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A new approach in the design of cable nets: The National Campus for the Archaeology of Israel

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Abstract

The project consists of the development of three separate cable nets clad in Tenara fabric, to be suspended above the National Campus for the Archaeology of Israel. Canopy 1 is a large scale inverted teardrop with a surface area of approximately 1400m^2. Canopies 2A and 2B are classic hypar shapes, each with a surface area of approximately 400m^2.

The design of the canopies touched upon many of the typical challenges of lightweight structures while trying to push the envelope of conventional design using new fabric materials, digital tools, and project documentation procedures. This paper provides a summary of the project development, discussing the technical aspects of net analysis and design.

We have endeavored to refine the design and construction of cable net structures by combining existing analysis techniques with 3D modeling technology for direct fabrication.

This paper includes a description of each of the following design aspects: development of net geometries, dynamic relaxation modeling to develop appropriate net tension fields, interpretation of net behavior and cable net performance, fabric/cable net detailing methodologies to allow for construction and tensioning, and the utilization of 3D modeling for direct fabrication.

Keywords: Tensile Structure, Dynamic Relaxation, Form Finding, Digital Tools, Optimization, Fabric, Membrane Structure, Cable Net.

1. Introduction

The National Campus for the Archaeology of Israel, designed by Boston-based architect Moshe Safdie and Associates, Inc., is the proposed new 25,000m^2 headquarters of the Israel Antiquities Authority. The museum is will include centers for research, restoration and exhibitions of 15,000 fragments of the Dead Sea Scrolls. The building complex is embedded into a sloping site in the hills of Jerusalem. Three outdoor tensile canopies hover above the two main building courtyards. Symbolically, the canopies represent an archaeological excavation site, where traditional fabric tent structures are used to house archaeologists and cover excavations. Functionally, the canopies serve as covered spaces for both outdoor sculpture studios and public exhibitions. Buro Happold provided the design for the roof canopy structures, in coordination with the architect and an Israeli engineering firm in charge of the base building structures.

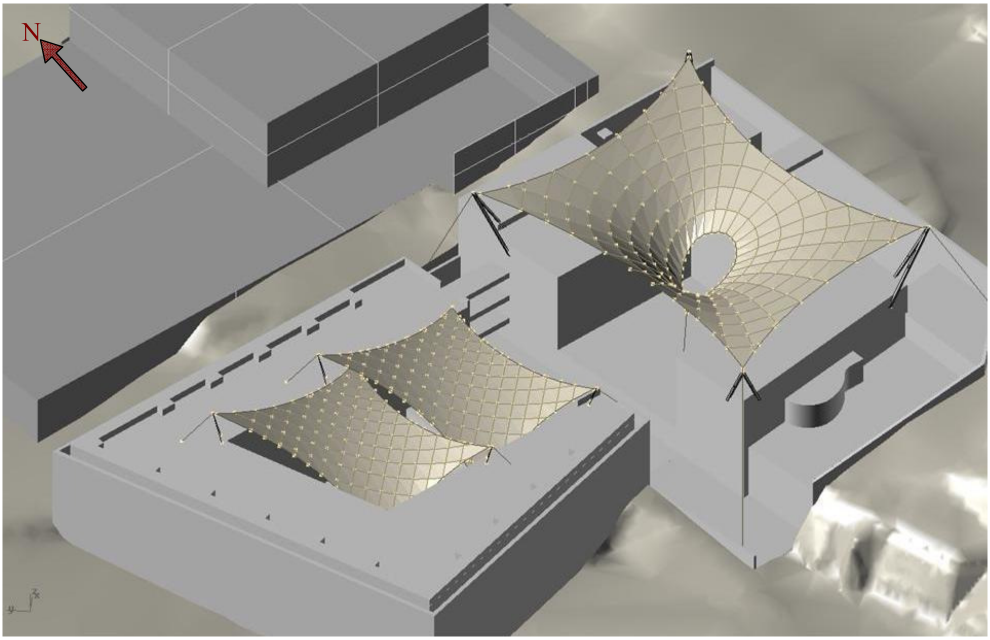

Figure 1: The three canopies in context

The roof canopies are cable net structures with a translucent fabric membrane suspended above. The choice of fabric for large canopies is limited to the strongest types of materials. Based on the architectural importance for translucence, color and durability, the project team determined that Gore Tenara fabric would be the most suitable material. This decision necessitated that the canopies be reinforced with a cable net in order to meet appropriate strength and serviceability requirements.

