The Amazon Waterlily Pavilion, Botanic Gardens Adelaide

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1.0 INTRODUCTION

Figure 1 *The New Amazon Waterlily Pavilion*

Since its discovery in 1801, *Victoria Regia*, now known as *Victoria Amazonica* or the Amazon Waterlily, has inspired plant-lovers and artists alike with its stunning flowers and enormous leaves. Joseph Paxton, former head gardener at Chatsworth House in England, based his design for the Crystal Palace on the structure of the plant's exceptionally strong leaves, which can grow up to 2.65m in diameter and can support the weight of an adult male. Paxton's enormous glasshouse, built for the Great Empire Exhibition of 1851, was designed to be innovative and grandiose, with an iron frame supporting over one million feet of glass.

More recently, the Amazon Waterlily Pavilion, in Adelaide's Botanic Gardens, has been showcasing new examples of innovative glass engineering and construction practices inspired by this exotic plant. This glasshouse was constructed as part of the Botanic Gardens' 150th anniversary celebrations and replaces the original Victoria House, designed in 1867. The Victoria House had been designed by Dr Richard Schomburgk, the Gardens' second Director, who had personally collected and classified specimens of the Waterlily during expeditions to Guyana.

The new Pavilion features load-bearing glass columns and beams, and was completed in July 2007.

2.0 THE DESIGN CONCEPT

Figure 2 *Photographs of the Original Victoria House (from National Library of Australia and Department for Environment and Heritage (DEH))*

The 1867 timber-framed superstructure of the original Victoria House had been replaced by an aluminium structure in the 1950s and this was in a dilapidated condition in 2005. The decision was thus made to replace the superstructure with a modern glass Pavilion, whilst preserving the original heritage-listed lily pond in the centre of the structure.

The traditional solution for a glasshouse would be to provide a metal framework, typically in aluminium, to support the glass panels. However, this solution would not have been in keeping with the surroundings. Aluminium also has a linear coefficient of thermal expansion three times greater than that of glass, which can cause problems at junctions between these materials. Structural glass would provide a solution that would not detract from the surrounding heritage buildings, but that would also provide a modern, minimalist and elegant centrepiece for the Gardens' Sesquicentennial Celebrations and for their future.

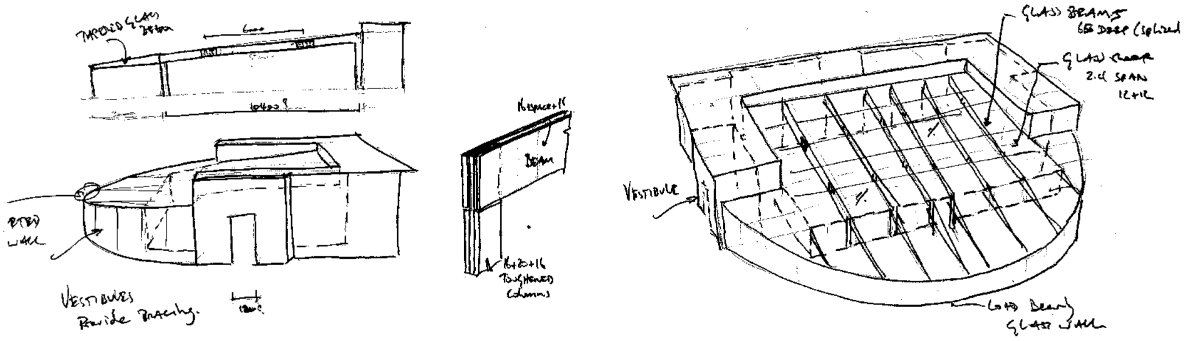

Figure 3 *Original Aurecon Engineering Concept Sketches*

The biological development cycle of the Amazon Waterlily flower had an impact on the aesthetic design of the Pavilion. The flower is white when it blooms initially, and this attracts scarab beetles to land and mate. During the mating process, the flower closes around the beetles and heats up overnight. This heating process involves a chemical reaction that changes the flower colour to a deep pink. In the morning, the flower opens and releases the beetles, which are only attracted to new white flowers, encouraging cross-pollination of the plants. The design of the Pavilion reflects the pink colour in accents in some of the glass panels, door handles and some steelwork.

