AURORA PLACE CABLE NET CANOPY ANALYSIS AND DESIGN

Peter MacDonald
Senior Associate, Ove Arup and Partners, Sydney

Abstract
This paper describes the design process from concept to fabrication to realise the desires of architect Renzo Piano for a canopy of glass supported by a "spiders web". The canopy has a plan area of about 650m^2 and is slung between a 20 storey residential tower and a 45 storey office tower in Macquarie Street, Sydney. A maximum span of about 30 metres. Support for the frame-less glass is provided by a cable net formed into an anticlastic surface to ensure structural resistance to both downwards and upwards loading. The cable form finding process is discussed along with a unique analysis method to warp the glass surface (form-find) into a shape that will provide positive falls to a single drainage point at the northern edge of the canopy. Design of all the net elements including glass, castings (spiders and nodes), rods and struts is presented. The developed erection methodology is discussed along with a brief review of the road that led to the current design.

Introduction

Ove Arup and Partners and Renzo Piano Building Workshop were appointed by Lend Lease to develop a concept for the canopy to cover the 650m^2 Piazza between the 45 storey Aurora place office Tower and the 20 storey Macquarie apartments. The concept developed was a thin layer of glass with no secondary structural members supported by a "spiders web" cable net, slung between the two buildings. The solution began with two cable nets, one each side of the glass (Figure 1), to resist upwards and downwards loads respectively. In order to reduce costs, an anticlastic shaped single layer cable net was developed above the glass plane (Figure 2).

Following tender negotiations, Austress Freyssinet were appointed as the canopy sub-contractor. Their proposal for the canopy replaced the spiral strand cables with stainless steel bar. Ove Arup and Partners were novated by Lend Lease to Austress Freyssinet to develop all aspects of the detailed design and erection procedure for the canopy.

The typical cable net is formed of 18mm diameter, high tensile, stainless steel rods connected at each intersection via stainless steel cast nodes. The glass is typically 16mm thick laminated toughened and patch supported at each corner via stainless steel cast spiders. The link between the glass plane and the cable net is via varying diameter (22mm O.D - 73mm O.D.) and length (300mm - 7000mm) stainless steel circular hollow sections.

Wind Tunnel Testing

A 1 in 400-scale model of the canopy was pressure tapped and tested in the Monash University boundary layer wind tunnel. Surrounding building were modelled to at least 500 metres from the canopy.

Two sets of results were derived from the wind tunnel. Peak cladding pressures were taken from the point pressures measured at each of 40 upper taps and 10 underside taps. Structural loads were determined by manifolding taps to form four area averaged panels. In order to accurately calculate the differential pressure across the canopy surface, pressures were measured on each surface and the difference calculated digitally.

The results gave peak cladding pressures for the glass design of about +/-900 pascals. The peak area averaged structural load was about +600 pascals (down) or -250 pascals (up). These results confirmed that down wash from the surrounding buildings was the dominant wind loading process, giving a very small net upward force on the canopy.

Cable Net Analysis and Design

Early development

The original concept for the canopy consisted of two cable nets either side of the glass plane. One to resist upwards load and one to resist downwards load. The typical net was made from single 19mm diameter spiral strand stainless steel cable (Grade 316). (Figure 2). Preliminary costing indicated a problem with the budget. After consultation with industry suppliers the following changes were made.

The typical cable net was changed from single 19mm to twin 11mm diameter spiralstrand. this diameter is significantly cheaper as it is commonly available for the yachting industry.

The cable net above the glass plane was re formed into an anticlastic shape and the lower cable net removed. This produced large cost savings in cables and connections.

As a result of the tender process further changes were made to the concept. The main change being the move from stainless steel spiral strand to stainless steel rods.

Form-finding
The cable net is a structure that derives its strength and stiffness purely from its form. Hence, some considerable effort was spent to ensure the anticlastic shape was stiff for both upwards and downwards loads. The structure was form-found using an in house dynamic relaxation program. The boundary conditions and support points were set then each intersection on the net restrained to a vertical greasy pole. An iterative process was then used to determine a prestress field such that the reactions on the greasy poles were negligible.

