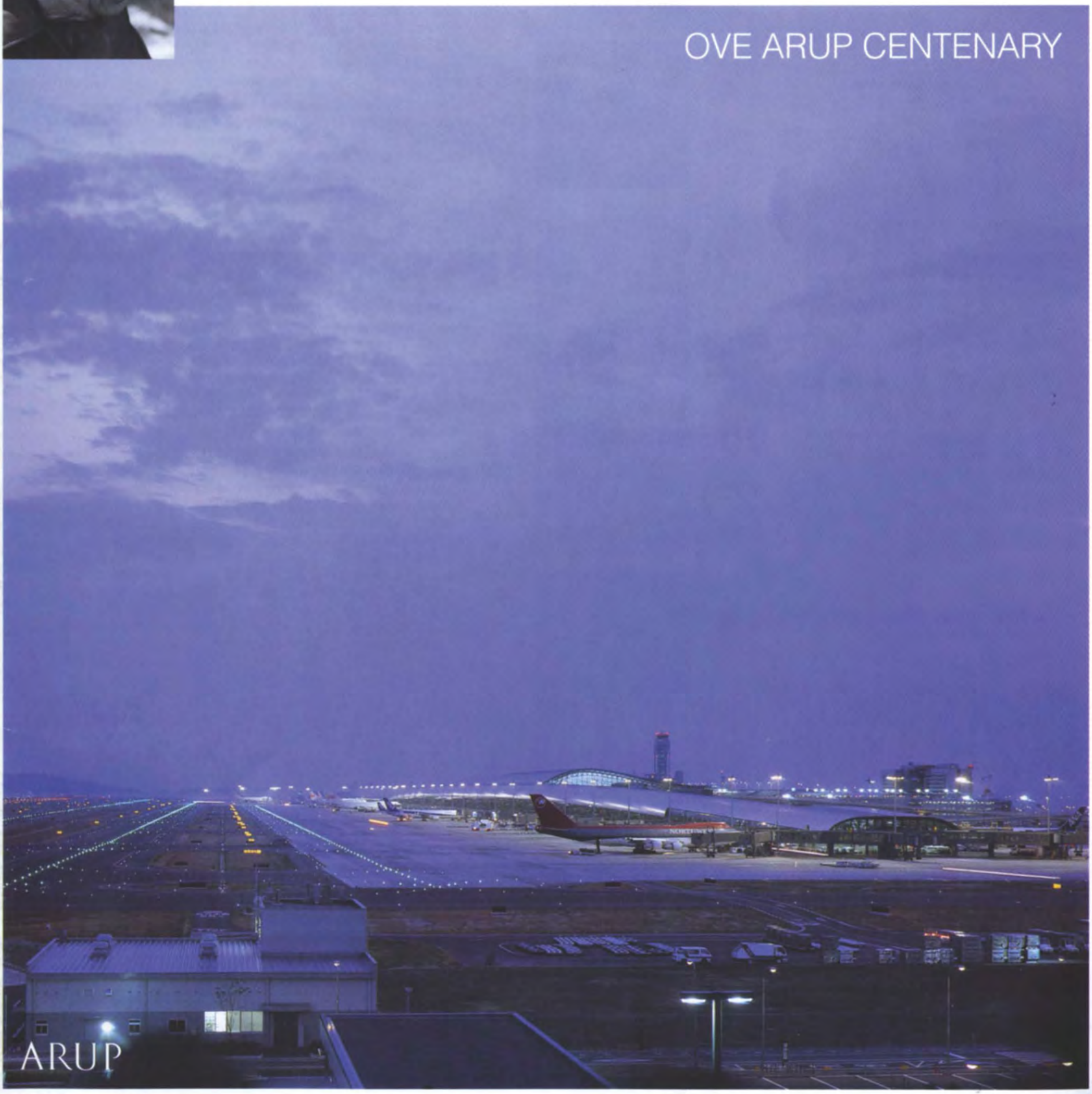
THE ARUP JOURNAL

1/1995

OVE ARUP CENTENARY



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Front cover:
Kansai International Airport Terminal.
(Photo: Dennis Gilbert)
Inset: Ove Arup in the 1970s.
(Photo: Harry Sowden)

Back cover:
The Hong Kong Stadium.
(Photo: Colin Wade)

Editorial

Our founder, Ove Arup, was born 100 years ago on 16 April 1895. Much attention is being given to his life, his work, and his legacy in this centenary year, but for the Ove Arup Partnership his enduring gift is perhaps more than anything an attitude of mind.

He was a relentless pursuer of excellence, a perfectionist down to the smallest detail. This is made abundantly clear in the personal account opposite by John Martin, Chairman of the Partnership from 1992 to 1995, of working with Ove on the design and execution of the Kingsgate footbridge, Durham, in 1963.

But his passion for quality was a constituent of a larger whole. He was indeed a 'holistic' thinker, long before the word became fashionable. No matter where the actual boundaries, physical or organizational, of a job fell, and no matter how small the project was or how apparently insignificant, Ove Arup was always aware of a wider context. This was encapsulated in his phrase 'Total Architecture' - a term wide open to misinterpretation, but quite clear in his own mind, as he expressed it in the 'Key Speech' (1970):

We are led to seek overall quality, fitness for purpose, as well as satisfying or significant forms and economy of construction. To this must be added harmony with the surroundings and the overall plan. We are then led to the ideal of 'Total Architecture', in collaboration with other likeminded firms or, better still, on our own. This means expanding our field of activity into adjoining fields - architecture, planning, ground engineering, environmental engineering, computer programming, etc.

It is not the wish to expand, but the quest for quality which has brought us to this position, for we have realized that only intimate integration of the various parts or the various disciplines will produce the desired result.

All the projects in this *Arup Journal* reflect these and other preoccupations of Ove Arup, though some in ways that 25 years ago were unlikely to be foreseen.

The Bangkok Elevated Road and Train System (pp.4-7) is a massive attempt to alleviate a capital city's traffic problems, and its design is necessitating world-wide collaboration to an unprecedented extent between different parts of the Partnership. In the same field of transportation, but half-way round the world and on a totally contrasting scale, the Arup Advanced Technology Unit's redesign of the driver's cabin of the British Rail Networker 465 train (pp.7-9) continues the tradition of Ove Arup's willingness to take on entirely new challenges, as well as his approach to tackling a design problem - from its fundamentals, and taking nothing for granted.

Both the new Cable and Wireless training college, at Coventry (pp.10-13) and the Kansai International Airport Terminal (pp.14-23), demonstrate the close collaboration between engineering disciplines that Ove Arup always sought. Both buildings use the shape of the roof structure to facilitate the heating and ventilating concepts.
The integrated structure and airflow system designed by Arups for the Kansai Terminal building provides an enormous column-free space for the environmentally comfortable and efficient through-put of up to 25M travellers per year. The wave-form roofs of the Cable and Wireless college are an essential contribution to its being a 'green building', enabling the use of natural ventilation and daylight as much as possible.

Ove Arup was an environmentalist in two senses, as much concerned with conserving and not abusing the natural world as with the quality of our built environment. He would have applauded the environmental design solution made by a team from the Cardiff office, Arup Associates, and Arup Environmental - in response to an approach from the BBC - for the reactor buildings of the disused Trawsfynydd nuclear power station in Snowdonia (pp.23-24).

The final project described in this issue, the Hong Kong Stadium (pp.25-29), demonstrates both a distinctive structural concept by Arups and the collaboration, which Ove Arup so energetically espoused, between different technical disciplines. Perhaps even more notably, however, it celebrates the successful co-operation in 'planning and organization of the work on site' on a large and complex project to an extremely tight time-scale. Ove Arup may have been a visionary, but he was also eminently practical. In 1973, deprecating the merit of his being awarded the Institution of Structural Engineers Gold Medal, he said:
...all the things I have spent my life trying to say and do and teach are simple, commonplace, and obvious, things that every moderately sensible person ought to know.

Working with Ove

John Martin

The Editor asked me to write about the time I helped Ove Arup design the Kingsgate Footbridge in Durham. I did describe the bridge itself in a *Newsletter* at the time it was built (1963) but David is right, I should try to recall my memories of those days.

Every company should surely have its own character and its own sense of purpose, its 'mission'. Ours was derived from Ove. It is not transient, a thing of fashion. It is about a quest for excellence and what he called 'truth'. How he transmitted this to us all still puzzles me, for he knew few of us personally and worked with even fewer. But the impact he made was pretty powerful, even at third hand. So, without describing the bridge again, I will share with you a few memories of working with Ove.

The story began with a trip to Durham for a briefing from the University Building Committee. Their idea had been to span the deep valley of the River Wear with a short bridge low down and many steps up each side. Ove lost no time in suggesting that it might be better, and affordable, if we used the height to advantage, to have a long high bridge, without the steps. He wasn't going to miss a challenge like that! We spent the four-hour train journey back filling pages of a sketchbook with an endless succession of ideas. They tumbled out, in concrete, steel and wood, in every structural form.

Of the three famous criteria, 'firmness, commodity and delight', firmness - structural adequacy - was hardly an issue; that was inherent in it all. The debate was about commodity and delight, and about construction. The design had to be derived from a good idea about how it should be built. We returned to Kings Cross more than 12 hours after we had left it that morning, and the discussion had never flagged. He rang me early next day to pursue it. Before long we went back to explore the city and view the site from every possible vantage point. By that time we had reduced the competing ideas to three or four families of schemes and the journey up was devoted to sketching these in innumerable variation, this time to scale.The 6in. (150mm) scale Ove used was the cause of a typical scene. Not only was the Old Man persistent, he also seemed to be extraordinarily lucky.

The 6in. scale disappeared somewhere, apparently in the upholstery of our first-class compartment. We stripped it bare in search of it, to the consternation of our fellow passengers - in vain. On the way home that evening with an angelic smile Ove conjured it from the depths of his seat - the same seat.

1.

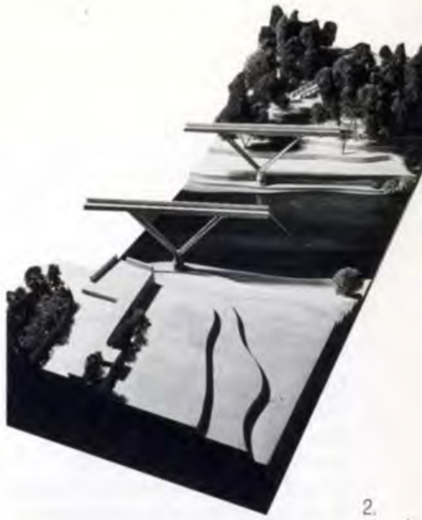
A consequence of that visit was that we declared that the line the client had proposed for the bridge was really not the best, and another was argued for, successfully, despite the fact that this meant moving the proposed new Students' Union building, Dunelm House. Ove's combination of powerful logic, ruthless determination, and an unforgettable charm made him practically irresistible.

Over the weeks that followed the detail evolved. The process was fascinating. Had it not been I would have found the relentless pursuit of the perfect solution impossible to sustain. The solution was to be found at the pinnacle where the results of the study of structural form, function, construction, and appearance converged. It took time. In the end there was not an arbitrary line. Incidentally I discovered that though his freely-sketched ideas might have an 'impressionist' quality, in his mind the picture was crystal clear, etched with great accuracy. It was part of my role to turn those sketches into engineering drawings. If my interpretation erred by a fraction, it was spotted next time we met.

An important part of the logic for the scheme we chose was the idea for building the bridge (see Figs. 2 - 4). The main spans consisted of two identical parts, one to be built over each river-bank, parallel to the water's edge. On completion they were to be turned at right angles and locked together over the middle of the river, some 55ft. (17m) up. This entailed designing bearings at the base of each part to allow rotation, and they had to be robust enough to rely upon but cheap, since each had to work only once. It provided an interesting essay into simple mechanical engineering, and some excitement too, twice over. There was no guarantee that the cheapest tenderer would build it as we had planned, and if he did we would face a rare day or two of suspense while the spans were turned.

In fact all went well - Holsts got the job and turned the bridge effortlessly. Ove never seemed to worry that anything might go wrong. That was fine, it just meant that one felt fully responsible for seeing that it didn't. But he got quite cross when the contractor took a few, to Ove's view unnecessary, steps to make doubly sure that construction went smoothly. I think that to him it was a question of spoiling the elegance of the idea.

It was only a footbridge, but I wish you could have seen how much fun we got out of it! Certainly, it was mostly a spare time activity - I had plenty of solid 'fee-earning' work to do as well. But it's the bridge that sticks in my mind.



2.

3.

4.

5. Kingsgate Footbridge between Dunelm House (also an Arup project of the 1960s) and the Cathedral. (Photo: John Donat)

International working: BERTS

Robin Forster John Loader

Bangkok Elevated Road and Train System

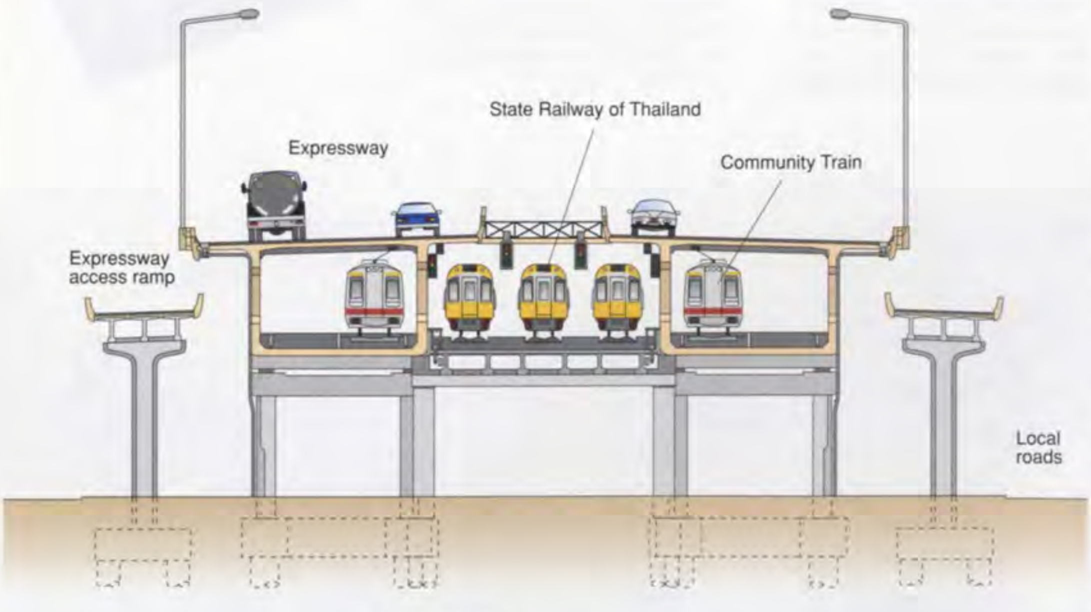
Introduction

Thailand's economic growth over the last 30 years has resulted in a doubling of Greater Bangkok's population and a substantial increase in car ownership, with consequent serious traffic congestion and air pollution. The State Railway of Thailand run their mainline trains at street level through Bangkok into the Central Station, so the operation of level crossings adds to the traffic congestion in the city. A number of privately-funded toll expressways have been completed, while others are at the planning stage, but the city needs a mass transit system comparable to those of Hong Kong, Taipei, and Singapore. Three separate systems are at the planning or early construction stage: Bangkok Transit System (BTS), Mass Rapid Transit Authority's Skytrain II, and BERTS - the Bangkok Elevated Road and Train System (Fig.1). BERTS has been under construction since May 1993, but Arups' involvement in the project goes back to 1988.

History

In 1986 the Hopewell Holdings Group investigated and developed a transport system that could be privately funded and provide the people of Bangkok with a mass transit railway similar to that in operation in Hong Kong.

1. Route plan.



2. Cross-section.

The concept of this integrated system was produced with input from Arups and presented to the Ministry of Transport and Communications and the State Railway of Thailand.

Following negotiations and an eventual international tender, Hopewell (Thailand) Ltd. signed a 38-year concession agreement with the State Railway of Thailand (SRT) and the Ministry of Transportation and Communication (MOTC) to build, own, operate and transfer (BOOT) the BERTS system, with Arups as a leading member of the design team.

