

The Envelopes of the Arts Centre in Singapore

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SUMMARY

This paper describes the planning and realisation of the envelopes for the Lyric Theatre and Concert Hall of the Arts Centre in Singapore, called The Esplanade Theatres. Starting with the geometry of the free form surfaces, the computer aided design process and the realisation by means of a customized building system is described.

The large variety of structural elements (members and nodes, glass panes and shadow panels) could be reduced by the application of complex, but rational geometric rules, to make the logistic of planning, fabrication, transport and erection feasible.

INTRODUCTION

At a site between Marina Centre and Marina Bay in Singapore, the arts Centre is progressing towards completion. The design is based on an earlier concept of Architects Michael Wilford and Partners in London and is executed by DP Architects (Vikas Gore and Pietro Stallon in charge) in Singapore. Significant characteristics are the envelopes of the Lyric Theatre and the Concert Hall (fig. 1).



Figure 1

The structures behind the envelopes are custom designed space trusses, providing triangular top chord grids for adjustment to the free form surfaces.

The cladding system comprises triangular panes of insulated glass and an arrangement of aluminium shading elements, giving the observer varying impressions of transparency and opaqueness [1].

In contrast, the roof cladding is opaque, consisting of a foil water barrier, which is covered by aluminium panels with open joints, similar to the façade shadow panels, but nearly flat. These panels also cover the deep gutters, which are positioned between each facade and roof structure.

The major challenges of the realisation have been

- the iterative adjustment process of the shading panels to meet the aesthetical and functional demands,
- the design, production, transport and erection of a very great number of similar, but different building components, and
- the coordination of an unusually large number of consultants, institutes and subcontractors.

THE GEOMETRY

Geometry on its own does not create a building, but without geometry the Arts Centre envelopes would never have become reality. Although dome and membrane structures are extreme examples for applied geometry, the practicability of many different structures depends on geometrical knowledge. Geometry played a major role from the design to the fabrication of the Arts Centre [7].

'Formfinding'

The surfaces of both envelopes are NURBS, which stands for 'Non Uniform Beta Splines', a mathematical description for free form surfaces. Stimulation for the development of NURBS came from the ship building, automobile and airplane industries. Coons and Bezier developed the theoretical basis for the implementation into CAD programs, which simplify the application. Parameters and equations were substituted by 'weights' and 'control points' and their influence on the form of the surface can be controlled by graphic representation.

With this technology available, the Arts Centre's envelopes were designed with the CAD program Microstation by 'Atelier One' in London, which were consultants to DP Architects. Four sided surface areas (Coons patches) were generated in a mesh of spline curves, which could be modified individually without changing the whole mesh.

Members and Nodes

After deciding on the surface form, a net of members and nodes could be generated. A method was applied, that is known from the generation of cable nets. A square net of constant 1,5 m module was 'laid' on the surface in such a way, that only the nodal points meet the surface and the connecting members remain straight.

The difference between Concert Hall and Lyric Theatre layouts is that the net of the former is orthogonal, while it is diagonal for the latter (fig. 2).



Figure 2

Splitting each rhombic configuration resulted in a net of plane triangles, which was required for the support of plane glass panes as well as for the structural stability. However, a square net of members was added 90 cm below the triangular net. Together with diagonal members between both nets, space trusses were generated that enhanced the stiffness without affecting the lightness of the structures (fig. 3).

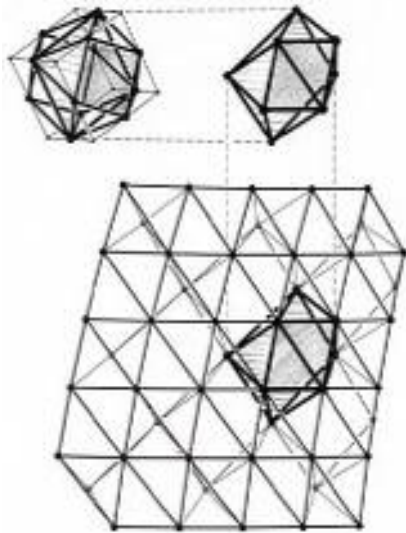


Figure 3

Colour Management

For the management of the great number of building components (8.300 nodes, 34.500 members, 10.500 triangular glass panes, 4.900 shading elements and 2.230 roof panels), colour identification marks for the nodes and members were introduced, which were related to their position. By means of this colour-coding it was possible to identify each group of components throughout the design, fabrication and erection.