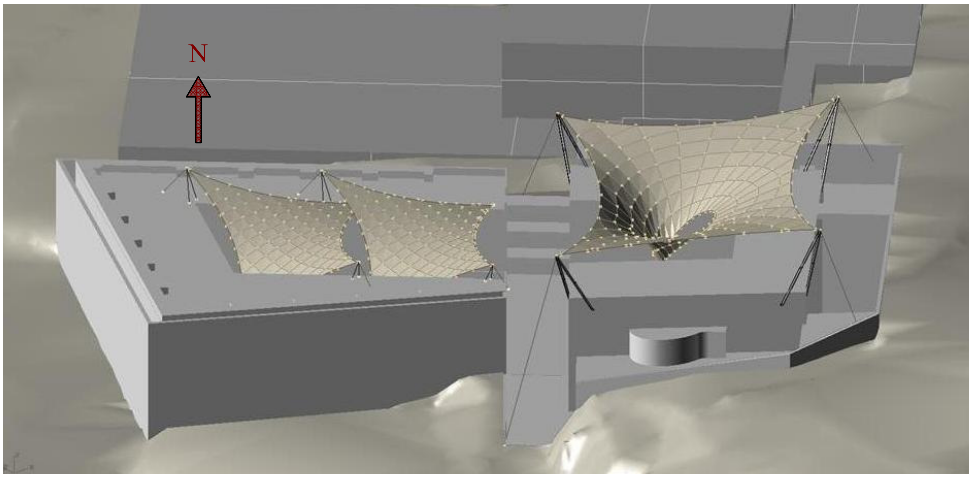

Figure 2: View of the canopies and sloping site

2. Form and layout

2.1. Canopy 1

Canopy 1 is rectangular in plan with maximum exterior dimensions of approximately 51m by 36m and a surface area of 1400m^2. The canopy is shaped into an inverted cone with a 7m wide teardrop oculus at the center. The oculus is tied down to the courtyard at a single point 7.5m above the courtyard elevation. The canopy has four corner supports, with eastern supports cantilevering 12m above the roof plane and western supports 9m providing the canopy with a sloping profile from east to west. The form for Canopy 1 was developed to provide clear unobstructed sight lines from the roof entrance of the eastern most building to the courtyards of the western building below. Originally the architect envisaged the canopy as a classic inverted cone fabric structure. However, it soon became apparent that the required depth of the oculus for a canopy of this scale would interrupt any roof sight lines into the adjacent courtyards. This was solved by forming a teardrop shaped oculus with a single tie down cable to the courtyard below.

The primary canopy structure is a cable net with a fabric tension membrane suspended above the plane of the cables. Inverted, pinned, steel V-struts connect the net boundary catenary cables to steel tie back tension rods. The teardrop oculus is formed by a cable loop which attaches to a steel tension rod at the oculus eye. The tension rod spans from the oculus to the courtyard below.

The principal structural element sizes are below:

Catenary cables: Ø70mm

Oculus cable: 2- Ø32mm

Radial cable: 2- Ø20mm

Hoop cable: 2- Ø16mm
East raking v-struts: Ø406mm
West raking v-struts: Ø356mm
Strut tie back rods: Ø76mm
Oculus tie back rod: Ø50mm

