Adelaide BMW Redevelopment Cable Net Glass Façade

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1. INTRODUCTION

Aurecon has recently been involved in the design of a cable net glass façade for the Adelaide Motors BMW Redevelopment Project. The new structure is due for completion in November 2009 and is situated in a prominent position on the corner of West Terrace and Phillip Street, Adelaide.

The original car Showroom was built in 2001 and includes an underground basement, suspended ground floor display area and a mezzanine office floor. The redevelopment will increase the total floor area of the building by approximately 1,000m^2, and provides additional ground and mezzanine floor space, with a third floor added to the rear of the building over the existing roof. The extension will be used as a two-storey car showroom space with some additional offices and a new training room to the rear.

The new showroom has a 9m high glass façade, which is supported by a series of vertical tensioned stainless-steel Ronstan rods. The glass façade spans two stories from ground to roof level. The mezzanine floor is set back from the façade to give the impression that it is 'floating', without being attached to the exterior walls. To the best of the authors' knowledge, there have been no similar cable-supported façade systems constructed in Australia.

Figure 1 *3D rendering of the Adelaide BMW Redevelopment*

Figure 2 *Photograph of facade during construction*

2. DESIGN PHILOSOPHY AND CONSTRAINTS

The architectural design concept for the project was developed by Aurecon, as lead designer, in addition to the company's typical role as engineering services provider. The design concept was influenced by the BMW brand characteristics, as outlined below:

Architectural Substance	**Form**	**Construction**	**Function**
	Orthogonal	Ingenious	Open
	Layered	Precise	Moving
	Projecting	Pure	Fascinating

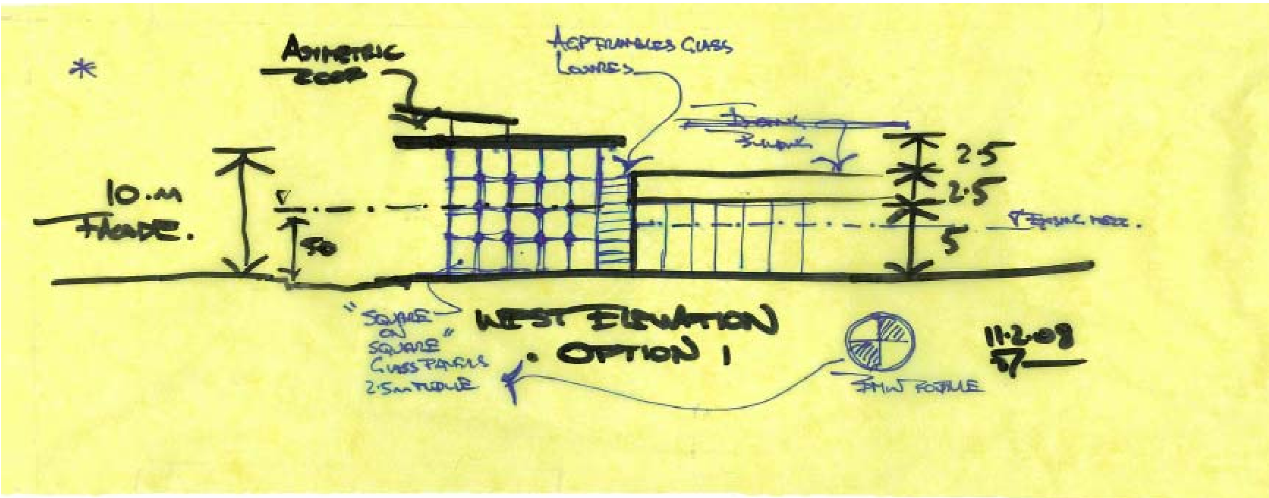

Figure 3 *Original Aurecon Design Concept Sketch*

To ensure that the project met the stringent design criteria of the BMW brand, a number of complex and challenging engineering requirements were developed, including:

- A roof structure with a maximum thickness of 500mm, including the depth of all structural steel and services.

- A glass-fronted car hoist to service the basement, ground and mezzanine floors (to lift cars into place in a limited floor area). Safework SA granted the project an exception to allow the car hoist to service three floors. The General Requirements section of AS1418.1-2002 *Cranes, hoists and winches* only allows for hoists to service two floors.