DESIGN AND CALCULATION

The design and calculation is based on the following steps:

- the bearing concept
- the evaluation of loads
- the calculation of deflections, member forces and reactions
- the dimensioning.

The Support Concept

The space trusses are supported at each second or third top chord node on the concrete edge girders. The upper edges of the space trusses are only supported at some bottom chord nodes on top of concrete columns (fig. 4).

The upper edge bearings differ from the lower edge bearings by

- the realisation of horizontal movements
- the vibration insulation.

Static Bearings

For the stabilisation of the facade structures it was necessary to support the lower and upper edges of the space frames. This was achieved at the lower edges by a full restraint of the bearing points.

However, at the upper edges it was necessary to choose a layout of bearings that allowed for the thermal expansion of the structures; each structure is rigidly fixed to the non resilient stair towers. All other bearing points are supported horizontally only where statically required.



Figure 4

The flexibility of the stair towers was considered in the analytical model, as well as the flexibility of the concrete girders at the lower edges and the concrete columns.

Vibration Insulation of the upper Bearings

The purpose of the vibration insulation is to prevent the transfer of body sound from the cladding into the concert and theatre auditorium. A possible solution had to solve the problems of unrestrained support, minimum size and sustainability. Taking the experience with similar applications into consideration, natural rubber was the appropriate solution for the problem. A low creeping value and a moderate increase of stiffness for dynamic loading can be achieved by special rubber compositions.

For the layout of a vibration isolation with rubber cushions, ARTEC Consultants Inc. from New York N.Y. / USA proposed the following design parameters:

- eigenfrequency < 10 Hz
- maximum strain < 15 % for permanent and < 45% for temporary loading
- static deflection \approx 4 mm.

These parameters were considered in a design concept, that was developed together with Wölfel Consultants from Würzburg / Germany and coordinated with Wilson, Ihrig & Associates from Oakland, CA / USA, specialists for vibration insulation, working for ARTEC.

The biggest problem of the layout of the rubber bearings was the strong interaction between static and dynamical requirements. Two values of support stiffness were considered to meet the stress depending Young's modulus of the rubber cushions:

- soft support for permanent loads
- stiff support for wind peak loads.

The horizontal bearings are structurally separated from the vertical bearings. As the rubber cushions can only transfer compression, two rubber cushions are required for each bearing. Furthermore, the rubber cushions are prestressed to avoid gaping and to provide an almost constant stiffness under varying loads.

The required surface area of the chosen 2 x 26 mm thick rubber cushions for the vertical bearings was iteratively evaluated on the basis of approx. 4 mm static deflection, thus keeping the eigenfrequency of the bearings below 10 Hz.

For the horizontal bearings, the required surface of the rubber cushions is derived from the prestress force, which is equivalent to the maximum wind load, equally keeping the eigenfrequency of the bearings below 10 Hz.

Loading

The following loads had to be considered:

- dead loads
- wind loads
- live loads and installations
- thermal loads

Dead Loads (DL)

The dead load of the space trusses was considered automatically by the calculation program (Meropro). The cladding dead weight is 0,85 kN/m².

Live Load (LL)

Local regulations require the consideration of 0,5 kN/m² live load. Furthermore, an installation load of 0,1 kN/m² was considered.

Wind loads (WL)

Wind tunnel tests were performed at the City University of London in the initial design phase to obtain the wind pressure coefficients for the envelopes.

The pressure tabs were applied to the smooth model skin, equivalent to the real building's glass skin. The shading caps were applied with a separate wire model. The tests were performed for 'caps off' and 'caps on'. For the design calculation, the average values of pressure coefficients from both measurements were applied. The drag forces were calculated from the pressure values.

As this approach left some questions open, the client requested additional tests for clarification. For this reason, the resulting reactions of the envelopes were measured in the wind tunnel of the steel building department at the RWTH Aachen / Germany [4]. Furthermore, the

pressure coefficients were measured again. The models from the previous tests could be used again by courtesy of the City University London.

