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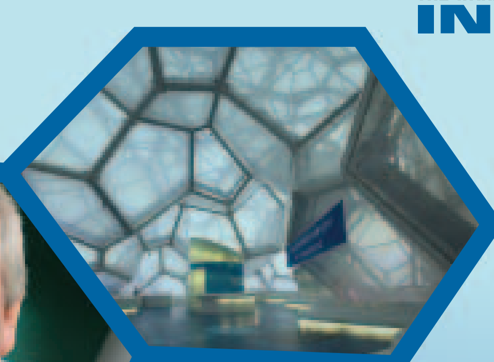
THE WARREN CENTRE

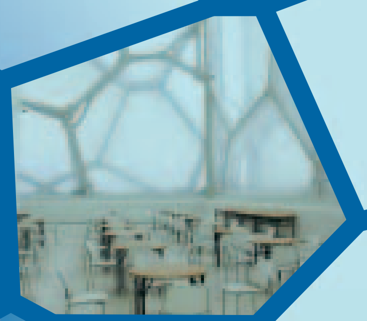
INNOVATION LECTURE 2008

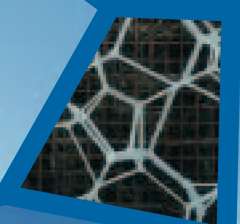


DELIVERED BY

Tristram Carfrae

STRUCTURAL DESIGN ENGINEER AND ARUP FELLOW





NETWORKING INNOVATION

THE Warren CENTRE

FOR ADVANCED ENGINEERING

NATIONAL SPONSORS

Arup can proudly claim to be the creative and inspirational force behind many of the world's most innovative and sustainable building, planning, infrastructure, transport and civil engineering projects. The Beijing National Aquatic Centre, for example, is a showpiece building for the 2008 Beijing Olympics designed by a consortium consisting of Arup, PTW Architects and the China Construction Design Institute (CCDI).

Arup Australasia is part of the Arup Group, a global firm of designers, engineers, planners and business consultants with 92 offices and some 10,000 employees in more than 37 countries. At any one time, Arup has over 10,000 projects running concurrently.

Arup came to Australia in 1963 to undertake the structural design of the Sydney Opera House. Today Arup Australasia is a multidisciplinary practice offering services across Australia, New Zealand and South East Asia with about 900 staff including engineers, planners, project managers and a diverse range of consulting specialists.

Arup has three main global business areas - buildings, infrastructure and consulting - and any given project may involve people from any or all of the sectors or regions in which the firm operates.

For more information: www.arup.com, *We Shape a Better World.*

ARUP

AusIndustry is the Australian Government's business program delivery division in the Department of Innovation, Industry, Science and Research.

AusIndustry delivers a range of more than 35 business programs - including innovation grants, tax and duty concessions, small business skills development, industry support and venture capital - worth about $2 billion to more than 10,000 businesses.

To help customers with product and eligibility information, AusIndustry has *customer service managers* located in more than 25 offices across Australia, a national hotline and website.

AusIndustry offers both entitlement and concession products. For a grants-based product, customers compete for limited funds, based on the merit of their application. For concessions, such as an R&D Tax Concessions, a customer makes a claim, based on their self-assessed eligibility.

An Australian Government Initiative

AusIndustry

Bovis Lend Lease is one of the world's leading project management, design and construction companies, operating in more than 30 countries and employing over 8,000 people. It is a wholly owned subsidiary of Lend Lease Corporation, which has been in operation since 1958. In the Asia Pacific region, the business has a turnover of $2.4 billion, as at December 2007, and employs 2,300 people across eight countries, with headquarters in Sydney, Australia. Its Australian regional offices are located in Sydney, Melbourne, Canberra, Brisbane and Perth. In Australia, Bovis Lend Lease has a specialist focus on the commercial, retail, healthcare, government and water sectors as well as multi-site account management and provides design expertise through its in-house specialists, Lend Lease design.

Bovis
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PricewaterhouseCoopers helps technology clients solve business issues and develop long term strategic objectives. We work with companies to help them achieve success and fulfil the promise of great ideas. We deliver industry focused assurance, tax and advisory services with a global perspective, local implementation, in-depth experience, and a forward thinking approach. As technology companies grow, the issues you face may change, but our ability to add value is something that you can rely upon.

PRICEWATERHOUSECOOPERS

Shelston IP is one of the largest and most respected intellectual property firms in Australia and New Zealand, delivering the full range of IP and related legal services and advice to our clients.

Built on a strong foundation spanning 150 years, Shelston IP's teams of highly qualified and commercially astute specialist patent attorneys, trademark attorneys and IP lawyers are finely attuned to the needs of modern business.

Delivering services that extend from patent, trademark and design registration to strategic portfolio management, due diligence, licensing and litigation, Shelston IP demonstrates a thorough commitment to our clients and their commercial goals, in Australia and beyond.

"Mind to market" reflects a crucial difference between Shelston IP and other firms. Our experience and knowledge of the processes involved in converting ideas and innovations into intellectual assets, and a deep appreciation of what it takes for our clients to successfully commercialise those assets, sets us apart.

Shelston ip

2008 INNOVATION HEROES AWARD

The annual Innovation Heroes Award is an initiative of The Warren Centre, awarded for outstanding Australian innovations in engineering technology. It recognises people who bring great ideas to life, and the role they play in driving economic and social progress. The award is made to Australian-based people or teams that successfully develop a new technology into a commercial product or service and who create great benefit for Australia.

1. ***Dean Cameron***, invented and commercialised the Biolytix wastewater treatment system - a compact waste treatment system which converts raw sewage, wastewater and food waste into high quality irrigation water.

2. ***Tristram Carfrae***, Principal at Arup Australasia, is known for challenging established ways and exploring better solutions, and for the design of award winning buildings. He is one of the world's leading designers of sporting stadia and light weight long-span structures.

3. ***John Russell***, responsible for founding Russell Mineral Equipment which designs and manufactures world-leading equipment to provide specialised solutions for mineral processing.

4. ***Alf Taylor & Nadia Taylor***, design, and manufacture at TNA Australia, the robag Vertical Form Fill and Seal (VFFS) system that improves productivity and reduces waste while packaging food.

SPONSORS & SUPPORTERS

The University of Adelaide's Entrepreneurship, Commercialisation and Innovation Centre (ECIC) exists to stimulate Australian innovation through entrepreneurship & commercialisation, research, education and training.

ECIC's academic leaders pursue cutting-edge research and provide further opportunities for PhD candidates. The Centre - with campuses in Adelaide and Sydney - offers a range of study programs - with awards to Masters level - in entrepreneurship, science & technology commercialisation and project management. This year, ECIC will launch a new Graduate Certificate in Social Entrepreneurship & Innovation and undergraduate programs in entrepreneurship, innovation, and creativity.

ECIC is the home of the University of Adelaide's echallenge. This contest provides mentoring opportunities and support, including cash prizes, for young innovators to develop business plans that turn ideas into viable businesses.