- A 9m glass façade extending the full height of the showroom. The only available support connection points to the base structure are at ground floor and roof level.

- A column-free northwest corner of the showroom to provide unimpeded views both into and out of the showroom. This resulted in a 7m double cantilever for the roof structure.

3. ANALYSIS AND DESIGN

The colour of the glass and size of the patch fittings is critical to the overall aesthetic of the building. The main aim, therefore, during the structural design process, was to minimise the thickness of the glass in order to reduce its green tint and to increase the interior penetration of natural light.

The design of the glass façade was an iterative process involving the optimisation of a number of parameters. These parameters included:

- The thickness of the glass required to resist wind-induced stresses while providing a cost-effective and aesthetically acceptable solution;
- The size and thickness of the patch fitting required to minimise glass stresses, while also providing an aesthetically acceptable solution
- The tension in the ARS1-SS-16 Ronstan rods required to limit the lateral deflection of the façade while remaining within the yield stress limit of the rod;
- The required strength and stiffness of the roof structure to withstand the rod tension loads without exceeding the depth of 500mm and a roof pitch of 1 degree.

3.1 Structural Glass Analysis

The structural glass was analysed using Strand7, initially assuming a simply supported design with the patch fittings fixed at each corner and with no allowance for the energy absorption and stress relief from the deflection in the cable. In effect, the dynamic loads from the wind were assumed to be fully absorbed by the glass and the associated patch fitting. The result was a very high stress in the glass at the fixing points. This would have required either larger patch fittings to increase the bearing area on the glass, or an increased glass thickness of approximately 20mm, to reduce the stresses to an acceptable level.

To optimise the thickness of the glass and size of the patch fitting, the authors considered the overall performance of the façade system. It was assumed that the dynamic wind loads would be shared between the glass patch fitting and the cable net system, with the glass shedding load through the fixings to the cables behind, which would then deflect, absorbing some of the stresses. The glass fixings were thus re-analysed in Strand7, taking the flexing of the cables into account. To do this, the stiffness of each rod was calculated and applied as spring stiffnesses to nodes over the areas of the patch fitting locations in Strand7. The in-plane movement of the glass panels was modelled using Strand7's compression-only edge restraint tool. This allowed the panels to "dish" into their centres away from the corner supports, while being restrained from outwards movement. This softening of the fixings reduced the stress in the glass without the need to increase the size of the patch fitting. Refer to **Figures 4 to 7** for clarification of the restraint conditions applied and the inward dishing deflection of the glass under wind load.