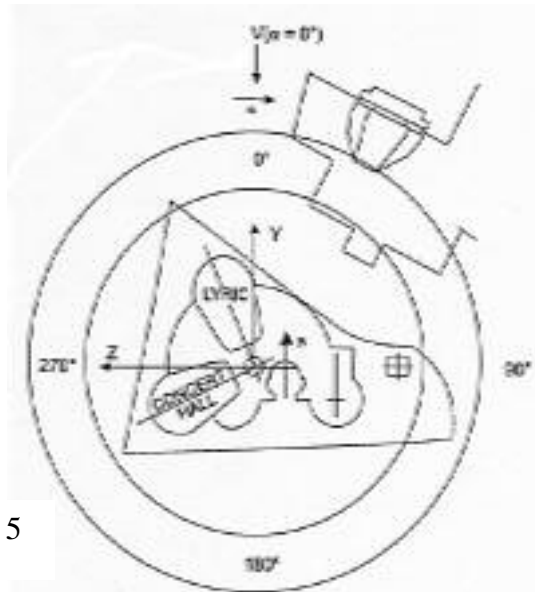


Figure 5

Test set up

Fig. 5 illustrates the set up on the turntable, which could be rotated up to 360°. The boundary layer and the natural wind turbulence were simulated.

Measurement of Pressure Values

The measure points, 1 mm bore holes with pressure tabs, were applied to the inside of the model. The position of the tabs is indicated on figures 6 for the theatre and concert hall respectively. The frequency of the measured pressure coefficients is shown in fig.7 for the Lyric Theatre, tab 5 / 150° wind direction.