Concept

When BERTS is complete, the total length will be 60.1km; of this, 53km follows the existing SRT railway reserve, which is the advantage that BERTS has over other systems in that land acquisition is minimal. Phase I follows the SRT north and east of the main line terminus of Hualumpong. The second phase of the project extends the system across the Chao Phrya River to link up with the SRT to the west and south (Fig.1).

The project has five key elements:

- A dual three-lane urban toll expressway to reduce journey time and congestion.
- An elevated mainline railway giving grade separation of trains and local roads. This provides SRT with a new central railway system with renewed trackwork and signalling, and a new central railway station.
- A high capacity community train (CT) with depots and stabling, and air-conditioned trains with a maximum of nine cars running at a peak frequency of two minutes and carrying up to 3M passengers per day.
- Improved local roads of two to four lanes each way, freed from the disruption caused by trains, running beside the elevated system to feed the expressway and to provide access to retail areas.
- Commercial development beneath the transport system along the route, and the commercial development (office, residential, hotels) of major SRT sites. The gross area could be in excess of $10Mm^2$ (Figs.2 & 3).

The main sources of revenue are mass transit ticket sales, urban expressway toll collection, and the commercial and residential property development. At the end of the concession period, the ownership of the entire system, including all the commercial and residential development, will revert to the SRT.

3.
Artist's impression
of typical length of BERTS.

Arups' role

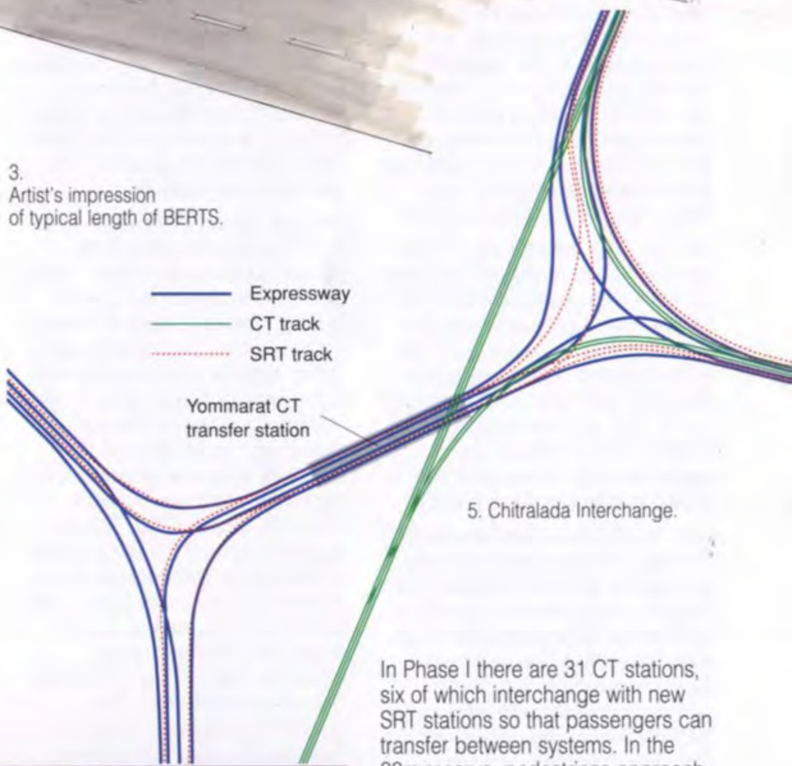
Ove Arup & Partners International were commissioned to design the civil engineering works, comprising elevated structures, stations, roads and drainage, together with the environmental services (temperature and pollution control, and fire engineering).

Arup skills used include:

- Bridge design
- Acoustics
- Structural engineering
- Concrete/material technology
- Road and railway alignment
- Environmental mechanical and electrical engineering
- Geotechnics
- Drainage
- Transportation engineering
- Fire engineering
- Environmental assessment
- Hazard and risk assessment.

Structures

Throughout the Phase I route, the BERTS system is built within the existing railway reserve. On the North Line this is up to 80m wide, but on the East Line the width generally reduces to 40m. For Phase II land will be procured, and the system will follow klongs (canals) and roads. Along the route, the BERTS vertical alignment has to accommodate existing and proposed expressway systems, and meet its own operational requirements. To achieve this, the 'typical' cross-section varies to allow the SRT, the CT, and the expressway to change in level independently to accommodate SRT ramps from ground level, clear the transverse flyovers, and to allow the CT to move between tracks via turnouts over the elevated SRT lines.



5. Chitralada Interchange.

4.
Model of external concourse station on the North Line.
Stations are generally located at major road crossings.

In Phase I there are 31 CT stations, six of which interchange with new SRT stations so that passengers can transfer between systems. In the 80m reserve, pedestrians approach the stations via stairs and ramps to a concourse constructed over local roads (Fig. 4). In the 40m reserve, space constraints force the concourse to be located beneath the boxes, with access to the platforms by external stairs. At Chitralada, where the North and East Lines meet, a complex junction provides through movements for the SRT, CT, and expressway systems (Fig.5).

Until now the railway reserve has also been used as a convenient services corridor through the city.

As a result, large diameter water mains, fuel pipelines, culverts, and electricity cables have to be accommodated in the alignment and foundation design.

For this immense project that is to be designed and completed in a relatively short time, it was essential that the main building components and details be standardised.

Overall, it was decided to divide the three passenger-carrying facilities within BERTS between two structural systems, the CT and expressway structures being separate from the SRT structure. The key element of the former is a prestressed, precast concrete box unit, spanning 45m between portal columns. The internal dimensions of the box (8.45m wide x 5.44m deep) allow for two CT trains to pass or can accommodate a single CT train plus a station platform. The top flange of the box is widened to 14.93m to form the deck of the three-lane expressway with hard shoulders. Each box weighs 1500 tonnes. Window openings in the sides provide cross-ventilation of the box and the SRT guideway in the centre of the whole elevated structure, as well as a view out for passengers. The boxes have to allow for horizontal and vertical curvatures in the alignment, and for gradients of up to 4%. Variations of structure allow for turnouts, expressway ramp connections and some shorter spans. Identical boxes are used at stations, where the openings become doorways leading from station concourses to the platforms.

The SRT deck between the CT train boxes is formed of precast concrete, double T-units spanning onto portal frames. The crosshead beams are precast concrete, connected to the in situ concrete columns by cast in situ joints. Generally the SRT column grid is 15m, and staggered from the 45m CT column module. Larger spans are required across klongs, as well as over some local roads.

Over 16 000 bored piles are needed in Phase I of the project. Following an intensive test piling contract, the largest ever undertaken in Bangkok, construction commenced with 1.5m diameter shaft-grouted piles to depths of over 50m. Bangkok's geology is complex and inconsistent but the shaft grouting allows working pile capacities to be varied to suit superstructure loadings. Generally for the support of the CT box, pile capacities are in the order of 1100 tonnes. For the SRT support structure plain piles are used, with capacities of around 500 tonnes.

It is a requirement that SRT trains run throughout the construction period, and up to eight stages of track diversion are necessary in some areas to allow for piling and pile cap construction. Elevation of the SRT lines into their new position as an integral part of BERTS will be carried out in phases; this has an impact on the design of the stations, and will dictate the sequence of construction of local roads, below-ground services, and commercial development at ground level.
At present the SRT uses diesel locomotives, which is a major factor in the design of ventilation and fire systems. However, provision is being made in the headroom for future electrification.

Handling the project

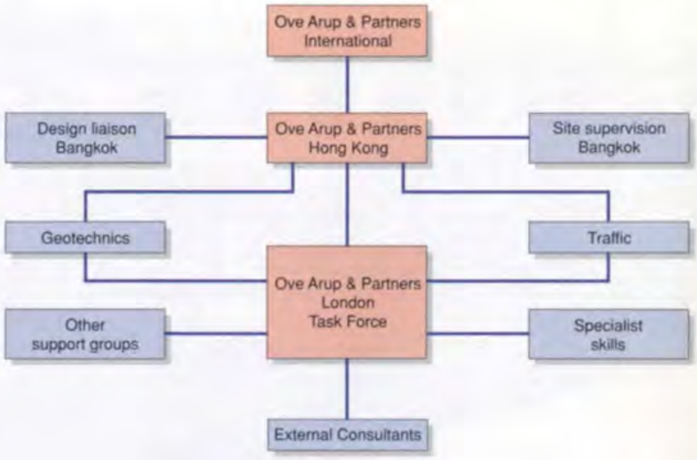
The concept and masterplan for the project were developed in Arups' Hong Kong office, which continues to provide the main client liaison.

During the first half of 1992, while survey work and geotechnical site investigation were proceeding in Bangkok, studies of patronage (patterns of demand and usage), structural element options, CT and SRT track planning and route alignments, stations and roads were put in hand.

The programme dictates that construction must proceed in parallel with the design. This is very interactive, with many cycles of evolution before elements become fixed.

In order to finalise piling, the following factors need to be taken into account: vertical alignment (height of the structure), locations of expressway ramps, the layout of local roads, drainage principles, existing services, ground conditions (which are variable), horizontal alignment (track layout), number of platforms at stations, station headroom, expressway geometry, box geometry, and loadings.

The size, speed, complexity, and multi-disciplinary nature of the project led to the decision to form a task force located in the client's building, Tileman House in Putney, South London. The intention was to gather together all parties involved in the detailed design of the project - eventually including the railway contractor - under one roof. The Arup task force was assembled in September 1992 and moved to Putney in January 1993. The size fluctuates to meet the requirements of the project, but averages about 70 staff, drawn from all parts of the firm in the UK as well as some of Arups' non-UK Partnerships (Australia, South Africa, Zimbabwe have all provided staff). Other specialist groups (e.g. Industrial Engineering, Arup Transportation, Arup Fire, and the Detailing Group) are assisting with the project.



6. Arup organization.

7. Piling.

8. Pilecap construction.

The task force works very closely with a small project team in the Hong Kong office. This team liaises with the client on design matters on a day-to-day basis, reviewing work done in London, and developing options for construction, again with the client. The principal Geotechnics team is also based in Hong Kong, monitoring site investigations and providing guidelines for the pile design. All aspects of the design have to be approved by the SRT and their checking engineers in Bangkok. Design submission packages are assembled in Hong Kong. In Bangkok, Arups has a small, site-based design team and a joint Quality Assurance team with the client, overseeing the construction of the piling and liaising with the SRT. The size of this design team will grow as the project progresses, to provide liaison between the task force and the contractor and local Thai consultants (Fig.6).

BERTS is being designed using Intergraph and Autocad computer-aided design (CAD) systems. A 3D digital survey model of the route provides the basis for the design and master alignments on the Intergraph system. This allows layouts for roads, railways and other infrastructure to be generated as model files in real co-ordinates.

Drawings are produced as a 'window' on a short length of the route. Geometrical files are transferred to the Autocad system to allow the production of layered structural and services drawings, which are transmitted electronically between offices in the UK and Hong Kong. These are issued to Hong Kong as 'plot' files where they are plotted for printing and delivery to the client. Drawings and other computer files can be sent electronically from there to Bangkok. Reinforcement drawings and schedules are also all computer-produced.

Day-to-day communications between the three main teams are by telephone and fax, and working relationships and co-operation are helped by the fact that many members of the Arup team worldwide have worked together previously. Project team members meet on a regular basis to review specific topics and general project progress.

An attempt is made to bring the reality of the project to the more remote design team members by regular feedback of project news, photographs, and videos of construction work under way. The time difference between UK and Hong Kong is seven or eight hours (depending on British Summertime), which restricts the time available for direct verbal communication but has the advantage that the UK design team can be responding to design requests while the Far East rests. In this way it can truly be said that Arups is working round the clock on this project.

Conclusion

By the end of 1994 design work was well advanced and the project had been on site for 18 months. Utility diversions, site clearance, and rehousing had proceeded ahead of piling to allow approximately 3500 piles to be cast. Pile cap construction was under way with column construction imminent (Figs.7 & 8). Preparation of the precast concrete yards was also proceeding, and tenders issued for mould and launch gantries. Work was accelerating and outstanding issues were being resolved between Hopewell (Thailand) Ltd. and the SRT. The first traffic on and through BERTS was planned for late 1997. Future *Arup Journals* will include articles on individual aspects of the project.

Credits:

Client:
Hopewell (Thailand) Ltd.

Lead designers:
Tileman (SE) Ltd. in association with Ove Arup & Partners International Ltd.

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OTHER LONDON GROUPS: Bob Cather, Geoff Whittle (AR&D), Chris Barber (Arup Fire), Juan Alayo, Aidan Eaglestone (Arup Transportation), Richard Cowell (Arup Acoustics), Les Davy, Les Dobinson (detailing), David Clare (Arup Geotechnics)

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Other consultants:
Asian Engineering Consultants Corporation Ltd.

Thorani Tech Ltd.

Thai DCI

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Designing safer trains in Britain

Alan Belfield Ben Egid Daniel Ruiz

Introduction

It may surprise some people to know that no trains built more than two years ago were designed to meet any form of structural collapse load - they were not expected to be crashworthy.

The reason for this is simple: they did not have to be. The British Railways Board (BRB), who write the design standards in the UK, required the structural body-shell of a train to withstand a series of 'proof loads' without yielding, but did not require any evidence of structural crashworthiness.

More recently, BRB have expected new designs to meet a level of structural collapse performance. This has posed new design problems to the railway engineer who traditionally did not have to consider post-yield behaviour or how to absorb energy efficiently.

Stated simply, the design problem is that for proof loads the structure needs to be as strong as possible, but for crashworthiness it has to be compliant, to reduce the accelerations of the occupants. This implies that the structural performance of the train's bodyshell has to lie within a tight envelope.

Arups' Advanced Technology Unit (ATU) were asked in 1992, initially by BRB and then by one of the train manufacturers, ABB Transportation Ltd., to help in the ongoing design of the new Class 465 Networker trains, which had been first introduced to Network SouthEast's busy Kent Link lines in 1991.

A change in legislation thus gave ATU the opportunity to work in the railway vehicle design field, and to employ the analytical techniques used for some years in the automotive and nuclear packaging fields to directly help the railway engineers.

Background

Following the 1988 accident at Clapham Junction in South London, where 35 people were killed and over 500 injured, the inquiry by Lord Hidden recommended that the design of new rolling stock should incorporate some element of crashworthiness. BRB introduced a new BR standard called Structural Design Loadcases (SDL) to define their requirements in detail, and it made some fundamental changes to the structural requirements of the ends of the vehicle.

Based on previous accident data and testing of existing vehicles, two structural collapse cases were defined by BRB:

- Full face loading - A symmetrical face-to-face collision with a similar vehicle
- Overriding loading - A loading across the vehicle body above floor level simulating overriding of two trains in an accident.

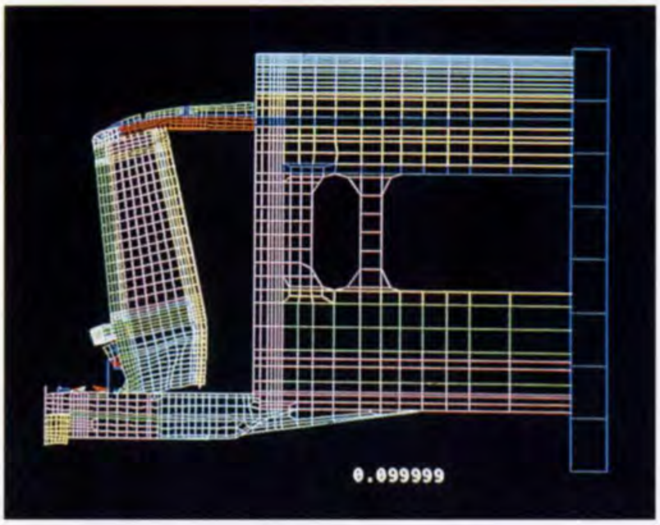
The general requirements for structural collapse are:

- Energy should be absorbed by the end of the vehicle before other parts are deformed.
- The end of the vehicle should stay attached to the vehicle after collapse.
- The vehicle must not collapse in a way that could form a ramp that would promote overriding.

