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From complex shape to simple construction: fast track design of "the future of us" gridshell in Singapore

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Abstract

The "future of us" exhibition celebrated Singapore's Golden Jubilee. The visitors of the exhibition experienced a stunning play of light and shade cast by a metal lattice, composed of a main steel structure that supports 11000 perforated aluminium panels, spanning approx. 50m and rising to 16m. From start of design to completion of installation was only 5 months. This document describes how the boundaries of simplicity have been pushed during all the steps of the project, by using basics construction concepts and compromises in order to meet the challenge of building a free form complex structure on time. The choice of structural system, the rationalization of the geometry, the material used, the choice in type of connections as well as solutions for the interfaces between the structural framing and the façade participated in building a simple complex structure.

Keywords: construction, steel structure, metal spatial structure, gridshell.

1. Introduction

The future of Us exhibition celebrated Singapore's Golden Jubilee. It was held from December 2015 to March 2016. More than 400,000 visitors experienced a stunning play of light and shade cast by a metal lattice, composed of a main steel structure that supported 11,000 perforated aluminum panels.

Figure 1: Aerial and inside view of the gridshell [Oddinary Studios]

The tropical shading and natural ventilation provided by the pavilion was achieved through a density-modulated pattern that integrated programmatic requirements, solar irradiation and aesthetics considerations.

Building freeform gridshell structures usually implies dealing with complex geometries. Complexity of shape often overtakes simplicity of buildability and this leads to complicated and costly steel members.

However, when strict time constraints are the priority, simplicity of fabrication and installation must become the driving design parameters. For the "future of us" gridshell construction, only 2 months were dedicated to the geometry definition and design phase, 2 months were dedicated to the fabrication and only 5 weeks were dedicated to the installation.

2. Rationalization of the geometry and choice of structural system

The pavilion is made of a main steel structure clad on top and bottom with a façade made of aluminum panels. The rationalization of the geometry, the choice of structural system and sections types was critical in order to simplify as much as possible the interaction between the structure and the façade as well as the installation and fabrication of the structure.

2.1. Preliminary concepts

The structural organization had to be a compromise between the architectural intent - tropical and organic structure - and the simplicity of fabrication and installation. From the shape of the envelope, several concepts have been studied for the structure organization and the structural systems. Two of the concepts studied are presented in Figure 2.

