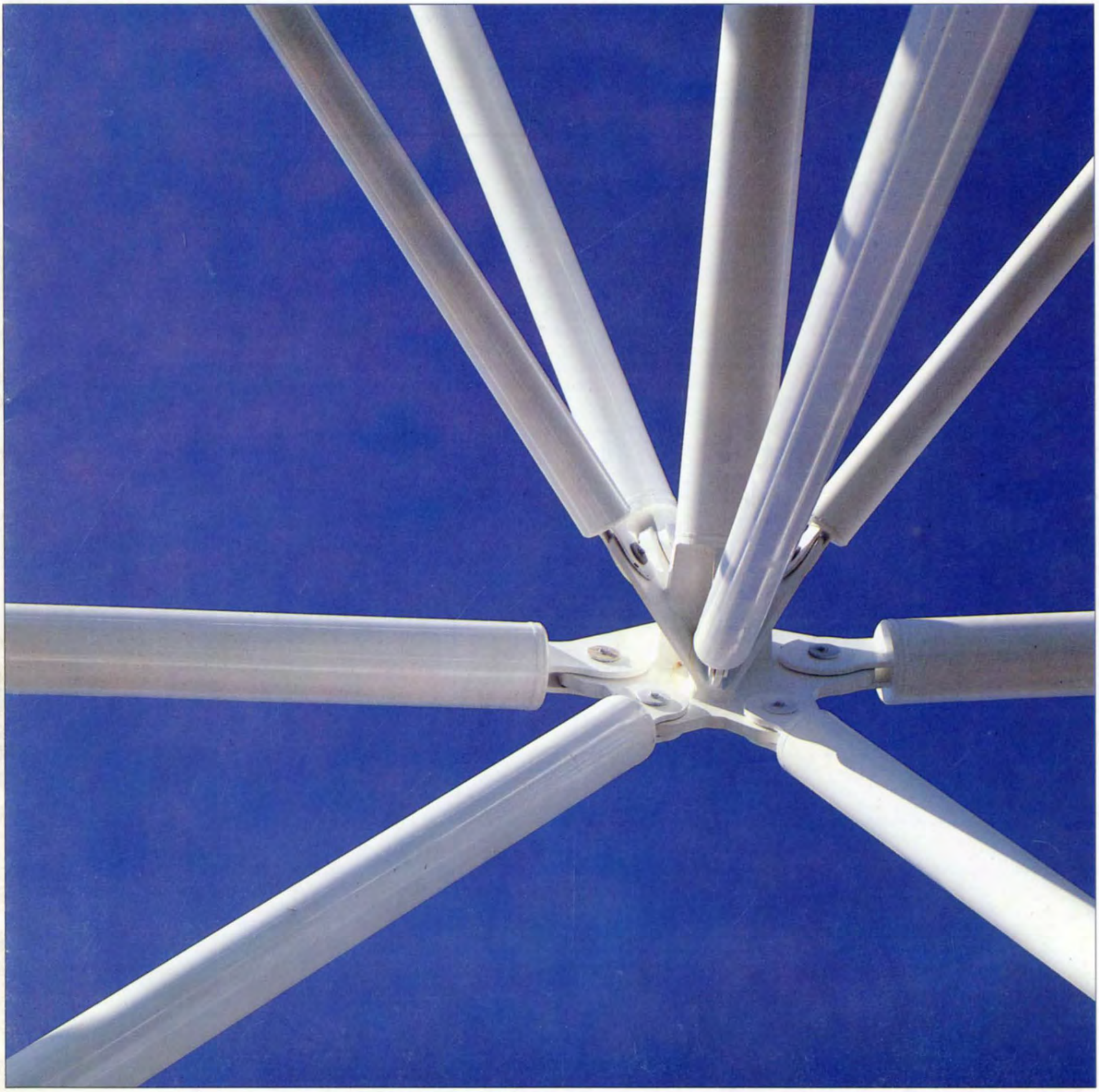

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Contents

Jack Zunz was awarded the Gold Medal of the Institution of Structural Engineers for 'personal contributions to the advancement of structural engineering' on 23 February 1989. The Institution of Structural Engineers also presented a 1988 Special Award to Ove Arup & Partners 'for the aesthetic form and technical excellence of the Sydney Football Stadium'.

Front cover: Sydney Football Stadium. (Photo: Patrick Bingham-Hall)
Back cover: St. Enoch Centre. (Photo: Alistair Hunter)

Continuing education and training: where do we go from here?

Jack Zunz

This talk was given at the conference on 'Continuing training and education for engineers: investing in the future', held under the auspices of the Careers Research and Advisory Centre (CRAC) at Churchill College, Cambridge, on Wednesday 27 September 1988.

Continuing training and education for engineers is, of course, only part of the whole spectrum of training and education. In discussing the subject 'Where do we go from here?', I can only do so by touching on the place of continuing education and training, or CET, in the context of engineering education as a whole and indeed on the place of the engineer in society.

To have taken on the subject implies an assumed prescience on my part. So to begin, let me disabuse you of any great expectations and merely remind you that 'He who's seeking wisdom's core is doomed to seek for evermore' (Ove Arup). There are no easy answers but there are some very distinct pointers which we ignore at our peril.

Of course, continuing education and training is, by definition, an investment in the future. But I assume that CRAC, the Careers Research and Advisory Centre, and its associated bodies who organized and sponsored this conference, specifically chose 'Investing in the future' as a headline title because of the mistaken concepts in our society concerning the term 'investment'.

When our politicians or economic analysts or the media talk about 'investment', they simply mean money. They use slogans such as 'lack of investment' as indicating short-sightedness in not directing financial resources into new plants and machinery or new enterprises, workshops, buildings and so on. While it may well be true that investment in monetary terms has been less than adequate, and while city analysts tend to ignore the benefits of long-term investment anyway, *real investment means selecting, training, educating, retraining and re-educating the people who create the wealth of the country.*

How often have we all heard the myth about the German economic miracle after World War 2 because their cities had been wiped out and their factories had to be replaced — often with US aid? We the victors, on the other hand, went into an ever-steeper economic decline because all our factories were old and there was no money to replace them. While there is in this, as in all bald statements, an element of truth, the overall reason why the Germans were (and are) more successful than we is simply because they have a greater number of well-educated and well-trained personnel than us, from factory operatives and workers on construction sites right up the scale to chartered engineers and their equivalents.

This process of industrial decline, or lack of ability to keep up with our major competitors, is of course more than 100 years old. Conventional wisdom would have us believe that we are making a right old mess of things because of this or that government policy, so that unfortunately a great, if not by far the largest, part of our population hasn't the faintest inkling of why we buy more foreign than British cars, why most of our household appliances are made in Germany, France, Italy or wherever, but not in Manchester or Dundee. Even in the construction industry the gap between imports and exports is becoming alarming. Our instant, and often superficial, supply of information is grossly misleading when we are told that it is this or that government action which is responsible for the demise of this or that industry.

It will come as something of a surprise to many to be told that for 100 years before World War 2, private and public bodies had attempted to convince the public and government alike that the battle for export markets was being lost in the schoolyards and quadrangles of Britain. As early as 1861, the Newcastle Royal Commission undertook the first-ever comprehensive survey of the shortcomings of the educational system in general and of the system's failure to instruct subjects of use to the pupils and to society in general. Three years later the Clarendon Royal Commission commented on science education, or rather the lack of it, in nine renowned public schools. And so over the years, commission after commission, investigation after investigation, consistently came up with findings which showed that our schooling and training was inappropriate for a modern industrialized society. In 1929 the Balfour Committee pronounced that 'before British industries, taken as a whole, can hope to reap from scientific research the full advantage which it appears to yield to some of their most formidable trade rivals, nothing less than a revolution is needed in their general outlook on science' . . . and so on.

More recently the Finniston Report into 'Engineering our Future' had terms of reference which could not have been more relevant to the needs of British industry. Yet its findings were watered down to the extent that they became barely noticeable.

It has been said that the Whitehall mandarin is able at a touch to transmute life into paper and turn action into stone. But we cannot blame inaction, in the face of such overwhelming evidence, repeatedly and carefully produced by eminent persons or commissions for more than 100 years, solely on civil servants or even on their political masters — at least not entirely. Repeated heavyweight warnings about an inadequate education and training system worthy of a first-class technological power have been majestically ignored. You may well ask — Why?

The answer is complex and deeply rooted in the social and economic history of this country — particularly during the formative years of the Industrial Revolution. But three factors in combination are worth mentioning — a *romantic idealism of the society in which we* *live* (a kind of self-delusion), *the cult of the 'practical' man,* by which I mean the lack of appreciation for the properly educated and trained technologist, and above all the *profound British dislike for coherent organization,* especially if centrally administered, more especially if under the aegis of the state, and particularly if there is a charge on public funds.

As a result, successive governments have failed to understand, or if they did understand, have failed to act on the fundamental issues concerning our industrial decline. The self-delusion of our people, aided and abetted by politicians, has perpetuated a decline which started in the middle of the last century. What is alarming to those who care about the future prosperity of this country, however, is the lack of appreciation, of understanding the problem, by the bulk of society. No problem is soluble until it is at least understood and a climate of determination to find appropriate solutions has been established.

I have so far deliberately sketched, albeit very briefly, the backdrop against which we have to look at the future of education and training. I won't belabour the point any further, but you will I hope share at least some of my concern and, in looking at the present nature of the issues confronting us with regard to continuing training and education, you might feel that you would prefer to solve problems which are understood and to which there seem to be some visible possible solutions.

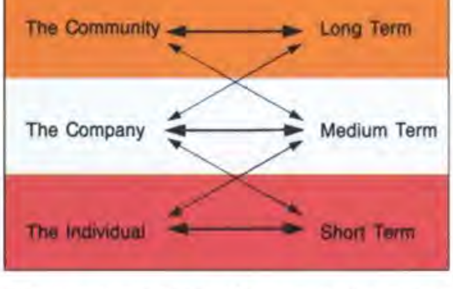
I am sure most of you are familiar with some of the background which I have tried to describe, but for those of you who still live in dreamland, I suggest some light bedside reading in the form of a paperback entitled 'English culture and the decline of the industrial spirit 1850 — 1980' by Martin J. Wiener.[1] The book, incidentally, has been translated into Japanese — they must be delighted with its contents.

Significantly Professor Wiener is an American who carried out much of the research which went into writing it whilst on a Fellowship in this country. If, after reading this little book, you still feel smug and self-deluded — there is no hope.

I personally believe there *is* hope. But we, and by we I refer to all of us associated with industry and producing things, must stop kidding ourselves that everything is rosy in the garden and that all that is British is best. It isn't — some is and more should be.

I suggest that at the root is education and training (or lack of it), including of course continuing education and training.

I intend to discuss my allotted topic under three headings.



These are not watertight and overlap extensively, as you will see. Indeed, these three headings could equally be *long-term, medium-term* and *short-term* respectively, in that action by the community will have longer-term consequences. In turn, actions taken by the firm or company generally have a longer lead time than those taken by the individual. These issues are interlinked, but I will separate them for the sake of clarity.

The Community

Government

Schools

Media

Under the heading of 'The Community', I want to discuss three important facets of training and education — the government, the schools and the media. I have not referred to the role of the engineering institutions — I take it for granted that they will more or less play their part, but it is clearly not enough.

Governments come and go, inducted and evicted by quotable slogans, none of which have any bearing on the training and education, or lack of it, of our community — unless you count Harold Wilson's 1963 speech to the Labour Party Conference when he said: 'We are redefining and we are restating our socialism in terms of the scientific revolution. The Britain that is going to be forged in the white heat of this revolution will be no place for restrictive practices etc., etc. . . .' The 'white hot revolution' turned out more like a long cold winter, discontent and all.

What then can, or indeed should, government do? In discussing these matters with members of the present government the immediate response is that there is 'no money' — an obsessive response which blurs the real issues. If we want to continue to enjoy and indeed improve our living standards, we have to be as good as, and in some spheres better than, our industrial competitors. If this simple logic is understood, we must realise that we cannot achieve that blissful state without having people adequately trained and educated to achieve these ends — again, simple logic which any idiot should understand. The simple truth is that we are not achieving these goals, so what is wrong?

I said earlier that there is an extraordinary misconception about what 'investment' is all about. Ultimately it has nothing to do with money, buildings, plant, equipment and so on. It is only people that matter; everything else flows from that. If we train and educate our people properly, financial sources will invest their money because in the end it is only through our people's skills that money will be created. The Japanese, the German and now, of course, the 'new wave' industrial countries — the Koreans, the Taiwanese — all understood this, so why can't we? And here government *can* help.

Government can help create a climate. Politicians are listened to if not always respected, but perhaps they would be respected a little more if they emphasized some of these basic issues and then lived up to doing something about them. So to repeat, government can by various actions create a climate for gradual cultural change, for that is what is needed. Witness the current penchant for creating an 'enterprise society' — all fine rousing stuff, but there is little future in thinking about being more enterprising when you have no skills to back your aspirations. It only encourages the wheeler-dealers and fails to get to grips with the fundamentals.

I am here caricaturing an attitude which in some respects is laudable, in order to make my point.

Again, if this change of emphasis in our culture means that we must fundamentally reappraise our training and educational establishments *and* this has financial implications, we simply cannot afford not to invest at least some money in educating and training the very people on whom the continued prosperity of our society depends. I believe that if we are to escape from this vicious circle of Royal Commission after Royal Commission analyzing the shortcomings of our industry, and have governments and society responding positively to repeated blandishments, then government by using its considerable powers of communication, legislation and privilege must outline a game plan, the basis of which must be rooted in improving our general and particularly technical and scientific education. Continuing education is a part of this process, because the days that education ceased with the acquisition of a school leaving certificate or a first degree or a technical diploma of some kind have long gone. There is now a cradle-to-grave equivalent from graduation to retirement, where continuous development and acquisition of new skills are prerequisites to staying at or near the front of one's chosen vocation. And government can, as I said, first create the right climate for cultural change and then help financially if that is necessary to achieve stated objectives.

The community must also play its part in the schools. Young men and women are bombarded today with ideas, images and propaganda in their homes in a way which was inconceivable even a few years ago. It is absolutely essential that the best of them are attracted to careers in technology, in science and into industry on the basis of skills which can only be acquired at the expense of some personal effort.

I am sure that researchers somewhere have compared the hours spent by modern youth slumped before television sets with former times when reading, writing or playing games was the vogue; but whatever the conclusions of such research, there is surely a greater temptation now to bypass some of the rigour inherent in acquiring knowledge and skills, particularly when so many seemingly easy (and ultimately often false) options are placed in front of their noses. Witness the recent 'quick buck' rush to the City. Unless we attract more of these talented young men and women into the technological arena, we will get nowhere. There has been a visible effort, by the Engineering Council through its Opening Windows scheme, by the CBI through 'Understanding British Industry', and many other worthy if ill co-ordinated attempts, to bring the idea of training for a career in industry into the schools of this country and to imbue 13-16-year-olds with the excitement, as well as the social and personal benefits to be derived from doing something useful and creative. Surely this is better than perpetuating the myth that we can carry on improving our living standards by spending more than we earn? A major, co-ordinated effort must be made to inculcate a desire on the part of the young to make a career in some part of productive industry or engineering. The Engineering Council is the best body to co-ordinate this effort, but on past performance it has to be more organized and aggressive to succeed and it must, of course, be given appropriate resources to do so. The sums of money, if any, required are modest — the return incalculable.

