Lightweight Structures
– Where We Have Come from and Some Current Issues

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Introduction

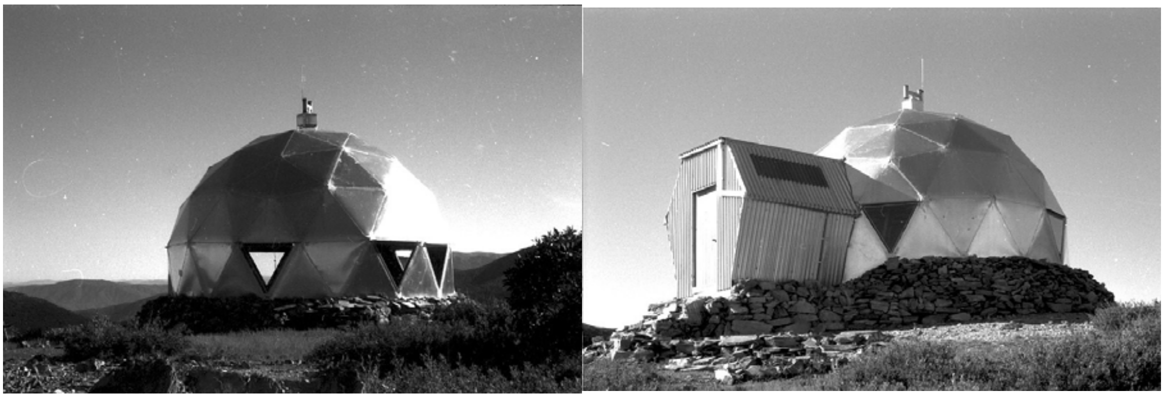
This paper is a recollection of personal and industry developments for lightweight structures over the past forty years. During this time, some great technology advances have occurred whilst other issues have essentially remained ”on the table” and require further debate.

My early ambition was to be a hybrid architect / engineer after the great Italian Pier Luigi Nervi who designed and built many large span roof structures in which the pure structural form was exposed. Many of his structures were constructed in concrete. To this day, I have not designed a lightweight concrete shell so I have fallen short of my original goals. Nervi carried out optimization processes to minimize the use of material, or to maximize the benefits of having an appropriate three dimensional shape.

Spaceframe Structures

Mt Feathertop Dome

Aluminium was my first lightweight material and a small 6.5m diameter geodesic dome my first project completed in 1966 on Mt Feathertop in Victoria. It is both a memorial hut for the Melbourne University Mountaineering Club (MUMC) and a refuge hut for hikers and winter expeditions. It just survived the devastating 2002/03 bushfires. The upper sleeping floor is suspended from the geodesic dome and the log book has recorded over 30 occupants on a number of occasions.



All materials including red gum posts, timber flooring, cement and sand were carried in by hand from as far away as Mt Hotham or up the 1250m climb from the Ovens Valley along the new track constructed by the MUMC. The final dome diameter was determined by the width of the flat sheets (0.6mm thick) of aluminium cut into triangles to form the skin. These were designed to act as a membrane between the recticulated aluminium RHS. All frame members were cut to length by students of the MUMC. The custom designed joints were also cut and drilled by the students from aluminium sheets. The dome was assembled joint by joint using a theodolite positioned at the centre of the sphere to give the correct angular location – the radius being measured with a tape. All calculations were done using a slide rule and there were no engineering drawings other that sketches of the various components.

There were fire requirements to be met – as prescribed by the National Parks authority – with several of the lower windows offering an alternate escape route and tomahawks placed on the upper level to hack through the top sky light if necessary.

Today the hut remains in excellent condition but shows the effects of the bushfires which burnt to within 0.5m of the surface. The hut was saved by helicopters dumping fire retardant on the roof.

Exhibition Building Sao Paulo

The next aluminium structure in 1968–69 was a bit bigger – in fact the largest Aluminium structure in the world. It is the exhibition building in Sao Paulo and measures 260 x 260 metres. It is a double layered two way spaceframe using tubes approximately 3.33m long. The ends of the tubes were flattened and bolted to a cruciform welded steel plate joint. The complete roof was assembled at ground level and lifted in one operation. Umbrella type supports were used (a simple ”tree”) at 60m spacing for the inner spans and 53.3m outer spans. These umbrella supports sat atop bipeds which were orientated perpendicular to a radius from the central fixed point. Thus, the considerable thermal expansion could take place without restraint but the plurality of differently orientated bipeds would combine to resist horizontal wind loads from any direction.