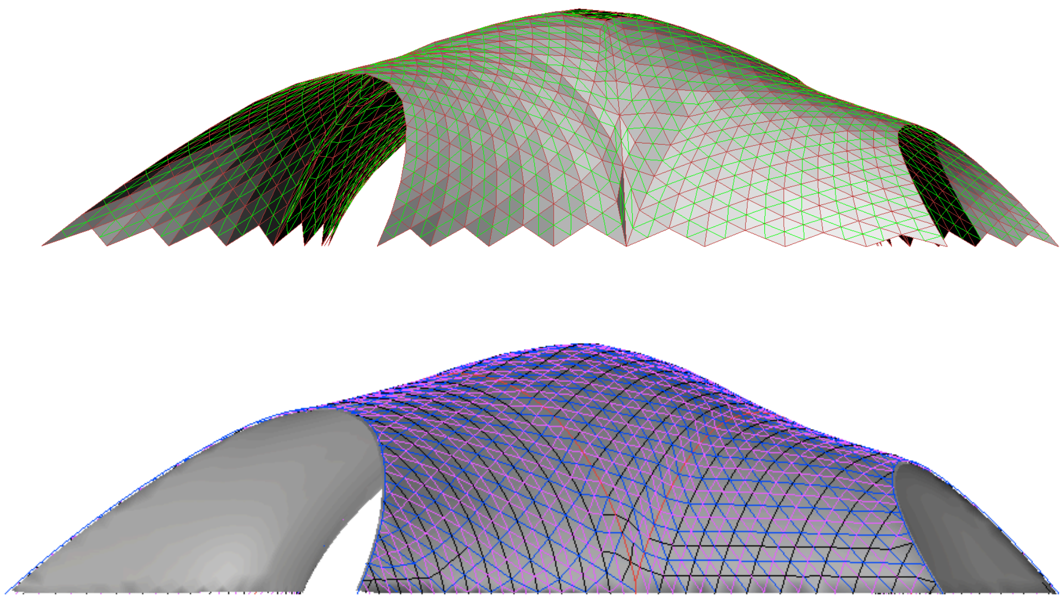

Figure 2: Preliminary structure organization concepts – Top : Main arches non vertical – Bottom : Main arches vertical [Passage Projects]

Due to the time constraints, it was decided to avoid using typical gridshell structural grids requiring either 3D nodes systems or welded connections. Hence the structure had to be decomposed into main and secondary members. To ensure a simple and fast installation, inclined main arches should be avoided and vertical reference members should be used.

The priority for the structural system was to have a standardized connection between the façade and the structure. The simplest way to ensure this is either to have members whose orientation follows the normal to the surface or to ensure that at least the top and bottom of steel is perpendicular to the normal of the surface. As explained previously, the main members had to be vertical to simplify the installation and as a result could not be oriented normal to the surface. Two of the concepts studied are presented in Figure 3.

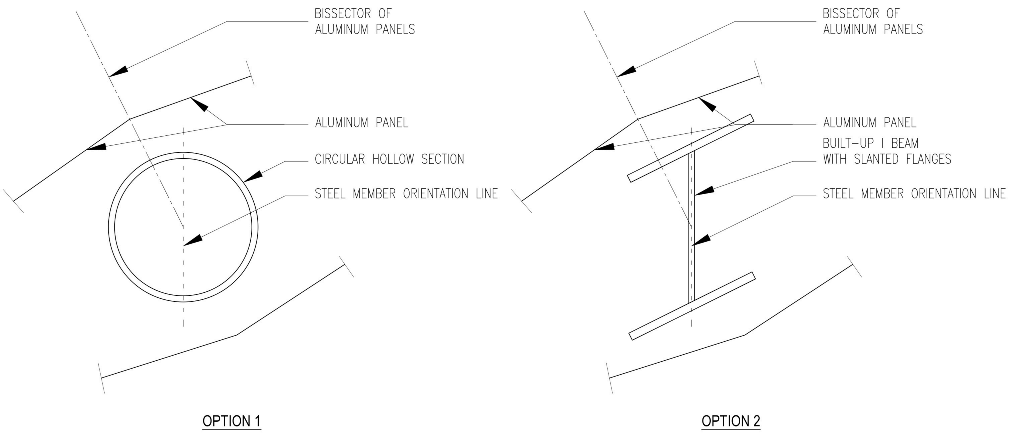

Figure 3: Preliminary structural system concepts [Passage Projects]

Procurement time for Circular Hollow Sections is much longer than I Beams or Built-up Rectangular Hollow Sections. As a result, it was not possible to use Option 1 shown in Figure 3. The built-up I beam with slanted flanges was a viable solution in terms of procurement time and installation. However, the fabrication of the members would have been complicated and highly subject to errors.

2.2. Parametric modeling

The original architectural form and aesthetics combined with the construction logic described in the previous section define a narrow solution space. The goal was to find an elegant and buildable geometric configuration that existed in this space of possibilities.

In order to rapidly explore this space and find the best configuration a series of parametric models were defined. The flexibility of these models facilitated a sequence of steps that eventually converged on the rationalized structural configuration. First, based on the heuristic premise that the rationalized version should be based on a system of primary arch-like members defined in vertical planes the original geometry was dissected and examined. These studies informed the definition and control of geometry describing a primary structural system. This system was progressively refined to closely match the original architectural geometry.