Then, the community can play its part in bringing the message into people's homes. Television has become *a*, if not *the*, most powerful medium in influencing attitudes and behaviour patterns. Television in this country, whatever its shortcomings, does produce some marvellous material; witness the quality of the programmes produced by the BBC's Natural History Unit. They produce programmes of a consistently high standard and in that way influence millions of people in their interest in, and attitudes to nature, wild life and so on. Why cannot the BBC or for that matter the independent companies have a 'technology unit' where the infinite challenge, variety and the excitement of so many aspects of technology and industry are portrayed in a manner which will enthuse young and old alike? There is every indication that an exciting and well-produced series of television programmes, particularly if presented by a reasonably charismatic figure, will have a substantial effect on people's perception of engineering in general and attitudes to training and education in particular.

Under the heading of 'the community', therefore, government, the schools and the media can all play a significant role in education and in continuing education.

The Company

Culture

Short Termism

Adaptable Training Systems

We then come to the company, the firm, the partnership, the immediate group under whose umbrella most of us function. What role should it play in continuing education and training?

First and foremost is the *company culture*. We have all heard about the variety of corporate cultures, when they are benign and constructive and when they are decaying and retrogressive, but there is no question that any company, any grouping of people engaged in an activity which has common objectives, acquires a distinctive culture of its own. It may simply be a consequence of the dominant, magnetic personality of the boss, or it may be the result of carefully nurturing common aims and objectives, but any organization which does not acquire or at least aspire to take on its own particular aura, will soon become an amorphous group of worker ants without any visible character and will be more prone to all the well-known industrial diseases. There are many familiar examples of companies who fall victim to this so I am reserving my comments only for those companies who care, who realise that ultimately their only real asset is the people who work within their group. One of the most important aspects of this company culture is that continuing training and education should be part of its way of life, part of its culture. We are so accustomed to tight-fisted budgeting and penny-pinching that when we hear of organizations sending some of their new recruits on training courses almost as soon as they join the firm, we are pleasantly surprised and yet this is precisely what a firm *should* do. Unfortunately, so much of our industry is governed or at least heavily influenced by accountants and lawyers who are preoccupied, quite understandably, with legal and financial matters. How often do we hear that there is no money for training because of the rising value of the pound with City analysts looking very closely at every short-term result?

Short-termism is a debilitating disease — money invested in training, and for that matter research and development, is *real* investment and companies taking these wise long-term decisions should not be subjected to the blandishments of investment managers or be prone to corporate raiders. Here again we can probably learn something from our international competitors. Statistics seem to indicate that our expenditure on training and education, as well as on research and development, is much less. Again, profit margins in many of these foreign companies are very modest because the financial climate encourages investment and growth rather than handouts to the shareholders. Again government *can* help, by giving greater tax incentives. For instance, training facilities and equipment expenditure, including specified buildings, should qualify for tax relief in the year of expenditure along the lines of scientific research.

Corporate strategies including tax incentives geared to the future are useful if not essential. And while the 'community' issues I discussed earlier are geared towards the long term, the company *can* in the medium term do a great number of things to stimulate training and retraining.

Rigid, disciplined training schemes can be counter-productive in today's climate and the company must try and strike a balance between outright paternalism and a 'you do what you like' attitude. This requires much sensitivity, for example discriminating — for a while at any rate — in favour of women. Women are entering industry in increasing numbers and while the rate of increase may be too slow and too modest for some of us, women as a resource, particularly in the light of the general shortage of skills, are an invaluable asset, and special attention should, therefore, be paid to their professional development. Career breaks for women who want to combine a career in industry with having a family must be made available in the context of not losing touch, maintaining and improving skills and retaining chances for promotion.

The company must also follow trends in society where regimentation is frowned upon and more and more freedom is given to the individual. This means that in future, successful continuing education and training programmes will have to find a matching fit between the needs and aspirations of the individual and the plans and programmes of the company. That is, of course, if the leaders of the enterprise really care about the people they are leading and who are the key to the success of their enterprise. If in the short and medium term we are to make the best use of our resources, it is essential that the company creates adaptable systems, included in the conditions of engagement, for paid or unpaid study leave and a generally perceived ethos that continuing training and education is not only desirable but a necessary adjunct for personal development and work satisfaction, as well as for corporate success and prosperity. At the lowest level there are still too few companies willing to help and encourage young people attain their basic professional qualifications. The arrangements must suit the individual — they must be flexible. Rigid training systems are often self-defeating in breeding resistance from the trainees.

And the company can place some signposts. What I have in mind here can be exemplified by the typical graduate engineer whose training has, during his or her latter years in school and through university or polytechnic, been almost totally science and technology-based, and who is in real need of acquiring communication skills, both verbal and written, and who is often unable to place his or her profession in the context of the society in which they have to practice. Understanding of legal and financial matters as well as presentational skills, the ability to communicate information and persuade clients or colleagues of one's ideas, are essential in a successful career. How often do we hear complaints from distinguished people in public life about the engineer's inability to communicate his ideas effectively. The objective here is not only to improve the individual's performance and enrich his working life, but also to present to society a more rounded individual, who in turn will provide an attractive role model for other young people to follow. I am not particularly patient with the whingeing members of my profession who constantly complain about the status of the engineer. If and when we present a more consistently attractive face to society, society will give us the recognition we deserve.

So all this means that the group or the company must have as part of its culture and ethos a visible, high-profile policy towards investing in its people, because at the risk of becoming boring and repeating myself, *that is the only investment which really matters.*

The Individual

Self Motivation

Self Motivation

Self Motivation

Thirdly, we come to the individual; what can he or she do? There is no doubt that in our changing society more is expected of the state or the group than was the case 20 or 30 years ago. Individuals were more self-motivated — if you wanted to acquire more skills you went to night school or studied, or at any rate did something about it yourself.

Young people today do expect more from the groupings to which they are attached and that is the paradox which I mentioned earlier and which requires sensitive handling. The individual wants his freedom and independence, but also wants physical and financial assistance for personal betterment.

So the important factor is for the leaders to motivate their people to *want* to better themselves, to *want* to acquire new or additive skills to keep up with rapidly changing technology. Ultimately there is no substitute for self-motivation, but this must be complemented by corporate assistance. A good example of what the individual could or should do is in preparation for 1992 when the European Market will become unrestricted.

There must surely now be a major incentive to learn one or more other European languages because without these, even if we are sufficiently skilled technically, we will not be able to hold our own in a very competitive environment. We must motivate our young men and women to acquire and improve their language skills and give them help where appropriate.

We do hear time and again complaints about the cost of training the individual and just when they become useful they pack up and work for the opposition or go to the City, or emigrate. It doesn't matter — one has to take a 'roundabouts and swings' attitude — you lose some and you win some. The important thing for society is to have well-trained, rounded people in industry. If some of them want to leave that should be all the more incentive to make life more attractive for those who stay. And if some of those who leave enter politics or go to the City or enter other walks of life, what better advertisement for engineers and engineering if they are well-trained and well-rounded people. For make no mistake, we are dependent, totally dependent on the comparatively few, dedicated, technically able people, who keep the wheels turning until there is the shift in our culture which I have spoken about earlier.

To sum up then in response to the question 'Where do we go from here?' — the short answer is '*nowhere*' — unless we get our act together. I have, of course, been deliberately provocative and neglected to mention the many centres of excellence which exist, the many men and women who keep the wheels of industry turning so admirably and the many products which are internationally renowned and successful. But what I am talking about is the aggregate, the trends, the overview — the comparison with other industrialized countries. Comparisons are necessary in a competitive world — they are particularly necessary to the people of this country who have lived in a state of ignorance and self-delusion for so long. Smugness and self-delusion are cancerous in their effects. I have suggested that technical education in general and continuing technical education and training in particular are not only an investment for the future but an imperative without which the prosperity of this country will continue to decline compared to its historical peers.

To assist and ultimately to reverse these trends I believe that there is a role for the community, the government, the company or corporate body for whom we work, and for each of us individually.

The government's long-term role is probably ultimately the most important, in that by word and deed it can bring about a cultural change because that is what is needed. I have suggested some obvious ways in which government and the community can bring about change. Contrary to conventional wisdom, governments might actually *gain* in popularity when seen to be taking measures which have real long-term, rather than electorally advantageous, short-term benefits.

In the meantime, however, the company can do a great deal. Our aggregate expenditure on education and training is not very generous in comparison with that spent by our competitors. Again, the corporate culture should have CET at its core. The success of the companies who have done this bears witness to the results which can be achieved by visibly investing in one's staff, one's work force.

Finally, it is up to the individual, to each of us, not only to play our part in our country's and our company's affairs and hence to make our voice heard, but also essential for each and every one of us to be self-motivated, to set ourselves goals, targets of achievement, for acquiring new technical skills, improving our presentational skills not only for our own good, but also to set an example to others. By being seen to be good and useful to society we will perhaps inspire others, particularly the young, to do something creative and swell our ranks.

Samuel Smiles, the famous 19th century biographer, found engineers to be 'strong-minded, resolute and ingenious men; impelled in their special pursuits by the force of their constructive instincts'. His book 'Lives of the Engineers', written between 1858 and 1861 about Brindley, Rennie and Telford, caused Prime Minister Gladstone to write: 'it appears to me that you have given practical expression to weighty truth — namely that the character of our engineers is a most signal and marked expression of British character . . .'. For a contemporary Prime Minister to utter similar sentiments, albeit in less pompous language, is inconceivable — yet if we are to prosper we have to work towards making such statements once again credible.

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(1) WIENER, M.J. English culture and the decline of the industrial spirit, 1850-1980. Penguin, 1985.

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Sydney Football Stadium

Peter Thompson
Bill Thomas
Tristram Carfrae

Background

In 1788 Captain Arthur Phillip established the colony of New South Wales in The Rocks area of Sydney. So began the European influence that would change Australia's course and direction for all time.

The men and women that followed brought with them social and cultural heritages that were then moulded to suit their new homeland. A town plan emerged, services were provided and precincts for recreational usage set aside. By the late 19th century the Moore Park area, 3km south of the city centre, had developed into the main sports and exhibition area, eventually comprising the Sydney Cricket Ground, Sports Ground and Show Grounds.

The Cricket Ground became the city of Sydney's major sporting venue, catering not only for cricket but also for rugby league and rugby union in the winter months. Soccer was relegated to the lesser Sports Ground immediately adjacent. In 1982 a Sydney team was included for the first time in the national Australian Rules Football competition, with the home matches played at the Cricket Ground. The subsequent over-use during the winter led to a gradual deterioration of the playing surface, particularly affecting cricket.

A cricket ground is not in fact ideal for watching football, apart from Australian Rules which uses an oval pitch and was developed as a game to be played by cricketers in the winter. Games requiring a rectangular pitch leave the spectators too far from the combatants when they are played in the middle of a cricket oval.

In 1985 the Sydney Cricket and Sports Ground Trust decided to develop a new football stadium with a capacity for 40 000 people, to be completed for the Bicentennial celebrations commencing in January 1988.

The Trust envisaged the Stadium not only as the premier playing venue for rugby and soccer in New South Wales, but as an integrated sports complex comprising sports training facilities, tennis and squash courts, swimming pool and car-parking, all contained within a formal garden setting.

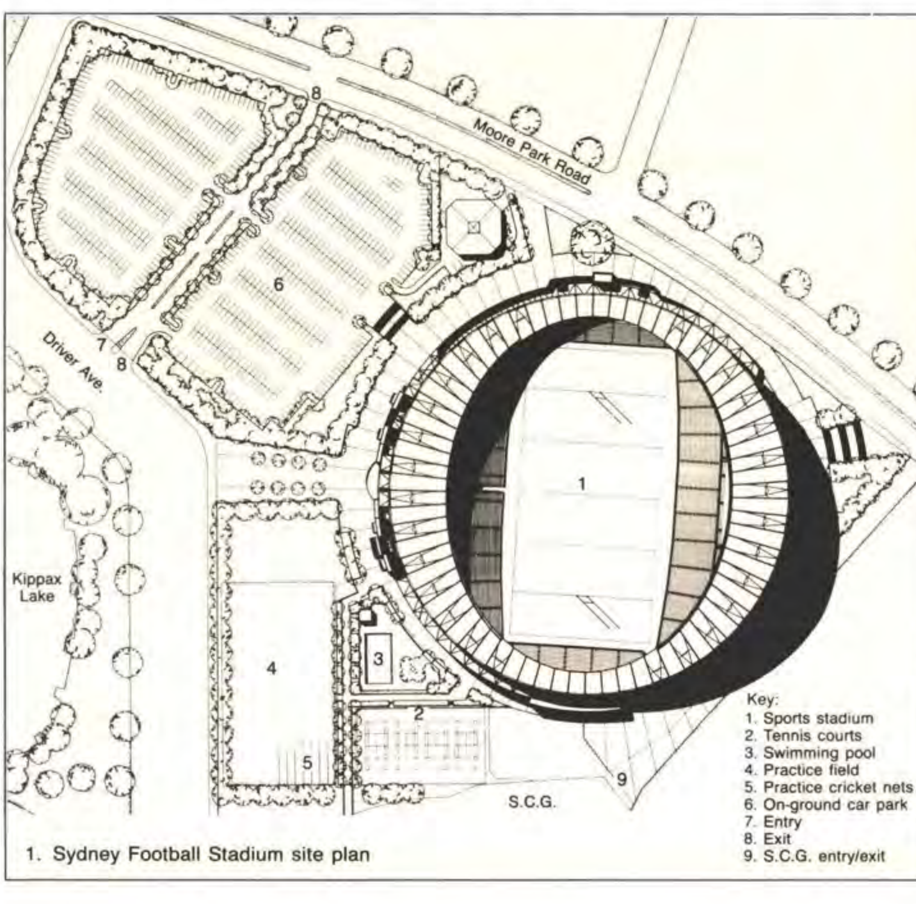
Funding for the complex, although backed by government guarantee and sponsorship, was to be achieved through membership subscription. There had been a waiting time of about 20 years for membership of the Sydney Cricket Ground, but these new facilities meant that membership could be enlarged. In fact new membership has accounted for a large part of the stadium's funding to date.

Invitations were issued to major building contractors to provide the facilities via a design-and-construct competition in August 1985. The design and costs submitted by Civil & Civic Pty. Ltd. with the design team of Philip Cox Richardson Taylor & Partners as architects, and Ove Arup & Partners as structural and civil engineers, were accepted by the Trust in October 1985.