ECIC also manages the Incubator, a purpose-built facility at the University's Research Park on its Thebarton Campus. The Incubator complements and supports participants in the University's Graduate Entrepreneurial Program and provides furnished offices for other early-stage innovative, knowledge-based businesses.

ECIC - helping to build brilliant ideas into business wealth.

The Department of State and Regional Development (DSRD) is the New South Wales Government's business development agency. DSRD delivers programs and services that support the NSW Government's commitment to winning new business activity for NSW, and developing the capacity and productivity of the State's economy. DSRD provides advice and assistance to help businesses of all sizes establish or expand in metropolitan and regional NSW. It works to attract significant investment projects to NSW as well as major events that have the potential to benefit the State's economy and promote Sydney and NSW nationally and internationally.

For more information, please visit www.business.nsw.gov.au

The South Australian Government's ***Department of Further Education, Employment, Science and Technology*** plays a pivotal role in the employment growth, wealth creation, innovation and economic development in South Australia by building the breadth and depth of workforce skills in the state. Through the Department's Ten Year Vision for Science, Technology and Innovation in South Australia (STI10), South Australia aims to build research and innovation capacity and infrastructure, encourage a strong culture of innovative collaboration and build people, skills and community across the state.

The Department of Trade and Economic Development (DTED) recognises the critical role of innovation in helping to secure the State's economic future.

Accordingly, we have collaborated with universities, industry groups and business to create the **Centre for Innovation (CFI)** to help businesses cross the innovation bridge. Today, the centre is leading the way in encouraging innovative practices throughout the business sector.

DTED is committed to encouraging breakthrough ideas that lead to new products or services. We also recognise the value of incremental ideas that improve the efficiency of existing processes or revamp and refresh the goods and services our State offers.

DTED and CFI offer programs and services to support all business activities – from small businesses through to billion-dollar projects and major investments.

www.sacentreforinnovation.org.au

The University of Queensland is a leader in research, teaching and technology transfer in a comprehensive range of disciplines. UQ encourages and develops innovative new technologies that will contribute to the future of engineering. The University's Sustainable Minerals Institute and the Faculty of Engineering, Physical Sciences and Architecture have established research activity in a diverse range of areas including social responsibility, safety, risk management, and sustainable water use, to complement long-standing expertise in the engineering aspects of mining and processing. This research is commercialised by JKTech Pty Ltd, which helps to bring new technologies to life. By combining modern infrastructure with a culture that champions research excellence, UQ and its diverse community of scientists and engineers will continue to provide the answers to our most important engineering questions.

Victorian Department of Innovation, Industry & Regional Development
"Innovation and creativity are essential in a global economy where knowledge is the key to competitiveness."

Worldwide, innovation is now recognised as the single most important element in a successful modern economy. The Victorian Government has long supported innovation for this reason. Innovation is not only about technology. Innovation is about people. It is about making sure we use ideas, technology and knowledge to give all Victorians a higher standard of living, more satisfying and rewarding jobs and a better environment in which to live, work and raise their families.

The Victorian Government, through the Department of Innovation, Industry and Regional Development, is delivering an unprecedented boost to innovation. Since it was elected the Bracks/Brumby Government has committed in excess of $2.1 billion through to the end of 2011-12 to initiatives which cover the full spectrum of innovation activities including infrastructure, skills, technology and collaboration.

The Victorian Government is pleased to be supporting the Warren Centre Innovation Lecture 2008 because we recognise that knowledge and innovation is important for building a Victorian economy that is innovative, internationally competitive and globally connected - an economy that can generate new opportunities from the changing world economy for all Victorians.

PROLOGUE

Welcome to The Warren Centre 2008 Innovation Lecture - our thirteenth! The longevity of this event and its increasing popularity speaks volumes for the Centre's focus on Innovation over the years and the need to keep pushing for things that are worth pushing for.

When the Innovation Lecture was first conceived in the mid 1990s 'innovation' was not really an issue, let alone a mainstream activity. Now innovation is rightly recognised as at the centre of Australia's government and business priorities - as the Prime Minister and Senator Carr have noted *"In the twenty-first century, industry policy is innovation policy"*.

Governments want to understand how innovation works and how to make it work better. We applaud Senator Carr and the Cutler review to which, like some 600 others, The Warren Centre made a submission.

We are all eager to see the positive outcomes of this review. The challenge is to harness the enthusiasm for innovation to generate tangible and practical initiatives which will make an impact. The Warren Centre and the Faculty of Engineering at Sydney University are creating the Warren Centre Chair of Engineering Innovation. Former Warren Centre Chairman Peter North AM is leading the fundraising campaign for this important contribution to Engineering Innovation in Australia.

The Chair of Engineering Innovation will focus on how the established corporate enterprise can come to understand the commercial potential of new engineering and scientific technology, and how this potential can be captured and exploited to create and stimulate profitable and sustainable corporate growth.

This brings us nicely to Tristram Carfrae, this year's Innovation Lecturer, who has demonstrated an ability to extract commercial value from new ideas and create new engineering technology. Collaborating with multiple international partners and working with teams from across the ARUP world, Tristram has delivered an exciting range of structures that literally ooze innovation!

Tristram clearly meets our definition of an Innovation Hero as someone who has been intimately involved with the entire process, linking invention with significant commercial success. We salute all our Innovation Heroes: Dean Cameron with his Biolytix waste management technology, John Russell with novel mineral processing equipment and Alf & Nadia Taylor who have built a highly innovative packaging machinery company.

Finally I would like to thank all the sponsors of this year's Lecture. Without them, and the companies that sponsor all The Warren Centre's other activities, we would not be able to bring you this event highlighting these wonderful role models for innovation.

Professor Michael Dureau
Chairman & Executive Director
The Warren Centre for Advanced Engineering

THE Warren CENTRE
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CONTEXT FOR INNOVATION

I will not start this paper with a definition of innovation. I tend to be a pragmatist rather than an academic and will assume that its meaning is generally known and that my particular meaning will be apparent from the paper.

Industry

I have spent my life as a consulting structural engineer in the building industry and this paper is necessarily written from this perspective. When I refer to engineer or industry it is likely that I mean consulting, structural or design engineer and the building, property or construction industry.

Innovation is a difficult concept in the world of building design. There are many people from different organisations involved in the design process: from clients and developers; through project managers, architects and engineers; to builders and subcontractors. Each party has a different view of the risks and benefits of innovation and most are risk averse. The Warren Centre is currently undertaking a project in this area called "Professional Performance, Innovation and Risk". Step change or breakthrough innovation is rare; more common is continuous improvement using more modest innovations as their feedstock.

Within my own profession of structural engineering, radical innovation is perhaps even less common as we continue to use steel, concrete, timber and masonry as our basic building materials and the applied loads from gravity, wind, snow and building occupation have not changed. Our factors of safety are not so much calculated from any theory but more tuned to historical results and performance. It is quite difficult to propose radical ideas in the context of safety standards that are largely empirical.

It is often said that to encourage innovation and creativity, you must be prepared to tolerate failure. But society, quite rightly, does not tolerate failure in the building industry. The consequences of failure are too large and, according to most, building performance should be readily determined. Very few realise how little engineering is absolutely predictive and how much is based on judgement. The results of engineering analysis depend more on what we have chosen to analyse and how we have chosen to perform the analysis than the analysis itself. And these choices are made using the judgement born of experience.