Once a close match between rationalized and original geometry had been defined parametric studies of the secondary system were undertaken. Initially driven by construction simplicity equal member length node spacing was sought for secondary members. Ultimately a non-uniform spacing was chosen as it provided more even aesthetic and regardless of length each secondary member was unique due to the angles they intersected the plane of the primary members.

The parametric approach not only allowed definition, control and refinement of geometry but also provided the opportunity to continually analyze and check that the proposed configuration conformed to the proposed construction methodology. Angles between secondary members and surface normals were extracted and studied, which ultimately led to the decision to orientate some of the primary arches on inclined planes.

The ease with which secondary information is accessed in a parametric model supported the project construction documentation. Angles between secondary and primary members were extracted and used in steel fabrication drawings. Orientation geometry for secondary and tertiary members was exported as simple lines in space to assist the solid modeling of steel members.

The structural organization and structural system chosen are presented in the next section.

2.3. Organization of the geometry and structural system

The free-form shape is divided into four parts: three vaulted arms and a central shell, as shown in figure 4. The structure is composed of 49 primary arches, connected with 1,137 primary purlins and 3,320 secondary purlins. Overall the structure works as a series of fully triangulated arches, which allow it to develop a hybrid gridshell behavior.

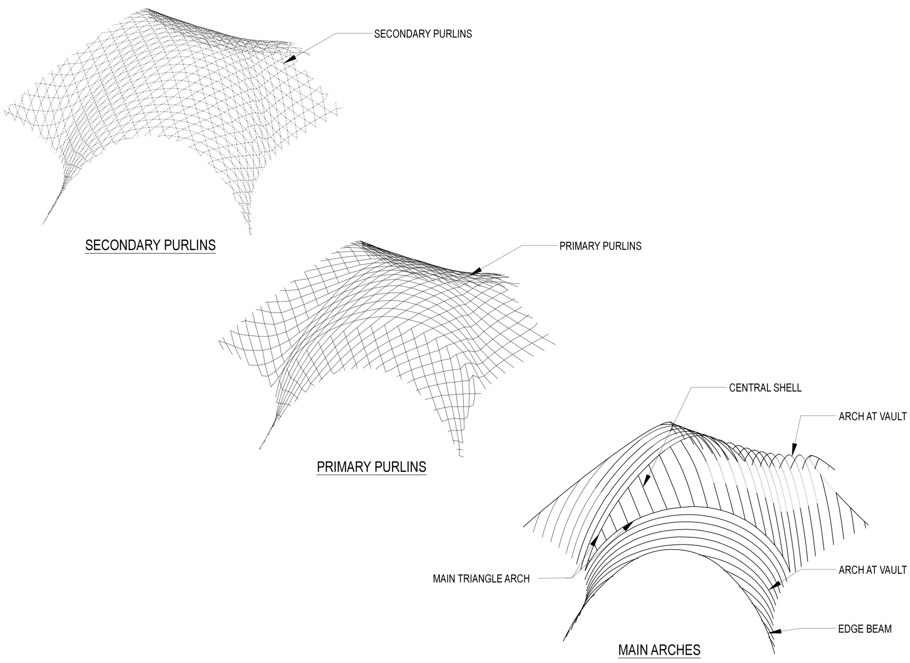

Figure 4: Exploded view [Passage Projects]

2.3.1. Main Arches

All the main arches supported on the ground are vertical. 9 of the arches in the central shell supported by the main triangle arches are orientated following the normal of the surface. If those arches were vertical, the steep slope of the shell in this area would have made the connections between members and between the structure and the façade too complicated. Orientation of the arches is presented in figure 5.

Each arch is decomposed into maximum 4 radii. Additionally, each arch is decomposed into segments of maximum 6m long to make them transportable from the factory to the site. The arches are I Beams or Rectangular Hollow Sections directly built up with plates. This made the fabrication of the members very simple, the flanges could be easily rolled to the desired radius and the webs could be cut through CNC machine. The assembly of the members and the site installation could be controlled using traditional methods of construction, i.e Plumb line. Installation could be controlled using one single dimension in one direction only, i.e Z direction. The decomposition of the gridshell into bays delimited by the arches enabled to control installation tolerances within one bay and not cumulating them across the full length of the shell.