In terms of the technology of the day, the analysis of the roof with some 48,000 tubes and over 12000 joints was a challenge. The existing method for analysis of flat spaceframe roofs was to replace the frame with an equivalent plate and to use plate or shell theory – generally in the form of published coefficients for shear forces and bending moments. Timoshenko had written the classical works in these areas. However, when unusual support locations and boundary shapes were present, there were no accurate solutions.

The ”matrix theory” for structural analysis of frames was known and some software programs such as SAP (Berkeley) and STRUDL (MIT) were starting to appear. These appeared to be the way forward as the actual frame and support conditions could be accurately modelled. Conceptually, the theory was easy – a set of equations P=KD would be formed in which D was a vector representing all the unknown joint displacements, P the applied load components on those joints and K the stiffness matrix describing the structure elastic properties.

Personal computers were still some time off and the number of computers available was very limited. Computer memory consisted of tiny iron rings with electrical wires passing through – a current would produce a magnetic field in the rings which was interpreted as a 0 or 1 – a ”bit” of information. Eight of these rings would be combined into ”bytes” and then four of these ”bytes” into a ”word” which was sufficient to represent a single precision real number. At the time of this structure, the largest computer available (the 2nd largest in Canada) shown below had a total memory of 4Mb of which at most only 1Mb was available by special arrangement and normally only 256Kb was allocated. This 256Kb had to include the machine language version of the program as well as any data that was needed. For the roof, the stiffness matrix K could have some 1,400Mb worth of (single precision) numbers to store. Virtual memory was not around either and the scientific programming language was Fortran (which is still used today). All input was done using punched cards (these had displaced punched paper tapes in the early 1960s). Dumb terminals didn’t appear until the late 1970s.

How was this structure solved? By careful use of symmetry of the structure, several representative sections of the total roof were analysed. A small Fortran program was developed for the project and most of this development went into refining the methods for solving large sets of banded simultaneous equations. Several bugs were found in the Fortran compilers and computer operating system during this project. Subroutines were written to generate the data but the listed member forces were processed manually and new tube sized determined. The revised structure was reanalysed. Some months afterwards, the members were selected by the purpose written software – one of the first applications of ”computer aided design” as we know it today.

Victorian Arts Centre Spire

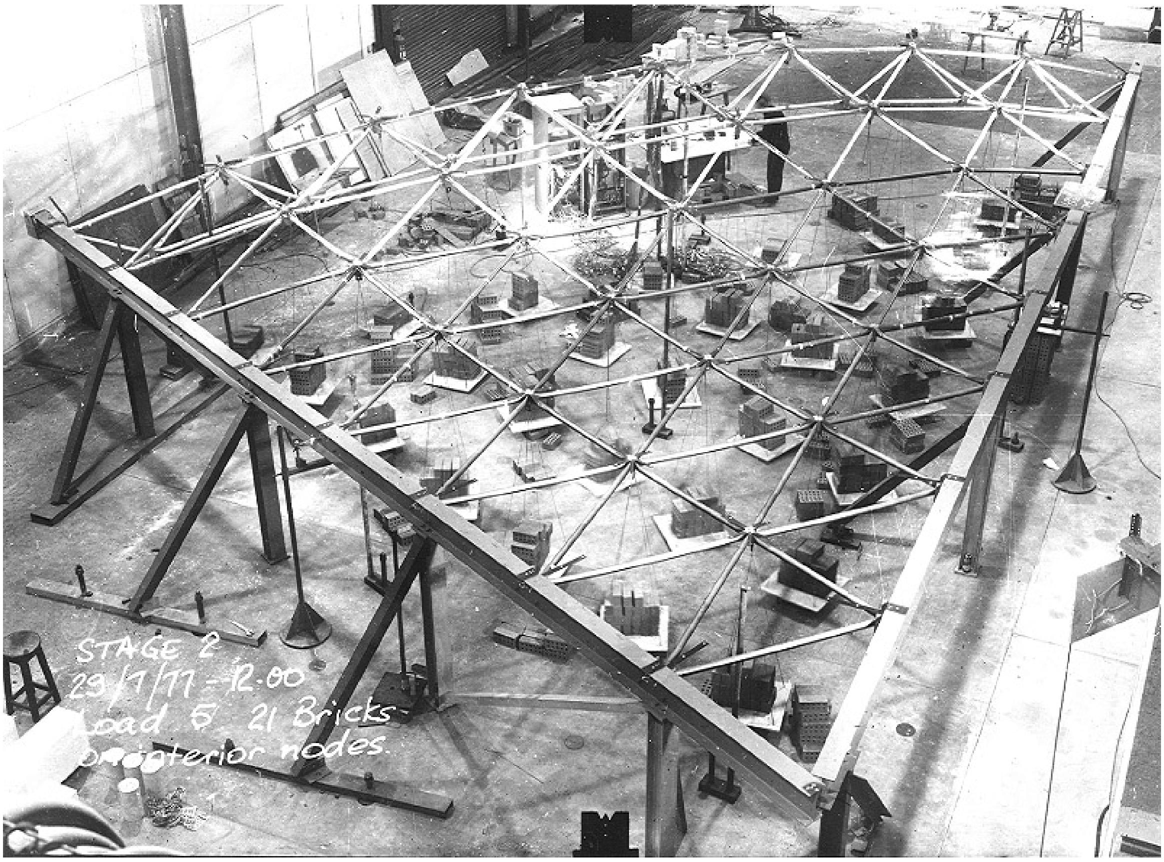
The next major Aluminium (in part) structure designed was the spire for the Victorian Arts Centre in the mid 1970s for Sir Roy Grounds and John Connell & Associates. The lower ”skirt” comprises four complete hypars and eight truncated hypars subdivided into 16 parts with diagonal members in the shortest direction. The Triodetic system was used for the lower shells which involved extruded slotted hubs as joints into which coined tubes were inserted. This coining process meant that each member had virtually no bending strength about one axis but full strength about the other. Each joint was orientated normally to the surface of the hypar which meant that there was a ”twist” angle associated with each member. Since this would impact on the distribution of forces, it was necessary to describe each member more accurately than simply connecting two joints.

