The CONCEPT DEVELOPMENT and TECHNICAL DESIGN of the TENSEGRITY SUPPORTED SAILS at MARINA MIRAGE

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SYNOPSIS

Because of its relative uniqueness the Marina Mirage Project has attracted considerable attention. A significant feature, certainly the most visual, is the tension membrane 'sail' roof system described in this paper.

The end result was a clear reflection of the client's wishes, the site characteristics and the dedication of the design/ construction team.

A general background to, and development of the project is outlined, together with details of the material selection, design, manufacturing and erection phases.

GENERAL BACKGROUND

Right from the start, Marina Mirage was going to be something different. The client, Qintex Ltd., in line with their contemporary ideas stipulated a complex at the leading edge commercially, architecturally and technically.

It is interesting to note that an earlier retailing scheme for the site had been prepared (which also sported an extensive membrane structure). Qintex had developed a proposal for a five-star hotel across the road from the Marina Mirage site and it was not long before they purchased the site to combine both into one integrated development.

Figure 1. The Site location.

THE SITE

Figure 1 shows the project location. Two aspects of the site imposed strong influences on the ultimate design:

(i) Its proximity to the populous resort centre of Surfers Paradise, with the heavily trafficked Pacific Highway across the Broadwater; and

(ii) Facing the Broadwater on one side and the ocean on the other, with the tourist busy Seaworld Drive in between.

A further aspect of importance was the planning restriction on the height of buildings along Seaworld Drive.

The client required a complex which would capitalise on all of these. It is clear that the site was very exposed, almost on four sides, and because the overall project comprised two major buildings linked across Seaworld Drive, the key theme of integrating both to the fullest extent added to the demands of the design.

Adjacent development comprised a mix of rather tired shopping/entertainment centres and 'marine industry' trappings.

With the planned construction of a monorail link from the Casino through to about 1 km north of Marina Mirage, suddenly this area has literally rocketed out of the "backwater' niche of just a few short years ago.

CONCEPT DEVELOPMENT

As noted above the overall project comprised a five-star hotel on the ocean side of Seaworld Drive, and an up-market shopping complex on the Broadwater side. This complex soon grew to incorporate an extensive marina, the whole being referred to as Marina Mirage. Media Five Architects and McWilliam Consulting Engineers were the appointed consultants for both projects.

The Hotel and Marina Mirage were restricted to a height of some 9m by Town Planning regulations, so each developed into extensive two storey blocks with maximum site coverage.

In particular, Marina Mirage incorporated a large courtyard area designed to be essentially 'open', Refer Figure 2. To provide a measure of weather protection (wind, rain and sun) the use of tension membranes was investigated. Because such structures did not form a continuous roof, nor provided usable space, Council approved a height limit for them of some 10m above the building limit.

Numerous meetings between Des Brookes and Brett Saville of Media Five and Bernie Davis of McWilliams were required to establish a concept theme for the courtyard coverings.

Various conventional membrane solutions were initially proposed and passed over, until the engineers tentatively offered a model of a repeating sail like module. This was immediately adopted as it satisfied all the client's demands, viz.