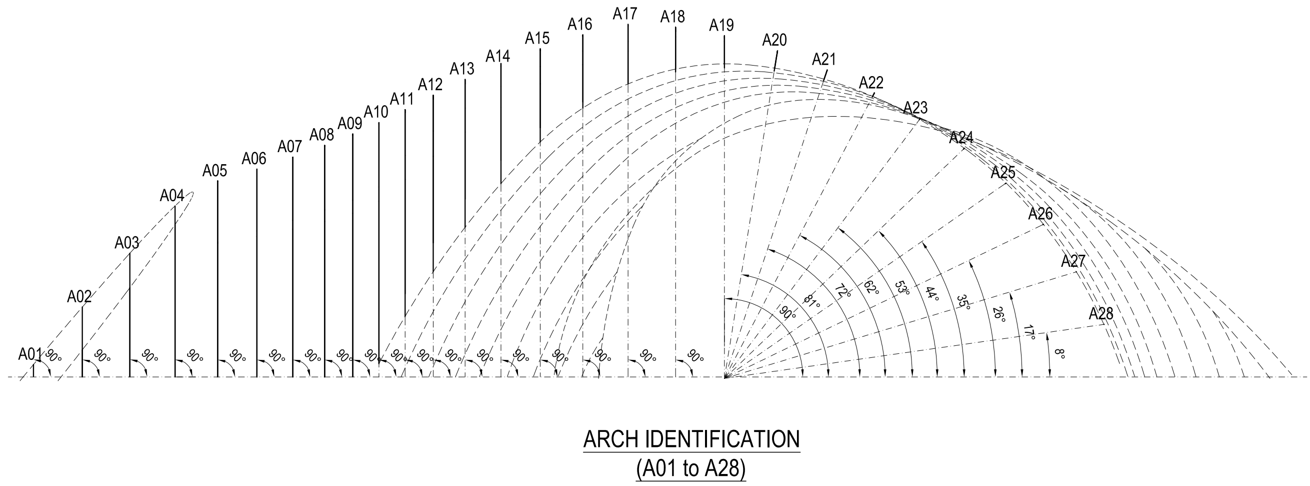

Figure 5: Orientation of the central shell arches [Passage Projects]

2.3.2. Purlins

The primary purlins are straight elements that connect the arches together. Orientation of the primary purlins is always normal to the façade surface allowing a standard connection between the aluminum panels and steel structure. The primary purlins are built-up I beams.

The secondary purlins do not participate to the overall structural stability. Their function is to provide a lightweight straight steel member support with an orientation normal to the surface for simplicity of the façade fixing. The section used is a C-Channel, easily available and easy to produce.

2.4. Interface between the structure and the facade

Due to the short time constraint, it was a priority to define a connection between the structure and the façade that is standard, easy to fabricate and install and can be used on the whole surface.

As presented in previous section, most of the arches are vertical and hence not normal to the surface. As a result, the aluminum panels do not connect to the arches. They are only connected on two sides, to the members normal to the surface i.e the primary and secondary purlins, avoiding any non-typical connection.

The connection chosen to connect the aluminum panels to the steel structure is presented in figure 6. It is a very simple and standardized connection: the aluminum panels were fabricated with 90 degree angle legs on each side and only 6 self tapping screw per panel side link the leg to the structure.