3.0 GLASS AS A STRUCTURAL MATERIAL

The use of glass as a primary structural material is a nascent technology in Australia, and one that has only really taken off worldwide over the last decade. Engineers tend to have a fear of using the material, due to its brittle nature and perceived difficulties in analysis and detailing. There has also, until recent years, been no single comprehensive code of practice for structural glass design. However, glass is becoming more and more sought after by designers, as it provides the ideal aesthetic properties of transparency and/or translucency that are central to modern architecture.

Structural redundancy is extremely important in glass structures. The material itself is much stronger than concrete in compression but can fail in a sudden, brittle manner. All glass elements therefore are designed to facilitate safe removal and replacement, without leading to the collapse of surrounding elements. All planar elements in the Amazon Waterlily Pavilion (such as the walls and roof) are composed of laminated toughened glass, while critical load-bearing elements, such as the glass beams and columns, are triple-laminated. Each single layer of glass in the laminate is designed to withstand serviceability loads until replacement can be effected.

4.0 ENGINEERING DESIGN OF THE PAVILION

Glass forms the majority of the Pavilion's supporting structure; it contains around 400 separate glass panels covering an area of approximately $500m^2$. Due to cost constraints, it was not possible to create the structure entirely from glass, and steel was adopted to provide lateral support and to support part of the sloping side canopy roof; constructed in a pattern resembling the veins on the waterlily's giant leaves (refer **Figure 4**).

Figure 4 *Underside of A Waterlily Leaf (source unknown)*

Aurecon invested over 1000 design hours in the project to detail every junction and fitting, at 1:2 scales, to achieve the accuracy and tolerances required. Toughened glass cannot be re-drilled after processing, and entire panels have to be discarded if they don't fit. Tolerances are much smaller than those of steel or concrete.

State-of-the-art finite element analysis (FEA) software was employed to analyse every unique panel; glass has no ability to yield and the effects of stress concentrations and lack-of-fit at bolted connections cannot be ignored by engineers in this specialist field. Using FEA, Aurecon was able to reduce the thickness of the roof panels from the concept phase depth of 20mm down to 16mm; a sufficient saving to enable the client to purchase glass with a self-cleaning coating, thus reducing both maintenance costs and reliance on cleaning chemicals.

Figure 5 *Construction Worker Cleaning Glass Roof – Viridian 'Activ' Coating will reduce the frequency by which this is required (photo Jeremy Prentice, DEH)*

4.1. Design of Glass Columns and Beams

The authors are not aware of any other public buildings in Australia that feature structural glass columns and beams. These are possibly the most unique features of the Pavilion project. As the columns and beams are critical load-bearing elements in the structure, it was important to consider redundancy and prevention of disproportionate collapse in their design.

A safety factor of 3 was considered appropriate for the beams and columns. This was achieved using triple laminated glass, with each separate lamina of the beams designed to support serviceability loads until replacement can be effected. The glass columns comprise a central 19mm toughened core layer, with 10mm ‘sacrificial’ layers either side. The 10mm layers will provide scratch protection to the central core, and the 19mm layer can support serviceability loads (these columns provide support to the sloping steel-framed portion of the side roof). The columns were analysed using Strand7 to determine maximum stresses and also to carry out a buckling analysis, as they were originally intended to be free-standing. For the final design, glass panels were incorporated either side, which provide additional restraint against buckling.

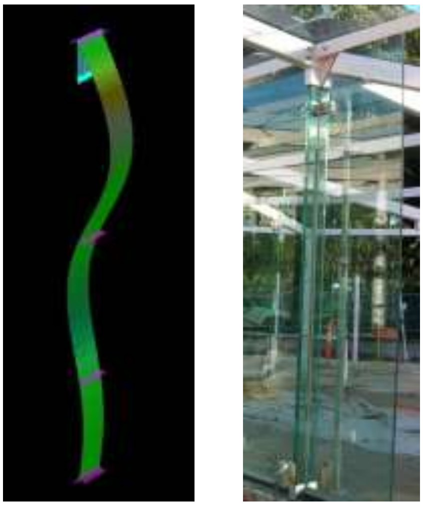

Figure 6 *Glass Column - buckling analysis in Strand7 and final installed photograph*

4.2. Design of Planar Elements (Roof and Walls)

The planar elements are less critical to the overall stability of the structure, so they were designed incorporating a factor of safety of 2; all of these elements were laminated. For the roof panels, each lamina can support temporary maintenance loads (for example, if a panel shatters while a cleaner is standing on it). The laminate will also prevent pieces of glass falling on to the public below in the event of failure. Maintenance rope support points (davits) were incorporated in to the design, and fixed through carefully designed holes in the glass to the steel supports below.