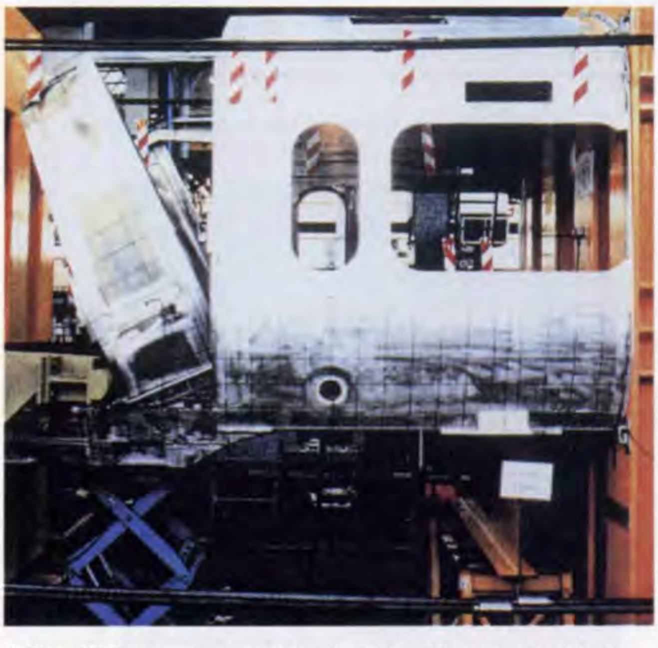
The detailed requirements specified a maximum collapse force and a minimum absorbed energy, both to be attained within a specified distance. The peak force requirement is a simple way of ensuring that during an impact, the decelerations felt by the passengers are within reasonable limits - high peak forces imply high deceleration levels and hence more injuries.

1. Class 465 entering Charing Cross beneath Embankment Place (also an Arup project).

2. The SDL test rig at BR Research, Derby.



3. Class 465/0 computer prediction of deformation under the overriding loadcase.



4. Class 465/0 deformation seen during the testing of the overriding loadcase.

BRB proposed to demonstrate meeting the SDL specification by conducting a series of quasi-static crush tests on full-scale specimens made of the end sections of the cars. The testing of only the end sections was considered acceptable because the structural collapse was to be localised to the cars' ends. The tests had been carried out by British Rail Research (BRR) in Derby, with the test set-up shown in Fig.2.

Material properties

All 465 Networker trains have been made from extrusions of aluminium. The use of long extrusions (up to 26m) enables the manufacturers to reduce their production costs due to the low number of parts and the automatic welding machines used.

The extrusions are of 6000 series aluminium alloy, which has the advantages of being easily formable and relatively strong. However, it is heat-treatable, so during welding the material properties alter in the weld's heat-affected zone (HAZ). Here, the material's yield strength and ductility are approximately halved, which has a dramatic effect on the structural behaviour of the design under large loads and has to be accounted for in any analytical simulation. In addition, material failure and tearing must be modelled. The computer simulation must be able to represent the failure in the HAZ to represent realistically the deformation.

The structural collapse of the end of a train is a highly complicated process. The large deformations, up to 1m, required to absorb the energy produce a range of non-linear behaviour including geometric non-linearities (contact and buckling) and material non-linearities (plasticity and fracture). The non-linear behaviour requires specialised analysis techniques and extensive computing resources. OASYS DYNA3D, the finite element program maintained and distributed by ATU, is one of the few programs which can solve this type of problem.

Class 465 Phase 0

During 1992, BRB placed a follow-on order for 188 Class 465 Networker vehicles with ABB.

The Class 465/0 (as they were subsequently designated) original vehicles were never designed for the proposed SDL legislation and BRB wished to know how they would behave. They approached Arups to undertake a computer simulation of the cab and intermediate ends of the 465/0 under both types of crush loading.

Detailed computer models of both ends were created using data provided by ABB. The new SDL loadings were applied and the force-deflection curves derived. While the analyses were being performed by Arups, British Rail Research (BRR) were undertaking full-scale crush tests of the vehicles needed to reassure the railway industry that the analytical techniques could be used in the design environment. This was quickly confirmed - Fig.3 shows a computer prediction of the deformation of the cab end under the overriding loadcase and Fig.4 the deformation seen in the test.

The peak loads seen in both the computer prediction and in testing were much greater than BRB required in the SDL standard. Following these tests BRB actively encouraged ABB and Arups to work together to reduce these peak loads for the future 465 Phase 2 trains.

Class 465 Phase 2

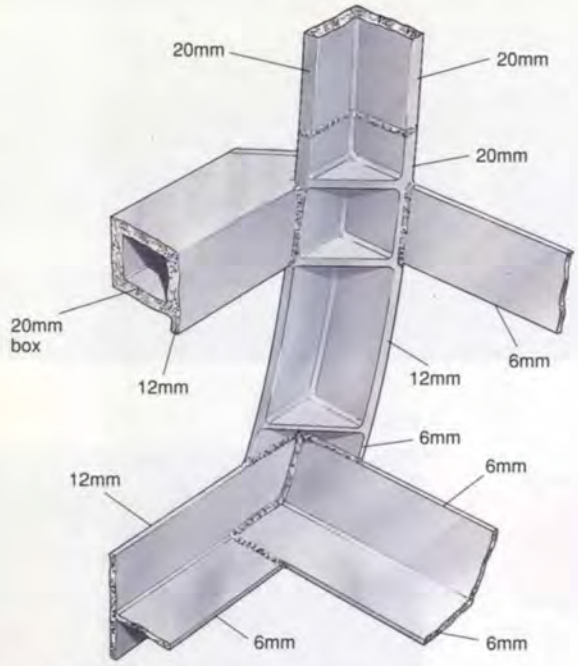
The design period for these vehicles was extremely short, so it was essential that the structural envelope remained the same, which meant that all the interior fittings need not be changed. As this was the first aluminium vehicle that had to meet the SDL requirements, ABB set up a specialised team of engineers, including members of ABB's own Advanced Technology Division, plus a number of other consultancies in addition to Arups.

It was evident from the 465/0 project that the existing design was far too strong and drastic action would be required to reduce the peak loads. In order to minimise the risk it was decided to build a 'speculative cab end' - a prototype. This is not unusual in other industries but it is for the railway industry. However, the design methodology of the speculative cab was unusual even for other industries. 25 engineers specialising in railway crashworthiness from a number of organisations, including Arups, went to ABB in Derby and spent one day brain-storming. The best ideas were quickly sketched and the resultant structure was built and tested within one month. It collapsed at a peak load of 4900kN under the full face loading, which was considerably better than the original structure which did not collapse at all under a load in excess of 7000kN - a force which would subject passengers to accelerations of over 100g.

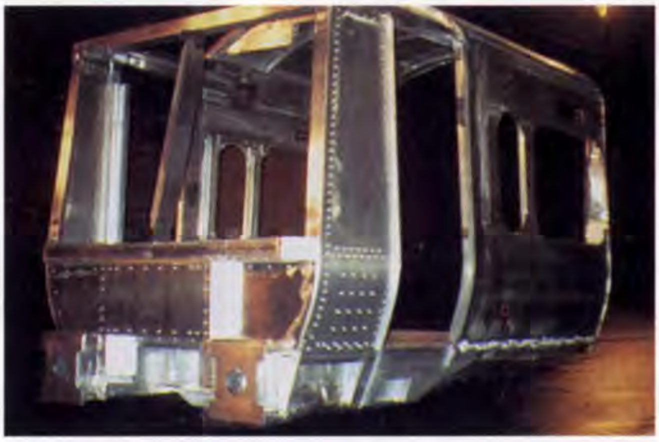
The ideas used in the speculative cab were built upon throughout the design process. Detailed computer models of both ends were again used to aid the design engineers.

One of the most significant achievements was to change the design of the coupler area such that under the full face load the coupler sheared out of its mountings. This part of the vehicle structure is very strong and the only way of limiting the peak load under the full face load is to de-couple major load paths such as this one. The coupler was designed to shear out under a load of 2000kN before any other part of the structure has been loaded.

Prior to the tests Arups provided ABB with a prediction of the test results. The correlation between analysis and test was very good and increased ABB's confidence in the use of analysis techniques.



5. Class 465/3 cab end: proposal for corner pillar machining.



6. Class 465/3 cab end test sample.

Class 465 Phase 3

In spring 1994, ABB were awarded another follow-on order for the 465 Networkers. This was the Class 465 Phase 3 (465/3), and again Arups were commissioned to assist in designing them to meet the new proof load and collapse requirements specified by BRB. This time, however, Arups were the only consultants helping ABB with the design.The original requirements for structural collapse for the 465/3 cars were much more demanding than those specified for the 465/2.

Following an assessment of the 465/2 end structures, it was evident to ABB that meeting the requirements specified by BRB required a major redesign. The overall concept employed was to design a relatively soft and flexible collapse zone that would crush between two stiff frames whose function was to absorb energy during collapse. The function of the frames was to carry proof loads (front frame) and react loads from the collapse zone (back frame).

The 465/3 vehicle ends employed a softer grade of aluminium alloy (6082-T4) for floor panels and simple extrusions. This is an ideal material for collapse applications in that it is relatively soft with good ductility, and its material properties are not affected by welding.

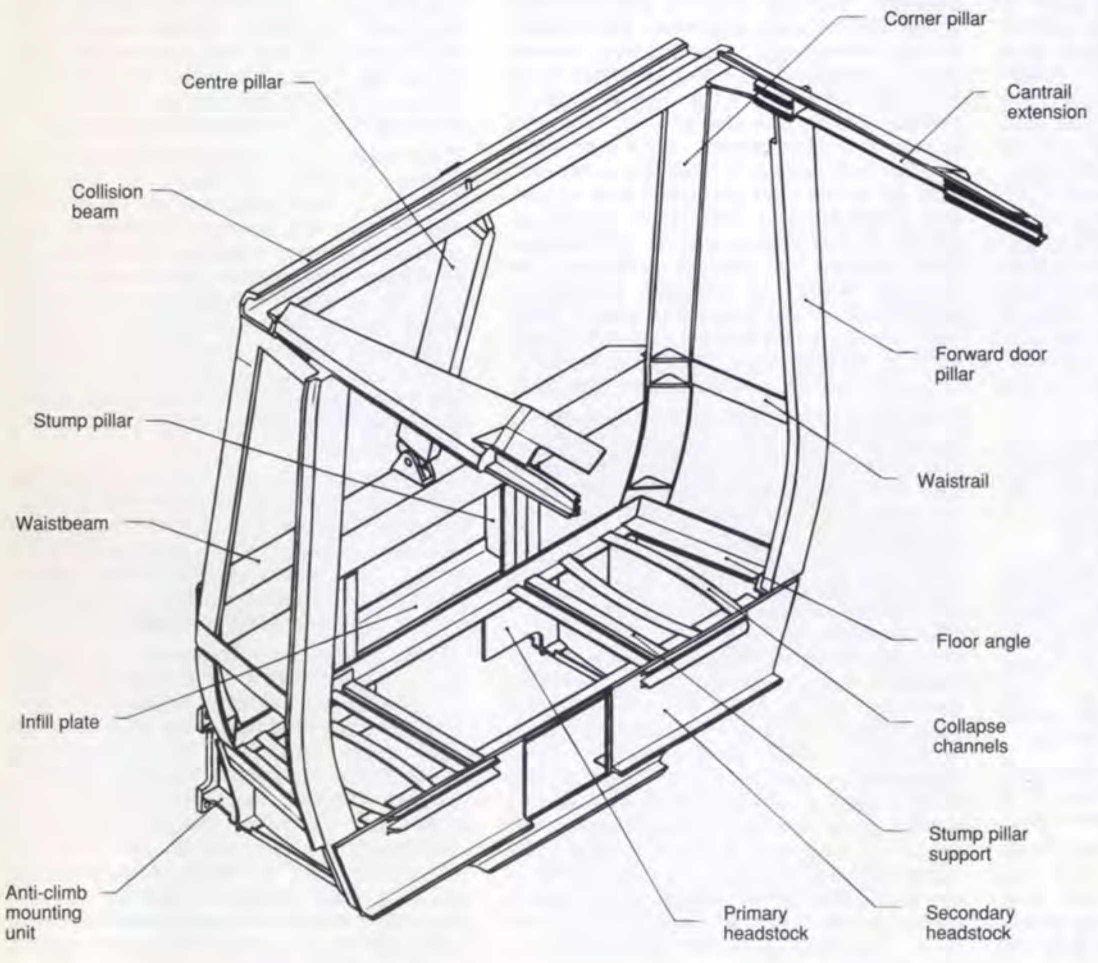
A new concept adopted in the design was to connect the collapse zone components, which are relatively flexible and undergo large deformations, by bolting.

The stiff frame components which have to sustain relatively small deformations were connected by full penetration welds. Several of the critical structural components were made by machining, for example the corner pillar, door pillar and cantrail extension in the cab end and the corner pillar/collision beam joint in the intermediate end. Machined components have a number of distinct advantages over welded assemblies. They are more robust as there is less welding; they are easy to tailor to the design constraints; they are repeatable and consistent; and the overall number of parts used is reduced. Arups were very actively part of the decisions made during the 465/3 project (Figs.5-7). Once again the firm's computer models were used to help the designers but more importantly Arups had the opportunity to liaise with the designers on a day-to-day basis and guide the design using their expertise. As before, a full prediction was provided of the test results prior to test. The 465/3 fully met the requirements specified by BRB and the correlation between analysis and test was good.

ABB were very pleased with the new design and, besides meeting the SDL requirements, it provided other considerable benefits. The 465/3 vehicle is over 100kg lighter than the 465/2 and has over 70 fewer parts.

Conclusions

BRB specified significant improvements in crashworthiness for the second and third phases of the Class 465 Networkers, and ABB, assisted by Arups, provided vehicles which met these requirements. This was only achieved through extensive testing, detailed computer simulation and innovative design. Ove Arup & Partners helped design these vehicles and in less than three years have become the leading consultancy for railway crashworthiness of aluminium vehicles in the UK.



Credits

Client:
British Railways Board/ABB Transportation Ltd.

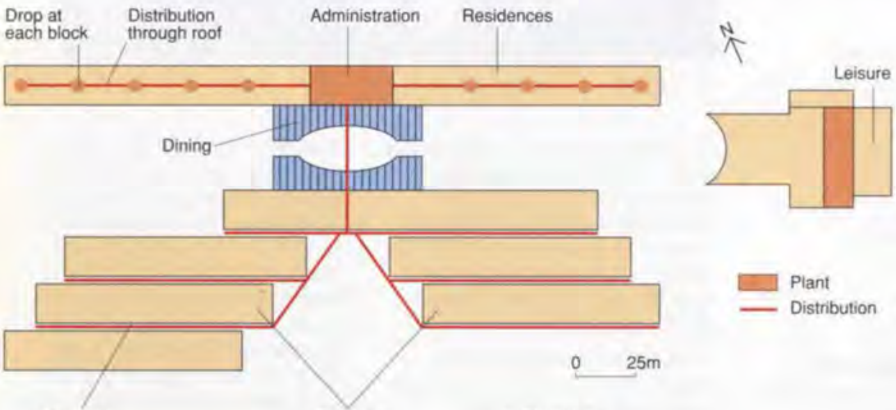
Mechanical engineers:
Ove Arup & Partners
Alan Belfield, Ben Egid, Daniel Ruiz

Illustrations:
1: Peter Mackinven
2, 4, 6, 7: ABB
3: Ove Arup & Partners
5: Fred English

7. Drawing of Class 465/3 cab end.

The 'green wave': Cable and Wireless training college

John Berry
Alan Browne
Michael Edwards



1. Site plan.

2. Architects model.

Introduction

The decision by Cable and Wireless to move their present college from Porthcurno, near Lands End in Cornwall, and to build a new training college elsewhere was in response to a changing market place and followed their policy of investing heavily in training. The deregulation of the telecommunications industry opened new opportunities for the company, which had traditionally operated solely outside the UK. The isolation of Porthcurno was of little significance when it simply received students from overseas for a period of technical training, and then quietly returned them to operate and maintain the vast telephone networks run by Cable and Wireless in places like Hong Kong and the Caribbean. Once business operations commenced in the UK, however, it became a different story. The once splendid isolation of Porthcurno was now a distinct disadvantage and a more central location with good transport connections was sought. Coventry was finally chosen, not just for its geographical location but also for its proximity to Warwick University, which was considered an important link for the technical education at degree level which the college offered.

A move from Porthcurno was always going to be an emotive issue for Cable and Wireless, for it was here in the latter half of the 19th century that their first transatlantic cable was laid. However the need was overriding.