Analysis and load cases
Once form-found, the following loads were considered;

Selfweight (rods, droppers, castings and glass)
Live (not critical for net design)
Wind (as per wind tunnel report)
Prestress
Temperature (+/-25 degrees)
Earthquake (found to be negligible for such a light structure)

Rod design (refer figure 3)
Rods were designed on the basis of results from an ultimate limit state (ULS) analysis of up to 30 combination load cases from the above basic load cases. The bars chosen were cold worked grade 316 stainless steel with a yield at 0.2% strain of 530MPa. With a material safety factor of 1.2, the typical 18.3 diameter rod had an ultimate capacity of approximately 116kN.

For the main backstay rods between the "puntone" or bowsprit struts and the building anchorages, a higher grade of stainless steel bar was adopted to resist the large forces. The bar grade had greater resistance to corrosion than G316 and a yield at 0.2% strain of 1000MPa.

Casting design
All connections between rods within the net and at the boundaries of the net are being made using stainless steel investment castings. Typically the material is grade SAF2205 with yields at 0.2% strain of between 450MPa and 550MPa.

The two typical net nodes are shown in figures 3 and 4. The flatter node can be used on about 70% of the cable net connections. The large node is used where the angle changes between rods are large. The node is made up of six parts. The main body or ring, the dropper head ball and four spherical washers. This configuration ensures free movement of the dropper to cope with ever changing dropper angles and sufficient angular tolerance for the typical net rods in the horizontal and vertical plane. Analysis of the nodes was carried out using a simple beam model(Figure 6).

The edge nodes for the main catenary are shown in figure 5. These elements were analysed using finite element plates.

One, two, three and four legged spiders were developed to connect the glass to the droppers. Architecturally shaped, the spiders had a requirement to rotate at the neck to accommodate the varying angle between the glass plane and the vertical droppers. Once in place the neck is locked to resist bending moments from out-of-balance live load on the glass panels.

Dropper Design
The primary design action for the droppers was the downwards dead, live and wind loads (i.e. tension). However, upwards wind loads are sufficient to induce compression in the droppers. Slender circular hollow sections were chosen as suitable to resist these loads, along with some bending moment due to out-of-balance live load from the glass. A slenderness limit of 350 was used in the design.

Testing
In order to verify design and as a check on the manufacturing process, three of each type of casting is to be load tested. The load testing includes proof load testing (1.25 times working load) and then testing to destruction.

Glass Analysis and Design

Glass loading
Glass loads were determined from AS1288-1994, AS1170.1 and the MEL Consultants wind tunnel report. Loads adopted included;

Glass selfweight of 25kN/m^3
Uniform live load of 0.5kPa (higher on some smaller panels)
Point live load of 1.1kN on a 150mm diameter disk - applied at a few critical locations
Wind load of +/-0.9kPa (Vp)

Temperature load +/-25 degrees Celsius (point supports were detailed to allow the glass to expand and contract)
Warping of 5mm per square metre.

Glass Analysis
Due to the irregular shape of the glass and the point supports, non-linear finite element analysis was used to size the glass. Typical panes were analysed for the above load cases. The result was two different thicknesses of glass. Typically the glass was two sheets of 8mm thick toughened glass laminated with a pvb inter-layer. Glass with any dimension greater than about 2000mm was increased to two layers of 10mm thick toughened glass.

As a cost saving Austress proposed an alternative glass of the same thickness but with one layer heat strengthened and the other toughened. This has been accepted subject to satisfactory results from an extensive testing program.

Warping Analysis
A major architectural characteristic of the canopy was a clear glass plane draining to a single point at the northern edge of the canopy (figure 6). Due to the irregular shape of the canopy there was no single shape (e.g. cone, sphere, cylinder) that could be formed with flat sheets of glass to achieve the desired drainage.

A finite element analysis was therefore undertaken to push the glass surface in to the desired shape for drainage and then measure the warping stresses induced in the glass. The analysis was set up using the Strand7 finite element analysis package. Two structural layers were used in the analysis. The bottom layer was a relatively flexible continuous membrane spanning from supports on the adjoining buildings. The top layer was made of individual sheets of glass disconnected from each other but connected to the continuous membrane below. Patch loads were applied to the continuous membrane, and an influence coefficient method used to achieve the desired deflection under each patch. The stiffness of the lower membrane was chosen as an order of magnitude lower than the glass membrane such that all the load was resisted by the individual glass panels. Once the required shape had been determined the maximum stresses in the glass were found to be in the order of 4MPa (long-term). These stresses were then taken in to account in the design of the glass. The induced warp of around 5mm per square metre was considered acceptable.