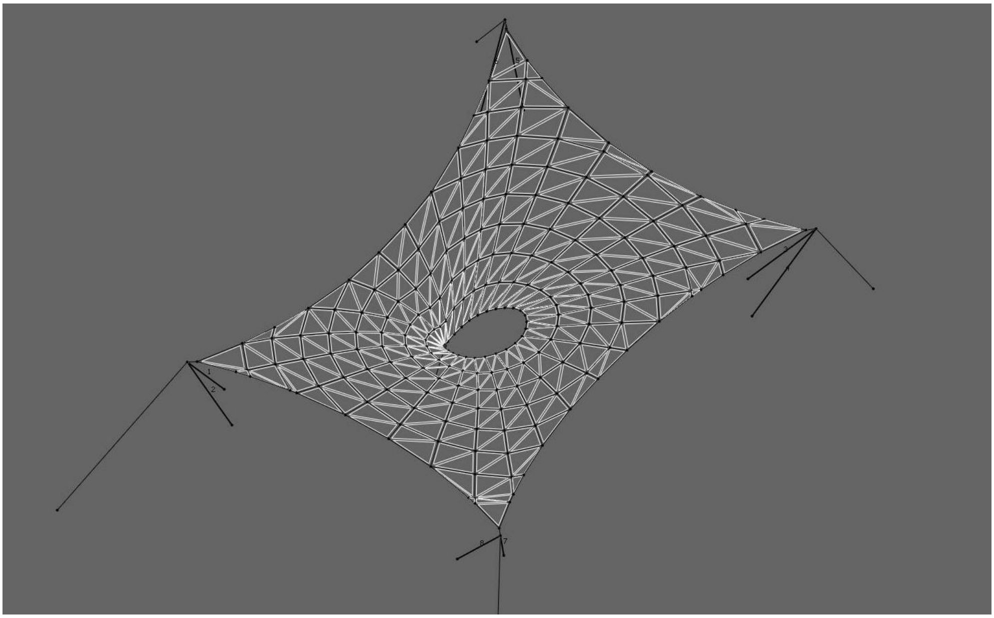

Figure 3: View of Canopy 1

2.2. Canopies 2A and 2B

Canopies 2A and 2B are both rectangular in plan with maximum dimensions of approximately 30m by 56m and a surface area of 400m^2. Each canopy is shaped as a hypar covering a rectangular courtyard formed by a U-shaped building below.

The development of Canopy 2 as a double hypar solution has been the result of an iterative process in which several options have been developed to best meet architectural goals and structural constraints. Achieving adequate shading on the north side of the courtyard without blocking views to the south was a critical design element. This proved difficult to accomplish with a single hypar solution due to large spans and insufficient canopy curvature. Several options were tested during design development, including six-point hypar shapes and inverted cone canopies similar to Canopy 1. The final solution was found by creating two smaller hypars with the high and low points pulled above and below the roof plane.

Canopies 2A and 2B follow the same structural system as Canopy 1, utilizing a cable net with a fabric tension membrane suspended above the plane of the cables. Four of the eight support conditions (two per canopy) are inverted, pinned, steel V-struts, connecting the net boundary catenary cables and steel tie back tension rod. The four remaining support points are attached directly to the base building concrete slabs.

Structural sizes are summarized below:

Catenary cables: Ø50 mm

Internal net cables: 2- Ø16mm each direction

Tie back rods: Ø50mm

North raking v-struts: Ø273mm

South raking v-struts: Ø219mm

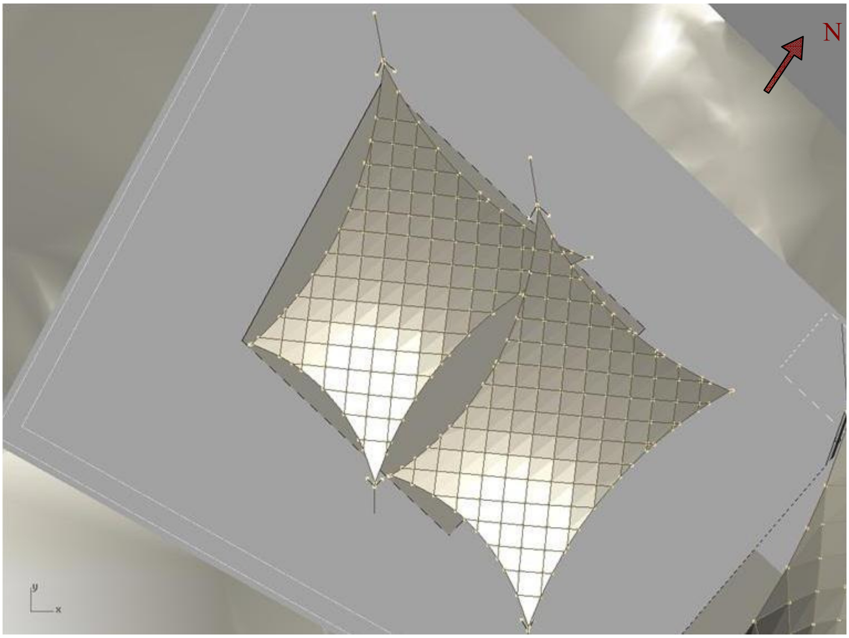

Figure 4: Plan view of Canopies 2A and 2B

Buro Happold provided the design for the cable net, supporting struts, and tie downs for both canopies. The design was based on the Israeli Building Code in combination with ASCE 7-05