Increasingly, the Australian economy is based on service industries and if Lord Nuffield is correct in supposing that "innovation is the capital of a knowledge economy", then we must encourage innovation even in the property industry. However it is also interesting to note that as a service industry, consulting engineers are meant to do "what their client wants" and it is rare to find a client who wants to do something different.

Individual

I was told recently, that for an individual to innovate they have to:

- want to
- have an independent spirit, and
- believe in themselves.

This latter is a paramount quality for an engineer. For all the reasons set out previously, engineers tend to be conservative. They correctly worry about getting it wrong; about coming too close to the edge of the cliff beyond which is nothing but failure and disgrace. It is rare for an individual engineer to have sufficient self confidence to wish to approach that edge; to find out just how close they can get, even if they cannot see the edge clearly. I therefore suspect that innovation by engineers is often driven by ego.

I read an interesting book by Ben Rich who helped found Lockheed Martin's skunkworks. In this book, Rich proposed that in their first decade, the engineer learns his craft and becomes skilled in his own trade. Based on this skill, in their second decade, they may become sufficiently confident that they are able to innovate within their own area; in Ben's case airframe hydraulics. In the third decade their ambitions become wider and they want to create better airframes; they dabble in surrounding technological areas. And in their final decade, they simply want to solve all the problems of the world. Unfortunately I can relate to this! But I can also become concerned about the decreasing number of good engineers who actually spend four decades practising their trade and do not become managers, leaders or captains of industry.

Organisation

While the three requirements for innovation appear to be properties of the individual, there is much that an organisation can do to encourage them. If I take my own organisation, Arup, as an example, the most obvious aspect is that our founder Ove Arup created the firm specifically to do things differently; a firm of engineers that was collaborative and proactive rather than reactive and independent as were his competitors. He was in part stimulated by the adoption of a new material, concrete, in the construction industry.

Ove studied philosophy before engineering and was brought up with a Scandinavian view of society. In the late sixties and early seventies he set down how he thought his twenty year old organisation should behave. He started from the premise that it ought to be possible to enjoy the act of working itself, as well as working in order to earn some money. Starting from this premise he suggested a set of "core values" that the members of the firm should adopt:

Our aims
- quality of work
- holistic approach - total architecture
- humane organisation
- straight and honourable dealings
- social usefulness
- reasonable prosperity

The means required to achieve these aims
- a membership of quality
- efficient organisation
- solvency
- unity and enthusiasm

The results of pursuing these aims
- satisfied members
- satisfied clients
- good reputation and influence.

Ove never claimed that these were a "perfect" set of values, but simply that they are a reasonable set and that their pursuit should result in the primary objective of "satisfied members". A few years later Ove Arup donated his firm to his staff so that we could maintain these aims without external influence. We have no owners, no shareholders and no creditors.

As a "self owned cooperative" we have grown our own culture: a flat organisational structure; a tendency towards chaos as opposed to order in our operational style; a belief that fairness is more important than financial success; that we grow organically at whatever rate naturally occurs; and that individual members have to look after themselves.

If Arup was based on a single formula it would be to "get good people and let them do what they want". The best people do not want to be managed in every facet of their job; they need to be well supported, see role models all around them and have a clearly articulated vision in which to subscribe. Yet the Arup vision is simply to continue to pursue our core values.

For three years I was the Chair of the Arup Design and Technical Executive. This arm of the Arup Group Board is responsible for the administration of foresight, research and knowledge management and also for fostering the best environment for design, creativity and innovation within the firm. After a full day of brainstorming this latter issue we concluded that the issues are wide ranging:

- recording our stories, histories and legends
- providing a variety of stimulating working environments with lots of break-out space and communal areas
- keeping senior leaders working
- leading by example
- having an environment of openness and trust.

It is very difficult to construct the successful formula that will encourage innovation within an organisation. Even with the evidence of Arup before me, I find it hard to determine which aspects of the organisational behaviour help and which hinder.

MY OWN CAREER

My mother was an architect designing barn conversions and house extensions in rural Devon. But she had studied at the Architectural Association in London and continued to read the leading architectural journals. Perhaps influenced by what I saw in these magazines, I remember suggesting at about age 16, that I might want to be an architect. Her response was instantaneous: "oh no my dear, your artistic talent is not very strong, why not become an engineer instead?" She even went so far as to suggest that I join a firm like Arup that so obviously cared about architecture.

I followed her advice and was fortunate to study engineering, or more properly "the mechanical sciences tripos", at Cambridge University. In a survey of British University students it was found that all students were less able to "think" upon graduation than when they had been at school. The only exception to this was graduates of Oxbridge but even their ability to think had not increased but simply remained constant through their time at university. A Cambridge education did not bother itself with making students "industry ready", in fact I graduated blissfully unaware that codes of practice actually existed. Instead you were deeply immersed in all branches of applied mathematics and given glimpses into the latest research projects being carried out by the Fellows; many of whom were of course world leaders in their field.

When I joined Arup in 1981, I was again fortunate in joining the lightweight structures laboratory, which worked in an area of structural engineering with neither codes of practice nor established ways of doing things. I wondered why I had been selected from that year's 100 or so recruits and found out later that I was supposed to "know a lot about steelwork design". Actually I had simply explained, on arriving at Arup, that I knew nothing whatsoever about the design of concrete structures.

At the time, the design of tensile or fabric structures was being revolutionised by the new age of computers. Prior to this it had been based on physical soap film and stocking models, painstakingly photographed and measure to determine the appropriate physical geometry. But in the late seventies my boss Alistair Day had invented a computer technique called dynamic relaxation, which allowed the complex mathematics to be solved by treating the continuous surface as a set of discrete points that were allowed to move around until they reach equilibrium.

In my early years I helped Alistair develop his program and added the ability to visualise the output. I wrote our first 3D graphics programs in 1981 because I realised the need to communicate. It really didn't matter how clever or accurate the digital "form finding" process was if all we had to show our clients and architects was a table full of numbers.

Later I was to work for several years with an eminent Irish engineer, Peter Rice, who famously persuaded his clients that it was "safer to innovate"; that repeating the same thing gave rise to complacency and sloppiness; while innovation required everything to be painstakingly considered and therefore reduced risk. This was perhaps said tongue-in-cheek but actually it contains a grain of truth; studying things afresh and in depth does reduce risk.

More recently I was appointed as an Arup Fellow; a position that we have created, right at the top of the firm, to indicate to our younger engineers that, despite Arup being a large organisation, they can pursue a rewarding career in engineering without the need to become a manager and losing direct involvement with design.