Erection Methodology
Erection of the net in the correct shape is essential to the structural performance of the canopy as it attains its strength from its shape. A complication to the erection is the need to erect an irregular and warping glass plane.

There is a separate paper on the erection of the net from the Contractors perspective. The current paper will describe the analysis used to prove the methodology.

The erection of the canopy can be divided into five main operations as follows:

- Erection of the cast-in plates on the commercial and residential towers
- Erection of the net to a snug tight condition
- Stressing the net
- Erection of the droppers
- Erection of the glass

Much of the erection analysis centred about taking the net from the erected snug tight condition to fully stressed. The technique used was as follows:

The form-found net was analysed under prestress only to determine the final net shape.
The net was then "cut" at two locations by inserting two very low area members. This caused the prestress to "fall out" of the net. This geometry was then taken as the snug tight geometry to which the unstressed net should be erected.
The displaced geometry from the analysis above was exported to become the starting geometry for a new analysis model. This model was then "stressed" by replacing the very small area elements and jacking the net by the application of prestress only at the designated jacking areas. The results of this re-stressed model compared very closely with the original form-found model. In particular the prestress field of both models was almost identical.

The analysis was then taken a step further by adding glass in patches to check the sensitivity of the net to the glass erection.

Summary
The Aurora place canopy is a significant lightweight structure in both architectural and engineering terms. It is an irregular structure that makes minimal use of structure to hold a thin layer of glass without the need for any secondary glazing support. A stainless steel spiders web supporting a thin layer of glass.