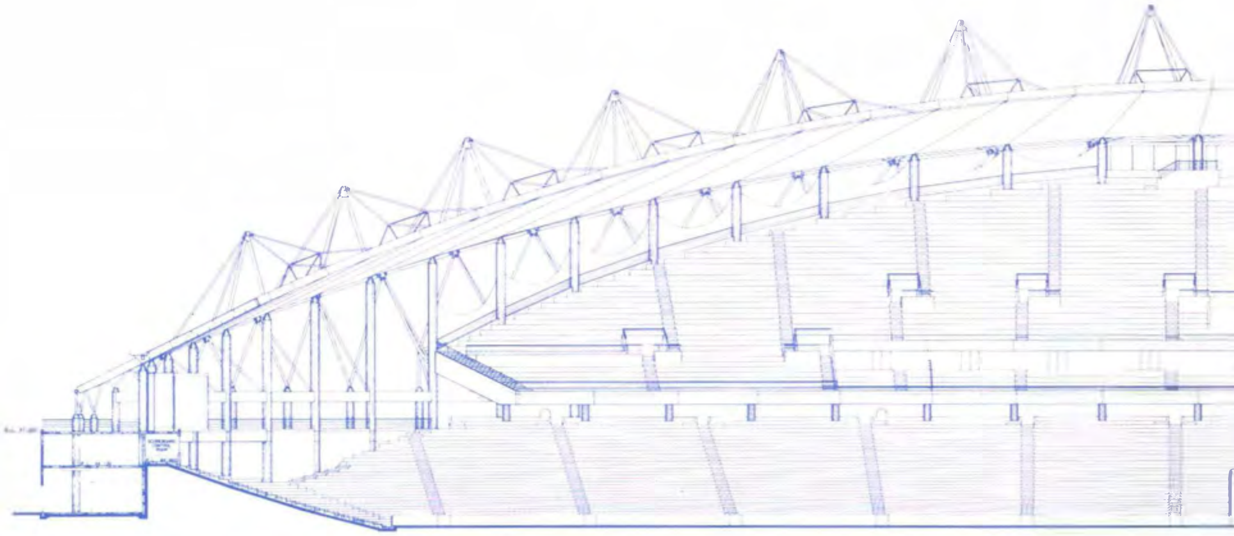
There followed a four-month period for detailed design, after which the costs were confirmed as being within the original tender offer. A contract was awarded and construction commenced on site in April 1986 and was completed for the opening in January 1988. The overall cost was within the original budget of $Aus 62M, of which the structural component of the stadium accounted for some $Aus 22M.

Design principles

The site for the stadium is adjacent to the Cricket Ground on land formerly occupied by the Sydney Sports Ground and facilities no longer required by the army. It is bounded by Driver Avenue to the west, Moore Park Road to the north and the Cricket Ground to the south (Fig. 1).



1. Sydney Football Stadium site plan



2. (Above) Elevation: West Grandstand

3. (Right) View from Moore Park Road

The basic challenge facing the design team was to create a stadium equal in quality to any other in the world, which would complement its surroundings and the historic Sydney Cricket Ground. However, a design-and-construct situation creates special challenges; not only does the design have to be of a high standard to make it stand out from its competitors, it must also be financially attractive to the client. Furthermore, decisions taken during the all-too-short tender period must stand the test of time. An incorrect decision can have disastrous cost implications after the design-and-construct offer has been accepted.

The client brief not only required all 40 000 people to be seated, but also that 25 000 of them should be under cover. It was decided by the design team at the outset that the seating would be of an 'all round' or bowl form and that the roof would be in a continuous strip around the stadium. While this is the only stadium of this form in Australia, notable examples exist around the world such as Wembley Stadium, Santiago Bernabeau in Madrid and the Olympic Stadium in Seoul.

The preferred location for watching football of all types is opposite the halfway line and the more spectators that can be massed about this location, the better. It is also preferable that everyone should have good 'sight-lines' — that is they should be situated less than 90m from the centre spot, have a clear view over the people in front, and face towards the middle of the pitch.

This was achieved by using tiers of seating which were slightly curved on plan and in section. These tiers were arranged in a continuous terrace around the pitch at the lower level, with two crescent-shaped grandstands on either side of the pitch at a higher level, the whole extending back to a circular boundary (Fig. 2).

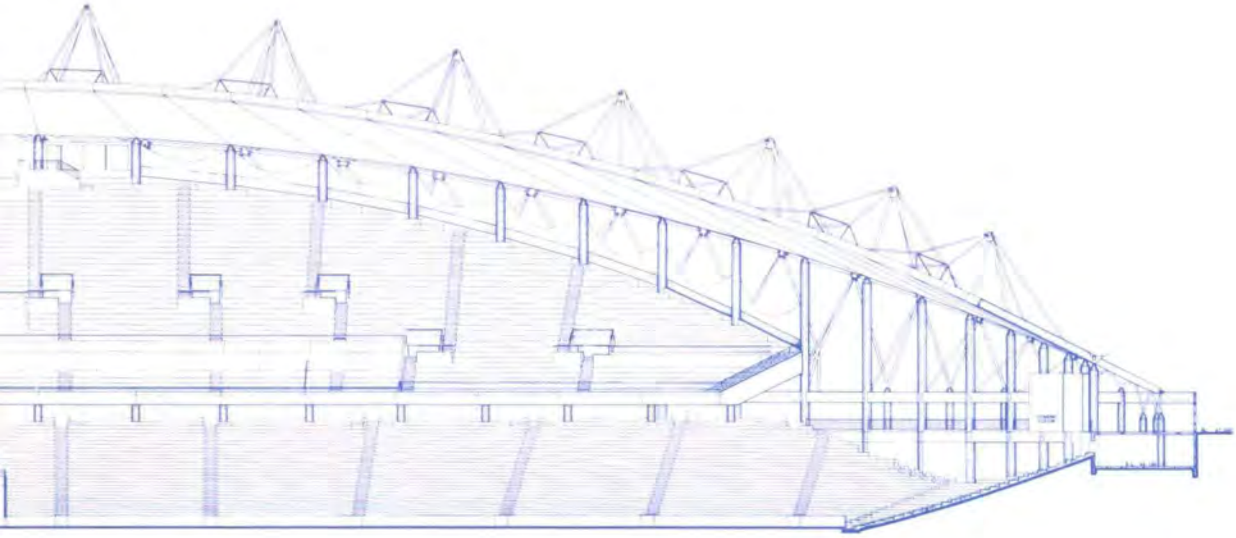
This gave rise to an undulating perimeter from which a continuous 'saddle form' roof was generated, rising high above the grandstands on the east and west sides of the pitch and curving down to the two ends. A cantilever of 30m at the halfway line, reducing to 10m behind the goalposts, was required to cover the specified number of seats without visual interruption. The resulting roof form gave the stadium its distinct and exciting character and provided the major engineering challenge.

The chosen form had additional advantages. Firstly it reduced the mass of the building at the north and south ends in sympathy with the residential area on Moore Park Road and the Cricket Ground, and secondly it allowed floodlighting to be positioned along the front edge of the roof, so that light spillage — a constant source of local irritation at the Cricket Ground — would be avoided.

Foundations

The site generally slopes away from Moore Park Road towards the south, and is underlain by two main geological strata: quaternary dune deposits, comprising medium to fine grained marine sand with podsols, above Hawkesbury sandstone. The depth to rock varied from zero at outcrops in the north-east corner to 20m on the west side.

4. (Right) Aerial view with stadium on left

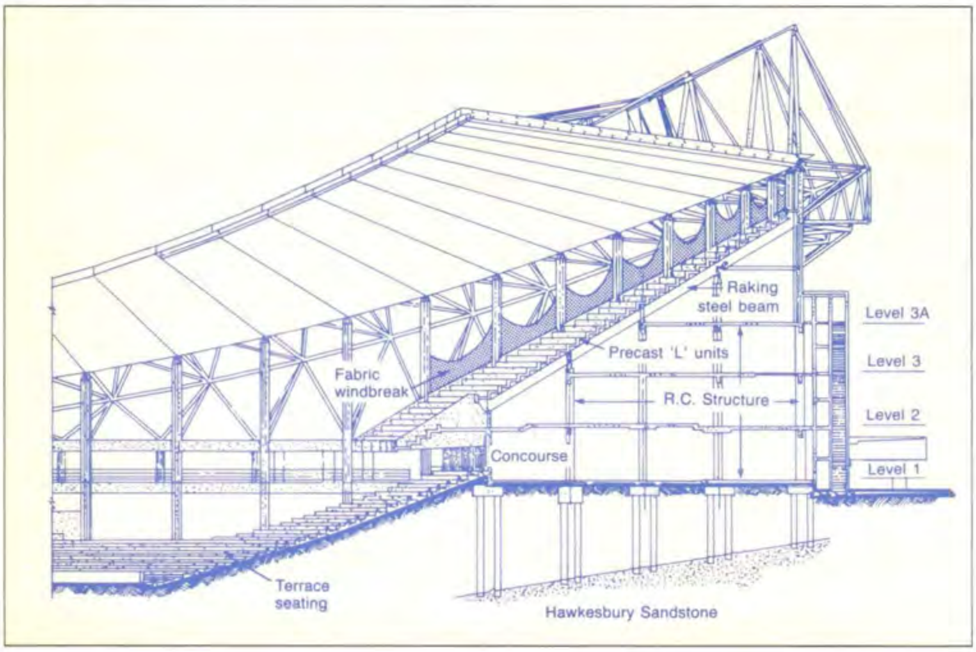


5. (Left) Stadium at entrance level showing structural bays

Two foundation systems were adopted to cater for the site conditions. The east grandstand, together with the north and south areas, are supported by in situ concrete *Frankipiles* varying from 400mm to 500mm diameter and placed singly or in groups. The west grandstand has 300mm square *Hercules* precast concrete piles driven 20m through the sand to the rock below. The decision to found in the rock was taken after an analysis predicted large settlements for foundations placed in the sand stratum.

Seating

A pedestrian concourse runs around the stadium at entrance level. A continuous band of open terrace seating runs between the concourse and the pitch, which is depressed about 5m below grade.



6. (Left) North facing section

This seating is constructed from in situ reinforced concrete, 150mm thick laid directly onto compacted subsoils and fill material.

Above the concourse on the east and west sides are the crescent-shaped grandstands, which cantilever 10m out over the concourse and lower terracing. Individual seats are supported by L-shaped tread and riser units of precast concrete spanning 8.5m between fabricated steel girders which rake down towards the pitch.

Because of the varying geometry of these raking girders, economic considerations favoured the use of structural steel. In any case the contractor felt that the non-standard formwork required for concrete raking beams simply could not be constructed within the limited time available.

The precast units are detailed in such a way that a waterproof lap joint is formed with the unit below, while the gap between units at the same level is sealed with a silicone sealant. A drip gutter is provided on the upper surface of the raking steel girders to act as a back-up system should the sealant fail or be damaged by vandals. Thus a waterproof construction is obtained without the need for any applied coatings.

The steel girders are in turn supported by a conventional concrete framework which houses all the facilities and amenities which make the Football Stadium an integrated sports facility (Fig. 6).

Roof design: Pre-tender

During the tender period, three structural options were examined in as much detail as time would allow and assessed against the following criteria:

(1) Cost

(2) Ease and speed of construction

(3) Dramatic form and aesthetic quality

(4) Environmental impact.

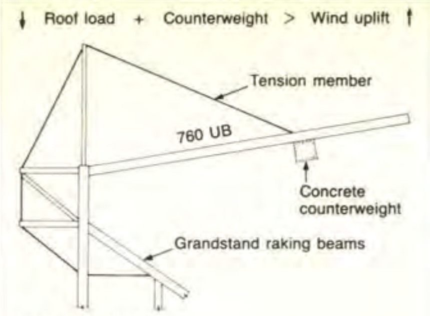
The roof types examined were:

(a) Simple cantilever using beams or trusses

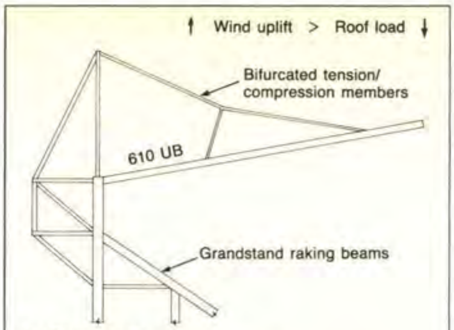
(b) Rafter beams supported by a tensile suspension system

(c) A three-dimensional system using the form of the roof surface, perhaps a cable net.

Due to uncertainties of construction and the associated risk to the contractor, who had a fixed date for completion, option (c) was soon discarded.



7. Pre-tender tension structure



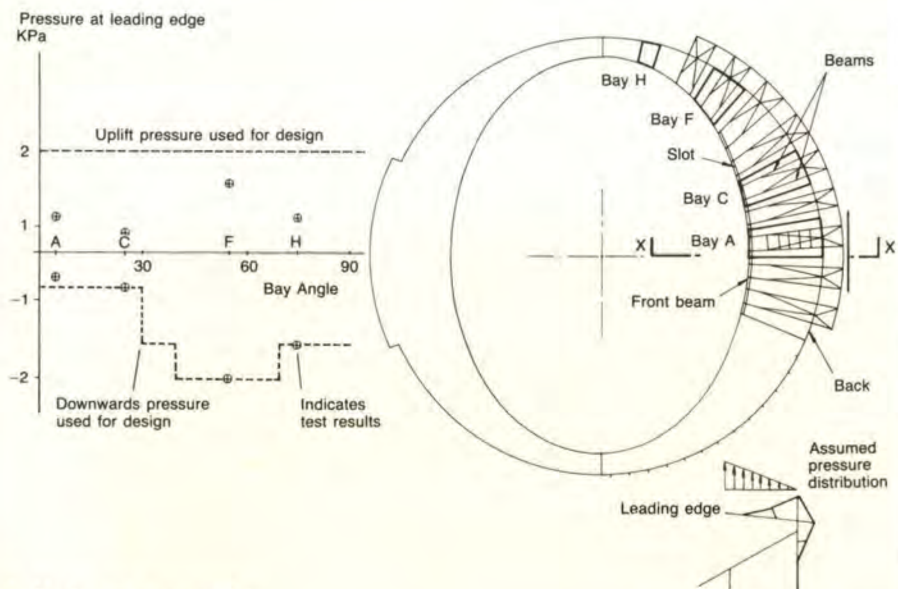
8. Post-tender tension/compression structure

After further (but necessarily brief) evaluation, option (b), the suspended beam system, was chosen because it certainly gave a more dramatic form and, after a cost benefit analysis, appeared to be more economical than option (a), the simple cantilever.

The initial design used 760 UB rafters (the largest size regularly rolled in Australia) at 8.5m centres around the periphery, supported by single tension rod stays which passed over tubular masts and outrigger elements to form vertical tie-downs.

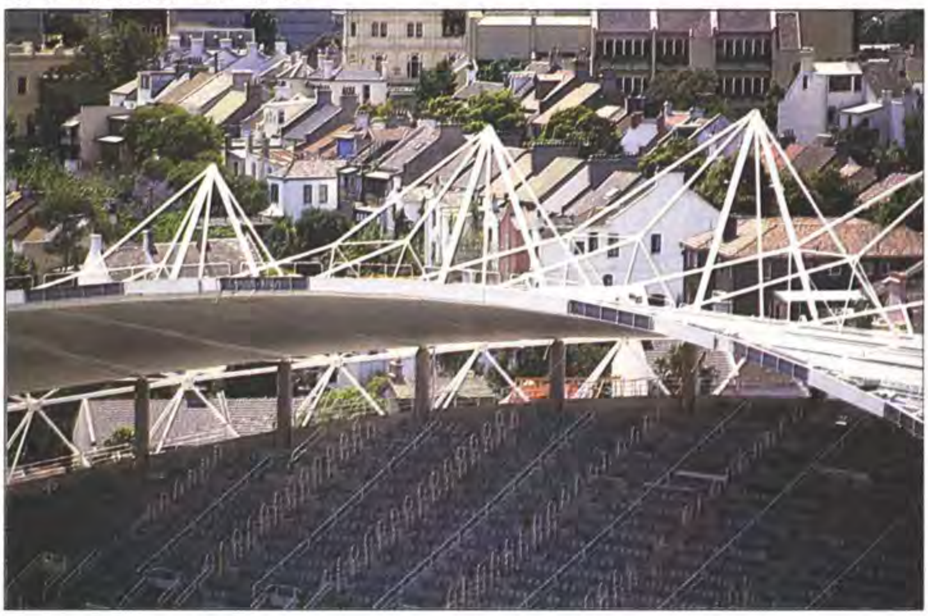
It was soon found that there were benefits in passing the tie-downs over another set of outriggers at a lower level, and anchoring them back into the concrete structure below the main grandstands. This eliminated the need for large tension foundations and also produced a stiffer suspension structure by removing the large extensions generated in the long, highly-stressed tie-downs.