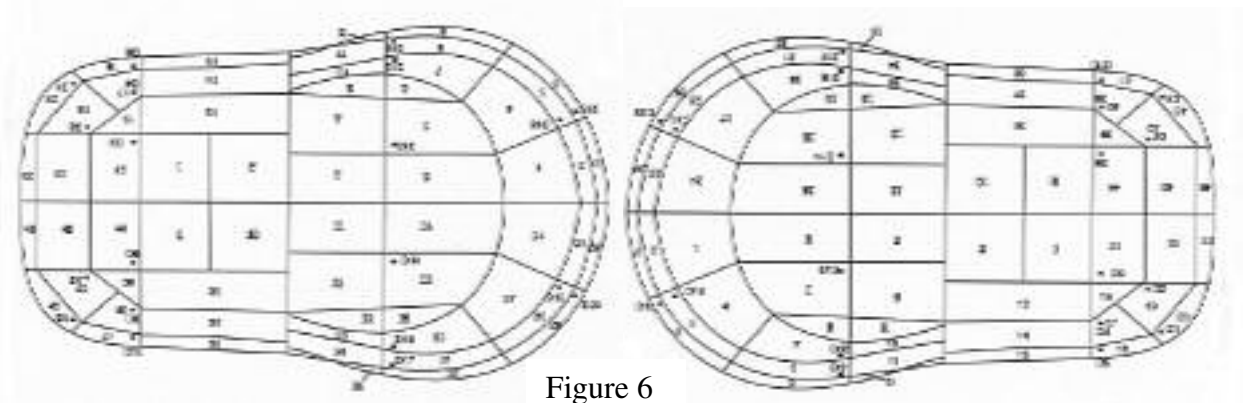


Figure 6

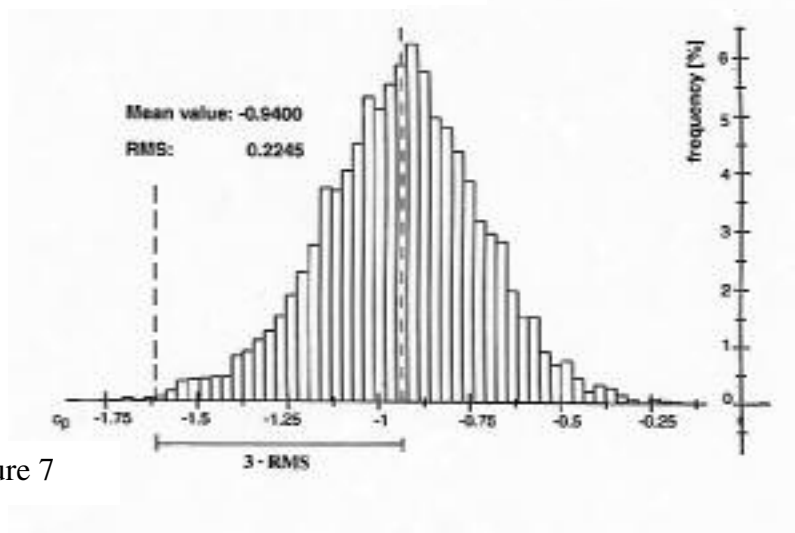


Figure 7

The foundation loads were measured for wind directions from 0° to 360° in steps of 30°. For comparison, the resulting forces were calculated from the measured pressure values. Measured and calculated results are listed in table 1 for 'caps on', indicating that the calculated values, with consideration of drag forces, are significantly greater than the measured values.

Table 1 angle α	Measurement				Calculation	
	'caps on'		no drag		drag	
	force [kN]	direction [°]	force [kN]	direction [°]	force [kN]	direction [°]
0°	924	170	536	178	1332	177
30°	616	262	504	252	1124	222
60°	594	275	550	274	1178	249
90°	1062	293	1024	286	1882	283
120°	581	326	784	301	1700	304
150°	206	302	228	282	1079	321
180°	398	8	194	54	923	6
210°	1127	22	387	37	1051	28
240°	827	41	567	34	1259	44
270°	840	53	598	52	1294	80
300°	1156	78	1005	79	1737	101
330°	568	108	836	117	1628	133

Evaluation of Nodal Forces for the Analysis

The nodal forces were calculated by a program from the surface loads, related to

- the loading zones with constant pressures (fig. 6) and
- the effective areas for the nodal loading.

As discussed above (chapter 2.3), the nodes in each loading area were assigned individual colours. Depending on the wind direction (load case), the program then related each colour to a certain value of pressure.

Thermal Loading (TL)

Temperature changes in Singapore are very small. The biggest temperature change would result from the air conditioning and was considered with a temperature difference of $\pm 20^\circ\text{C}$.

Static Calculation

Load Combinations

In principle, British Standards have to be applied in Singapore. BS 5950: Part 1: 1985 describes the combination of basic load cases, considering partial safety factors:

- 1.4 DL + 1.6 LL + 1.2 TL
- 1.0 DL + 1.4 W + 1.2 TL
- 1.2 DL + 1.2 LL + 1.2 WL + 1.2 TL

A design wind speed of 34,5 m/sec was calculated from a basic wind speed of 33 m/sec with CP3: Chapter V, Part 2, leading to a design wind pressure of 0,75 kN/m².

The evaluation of wind loads was performed as follows: the wind components orthogonal to the building surfaces were considered for 'caps off' and 'caps on'. Additionally, drag components were calculated for 'caps on'. This resulted in a conservative structural layout as indicated already in table 1.

Twelve wind directions were considered (0° – 330° in steps of 30°) for 'caps on' and 'caps off'. Together with three dead load cases, one live load and two temperature load cases, a total of fifty and two load case combinations were considered. Furthermore, eight erection conditions were calculated.

Dimensioning Concept

The basic calculations and the dimensioning were performed by the above mentioned Mero-prog. This program was developed by Mero for the design of space trusses, covering the steps from the geometry to the numerical controlled manufacturing.

The lateral bending of the top chord members from dead weight and direct support of the glass panes was not considered for the analysis, but for the following dimensioning of the members.

The related procedure is covered by a general approval from the German Building Institute [5]; the concept is adjusted to the German Standard (DIN 18 800), which again is generally equivalent to BS 5950 Part 1 (ultimate limit state design) and, therefore, was accepted in Singapore. The member sizes could be minimized by the iterative dimensioning procedure.

Stability checks were performed for selected load combinations with the optimised structures. The nonlinear analyses were performed with the program STAAD. This program was also used by the professional engineer in Singapore (who prepared all calculations and drawings for the accredited checker), so that only the input data had to be transferred to Singapore.