In terms of computer technology available at the time, the UNSW had a Cyber 72 and the ACES structural analysis program developed in South Australia. Virtual memory was available but from my recollection, the computer had to be restarted especially. As a result, one could only do one or two runs per week for large analyses. A special ”pre–processor” program was written which could generate the input data for ACES. The input format reflected the punched cards used. Advances now included being able to store this information on a disk file rather than physically carry boxes of cards all the time to the input station. However there were only a handful of computers for the entire University so it was a drawn out process. It was a ritual to make the journey to the computer centre to pick up your input cards hopefully surrounded by a nice thick bundle of paper to pore over for the rest of the day. Then to find a card punch machine that was free (and well adjusted – those punched holes if misaligned could mean the job would fail). One had to be very careful typing in the data – once a hole was punched, it could not be repaired – a new card was needed.

Anyway, the structure got analysed okay and the printouts sent by courier to Melbourne so that a design check of every member could be carried out. It was not long before a plea came back to see whether the computer could somehow do this. Well, there was no documentation on how ACES stored data on disk – all we had was the output file which fortunately we had copied onto a magnetic tape. A ”post–processor” was written which essentially had to read the printout page by page, skipping headings, page numbers etc until the appropriate results were found. Then these were compared to the design codes and appropriate pass/fail flags set along with stress summaries for each load case.

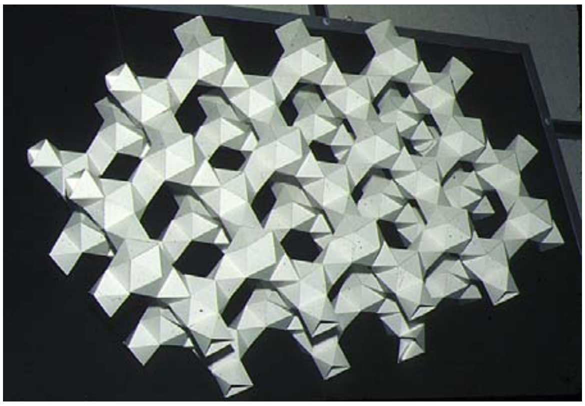
The structural analysis of the shells was a linear elastic analysis of each shell acting independently from each other – there were really no readily available tools to perform a large displacement analysis or to model aspects of joint tolerances.

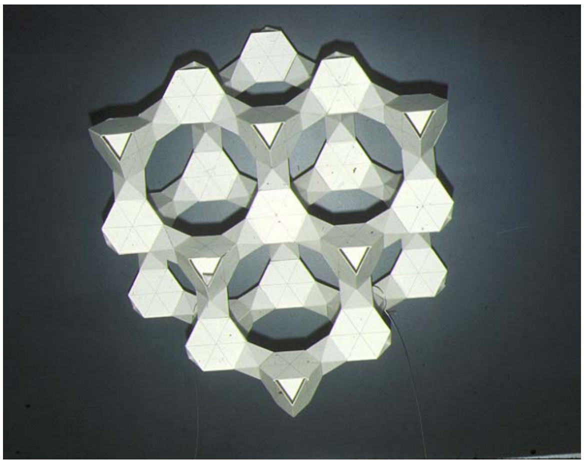
The project also required modifications to the manufacturing process and part of the work involved producing a reasonable sized prototype of one of the truncated hypar shells. All the tube lengths, end coining angles, bend angles and hub dimensions were calculated and the 1500 tonne hydraulic press was modified to be able to correctly produce tubes to match. The purpose of the prototype was to confirm all these changes but in addition it was used to carry out a load test. There was some available knowledge of complete hypars but none of truncated hypars. What degree of edge stiffening was needed and what influence was the lateral stiffness of the supporting edge beams were unknown.