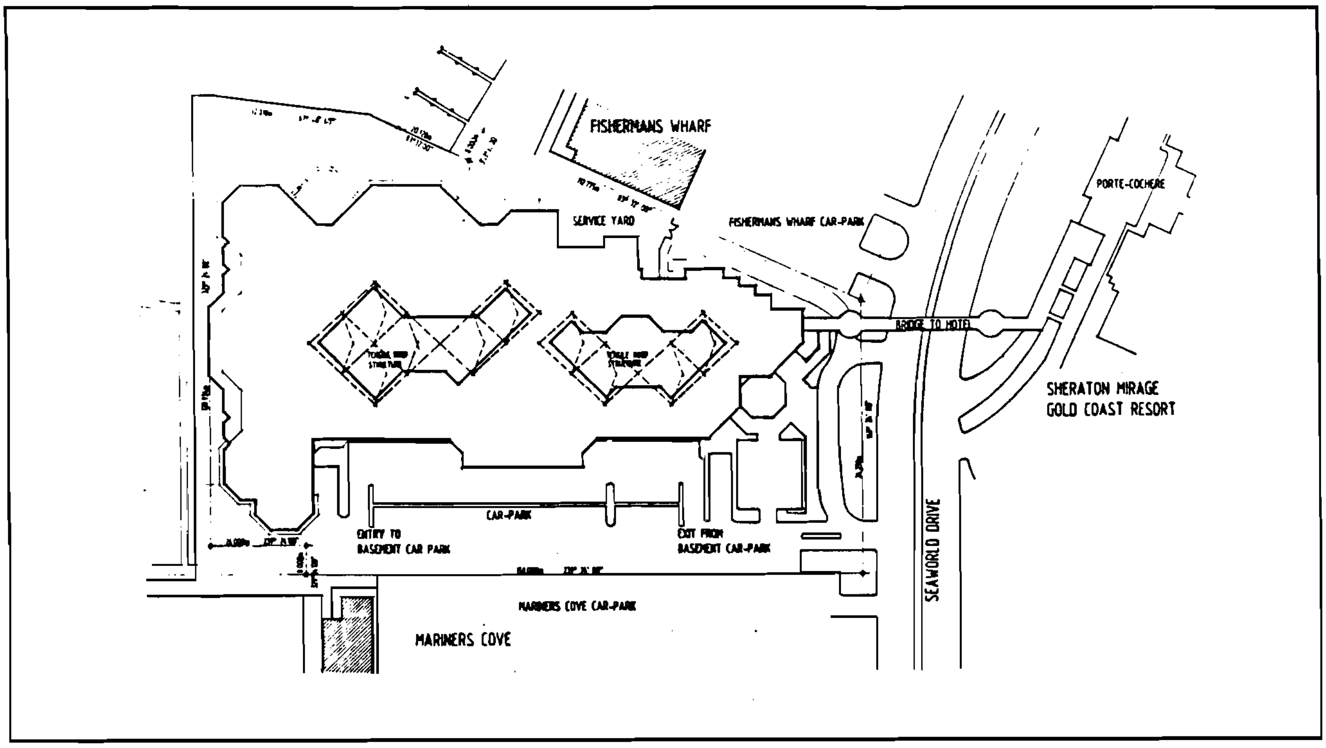

Figure 2. Site Plan

- It had a vitality and design edge commensurate with the centre generally
- It reflected perfectly the 'Marina Mirage' theme and the adjacent yacht harbour activity, the sails became instantly the trademark and emblem of the centre
- It capitalised on the height allowance while not forming a visual block above the buildings
- The modular system was a cost-effective solution and could be installed at the pre-set budget limit
- It was highly visible both during day and night drawing attention to the centre from considerable distance.
- It provided adequate environmental shelter to the inner court while satisfying Fire Authority's stringent requirements.

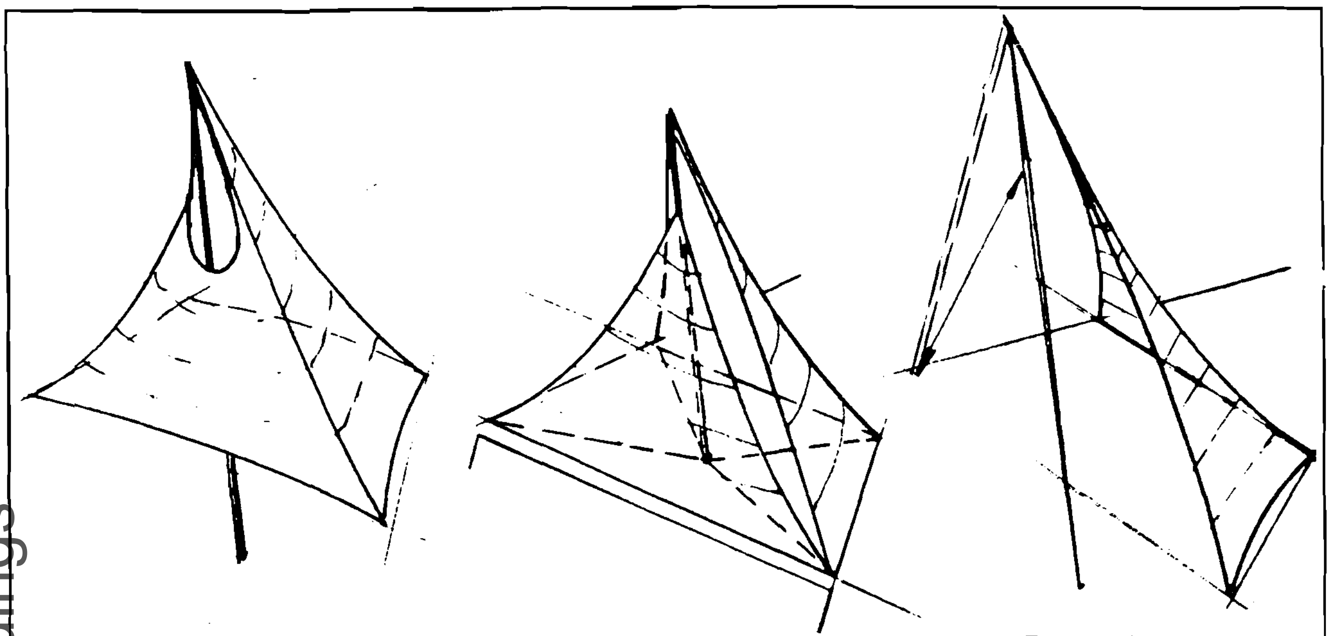

Figure 3. Proposed Module Shapes

The final form of each module was the subject of much debate. Three proposals together with their structural solution were submitted for discussion. Refer figure 3

- **Proposal (a)** shows two hypar sails coupled along two cable supported ridges with a teardrop opening at the peak. The sloping support mast would be supported from floor level.
- **Proposal (b)** required the two hypar saddle sails to be supported by a mast located on cross cables. Sails to be fixed to perimeter beams with drainage through columns.
- **Proposal (c)** located a single saddle shape supported from a strut located on the perimeter beam system.

Architects Media Five decided proposal (b) would be the best aesthetic solution for the overall development concept. It best satisfied their requirement for openness and lightness with strong marine overtones. Figure 4 shows the basic module - its resemblance to the mainsail and jib of a sailing yacht is hardly disguised. Two different mast heights were used, and all were given a common orientation to heighten the illusion of action. To add to the vitality of the design a tensegrity system for the masts and stays was readily incorporated.