These rafters supported purlins which were clad on top with lightweight profiled metal decking and would possibly support a ceiling. Whilst it was recognized that the uplift caused by wind action would be greater than the self-weight of the roof, it was planned to provide counter-weighting where necessary (Fig. 7).



9. Maximum pressures for different wind directions

10. 'A' frames seen from above



Roof design: Post-tender

Following the acceptance by the Trust of Civil & Civic's design-and-construct proposal, detailed design was carried out on the roof. The main aims were to reduce member sizes to a minimum and to eliminate the counterweights if possible.

Up to this time member sizes reflected our conservative estimate of wind-loading based on previous experience of conventional cantilever roofed stadia and grandstands. Given the unconventional form of the roof it was essential that wind tunnel testing be carried out. A 1:200 scale aeroelastic model was therefore built and tested at Monash University in Melbourne, using member stiffnesses deduced from the three-dimensional computer modelling. The wind tunnel model was tuned so that similar responses to equivalent loads were achieved.

A slot was introduced into the roof, just behind the leading edge, to reduce the peak pressures in this location by 'bleeding' the wind separation bubble. This technique was used by us successfully in the design of a grandstand roof at Parramatta two years before, where an overall reduction in wind loads of 25% was observed. This slot allowed the floodlights to be mounted behind the roof fascia to give a clean edge to the front of the roof, and when decked with an open mesh also served as the maintenance walkway.

Prior to the wind tunnel test it was assumed that the roof would dynamically deform under wind-loading in a similar way to a simple cantilever, so that the deflected shape under wind-induced oscillation would be similar to that caused by the mean wind-load. This allowed us to lump the dynamic and static actions together to produce a quasi-static load which was assumed to have a triangular-shaped pressure distribution with the maximum pressure at the leading edge.

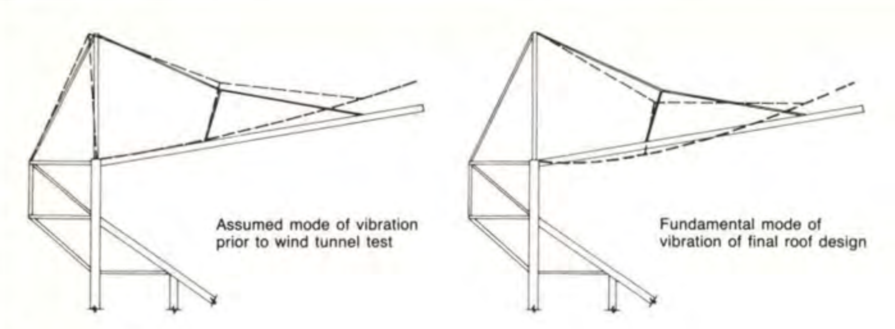
The maximum pressures for wind speeds relating to the 1 in 1000 year return period (used as the ultimate limit state condition) are shown for different wind directions (Fig. 9). These results indicated that we had slightly overestimated the upward loading while underestimating the downward case. As the upwards loads were critical, this result was clearly satisfactory.

The elimination of counter-weighting required that the suspension system be competent to resist the compressive forces which occur under uplift without buckling. The simple system on which the tender was based was unsuitable, as in order for the stays not to buckle, their diameters would have to increase to a point where they became visually unacceptable.

To overcome this, adjacent suspension systems were inclined together, their front stays were bifurcated to provide two support points for each rafter, and secondary bracing was provided at the point of bifurcation. This arrangement reduced the individual effective lengths and allowed small-diameter, thick-walled tubes to be used which could accept the compression forces and yet allow the total system to remain visually slender and elegant (Fig. 8).

Two further benefits were important by-products of this change. Firstly, the linking together of adjacent pairs of suspension systems to form stable A-frames greatly simplified erection. Secondly the rafter beams, being supported at two points rather than one, reduced in size from a 760 UB to a 610 UB, saving some 300 tonnes of steel.

This reduction in roof beam size almost proved to be our undoing as it altered the fundamental mode of vibration of the roof from one similar to a simple cantilever involv-



11. Modes of vibration

ing the whole suspension system, to one involving only deformations of the rafter beams with a very different deflected shape. This in turn undermined the principle of using a single quasi-static wind load. Instead static and dynamic effects had to be separated. The former could be modelled as a constant pressure (as before), while the latter was treated by imposing a multiple of the fundamental mode displacements, as determined by computer analysis (Fig. 11).

In order to ease construction and minimize problems due to fabrication tolerances and temperature effects in service, the roof in its final form is made up of statically determinate, independent structural systems at alternate bays, with infill bays consisting only of purlins (Fig. 12). In fact the whole roof was detailed with no special facilities for dimensional adjustment (apart from an ability to align the leading edge of the roof which was not used) and was erected without problems.

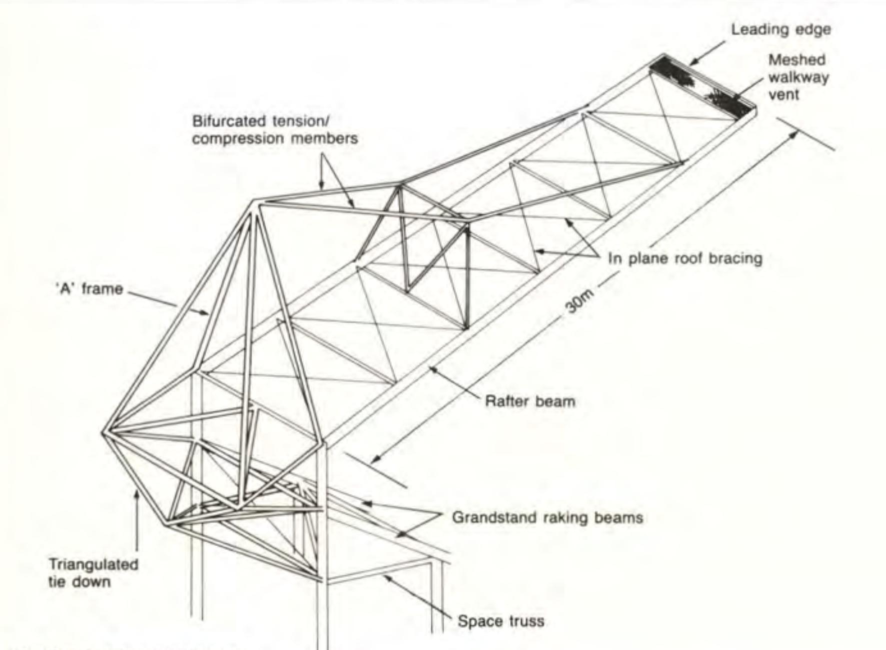
In the end, it was decided to use a perforated aluminium cladding to create a smooth soffit to the roof. The perforations act both to increase acoustic absorption and allow the wind pressures to pass through and load the structural cladding above. This ceiling improved the roof's appearance and prevented pigeons from roosting on the rafters. Ingenious detailing of the purlin system allowed installation of both layers of cladding from above without the use of scaffolding. In fact no scaffolding was used for the entire roof erection.

The structural system for the roof is completed by space trusses located below the grandstand seating which deal with the forces caused by the mis-alignment of the radial roof beams with the grandstand beams (which follow the more gentle curve of the seating arrangement).

The elegant form of the roof is reflected in the connection design. The topology of the roof support structure varies around the roof perimeter, from the triangulated masts and tie-downs along the east and west sides to simple cantilevers with vertical tie-downs at the ends where the span is considerably less. The detailing is such that these transitions occur smoothly and enhance the overall 'swoop' of the roof.

Each connection after structural sizing was modelled by the architect with scale models and three-dimensional computer graphics. The joints were then varied where necessary to achieve a satisfactory architectural and engineering result.

Following final connection design and profiling, typical connections were tested at the University of Technology, Sydney.

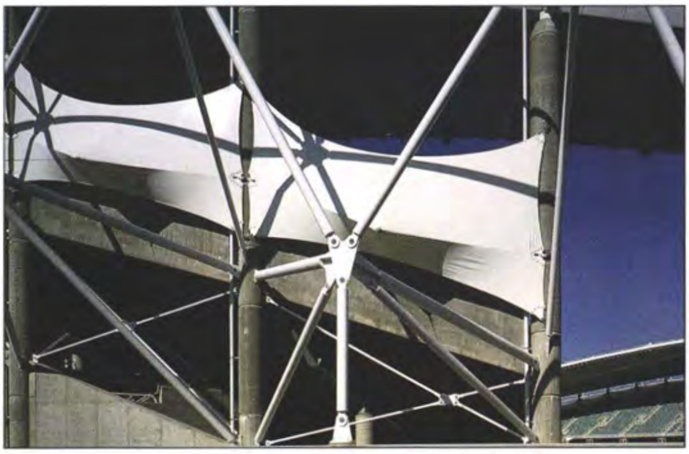


12. Typical structural bay

13-14. Above and left:
structural bays in the
course of erection

Photos:
3: Paul Simcock
4: Geoff Ambler
5, 15-17: Patrick Bingham-Hall
10: Richard Drew
13 & 14: John Nutt

15.



16.

A total of 1600 tonnes of steel was required for the whole project, 1100 tonnes of which were needed for the roof structure. The tubular suspension system was fabricated from grade 350 steel and all the other members are of grade 250 steel. All exposed steelwork received a three-stage corrosion protection of inorganic zinc silicate, high-build epoxy and a re-coatable polyurethane finish, all of which were applied in the workshop.

To add a visual contrast to the elevation and minimize wind intrusion, the gap between the upper edge of the grandstands and the rear edge of the roof is partially covered by tensioned fabric structures. The membrane is a pvc-coated polyester fabric which is tensioned by galvanized steel cables attached to the roof support structure.

Conclusion

The stadium was completed on time and within budget and was opened by the Premier of New South Wales in January 1988. A second stage, to fill in the southern end with corporate boxes, is now being constructed in the off-season.

Apart from football the stadium has been used for a variety of events including a monumental performance of Verdi's *Aida* complete with elephants.

During 1988 it was awarded an Engineering Excellence Award by the Institution of Engineers Australia and received a Special Award from the Institution of Structural Engineers.

Credits

Client, project manager and main contractor:
Civil & Civic Pty. Ltd.
Architect:
Philip Cox Richardson Taylor & Partners
Structural, civil and geotechnical engineers:
Ove Arup & Partners Australia
Steelwork subcontractor:
ICAL Ltd.
Cladding subcontractor:
Chadwick Industries Pty. Ltd.

17.

Broadgate ice rink

Arup Associates Group 2

Chris Twinn

Introduction

Broadgate is a new financial centre which has been built in the heart of London on a 3.6ha site, formerly a car park and railway station. It is close to the City and consists of offices, with shops and restaurants, planned around a newly-created public square. The master plan was based on the patterns of movement of the large numbers of people coming from Liverpool Street Station.

By planning vehicular circulation below ground, the development creates a series of new streets around the pedestrian square, which has been landscaped with planting and semi-mature trees and is designed to provide outdoor spaces and facilities for a range of activities. It is situated alongside a second square formed by the new buildings on Finsbury Avenue, and shops, restaurants and wine bars have been designed as an integral part of each of the two squares. The linking streets are marked by specially-commissioned sculptures designed by Segal, Serra and Lipchitz, and a free-standing circular pavilion housing an independent suite of offices has been planned between the squares.

The majority of the Broadgate offices are in a series of four buildings which define these streets and squares. Each building is focussed around an atrium and has been designed to provide spaces which can be used to accommodate the full range of office uses, dealing rooms and computer suites.

Their external walls consist of a three-dimensional sculpted grid of red granite which acts as a screen to the windows behind.

The buildings step back at the upper floor in order to create an appropriate sense of enclosure on the squares. At these upper levels there is a series of landscaped terraces alongside the offices.

The first four phases of development at Broadgate have been designed by Arup Associates and provide a total built area of 154 000m^2. Rosehaugh Stanhope Development plc were appointed as the developers for the project in 1984, construction commenced a year later and the first phase of the scheme was ready for occupation in 1986. Several financial institutions — Shearson Lehman Hutton, Security Pacific Hoare Govett, Mitsui Trust and the Union Bank of Switzerland — have subsequently moved into Broadgate and the total scheme was completed in 1988.

The ice rink

The new square is arranged in an amphitheatre form across four floors and is surrounded by terraces and colonnades covered in greenery. In the centre is a circular marble-finished piazza that, during five winter months of each year, becomes a 22m diameter outdoor ice rink.

A great deal of thought went into the design of Broadgate Square to make it a place of interest: a place to which people would be attracted; a place with quality finishes, soft planting and a depth to its modelling. All these elements are intended to make the Square an attractive environment for the concerts, exhibitions and many other events which take place virtually every day during the summer. However, in the winter the weather curtails these activities and from this stemmed the idea of providing something specifically for that season.

The rink concept was not easy to achieve. People were generally very interested and enthusiastic but the construction industry had its doubts. 'It is not practical with our UK weather', was a common reaction. (This is partly explained by the sum total of UK outdoor rink experience being a brine rink near Aviemore that fell into disuse some years ago because its ice surface condition was difficult to maintain.)

This prompted consideration of plastics synthetic ice. However, there are difficulties in using this material outdoors and the idea did not generate much enthusiasm. Fortunately, further investigations in the USA, Scandinavia and central Europe revealed that a real ice rink was technically feasible. Final confirmation came after visiting the very successful Leidse Plein rink in Amsterdam which is subjected to weather conditions very similar to our own.

Rink alternatives

There are four general types of rink available. The system most frequently used in the UK is the brine indirect system. In fact the 'brine' is a glycol/water mix passed through plastics pipes, normally cast in concrete, on top of which the ice is formed. This system, however, is not very responsive to spot heat loads; for example, sun shining directly onto a part of the rink surface.

At Broadgate there were practical difficulties in accommodating the large header trench required by the bigger pipes of a brine system along the perimeter of the rink.

1. View from rink level showing the colonnade with its recently-installed planting. Beyond is one of the Phase 2 atria. The rink is enclosed by a demountable timber safety barrier hung on permanent bollards.

2. Looking south-west across Broadgate Square from Phase 4 level 8. (Photo: Jeremy Cockayne)

A variation of this system, frequently used for temporary rinks, involves laying a grid of plastic pipe mats on top of a concrete surface, joining them together and to headers, through which brine is then pumped. Water is frozen around and over the pipes. Although this rink pipework would have had initial cost advantages, its limited lifespan means large maintenance costs, particularly as the normally rectangular pipe mats would have needed tailoring for a circular rink. This system is also more vulnerable to vandalism.

The alternative to brine is to pass refrigerant directly through the rink pipework. This necessitates steel pipework but, without the heat transfer between fluids, it works more efficiently and at a higher evaporator temperature.

The third alternative was the direct system emanating from Scandinavia which has expansion valves or chokes on each cross-rink pipe. This allows a certain degree of flow balancing. However, it then requires conventional pumps to overcome the rink pipework resistance. This type requires a much more modest header trench than brine systems, but still needs insulated and vapour-sealed headers and full access to valves and joints.