PROJECTS

The following projects help to illustrate the many potential reasons for innovation. For each one, I will attempt to identify why we innovated and particularly the specific working or project environment that caused it to happen

Exhibition Halls at Royal Agricultural Showground, Homebush Bay

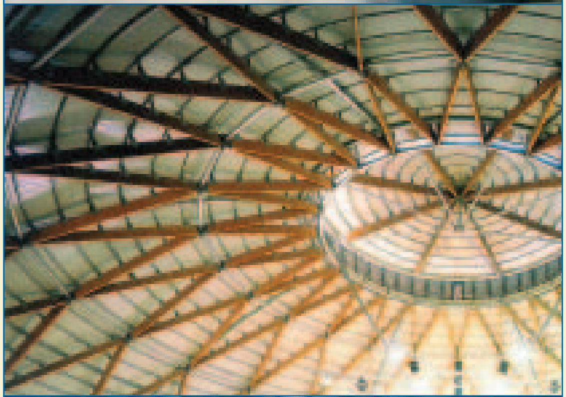
A traditional project manager's view is that a design can be represented by three mutually dependent variables: quality, time and money; and that to improve one of these, you must pay using one of the others. For example, we can improve quality by either increasing time or cost. In this case, it is very difficult to assess the value of the proposition. Has quality improved more or less than the cost increase? However, innovative design may be able to reduce cost while simultaneously improving quality. Indeed, within the Australian construction industry, the only valuable innovation is one that improves quality, reduces cost and reduces time.

In the late nineties we were commissioned, together with architects Ancher Mortlock and Woolley (AMW), to design the main exhibition halls for the new Royal Agricultural Showgrounds at Homebush Bay. The halls were to be temporarily used for the secondary indoor events at the Sydney Olympics 2000 and had to be designed and constructed in no more than 18 months. AMW proposed a series of rectangular halls culminating in a circular "grand hall" at one end. We decided that the most appropriate structural system for supporting the roofs was a series of lattice shells; a spherical one for the grand hall and a row of cylindrical barrel vaults over the rectilinear halls.

As an aside, it is interesting to observe the fashions in structural design. Despite the fact that the materials used, and the loads to be resisted, have not changed over the last fifty years, we have seen concrete shells dominate in the fifties, space frames become vogue in the seventies, cable stayed roofs in the eighties and steel lattice shells in the nineties.

For the RAS Halls, we were determined to explore the possibility of using timber instead of the usual steel for the main elements. A lattice shell, particularly one using single curvature as proposed for the rectilinear halls, has a propensity to buckle when in compression and requires a certain degree of out-of-plane bending stiffness to control this phenomenon. The members of a steel lattice shell, sized for their compression capacity, would not have sufficient natural bending stiffness whereas timber members with their naturally greater depth would. And more poetically, we thought it was "right" for the halls at the agricultural showgrounds to be made of timber.

To mitigate the construction risks, we designed the timber elements to terminate in a factory fitted steel shoe at each



end so that on-site erection consisted only of the interconnection of steel components by steel industry riggers. The comprehensive specification of these deep glue-laminated members was a new area for us in Australia and required considerable research and development but appeared a small price for us to pay for the "right" solution.

At every step of the way from conception, through design development, and on to documentation and construction we were assaulted by voices telling us why we couldn't or shouldn't take this approach. In the early days, the reasons given were simply that it hadn't been done before. And when we referred to similar projects around the world, this changed to "it hasn't been done before in Australia". When we cleared this hurdle, mainly through simple force of persuasion, the next hurdle was erected: "It won't be cost competitive". Our Quantity Surveyor measured the design was within budget but again this was insufficient. So, at our own cost, we developed a comparable steel design so that competitive tenders could be sought for both schemes in parallel. Meanwhile, we were also told by our client's multiple advisors that we couldn't meet the programme and or make it buildable.

The voices were all simply saying that if it was innovative, it hadn't been done before, and therefore was inherently risky. No-one (other than us) was really interested in the increased quality and value of the end product. Yet simple persistence eventually won the day. The tender prices showed timber to be cost effective and as we patiently answered every question the voices slowly died away.

There is another aspect of the engineering design of the RAS Halls that is worthy of noting in the context of innovation. The spherical timber lattice shell atop the "grand" hall is a very stable structure. The double curvature tends to prevent buckling and therefore the 900 deep gluelam beams are more than adequate for this 97m span and 45m high dome. Whereas the 900 deep gluelam beams are struggling to control the primary mode of buckling of the cylindrical shells over the rectangular halls that span a mere 70m, and we had to go to incredibly sophisticated levels of analysis to justify them. So the rectangular hall roofs probably took ten times more engineering effort than the dome, yet the dome is by far superior as a structure to experience. There appears to be no discernible relationship between effort and outcome.

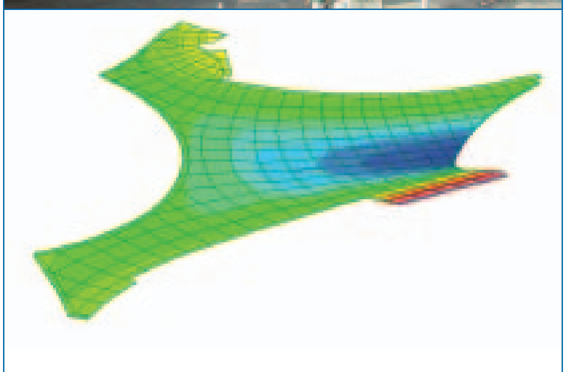
Piazza Canopy at Aurora Place, Sydney

There are three distinct innovations on this project that are worth discussing:

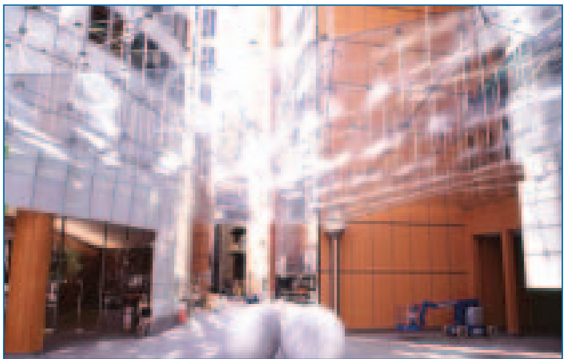
- separation of the glass plane from the structure
- rod to rod connection detail
- drainage system.

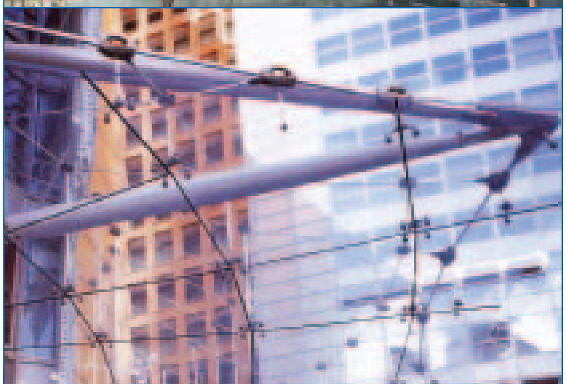
Each of these innovations came about in different ways and for different reasons. One was a simple decision; the second was born out of necessity; but the third was generated by simple persistence in requiring us to look for a better solution.