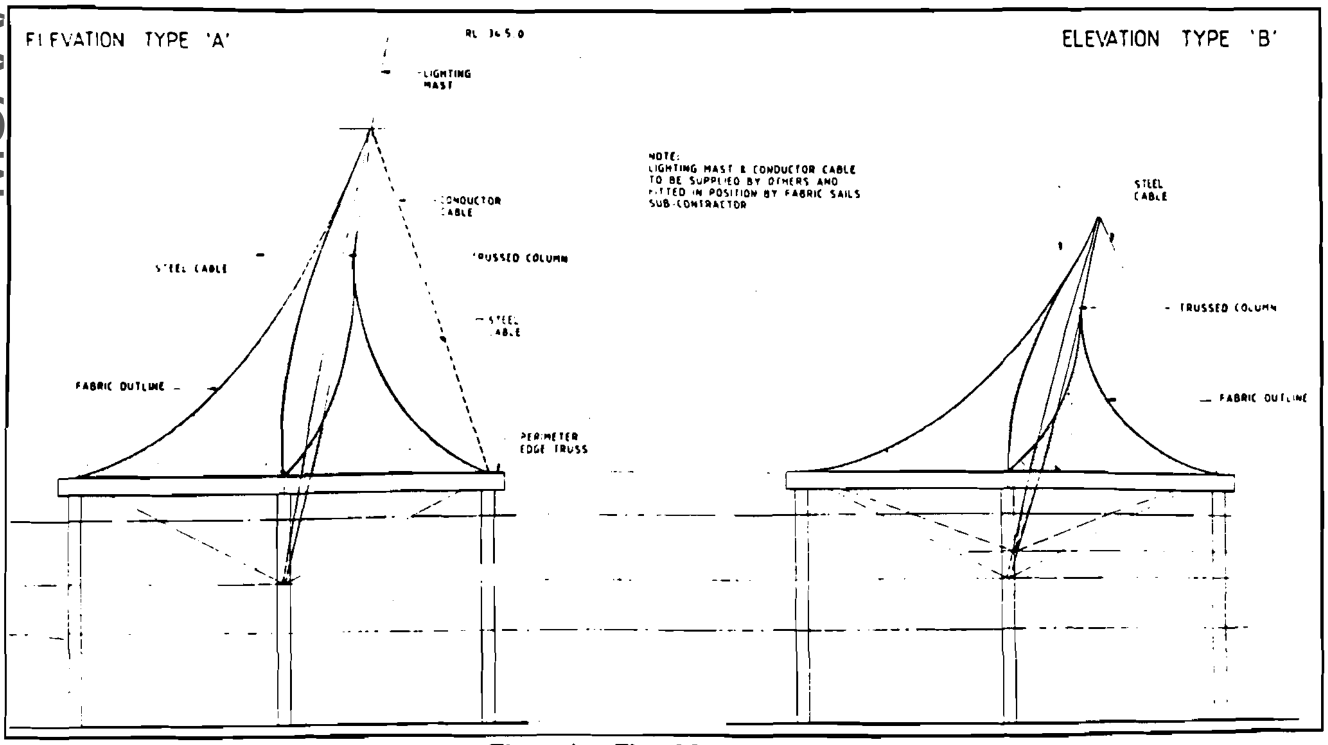

Figure 4. Final Module Shapes

WIND PRESSURE STUDY

To determine realistic wind loads it was decided to use the services of wind engineers, Vipac. A rough surface 1:40 scale model of a main and jib sail module was tested in Vipac's Boundary Layer Wind Tunnel. Some thirty-seven pressure taps were installed externally and three pressure taps installed internally (between the sails).

The results in figures 5 shows external wind load pattern of 1.2 kPa and 0.65 kPa for peak positive and negative pressures. The internal pressure between the sails remained relatively insensitive to wind direction and were in the range of +/- 0.38 kPa. It should be noted this wind tunnel test was performed on a single sail pair and did not reflect the shielding that would be expected from a cluster of sail pairs.

Also, an environmental wind analysis was carried out by Vipac to determine the ground level wind conditions. It was originally thought the open sided sail modules may direct winds into the courtyard area. A full scale model of the proposed development and nearby structures was subjected to a low velocity wind tunnel analysis (Refer Fig. 6).

The findings were that the double sail modules (main sail and jib sail) over the courtyard, enhanced the wind climate at ground level. Indeed it was Vipac's opinion that had only main sails been used, that the ground level environment would have been degraded by scooping wind flow into the courtyard.