3. Design and analysis

Due to the nature of their structural behavior, tension structures follow a strict set of design principles. The design and analysis of both canopies has been carried out with an optimized interaction between modeling and analysis software in order to achieve a form-found, rationalized, tensioned cable net. The final shapes are a result of an interactive process among Rhinoceros, Excel, and Tensyl (a non-linear dynamic relaxation analysis program developed internally by Buro Happold).

The procedure is composed of four main steps:

- Fabric form-finding (Tensyl and Excel)
- Generation of cable net geometry on form-found shape (Rhinoceros)
- Refinement and prestressing of cable net (Tensyl)
- Final analysis of cable net and results interpretation (Tensyl and Excel)

After the completion of final analysis, the prestressed net geometry is documented by importing a centerline model into BIM software (Autodesk REVIT Structure) using scripts written by Buro Happold.

3.1. Form-finding

A wireframe 3D model is created in Tensyl with the correct boundary conditions for form-finding. The fabric is given an initial prestress of $200kg/m^2$-$400kg/m^2$. Catenary cables are prestressed by imposing a slack length obtained from an Excel spreadsheet prepared to calculate the corresponding arc length of cable segments for a particular span to sag ratio. Tensyl then performs a form-finding analysis which is refined until the approximate membrane curvature, catenary cable sag, oculus size and depth is determined.

3.2. Surface geometry rationalization and cable net generation

Form-found control points and surfaces are imported into a 3D modeling software, Rhinoceros, for generation of cable net geometry.

3.2.1. Canopy 1

For Canopy 1, the net is composed of two types of cables, radial and hoop. In plan view, 28 radial cable lines are projected onto the form-found surface symmetrically and equally spaced around the oculus. The number of radial cables was driven by constructability considerations at connections to the oculus cable and the need to support the fabric membrane above at regular intervals. Next, the net hoop cable connection points are determined by dividing the radials into a set number of points, at 2.8m-3.3m spacing from the oculus outward. Connection point distances taper downward from east to west, thus allowing the hoop cables to follow the oculus geometry. The hoop cable layout mimics the natural flow of tension forces within the original fabric canopy while also minimizing the number of radial to hoop cable intersections near catenary cables.