The roof and wall panels are supported using stainless steel patch fittings, which employ a bolt fixed through a hole in the glass, with steel circular clamp discs either side. Synthetic gaskets are used to separate the steel parts from the glass. Holes in plates cause stress concentrations and the cut edges of glass panels tend to be weaker due to tiny flaws, or micro-cracks, produced by the cutting process. Lack-of-fit or poor tolerances can also induce additional stresses at fixing points. This means that patch fixings need to be designed carefully, and the stresses around them analysed to ensure they stay within acceptable limits (in accordance with AS 1288: 2006). These analyses were carried out in Strand7.

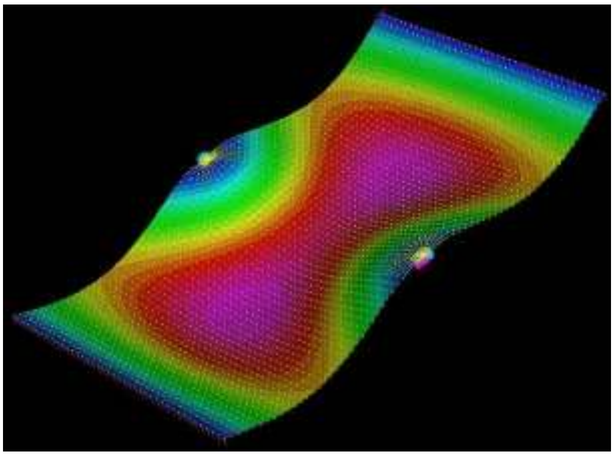

Figure 7 *Strand7 Analysis of Roof Panel*

Another design consideration, affecting the roof panels in particular, was possible de-lamination. The PVB (polyvinyl butyral) interlayer, used to hold the separate glass layers together, tends to soften at temperatures of around 60°C (easily achievable in the centre of a glass panel on a hot Adelaide summer's day). This softening allows de-bonding to occur. All horizontal panels on the Pavilion were therefore designed to support serviceability loads assuming total de-lamination had occurred, and the possible deflections arising from this de-bonding were also considered. The roof panels are composed of 6mm toughened glass laminated to 10mm toughened glass (bottom layer). The maximum deflections of the 10mm glass panels were calculated assuming they had to support a portion of the 6mm upper panels in the event of total de-lamination.

4.3. Design of Corners

The design intent of the corners of the Pavilion posed an interesting engineering problem. The design relied on the bottom corner panels to support the load of the panels above, which would cause problems when removing the lower panels in the event of breakage. The designers were also concerned about eccentric stresses on the corners leading to the peeling away of the silicone holding the panels together. This peeling action was analysed in Strand7.

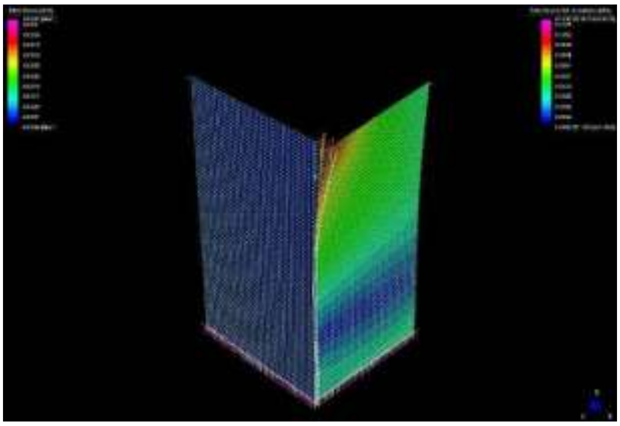

Figure 8 *'Peeling action' between glass and silicone analysed in Strand7*

The solution devised by the engineering team was to construct innovative stainless steel sphere fixings. These would hold adjacent panels in place while individual panels were replaced, and would also provide extra support against peeling away of silicone due to uneven corner loading. These fittings were visualised in AutoCAD by Aurecon engineers, and these details were then supplied to a local fabricator, who machined all the custom-designed stainless steel components for the project.