Another version is the 'pumpless' direct liquid refrigerant (dlr) system, which originated in the USA, that uses rink pipework without valves/chokes as its flooded evaporator. It is thermodynamically more efficient than brine, has a simpler plant configuration, with energy consumption advantages over alternative direct systems.

This latter system was finally chosen for the Broadgate rink, not only on its technical merits and suitability, but also on cost grounds. As well as reducing the capital cost, it also minimized allied works under other contracts for items such as the perimeter pipe header trench.

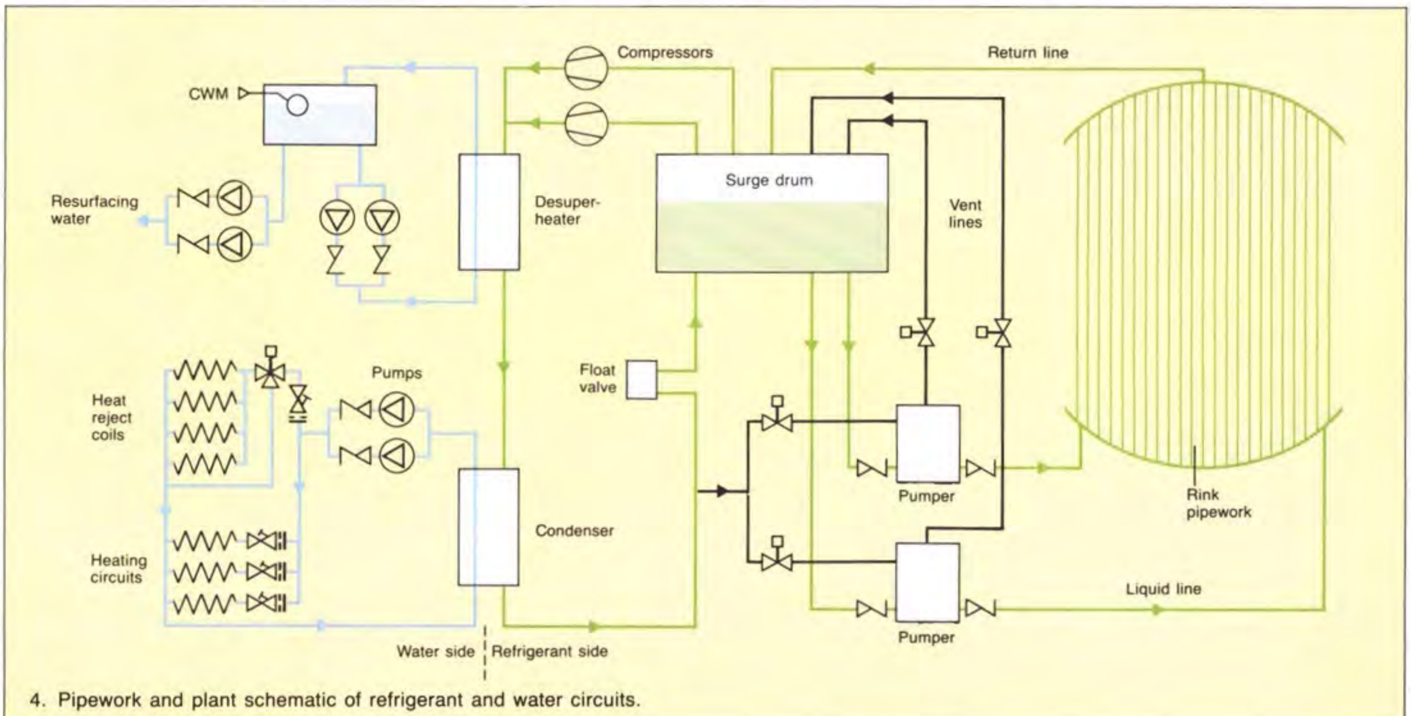
3. The central space designed to accommodate an ice rink during the winter months, is used as a public square throughout the rest of the year. (Photo: Peter Cook)

As is normal for ice rinks, the contract was performance-based and included all aspects of the rink: fridge plant and pipework, rink concrete pad, condenser circuitry, heating circuits, thermal insulation, electrics, controls, weather protection and temporary works. The project was built using a construction management type of contract.

The performance specification gave a list of the adverse weather and environmental conditions likely to be encountered. Each was given a value that would be exceeded on 2½% of days during a typical February. The aim was to ensure that the rink could cope with almost all weather conditions during December, January and February and, weather permitting, allow a rink season from the beginning of November to the end of March. In addition, the contract listed various operational cooling loads that could occur simultaneously with adverse weather, e.g. resurfacing the ice using hot water.

In accordance with the principles of a performance-based contract, the specification made clear that the trade contractor was free to apply diversity factors to any of the given performance criteria based on his experience and expertise. For example, winds that remove the insulating layer of cold air over the rink tend not to be at a maximum when the sun is at its highest. Similarly, the ice is always partially shaded from direct irradiation from the low winter sun.

In the event the contractor made use of considerable USA experience to check the design and plant sizing assessment. Having run for two complete seasons in parts of the mildest winters on record, the plant has shown that it is more than able to cope.



4. Pipework and plant schematic of refrigerant and water circuits.

Operating cycle

Fig. 4 shows the unconventional flooded evaporator fridge system (by today's building services' standards) as developed by Holmsten Ice Rinks Inc., in the USA. It is similar to fridge systems used more generally in industrial refrigeration and before the 1940s.

It consists of two separate circuits emanating from the common surge drum (receiver). On the one hand the compressor draws refrigerant gas (R22 — the only currently available 'ozone-friendly' one) from the top of the surge drum, passes it through a de-superheater and the condenser to dump its heat and then back to the bottom of the surge drum via a float (expansion) valve. On the other hand, the liquid refrigerant is drawn from the surge drum by pumper vessels, then pushed through the rink returning to the surge drum as a vapour/liquid mixture.

These pumps are simple small tanks that fill with liquid refrigerant under gravity from the surge drum when their vent lines are opened.

When full, the vent lines are closed and the pumper is lightly pressurized by opening a line from the discharge side of the compressor circuit. This pushes the refrigerant out to the rink and returns it to the surge drum. The pressure required is very modest, there being no expansion valves or similar constrictions in the rink pipework.

Heat gains to the ice surface are transmitted via the concrete pad to the refrigerant pipes below, and are countered by a small proportion of the refrigerant changing state from liquid to vapour. The resulting increase in pressure is almost instantly distributed across the rink pipework system with a slight temperature change.

The uniform refrigerant temperature and distribution of heat gains across the whole rink make this system more efficient than alternatives at coping with sun and wind heat loads, where these affect only parts of the rink surface as is typical for outdoor rinks.

The operation of the compressors and pumps is controlled by a temperature sensor installed in the surface immediately below the ice. Waste heat is rejected from the refrigerant into the water side at two different temperatures. Firstly the de-superheater provides limited quantities of high grade heat. With both compressors working, this is sufficient to heat the water used for ice resurfacing up to 70° C. Secondly, the condenser provides large quantities of low-grade heat of up to 30°C to be used for:

(1) *Under-rink heating.* These coils minimize the effect of cold on the habitable room below and ensure non-freezing conditions in the supporting structure and drainage layer under the rink.

(2) *Paving heating.* These coils minimize the freezing effect the rink has on rain that has fallen on the paved areas immediately outside the rink perimeter barrier, and helps to counter the cold air drift towards the surrounding shops and restaurants.

(3) *Snow pit heating.* These coils are located in the bottom of a tank called a snow pit where 'snow' dumped from the rink surface melts and runs to drainage. A rink is usually resurfaced using a vehicle that cuts off the roughened top surface of ice and puts down a layer of hot water which forms a flat-topped surface before freezing to the underlying ice. The ice thus removed from the top of the rink is called 'snow'.

Low-grade heat not used by the above heating coils is rejected to the atmosphere by four large heat-reject dry coils located in the fan discharges of the extract ventilation system that serves the Broadgate Square underground service road.

Rink construction

Fig. 5 illustrates a vertical section through the rink perimeter. The habitable room below is intended to be a food hall. As far as this room is concerned its roof with the rink on top is a variation on the conventional upside-down roof construction. Laid on the concrete structure is a screed containing the under-rink heating topped with the main waterproof membrane. The drainage layer is separated from the extruded polystyrene thermal insulation by a vapour barrier intended to limit water migrating up through the insulation where it would freeze and expand.

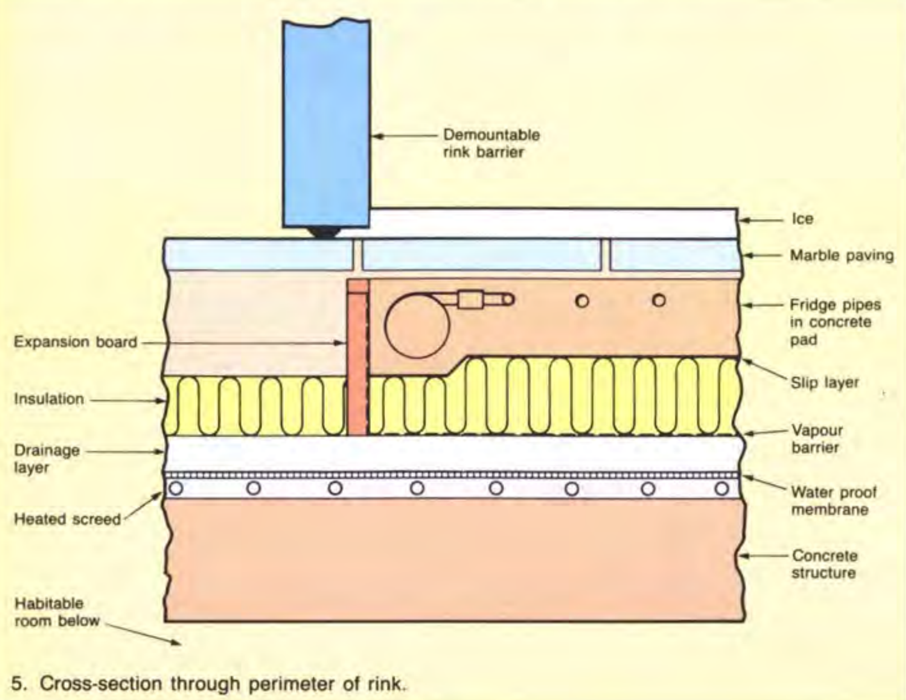
The rink pad is of super-plasticized, heavily-reinforced concrete laid on a slip layer to allow for the large differential movements that occur. The concrete pad is generally 100mm thick, locally increased to 125mm to accommodate the perimeter liquid and return header pipework. This arrangement avoids a separate header trench outside the rink pad area with all its associated lagging, vapour-sealing, access and aesthetic detailing problems.

The soft, mild-steel, small-bore, cross-rink pipework arrived on site in coiled bundles to be straightened and shaped to fit the rink. It was installed in continuous lengths between the headers, which are of curved, welded pipework with specialist compression joint connections to the small bore runouts. All this pipework was cast into the concrete pad.

There are various aspects of the Broadgate ice rink that are non-standard when compared with normal ice rinks. Permanent rinks normally consist of a concrete pad to form the finished surface below the ice. This is particularly so where the surface is used for other activities when the rink is not in operation. However, a concrete finish would simply not have been appropriate as the exposed centrepiece of the Broadgate Square development for seven months of the year. Terrazzo cast into the top of the concrete was considered but discounted as it would have given a very bland finish across the whole of the 25m diameter piazza area.

Travertine marble paving slabs were finally selected, and a great deal of investigation into the freezing resistance of the many types of travertine carried out. A full-scale 3m × 3m area mock-up of the rink was successfully tested under repeated freeze/thaw cycles. The marble did not form a part of the ice rink plant contract but had to be allowed for in the plant sizing. The rink pipework is more remote from the ice than is normal, so consequently the refrigerant temperature has to be considerably lower. The assessment of the lower evaporator temperature was hampered by the lack of thermal resistivity data for materials when fully saturated and frozen.

The summer drainage requirements of the piazza are in direct conflict with those of an ice rink. Usually, paving is laid to falls on a thick permeable bedding; however, firstly, fridge pipes cannot normally follow falls; secondly, the air in a bedding would act as an insulant, thus dramatically reducing the



5. Cross-section through perimeter of rink.

6-8. Rink plantroom:
The rink skid contains the refrigeration plant and controls. The chilling capacity is just under 200kw at −20°C evaporating temperature.

Condenser water pumps and pressurization unit in foreground, with refrigeration skid beyond.

The client's definition of 'value engineering' excludes plantroom-applied finishes; e.g., there is no aluminium or similar finish to the pipework.

effect of the cooling pipes below; thirdly, water naturally tends to form a horizontal surface before it freezes, independent of falls in the surface below. This could mean ice thicknesses in certain areas in excess of 150mm, and ice being an insulant of sorts, this would make it almost impossible to maintain an adequately consistent ice surface.

The design solution selected included a special bedding with a thickness varying from 5mm to 25mm to give nominal falls but still avoid the worst pooling of water on the paving in summer. This allows the concrete pad and fridge pipes to remain horizontal. Furthermore, drains that could be closed off during rink use were brought up through the centre of the piazza to reduce the distance from any point to a drain, as well as the height of falls.

An ice rink is a strange hybrid. Essentially, it is an industrial refrigeration plant, but with specialized reinforced concrete work, specialist fridge pipework, thermal insulation, controls, electronics, etc., all carried out by the relevant trade contractors under the direction of a refrigeration contractor. There are few people with the detailed knowledge of all these fields to bring them together. Consequently there were some pretty steep learning curves.

The rink in use

The rink has now been used for two seasons. Despite two very mild winters — at times exceeding design conditions — it has performed well and some interesting feedback can be noted.

The winter outside air in the UK has considerable moisture in it that continuously condenses and freezes onto the rink's surface. Substantial frost does not make for good solid ice and reduces plant efficiency as the thickness increases. Consequently, frequent resurfacing operations are necessary without laying hot water. In fact the resurfacing hot water has rarely been used.

Normally the plant will freeze surface water within two hours or so of the end of a rainstorm. In so doing the ice thickness builds up beyond the 25mm to 38mm optimum, thus affecting plant efficiency and energy consumption. This increase in thickness has to be kept in check by regular use of the re-surfacing vehicle without adding the hot water.

Any ice rink plant has controls for changing the ice temperature. Instructional skating requires soft ice at about −5°C, ice hockey requires hard ice at −9°C with recreational skating somewhere in between. Reduce the ice temperature too much and contraction cracks start appearing. However, an experienced operator can anticipate adverse running conditions by reducing the ice temperature control and pre-cooling the concrete pad to provide a cold buffer against temporary peak heat gains.

The thermal capacity of the concrete means that about two hours elapse before the ice responds to the plant. The concrete also assists should a power cut and mechanical failure occur, because ice can be retained for perhaps 12 hours without the plant running.

A lot of effort has gone into ensuring the operating and maintenance manuals are appropriate and usable. The rink is a non-standard, complicated, mechanical system, designed by industrial refrigeration engineers to be serviced by building services engineers and operated by laymen. Also it operates for less than half of each year so that continuity of staff cannot be guaranteed.

The initial enthusiasm for the idea has continued for the finished article. Broadgate Square is attracting ever greater numbers of children, families, office workers and passers-by, many of whom are tempted onto the ice.