The structural testing involved some basic technology as well as pushing into new areas. The basic technology was to manually add bricks to simulate increasing loads applied to joints. Strain gages were used on a selection of members with some primitive data collection equipment. The more advanced technology was to use photogrammetry to attempt to measure the joint deflections and rotations. A high quality camera was mounted on an overhead crane which was moved between two positions at each load increment to give the stereo images required. Special cruciform targets were attached to each joint. The down side of this was the amount of manual effort required to use expensive equipment to measure the positions of the targets from the films.

The geometry of the upper spire was designed from a background of work with polyhedron and studies of redundancy in structures in 1965 and 1970 with Professor M Burt. It was my first application of geometric non–linear analysis and the simulation of material (member) failure and manufacturing imperfections.





Studies of infinite polyhedra and minimal surfaces with Prof Michael Burt in 1970

Design documentation in those projects was still done manually on the drawing board and by fabricators later for the shop drawings. Revised sets of drawings were delivered by couriers across the country and storage and retrieval of correct drawings were a problem. Telephone conversations involving examining different drawings was a problem (speaker phones in the future still) so there was a tendency for more face to face meetings than is required today. Ah – the aroma of ammonia from the print rooms!

There was little in the way of standards used for exchange of information. Gradually information appeared in one place – such as on the architectural drawings for column spaces, layout grids, floor to floor RLs and so on. Beam and column sizes would be on the structural drawings which would have sets of typical details and specials. To produce the final set of shop drawings, the detailers would need to gather information from several sources and by the time this was done there might have been changes made which were overlooked. The shop drawings may have been subsequently checked by the engineer who may have moved on to a new project.

The real checks came on the job some considerable time after the design was developed. Contractors would make their money because of variations and delays whilst missing information or rectifications were worked out. The dreaded RFI.

We will revisit the current situation later in this paper.

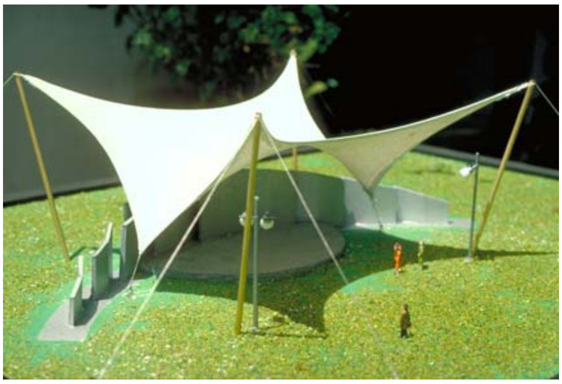
Membrane Structures

Bernie Davis is credited with designing the first significant (other than several pneumatic structures) tension fabric structure in Australia which was closely followed by the Dean Park Sound Shell in Townsville in the late 1970s by Geodome Space Frames.

Dean Park Sound Shell

A fixed price contract had been signed with the client which covered all engineering design as well as supply and erection of the sound shell. As there was no software in Australia, the suggestion was to approach one of the established overseas consultants to perform the design. No – problems. Pay up front approximately 15% of the total contract for a preliminary structural design of the supporting structure. Add to this the unresolved patterning needed and detailed design of connections suggested that we had to develop our own technology. The client was supportive and permitted a generous extension of time.

A small 1:100 scale model was constructed. On the computer side, an approximate 3D shape was generated using the technique of isoparametric shape functions from the finite element method to model a mesh over a quarter of the surface. This mesh was triangulated and flattened out into strips. The strips were not related to actual fabric roll widths but were used to create a 1:10 scale model using lightweight spinnaker cloth complete with pockets for edge cables. A guess was made at compensation factors for the final PVC coated polyester fabric. By stretching the model, some slope discontinuities along lines of symmetry were ironed out. An iterative structural analysis program was written in an attempt to simulate the behaviour under wind. The analysis did move in the right directions but failed to converge so an approximate hand analysis was done.



From what was known, an initial prestress in the fabric of 1 kN/m was assumed and this was translated into a calculated tie down force at the two low points of the structure. A reasonably clumsy arrangement was used at these tie downs which allowed for all sorts of adjustments. A hydraulic jack was inserted and used to impart an 86kN load. Threaded VSL bars took over after the jack was removed. Fortunately, the surface felt uniformly taut and subsequently performed well for the life of the structure.