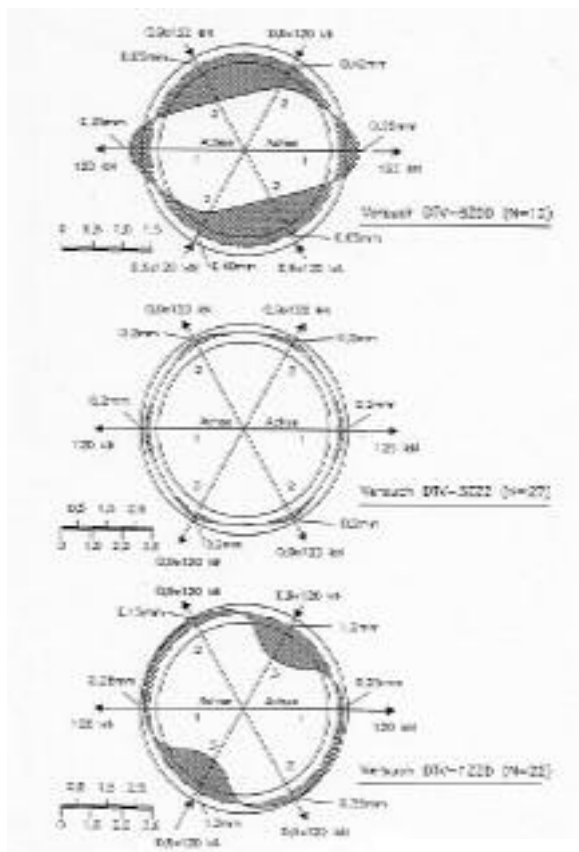


Figure 8

A speciality of any space truss design is the layout of the nodes. The main objective is, avoiding collisions between connecting members. A stress check is not possible, however, empiric rules from tests are available for the dimensioning [6].

Two different node types were used for the Arts Centre:

- spherical nodes for the bottom chord
- and
- bowl nodes for the top chord.

Tests were performed at the University of Karlsruhe / Germany with bowl nodes. They revealed that the bolts of the connected members failed before the nodes reached the limit state of serviceability (fig. 8). With these results, the check of the nodes could be substituted by stress checks of the connecting bolts.

Results of the Dimensioning

The relevant results from the dimensioning are listed in table 2.

Table 2	Results of the Dimensioning (mm)	
	Lyric Theatre	Concert Hall
Circular tubes for bottom Chord and diagonals	d = 48,3 – 88,9 95% d ≤ 60,3	d = 48,3 – 88,9 98% d ≤ 60,3
Square hollow sections for the top chord	60 x 60 – 90 x 90 98% h = 60 x 60	60 x 60 – 90 x 90 99% h = 60 x 60
MERO – spherical nodes	d = 110 – 155 90% d = 110	d = 110 – 155 92% d = 110
MERO – bowl nodes	d = 160; 200 98% d = 160	d = 160; 200 96% d = 160

CONSTRUCTION

The Steel Structure

DP architects and Atelier One had planned the structures as single layer tubular frames with welded connections. As an alternative, MERO suggested double layer space trusses with bolted connections, which provide high accuracy through machined fabrication and, therefore, could be easily adjusted to the free form surfaces.

This meant that MERO had to take the full responsibility for the cladding design and build.

The Space Trusses

To avoid a secondary support system for the glass panes, the top chord members of the space trusses had to be square hollow sections, which could directly support the glass panes.

Bowl type nodes have been selected for the connection of the top chord members and the tubular diagonal members. To keep the nodes small, special head plates were used for the square diagonal members, which divide the rhombic configurations into triangles (fig. 9).

The space diagonal members and the bottom chord members are made from round tubes and the nodes are forged spheres, corresponding to the design rules of the Mero approval.

All components were produced at the MERO workshops in Würzburg / Germany.