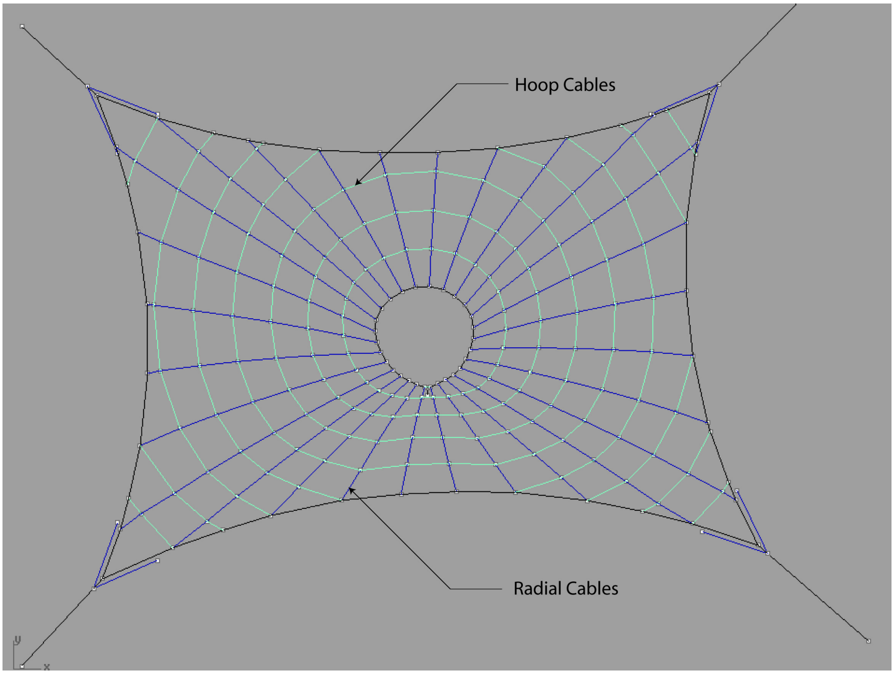

Figure 5: Net geometry for Canopy 1

3.2.2. Canopies 2A and 2B

For Canopy 2, the cable net generation involved the creation of a planar orthogonal grid projected onto the form-found surface. Different grid spacings were studied (1.75m, 2m, 2.25m, 2.5m) to establish the optimal solution to control the net density, number/size of cables, and minimize the number of perpendicular net cable connections occurring close to catenary cables. This was done using a Buro Happold tool called SMARTForm. This software has been developed as a special plug-in for Rhinoceros to provide surface rationalization for complex geometries by projecting orthogonal or polar grids on different types of surfaces. Utilizing this tool, the net layout for the canopy could be optimized into a series of orthogonal equal-sized links repeated on the surface.

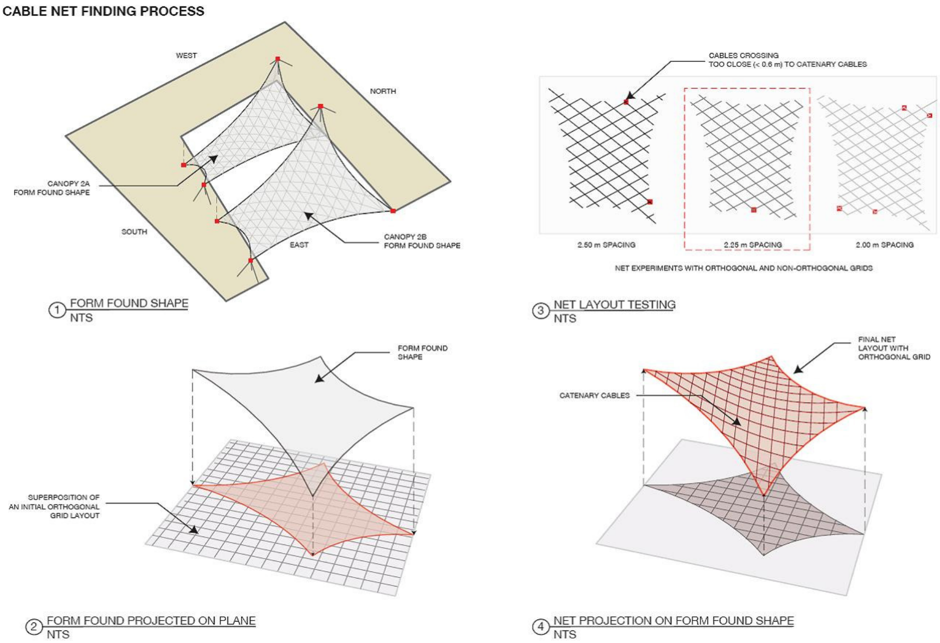

Figure 6: Net generation process for Canopies 2A and 2B

3.3. Net prestressing

The cable net intersection points defined in Rhino are imported back into Tensyl. Straight line cable segments and fabric membrane elements are introduced between net intersection points. A high prestress is assigned to the fabric in order to pull the net together. All cable lengths are then reset to their new lengths and the fabric prestress is reset to zero thus transferring the fabric prestress into the net while keeping the rationalized net geometry consistent.