The Aurora Place project comprises two buildings: a forty storey office tower to the west and a fifteen storey apartment building to the east. Both these building had curved facades facing each other across a south facing piazza and there was no relationship between the geometrical set out of the two facades on plan. During wind tunnel testing, after the scheme design of both buildings was finalised, we discovered that the prevailing north easterly sea breeze would tumble down the east



face of the office tower and make the shady piazza uncomfortable for most of the year. So it was decided to cover it with a canopy to intercept the wind before it reached the people. As both buildings were already designed with an open space between them, the architect, Renzo Piano, was very keen for the canopy to be minimalist; ideally for it not to exist at all. He described the only acceptable canopy as a spider's web floating between the two buildings.



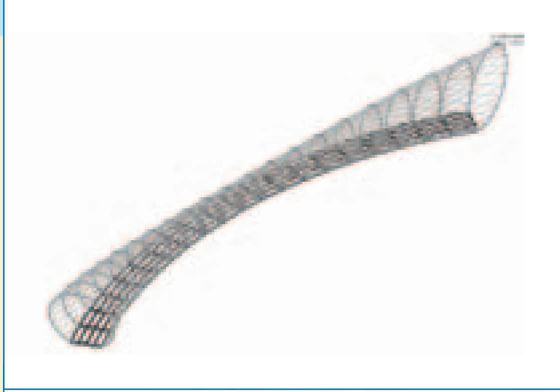


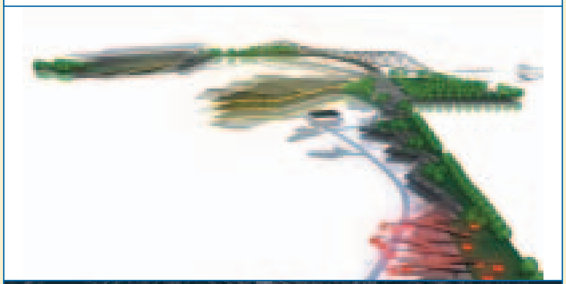
The lightest structural solution was obviously a doubly curved cable net spanning between the two buildings and the best cladding option was glazing. To provide the best protection for the people it would be better to have the glazing lower rather than higher. It was a quick and simple decision to divorce the "flat" glazing from the curved structure. But actually this is a very innovative decision to take; cladding is almost invariably attached directly to structure, most usually in the form of walls and roof. Yet we took this decision in the blink of an eye without really considering whether it was innovative or not, probably because we didn't need to refer it to any third party.

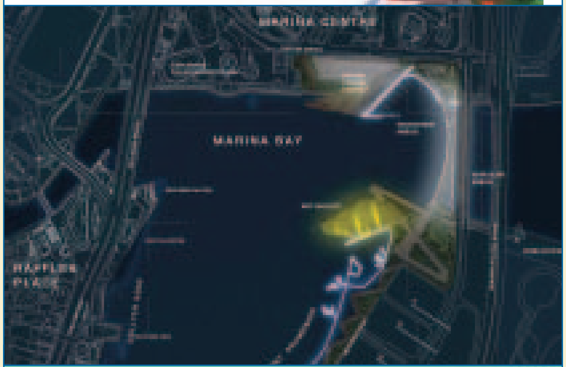
The scheme that was developed and sent to tender was based on cables that crossed over at nodes spaced at approximately 2000 centres. At each node the relatively flexible cable was to be diverted by a small casting and directed towards the next node. This was a system that we had used previously at Star City and was tried and tested. But the cheapest tenderer proposed to use rods in lieu of cables. Each rod has to be terminated at each node and the usual forked end fittings were 500 or so long. When combined with a fabricated node and some sort of turnbuckle adjustment, the entire 2000 gap between nodes was entirely consumed without any rod at all - hardly a spider's web. It took two months of stalemate; a complete inability to conceive of a solution; before the solution appeared in an instant without apparent cause.

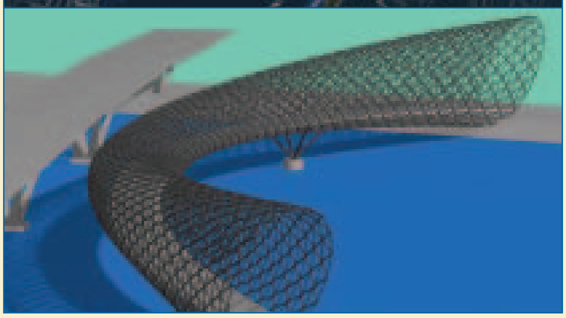
The constructed detail is based on a series of concentric spherical surfaces that minimise the physical size of the connection yet allows the single repetitive detail to accommodate all the different geometrical conditions that arise.

The simplest way to drain this "flat" plane of glass was to put a ridge along the centre with a minimal fall to each side and a gutter along each edge. However, Renzo did not find this acceptable; a solid perimeter gutter would not create the illusion of a floating spider's web but one that was well and truly anchored to each building. For several months we proposed alternative variations of this theme, only to be met each time with a "not good enough - must try harder" type of response. We weren't offered any alternative solutions, just a simple "no". After nearly six months we eventually came round to the solution that we built. We discovered that, by slightly twisting each pane of laminated glass on installation, we could create a surface that had a minimal 2.5% fall everywhere, away from the buildings and the southern edge and towards the north. In effect we made the entire canopy into a gutter. This had to be very carefully calculated as insufficient fall would cause ponding and water scum marks whereas excessive twist would generate shear stresses that would invalidate the warranty on the laminated glass. This subtle solution would not have been thought of had Renzo Piano been less stubborn. How did he know that a better solution was available?









Marina Bay Bridge, Singapore

The innovative structure of this bridge was a long time coming; probably two years elapsed between our first thoughts being set down on paper and the final solution. Sometime innovation occurs at the end of a long and tortuous journey of exploration as we change direction in response to the new knowledge we gain along the way.

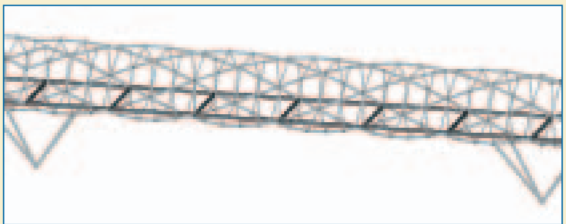
In answer to an early ideas competition for the promenade around the newly created Marina Bay, the Cox and Arup design team identified some key conditions for the design of the pedestrian bridge that would span across the mouth of the bay. We wanted a bridge that was curved on plan to encourage pedestrians to walk around the bay and signify that it was not simply a crossing point on the river. We wanted the bridge super structure to participate in the experience of crossing the bridge, not to vanish underneath the deck as soon as you set foot on the bridge. Our initial suggestion was to use a series of hoops supporting a cable net; much like a Wild West wagon.