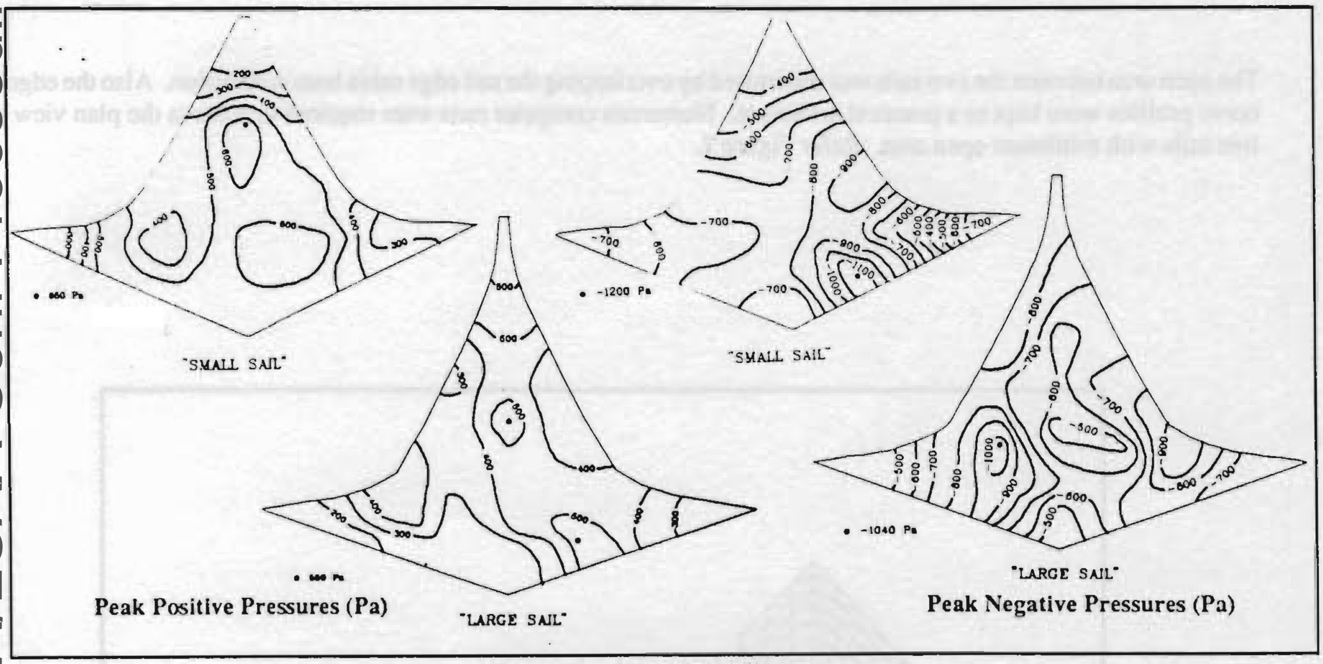

Figure 5. Wind Load Patterns

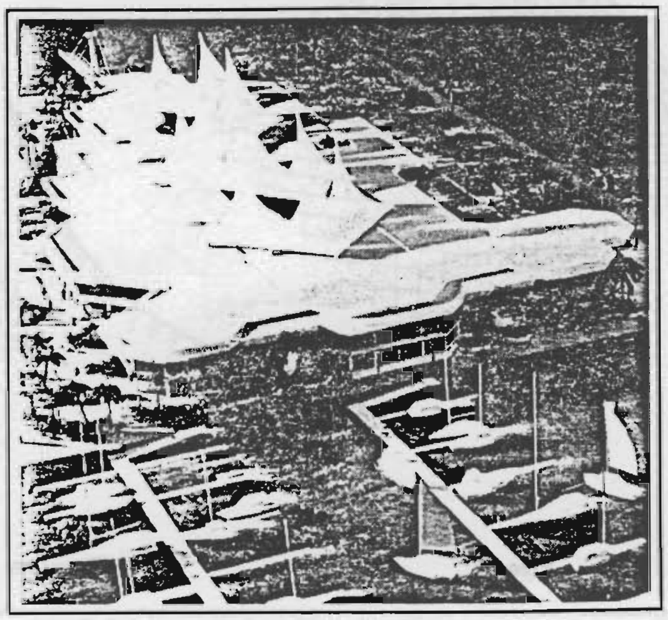

Figure 6. Scale Model

COMPUTER GENERATED SAIL SHAPES

The proposed fabric sails were shaped and analysed on a finite element computer programme developed specially for fabric and cable structures. The initial process was to generate the shape in two dimensions with a predetermined number of triangular finite elements. The element nodes are then assigned fixity and reduced levels. The solution process is by a modified Rapsom Newton method or Dynamic Relaxation in which the finite elements move towards an equilibrium position. Once the shape is in an acceptable equilibrium form, the finite elements are assigned fabric elastic properties and the line elements predetermined cable elastic properties.

This final prestress shape is used for load analysis as well as defining cutting patterns, cable lengths and interface geometry.

To maximise rainwater protection the relationship of the jib sail to the main sail was considered in detail.

The open area between the two sails was minimised by overlapping the sail edge cable base connection. Also the edge cable curve profiles were kept to a practical minimum. Numerous computer runs were required to achieve the plan view of the two sails with minimum open area. Refer Figure 7.