Isolation does breed a certain resilience and degree of self-sufficiency, so it was important therefore that the strong community spirit and corporate ethos that this engendered was not lost in the transfer to Coventry. To some extent the campus-like nature of the new college owes much to this culture: more university than company, some would say.

A 4ha site at the edge of the Westwood Health Business Park on the west side of Coventry was found and this seemed ideal.

A technical appraisal and planning study gave it a clean bill of health and Cable and Wireless purchased it in 1990. Later land acquisition and leasing arrangements wisely secured the open aspect and views from the college for future generations.

Design concept

It was natural that the starting point in the design briefing process should have been the existing Porthcurno college. However, the inherent danger in this line of thinking is 'more of the same, but bigger'; this needs to be avoided, of course, but at the same time the positive aspects of the original should not be obscured. Discussion quickly confirmed the basic requirement for residential accommodation, technical teaching and laboratory space, catering, administration, and a leisure facility. Interestingly, a gymnasium, squash courts, swimming pool and bar were to be included in the leisure complex; perhaps to compensate for the sea and air they were leaving behind. However, while Porthcurno and Coventry appear to have little in common they are in fact both greenfield sites in quiet and predominantly residential neighbourhoods. At this time a number of influences were shaping the design; principally the planning theme of separate residential, administration, teaching, and leisure buildings; and the notion that there was the opportunity to design a landmark 'green building'. The client was supportive and the site ideal.

A dilemma in the briefing was the need to articulate clearly and differentiate between the needs of the advanced telecommunications technology which would be installed in the college, and the building itself. It does not necessarily follow that a user of high technology needs a sealed and air-conditioned, high tech-orientated facility; confusing use with the building itself should be avoided. A clear concept could not evolve from muddled thinking, so it was important to separate, conceptually at least, the structural and primary servicing needs from the environmental requirements. From the latter point of view it was felt that natural ventilation and daylight were the way forward, and that by optimising these factors a humane and energy-efficient design would emerge. Of course things are not always as simple as that and it had to be recognised that the high computer and VDU use anticipated for the college would bring its own particular and often contradicting problems. Heat and glare-free lighting are two obvious ones.

In developing a servicing strategy for the campus the guiding principle had to be adaptability. By its very nature the college is an establishment dedicated to teaching at the sharp end of the telecommunications industry and over the years it is to be expected that significant changes will take place in the type of equipment and its installation. For instance the college houses a complete digital telephone exchange for the students to practice upon. Apart from the teaching aids the basic supporting telecommunications and building services systems are also likely to change many times within the life of the college. Primary distribution routes and structural systems had to reflect this need.

The campus theme evolved along the lines of separate buildings for residences, teaching and leisure. Fortunately the site permitted a development with a strong north/south axis and this was taken to its logical conclusion in the design. Although the site is a reasonable size, the density of building and car parking meant that for the teaching accommodation to be single-storey in height it had to be deep plan. It was the desire to ventilate naturally and bring daylight into the 45m-deep teaching blocks which generated the characteristic wave form roof.

The compact plan form has at its head the residential block in classic MacCormac Oxbridge style, laid out on a north/south axis with administration and the dining room at the centre. Two V-form teaching wings extend toward the road, giving passers-by a non-linear view of these north/south-orientated blocks.

Primary services distribution is an integral part of the general form and takes its lead from the logical circulation patterns. The central plant is located above the administration area at the heart of the plan. Distribution routes follow the V-form teaching wings in purpose-designed foundation trenches, and enter the teaching blocks along the north/south corridor spines and into the raised floor which is installed throughout the teaching areas. Services distribute through the open roof space of each residential wing to the vertical stair cores. The leisure building is self-contained.

3.
The lecture rooms:
with the curving,
'floating' roofscape.

Teaching roofs

General

Without doubt it is the curving roofscape which distinguishes this building from any other. The undulating form which floats above a plane of linking corridors and supporting structure is more than just an architectural statement, it is the culmination of an integrated environmental and engineering design strategy. Nothing has been left to chance and every facet of the design has a clear purpose. Even the glazed roof tiles protect the thermal insulation and waterproofing membrane from the degradation and movement that would be caused by exposure to direct sunlight.

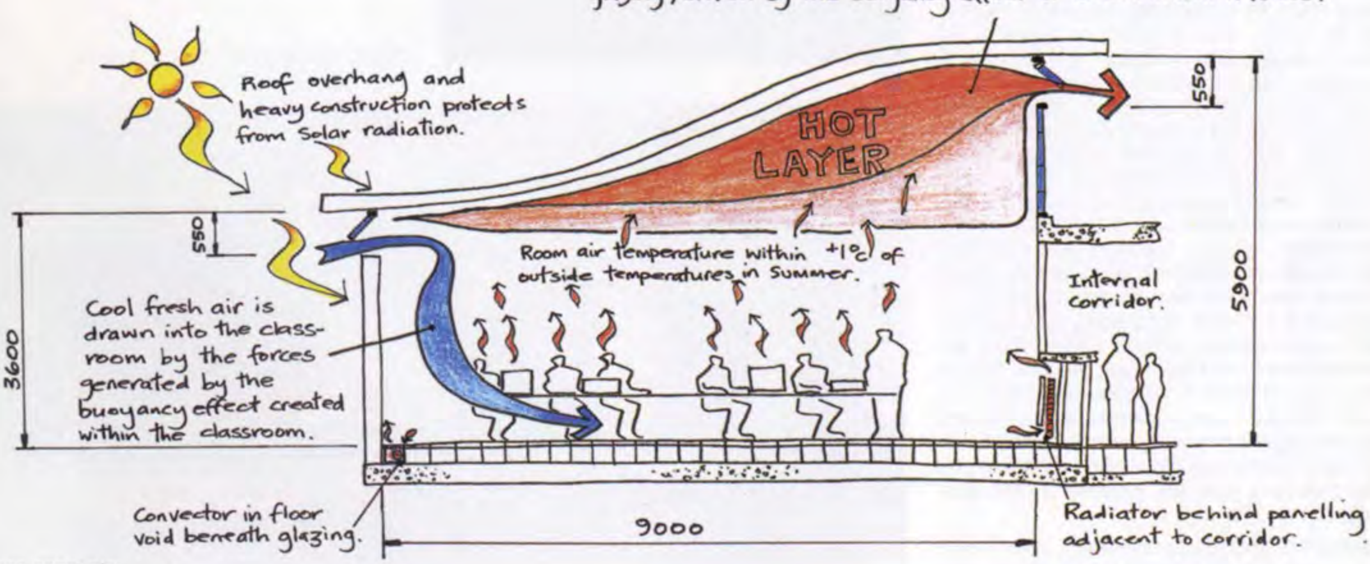
Natural ventilation and daylight were considered essential factors, and were probably the most influential in driving the design forward in the search for an appropriate roof form. The deep plan meant there was little or no opportunity to use the wall elevation, so the roof assumed added importance as the only practical means of meeting the objective.

4.
Administration area
(on left of picture)
overlooking the
dining room.

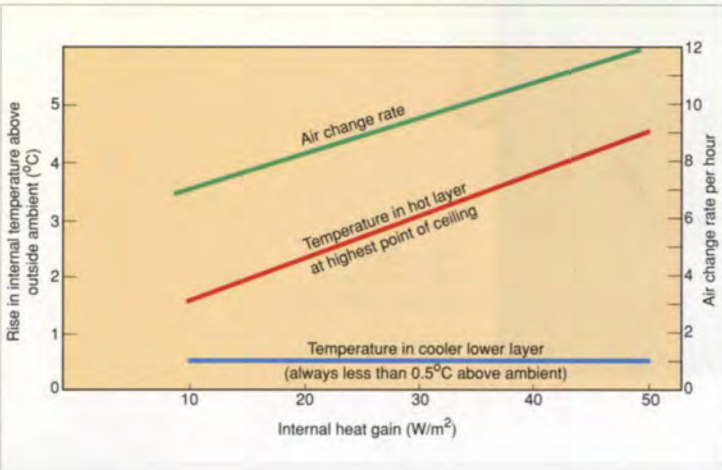
Intuition plays an important part in the design process and its importance should not be underestimated. In this instance it was felt that a tall room where air could enter and leave above the occupied level, coupled with a high degree of north light, should have advantages. Apart from wind, the only other driving force for natural ventilation is buoyancy, which relies on heat gain and the difference in height between the inlet and outlet for its effect. This led to experiments with a roof which had its lowest point at the normal room height and its highest at the level required for ventilation air flow. It was obvious (well, that's how it seems now but perhaps it wasn't at the time) that the solution lay in tilting the roof with the air inlet at the bottom of the southerly aspect and the outlet at the top of the northerly aspect. The vertical north face would be fully glazed to admit maximum daylight and the south would have an overhang to omit direct sunlight. Numerous forms were experimented with at this stage, but the double curve was emerging as the favoured solution because it best satisfied the engineering and architectural criteria.

Testing was an important aspect of Arups' work during the crucial design development. Apart from the computer-modelled air flow and temperature studies being undertaken at this time, the team were becoming interested in the work of Dr Paul Linden, a fluid dynamicist in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge, who was working on the physical modelling of buoyancy ventilation using saline fluids. It was felt that this technique would support Arups' computer modelling and give some insight into the dynamic behaviour of the system under different internal heat gain scenarios.

The first computer study indicated that the air flow increased with heat gain, meaning that to some degree buoyancy-driven ventilation is a self-limiting phenomena.



5.
Services concepts:
lecture rooms.



6.
The effect of internal heat gain on ventilation rates in a buoyancy driven naturally-ventilated building.

7.
Saline modelling: demonstrating the heat gain from computers and people.

Saline modelling

A 1:25 scale model was constructed from transparent sheets of perspex with adjustable openings for the windows, and was then totally immersed upside down in a large tank of cold fresh water. The heat gain from computers and people was modelled by injecting a saline solution of specific density at the heat source. Since salt water is heavier than fresh water the saline solution falls through the model and the rate of mixing with the fresh water causes a change of density which is numerically similar to that of temperature diffusion in air. The temperature at any point is given by a measurement of density and the flow rate is measured from the physical flow. Coloured dyes were added to the saline solution so that the process could be easily viewed.

Simply film such a model test through an inverted video camera and everything is the right way up!

Saline modelling confirmed the computer prediction that under the worst case of a hot and windless day a distinct two-layer system develops: a cool layer at near ambient temperature in the lower part of the room and a warmer, high level layer. The warm air contained within the curved roof volume above the occupied zone flows out through the high level north window, with cool replacement air flowing in from the south window. A proportion of this air flows into the occupied zone itself to replenish the heat source plumes.

Daylight modelling

Daylight has been mentioned before as an important consideration in the design, but in many ways, it is one of the most difficult factors to express satisfactorily. While the theoretical basis for quantifying the level of light is well-founded, the qualitative aspects of colour, shade and variation are less well understood. In this instance it was decided to model the daylight physically to gain a better understanding of the overall quality of light, in the same way as the fluid model provided insight into the temperature and air flow patterns. A simple scale model made by the architect was tested in the 'artificial sky' at University College, London. Experiments were made with different glass areas, types of glass and their importance assessed in terms of the overall light level and quality. With a pale ceiling sufficient light could be provided from the main north window plus a small but important contribution from the south, but glare was shown to be a problem from the large north-facing window. This finding was of particular importance because the main teaching aids are located on the wall under the window.

Translucent glazing panels were introduced as a result. Electrically-operated blinds are installed on all the high level windows for blackout and fine tuning of the daylight.

8.
View of leisure building flanked by residences (on left) and teaching wing (on right).

9.
Left, Museum area of library.

10.
Detail of roof corner support.

11.
Below, Residences.

12. Construction work in progress.

Performance

Numerical and physical modelling are fine, but the main concern of the client is: Does the result work in practice? Much has been written about the lack of measured performance data in buildings and Arups were fortunate in this instance to have the support of the client and the assistance of the Building Research Establishment for a limited measurement programme during the summer of 1994. Air flows and temperatures were measured in a typical teaching room using a tracer gas and thermocouples. Data logging equipment recorded the conditions on a continuous basis for later analysis.

At the same time external temperature, and wind speed and direction, were also recorded. The results were presented in a paper to the 1994 CIBSE National Conference. In essence, at high outside temperatures the ventilation performed satisfactorily as Arups' predictions indicated it would, but the combination of high outside temperature and no wind was a rare event suggesting that for most of the time wind-driven forces dominate. For a single-storey building the pressure differential generated by buoyancy is so low that wind speeds need to be less than 1.5m/s for buoyancy to dominate.

13. Teaching building from the main entrance.

Structure

The roof is constructed from double-curved universal beams spanning 10.75m at 2.25m centres, supported on slender exposed steel posts. The tapered ends of the posts and the connections are steel castings. To prevent moments developing in the tapered ends, the posts are supported on spherical bearings, the most economical design being a standard SKF bearing fully contained in a grease-filled, cast steel housing.

The roof finishes are an upside-down roof system covered by glazed clay tiles 615mm long by 300mm wide. To hold them on the slope, while minimising penetrations, they are laid in a net of stainless steel wires and angles which is only fixed at the top. The tiles are loose laid and so depend only on gravity to hold them down. Based on research which has been done on tiles in upside-down roof construction, a general tile thickness of 35mm was recommended, increasing to 70mm in the higher wind suction zone around the edge. In practice the supplier increased the general tile thickness to 50mm to suit manufacturing constraints.

Conclusion

Construction work began on site in September 1991 and the college opened for the first student intake in September 1993. Staff and student response so far has been positive, with the spirit of Pothcurno alive and well on the new campus. While the design and development of the teaching block roofs tell only a small part of the overall story, they do capture the imagination and encapsulate the advocacy of integrated engineering design. The apparently effortless simplicity of the solution belies the intellectual effort and technical complexity underpinning it. This is how it should be and is the undoubted hallmark of good design.

Reference

(1) EDWARDS, M., et al. Theory and practice - natural ventilation modelling. Chartered Institution of Building Services Engineers. National Conference, 1994.

Key statistics

Site area: 4.25ha

Total built area: 12 000m²

Teaching area: 5100m²

Leisure area: 1225m²

Residential rooms: 167

Car parking spaces: 20

Credits

Client:
Cable and Wireless plc

Architect:
MacCormac Jamieson Pritchard

Consulting engineers:
Ove Arup & Partners Alan Browne, Humayun Hanif, Evelyn Murray, Paul Summers, Colin Whewell (RE), Aaron Wong (structural)

John Berry, Neil Beverly, Stas Brzeski, Michael Edwards, Edward Lam, Trevor Levesley (RE), Sarah Nicholson, Nigel Tonks (mechanical/environmental)

Alex Perkins, Alan Rowell, Mike Storey (RE) (electrical)

David Carroll (public health)

Patrick Bolger, Jim Read, Bill Southwood (telecommunications)

Y C Choi (geotechnics)

Quantity surveyor:
Northcroft Neighbour & Nicholson

Landscape architect:
Colvin & Moggridge

Illustrations:
1, 6: Denis Kirtley.
2: Courtesy of the architect.
3: Tony Weller/Builder Group.
4, 11, 14: Alex Ramsay. 5: John Berry.
7: Ove Arup & Partners.
8,9,10,12,13: Peter Mackinven.

14. Leisure building bar seen from access bridge.

Kansai International Airport Terminal Building

Philip Dilley Alistair Guthrie

Introduction

The new Kansai International Airport opened on 4 September 1994, marking completion of one of the world's largest and most ambitious construction projects. Built on a man-made island 4.5km long and 2.5km wide some 5km offshore in Osaka Bay (Fig.1), at the south side of the main Japanese island, Honshu, it is located to avoid the limiting effects of noise pollution and so can operate for 24 hours per day - the first such airport in Japan.

At full capacity it will cater for 160 000 aircraft movements a year from its single 3500m runway. The island supports a complete modern airport facility including maintenance hangars, cargo handling, fuel storage, car parking, a railway station, a shopping centre, and even a harbour. But the building for which Kansai International Airport is already famous is the new Passenger Terminal Building (PTB), commissioned through an international architectural competition held in 1988. The winning entry was submitted by Renzo Piano supported by Arups.