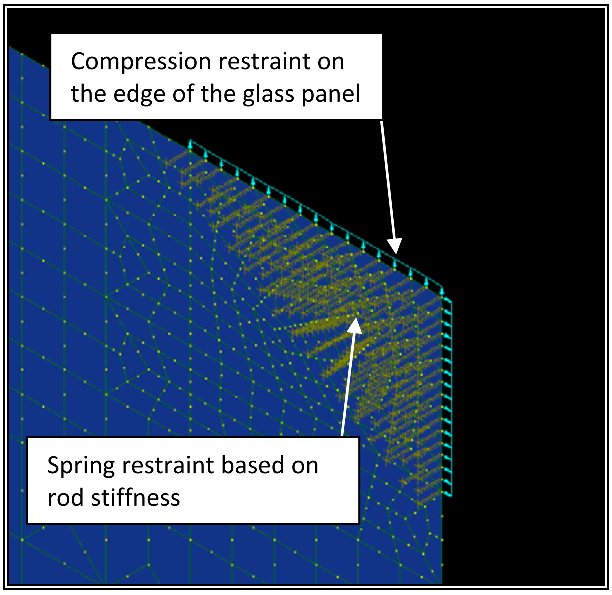

Figure 4: *Spring stiffness and compression restraint applied in Strand7.*

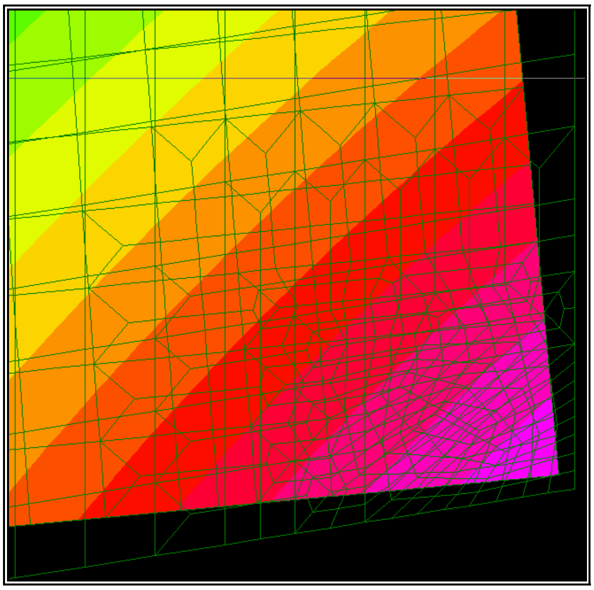

Figure 5: *"Dishing" deflection of glass at corners under wind load.*

One of the challenges in optimising the design of the glass was to determine a suitable allowable deflection and stiffness for the rods. Greater deflections would increase the softening effect at the fixing points, but would provide problems in terms of human perception of a flexing facade. Stiffer rods (with increased pretension) would reduce facade deflections, but would increase the stresses in both the glass and the rods and increase the loads on the thin roof structure. A serviceability wind deflection criterion of Height/80 was adopted for the design of the tensioned rods and the individual deflection of the glass panels; this was deemed to be within the acceptable visual limits for flexure under wind loads.

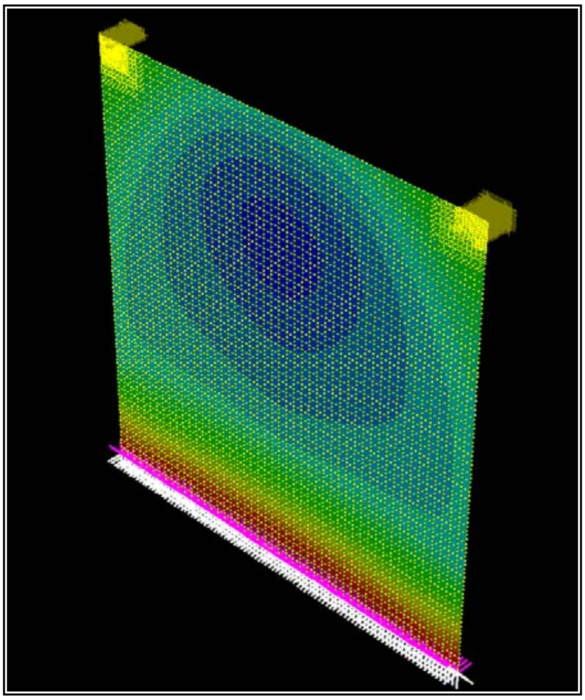

Figure 6: *Bottom panel restraint conditions and deflected shape.*

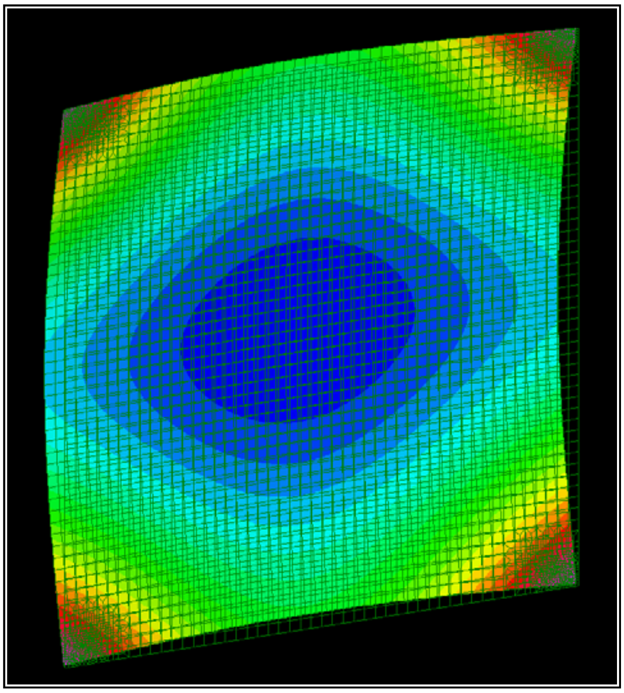

Figure 7: *Typical deflected shape of mid-level panel with spring stiffnesses applied at corners*

3.2 Overall Structural Framing and Rods Analysis

A 3D non-linear analysis of the steel building structure and tensioned rods was performed using SPACEGASS (**Figure 5**). This model was used to predict the deflection of the roof structure and elongation of the rods. The calculated theoretical deflections were used to preset the couplers above their required finished position (refer **Figure 8** and **Section 6**).