Queen Street Mall, Brisbane

The next major structure was two inverted conical umbrella structures in Queen Street, Brisbane in the early 1980s. A HP85 small computer was available with 32Kb of memory. An approximate shape generation procedure had been programmed using the Basic language and considerable progress had been made in the patterning so that it was no longer necessary to construct a large scale physical model to measure up for the patterns. The form finding of these and several other conical structures was done by eye without any soap film or simulation of a stressed condition. A major step forward in this project was the first known use (by Bullivants at least) of the threaded swaged end for edge cables. This meant that reasonably compact connections could be designed.

Major software developments were happening overseas by Birdair. A VAX computer with a graphical monitor was being programmed by consultants from the emerging computer graphics area. It was possible to define a number of key points (on the monitor) and generate a suitable mesh. This program is now available as MCM–lite.

In Europe, the finite element programs were being used extensively and software by Prof. Lothar Gründig developed for the form–finding and analysis of the Munich Olympic Stadium cable net roofs has since evolved into the Easy program and latterly the Technet program in the 1990s. In the UK, the ”dynamic relaxation” method was refined by Barnes at Bath which has evolved into the Tensys program.

The form–finding process for the Munich Olympics was supplemented by elaborate physical models. An earlier cablenet was designed for the German pavilion at Expo 67 in Montreal and a smaller prototype structure was constructed at Stuggart which forms the home of the Lightweight Structures Institute (IL). The IL was the source of much of Frei Otto’s work. Many students were attracted to the IL including Prof Vinzenz Sedlak the founder of the MSAA which later became the LSAA in Australia (see above picture with his model of the demountable stage for the Sydney Festival).

A lot of the early work of the IL involved models of soap films and minimal surfaces. Soap films can be a brilliant starting point for tensioned fabric structures and have been incorporated into software packages. Unfortunately some forms such as high–rise cones give rise to crazy soapfilm shapes and forms that involve non–uniform stress distributions had to be used.

The concept of having geodesic strings floating around within a soap film was utilized some fifteen years ago. The idea was that the triangulated mesh could be pulled into the shortest lines across a surface. When used later for patterning, it was thought that these geodesic strings would produce the straightest strips of fabric and maximise the use of material.

Computer Modelling of Materials

Several software programs were developing more complex elements to model the material. Thus a layered material having a homogeneous base representing the coating and two separate disconnected layers of yarns for the warp and weft fibres was found to behave more realistically that a simple elastic material. In addition, these layers of fibres could be defined so that they could not resist compression. Cable elements that could be defined with prestress or initial strains and being tension only started to appear in general purpose finite element packages in the early 1990s. Packages were also performing large displacement analyses with geometric stiffness matrices for common structural components.

The ability to handle different contact problems also assisted the fabric structure industry. Now it would be possible to simulate the sliding of a fabric sheet across a supporting arch, or to permit the fabric to lift off from a support under wind loads.

Of course, there still remain some computational areas awaiting development. These are related to better refinement of material modelling under biaxial stress conditions including localized wrinkling and the crimp interchange behaviour first mentioned in the 1980s. It is still an industry issue to obtain realistic data on fabric behaviour – both short and long term. Great advances have been made in the simulation of composite materials such as carbon fibre and resin.

Modular shade structures using seat belts for edge cables and knitted shade cloth were developed by the writer and have become industry standard.

Above is the large deflections due to hail loads and on the right an Award winning conical structure designed with planar panels and the flexibility of the shade cloth material (Green Scene, Victoria)

Computational fluid dynamics is a field that could be applied to free form structures to obtain a better understanding of wind pressures, external turbulence as well as internal air flows, heating and cooling loads and lighting requirements at different times of day and seasons.

Expo88 in Brisbane was a major project designed by European Engineers. Australian Companies constructed several elegant smaller structures.

The MSAA / LSAA sponsored some wind tunnel tests on a range of conical surfaces

Computer Technology – Communications and Data Interchange Standards

Great advances in computer technology have been taken up by every professional. The use of email for instance, when combined with the ability to send all sorts of files as attachments (drawings, photos, spreadsheets, data files, manufacturing data etc). The Internet has enabled communication and design/construction development to be a world–wide 24/7 operation because of the different time zones. There is no doubt that the Internet is a vital element in the ability of Australian / NZ designers and contractors to be able to tackle overseas projects.

The other area which is still improving is in the adoption of various ”open” standards for electronic data interchange. This is when, for example, a CAD application may generate geometric information which in turn can be read or transferred without loss of attributes into another application such as a structural analysis program.