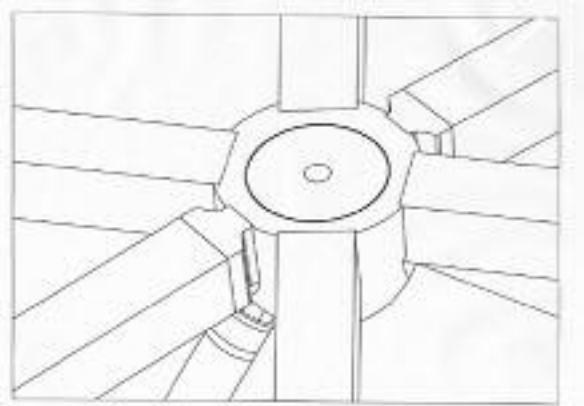


Figure 9

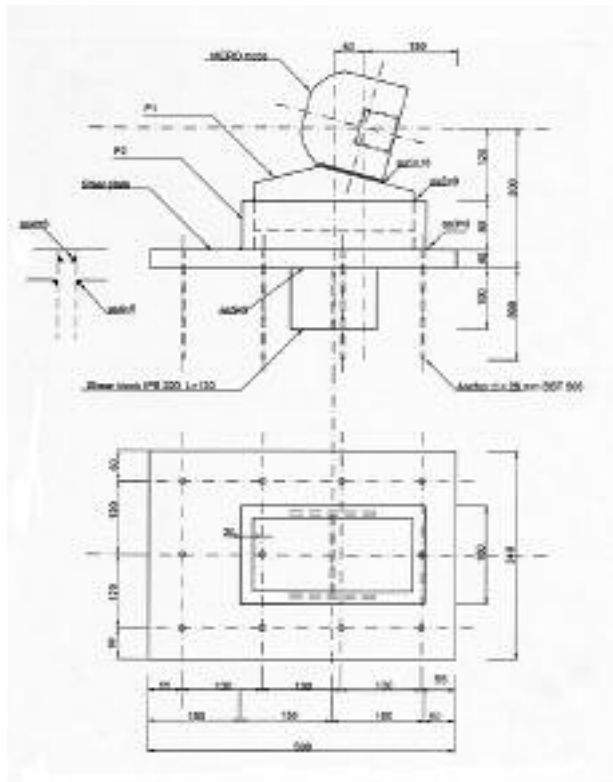


Figure 10

The bearings

Corresponding to the support concept the bearings were realised as follows:

- the fixed bearings on the concrete edge girders support the space trusses in the top chord nodes. The bowl nodes were welded to rectangular interfaces, that were guided within rectangular hollow sections, which eventually transfer the support loads to the bearing plates. The chosen layout allowed the compensation of vertical and horizontal tolerances (fig. 10).
- the bearing nodes of the upper edges were realised by cylindrical stubs with hemispherical heads. The cylindrical stubs are guided in tubes for vertical adjustment. The horizontal adjustment was done by moving the tubes on the head plates of the rubber bearings prior to welding (see fig. 4).

The Glazing

Theoretically, only every second of the 10.500 glass panes is identical. By allowing a tolerance of $\pm 2,5$ mm, which could be adjusted within the joints, the number of pane types could be reduced to approximately 1.500.

The layout of the insulated glass is equal for all panes: outside 6 mm fully toughened green glass, followed by 12 mm airspace and inside 2 x 5 mm laminated heat strengthened glass. A low E-layer is positioned on the inside of each laminated pane.

The glass panes are fixed against wind suction by means of aluminium discs at the top chord nodes and by two additional clamps at each top chord member (fig. 11). The clamps are positioned on top of the glass, as the durability of the glass compound could not be guaranteed for clamps applied within the edge sealing of the insulating glass panes.

Special attention was given to the layout of the joints between the glass panes. A drainage system of primary and secondary EPDM gutter profiles guide the water, that may occur from condensation, to EPDM discs, which are positioned on top of the bowl nodes, and further down to the main gutter of the concrete edge girders (fig. 12).