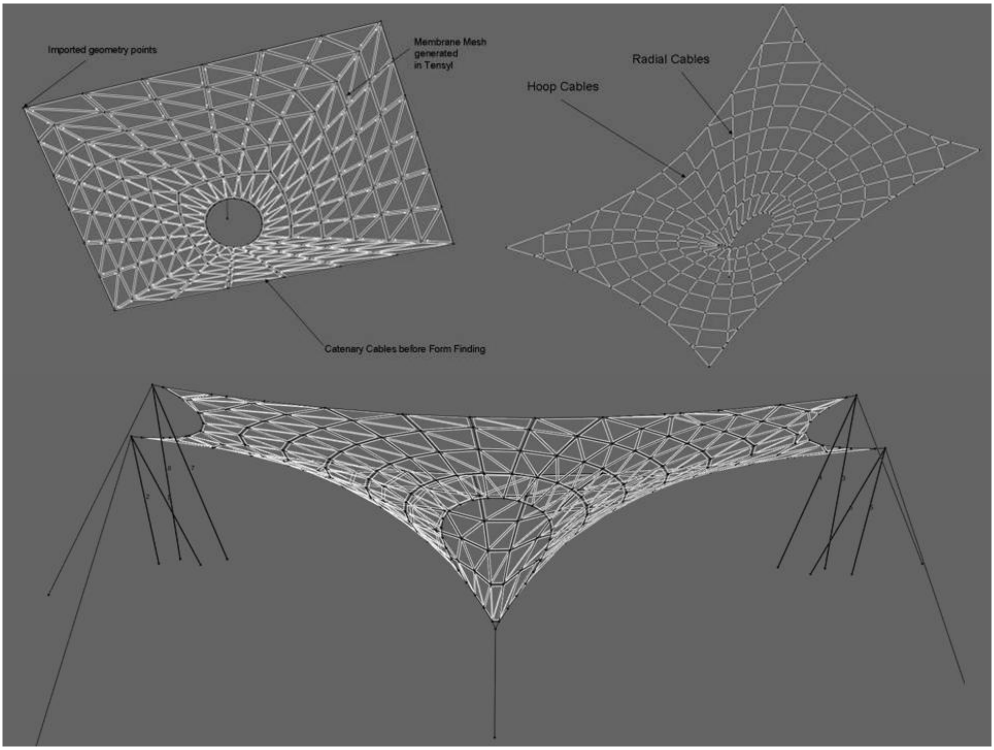

Figure 7: Design and analysis process for Canopy 1

3.4. Final analysis

The final step is to tension the fabric with a nominal prestress on top of the tensioned net and apply design loads into the model. Through several iterations, the appropriate net tensioning is determined to meet strength and serviceability criteria. Significant consideration was given to the determination of realistic preliminary wind and snow loads. At the conclusion of the design development phase wind tunnel testing had not been performed. The design wind velocity specified by the Israeli Building Code was used in tandem with wind load coefficients from ASCE 7-05 for an initial estimate to be verified by future testing. The model has been designed to a wind velocity of 52m/s and snow load of 90kg/m^2.