An early attempt was the IGES standard which was adopted by several software companies originally for the exchange of information such as might be needed for a finite element analysis of a structure. This standard didn’t really get off the ground as it was realized that so much more intelligence needed to be associated with the myriad of potential data that is needed to describe a product or structure. In the early days, a beam might simply have a section size specified (610UB101) which would be enough to locate the geometric properties needed for an analysis. Now, we might also add in connection types at both ends, position and types of added stiffeners, cut outs, shear studs, material grade, supplier, paint or surface finishes, centre of gravity for lifting purposes, required delivery times and so on.

Obviously a structural analysis package will not need to know about the paint finish but will need to know the geometric properties and ideally the stiffness properties of the end connections. A package needs to get what data it needs from a centralized data base for the structure but also leave other data intact. Many packages now are able to perform a design check of members against local design codes and may offer the ability to automatically select alternate member sizes to meet the design criteria. Such changes will cause a ripple effect such as changing surface areas, self weight, costs and so on.

The industry, which is often being driven by software companies, is working on open standards to permit the above types of data storage and interchange. More and more information is being generated and is kept basically in one database or model. Terms like intelligent 3D or 4D model or BIM are common now.

Yes, time is the fourth dimension as a structure doesn't miraculously appear. It is a growing requirement that structures are assessed for all major stages of construction and the centralized database needs to be able simulate the stages of construction. This is a great bonus for erection planning and transport requirements including loading, unloading and on–site storage needs not to mention craneage.

In the past, after a structure (building) was completed, the original drawings were modified manually to become an ”as constructed” set of documents, copies of which were handed over to the clients. Ongoing maintenance and alterations throughout the life of a building (new partitions, stairs, services etc) somehow just happened. Now, the developed 3D or 4D model is handed over and can be used throughout the life of the building. It may well be available so that fire departments can predict which evacuation or fire fighting techniques might be used in emergencies. This is a far cry from the days when a bundle of computer punched cards was the only static representation of the building for a brief moment in time.

In the past, we relied very heavily on the 3D thinking skills of structural detailers to visualize what was going on and to represent the various components on the drawings. The early CAD systems were simply a 2D drafting tool to replace the pens, T squares and scales of the drawing office. What was drawn was still controlled by the operator. The later stages of documentation (the shop drawings) collated all the bits and pieces together and final costs could be established. Unfortunately cost estimates and contract prices needed to be determined early in a project before final details were determined.

In the field of tension membrane structures, it was soon learnt that connections of cables for example had to consider large variations in geometry from the initial attachment of a loose cable to a mast right through to when the structure has been stressed. Corner connections in fabric structures visually demonstrate the relative forces meeting at a point. More traditional structures modelled in 3D can be examined for access of spanners and wrenches to insert and do up bolts for example. This is called clash detection which originated in structures such as refineries where pipes and other services must avoid each other.

Structural engineers were often upset when the architectural requirements demanded that air conditioning ducts had to pass through our carefully optimized beams. All the other pipe work in buildings (water, gas, electrical, communications) had to somehow get around our structure and didn't show up on our drawings.

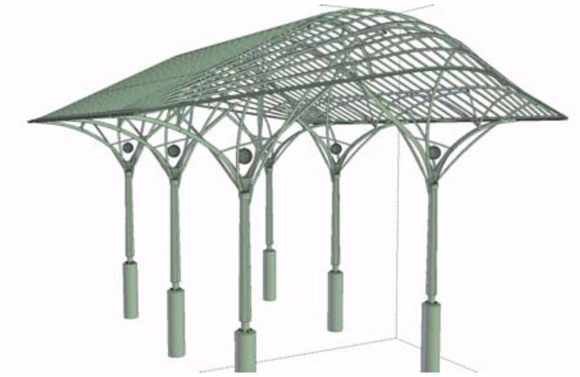
With the present situation, all this other information can be absorbed into the same 3D/4D model. This poses a small procedural problem in that we don't want unauthorized people being able to stuff things up – say by altering some pipe locations that then pass through a beam or column. Thus a system of data organization and access is an inherent part of the models. Service engineers, contactors and other trades all need to at least be able to view the structure and piping and to be able to query the database with relevant questions. In the early days of CAD, the concept of layers was introduced. No real standards were adopted industry wide but normal practice lead to different layers for grid layouts, roadworks, dimensions, walls, windows and so on.