The competition

A conceptual design was required for a single building, housing all the necessary facilities of a modern terminal. It was to cope with 25M passengers per year, and provide 41 aircraft parking spots, each served through a boarding bridge. The basic layout and functional planning of the building were already established in the competition brief. The main terminal building (MTB), housing the arrivals and departure halls with check-in, customs and security, baggage handling and concessions, would be arranged on four levels. From the MTB, two projecting 'Wings' would serve the aircraft gates with departure lounges and separate access for arriving passengers, with movement between the MTB and the Wings either by foot or shuttle train (AGT).

The overall PTB is 1.6km (one mile) in length, Wing tip to Wing tip (Figs.2 & 3). Perhaps the most important architectural idea was to give a clear sense of orientation and direction to the building users - of movement between landside and airside with a visual connection between the two. In the main departure hall, this sense of flow is assisted by the design of the climate control, lighting and structure. Passengers arriving and leaving the building encounter an enormous landscaped daylit atrium space, forming the interface between the landside and the working core of the building.

This 25m wide, 30m high 'Canyon' extends throughout the 300m length of the MTB. The volume allows passengers to move laterally or vertically on walkways, escalators, lifts and stairs; it performs the crucial role of orientating arriving passengers and at ground floor level provides the meeting and greetings concourse. Each of the four floors in the rest of the MTB has a single principal purpose: the topmost for international departures; the next for concessions (shops, restaurants, etc.); then domestic arrivals and departures; and fourthly international arrivals (Fig.4).

Thus, once the departing passenger has identified and arrived at the check-in zone, he is immediately orientated: he can see the aircraft, and his progress is linear, landside to airside. At the bottom of the building are plantrooms, etc.

1.
Kansai Airport,
on its artificial island,
shortly before opening.

3. Airside of Kansai International Airport Terminal Building, photographed from the bridge.

The competition concept for the air-conditioning was to provide a background level of climate control to the whole space. This 'macro' control was to be achieved through large air supply nozzles on the landside of the passenger concourse. These blow the air 80m in the direction of passenger movement - towards airside - providing air movement and conditioning to the whole space.

The macro system was supplemented by microclimate control systems around check-in desks, waiting areas and offices.To achieve effective air distribution the air stream from the jet nozzles must attach to and follow the roof. This is to ensure that the supply air is adequately mixed with warm air, and does not form draughts in the zones occupied by passengers and staff.

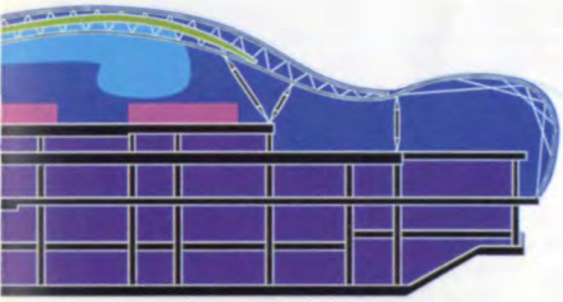
The shape of the roof is important in controlling this, and so was chosen to suit the path of the air trajectory from a nozzle in free space. These curves became the basis for the roof shape. Another strong competition concept was to daylight the space. Long strips of roof glazing, landside to airside, were to be visually dominant, reinforcing the direction of movement. These strips connect the Canyon, with its high daylight levels from top glazing, to the departure and arrivals Wings with their huge curved glass façades facing the aircraft stands. The level of daylighting in the large spaces significantly reduces the length of time artificial lighting is required, and hence energy consumption.

Capital cost prevented this concept from being entirely carried through to the completed building. The landside/airside connection was further emphasized by the long arched structure, spanning the 80m width of the departure concourse and supporting the curved roof. The competition design had arched triangular tubular trusses supported on splayed column legs - a distributed means of coping with earthquake-generated lateral loads (Fig.5). The secondary structure was to be a series of cantilever brackets from each side of the main truss meeting at a pin mid-span - a form subsequently changed for a simpler and more ductile system. In the Wings, the structure changed into a series of ribs strengthened by tie bars.

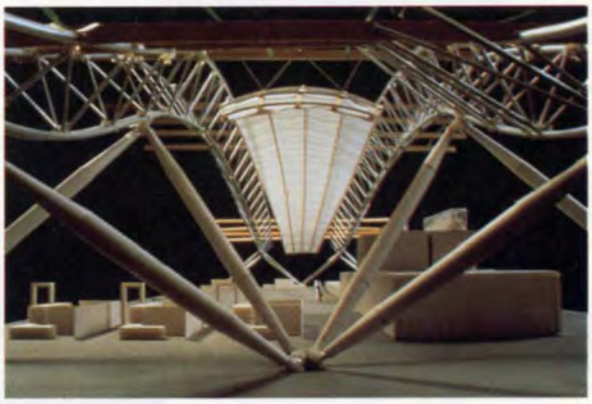
The curious boomerang shape of the ribs at competition stage was architecturally driven rather than designed to enhance their load-carrying performance.

It was realised that height constraints (governed by the air traffic controllers' need for direct sight-lines to aircraft from the control tower) would not permit an 'extruded' geometry. The roof of the Wings would need to slope away from the MTB.

2.
Artist's impression of the 'world's longest building' against a familiar landmark: The Terminal superimposed on Hyde Park, London.



4. Section through the MTB.



5. Study model of MTB roof, July 1992.

To maximise repetition in the cladding panels, a toroidal geometry was proposed and subsequently adopted. This also gave a reduction in volume and floor area towards the ends, corresponding to fewer passengers using these areas.

Renzo Piano won the competition and was appointed as design leader of a joint venture design team with Ove Arup & Partners as consulting structural, building services, and fire engineers. The other joint venture members were Japanese architects and engineers, Nikken Sekkei; airport planners, Aéroport de Paris; and specialist advisors on customs and security, Japan Airport Consultants. This team completed the Kihon (basic) design, and the Jishi (detailed) design. Nikken Sekkei handled the construction supervision.

The engineering and architectural work during detailed design was split between Nikken Sekkei and Piano/Arups, the former designing the base building below the main concourse level, and Piano/Arups the 500 000m^3 of large public spaces, the roof, and glazing support structures.

Geometry

The entire roof geometry is set out from the cladding surface, and is based on a toroidal (rotated) geometry to maximise repetitions of cladding and structure, the two-dimensional section being defined as a continuous series of tangential circular arcs. The basic shape is derived from the air flow trajectory in the MTB, the space requirements, and parametric studies in the Wings. The three-dimensional geometry is created by rotating the two-dimensional shape around an inclined circle 16.4km in diameter, chosen on a trial-and-error basis to give the required boundary dimensions. In fact the MTB geometry is 'cylindrical', formed from an extrusion of the two-dimensional shape, so all of the MTB trusses are identical, and end walls are vertical (Fig. A). In the Wings the grids are radial grid-planes and the columns are not vertical, but radial. In this way, each rib is identical in profile, varying only in the termination point of each end. This repetition was used to substantial advantage in the fabrication.

A. Early Wing geometry study, November 1989.

Fire considerations at Kansai Terminal

Paula Beever

Design issues

The PTB design demanded that the main spaces, totalling over $1Mm^2$ remained undivided. This allows people to identify their way through the building and to reach their destinations with minimum obstruction. It became clear at a very early stage that strict compliance with the BSLJ fire safety rules would not be possible without serious compromise to the design, so it was decided that a fire engineering approach would be adopted. This would aim to identify the goals of the fire safety legislation and demonstrate that these could be achieved by methods other than following prescriptive rules.

Regulations and approvals

It is usual in the fire safety regulations of most countries for a limit to be placed on the area or volume of a building that can remain undivided by fire-resisting walls, so as to prevent a fire becoming too large before firefighters arrive. Each of the airport spaces, even if disconnected, is enormously greater than the $1500m^2$ limit normally applied to compartments in Japan. In addition, the depth of the building and its open planning make the distances to exits very long - some 120m at most compared to a maximum of 50m permitted in normal Japanese buildings. Apart from the need to depart from the BSLJ provisions, it was desirable from an architectural point of view to leave the steelwork exposed, particularly in the Wing, though the BSLJ would have required fire protection. Preliminary talks were held with the local Building Construction offices,who referred the issues to the Kansai Prefecture. They in turn passed the matter to the Ministry of Construction, who established a special committee to consider these matters as a whole. The committee comprised university professors and government scientists specialising in architecture, steel construction, and smoke movement, together with legislative experts from the Ministry of Construction.

Fire safety strategy

The fire safety strategy proposed relies on the fact that airport terminal buildings have very large spaces with little combustible material and that those areas with high fire load: shops, offices, storage areas; are well-defined and limited in extent. It was proposed that these areas should have a sprinkler system plus a smoke extraction system designed to keep smoke within its area of origin. In this way, it was argued, the spread of fire and smoke would be contained even in

A.

B.

A Calculations showed that fire spread would be limited even in the absence of compartment walls.

B. Calculations demonstrated the stability of unprotected Wing steelwork under fire conditions.

the absence of compartment walls. The study group requested additional calculations to demonstrate that uncontrolled fire spread throughout the space would not occur and required additional sprinkler protection over check-in desks. With these measures it was agreed that the large space could safely remain undivided. The arguments to justify long escape distances chiefly centred on smoke control. Again the fact that the areas of high fire load were separately protected helped considerably. The high ceiling was also a safety benefit. Some staircases within the Canyon had to be enclosed, and a 280m long smoke curtain was required to contain smoke within the 2nd level Domestic Departures Lobby. Otherwise the case was accepted, even to the extent that escape routes crossing the Canyon via the bridges at both levels were accepted.

Structural steelwork

One of the more interesting discussions in the study group meetings concerned the structural steelwork. BSLJ would require that it be protected to a height of 4m from the floor. It was agreed that this would be done in a conventional manner for the main steel props at the 4th level, since collapse of these members would have serious consequences for the roof.

However, the same considerations would not apply to the Wing steelwork and it was desirable from an architectural point of view to leave this exposed. In Japan it is normally assumed that steelwork fails at 350°C, compared with 550°C used in the USA and Europe.

How this very conservative figure came to be adopted in Japan is unclear, but it has a considerable effect on design in steel.

Structural design criteria

Superficially, the competition model closely resembled the finished building, but some strategic differences were introduced during design development to accommodate the unavoidable design conditions - generally severe in Japan, and especially so at this site.

Site conditions

Osaka Bay already hosts other man-made islands, Kobe Port Island and Rokko Island being two of the largest, but Kansai Airport is further from the shore and in much deeper water (18.5m) than any of its predecessors.

The island required the deposition of $178Mm^3$ of material, over three years, at a point where the seabed is underlain by 20m of soft alluvial clay, and over 400m of diluvial clay. Given the weight of the island fill, the anticipated settlement due to consolidation of the clay layer could be predicted, but the differential settlement caused by building the island, sequential construction, and excavation for an 8m basement was more difficult to assess. The differential loading from the Wings, the roadway, the MTB itself, the runway, and ancillary buildings, coupled with different arrangements for ground improvement, would certainly lead to some differential settlement.

Settlement predictions made in Japan showed that consolidation of the alluvial clay would be all but complete by the start of building construction, but the long-term consolidation of the diluvial clay would give 2m of settlement from the start of construction until 50 years after completion. To control this, consolidation of the alluvial clay was accelerated by the installation of a million vertical sand drains at 2.5m centres over the entire island.

6.
Typical column jacking detail with jack in position.

Of course absolute settlement does not affect the building, but differential settlement does. For serviceability reasons the entire building is arranged to permit adjustment of its level by jacking at each column position (Fig.6). A design criterion for the structure was set as a defined distortion, at which point correction by jacking will become necessary.

A differential settlement of 1:400 in the MTB and 1:600 in the Wings was selected, limited by practical reasons and also to protect the building finishes.

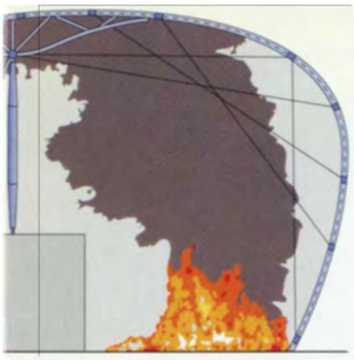
Seismic design

The seismic design rules in Japan are the most severe in the industrialised world. The Building Standard Law of Japan (BSLJ) envisages two levels of earthquake for design - level 1, which has a statistical probability of occurring once during the design life of the building, and level 2 for an extreme event. The design must cope with the level 1 event without any damage to the building structure, or significant damage to the building fabric. The building must remain serviceable. The level 2 event can cause loss of the building with the structure at the point of collapse. Storey drift is restricted by the BSLJ to 1:200 for a level 1 event and 1:100 for level 2.

For a given building, each of these design levels can be defined as equivalent static loads and only for buildings of extreme irregularity (e.g. a storey with a low relative stiffness, or over 60m in height) is a time-history analysis demanded by BSLJ. To comply with the regulations, the building is designed to carry the quasi-static lateral loads, but it was considered that the unusual form of the structure warranted examination of its dynamic behaviour. Apart from the unusual shape of the roof, the Wings exhibit unisotropic and non-linear stiffness characteristics. Furthermore the Wing supports link two different storeys of the movement frame beneath.

The dynamic analyses performed were comprehensive. Modal analyses on 3D models of the roof structures were performed to establish lumped parameter models to represent the roof dynamic characteristics. These models were extended to include the lower levels of the superstructure and the soil characteristics. The final models were subjected to time history analyses for specific actual and artificially generated seismic events.

Because the roof structure is the top storey of a five-storey frame, it attracts a disproportionate share of the total seismic shear. The equivalent static lateral design loads for the roof structure are 0.6 of the mass for a level 1 event, and 1.2 times for level 2. At 8.46pm GMT on 17 January, a major earthquake occurred with its epicentre 20km under the island of Awajishima in Osaka Bay, about 30km from the airport island. This catastrophic earthquake measured 7.2 on the Richter Scale, and resulted in over 4000 deaths.The airport island suffered some local settlement at its perimeter, but the MTB was unscathed.



Illustrations:
Trevor Slydel

A Japanese Design Guide gives tables and equations for calculating steel properties at elevated temperatures, and in particular changes in yield stress and elastic modulus as temperature increases. It is possible to estimate the temperature of the steel when exposed to fire, taking into account the rate of heat release of the fire and the potential exposure of the vulnerable elements.

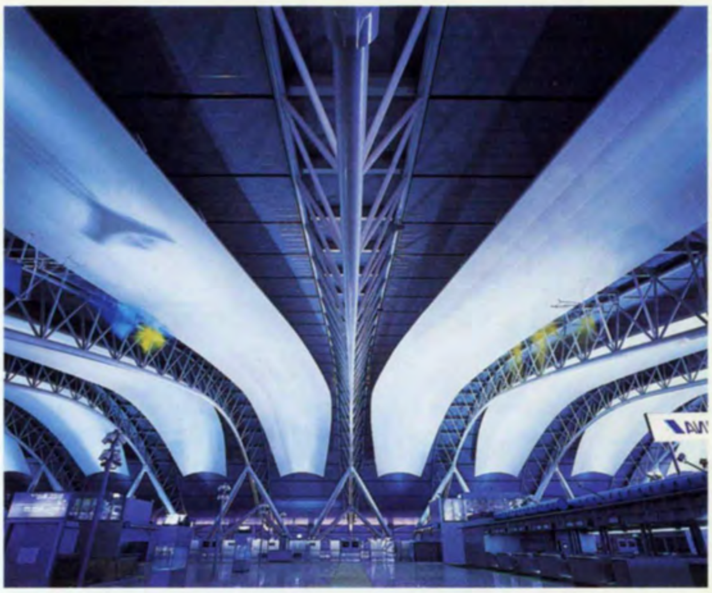
Structural calculationcan be made of the imposed load on any particular element, subject to the altered steel properties. In this way it can be established whether an element is subject to excessive loads, the concept of a universal failure temperature is thus avoided.

It is accepted in Japan and elsewhere that all exceptional loads for which the structure is designed will not act at once. In Japan structures are designed to resist loads due to earthquake, snow and high winds, which means that under normal conditions the elements are relatively lightly stressed. This gives higher failure temperatures for structural elements and correspondingly longer survival times for the structure under fire conditions.

The analyses for the steel were performed in two ways. Assuming initially that there is a fire which is growing rapidly, the calculations showed that the steel would survive without undue deformation for the escape period. The calculations were then repeated for a serious fire with no intervention by firefighters. It was shown that though local damage would occur, even in the worst case there would be no progressive collapse.