The tensioned rods were modelled in SPACEGASS using both the *shortened cable* method and the *prestress in the cable* function. The deflection and behaviour of the structure were first modelled in a simplistic way by placing point loads on the roof structure equal to the expected tension in the rod, without modelling the cables. The deflection of the roof structure was determined using this model, and this was used to calculate the shortened lengths of the cables, taking into account the elongation of the rods due to the prestresses.

The shortened cable method and the prestress function in SPACEGASS were found to produce almost identical results. The authors were therefore able to conclude with confidence that the theoretical structure modelled in SPACEGASS was a reasonable representation of the actual structure. The deflection results from SPACEGASS and the elongation of the rod were used to preset the couplers above their final finished position to within an accuracy of +\-1mm (refer **Section 6**).

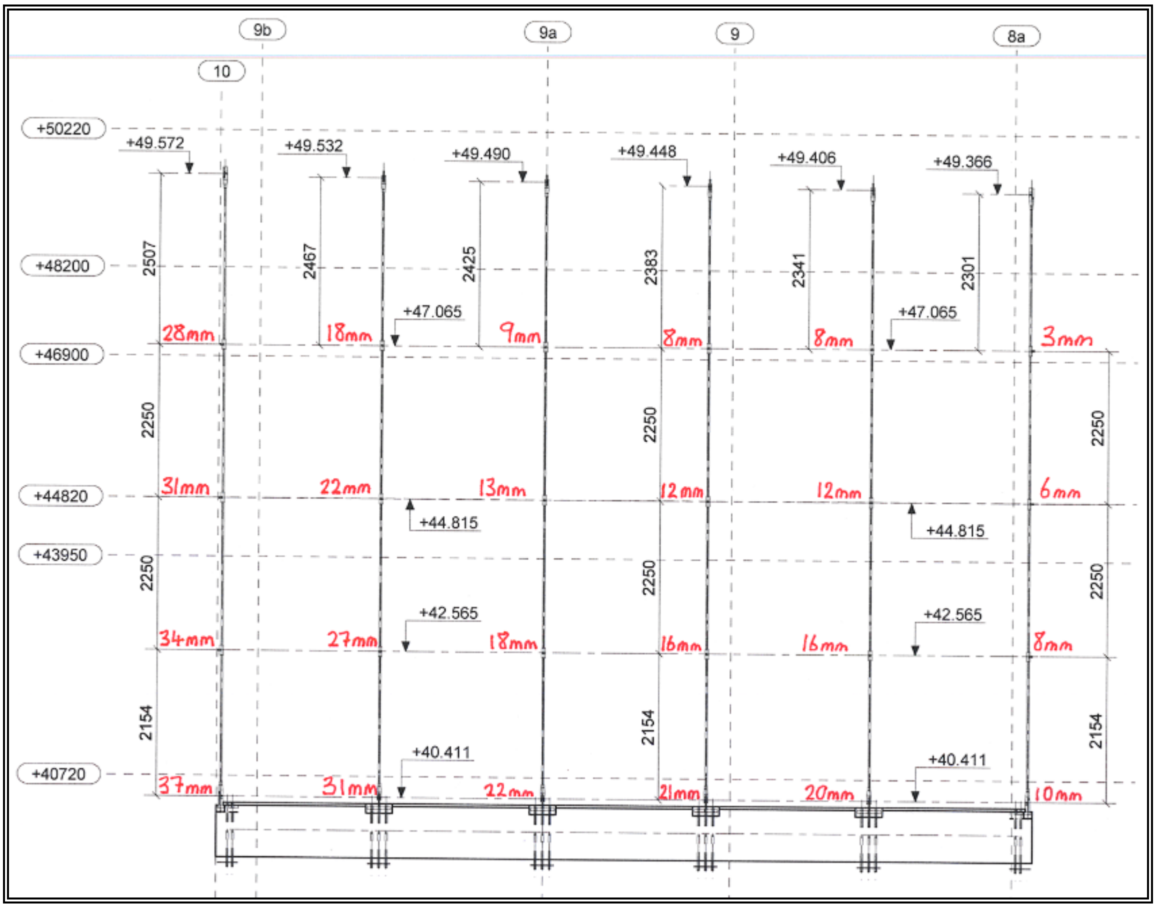

Figure 8: *Preset coupler locations along the western façade to allow for the deflection of the roof structure and elongation of the rod under load.*