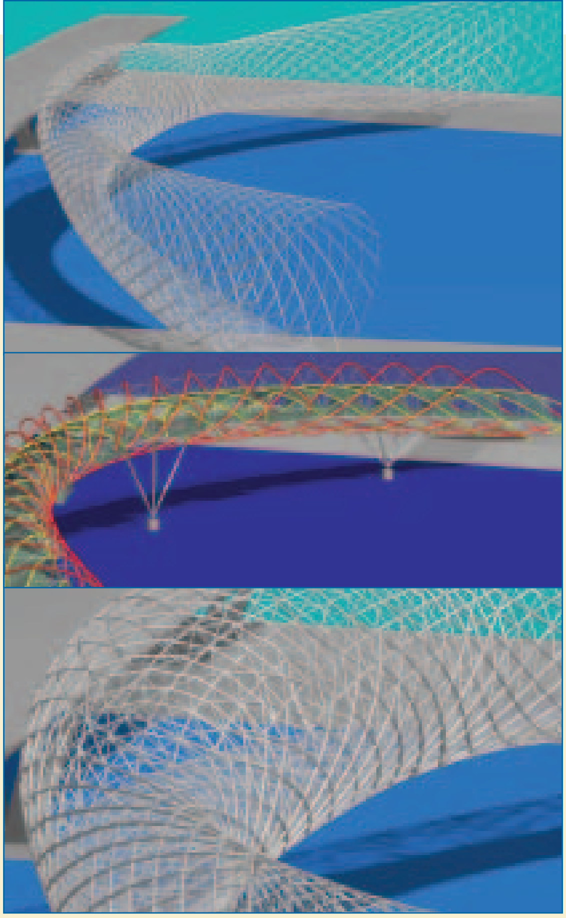
When we were appointed, based on our ideas, we quickly realised that such a structure does not readily curve on plan; the tensions in the cables want to straighten it out.

So we moved to a trussed tube consisting entirely of compression members. In doing so we entered a realm of cause and effect that is hard to resolve successfully. We wanted a bridge of delicacy; people should pass through a filigree structure that would not detract from the view beyond. But as we made the tube diameter greater in order to reduce the members' sizes, the tube had an increasing propensity to buckle that could only be controlled by making the member sizes larger again.

Our initial solution was to add a second layer of tension members within the compression tube that would stabilise the tube and allow us to use thin compression elements. We also added areas where the overall tube would get fatter and thinner in the hope that it would allude to traditional Malaysian fish traps and tell an interesting story. But when this scheme was presented to our client, the Urban Regeneration Authority, the response from Mrs Koh was "Professor Cox, Professor Carfrae, why would Singaporeans want a bridge that looked like a Malaysian fish trap? And even if they did, why would they want to be caught in it?" Which was actually a very good point; we had created a cage or prison for the people crossing our bridge.

On taking a step back and re-examining where we were, we realised that the key attribute of the bridge that we liked, was that certain members spiralled their way around the tube. Unfortunately, a single spiral does not constitute a structure and when we add an equal, opposing spiral, we end up with a triangulated lattice tube. I cannot tell you when or how or why, but one day it dawned on me that we may be able to create a structure using two opposing helices that were placed on different surfaces. One could lie on the outside compression tube surface and one on the inside surface where the tension elements were located. If they were properly interconnected, they would act as a single triangulated lattice tube but with the added bonus that lying on different surfaces, each would prevent the other from buckling out of (curved) plane. Better still, our new story was based on the famous double helix of DNA and Mrs Koh far preferred the "bridge of life" to the "Malaysian fish trap".





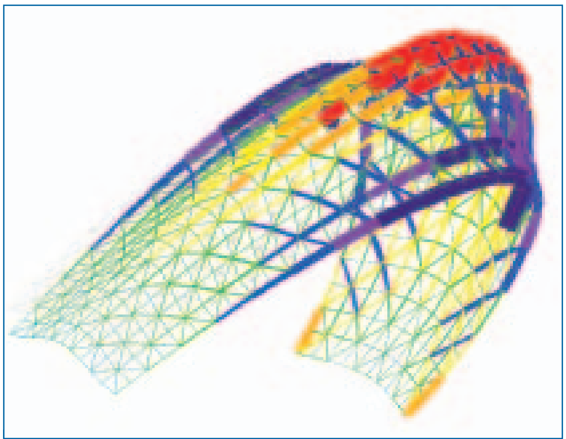
Would this idea have occurred to me had we not already have been exploring double surface tubes as way of providing delicacy without suffering from buckling? I doubt it.

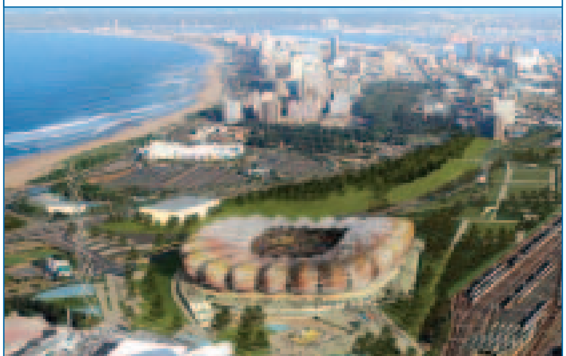
As an aside, I am not actually capable of determining whether such an idea is structurally feasible; just how, and even if, you can interconnect two independent spirals successfully. At these times of uncertainty I turn to the same computer program that I helped develop with Alistair Day in 1981 to simply experiment; each attempt to find a structure that fails teaches you something and indicates what you should try next. So I no longer try to resolve issues in my head, nor even on a napkin after a good dinner, but instead use technology as my sounding board.

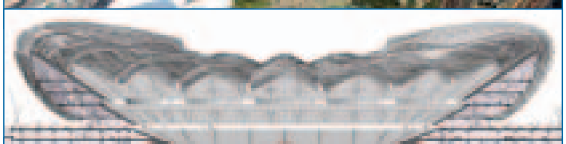
A proposed stadium for the 2010 Soccer World Cup in Durban

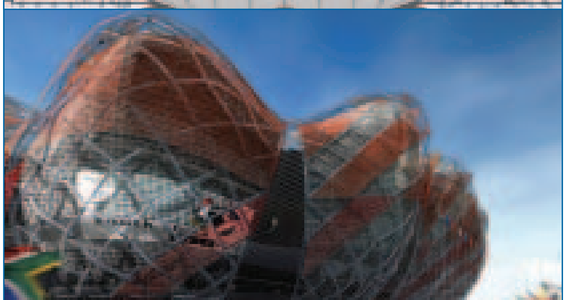
In recent times, Herzog De Meuron and Arup have changed the face of stadium design, first with the Allianz Arena in Munich and more recently with the Beijing Olympic Stadium. For both of these projects the structure is less important than the surface or cladding. The structure is eminently suitable for its purpose, but is hidden within elegant, even haute couture, cladding. Measuring 7m deep in Munich and a mighty 14m deep in Beijing, the roof structure is concealed between layers of clothing both inside and out.