Credits

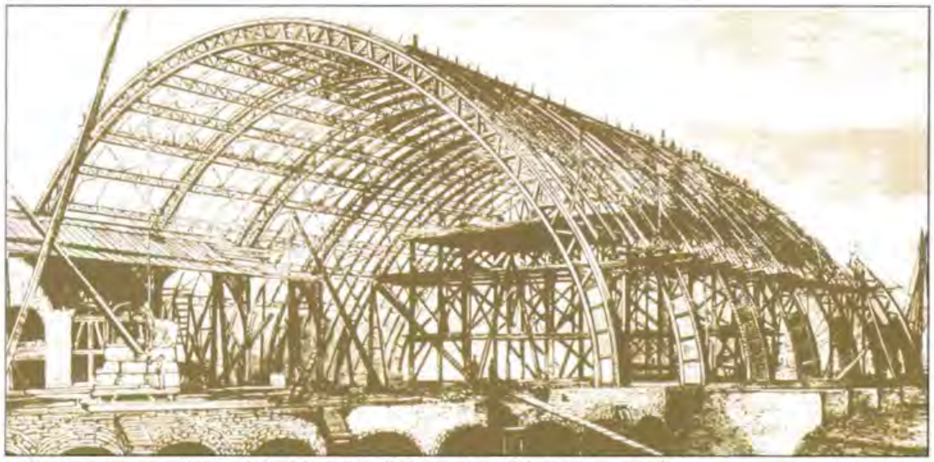
Client:
Rosehaugh Stanhope Developments plc
Architects & Engineers & Quantity Surveyors:
Arup Associates
Construction manager:
Bovis Construction Ltd.
Ice rink contractor:
York International Ltd.
Photos:
Arup Associates except where otherwise stated

9. The rink floodlit during evening use.

The St. Enoch Centre

Architects: Reiach and Hall + GMW

Tom Ridley
Derek Blackwood
Jack Carcas



1. Roof structure of the original building (from a late 19th century print)

2. Plan of site after demolition of station

Introduction

Glasgow has received much publicity from the recent highly successful Garden Festival and from its nomination as Cultural Capital of Europe in 1990, but its future prosperity rests on its continuing as a major commercial and business centre. The St. Enoch Centre, now nearing completion, is a further bold symbol of confidence in Glasgow's commercial regeneration and city centre revitalization, to join other important recent projects such as Princes Square and the Britoil Headquarters building.

Located in the heart of the city, next to the main shopping area, the site was that of the old St. Enoch Railway Station and hotel which were closed down in the late 1960s as part of Dr. Beeching's cutbacks. Their demolition created an enormous gap site of some 6ha and a major urban regeneration task, which was not tackled until the Scottish Development Agency was able to take the initiative in the mid-1970s. Initially a large part of the site was to rehouse Ministry of Defence staff who were to be transferred to Scotland as part of a programme of decentralization, but when the decision was taken to relocate these offices in another part of the city the full area of the site became available for commercial development.

It was temporarily transformed by the Scottish Development Agency into a large ground level public car park providing 1500 spaces, a major contribution to the continued success of the nearby existing shopping facilities. Meanwhile, a design team was selected by the Agency to prepare a concept for the new development. The architects chosen for this task were, unusually, a combination of two well-established practices, the GMW Partnership of London and Reiach and Hall of Edinburgh. This association was seen to bring together the benefit of world-wide, large-scale commercial experience with long-standing knowledge of local conditions in Scotland. We were very pleased to be selected as the structural and civil engineers.

Over the years many schemes were investigated, but finally the concept of a 75 000m^2 commercial development incorporating multi-storey parking for 750 cars emerged, and this was transferred in 1984 to the private sector in the form of the Church Commissioners for England and Sears Holdings plc, who became developers for the scheme. The basic concept was adopted by the new clients, as was the original design team, and Chestertons were introduced as project managers.

Concept

The architects believed that in addition to providing economic commercial space, the new development should make a strong architectural statement and should result in a civic building worthy of its important location. Another notable factor affecting the concept was the desire to ensure a light and airy interior.

During the early 1980s the concepts behind the design of large shopping centres in the UK and elsewhere had been evolving rapidly. The old ideas of small covered malls between shop units linked from one 'anchor' department store to another, had been overtaken by the 'atrium' concept of covered public space combining shopping and leisure. There are many examples in Europe, the United States and Canada, and their impact on city centre sites has been to reinforce and improve existing urban conditions. The climate in Scotland certainly encourages such enclosures of public space, as witnessed by the success of Victorian shopping arcades.

This led to the basic concept for the St. Enoch Centre as a large, simple, glazed enclosure in which the final layout of shop units could remain to be planned in detail late in the construction period, with maximum flexibility to adapt to future changes without altering the external appearance. A multi-storey car park structure being a main feature of the building, the idea of utilizing this to provide stability to the glass roof structure followed.

The glass envelope itself was conceived as a simple wind and weathertight barrier which would also provide an opportunity for solar responsive passive energy systems to ensure a pleasant internal environment without the need for air-conditioning in the malls.

The final element in the concept was the desire to reflect Glasgow's vigorous engineering tradition. To this end, the steel roof structure was to be strongly expressed to make a major contribution to the visual excitement of the interior, while externally a cable-stayed bridge would mark the high level entrance to the car park.

In addition to our role as structural and civil engineers, we were able to advise on fire and traffic engineering, other important aspects of the feasibility of the concept.

Due to the unconventional form of the building several Building Regulations relaxations had to be obtained. One of these, relating to fire compartmentation, was the subject of a very detailed study on smoke control to which Arups' fire engineering section contributed.

Another most important planning consideration, which the transportation group advised on, was the impact of traffic generation on the existing city centre road system. In addition they studied the interface with bus and rail transport as well as car and pedestrian movements.

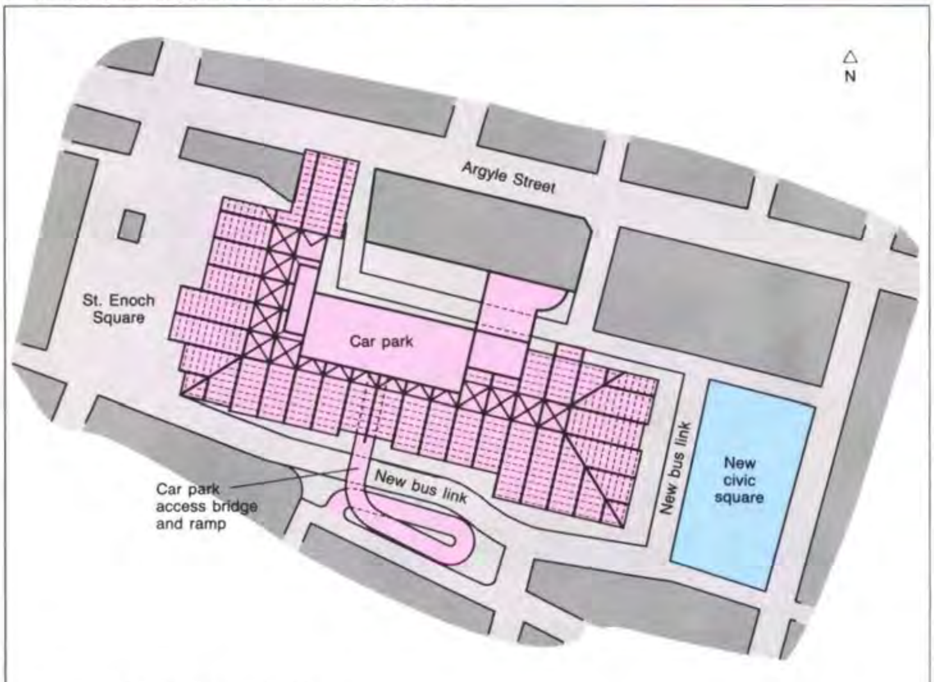
General description

The glazed envelope of some 30 000m^2, claimed to be the largest in Europe, encloses a volume of 250 000m^3 above the lower, main, mall level. Below this the substructure incorporates access for the largest articulated lorries to unloading bays with goods holding areas, plant spaces and shop servicing corridors, all at basement level.

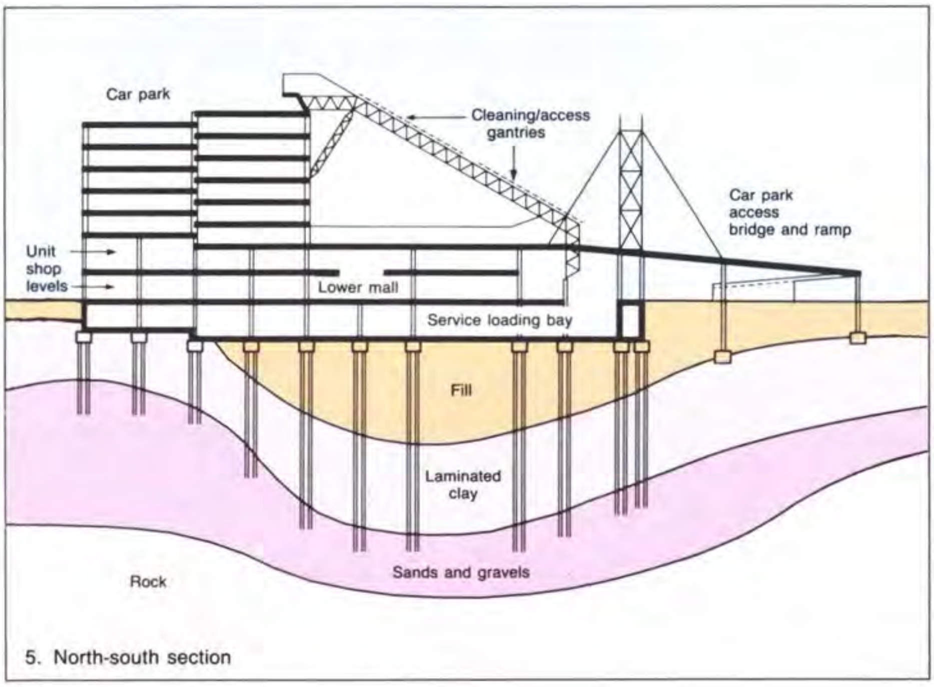
The ground floor, or podium, forms a roof over the basement and acts as a base for the structures above. The glazed enclosure is supported by structural steelwork which provides a headroom of approximately 9m at the periphery of the building and rises to 25m at the central cores.

These include the seven-storey car park, a five-storey, multi-purpose building and a three-storey structure which is linked to an existing adjacent major shopping store.

3. Model of development in relation to city centre



4. Plan of new building on site



5. North-south section

Rising from the lower mall and constructed within the glazed enclosure are the internal structures. These comprise four major stores, 75 unit shops, a 450-seat food court, and leisure areas which operate on the two main mall levels. The main store has a third-level sales floor. Elsewhere, at high level, are the centre management suite, a restaurant and a 'park' which, it is hoped, will become a market garden open to the internal environment of the atrium.

Internal features make extensive use of planting. On the car park wall, overlooking the shopping malls, steel-framed plant boxes and illuminated panels form a hanging garden. Mall bridges and pergolas in the centre are decorated with plants, and tree pits have been provided at lower mall level.

Cars will enter the car park over the heads of the shoppers via a 360° ramp which rises 14m from ground level to bridge a main road and penetrate the glass enclosure in twin tubes. These are clad in one-way mirror glass allowing views outward to the shopping below, as well as acting as a smoke separator.

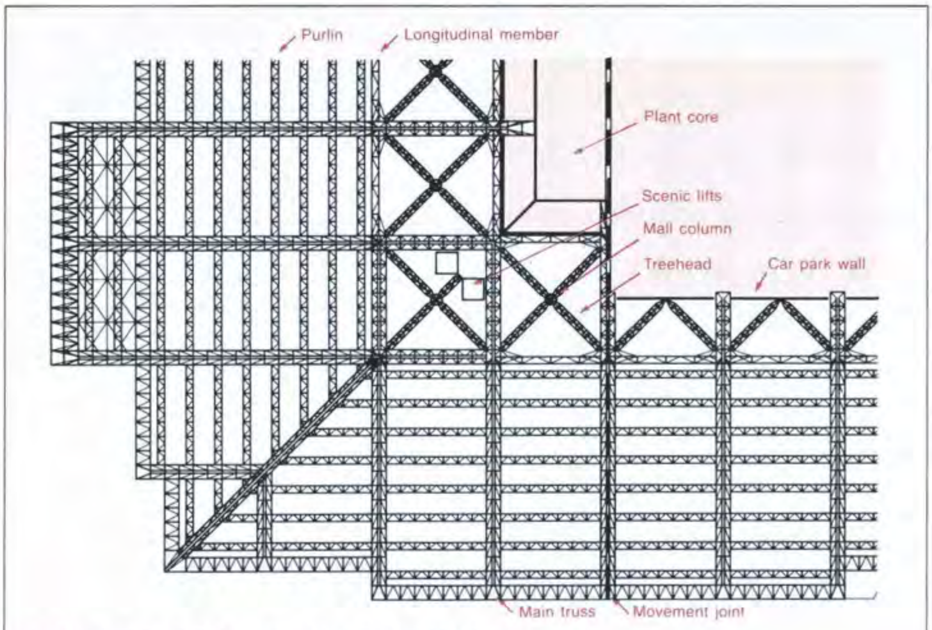
The provision of permanent access systems to maintain the glass envelope and service the high interior was an important consideration. External access to the glazing is achieved from ladder-type gantries at the 30° pitch of the roof, traversing the length of the enclosure on rails supported from the structural steelwork purlins. Internal maintenance is combined with the need to service lighting, clean internal glazing and to tend the plants on the wall of the car park, which rises 20m above the upper mall for a length of 86m. The main system of access is from horizontal gantries which span 14.4m between main trusses. These traverse the slope to a lateral transfer beam at high level.

The clear south-facing glazing ensures a light interior, but computer-controlled, motorized solar shades are installed to prevent direct sunlight falling on populated areas of the shopping malls.

Site and substructure

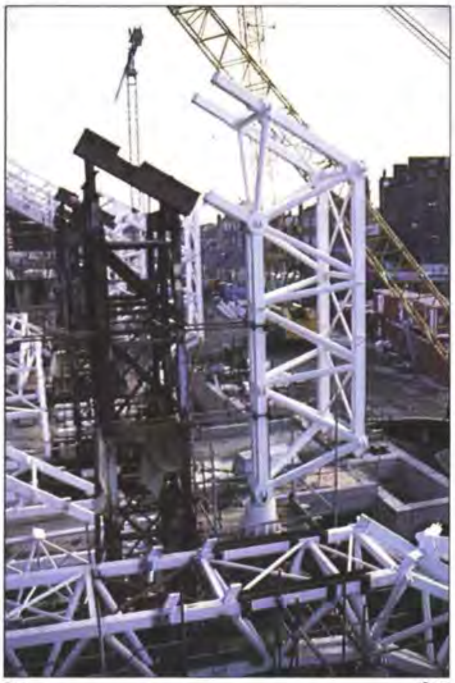
Extensive site investigations comprising boreholes, cone penetrometer tests and trial pits revealed highly variable subsoil conditions. The upper layer, within 3-4m of the ground level, generally consists of filled ground overlying soft to medium clay which occurs in thicknesses ranging from zero to 25m. Beneath the clay, lower sands and gravels occur above rockhead which is at a depth of approximately 35m. Shallow pad footings were considered but eventually discounted because of the variable thickness of the clays giving potential for large differential settlements. Nor were the clays considered suitable as a bearing medium for the wide variety of loads imposed from the structure, because of the variations in settlement that would result.