4. ROOF STRUCTURE

As noted previously, the roof incorporates a 7m double cantilever at the northwest corner of the building, within an overall depth of just 500mm. The majority of the roof steelwork consists of 350WC280 welded sections at 2.4 m centres, forming a steelwork grillage. This creates a rigid diagram and, therefore, the very stiff roof structure that is necessary to resist the large imposed loads from the tensioned rods. To simplify construction in the constrained site, the roof steelwork was split into 8 main sections and craned into position. Each section is connected with full moment splice connections using M24 Unbrako countersunk bolts.

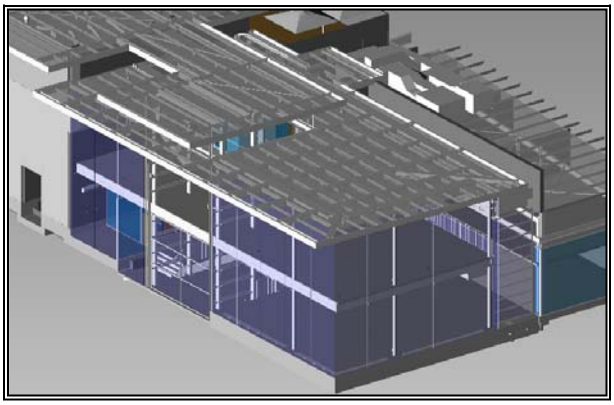

Figure 9: *3D model produced in Revit showing roof steelwork grillage*

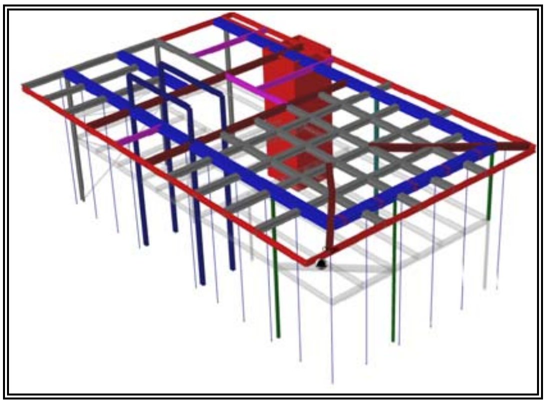

Figure 10: *SPACEGASS model of roof steelwork and rods*

5. STRUCTURAL GLASS FAÇADE

The final structural glass makeup selected for the 9m north and west facades comprises 10mm toughened glass (with a low e coating) laminated to 6mm low-iron toughened glass, with a 1.52mm high-performance ITO PVB interlayer. This glazing system has a very high thermal performance with a calculated shading coefficient (SC) of 0.57 and U-Value of 3.8. This high performance glass was adopted to reduce the amount of solar load transmitted into the building, as required by Section J of the Building Code of Australia. The low-iron composition reduces the green tint normally associated with this thickness of laminated glass.

The 1.52mm ITO PVB interlayer has a maximum size of 2.5m x 2.5m. The glass façade was therefore divided into panels measuring approximately 2.4m x 2.25m. The glass is supported by custom-machined patch fittings and 44m x 6mm aluminium channels at the top and bottom of the façade.

6. RONSTAN RODS

26mm diameter ASS1-SS-16 stainless steel Ronstan rods were selected to support the facade. There are a total of 15 rods, spaced at 2.4m centres, spanning 9m between ground floor and the roof. The rods have been designed to withstand lateral dynamic loads as well as the weight of the glass.

Each rod was tensioned to between 75kN and 150kN, depending on the location and loading condition on the rod. Each rod was split into four equal segments with a coupler at the ends to create a single 9m high rod. The rod couplers had to be preset above the required finish position to allow for the deflection of the roof structure and elongation of the rod under tension. The preset locations were determined by detailed design calculations, as described in **Section 3**, to determine the theoretical expected deflection along each rod. These preset positions varied and were dependent on the following:

- The location of the coupler in the vertical direction along the length of the rod;
- The elongation of the rod under load; and
- The location of the rod in plan (i.e. by a column or at the end of the cantilever).