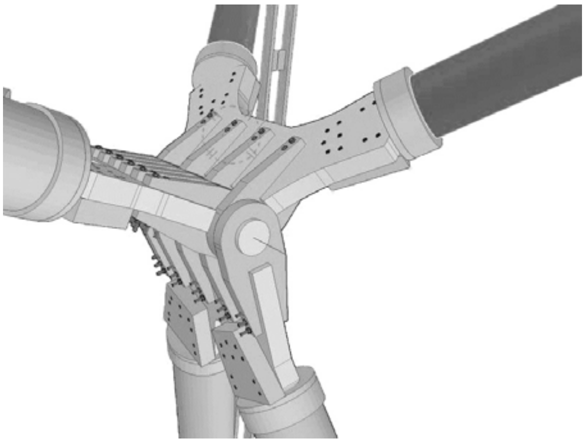
A special form of ”query” is to ask the modelling software to do the ”drawings” – framing plans, connections and shop drawings for itemized components. If one reflects on this, the whole design process is reversed to the early days when suitable drawings were needed to build up a picture of the final structure. Shop drawings were commenced when everything else was finalized. Now drawings can be produced almost at any stage of the modelling process. Extra information can be added to the model without having to find some real estate on a sheet of paper to add notes or specifications. Different trades can ask for whatever drawings and data they need and get it from a centrally stored model.

In the 1990s, several well established CAD packages had to be re–written when the demand for working in 3D grew. Newer systems appeared which could target specific areas like steelwork. A lot of the development in computer applications has been driven by architects and their need to visualize the completed building environment. Great steps were achieved when hidden lines could be removed. Various techniques for shading surfaces became common and the demand soon followed to be able to model the optical and textural properties of surfaces such as windows, carpets, floors and walls.

It has been my observation that students of architecture often have computing skills in advance of engineers. As a student in the 1960s, a major first year subject was engineering drawing but the present skills possible with computer modelling of buildings or infrastructure does not seem to rate highly. Some of this is because of the lack of direct practical experience of academic staff and the pressures by accreditation bodies to insist that a significant proportion of courses is devoted to ”management” and the ”environment”.

So, we have arrived roughly at the present situation. The figures below show the transition from physical to virtual models by computer. Computers are an essential part of our daily life and design work. Certain levels of computer skills are taken for granted although I have only met one or two people who can use a word processor correctly!





Current Industry Issues

To a certain extent, the current industry issues are reflected in part by the content of the MSAA/LSAA Conferences and Symposia held since inception and a quick summary follows:

- In the inaugural meeting in 1981, fire was discussed as several projects comprised atriums. In most cases, the fabric roof had a gap between it and the structure underneath and smoke could escape.
- The 1984 Conference had several technical papers on fabrics – predominantly PVC coated fabrics originating in Europe
- In 1985, fabric durability was covered along with wind loadings on structures.
- 1988 and 1989 saw discussions on material behaviour continue and Bernie Davis gave some insight into fire and the requirements of AS 1530

- In 1990 the MSAA presented some sponsored research results of wind pressure coefficients on a range of conical structures
- In 1991, Peter Lim talked about fabrics mentioning silicon coated fabrics and foils – both getting a revisit at the present conference
- Mike Lester and Peter Kneen talked about computer software for determining patterns from 1993
- Tristram Carfrae covered high technology glazing systems in 1994 when the MSAA expanded its range of structures and became the LSAA
- A number of exciting and larger projects have been presented at most meetings and today we have seen that many of the projects are of truly world class and have been designed by members who have grown up with the industry from the early days
- One of the first such projects presented by Ian Norrie in 1994 was the innovative Hong Kong stadium using long span arches – interesting to see how often this design concept has been adopted since.

So what remains as issues for the industry and for LSAA to address?

Fire

Fire is the current hot topic and needs to be studied in an objective manner. It would seem that because of the wide range of unusual structures designed, an all encompassing prescriptive based code or regulation is not advisable. There is more to it than fire tests on pieces of fabric.

The codes AS 1530 Parts 1, 2 and 3 have the latest versions dated as 1994, 1993 and 1999. There is considerable pressure to update standards every five years so by this criteria alone, the industry should be prepared to contribute. The Building Commission of Australia is now a driving force for change and we must work cooperatively towards a workable outcome.

For many steel structures, where fire is also an issue, there are deemed to comply approaches but also there is the chance to have a proper fire risk assessment made of a given design. This may lead to a detailed assessment of safety and maintenance procedures, alarm systems and so on. It is known that computer simulation of panic situations and demands placed on emergency exits have been used and some solutions such as increasing stair and door widths can markedly change escape times.

The basement bomb scare on the World Trade Center in the 1990s saw evacuation times of many hours (10+) but with subsequent evacuation drills and procedures, these times were reduced to an hour or so – perhaps the main reason why casualties in 2001 were relatively low. The casualties would have been much lower still but for communication confusion and the opposing traffic on the stairs with fire personnel trying to go up and tenants going down. Perhaps increasing the width of these stairs by 600mm would have helped enormously.

Many permanent fabric structures have the fabric some distance away from being easily accessed – usually a large roof is much higher anyway but otherwise for vandalism reasons. The fire load is low because there is little in the way of material to burn (even if it does) and there is likely to be an escape path for smoke built in for ventilation anyway, or created if there is a sustained flame close to the fabric creating a hole.