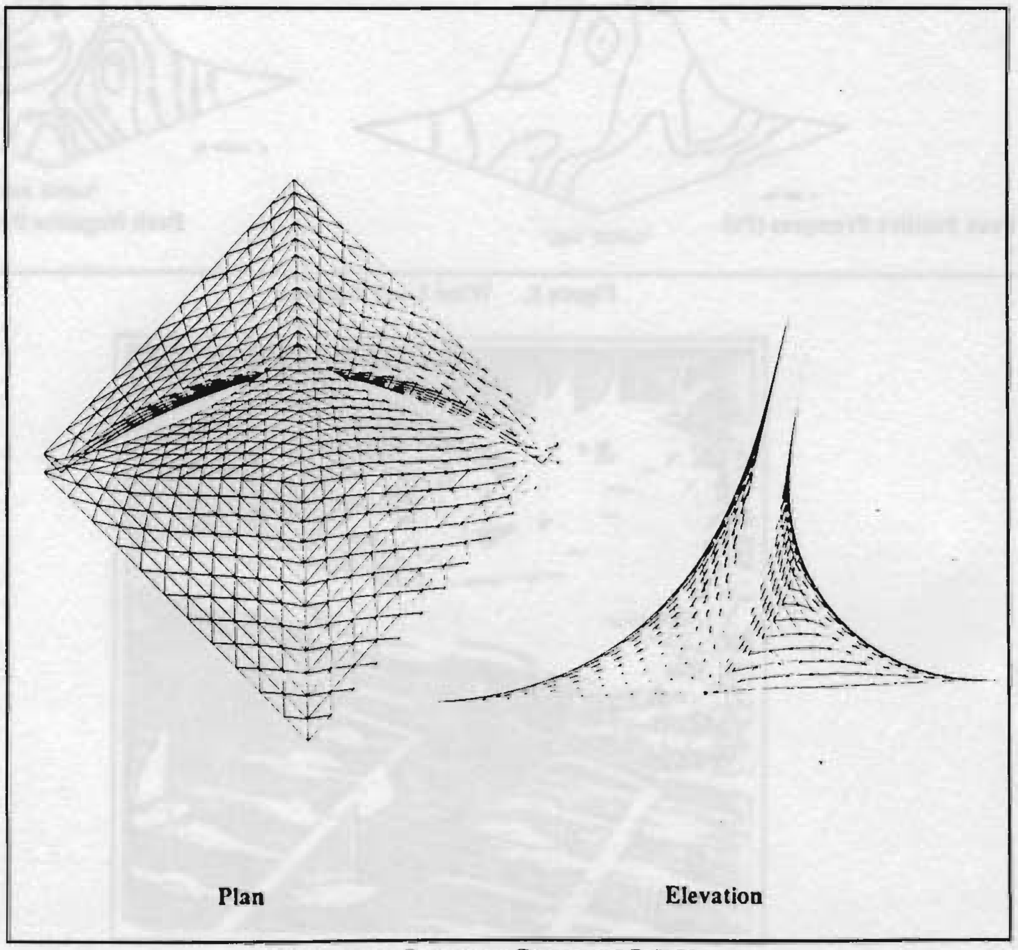

Figure 7. Computer Generated Sail Shapes

SAIL SHAPE ANALYSIS

Because this form of structure is load averaging, the wind study pressure results were rationalised for uplift and downward wind load cases.