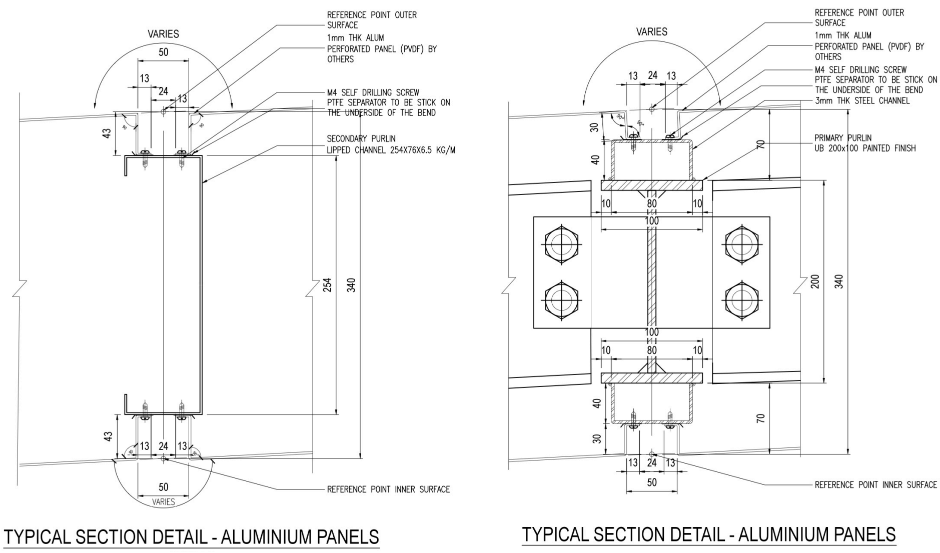

Figure 6: Connection of the façade to the structure [Passage Projects]

3. Structural Design

3.1. Modeling

The steel structure modeled in Rhino was exported to the analysis software. Only the arches and the primary purlins have been modeled – as the secondary purlins are considered non-structural. Loadings have been applied as per Eurocodes. All the arches are fixed to the ground. At the early stages of the design, all the connections were modeled as simple connections. A general view of the structural model, with supports conditions and releases conditions is presented in figure 7.

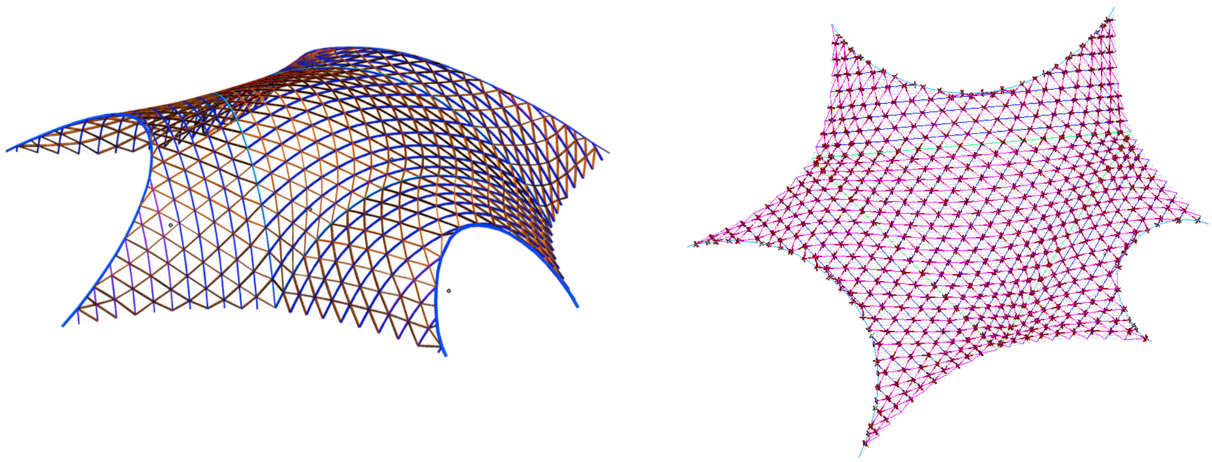

Figure 7: Overall view of the structural model (Left) and plan view showing the release conditions (Right) [Passage Projects]

3.2. Instabilities investigations

A modal buckling analysis has been carried out. Arch buckling modes were found to have buckling factors smaller than 3. The corresponding buckling shape is presented in figure 8.