The maximum elongation of each rod was calculated to be 17mm and the maximum deflection of the roof was calculated to be 37mm at the end of the cantilever. The location of each glass joint and coupler in the vertical plane was critical to ensure that the joints in the glass formed a perfectly horizontal line. A tolerance of +/-2mm in the vertical plane was adopted for the fully tensioned final rod position.

7. PATCH FITTINGS

The patch fittings are typically 300 x 200 x 25mm thick stainless steel grade 316 plates. The diamond shaped patch fitting and associated plates were specially customised to suit the requirements of the project including:

- The onsite constructability of the façade;
- The ability to remove individual panels if required for maintenance;
- Optimisation of the thickness and size of both the patch fittings and glass; and
- Required tolerances for the glass installation of up to +/- 10mm.

The form of the cover plate was critical to the overall design of the patch fitting. A groove reflects the line of the glass joints. The fitting provides tolerances in the vertical positioning of the glass panels of up to +/-5mm. An 8mm thick square section was machine cut from the rear face of the cover plate to allow space for a 6mm locating plate (refer **Figures 11** and **12**). The locating plate was drilled and tapped during construction, after the erection of the glass. The locating plate was critical as it held the glass in position temporarily until the cover plate was installed and it allows for replacement of individual panels if required.

The glass was clamped in the patch fitting between the front and back plates using an M12 Unbrako countersunk set screw. The M12 Unbrako set screw was drilled and tapped through the cover plate and into a 25mm diameter stainless steel bar, which was welded to the back plate and coupler. The steel bearing plates are separated from the glass using a special 3mm thick hypalon gasket (with a 40 Durometer Shore A hardness rating), designed to compress to 1mm when the glass is clamped in position. The hypalon gasket is critical to the functionality of the patch fitting and serves two important roles: the first is to ensure a smooth bearing area on the glass and the second is to provide a soft cushion between the glass and the stainless steel patch fitting under external loads, reducing stresses on the glass.

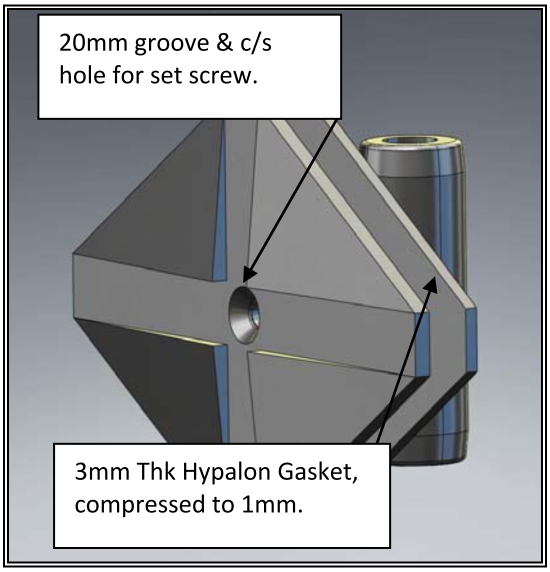

Figure 11: *3D isometric of the stainless steel customised patch fitting.*

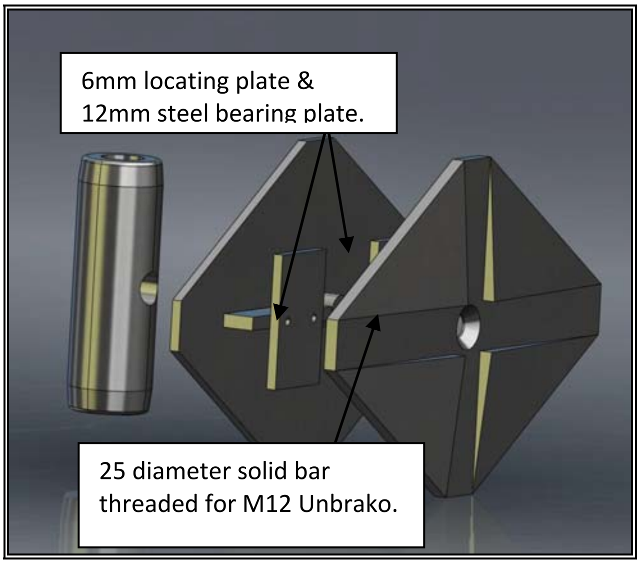

Figure 12: *3D exploded isometric of the stainless steel customised patch fitting.*