The study group accepted the arguments. However, a view was expressed that an extra level of safety should be introduced since damage to a major building in the event of fire might be unacceptable for political reasons. It was suggested that use of intumescent paint might be appropriate.

This was notable, since intumescent paint was not at that time approved for use in Japan. That position is now changing, partly as a result of its use for the airport.



7. MTB roof trusses, and (below) 8. during erection in April 1993

It had been fitted with seismographs, and so horizontal and vertical ground acceleration data are now available, measured at basement level and at the roof. Preliminary information suggests that the severity of the earthquake was less than a level 1 event, but with a large vertical component. The structure was designed to withstand such an event and its performance is no surprise, but it is particularly satisfying that there was no damage to the cladding systems. Their survival depends on the predicted movements and complex joint details which absorbed so much design effort.

Wind

Japan suffers from hurricane wind conditions, design pressures being given by the BSLJ. For this project, a wind tunnel test was commissioned to establish pressure coefficients for the building generally, as well as local coefficients to be used for cladding elements and various canopy and overhang conditions. Because of the building's size and exposed position, a 10-second gust averaging time was used for design of the primary structural elements, with a 40-second gust for overall building loads.

A static model tested at Bristol University provided the required design data. Typical (one-second gust) wind pressures on the façades were 1.8kN/m², but with local pressures on cladding up to 4.0kN/m². Later, during detailed design, the arrangement of the cantilevered landside canopy under a particular condition was found to be excessively flexible, and a separate dynamic wind model tested at Rowan Williams Davies & Irwin laboratories in Canada confirmed its dynamic response and to ensure that there was no long-term risk of fatigue.

Structural form

Floors

These are steel moment frames with concrete floors cast on steel deck plate - a common and effective form of construction in Japan, providing a ductile structure able to absorb the maximum energy in a seismic event. Spans are typically 14.4m.

MTB roof

The MTB roof structure is formed by three-dimensional triangular section tubular trusses spanning onto splayed support legs 82.5m apart. The shape generates arch action for vertical loading, but acts as a bending frame under seismic load along the length of the trusses. Any structure of this kind provides limited ductility since individual members can fail by buckling, so for a seismic event in the direction of the truss spans, BSLJ demands that the design is elastic, with design loads selected according to the slenderness of individual elements.

In the other direction secondary beams, spanning continuously across the tops of the trusses at about 4m centres, form plastic hinges close to their support points and so provide energy absorption. This form was adopted in preference to the cast-steel brackets envisaged at competition stage, with corresponding fabrication benefits. In this case the braced roof surface can carry the distributed lateral loads to the splayed support legs and so to the framed structure below (Figs. 7-8). At landside, each roof truss extends beyond the splayed support legs to form the roof to the Canyon. A single prop supports the truss from a frame at the landside of the Canyon, after which the roof cantilevers a further 15m to create a canopy over the access and drop off areas. Since the landside frame is structurally separate from the main floor frames, the two structures could move laterally out of phase with each other in an earthquake. The single prop support has spherical bearings at each end to permit relative lateral movement in all directions. At the airside of the MTB, the main trusses merge into the Wing structure at a low point corresponding with one of two major gutter lines.

The Wings

The Wing structure covers a 20m wide space from the airside edge support to a series of columns at the base of the Wings. The comprehensive solution - in effect a half-portal spanning across the 20m space - turned out to need a structural depth of around 1.5m.

A series of such structures viewed along the length of the Wings would have presented a substantially 'solid' appearance to observers, so instead a lattice shell structure was developed, spanning longitudinally, and resulting in a much more slender appearance. Its cantilever supports act as 'springs' on the airside, alleviating the differential settlement effects which otherwise would have induced unmanageable imposed deflections and stresses. Circular hollow section (CHS) ribs occur at 7.2m centres with high strength tie bars in a 'spoke' arrangement to restrain the shape of alternate ribs and so act as a diaphragm. Longitudinal rectangular hollow section (RHS) members are fixed to the outside face of the ribs to which the cladding and glazing is fixed. Diagonal RHS members complete the shell surface.

The shell was analysed using the FABLON program, which takes account of the displaced shape of structure under load and can simulate buckling.

9. Macro jets supplying air to MTB using open air-ducts.

Various parametric studies were carried out to define the shape of the Wing, and to check for snap-through buckling. The central part of the shell structure (corresponding with the MTB) derives its lateral support from the MTB roof; this adds complexity to the analysis, but simplifies the building through the absence of any joint at this position. Movement joints are provided, one on the centreline of the MTB and others at varying centres of up to 200m in the Wings. This spacing, greater than considered normal in the UK, is commonplace in large buildings in Japan. The difficulty of dealing with joints in seismic conditions outweighs the thermal-induced disadvantages. Of course, thermal range becomes another base load to be applied to each of the various loadcases.

Connections

In such a structure, much effort goes into designing connections which transfer forces and moments securely, are aesthetically pleasing, and aid fabrication. In the MTB, the trusses are fully welded. Each was delivered to site in either seven or nine sections, and later site-welded to form the complete unit. Site-welding is common practice in Japan, and this design requirement was considered to be entirely routine by the Japanese erectors. The truss sections came to site with the corresponding end sections of secondary beams welded in place.

All other connections (column to truss, secondary beams, etc.) were bolted with HSFG bolts - again the normal practice in Japan since the earthquake conditions require joints to withstand repeated reversal of loads. The connections in the Wing structure were made with a fabricated component welded to the ribs at each intersection point.

The secondary and diagonal members were bolted into position, and the T-connecters subsequently hidden by cover plates.

The various fork connections for the tie bars were machined from steel plate, since castings would have needed a time-consuming special approval procedure in Japan.

Building services

Design criteria

It was decided early on that it was not necessary to provide precise temperature control in most of the large concourse spaces. This led to the concept of a 'macro' or overall climate control system, maintaining the space at between 20°C in winter and 26°C in summer. Humidity is controlled between 25-55% RH. The design requirements were based on a high population level of $2m^2$ per person leading to a large fresh air requirement. A similar macro strategy was adopted for the lighting system, providing an overall illumination of 200-300 lux.

More precise local control in areas such as lounges and check-in counters is achieved by a micro system of localised lighting and air-conditioning. (It is interesting to note that a higher level of illumination is required to comfortably read Japanese Kanji characters than alpha-numeric script.)

The MTB macro system

In the international departures lounge the macro conditioning is from large nozzles blowing temperature-controlled clean air 80m landside to airside. These nozzles blow air across the ceiling, inducing air from the space. This causes the air jet to expand and slow down, creating a circulating current to ensure air movement and effective ventilation. The nozzles blow against a suspended curved fabric ceiling which acts as an 'open air duct', ensuring that the stream of air reaches the other side without dropping prematurely. Air is returned to the plant via large grilles about 3m above the concourse at the end of the check-in islands.

The supply nozzles serve a number of functions:

- They eliminate the need for air distribution ductwork in the roof or from the floor of the space.
- They control heat flow through the roof at source.
- They provide air movement humidity and temperature control.
- They provide filtered outside air to the space.

10.
Wing under construction, August 1993.

Computational fluid dynamics analysis

Alistair Guthrie
Raymond Yau

Three different proprietary CFD programs - PHOENICS, FLOW3D, and STAR-CD - were used to carry out the CFD analysis. The reasons for this were rather complex and represented a mix of considerations, partly historical in that two of the programs were already at Arups, and partly to do with the need to evaluate the best programs for particular tasks. The main technical criteria for selection were:

- the ability to create a curvilinear mesh system to represent properly the curved roof and the initial projection of the large nozzles
- the need to define the nozzles properly
- the availability (and costs) of programs for use on the in-house computing platforms used in-house
- a record of successful previous use on building room air movement applications
- in particular, the capability to compute buoyant flow.

Analyses were carried out over many months, starting at the competition stage when PHOENICS was used to demonstrate the possibility of projecting a jet with differing temperatures from the surrounding air for the required distance. At the start of the scheme design, preliminary CFD runs were made using a two-dimensional slice in an attempt to establish the influence of the roof shape on the jet trajectory and the effect of the exhaust location. These initial runs indicated that the concept of large nozzles could work.

To determine the influence of the macro jet performance on the temperature and air movement in the occupied area, a three-dimensional representative section of one bay was modelled using Harwell's FLOW3D program.

To achieve the response needed at this particular and critical stage of the project a limited number of simulations were commissioned on a super-computer.

For the final series of simulations, prior to physical model testing, the in-house STAR-CD program, which had recently been updated, was used (Fig.A).

This gave particular flexibility in generating complex three-dimensional meshes and post-processing results. In this analysis, the body-fitted co-ordinate mesh contained approximately 16 000 cells.

Table 1: CFD model design parameters

Test	Type of Simulation (m/s)	Jet exit velocity angle	Nozzle inclination	Jet exit temperature (°C)	Temperature difference between jet ΔT (°C)
1	Isothermal	6.0	30°	—	—
2	Summer (a)	6.0	30°	16.0	10.0
3	Summer (b)	6.0	30°	21.0	5.0
4	Summer (c)	9.4	30°	19.87	6.13
5	Winter	6.0	30°	22.4	-2.4

The results of different scenarios described in Table 1 are:

(1) The macro jet attaches to the roof until it passes the macro exhaust. The circulation induced creates average air velocities of 0.28m/s in the occupied zone.

(2) The cold macro jet detaches from the roof and reaches the floor c.30m from the landside of the main concourse. This early detachment of jet due to strong buoyancy forces (characterised by high Archimedes number) creates a strong draught at occupancy level, which would result in discomfort.

(3) The cold macro jet remains attached to the roof because of reduced buoyancy forces. However, because of buoyancy the jet gradually thickens (downwards) as it projects towards the airside of the main concourse. The velocities and air temperatures at occupancy level remain within acceptable comfort criteria.

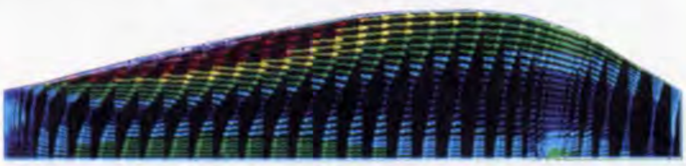
(4) The cold macro jet stays attached to the roof as a result of the lower Archimedes number following from increased jet momentum. Higher velocities are induced in the occupied zone although they are still within the comfort criteria.

A combination of these results allowed the design of a jet nozzle which has acceptable performance in both summer and winter conditions without change of velocity or trajectory.

Physical model tests confirmed this design (Fig. B).

Illustrations:
Ove Arup & Partners

B. Model testing of open air duct.



A. CFD air movement analysis assisted in choice of roof geometry.

Early on in the design, it was decided that the optimum solution for the air nozzles would be one with a fixed opening size and trajectory angle for both heating and cooling situations. In order to predict the performance and so design this macro system, both computer and physical model testing were carried out. Computational fluid dynamics (CFD) modelling was used to predict air movement and temperature distribution within a section of the departure lounge (see panel above).

This analysis determined the influence of factors like the exit velocity of the air from the nozzle, the shape of the roof, and the air temperature. Simulations were done for winter design conditions, isothermal conditions, and summer design conditions. As well as CFD analysis, reduced scale physical model tests were performed to refine further the parameters of the nozzles. These tests, on a 1:10 scale model large enough to walk inside, were performed in two stages.

11. Canyon view.

12. Computer model for Canyon lighting study.

Smoke was injected into the nozzle air stream and a photographic record made of its movement across the space, noting the flow pattern, point of detachment from the roof, and direction of flow on the concourse. Patterns were established for a range of temperature conditions, mass flow rates, velocities, and angles of jet trajectory relative to the roof.

Under isothermal conditions the optimum angle of discharge for the jets was 30°. Various summer regimes were examined and the optimum angles of discharge for each condition were found to lie between 25° and 27.5°. With the optimum conditions established by smoke testing, the next step was detailed measurements of air velocity and temperature, plotted on a regular three-dimensional grid throughout the space and used to calculate comfort indices for the occupied zone.

As a result, it was predicted that for all but the extreme design conditions, over 90% of the occupants would be comfortable with the proposed temperatures and air distribution.

As a result of the tests, the geometry of the air nozzles was established and construction details of the nozzles defined. The architect then designed the glass fibre covers which form the visible shape of the jet.

The MTB micro system

Additional cooling to areas such as the check-in desks, lounges, concessions and the large end walls is provided by small, local, fully recirculating air-handling units. These take air from the space, treat it and provide spot cooling from small localised nozzles to these areas. These systems can be turned off at times of low occupancy.

The Canyon system

The floor of the Canyon houses the arrivals concourse, whilst departing passengers cross on bridges 20m above (Fig.11).

As envisaged at the competition stage, the Canyon is a transition zone between outside and inside spaces, much of its external wall and roof being glass (Fig.12). The air-conditioning concept is to provide a conditioned environment at concourse level, allow the air to stratify, and extract the warm air in summer at high level. Shading is also provided to the Canyon roof to reduce direct solar radiation onto the concourse. When allowing the stratification, it is important to prevent both overheating on the arrivals bridges across the Canyon, and the warm air from the Canyon roof migrating to the arrivals concourse.

As in the arrivals concourse, micro systems provide closer temperature control in places like information booths and shops.

The Wing system

The Wings contain the departure lounges which have a view of the runway through a large curved single glass façade (Fig.13).

To provide adequate protection from solar radiation and glare, and to reduce the air-conditioning load, a number of shading options were studied. The built solution is a small overhang shading the top of the glass, plus solar reflective coatings on the glass itself which decrease in reflectivity from top to bottom (Fig.14).The occupants are protected from high glass temperatures in summer and low glass temperatures in winter by cooled or heated air blown from below, up the face of the glass, through perimeter slot nozzles.

The rest of the Wing area is supplied with conditioned air to provide fresh air ventilation, humidity and temperature control from wall-mounted grilles and nozzles. In tall areas of the Wing this air conditions only the lower occupied spaces, allowing the temperature to increase at high level.

13. 'Fish tail' ducts supply air to Wing.

14. Interior of Wings housing boarding gates.

15. Interior of international departures floor, MTB, February 1995.

16. Arups-designed MTB end wall glazing.

Lighting and daylighting

The public areas of the terminal building are designed as open, transparent, column-free spaces with large areas of glazing and no false ceilings (Fig.15). Lighting and other equipment such as public address, signage and flight information is therefore generally mounted on posts which have become known as 'technical trees'.

In the international departures hall, the desire to emphasise the roof and remove visual clutter led to an uplighting solution. 1kW metal halide floodlights are mounted on the tops of check-in counters and on technology trees, so that light reflects from the white fabric open air ducts suspended below the roof. The lighting level of 200lux throughout the space provides background lighting, whilst local task lighting increases illumination for specific functions.

The Canyon was conceived as a tall, largely daylit space with planting, and after dark a 'garden at night'. Lighting is non-uniform and from a variety of sources: the floor is lit by post-mounted luminaires, reflecting the style used throughout the building, with 400W metal halide lamps giving an average illuminance of around 50-100lux. The escalators have built-in handrail lighting, whilst the undersides of the bridges incorporate mains voltage halogen downlights to create sparkle and add further to the variety of light on the floor below. The bridges themselves have linear lighting combined with handrails. Uplighters in planters will cast light into the trees, whose growth will be sustained by 1kW metal halide hi-bay luminaires suspended above the planting areas. This is the only public area in the terminal building where luminaires are hung from the roof.

In the Wings the design concept is similar to the MTB, with open areas and glazing allowing a clear view of the aircraft. Lighting is mainly by post-mounted luminaires with some general background uplighting of the roof from the mezzanine concourse. In the gate lounges, the posts are related to seating areas and 250W metal halide luminaires provide an average 275lux.

Technical trees

These posts of varying height are used extensively throughout to provide local services (Fig.17). As well as uplighting and downlight they house emergency lighting, public address, fire alarm signals, CCTV cameras, and video monitors. Each type of post was developed to include the necessary mounting brackets, trunking compartments, and access for rewiring.

The public address system was designed as a micro system using a large number of small speakers mounted on the trees - necessary to give the required clarity within the large reverberant spaces.

17.Technical tree:
carrying fire alarm sounder (top left),
public address speaker (bottom extreme left),
emergency light (bottom left),
light for general illumination (right).