Discussions took place with piling contractors to establish which systems would be most suitable and economical for the site. Large bored piles to rock were eliminated on the grounds of cost and the uncertainty of being able to achieve a good end-bearing condition. Following further detailed design work, three piling specialist firms were asked to tender for piles to carry the building loads to the sands and gravels either in friction or end-bearing. It was finally decided to construct two types of pile: driven cast-in-place (*Franki*-type) up to a maximum length of 20m, with load being transferred to the sands and gravels in end-bearing; and continuous flight auger piles up to 30m long with friction being the main load transfer medium. The cfa piles also had the advantage of virtually vibrationless installation and so were used close to existing structures, tunnels and sewers.



6. Detail plan of roof steelwork at south west corner

7▽ 8△ 9▽



7. Section of a main roof truss

8. Erection of a leg of a main roof truss on pinned bearing (November 1987)

9. Fitting a longitudinal truss to a main truss (November 1987)

10. Temporary towers to support steelwork during erection (July 1987)

Photos:
3. The architects
7-10. Ove Arup & Partners Scotland

Superstructure

In the design of the structure the roof steelwork was by far the most demanding element. The combinations of load cases, including temperature changes, are extensive, and the calculations were processed using plane frame analysis and three-dimensional analysis for each combination. Wind model testing, using a solid block model specifically related to the assessment of pressures, was carried out at Bristol University and confirmed that interpretation of the British Standards for wind loading on the St. Enoch glazed enclosure was appropriate.

The steelwork relies for lateral stability upon the car park and the east and west core structures at the centre of the building. 1m diameter reinforced concrete columns at the periphery provide vertical support. The triangulated main trusses, 1.8m deep, span 36m onto 'treehead' members which spring from the core structure and from isolated columns at 14.4m centres. Triangulated purlins 900mm deep span 14.4m between main trusses. Restraint to lateral and rotational forces is afforded to main trusses by longitudinal lattice members.

The in situ reinforced concrete basement is designed to resist water to a head of approximately 2m, with the self-weight of the basement slabs and the suspended podium above providing the necessary balancing forces. The structure is designed as watertight concrete but, in the event of seepage, and as a protection against penetration of dampness through the concrete structure, drained cavity construction is employed. On top of the basement slab a 'no fines' concrete layer beneath a damp-proof membrane and screed ensures that no moisture reaches the 'habitable' environment.

The podium slab supports the main mall and the associated shop units. Cost exercises indicated that in situ reinforced concrete was the most economical solution and troughed construction with ribs at 1.8m centres was adopted. The heavy partition and live loads dictated the adoption of a 125mm thick topping concrete and the subcontractor elected to use polystyrene formers, usable two or three times. Tree pits, escalator and lift bases, fountains and water features at this level introduce a high degree of complexity into the otherwise simple structure.

10

A feature of the design of the enclosure steelwork has been the close co-ordination required with the glazing. The steel trusses were detailed on nodal geometry and accessory steelwork formed the link with the glazing geometry. The main benefit of separating these elements was to allow the main structure to be erected and depropped, thus enabling the internal structures to be built in parallel with the accessory steelwork and glazing overhead.

The decision to build these structures within the erected envelope was an important factor influencing the adoption of in situ reinforced concrete, ribbed slab construction (similar to the podium slab), since this minimized the access and handling problems which would have arisen had structural steelwork or precast members been used.

The car park is of the split level type on 13 half-decks and was planned to coincide with the 7.2m grid of shops below. This resulted in a parking bay of 2.4m. Discussions with Strathclyde Regional Council, who will operate the car park, led to outboard columns and a clear span of 16m. The penalty for seeking the economy of inboard columns would have been a bay size of 2.5m, which would have disrupted the vertical planning. In situ reinforced concrete, troughed slab construction spanning 7.2m onto portal frames over the 16m span, has resulted in a good open structure with 'slow up' and 'fast down' ramps at each end.

Advance and external works

Design of advance works included a new bus link, following closure of an existing road which intersected the site. Along the line of the road, twin sewers had to be diverted. The first was an old egg-shaped sewer which lay with its crown above the proposed basement level, whilst the second, a 1.2m diameter, brick-lined, cast iron pipe, lay at a lower level. Negotiations took place with Strathclyde Regional Council Department of Sewerage to replace the twin sewers with a single 1.6m diameter concrete pipe whose invert followed that of the 1.2m diameter pipe. In the unusual circumstances of a sewer being allowed beneath a new building, particularly with such limited cover available, it was necessary to provide large access chambers at either end of the diversion so that obstructions entering the sewer could be readily removed by the statutory authority. No contact could be permitted between the building structure and the sewer and the basement

11△

12▽

slab was carried from pile caps either side of the new pipe with soft packing to prevent load transfer to the sewer.

Part of the above works involved design and construction of a new stair tower linked to an existing commercial building in Argyle Street and large openings formed through the existing masonry wall. A feature of the design was the removal of an entire section of masonry wall at street level with needling and pinning to support the structure above until new structural steelwork columns and beams could be inserted. During the construction of the new work the inside of the building was stripped out, floors were surveyed and new stairs designed and inserted as part of the replanning.

External works include the major car park access ramp and bridge, stone-clad podia at the perimeter of the development and a new civic square at the east end to complement the existing St. Enoch Square.

Construction

Approval to start on site was given in September 1985 and two months later the advance works packages commenced.

The start of the main contract followed in May 1986 and after some construction difficulties with the cfa preliminary test piles, the installation of the 1500 piles was completed within five months.

Fabrication of the 2500 tonnes of steelwork was carried out in Manchester and Cambuslang, near Glasgow, and erected between May and December 1987. Painting was further subcontracted and shop-applied. Because of the amount of additional work, constructed under subcontract packages, which followed the erected steelwork and took support from it, extensive corrosion protection touch-up and decorative finishing paintwork were necessary on site.

The subcontractor for the internal structures, constructed within the enclosure, elected to use track-mounted cranage, gaining access for materials through temporary openings in the glazing. At this stage of the design and, against the constantly-changing background of client needs, early decisions made as to the extent and configuration of piling were put to the test. By a combination of some minor replanning on occasion and re-routing loads, the clients' revised needs were met. There is flexibility in certain areas of the development for future extension and this will probably be exploited in the near future.

13△

14▽

11. Interior looking east, mirror glass car park access tube in foreground
12. Erection of glazing on roof steelwork
13. Treeheads
14. Aerial view of construction in March 1988

Photos:
11, 13, 15 & 16: Alistair Hunter
12 & 14: Guthrie Photography

15. Interior view at east end (columns wrapped with protective covering)

Conclusion

A building of this scale and novelty has inevitably led to the involvement of many specialist consultants. These have included the American interior designers, Hellmuth, Obata and Kassabaum (HOK), and the US services engineers Cosentini who assisted with the design of the internal environment systems. Our design has also been subjected to close scrutiny by others. The clients' decision to obtain decennial insurance necessitated an external consultant checking the design and detail of the building fabric, while the local authorities have shown a very keen interest and Glasgow City Department of Building Control have examined in detail every aspect of the structure.

The Centre is due to be completed, at a building cost of some £65M, in the spring of 1989 after approximately three years on site. Our involvement, however, goes back 11 years, during which we have seen it grow from quite modest beginnings to one of the largest and most challenging structural projects undertaken by the Scottish practice.

Credits

Clients:
Church Commissioners for England and Sears Properties Glasgow Ltd.
Development conceived and initiated by the Scottish Development Agency
Project manager:
Chestertons
Architects:
Reiach and Hall + GMW Partnership
Structural and civil engineers:
Ove Arup & Partners Scotland
Services engineer:
Blyth & Blyth (M&E)
Quantity surveyor:
Muirheads
Management contractor:
Sir Robert McAlpine Management Contractors Ltd.

16. East elevation

Risk analysis for the Channel Tunnel

Douglas Parkes
Charles Milloy

Almost everyone must be aware of the construction of the Channel Tunnel, but readers may not know about Arups' involvement in the project over the past two years. This has related mainly to safety during construction. Initially, Bush & Rennie were involved in flood prevention measures and subsequently carried out a safety audit on the first tunnel boring machine (TBM), to be used for construction of the UK marine service tunnel.

Bush & Rennie and Industrial Engineering were then asked to carry out a probabilistic risk assessment (PRA) of the construction stage for the UK contractor, Transmanche Link (TML).

Although PRA techniques, which involve the step-by-step statistical assessment of a wide range of parameters that could affect safety, have been applied in the nuclear and chemical industries for a number of years, this is probably their first involvement on a civil engineering project. The task of the PRA was to determine whether the safety systems provided were suitably reliable and whether the planned methods of construction were safe, in view of concern for the TBM crews working at such a distance out under the seabed in a sophisticated tunnelling machine. Risk from fire was a particular concern as the TBM has a number of high pressure hydraulic circuits using mineral oils; risks due to flooding, electrocution, asphyxiation and mechanical shock (i.e. falling or being struck) were also considered. The PRA concentrated on construction of the marine service tunnel for a number of reasons: this would be the first tunnel to be driven, and planning for the other drives was not as advanced; the marine service tunnel would be used to prove the ground, with regular stops for exploratory probes, and would therefore be exposed to the greatest risk; and all six drives from Shakespeare Cliff, just west of Dover, will use TBMs that have many similarities of design.

Construction work on the Channel Tunnel has now been going on for over a year. When complete, three 50km tunnels will link the UK with the rest of Europe: one running tunnel in each direction, and, in between, a smaller service tunnel that also serves as an emergency escape route. In addition there will be interconnecting passages at regular intervals, pressure relief ducts, sumps, large crossover point tunnels and other ancillary tunnels.

On the British side, tunnelling work is based at Shakespeare Cliff. From here there will be three 8km landward drives to the new terminal being constructed north of Folkestone, and three 22km seaward drives to the agreed meeting point with the French members of the construction consortium. The alignment of the tunnels follows the blue chalk-marl band under the Channel. In tunnelling terms this is an excellent material, relatively impermeable and reasonably easy to work without being too friable, and its presence greatly facilitates tunnelling from the UK side. However, from the French side it is necessary to pass through some very poor ground before reaching the chalk-marl and even then the stratum is somewhat folded. This makes working conditions worse for the French, who have had to provide a more sophisticated type of tunnelling machine.

The UK marine service tunnel TBM, shown diagrammatically in Fig. 1, is a full-faced boring machine with a rotating cruciform cutting head. It consists of two cylindrical steel sections of 5.38m diameter followed by a 200m long machinery train, housing equipment for tunnel construction and for powering the forward sections.

The first cylindrical section is the main body. This houses the cutting head with its electric motors and gearboxes, the hydraulically powered steering rams and the driver's cab. It is connected by a telescopic steel shell and the main push rams to the second cylindrical section or gripper body which houses the grippers and their large rams. A conveyor belt runs the length of the machine to carry the excavated chalk from the face. Tunnel excavation proceeds in a series of 1.5m steps. As the cutting head is rotated, the main body is advanced by the main push rams against the reaction provided by the grippers pressing against the tunnel wall.

After 1.5m, the steering rams are activated, the gripper rams are released and the push rams are retracted to draw the gripper body and the rest of the machine forward. The cycle then recommences.

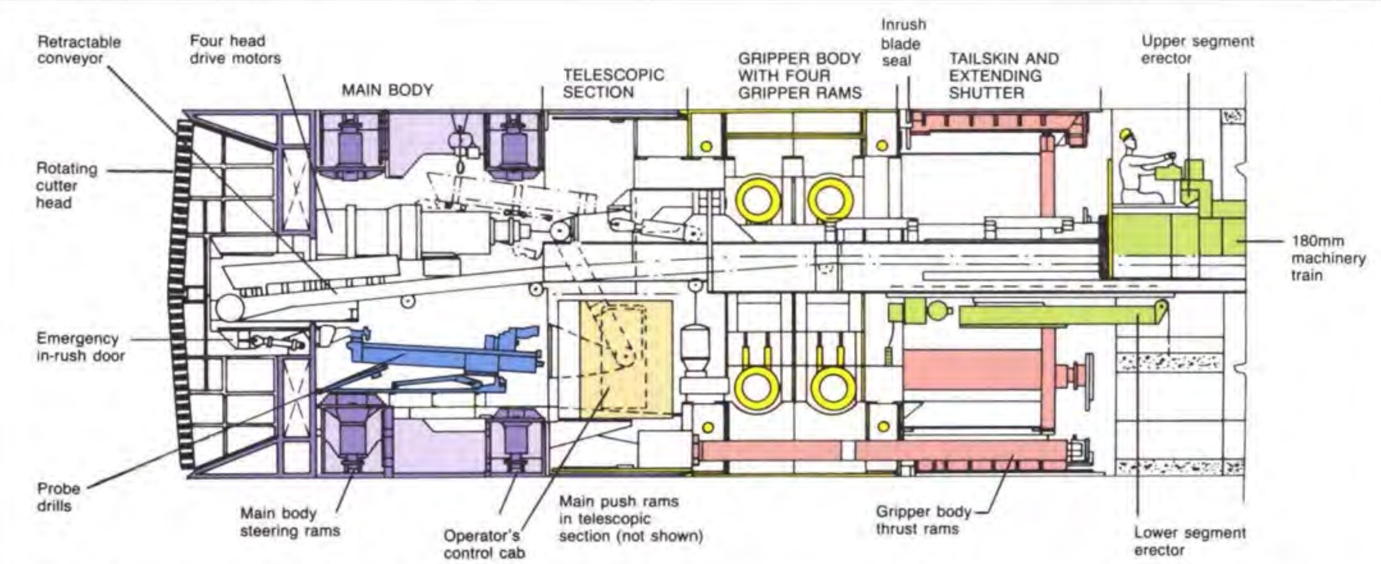
Immediately behind the gripper body is the segment handling and ring building equipment. The tunnel lining is 4.8m internal diameter, built in 1.5m long concrete rings.

Seven precast segments form a ring, the seventh being a key which must be rammed home, holding the other segments in place much as a keystone secures an arch. The segments have raised pads on the outside which bear on the excavated chalk, leaving an annular gap which is subsequently filled with grout.

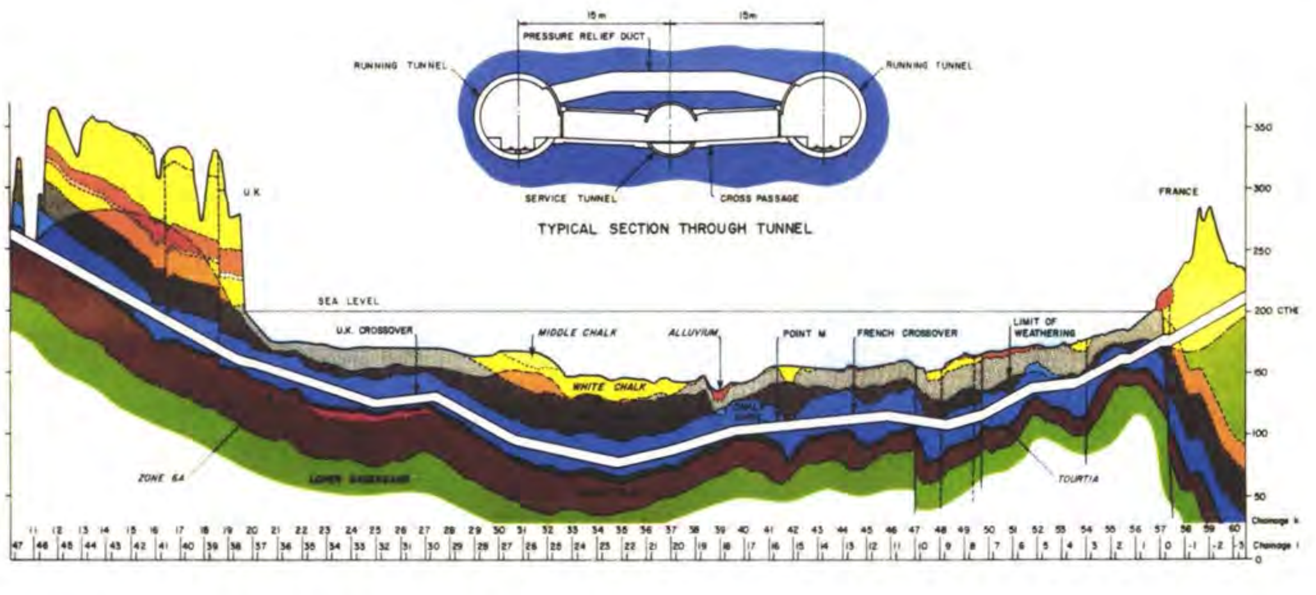
At the rear of the ring building area, horizontal deck units are placed across the lower segments, and on this deck temporary, and eventually the permanent, rail tracks are laid.