The coupler used to connect the patch fittings to the rods and the rods to each other is a standard SS 329 DIA52.5 Bar Ugima CF x 220mm long coupler, provided by Ronstan International Pty Ltd. The length of the coupler was fundamental to the design as it allows for adjustment in the length of the rod between couplers. This was particularly important when presetting the couplers above their final finished position (as described in the previous section).

8. CONSTRUCTION

The tight construction program and 6-week lead time for the structural glass meant that the glass had to be pre-ordered before the rods were tensioned. It was therefore critical that the theoretical deflections were accurate as the glass had a tolerance of just +/-2mm horizontally and vertically. The pre-ordered glass was profile cut to allow for the calculated deflection in the roof. The actual deflections were found to be within +/-2mm of the calculated theoretical deflections, which was an excellent result for the design team.

Scaled 1:2 drawings (**Figure 13**) were produced by Aurecon for the construction of the glass façade and Ronstan rods.

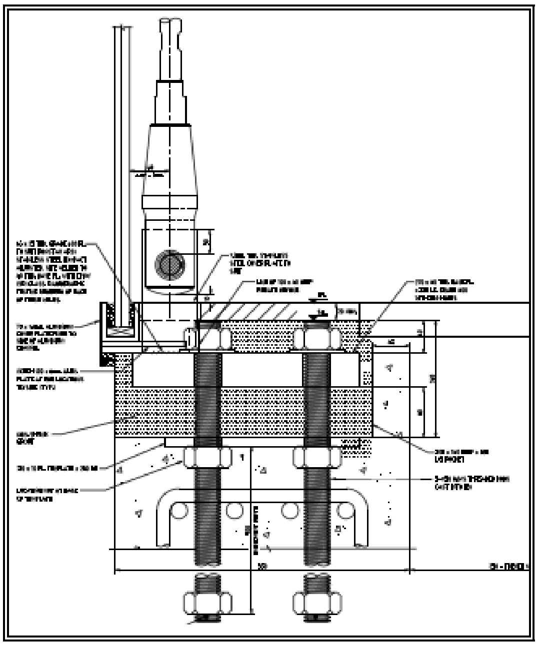

Figure 13: *Scaled 1:2 construction drawings by Aurecon.*

Figure 14: *Photo of base connection during installation of the glass façade.*

The rods were tensioned using a hydraulic jack, which was used to tighten the bolt on the base plate. The bolt pushed the base plates downwards, tensioning the rods. A strain gauge was attached to each cable, and the gauges were connected to an on-site computer, providing live readings of the tension in each rod during installation.

The rod tensioning was a gradual, iterative process. The rods were initially tensioned to their design load and all three couplers on each rod surveyed to determine their position in the vertical plane. The coupler locations in the horizontal plane were compared to ensure a smooth horizontal joint line was produced along the glass facade. The coupler locations from the survey were compared to their required final design position and any couplers that were not within +/-2mm were adjusted. This process required the full time onsite presence and experience of Aurecon's engineers.

9. CONCLUSIONS

An innovative approach and very early conceptual phase input by Aurecon led to the creation of this unique cable net glass façade for the Adelaide BMW Redevelopment. The project demanded an extensive knowledge of structural glass, innovative thinking and design excellence. There were many challenges presented to the design team, including glass connections, tolerances, rod tensioning methods and creation of 3D geometry. These challenges were overcome by engineers working closely with both the glazier, Construction Glazing Pty Ltd, and the rod suppliers, Ronstan International Pty Ltd, to develop a new project-specific design. This close collaborative design approach has produced an outstanding result for the client and has broadened the experience and skills of the whole design team.

ACKNOWLEDGMENTS

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- Matthews Architects, the Project Architect

- Ronstan International Pty Ltd, for supply and installation of the Ronstan Rods, Couplers and Patch fittings. Ronstan also provided guidance on their design.

- Construction Glazing Pty Ltd, for the supply and installation of the structural glass façade.