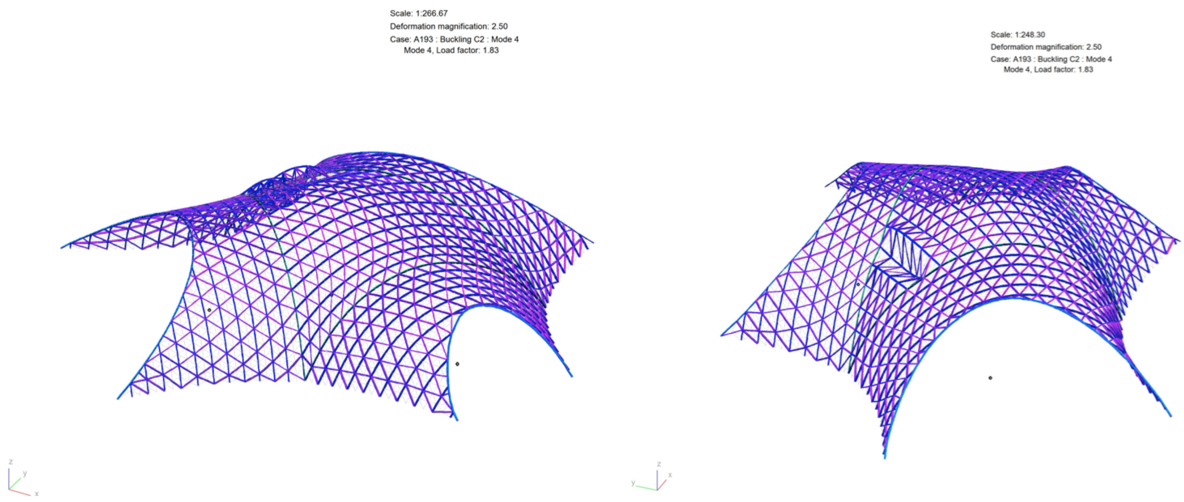

Figure 8: Buckling shape of a buckling mode with buckling factor smaller than 3 [Passage Projects]

The arches buckling in this mode are very flat and subject to high compression forces, hence highly prone to buckling. It was decided to stiffen these flat areas of the gridshell by using moment connections between the primary purlins and the affected arches, as shown in Figure 9.

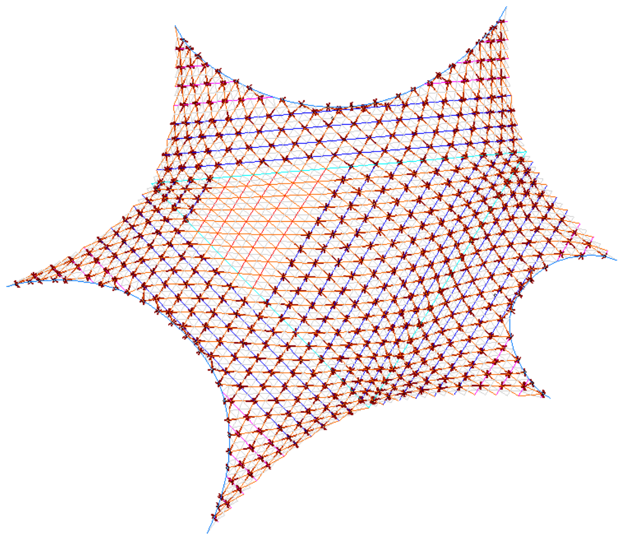

Figure 9: Plan view of the analysis model – Primary purlins at flat area are fixed to the arches [Passage Projects]

This increased the buckling factor from 3 to 8. First arches buckling mode is presented in figure 10. To cater for the remaining buckling modes with a buckling factor lower than 10, a geometrically non-linear elastic analysis was performed, as described by Bulenda and Knippers [1]. Global imperfections were included in the model, using the deformed shape of the first global buckling mode, with the maximum amplitude of the global imperfection limited to 30mm. Local imperfections were taken into account through members checks.