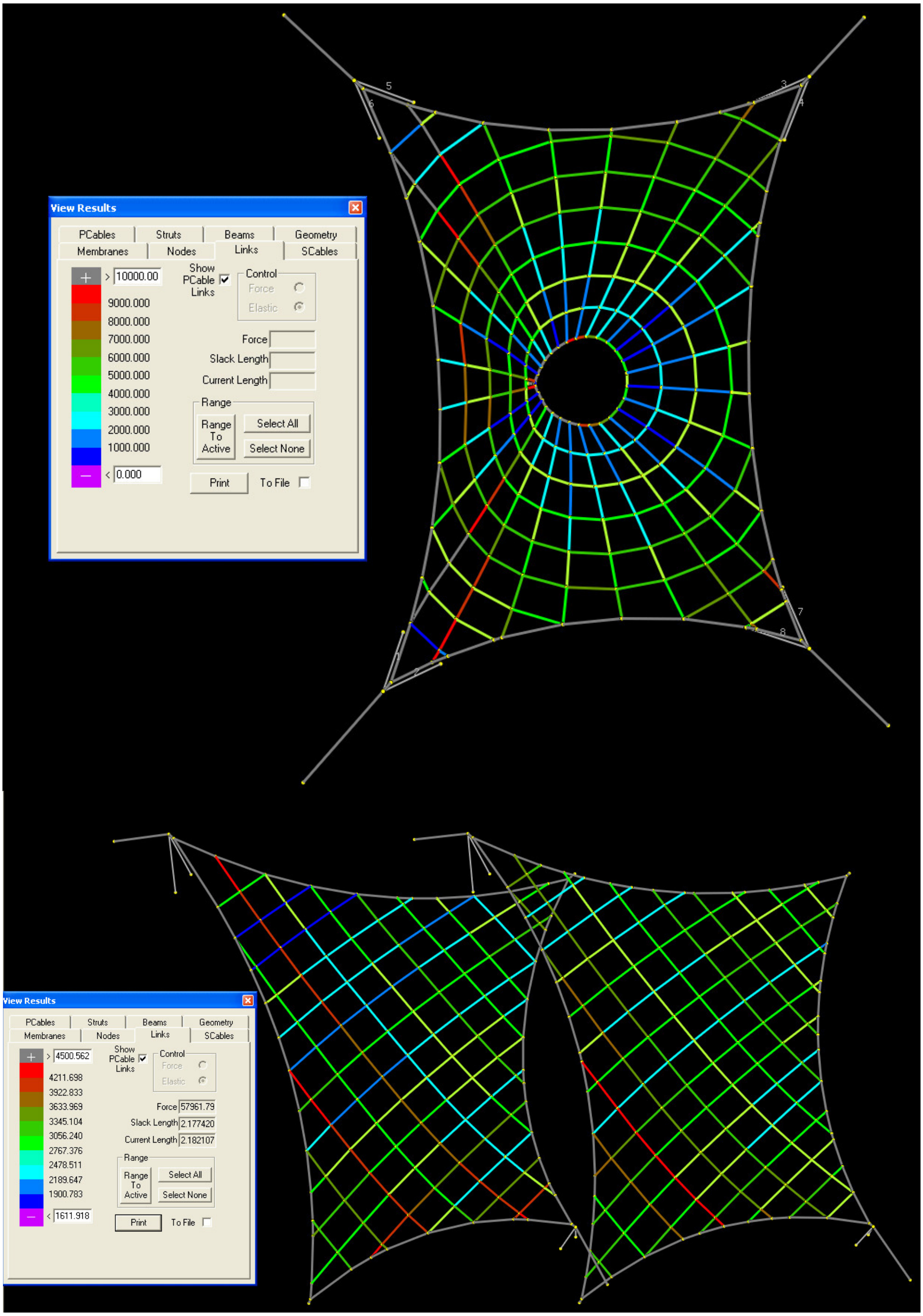

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Figure 8: Final prestress forces (kg)

4. Technical challenges

The Canopy 1 net behaves predictably with wind suction pressures increasing radial cable tension while decreasing hoop cable tension. Downward loads elicit the opposite behavior. To maintain stability the net must remain tensioned under all load cases. In general, for both canopies, localized de-tensioning of individual cables under full design loading is reasonable. For this project an acceptable amount of cable slackness, under full loading, for a 2m-3m length of cable was determined to be 30mm. This amount of deflection would correspond to cable sag of 240mm-350mm. The fabric membrane would need to be offset at least this amount above the fabric membrane to avoid a sagging cable damaging the fabric. Areas in which net de-tensioning is likely to occur in Canopy 1 include discontinuous hoop cables near the four canopy corners and at radial cables near the eye of the oculus.

Using a cable net with fabric infill has the added benefit of increasing the overall stiffness of the structure versus that of a reinforced fabric canopy. Due to the scale of these canopies it became critical to limit the deflections of the net. For Canopy 1, maximum deflections occurring at mid-span of the eastern portion of the net have been limited to 1.3m under worst case wind loading; for Canopies 2A and 2B, maximum deflections occur in the middle of the net and have been limited to 0.5m under snow loads. Roughly half of all deflections are due to the rotation of catenary cables and half is due to deflection of the net cables.

5. Digital design methodology

The canopies offered many technical challenges throughout the design process but also allowed for a great deal of exploration into digital design techniques. Digital models represent the opportunity to embed design intelligence into a three dimensional format. Fabric structures are an ideal typology for this technology in which geometrical, analytical and fabrication information are linked through a non linear process of design. Using a digital methodology, the geometrical model of the components of a fabric structure are linked directly to an analytical engine capable of performing both form finding operations and overall structural design. In this case, the overall geometry of the canopies as well as the material and sectional properties of the cables and connections were housed in Autodesk's Revit Structure as a database.

Parametric design of the connection details was studied using three dimensional solids in Solidworks (See Figure 9). Parametric components in the model allow their geometry to be influenced by the results of the analysis. Various connection components of the structure can be individually analyzed using finite element analysis based on the results from the overall structural analysis.