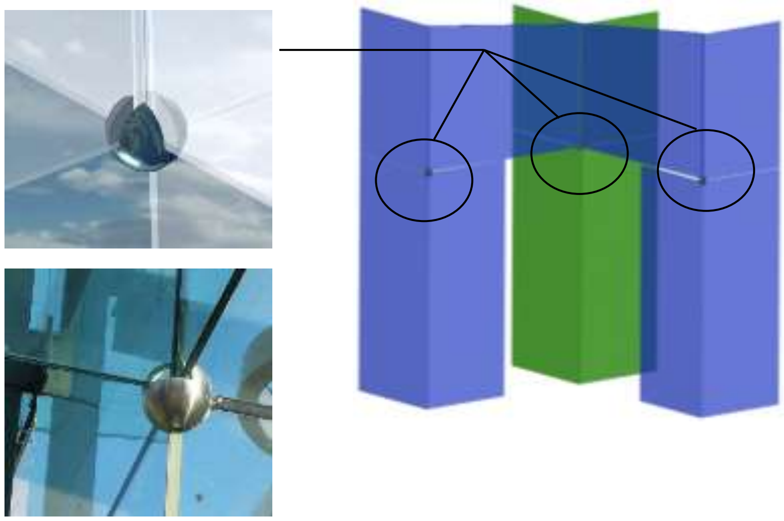

Figure 9 *Sphere corner fixings visualised in CAD by Aurecon, and a photograph of a finished fixing*

5.0 TEAM COLLABORATION DURING DESIGN & CONSTRUCTION

Aurecon worked closely with Flightpath Architects at preliminary design stage, and then with the glass installer, Construction Glazing, at detailed construction stage to ensure that tolerance and adjustability issues were accounted for. A specialist shop drafter was engaged to produce a 3D shop drawing of the Pavilion, from which all steelwork and glass was ordered. This meant that the glass installer assumed responsibility for dimensioning the steelwork as well as the glass. Approximately 3,700 part drawings were produced; only a few nuts and bolts were standard “off-the-shelf” items. The use of this fit-first-time philosophy, where the project was detailed to the level of the bolted connections on the computer screen before ordering took place, provided a much higher degree of accuracy than is typical, enabling the glass installer to order components with greater confidence and less risk.