Construction

Separate contracts were let to two consortia led by Takenaka and Obayashi, for them each to build half of the project. This was literally so - conveniently the building had a movement joint on its exact centreline, and each contract was for half the building either side of the joint.

Unusually, some major subcontracts were placed outside Japan, with YKK Cupples (USA) supplying the airside glazing, Eiffel (France) the crafted steel trusses and glazing to the MTB end walls , and Watson Steel (UK) a major part of the roof steelwork. Indeed, this was the first Japanese building structural steel contract awarded outside the country.

Construction of the foundation raft began in May 1991. The building was completed by July 1994, on schedule for the official handover two months later. Although this was later than originally envisaged, due to additional ground improvement measures introduced by the client team responsible for the island, the construction contract itself progressed to plan. A 300 000m^2 building costing 15bn yen completed in less than 36 months is impressive indeed.

Credits

Client:
Kansai International Airport Corporation

Design team:
Renzo Piano Building Workshop Japan

Ove Arup & Partners International
Andrew Allsop, Tom Barker, John Batchelor, Paula Beever, Rod Buchanan, Mark Chown, Martin Cooper, Rob Davis, Nick Dibben, Philip Dilley, Ian Feltham, Giovanni Festa, Andrew Gardiner, Alistair Guthrie, Jeppe Hundevad, Rory McGowan, Alan Michaelis,Paul Murphy, Roberto Muzzetto, Heraclis Passades, Tony Philiastides, Peter Rice, Andrew Sedgwick, Tony Stevens, William Stevenson, Chris Taylor, Tom Tomaszczyk, Mike Willford, Raymond Yau

Nikken Sekkei

Aéroport de Paris

Japan Airport Consultants

Main contractors:
Takenaka (Joint venture leader)

Obayashi (Joint venture leader)

Illustrations:
1: CKIAC.

2: Aerofilms/Nigel Whale/Tony Mitchell.

3: Kazuo Natori.

4: Nigel Whale.

5: Ove Arup & Partners.

6, 8, 17: Rory McGowan.

7,10: Yoshio Hata.

9, 13, 14, 16: C.Y. Kinumaki.

11: Phil Dilley.

12: Renzo Piano.

15: Neil Ray.

'Power to change'

Tom Armour

How it started

In June 1994 four teams including one from Arups were asked by BBC Wales to present ideas on how to deal with the recently decommissioned Trawsfynydd nuclear power station in North Wales.

The project was sponsored by the BBC, the Development Board for Rural Wales, Nuclear Electric and the Training Initiative Council. The proposals were shown in three programmes broadcast on television in Wales in November 1994.

The site

The 580MW Magnox station is in the heart of Snowdonia National Park, in a unique valley dominated by dramatic hill topography. It stands on the northern shore of Lake Trawsfynydd (510ha), now a popular fishing resource, but originally created in the 1930s for an hydro-electric station.

A 1950s forecast of booming electricity demand led to the station's construction in the early 1960s. The Public Inquiry lasted only three days, though there was concern about the visual impact of the station and pylons. The CEGB, however, argued that the site was perfect for a nuclear power station - isolated, near cooling water, and adjacent to a community requiring jobs following the decline of local industry.

It was designed by Sir Basil Spence and the landscape architect Dame Sylvia Crowe. The twin reactor buildings, some 54m high, are the dominant features, visible for great distances over the surrounding rural landscape. The remaining buildings and site structures are partially concealed below ground level. The town of Blaenau Ffestiniog lies to the north. It has strong connections with the power station, a major local employment provider over its 30-year life, whose closure has inevitably had a negative impact on this community. The legacy of the once prosperous slate mining industry also remains in the form of massive spoil tips.

Although they symbolise its existence and history, the tips have had a negative impact on Blaenau Ffestiniog, reflected in the fact that it is excluded from the Snowdonia National Park boundary although it lies within its heart.

Nuclear Electric's plan

Nuclear Electric made public consultations when deciding their decommissioning strategy, and strong desires were expressed to reduce visual impact of the reactor buildings and their detrimental effect on the National Park. County and District Councils favoured early site clearance and restoration to its former appearance, but Nuclear Electric's plans are not so far-reaching.

These are to:

- dismantle the non-radioactive plant (1996-97) and lower the height of the reactor buildings approximately 30m
- build 'safestore' structures around the main reactor buildings containing radioactivity (1996-2000)
- monitor the safestores by remote security surveillance (2001-2127) until the buildings can be dismantled
- clear and restore the site (2128 - 2136) which would thus become available for alternative use in 140 years' time.

The Arup plan

Decommissioning Trawsfynydd is significant because it not only creates opportunities for major environmental benefits, but also has implications for other sites to be decommissioned. The technologies and skills developed in Arups' proposals could be transferred and adapted elsewhere. The aim is to return the site to nature by using slate spoil currently disfiguring Blaenau Ffestiniog as raw material to bury the two reactor buildings and create a series of hills at the edge of Trawsfynydd Lake. Prior to burial, the buildings would be prepared to a safestore condition, and the other buildings and facilities demolished. After due community consultation, slate spoil would be collected from carefully chosen sites around the town and brought by lorries and a conveyor system to the old sidings in the town for bulk rail transfer to Trawsfynydd. A slurry of cementitious slate would be pumped into the reactor buildings to harden and form a weak rock core around all the radio-active zones, as well as a foundation for the hills above. These to be made by conventional spreading compaction techniques, incorporating access routes to act as arteries for monitoring probes. In due course they could be used to mine out any material as required without altering the mature landscape above. Although the new landform would be entirely artificial, it would be designed to reflect the surrounding landscape's dramatic form and vegetated to blend in. The natural shaping for the hills would avoid any sense of a dominant man-made structure in this unique topography. Although the power station would be buried, its role in the community would not be forgotten. The two main summits would be 'marked' with symbolic tree circles positioned directly above the de-commissioned reactor cores to act as reminders of the former use of the site.

The lighting proposals are integral part of the concept. Light from the sun - a source of sustainable energy - would be used to create a beacon for the site, a former 'producer of energy'. This would act both as a reminder of its former use and as a symbol for the future by its use of sustainable power. Lighting would be designed with careful optical control to avoid light pollution. The Arup proposals would have dual benefits: first, by enhancing the site it would be available for recreation far sooner than with Nuclear Electric's plan; secondly, the town environment would be significantly improved. It is also the most economic solution, there being no need to dismantle the buildings buried in their safestores.

Environmental benefits assist economic and social value, and to enhance both the site and the town would directly contribute to this creative process.

The plan does not predict what new developments should occur, but rather sets a scene which could trigger a regeneration process. Carefully-judged promotion of tourist activities, especially recreational, could be encouraged. The 'new landscape', the lake, and the surrounding hills could form important foci for water sports activities, hiking, biking and riding, with discreet resort facilities along the lake shore at the base of the new hills. Blaenau Ffestiniog, with local landscape enhancement and urban improvements, could provide a more appropriate environment for better residents' and visitors' facilities. Its inherent character and history could be reinforced in a more creative and attractive way, and the lake resort and symbolic hills thus become the focus of a wider network of tourist facilities, and a centre of recreation, local culture and entertainment.

Outcome

In the final programme (a televised open debate held in the station's Turbine Hall with the sponsors, designers, a panel of judges, and people from the local community) the Arup proposal was selected as the winner.

A book of the programme 'Power to Change' is published to coincide with an exhibition of the four teams' proposals at RIBA in April 1995. Nuclear Electric have shown interest in the Arup scheme and discussions are taking place.

Something positive may ensue.

Arup team

Mike Lowe (architect+urban designer),

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Graham Phoenix (lighting consultant, Lighting Design Partnership).

Felix Medina (architect),

Andrew Lord (engineer),

Andy Bascombe (ecologist) also assisted.

Photos:
1: Five Valleys Photography
2: Mike Lowe

Montages:
Tom Armour/Jon Carver

1. The Arup proposal for the power station.

a. Trawsfynydd as it is.

b.
The reactor buildings lowered to c.30m.

c.
Mid-way through burying the reactor buildings with slate from local tips.

d.
The final scheme, with symbolic tree circles positioned directly above the reactor cores.

2. The town.

a.
Blaenau Ffestiniog as it is, surrounded by slate tips.

b.
As it could appear, after removal of slate tips and restoration work.

1.

The Hong Kong Stadium

Robert Cheung Russell Cole Paul Suett

Introduction

Lack of international-standard sports facilities has been a long-term problem for Hong Kong: nearly 6M people in about 1000km² inevitably leads to other priorities in land allocation. Nevertheless this deficiency has long been a cause for concern, not only on behalf of professional and amateur sportsmen and women, but also the masses of children who spend most of their days in multistorey schools. The solution, as is often the case in Hong Kong, came from the Royal Hong Kong Jockey Club, which operates the only legal betting franchise in the Territory. A staggering HK$1bn is now wagered at nearly all the 40 race meetings held annually at the Club's two racecourses. After taxes the RHKJC is left with a sizeable income for funding a wide variety of public projects.

In October 1990 Arups learned that the Club had commissioned the American architects Hellmuth, Obata & Kassabaum to study modernisation of the Government Stadium at So Kon Po, south of Causeway Bay on Hong Kong Island. Contact was made, and the firm began to assist the architect with the engineering aspects. This Stadium was built in the 1950s in an area of hospitals, schools, sports facilities, and temporary housing (Fig.2). Although badly needing modernisation, it was much loved as the venue for the annual Hong Kong International Rugby Sevens Tournament - a major event in the Territory's social as well as its sporting calendar. Four plans were initially investigated, two involving renovation and two renewal. Alternative capacities of 30 000, 40 000, and 50 000 seats were considered, with a variety of sports facilities including an international standard running track. Each scheme was analysed on a cost benefit basis, including design, construction, operating, marketing, and financial factors.

The brief

Government approval came in May 1991, by which time the brief had been developed further with the client. As a result the RHKJC Stewards, who have the final decision on budget, decided on a brief based on the following requirements:

- 40 000 seats, 75% covered by the roof
- Football and rugby catered for, but no running track
- 50 air-conditioned corporate boxes, each with its own catering facilities
- Facilities suitable for major pop concerts
- No underground car park
- Construction scheduled so that the yearly Rugby Sevens Tournament could take place
- Construction period not to exceed three years.

Consultancy services

Arups were appointed to provide the following consultancy and supervisory services:

- Structural engineering design
- Building services engineering design
- Geotechnical and traffic engineering
- Resident engineering supervision for structural and building services works
- Authorised Person responsibility for all submissions for Government Approval.

Other consultants included Wrightson, Johnson, Haddon & Williams Inc. of the USA (public address consultants), and the Graf Consulting Group (catering facilities design and business plan). The Stadium was to be handed over to the Urban Services Department on completion; they in turn employ Wembley International as operators.

Tendering arrangements

The first priority was to phase construction to accommodate the Rugby Sevens Tournament, traditionally held every April. It was decided that construction must commence immediately after the 1992 event; this gave a little over eight months to prepare a scheme design and tender package, get a contractor mobilised, appointed, and ready to start.

2. The old Stadium looking north.

The design team clearly had insufficient time to assemble a fully detailed tender package. To overcome this problem a comprehensive scheme design document was prepared, accompanied by a cost plan from the quantity surveyor. The contractors selected were required to tender a 'not to exceed' lump sum, with a schedule of rates. Programme completion was set as 36 months.

The structural scheme was based on an in situ reinforced concrete frame and slabs with precast concrete bleachers. The roof was to be carried on two main arches, each spanning 240m north to south and rising a maximum of 55m. Steel trusses at 6m centres were to span between the arches and back to reinforced concrete rakers. There were four tenderers, but only Dragages et Travaux Publics offered an alternative design. This had a 24-month construction period and substantial cost discount, and was based on using precast concrete secondary beams and floor slabs for the concourses and the steel roof trusses at 12m centres instead of 6m. Their offer was conditional on the design team being under the direction of the contractor and not the architect, so that information could be prepared in a sequence to match the ambitious phasing. Naturally, the Jockey Club was interested, as this alternative offered not only a cash discount but disruption of only one Rugby Sevens Tournament rather than two. After assessment the contract was awarded to Dragages.

Basic Stadium layout

The pitch is sized for international soccer and rugby. The stadium is built over a subterranean service level containing most of the support activities including changing rooms, kitchens, security, management offices and storage areas. An east/west driveway under the North Stand gives access for goods vehicles, outside broadcast trucks, and containers for visiting concerts and events (Fig.3).

The layout and the rise between bleachers ensures clear views of the pitch for all 40 000 seats. The lower deck surrounding the pitch is a continuous band of 18 rows except to the south, where another 28 rows extend back. Access is from the Main Concourse, a clear loop-shaped plaza at the top of the seating and in sight of the pitch, where spectators meet friends and visit the numerous food and sales outlets located against the rear wall.

3. Access driveway for goods vehicles.

The main entrances to the Stadium are at the north end of this level, with ramps and escalators to the higher level on the north east and north west corners of the Main Concourse (Fig.4). The East and West Stands are multi-storey. The lowest level houses the 50 private suites, facilities and seating for event organisers, television boxes, scoreboard controls and a restaurant. Exits from the East, South and West Stands are in the rear wall. Above is the 10 000-capacity, 35-row upper seating deck, served by the Upper Concourse. The triangular area closer to the pitch is filled with food and sales outlets. The deck projects over a loop road and the valley slopes below, and is covered by the roof (Fig.6).

Facilities

Escape strategy

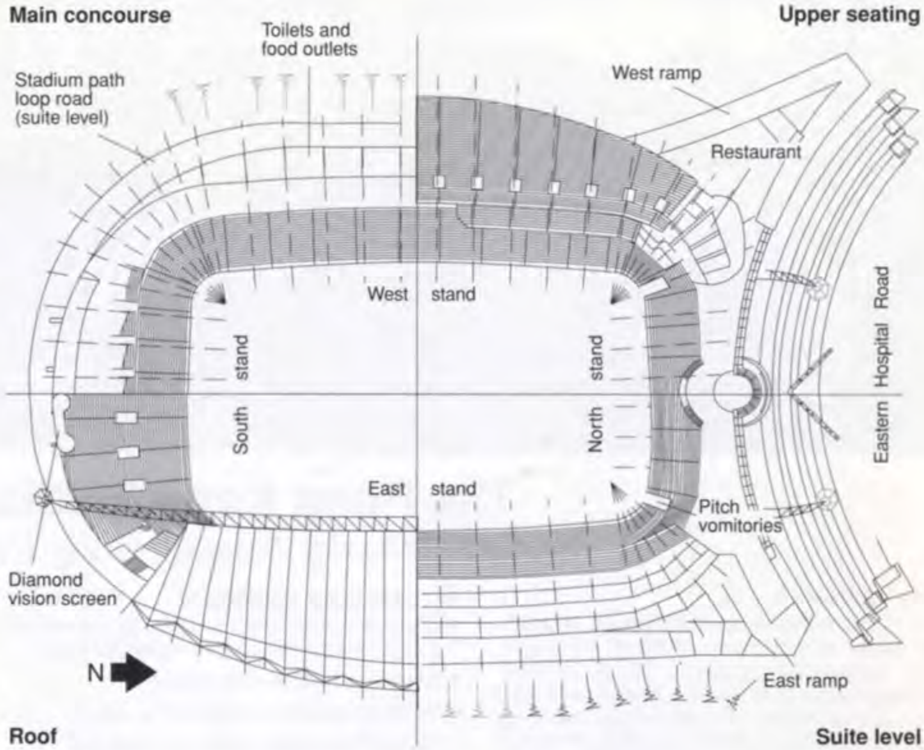
The escape routes were designed in accordance with NFPA requirements. The Stadium could be cleared in a calculated 11 minutes. As it is in a 'blind' valley, all exit routes have to lead north to Eastern Hospital Road, via two main routes. Spectators around the pitch will probably use the Main Concourse while for the higher levels escape stairs lead onto Stadium Path, the original loop road. This had to be widened, but inwards due to the valley slopes, which required a slight reduction in the Stadium site area.

Catering

The three levels have 30 concessions areas for food outlets, many leased to well-known franchises. A main kitchen on the Service Level provides pre-cooked meals to two satellite kitchens on the Suite Level for the private boxes, whilst the restaurant has a separate kitchen. Catering equipment selected by the catering consultant was predominantly electrically-operated for fast heat recovery.