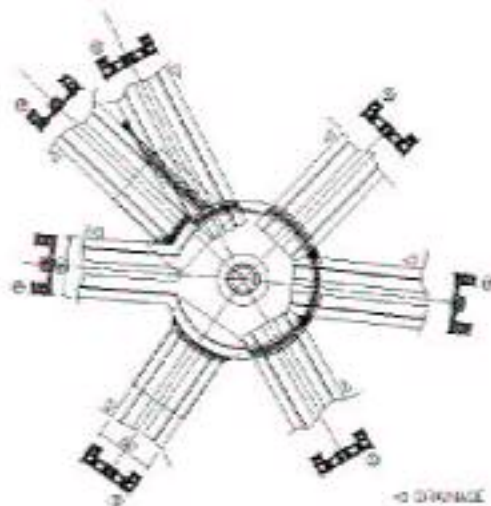


Figure 12

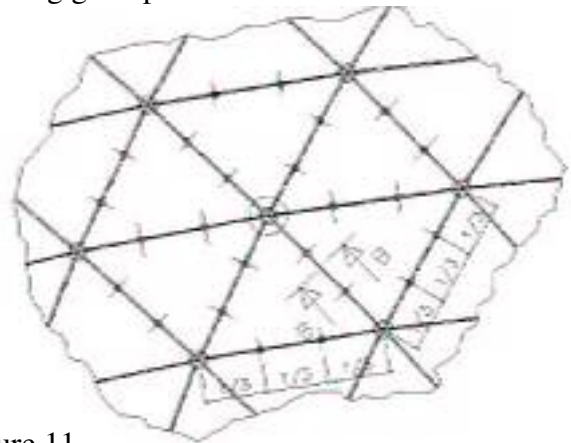


Figure 11

The outside sealing was realised by silicon joints with a constant width of 20 mm.

The drainage system can only work if the joints are ventilated. Because of the possible condensation of humid air inside the joints, a ventilation to the outside seemed risky. It could be shown however, that condensation can only appear for very short periods of time.

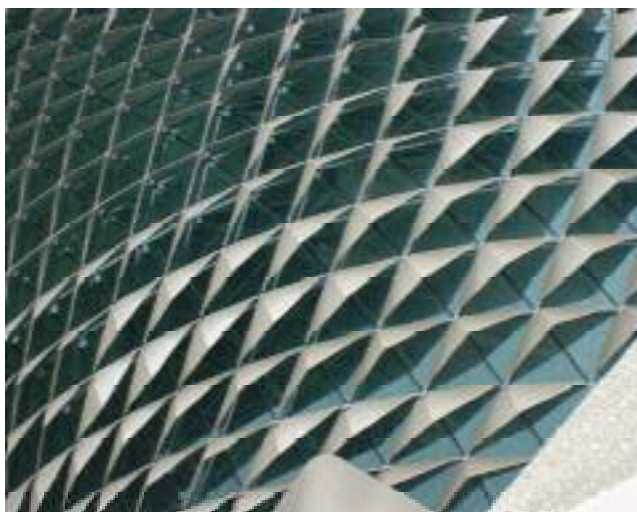


Figure 13

Shading Panels

The facades of the Lyric Theatre and the Concert Hall are covered by 4.900 panels and the roofs by 2.230 panels. The design proceeded in two steps:

- first step was the iterative optimisation of the rise of each panel, which required the intense cooperation with the architect and the cladding consultant (fig 14),
- second step was the optimisation of panel cutting types, similar to the glass panes. This step produced approximately thirty basic panel patterns and thirty more special patterns for the edge panels.

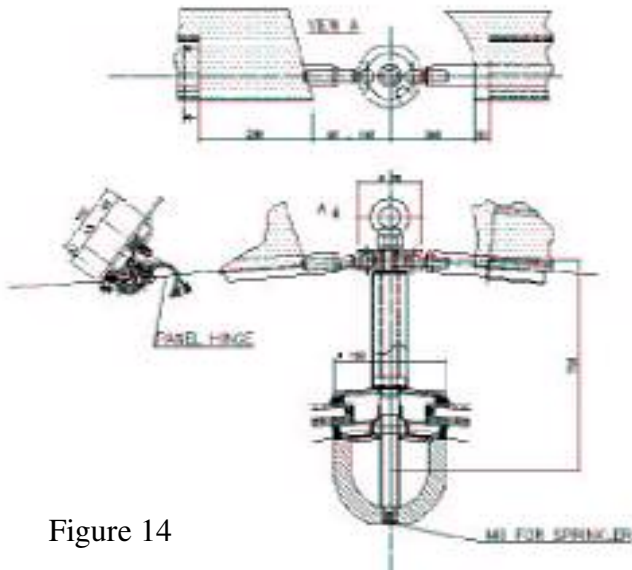


Figure 14

The panels consist of 4 mm thick aluminium sheets, which are supported approximately 300 mm above the top chord of the space trusses by means of aluminium tubular frame structures with special connectors (fig.14).