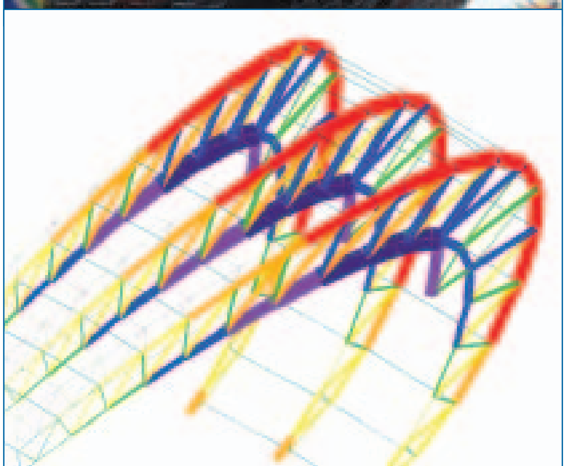
For Durban, I was convinced that an architectural and engineering team that would collaborate as equals could devise a surface that was both beautiful and structural; that could accomplish the task without needing concealment behind cladding; that would be gorgeous in its own right. In devising a major (70m) cantilever using only shape, there has to exist a high degree of sympathy and trust between the two major proponents. The architect has to trust the engineer to appreciate beauty and the engineer, to trust the architect to believe them when they say what can and can't be achieved. Similarly, the engineer has to try as hard as they can to provide a form that the architect wants and the architect, to adapt their vision to lie within the bounds of the possible. This is harder than it sounds but in this case, collaborating with Philip Cox with whom I have worked for twenty years, we came up with the goods only to lose the competition.

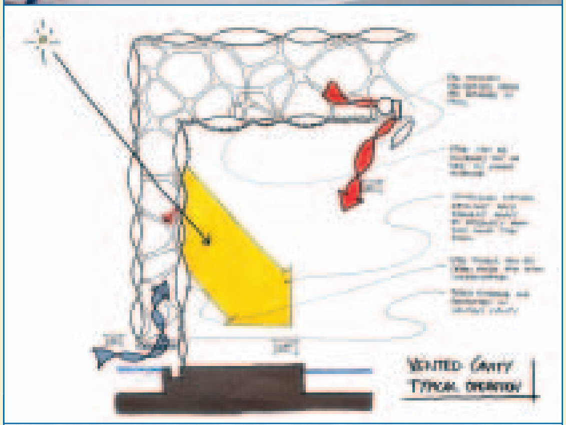


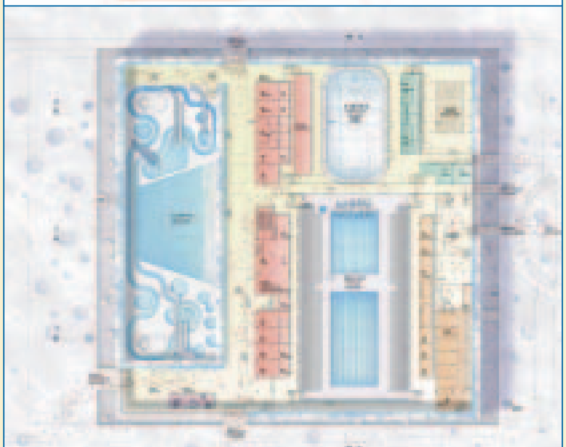


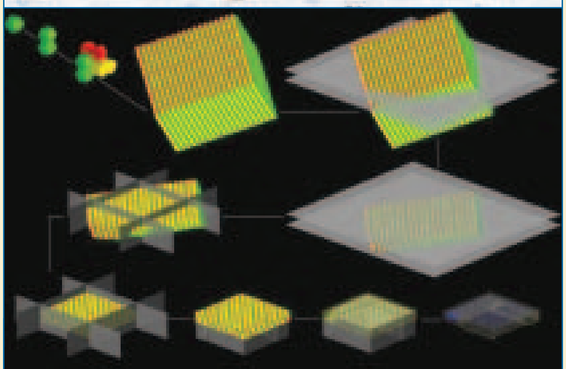


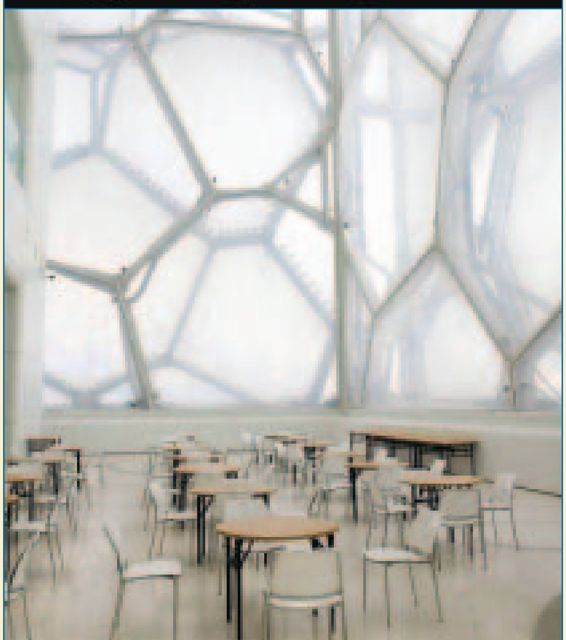












The Water Cube, Beijing

The design of the Beijing National Aquatics Centre is a remarkable feat not only because of what has been built but because it was created by an innovative team. There were at least twenty people sitting around the table, contributing their ideas and determining the design direction when the key decisions were made. My previous examples of innovation rely heavily on one individual, albeit using input, and relying on feedback, from others. But for the Water Cube, no individual can claim to be the main author of the work. The ideas that coalesced into a single solution came from many participants.

Having embarked on a ten week design competition, we started the process by asking each different discipline or skill (about a dozen people) to articulate what a perfect swimming centre would look like from their point of view. For instance, the mechanical engineer wanted an insulated greenhouse that would trap as much solar energy as possible to help heat the swimming pools. The acoustician wanted a “transparent” envelope to reduce the reflection of sound within an inherently noisy environment. The architectural planning team wanted a square footprint to efficiently operate the centre both during and, more importantly, after the Olympics. The architectural designers wanted a building that had a visual connection with some aspect of water. The urban designers wanted to address the Bird’s Nest stadium on the other side of the main Olympic Boulevard. The lighting people wanted to maximise natural light with its uplifting quality but without creating glare from the surface of the water. And the structural engineers wanted to have a lightweight steel structure (to reduce earthquake loads) isolated from the internal pool hall environment with its corrosive humidity, laden with hydrochloric acid from the pool disinfectant. Meanwhile our client wanted a building that would embody their ambition for the “green games, high tech games and people’s games”.

After four weeks these independent ambitions were still just that, independent ambitions. But one day at a regular meeting we decided to design:

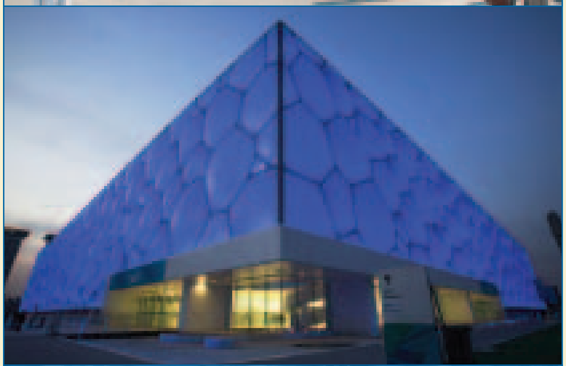
- a blue box greenhouse that would complement the round red stadium across the street, accommodate the best pool arrangement and heat itself
- a building clad with ETFE to give the best acoustic, lots of natural light and minimal weight.
- two layers of ETFE pillows to provide the insulation for the greenhouse and to create a cavity in which to shelter the structure.