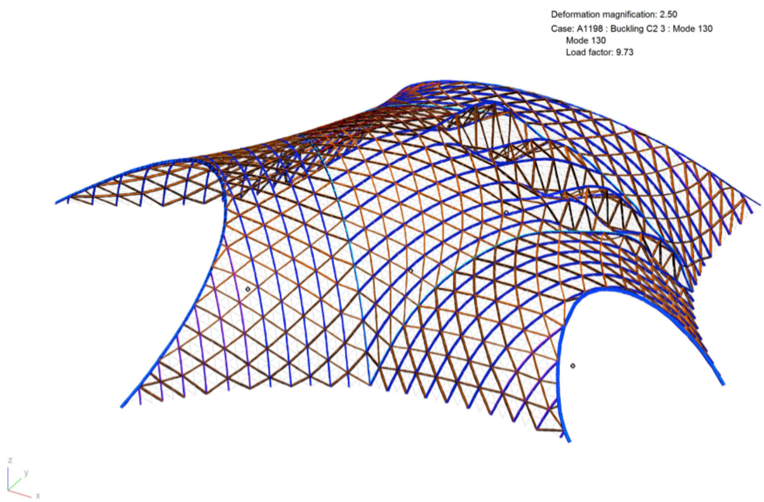

Figure 10: Buckling shape of a buckling mode with buckling factor smaller than 3 [Passage Projects]

3.3. Connections design

In order to avoid any welding works on site and to ensure a fast installation of the steel structure, all the connections have been designed as bolted connections.

The connections between the secondary purlins and primary purlins or arches are simple fin plateconnections, with a slotted hole to allow for installation tolerance. The connections between the pinned primary purlins and the arches are fin plates connections.

The segments of each arch are connected together using moment end plate connections. The rigidity of these connections and their moment resistance is evaluated as per described in Eurocodes 1993-1-8.

The primary purlins fixed to the arches are decomposed in three pieces. Two stumps are welded in the factory to each arch from either side of the purlin. The central piece of the purlin is then assembled on site to the stumps through bolted moment end plate connections, as shown in Figure 11. As a result, using such a connection enabled to avoid any welding works on site.

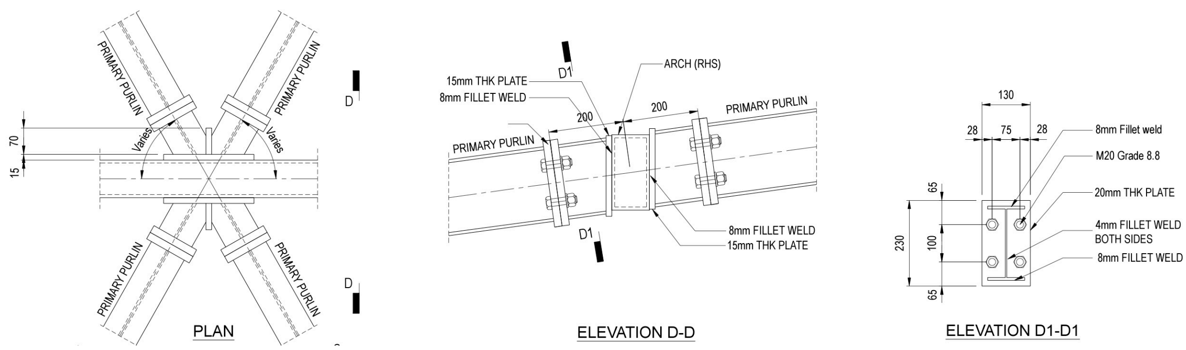

Figure 11: Connection of fixed primary purlins to arches [Passage Projects]

4. Coordination and Fabrication

The time constraint and the complexity of the encountered issues required steel fabrication drawings to be prepared by the structural engineers instead of the steel fabricator. This was also applicable to the aluminum panel's fabrication sheets that were prepared by the architectural team.