To the rear of the building area a series of sections of travelling stage in the TBM train carry the conveyor above the rail track and house the various items of plant required for operation of the machine. This includes the hydraulic tanks and pumps for the rams in the main body and a gripper body, grouting equipment, ventilation equipment, emergency inundation pumps, transformers, compressors and electrical control equipment, as well as a workshop and mess facilities for the tunnelling crew. At the rear of the machine incoming services are connected. These include an 11kV electrical supply, fresh air ventilation duct, and water and pumping mains.

Lining segments and deck units, temporary track materials and pipework are brought in on trains which run into the TBM to within 40m of the working face. These trains also bring empty muck wagons for removal of the excavated chalk. The trains are driven by electric locos powered by battery whilst in the TBM area, but with overhead (pantagraph) pick-up further down the tunnel. Funicular traction is also provided for the ascent of the access drift to the surface when required.



1. Tunnel boring machine for UK marine service tunnel



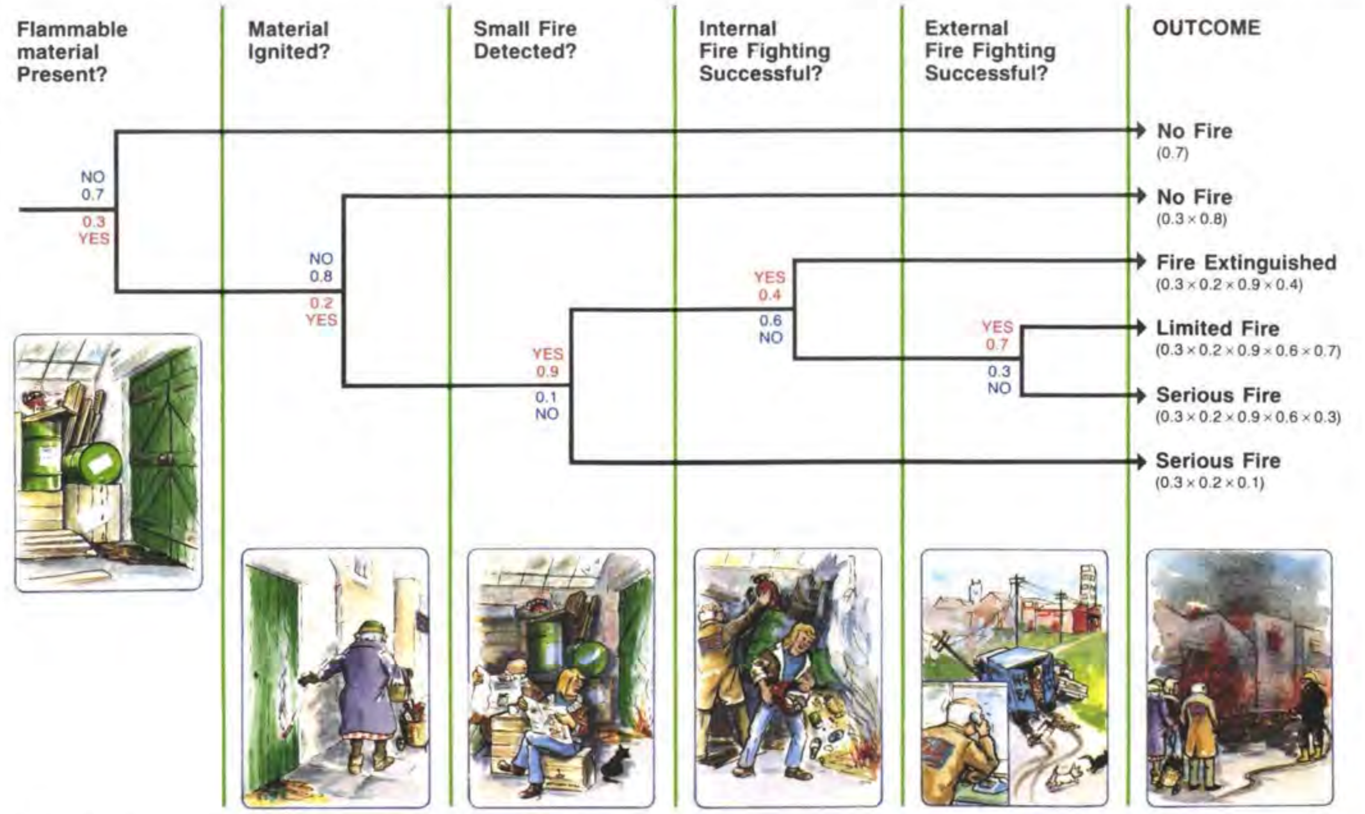
2. Longitudinal section through tunnel

Fire is an emotive subject because of its potential for disaster. There have been few serious fires in tunnels being driven and no definite pattern is apparent. However, 'good housekeeping' can play a significant part in keeping down the incidence rates by preventing the accumulation of waste materials like old cement bags and other paper, straw, timber, spilt oil, etc. Good maintenance will reduce the risks of overheating of bearings or damaged cables, or 'flashovers' due to damp ingress. Good practice in the use of gas cutting and the prohibition of smoking will reduce probabilities of ignition from these sources.

In such a highly mechanized tunnel, the large amount of equipment with the potential to overheat poses an obvious threat. Fire detection and other environmental monitoring equipment is positioned along the length of the machine. Fire extinguishers are provided throughout, and at particularly hazardous areas where there is a risk of mineral oil fire, there are foam extinguishing systems. In addition, all major power units and systems are protected against overload and overheating, and automatic halon extinguishing systems are provided in enclosed electrical switching cabinets. Emergency stop systems exist for all power and moving equipment; and in the event of a major inrush of water at the working face it is possible to seal the main body to prevent flooding.

The assessment of technical as opposed to economic risk in the construction industry has been often neglected, and understated where consideration has been given to it. Design codes rarely discuss risk openly but incorporate load and strength uncertainties into partial safety factors. For tunnelling work, site investigation techniques, construction methods and operational practices that have developed over many years are incorporated into construction planning, which is a first step, of course, to controlling these technical risks.

It is necessary to define what is meant by risk in this context. Risk is the product of the expected frequency of an accident and its consequences. The frequency is usually expressed, for example, as 'once in a million years' which is the same as 10^{-6} chance per annum. Consequences may be the number of deaths which the accident causes.



3. Event tree analysis

Unfortunately, risk is in itself not an absolute guide. A different view is taken of the risk of road traffic accidents killing 6000 people each year, mostly in ones and twos, from that of major disasters each year such as Piper Alpha and King's Cross. The magnitude of the risk due to traffic accidents is greater but our perception of the tragedies is not.

Thankfully, disasters during tunnel construction causing multiple loss of life are rare and the accidents which take place are mostly due to carelessness or lack of awareness rather than gross mismanagement of risks.

Each year, the Health and Safety Executive collects and publishes construction accident data. For a conventional project it is possible to establish an estimate of the expected accidents and injuries, knowing the workforce, equipment and working methods and schedules. For large, unconventional or complex projects there will, however, be little useful historical accident data and a more innovative approach is required.

In the case of the Channel Tunnel it was necessary to chart all the operations using planned working methods and individual items of equipment as building blocks. Individual probabilities and failure rates were assigned to these elements of the tunnelling work, and the Arup team then used the technique of Event Tree Analysis to estimate the rates of occurrence of serious accidents. The analysis included provision for human error, which is frequently a significant contributor to major accidents.

Event Tree Analysis calculates the expected frequency of an accident. Consider, for example, a serious fire developing. A chain of events (and failures) is needed to cause the fire. By breaking down the chain into discrete stages as shown in Fig. 3 it is possible to calculate an overall likelihood of fire occurring. Taking the simple example represented by the figure, we are concerned with calculating the frequency of a serious fire. Looking at it we can see that flammable material may be present only part of the time. A credible source of ignition — for example burning, welding, or lighted cigarette — will only come into contact with the flammable material occasionally. A small fire will only be detected if there is a person or a suitable detection device in the area. There will be times when appropriate fire extinguishing equipment is unavailable or inoperable. Most of the time the 999 call will be effective but there will be occasions when the Fire Brigade cannot be mobilized. At each step or branch in the tree, probabilities are assigned to each branch.

The overall frequency of serious fire can then be estimated by aggregating the individual probabilities for each line resulting in a serious fire.

The way to reduce the risk of such an accident would be to reduce the probabilities of the presence of the flammable material and its ignition. To do this, one must either exclude the use of the flammable materials or sources of ignition altogether, or ensure the establishment of procedures which do not rely so heavily on the diligence of those carrying them out. The Event Tree will demonstrate this either by reducing the individual probabilities or introducing another branch in the chain which results in a significant reduction in the overall probability. In practical terms for our example, the oil must be stored in a special enclosure, smoking prohibited in the area and the fire-fighting equipment regularly checked.

Even with the techniques described, obtaining the necessary data is often a major difficulty. There are national and international data banks of failure rates but great care is needed to avoid the data being misused because it was collected in circumstances not appropriate to the problem. In many instances the incidence data do not exist and it is necessary to apply best judgement based on knowledge and experience of the operations involved.

The more subjective the estimate of event probabilities, the more need there is for sensitivity analysis to assess the effect of judgements on the final result. There are times when a large change in isolated probabilities has a very small effect on the result. Even so, the results should always be treated with caution and not viewed as absolutes but rather as a guide for comparison.

For the Channel Tunnel the study found that the highest expected incidence rate was mechanical shock (falling or being hit), followed by asphyxiation, fire, electrical shock and lastly, inundation. This is much in line with construction generally, where accidents due to falling or being struck by machines or falling objects are by far the most numerous.

One of the greatest benefits to come from an analysis of this type is that it concentrates attention on the most probable causes of accidents so that more effective action can be taken to reduce overall risks. Examples of this on the Channel Tunnel were the installation of additional fire detection equipment and imposition of a ban on smoking underground. The smoking ban alone reduced the risk of fire by a factor of 10. The various measures will not eliminate accidents during Channel Tunnel construction, but the study has allowed an informed and cost-effective use of resources to limit risk.

At the time of writing, the Arup team have been instructed by TML to proceed on a second PRA. This will cover the construction of the UK undersea crossover tunnel. This is a cavern where the trains can change from one line to another. The cavern will be 160m long × 20m wide × 14m high. This PRA will cover the geotechnical aspects to a considerably greater extent than the first one and will involve Arup Geotechnics as well as Bush & Rennie and Industrial Engineering.

Credits

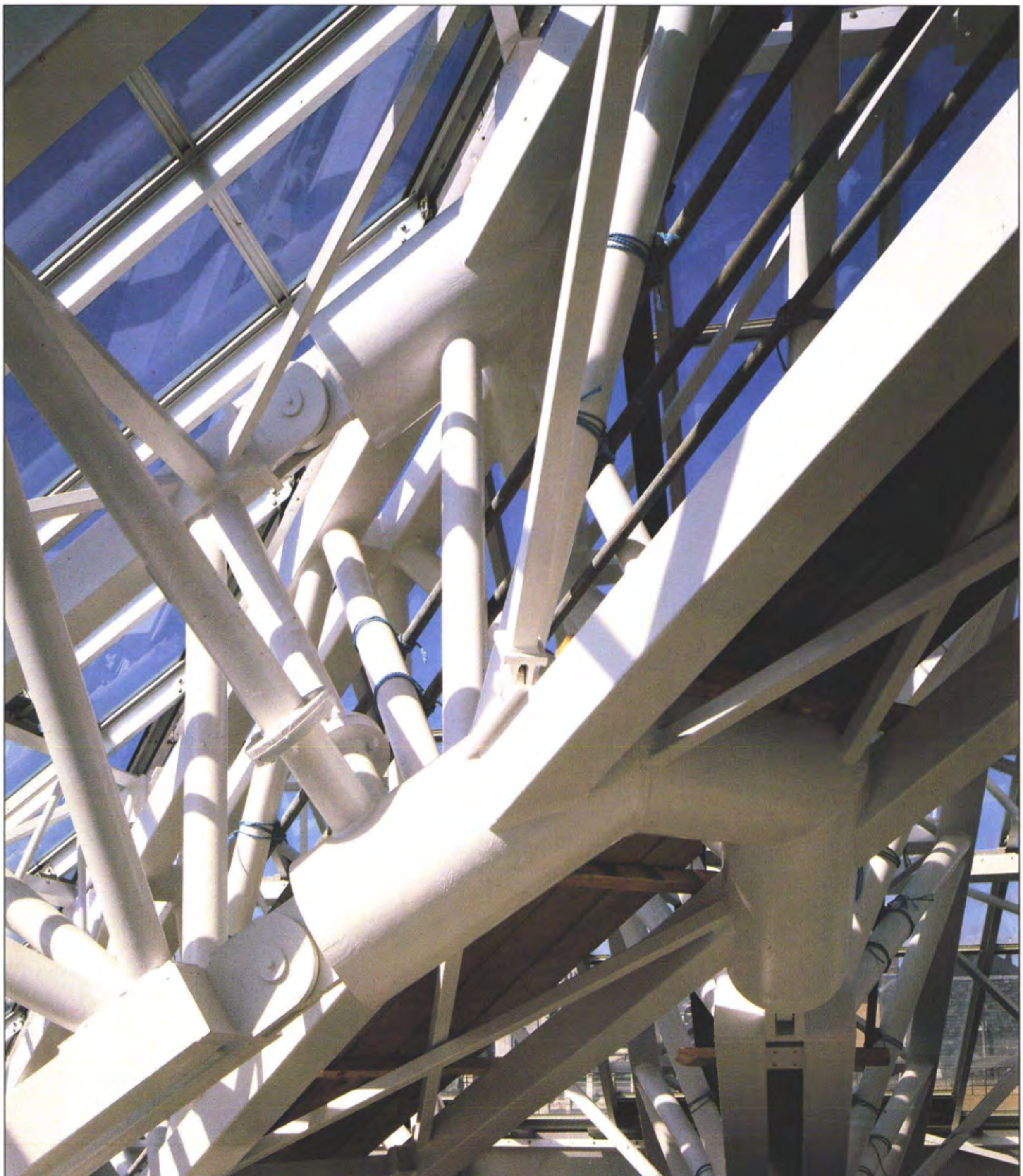
Client:
Transmanche Link (TML)

Consultants:
Bush & Rennie and Ove Arup & Partners
Industrial Engineering

In the summer 1989 edition of The Arup Journal

Harry Sowden

Heroes' Acre, Zimbabwe



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