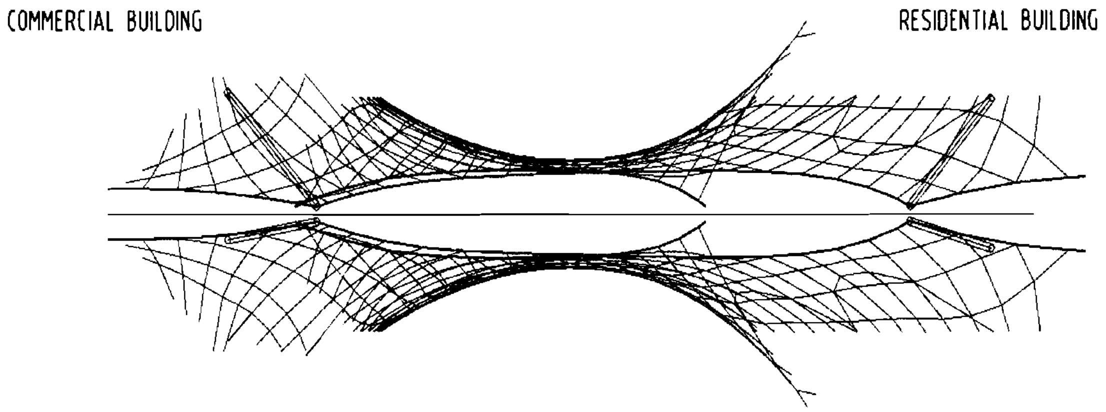

Figure 1 Dual Cable Net

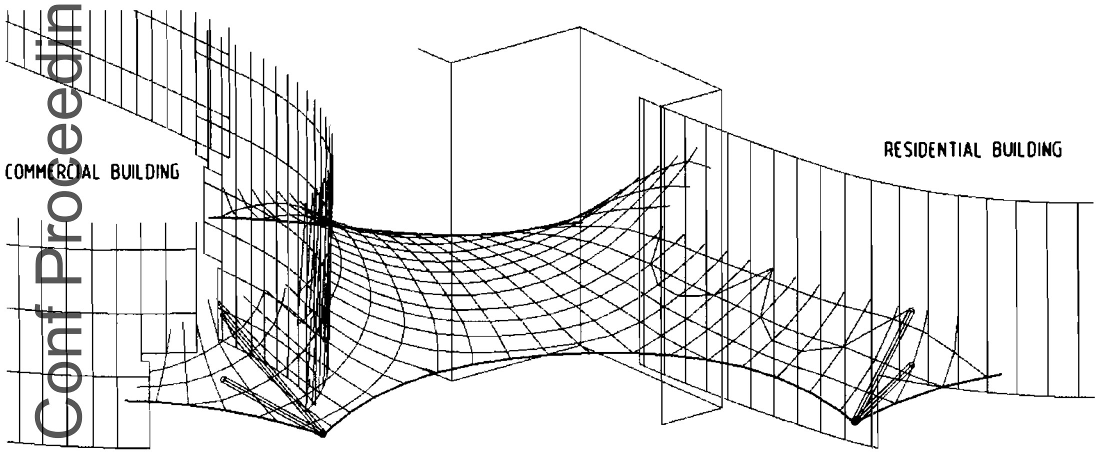

Figure 2 Single Anticlastic Cable Net

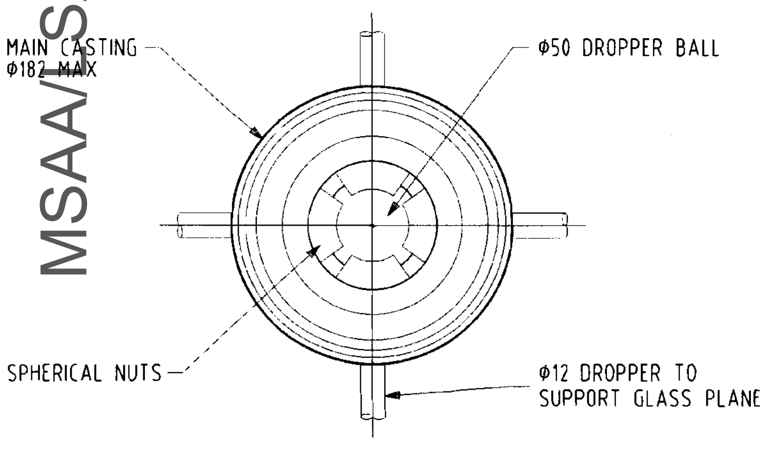

Figure 3a Plan on typical small net node (large similar)

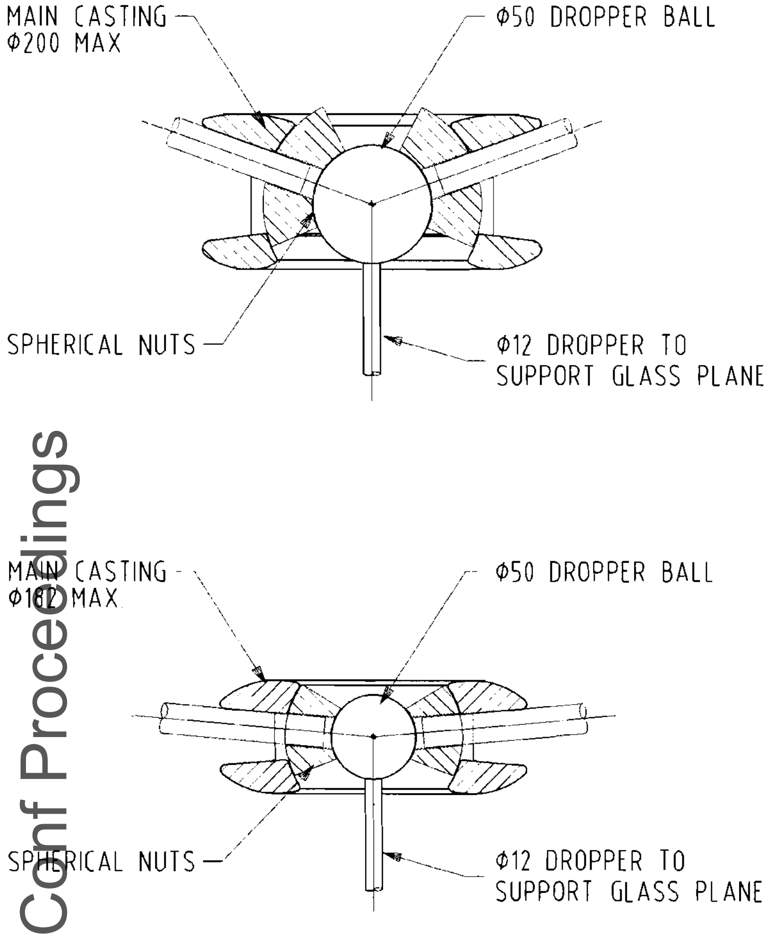

Figure 4Typical net node section (large and small)