Average outwards normal wind load -

Main Sail	(-)	1.1 kPa
Jib Sail	(-)	0.9 kPa

Average inwards normal wind load -

Main Sail	0.75 kPa
Jib Sail	0.75 kPa

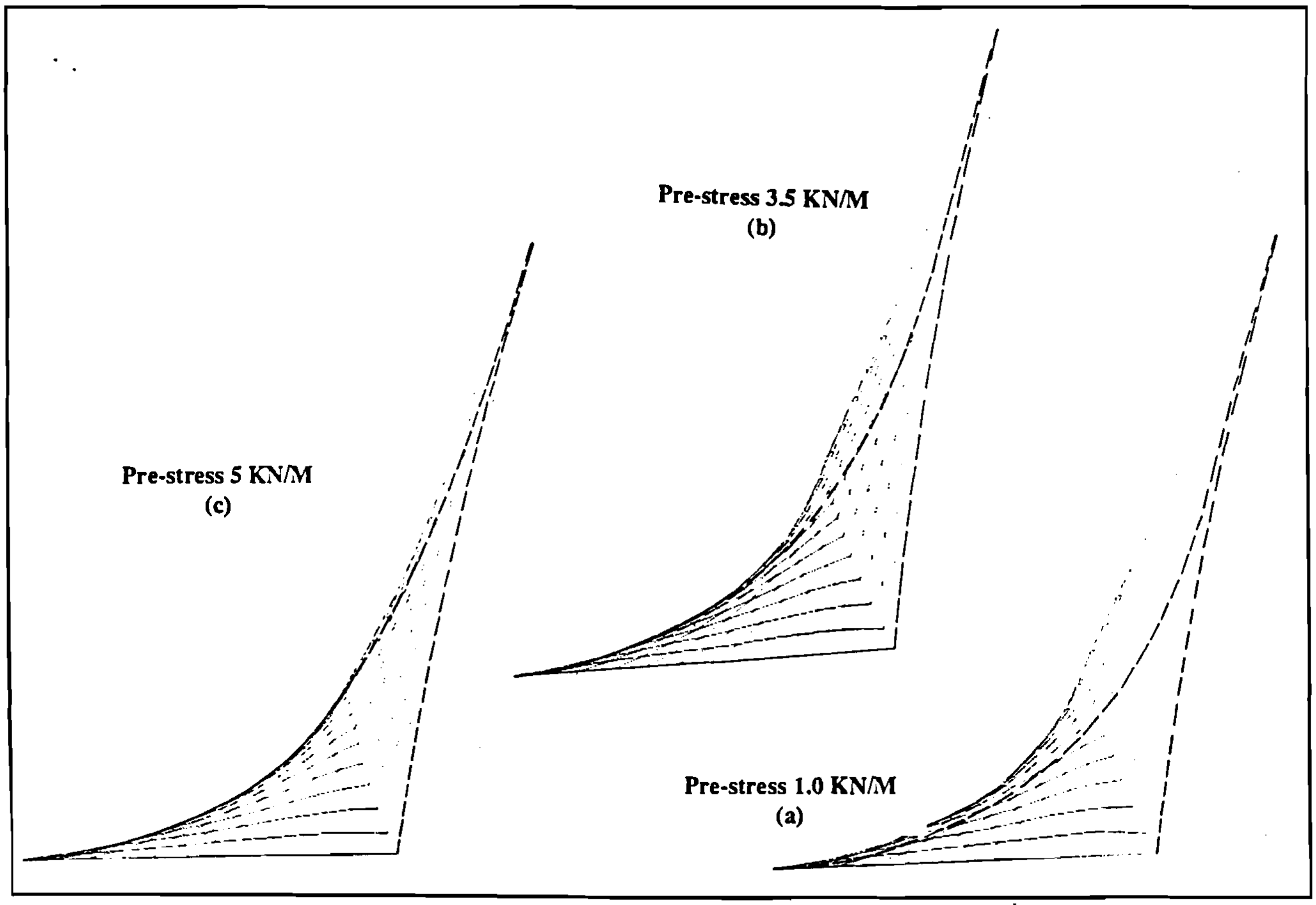

Figure 8. Wind Load Deflection at Pre-stress Cases

The above wind loads were applied for three prestress conditions. Prestresses of 1, 3.5 and 5 kPa were considered - figure 8 shows the membrane deflection for these three conditions. It can be seen that the fully restrained base edges stiffened the lower half of the sail in relation to the cabled edge upper areas.

Because of the controlled deflection and in spite of some local higher fabric stresses in the mid area, a prestress condition of 5 kPa was adopted for these sails.

The maximum fabric stress at any point under prestress and wind load was 21KN/M for the main sail and 16 KN/M for the jib sail. This allows for a safety of 4.9 on the minimum tensile strength of the fabric seams, which is a minimum 90% of fabric ultimate strength. For long term fabric structures a prestress level of 5% and a maximum fabric stress of 20% of the strip tensile is recommended. These parameters are used to eliminate or minimise tear propagation from either intentional vandalism or accidental damage (eg wind-blown sheet metal).

SAIL FABRIC

Two types of architectural fabric were considered structurally adequate for this project, PVC coated polyester and teflon coated fibreglass.

The PVC coated polyester fabric is slightly easier to fabricate and requires less care during handling than teflon coated fibreglass. While test and field studies show the lifespan of PVC coated polyester fabric with the newer coatings is 15 to 20 years, the lifespan of teflon coated fibreglass structures is claimed to be 30 or 40 years plus.

Also, while achieving a low spread flame rating in fire tests, PVC coated polyester will burn when in contact with flame only. Teflon coated fibreglass is effectively incombustible.

The teflon coating on fibreglass fabric provides an inert self-cleaning surface which generally eliminates any maintenance cleaning. The commonly used acrylic coated PVC fabric requires regular cleaning as dust particles will adhere particularly with ageing. However, PVC coated fabric can be laminated with a tedlar film on the external surface. The tedlar film has the same roughness coefficient as teflon which makes its self cleaning properties similar. Other surface treatment for PVC fabric were considered, however, these were dismissed because of lack of technical and field service data.

Another consideration is that PVC coated polyester is considerably cheaper than teflon coated fibreglass.

The final decision to use a tedlar laminated PVC coated polyester was for the following reasons:

- The useful life of tourist developments appears to be only 8 to 12 years before major facelift or redevelopment occurs.
- Local Council fire requirements for the open sails accepted the PVC coated polyesters.
- The client required a maximum number of sails for the set budget.

Three tedlar/PVC fabrics from different manufacturers (1-USA, 2-West Germany) were considered for this project. Assessment consisted of cost, technical, laboratory, field service data and guarantees. Information from the two West German manufacturers at the time was limited and field service data virtually non-existent.

The American fabric manufacturer provided field test data on existing tedlar/PVC structures dating back some 18 years. Fabric tear strength, guarantees and cost comparisons also favoured the American fabric. Therefore it was decided to nominate only the Seaman Corporations (USA) fabric, grade 9032 for this project.

The fabric chosen has an ultimate strip tensile strength of 114 kN/M in warp and weft direction and a trapezoid tear of 623N.

FABRIC/PERIMETER BOX TRUSS INTERFACE

Edge Tube Connection

The straight edge fabric connection to the perimeter box truss was via rigging screws, connected to a steel hollow tube located in a fabric edge pocket. To facilitate stormwater runoff the rigging screw connections were located off centre of the supporting box truss. As can be seen from figure 9 a stainless steel box gutter was positioned below the top surface of the box truss bracing members.