A master model joining the structure fabrication model and the façade fabrication model was created. Programming enabled to easily detect clashes and deviations between the structure and the façade. It helped to control the acceptable deviations and to reduce the exceptions to a small number as well as locate them, avoiding the time consuming effort of eliminating them entirely.

The fabrication drawings were directly extracted from the model and sent to the steel and aluminum fabricators, keeping the complexity in the hands of the consultants. A typical fabrication drawing of a piece of arch is presented in figure 12. Resolving all the possible interfaces issues before starting the construction permitted to deliver a fully coordinated design with a seamless integration of all parties involved.

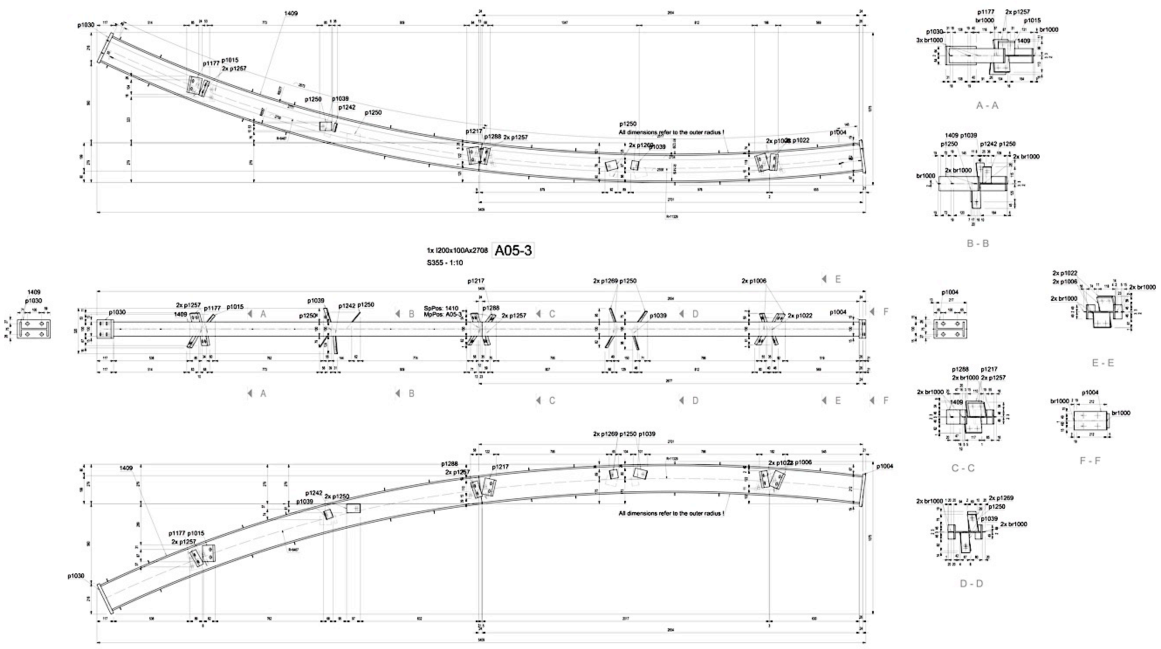

Figure 12: Arch Fabrication Drawing [Passage Projects]

5. Conclusion

From a structural point of view, boundaries of simplicity have been pushed during all the steps of the project, by expressing the freeform geometry in a structural language of basic and traditional construction. The close coordination between the architects and the engineers, up to the fabrication phase, allowed the structure to be built in just below 5 weeks and delivered to the client one day in advance.

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References
[1] Bulenda Th., Knippers J., Stability of grid shells, *Computers and Structures*, 2001; **79**; 1161-1174.