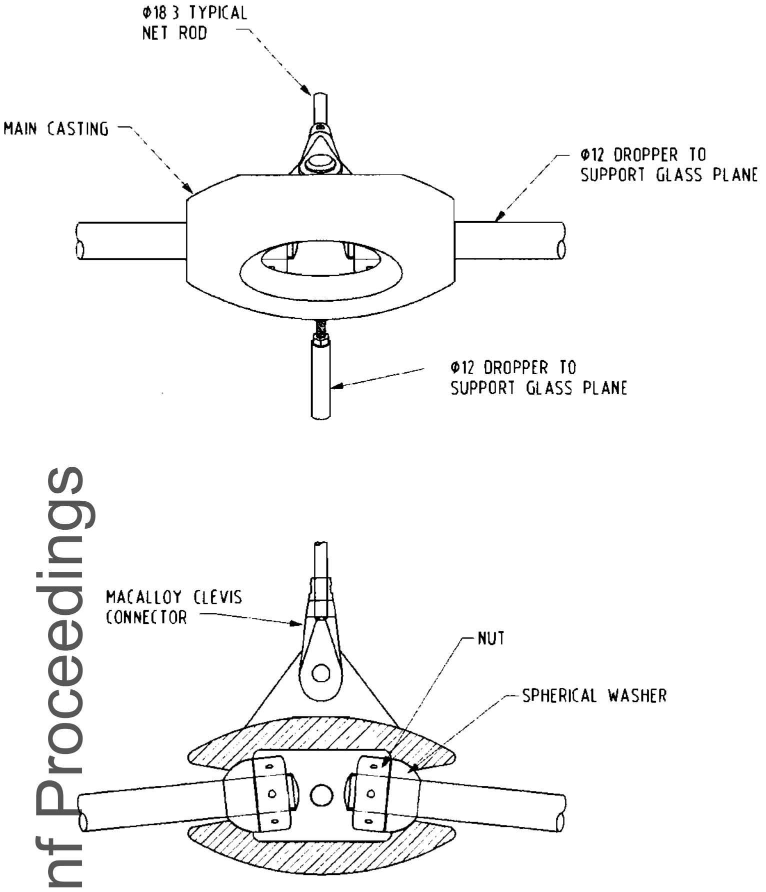

Figure 5 Typical edge node

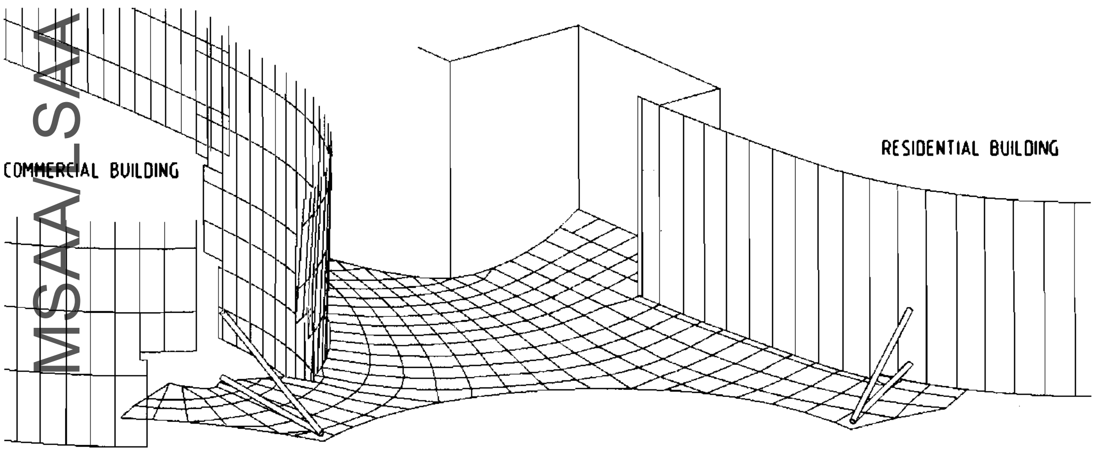

Figure 6 Warped glass plane