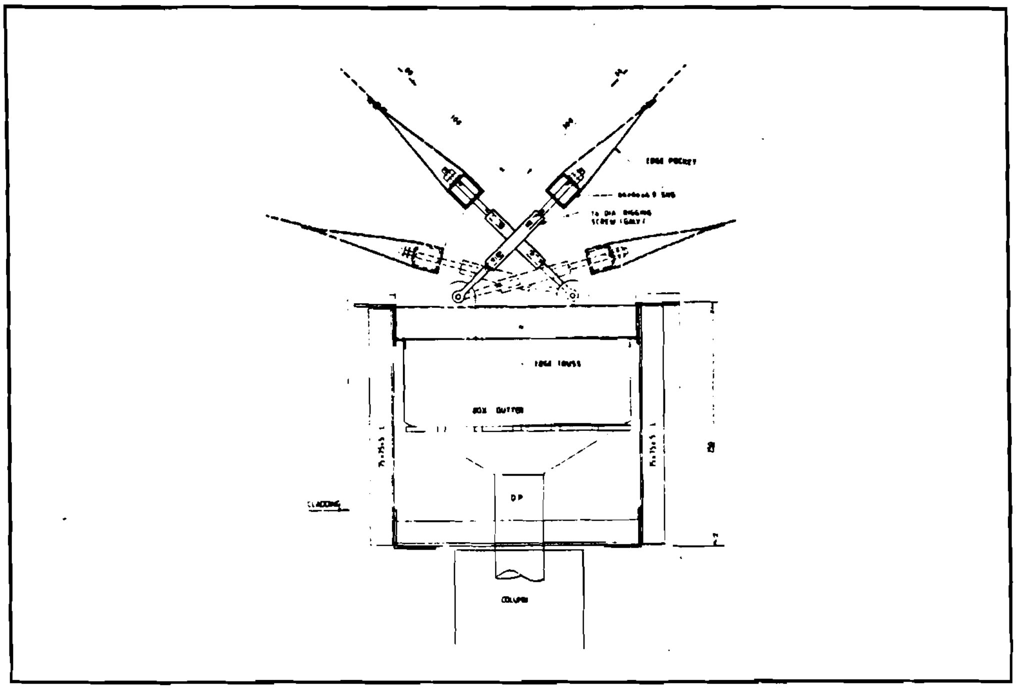

Figure 9. Section Permiter Box Truss

Cable Connection

The fabric edge cable connection to the box truss was originally detailed with a surface mounted bolt. However, it was considered this type of termination would be too cumbersome and unsightly when viewed from ground level. After consultation with both the steel and fabric contractor it was decided to terminate the edge cables inside the base truss intersection. Stressing was then accurately achieved by VSL stressing jacks located inside the box truss. Refer figure 10 for plan elevation of box truss intersection.

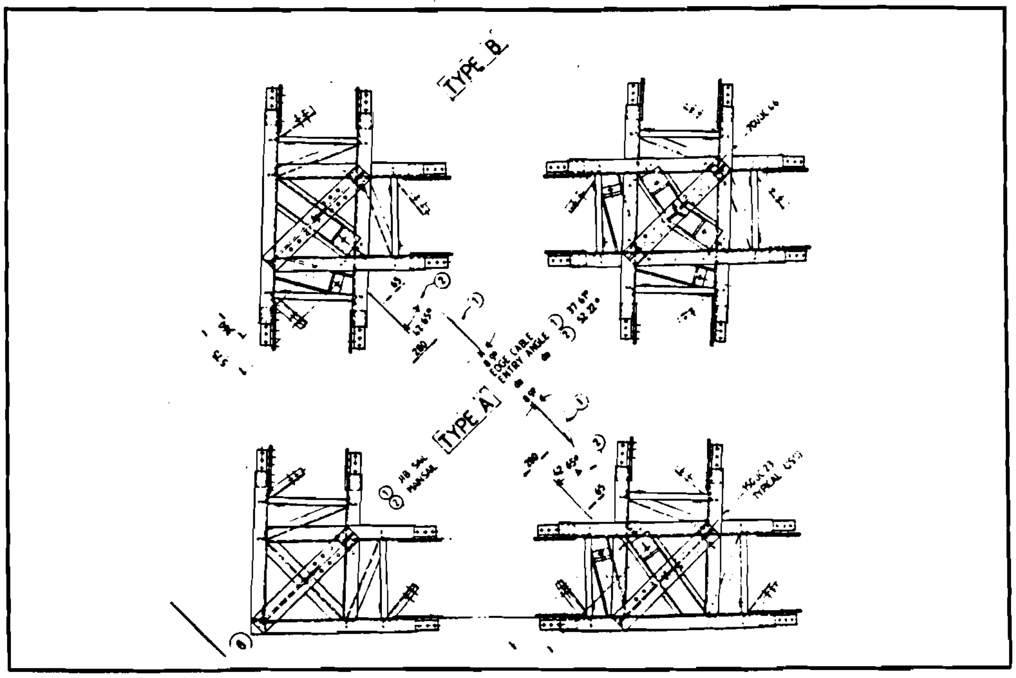

Figure 10. Box Truss Interstructures

FABRIC MANUFACTURE AND ERECTION

The contract to manufacture and erect the fabric sails and supporting mast system was awarded to Vesl Membrane Systems of Brisbane.

Because of the specialised nature of the project and the demanding need for high standards of workmanship, a close liaison between fabric contractor and design engineers was required.

For this project steel, cable, fabric cutting patterns and details were supplied by McWilliam Consulting Engineers as part of the building contract. It should also be noted a comprehensive testing programme was completed during this project. These included

- Biaxial testing of the fabric supplied for exact warp and weft stretch correction factors at the nominated prestress.
- Strip tensile tests at ambient temperatures were performed on fabric seams to ensure seams were minimum 90% of fabric tensile strength.
- Tensile tests on the edge pockets were required to determine the acceptable pocket depth.
- Quantitative peel tests on fabric seam samples were completed before every welding session.
- All cable termination types were tested to destruction to confirm ultimate strength.
- Stretch corrections of all cable types were tested for prestress loads.
- Welding on the tensegrity steel masts was x-ray tested.

The erection procedure nominated by Vesl dictated a number of final design decisions. These included cable termination and stressing procedure. The masts supporting cables were erected by onsite cranage and the sails individually erected by manual winching.

The contract was let in September, 1987 and all cable and masts were erected by December, 1988. The sails were erected and stressed by May, 1988. This work was within the timeframe required for this project. It should be noted that the fabric was manufactured and erected within tolerances of ∓ 2mm.