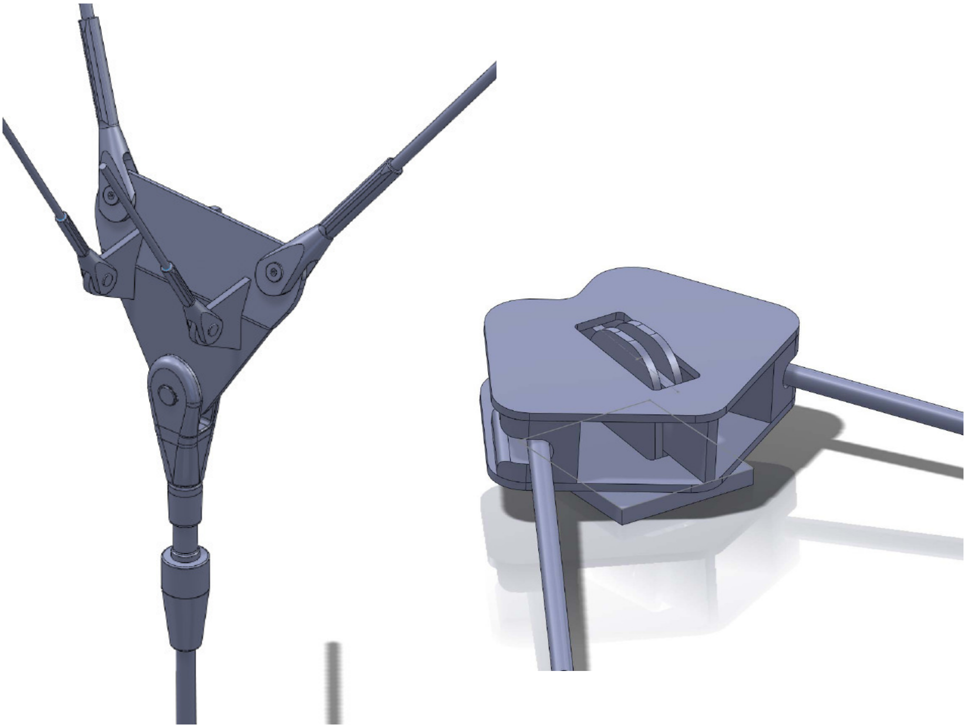

Figure 9: Solid 3D models of components

Further, limitations of the fabrication process can also be set as parameters for the post processing of the digital model. Allowable widths of machinery used for coating processes, for example, can directly impact the patterning of the fabric. Fabrication parameters therefore influence the design process in a non-linear fashion. (See Figure 10).

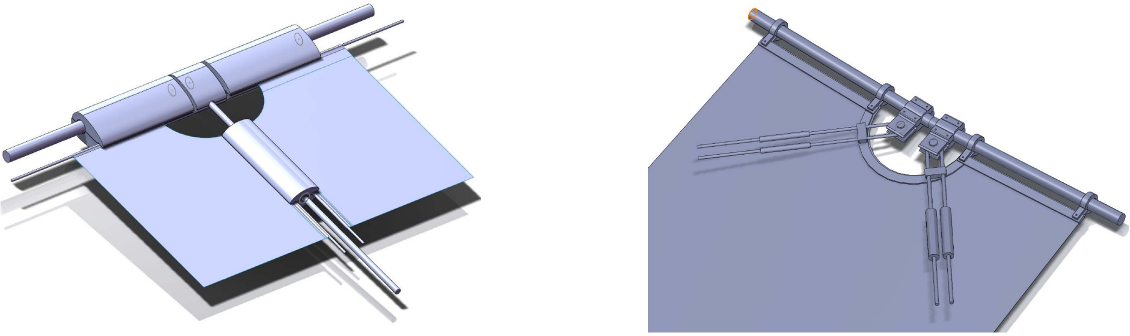

Figure 10: Solid 3D models of components

The exploration of a digital method for the analysis and documentation of tensile structures challenges the traditional notions of design and fabrication as distinct processes. The potential for this technology is to broaden the traditional role of the design engineer and further his involvement in the production of the built form based directly on the completed digital model. Fabrication level information for cables, connections, fabric panels, etc. can be extracted directly from the digital design model and used to drive the actual production.

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