The panels are curved along the short diagonal and are fixed to the tubular frames by means of hinges, so that each panel can be opened in two directions for maintenance.

A certain worry was the possible wind vibration of the shading panels. However, a calculation revealed, that the lowest eigenfrequency of the folded panes was well above 10 Hz, so that a gust excitation of vibrations could be excluded. A high frequency vortex vibration, however, could not be observed during tests performed in Singapore.

THE ERECTION

It was intended to base the erection planning on the sections introduced for the representation of the wind loads and used for the colour the management. The erection would follow the sections from top to bottom and proceed to the horizontally adjacent sections.

Erection Planning

Two independent working groups would start erecting from one end of the symmetry lines. This meant that the scaffolding had to be provided in due time prior to starting the erection in the consecutive sections.

A scaffolding, similar to the locally common bamboo-scaffolding, was chosen to allow adjustment to the hardly predictable requirements of the three dimensional space truss geometry. For that reason, the loads from supporting the space trusses had to be calculated 'real time' with the erection progress and considered for the layout of the scaffolding.

The erection of the cladding system (drainage, glazing and shading) was to follow the same procedure by means of temporary platforms. They were to be provided in horizontal sections consecutively from the upper to the lower edge. For the practical realisation however, it proved favourable to provide the platforms for all levels and several sections simultaneously.

Erection Performance

The erection started with the installation of the bearing plates, including anchor bolts and shear studs. After fixing the plates with grout and after a final measurement, the bearing components were adjusted and welded to the bearing plates.

Next, some space truss units of 4,5 m x 4,5 m up to a maximum of 9 m were preassembled on ground and lifted on top of the concrete edge girder. This units were stable after connection to the bearings and required no additional support.

After completion of these basic units, the erection proceeded with single members and nodes, first in the horizontal and then in the vertical direction of each section. However, the machined faces of the nodes and members fabricated with intentionally small minus tolerances, together with permanent measurements of the node positions, enabled the erected structure to meet the prescribed geometry.

The erection of the glazing and of the shading panels followed after the completion of two space truss sections. The erection of the drainage system for the façade glazing started from the upper edges with two working groups and proceeded downwards in each section. The EPDM gutter profiles were temporary fixed on top of the RHP members by self tapping strips and finally fixed by screws.

The erection of the glass panes followed immediately after the gutter profiles were fixed. The glass panes were delivered in frames, each containing six panes. They were lifted to the erection platforms and distributed to their individual positions on top of the EPDM gutter profiles. After adjustment and horizontal fixation, the joints between the panes were sealed with silicon, before the panes were fixed vertically by means of discs at the nodes and two clamps at each supporting beam.



Figure 15

The erection of the shading panels followed the same procedure (fig. 15) and started with the erection of the clamp nodes for the fixation of the tubular frame members. These provide spherical end pieces, which fit into the clamp nodes and allow the adjustment to any angle prior to fixing the clamps. Finally, the shading panels were fixed to the tubular frame members by means of hinges.

CONCLUDING REMARK

The envelopes of the Arts Centre in Singapore have proved, that modular systems together with the application of CAD tools allow the realisation of complex structures without unreasonable restrictions to the architects conceptual design.

PARTICIPANTS

Client: The Esplanade Company Ltd. Singapore
 Architect: DP Architects Pte. Ltd., Singapore
 General Contractor: Penta-Ocean Construction Co. Ltd., Singapore
 Project Manager: Public Works Department (PWD), Ministry of National Development;
 Arts Centre Development Division (ACDD), Singapore
 Cladding Consultant: Atelier One, London / U.K.
 Cladding Contractor: MERO GmbH & Co. KG, Würzburg and
 MERO Asia Pacific Pte. Ltd., Singapore

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