Tensegrity Mast Supported Bird Aviary

Also one of the many special features of this project worth noting was a stressed wire mesh bird aviary. A walkway at the first floor level provides an opportunity for visitors to pass through the aviary among colourful tropical birds.

The aviary consists of a fine steel mesh suspended from the cables of the sails above, draped down to a floor area approximately 12 metres square. The mesh is galvanised and painted and is composed of wires 1.6mm thick to resist the beaks of the larger birds. Visually the mesh is fine enough to be almost invisible to the visitor, but strong enough to take the prestress load giving the aviary its form. Any sharp corners have been avoided to eliminate damage to the wings of birds in the aviary whilst flying.

The aviary was suspended from the tensegrity mast via a series of ridge, eaves and corner cables located between the tensegrity's mast support cables. Refer figure 11.

The mesh panels of the aviary were cut to final patterns before erection, tied together and then lifted into place. Prestress was carried out by means of a perimeter ring beam at the base. The final effect allows visitors to Marina Mirage the opportunity to view rare birds in an elegant and tranquil environment.

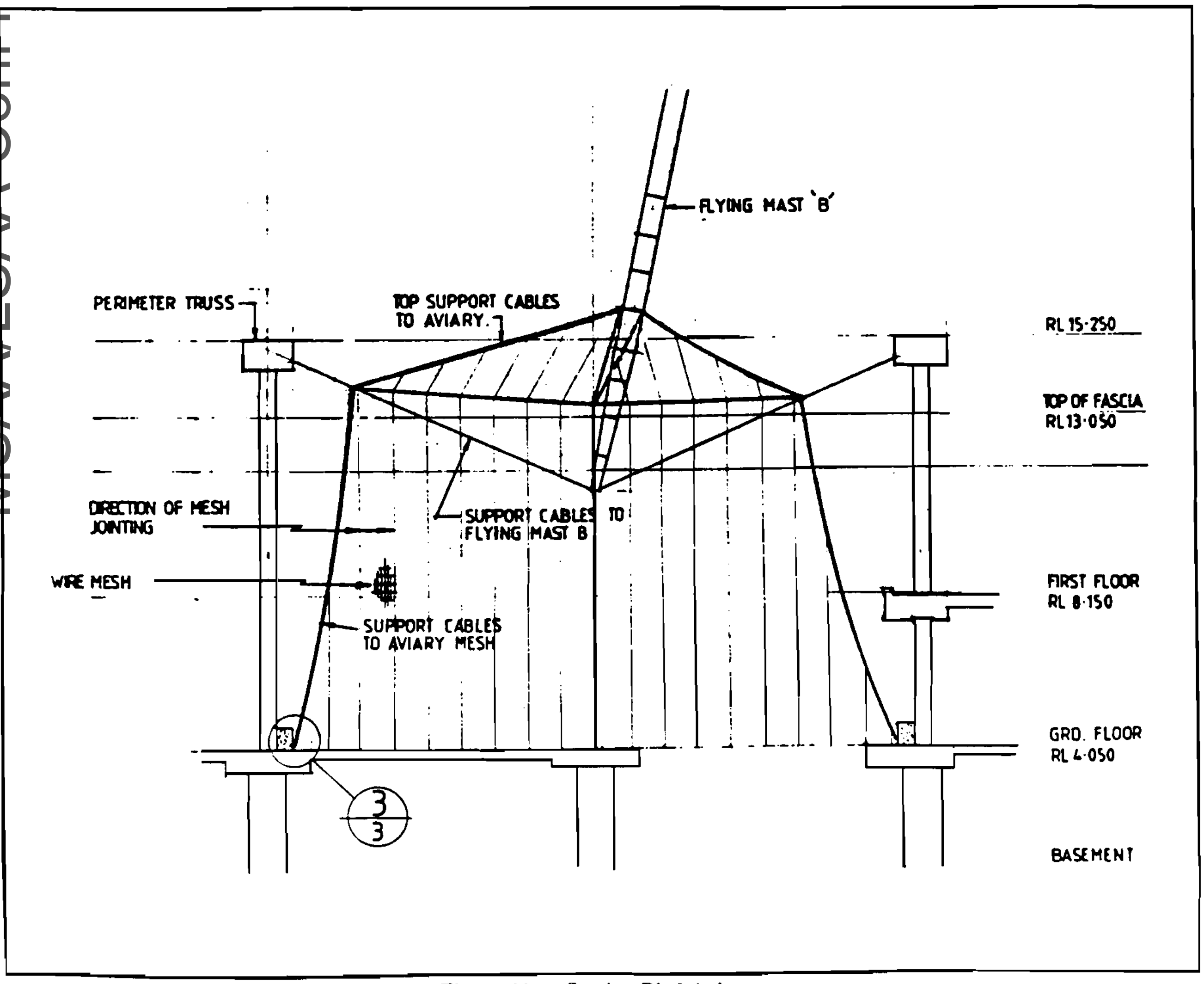

Figure 11. Section Bird Aviary

Building Data

Fabric Sail plan area	—	1500m^2
Fabric surface area	—	4500m^2
Total number of sail modules	—	10
Construction cost of perimeter beams, masts, cables and fabric	—	$850,000

Acknowledgements

Client .... Qintex Ltd

Architects .... Media Five

Engineers .... McWilliam Consulting Engineers

Main Contractor .... Watpac

Fabric, mast and cable contractor .... Vesl Membrane Systems