Pitch lighting

Originally, floodlights were to be mounted on the arches, but it was concluded that such a scheme would result in a high level of horizontal illumination but insufficient light on the vertical plane, giving problems for television cameras. The line of floodlights was pulled back from the arch to the optimum location for vertical illumination but keeping glare within FIFA recommended limits. Additional floodlights on the arch at the four corners of the pitch boost the lighting level in the penalty areas.The pitch lighting was designed to 1400lux towards the main camera as recommended by FIFA for colour television broadcasting, and a uniformity of 1:0.7 (maximum to minimum) over a distance of 5m across the pitch was achieved. Four levels of switching, controlled by a Building Management System, vary illumination for different activities. Altogether there are 340 floodlights with 1.8kW metal halide lamps for high efficiency and excellent colour rendering, operating at 380V to reduce cabling costs. Catwalks on the underside of the roof structure provide a platform for the floodlights and their control gear, also supporting distribution cables and giving maintenance access (Fig.5).



4. Site plan.

Foundations

The underlying granite varies greatly in level but, in spite of quarrying, generally follows the trend of the valley; the extent of the service level was determined by the point at which the underlying rock rose above it. The North and South Stands are relatively light and supported on pad footings on completely decomposed granite, whilst the East and West Stand columns and the arch abutments are carried on caissons to the granite below. Conventional retaining walls were generally adopted, though the contractor chose to use permanent soil nails for the 10m high service level excavation - the first application of this method in Hong Kong.

Main Stands

The Stands' reinforced concrete frames are arranged radially around the pitch at approximately 12m centres, with the precast, prestressed bleachers spanning between.

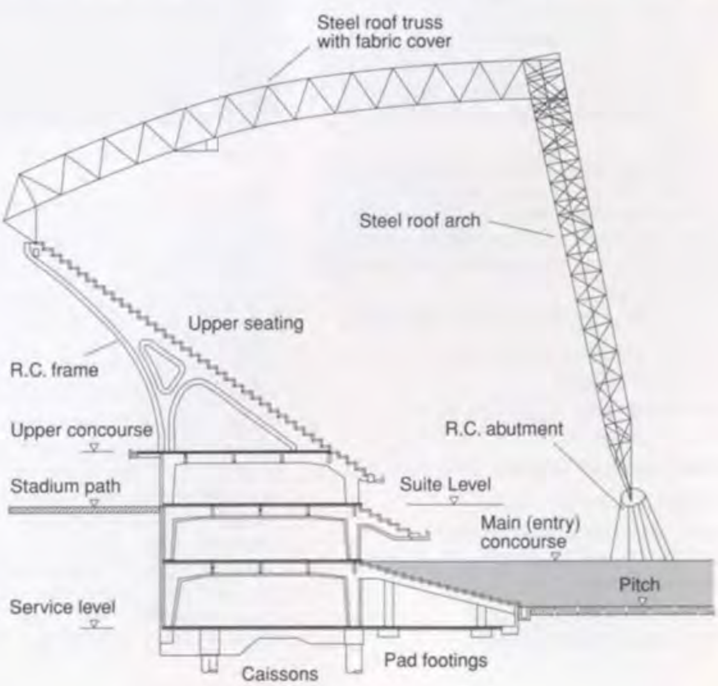
The concourses feature precast, prestressed secondary beam downstands supporting a precast slab with a structural concrete topping. The North and South Stands are single raking beams, spanning between the columns on pad footings with their geometry completely defined by the shape of the seating bowl above.

The East and West Stands' main beams span 18m between the column pairs, perpendicular to the pitch, with 2m and 4.5m cantilevers at the edges of the Suite Level and upper seating respectively.

The upper seating is carried by raking beams cantilevered up to 13.3m on plan past the outer of the columns to support the roof columns.

These beams have semi-circular soffits.The geometry of the rakers is a major feature, the flowing line of the column/beam connections

5. Catwalks on underside of roof structure.



giving the space under the upper seating a dramatic quality (Fig.7). By increasing the cross-section of the elements, the contractor found a family of shapes which allowed the majority of the rakers and their columns to be formed by just three sets of formwork. The curved exposed concrete finish was achieved using wooden forms on steel sub-frames, lined with thick plastic sheets (Fig.8).

The precast prestressed bleachers and secondary beam downstands were cast in Zhuhai (a Special Economic Zone of the People's Republic of China next to Macau), shipped to the site, and installed by tower cranes. The bleachers sit directly on the rakers with fixing dowels. Bleacher lengths and the height of the risers varied throughout the stands. The typical units were L- or T-shaped, the latter at the lower, small riser, levels. Generally the same riser and slab thickness occurs throughout, minimising adaptations of the casting bed.

The upper and lower edges of each seating area required non-typical units.

7. Raking beams supporting upper seating.

Development of the roof design

Robin Forster

The roof profile was controlled greatly by the topography of the So Kon Po Valley. HOK's concept architect was anxious that the massing of the Stadium should reflect its location in the valley floor. Various layouts were investigated with the use of models - including one of the valley floor - and useful comparisons made with previous Arup stadium projects in Australia and Italy. All projects have constraints and operational requirements, in this case insufficient design time and the requirement for 75% of the Stadium seating to be covered, which would need roofs more than 50m wide over the East and West Stands. A cantilever design from the top of the terraces was investigated, but this would have resulted in heavy stand structures with associated uplift forces.

Since the value of these forces could only be confirmed by wind model testing, the concept for the roof as a separate structure was developed.

Hong Kong Stadium is a high profile project where all the structures should be expressive.

There was a temptation to design roofs to span east to west from valley side to valley side, but since this would not reflect the valley concept a scheme was developed that would span north to south parallel to the pitch. In an attempt to follow the leading edge profile of the roof a large-span truss arch proposal fell out from the schemes investigated. HOK saw this as a significant statement, and eventually the arches came to span the entire stadium and to become a prominent feature at the entrance. They clearly needed to be symmetrical, and at the southwest corner a rock slope on the far side of the loop road gave the abutment position. The arch then has to rise sharply to provide vehicle headroom, becoming a cycloid in a plane 12° to the vertical. The trusses then span from an arch node to the top of the concrete raker at the top of the stand. The angle of the arch at the truss connection set the angle of the truss to the vertical. More of a feature than a structural requirement, the roots of the arches are detailed as pin joints - which also feature where the secondary beams connect to the terrace structure.

The roof was over 8000m^2 in plan and it was obviously important that the structural dead weight should be as little as possible. Fabrics had not been used to such a large extent in Hong Kong, but this type of covering was considered appropriate, so a PTFE-coated, glass-fibre, woven fabric was proposed.

Unfortunately, rear support to the roof had to be provided at the top of the terraces, but these loads were significantly less than those for a cantilever. Costings were made, and the scheme of twin arches 240m in span to a crown height of 55m with a fabric cover was presented to the RHKJC. Methods of construction were also presented, but the advantage in staged construction, and the magnitude of the roof's scale, were enough to convince the Club.

Tender information was prepared using the basic wind loading from the Hong Kong Building Regulations and a contingency for wind tunnel testing. With costs in mind, a value engineering assessment of the roof was carried out. Profiled metal cladding was substituted for the fabric, and a cantilevered scheme prepared, with several other cost-reducing concepts.

Tenders returned demonstrated the roof to be within budget. In conjunction with the successful contractor, wind tunnel tests were carried out to study the effects of the surrounding area on the wind environment in the valley, and to establish parameters for localised pressures on the roof. An aero-elastic model was used to assess the interaction of the roof structure and wind. Higher than expected loads were found, with the critical load case of the wind direction parallel to the arch in a northerly direction.

8. Wooden formwork on steel subframes used in achieving the exposed concrete finish on raking beams.

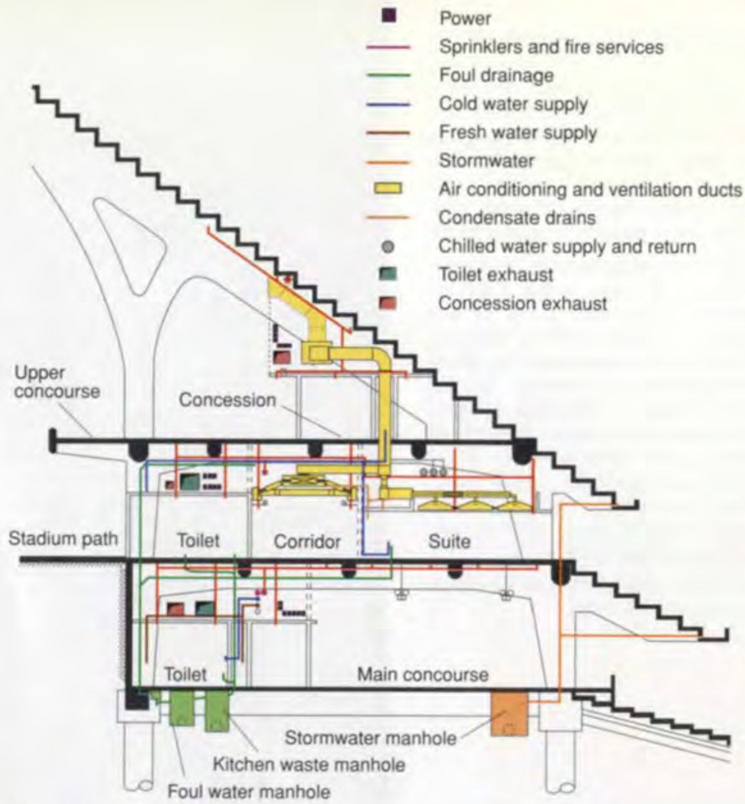
Roof

Steelwork structure

The arches are 3.5m square steel trusses at 12° to the vertical, their cords being 406mm diameter circular hollow sections (CHS) of grade 50 steel. The arch truss module is approximately 5m, constructed in pairs, so each arch consists of 24 straight units. Verticals, horizontals, and diagonals are 193mm-273mm diameter CHS.

The curved secondary trusses, spanning between 40m and 55m, have a triangular cross-section 3.5m deep, with diagonal bracing, and are connected to the arches by stainless steel pins. At the raker ends the truss becomes a column, connected by a single pin to a baseplate on the end of the reinforced concrete raker beam. In addition to these principle support trusses there are other elements. Between the column at each raker position runs both a horizontal truss and vertical bracing, the latter stabilising the secondary trusses and providing resistance to wind loads along the roof length.

9. The fabric roof.



11. Stand section.

10. The restaurant.

The valley cable, midway between secondaries, is tensioned between the horizontal truss and a similar truss in the top plane of the arch. These horizontal trusses span between pairs of secondary trusses, resolving the cable tensions.

Fabric

On each roof small areas of the fabric were welded into five large panels, each covering three bays, and held in place by a continuous series of clamps around the edges. The fabric is not fixed to the tops of the intermediate trusses. Prestressed 80mm diameter cables run in each valley between the trusses, providing a small prestress to the fabric in conjunction with the clamps. Under wind loading the cables become the principal method of preventing fabric uplift.

Building services

The restaurant and administration offices are air-conditioned, while the suite boxes and lounges, kitchen and changing rooms have comfort cooling. The occupancy and usage pattern for these areas was modelled and analysed in detail to obtain an optimum chiller plant size. Three 230-tonne air-cooled chillers were installed on the Sports House roof with chilled water pipes running across to the Stadium complex via an underground duct. In keeping with statutory requirements, acoustic enclosures limit noise from the chillers. Placing traps at the bottom of each vertical stack to remove grease from kitchen waste reduced the number of traps from 34 to 12. The statutory authority was involved in the planning stage and was convinced of the viability of the scheme. Where food outlets are located one above the other, stainless steel enclosures for drainage from the upper level, fitted with drain points, minimise health risks in the event of leakage.

All major plantrooms are on the Service Level, with primary mains rising to the Main Concourse and horizontal distribution in service zones located above the toilets and concessions. Distribution within the service zone is arranged to enable easy tap-offs to serve the Main Concourse and the levels above.

Power is supplied from two substations housing five 1.5 MVA transformers. A 360kVA standby generator starts automatically on mains failure to supply fire services and other essential loads within 15 seconds.

Construction

First year

The contractor planned to build all the concrete terraces and concourses in the first year. The programme allowed little leeway for loss of time through bad weather, which in Hong Kong's notorious wet season includes the constant threat of typhoons. Demolition of the old Stadium began the day after the 1992 Rugby Sevens Tournament, and foundation excavation swiftly followed. The only part retained for the 1993 Sevens was the old pavilion, as changing rooms.

Construction began at the South Stand and then moved on two fronts over the various levels northwards through the East and West Stands. Five travelling tower cranes transported formwork, placed concrete, and erected precast units. The pitch area was used for storage, casting of slabs and small precast elements, and for the adjustment of formwork. As the main beams were completed the precast bleacher units would be erected to avoid storage. Cantilevers and the lower, ground-bearing bleachers were the last sections to be constructed, to avoid blocking the path of the tower cranes. Early completion of the concrete works was necessary to allow the temporary pitch to be laid. A major effort was required to complete the services systems for the 1993 Sevens. This included those needed for operational reasons - services to all toilets, temporary lighting and power, and all underground drainage - as well as those for safety reasons

◀12.
1993 Sevens Tournament held before completion of construction.

13.▶
Raising the arches.

14.
On far right: erection of central sections.

15.
View of roof truss bearing and abutment.

During the same period a separate exercise was carried out for the Stadium operator, Wembley International, to investigate the possibility of enhancing the basic provisions of the design.

This included adding air-conditioning to suite lounges and food outlets, installing cable ducts and power supplies under the pitch for concert use, and placing lit advertising panels around the Stadium.

In the meantime, installation had to proceed at full speed to maintain the ambitious construction programme, and very close cooperation between consultants and contractors was required to minimise the disruption to progress.

That construction was completed on schedule is a tribute to the teamwork of all involved. Despite all the obstacles and setbacks the new facility has been a huge success and much credit must go to the contractor for the considerable achievement of constructing a Stadium of this size and complexity in just two years.

such as fire services installations. For the 1993 Sevens Tournament, 32 000 tickets were sold, with seating for 4000 more people than the contractual requirement. In addition, many extra seats were available as all the bleachers in the East, South and West Stands were erected before the event. Spectators sat on the concrete, and facilities were provided to the same level as the old Stadium. After a very successful event construction resumed.

Second year

The main tasks for the second year were to erect the roof, complete the services and finishes, lay the permanent pitch, and fit out the kitchens, concessions, restaurants, and suites. The roof trusses and arch sections were assembled on trestles erected on the pitch, the units being welded together before the final layers of corrosion protection were applied. Each arch was erected in four sections, with crane masts supporting them at the joints and providing working platforms for the in situ splice welds. The roof elements were erected by pairs of tracking cranes.

The lower sections of each arch were raised first, followed by their associated trusses. The central sections were then erected with the key locating trusses before the central splice was made and, following the placing of the remaining elements, the supports were released. The arch apexes deflected approximately 220mm under the steel structure's self-weight.

Once the steel roof structure was painted the fabric covering was installed. The panels were shipped - from Australia - in rolls, which were then mounted onto scaffolding over the rear bracing. Wires were attached to the free edge and the fabric pulled towards the arch by winches mounted on the truss chord. The loose, deployed fabric was then gradually hauled towards its fixing points by tightening threaded rods to the permanent clamps. Once all the clamps were fixed, the valley cables were pulled up from the pitch, the rear side pin installed, and the pre-tension applied by a jack on the arch.

Following roof erection, construction of the permanent pitch could begin and seating be installed. Detail design of services for the food outlets started during the second year, followed by a pricing exercise to agree costs before installation on site. At the same time, the 50 hospitality suites had to be redesigned to accommodate a radical revision to the brief, including the addition of toilet facilities, and the changing rooms redesigned to accommodate space for dressing rooms for star performers.

14.

Credit

Client:
Royal Hong Kong Jockey Club

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Quantity surveyors:
Davis Langdon & Seah

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2: Courtesy *South China Morning Post*
1,3,5,7-10,12-16: Colin Wade
4: Au Leung Chi/Trevor Slydel
6,11: Kwok Man Tai/Trevor Slydel

16.
Below: Spectators at the 1994 Rugby Sevens event in the completed Stadium.

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