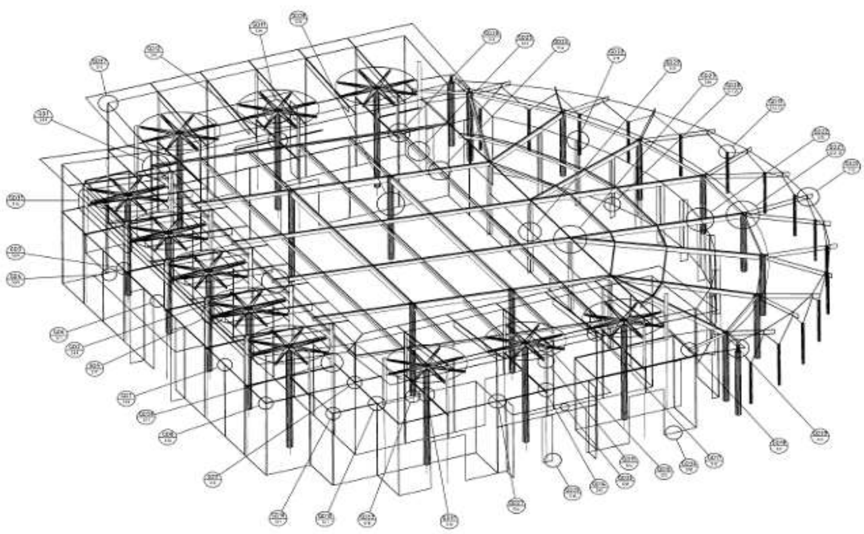

Figure 10 *3D Structural Steel and Glass Model*

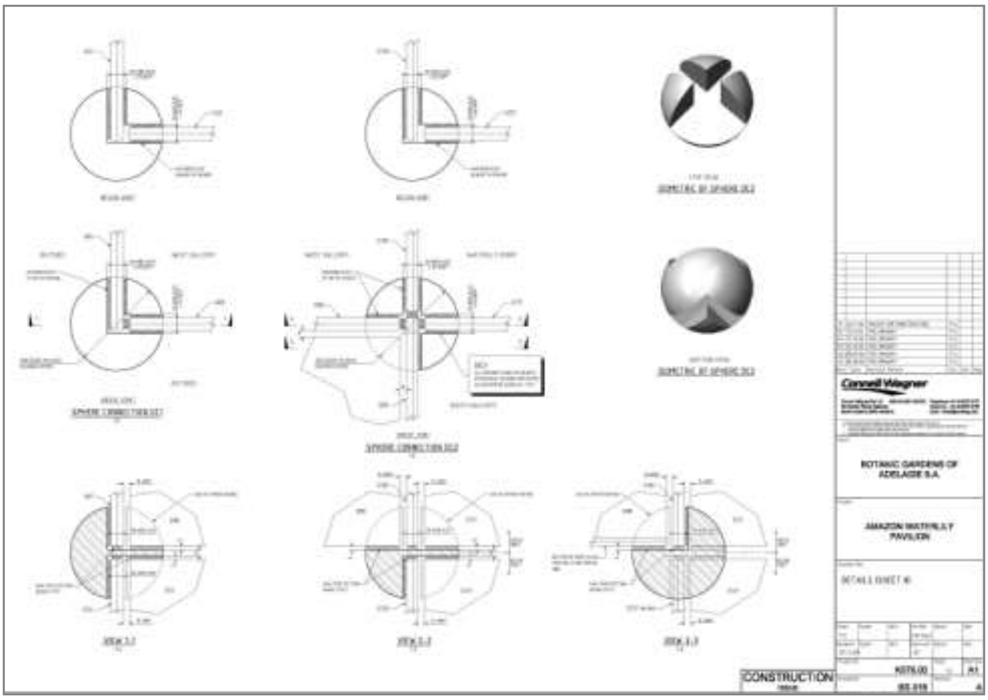

Figure 11 *Detail Drawing by Aurecon at 1:2 Scale*

6.0 IMPROVED EFFICIENCIES IN HEATING & COOLING

Lucid Consulting was engaged to create a new heating and cooling system for the Pavilion. This involved the design of the heating system (for the Pavilion and the water in the pond), in addition to a passive cooling system. The heating source selected was a natural gas fired boiler, which supplies warm water to two heating loops – one within the pond and another around the pavilion. The heating process takes advantage of the natural convection cycles within both the pond and the pavilion to maximise heat transfer from the pipes. The heat output of each loop is automatically controlled by multiple temperature sensors and modulating valves. The boiler burn rate and pump speed both adjust to match the load, which helps minimise energy waste. The passive cooling system was also developed using a cost-effective combination of automatic louvers, which open during regular warm summer conditions, and back-up exhaust fans, which operate in extreme conditions.

7.0 BUDGETS AND TIMEFRAMES

As the Amazon Waterlily Pavilion was largely a publicly-funded project, there were stringent requirements in terms of meeting specified budgets and quality targets. $2.6m was provided from the State Government, $1.58m from “Gardens 150” project donations and $0.17m from the Gardens’ Board and Trust Fund. $3.5m was spent on the structural glass and $0.5m on the structural steelwork.

Aurecon worked closely with Construction Glazing to develop a design schedule both to rationalise the number of separate glass analyses required and to meet the ordering deadlines for the glass components. Completion and handover was scheduled for mid-July 2007, and this was achieved, with all glass and other structural elements completed by mid June 2007.

8.0 CONCLUSIONS

The Amazon Waterlily Pavilion continues the proud tradition of innovative structures inspired by the exotic flower. The building stretches the application of glass technology in Australia to its limits and compares favourably with other, more costly, structural glass buildings internationally.

The design team can claim many “firsts”, such as creating the first Australian public building to utilise structural glass as its main supporting material and the first building in Australia to use load-bearing structural glass columns.

Best practice approaches to design and construction were adopted, with the use of 3D CAD technology being invaluable in increasing the accuracy of ordering steel and glass components.

Most importantly, the Pavilion highlights the value of engineers working closely with suppliers, and thoroughly understanding a material and its limitations, to achieve an outstanding result.

The resulting Pavilion is a sophisticated, innovative structure that provides a unique intersection between the interior and exterior Garden spaces.

ACKNOWLEDGEMENTS

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- The Architect, Flightpath Architects, and the Builder, Built Environs
- Construction Glazing, the installer of the glass and Aurecon’s Client during construction stage
- Lucid Consulting, Services Engineers