On the other hand, many temporary enclosed pavilions may have walls made of fabric and may be expected to have reasonably high numbers of people who are visitors and therefore are not in a position to study evacuation procedures. The high strength fabrics are tough and it would be difficult for occupants to simply tear the walls down. Of course there could be the perception that this could be done and may lead to a stampede towards the side walls with people being crushed.

Having highly visible sharp cutting equipment (Stanley knives or similar) next to regularly placed fire extinguishers would be one suggestion. The other is for wall panels to be affixed using prequalified connections which would fail under crowd loading.

Education

The successful projects involve assembling a talented team where everyone can make a contribution and respect the contribution by others. Very few people have the complete range of skills to design these structures.

There has been virtually no teaching of lightweight structures in Australian Universities other than during the Sedlak / Kneen era at UNSW or by isolated guest lectures by several of our members.

It is encouraging to see the recent developments at UNSW with the new Architectural Engineering course as described by Zora Vrcelji earlier today.

As hinted in my paper above, the expertise of academic staff in the area of practical design skills with lightweight structures is lacking and it is this area that perhaps the LSAA could contribute. It is probable that this is well beyond the resources of the current LSAA but maybe a case could be made for a Government grant.

Marketing of Australian Capabilities

The LSAA website has recently featured company profiles for its financial members. It is known that hits on our site have been steadily increasing and more work could be done to further promote our members.

The company profiles could be extended into an industry capability matrix where all the skills and resources are indexed. Again, this work would require funding and planning. There may well be some scope for assistance to industry bodies by the Government as illustrated by the talk by Jeff Turner yesterday.

Through the LSAA Design Awards there is the potential to publicize our industry and there may be opportunities to be developed with the RAIA and IEAust.

Design Tools

This paper has described the enormous strides in computer technology and software that has taken place. It would seem that the LSAA should consider as a major theme for a future Conference the design tools used by the industry – architects, engineers and fabricators. It is suggested that this could attract a much larger audience and sponsors. It would lift the profile of the LSAA.

A particular issue with these tools is cost which is relevant for smaller operators / fabricators that find it difficult to justify engineering or specialist design input for small projects. Unfortunately these small projects may require certification and have warranty implications.

An appendix lists some of the software found by a simple internet search – no checking was done on the relative merits of any particular program.

Concluding Remarks

This paper has been a walk down memory lane looking mainly at the evolution of computer technology and software applications and how these changes have aided the design process. There remain some ongoing industry issues which have been briefly described.

Appendix – Some Software Links (reproduced from a Google search)

- **Easy** Complete engineering design of lightweight structures. Force equilibrant formfinding. Geometrically non–linear load analysis. Cutting pattern generation. Visualization. (Technet GmbH).
- **Surface** is a program that allows you to create your 3D tent membrane shape and then works out the shape of the panels that must be cut out and joined together to form that 3D shape. You can either create the shapes directly in the program using the powerful features that allow you to modify the shape by altering tensions within the membrane and it's supporting ridge, valley and edge cables or if you have already developed the shape in other conventional CAD systems you can make use of the extensive patterning and geodesic panel edge finding features of Surface to create any panel arrangement that you want. (Surface Software).
- **Patterner** is a powerful collection of tools for working with 3D surfaces. Patterner is primarily for the design and manufacture of tents and fabric structures. Powerful manipulation and drawing creation tools make it useful for anyone building complex 3D forms from sheet materials. (Rudi Enos Design).
- **Surface Evolver** is an interactive program for the modelling of liquid surfaces shaped by various forces and constraints. The program is available free of charge. (Ken Brakke).
- **ForTen** is the first commercial software specifically developed to calculate and model tensile and fabric structures. Forten is both a geometrical and mathematical modeler that permits to you to obtain the exact building shape, starting from free form 3D mesh, joint conditions or stress conditions. (Europe Engineering Division).
- The **Tentnology CAE** program provides an easy–to–use solution for design and analysis of tension structures. Operator can generate 3D models of a concept, then apply wind and snow loads to view force, reaction and stress. When satisfied with the results, the user can readily produce cutting patterns for manufacture. (Tentnology).
- **MCM–lite** is the hassle–free software that lets you create tensile membrane and cablenet structures without mastering complex engineering principles. The complete engineering version of MCM is also available on a limited basis to professional engineers. This version includes full analysis capabilities – large deflection finite element method analysis. (Birdair).
- Engineering Pte Ltd provides a suite of programs for design (according to British standards) and analysis of tension structures: **WinCable** for cable and cablenet design and analysis and **WinFabric** for tensioned membrane structures design and analysis.