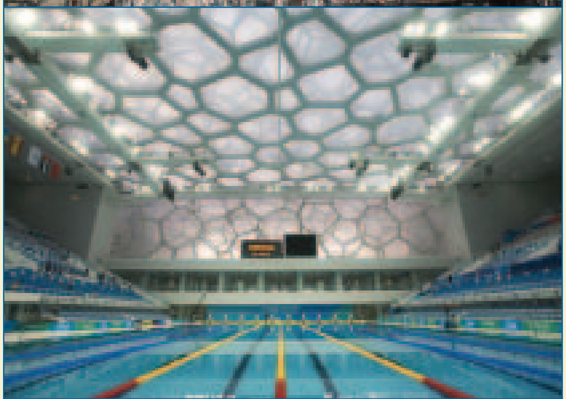
Suddenly all our ambitions had come together to form a single coherent response. The only outstanding matters were how to link the design to some aspect of water and what pattern would be best for the ETFE pillows?

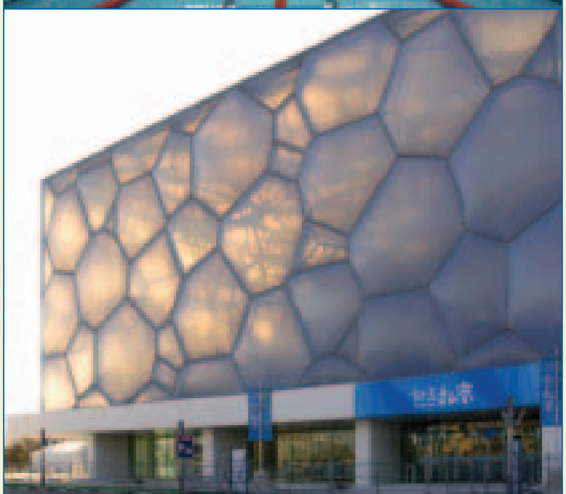
For some reason, once we had decided to put the structure in a cavity, I became interested in how structure might or should inhabit space. This is not a common question in building design as we are usually using structure to create space for people to inhabit, but the idea of a space (the cavity) whose only occupant was to be structure set me thinking: what is the optimal way that structure should occupy space?

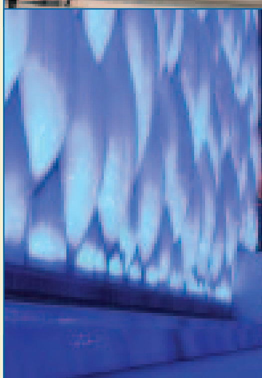
Fortunately even slightly abstruse questions such as this can readily be researched using the internet and after a few days I learned that my quest was related to a classical mathematical problem first posed by Lord Kelvin in the 1890s. He asked "what is the most efficient way of subdividing space into equal volumes using minimal partitioning area?" His own solution to this conundrum was the best available for a hundred years until Professor Weaire and Dr Phelan of Trinity College, Dublin published "Weaire-Phelan foam" in 1993. I borrowed this geometry and found that it could be used to make an intriguing structure that was good at absorbing earthquake energy (the dominant force in Beijing) and produced a wonderful yet repetitive pattern for the ETFE pillows.

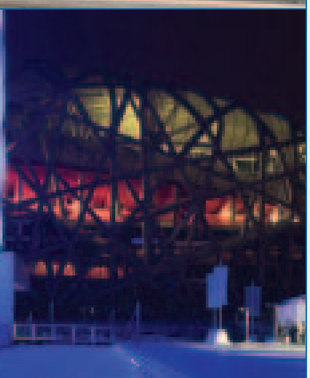
Through some piece of serendipity, Weaire Phelan foam is also the geometry of a perfect array of soap bubbles so we had now achieved everyone's ambition and designed a building full of water that was carved from a block of perfect bubbles and clad in ETFE pillows that look like bubbles.

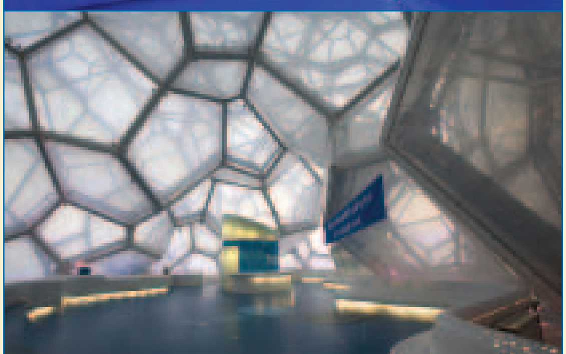












THE FUTURE

In the nineties, engineering became commoditised through the ready availability of good analysis software. I sense, however, that we are now bouncing back. More sophisticated software that connects three-dimensional geometry, not only to simple analysis, but also to: construction drawings; quantities take-off; construction programming; minimisation and optimisation techniques; parametric modelling; instant communication and visualisation of outcomes; sustainability assessment, facilities management, and direct manufacture of the building itself, will make innovative, collaborative, design focussed engineers as desirable as the architects with whom they often work.

Engineers will enter a three (or more) dimensional digital world at the start of a project. They will explore, using parametric CAD programs, potential building forms and solutions with no clear idea as to their suitability in terms of strength, stiffness, stability, material consumption or other performance requirement. But suitable software “agents” will be tracking these parameters in real-time and reporting the consequences of every exploratory change. The resulting model will contain all the relevant information for costing, performance, ordering, construction, operations, and ultimately demolition and recycling. The model will gradually accumulate all information required for the building’s use, re-use and eventual demise and will be updated continually.

In a time when we consume more than the planet can provide, we need to design buildings that are much more efficient at all stages from construction through adaptation and reconfiguration to demolition and recycling. Building Information Modelling and allied techniques will help us do this.

The future engineer must become comfortable working in this environment with many, often conflicting, reports and results flowing from vast amounts of data. They must be able to synthesise these data streams, make sensible decisions and convey their reasoning to clients and collaborators (who may also inhabit the same virtual digital world).

During this potential renaissance of the profession we will need slightly different engineers. Tomorrow’s designers and engineers will need to be innovative and apply creative and analytical thinking to a range of data which, while not necessarily right or wrong, will have the potential to significantly impact on the aesthetic, the functional and the resource consumption aspects of each project.

Innovation will become much more commonplace when the software “agents” assess the risks and the engineers use their judgement in deciding which avenue to explore. Such a process will not judge innovation as risky per se; it will instead compare the risks of different options regardless of whether or not they are innovative.

Disclaimer

The ideas and assertions put forward in this handbook are from the presentation of the 2008 Warren Centre Innovation Lecture, a Warren Centre event held at:

• the PricewaterhouseCoopers building in Brisbane on 3 June 2008

• the Powerhouse Museum in Sydney on 5 June 2008

• the PricewaterhouseCoopers building in Melbourne on 10 June 2008 and

• the National Wine Centre in Adelaide on 11 June 2008.

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It has three principal objectives:

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