X International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2021
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LUNAR DOME - TENT FOR THE APOLLO 11 ROADSHOW

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Key words: membrane, ETFE foil, cables, temporary structure, formfinding, analysis

Summary The paper is about the structural design of the main structure and the integration of the secondary elements for the projection membrane and the entrance façade. It describes the design process, from the formfinding process to the structural analysis, the cutting pattern generation and the installation process.

1 INTRODUCTION

In the year 1969 Apollo 11 brought the first humans to the moon. On the occasion of the 50th anniversary a big roadshow was designed which should travel through several cities of the United States of America. A huge theatre tent with 1600 seats was developed. As temporary building, the tent consists of single elements which are optimized for a fast assembly and an easy transportation.

An arch-supported main membrane, an elastically supported projection dome and a huge ETFE façade form the various envelopes and reduce the tent character of the project. Adaptable base elements, anchored with long pegs, are used as flexible foundation for the different locations. In summer 2019 the temporary theatre for “Apollo 11 – the immersive live show” was in Pasadena.

Figure 1: view at night

The supporting structure is composed by four steel trussed arches. All four arches consist of rectangular framework elements connected together with bolts. Steel cables link the whole structure in order to keep the arches in position. Steel ridge cables are integrated into the membrane under the arches They transfer the membrane loads into the steel structure and serve as field joint.

2 DESIGN

The structure of the Apollo Theatre consists of 5 truss arches. Two main arches are in the central area, with slight inclination. One smaller arch carries the membrane in the backstage area, and the top line of the front façade is formed by another arch. The arches are made of single truss elements, which are coupled with pin connections. Steel cables, spanning over the whole structure, keep these arches in their final position. The base points are pin connected and anchored with huge pegs.

Ridge cables run under the main arches and the backstage arch. Made as twin cables, they are at the same time installation joints. Along the perimeter catenary, cables keep the membrane in place and under tension.

In order to minimise deflections under wind suction two valley cables are placed on each membrane saddle. These cables are attached to the base points of the arches, and balance a large amount of the inner forces with in the structure.

On top of a peripheral timber wall inside the structure, and around the spectators stand, a large projection dome is attached, and tensioned towards the main membrane. This dome membrane is made of sound absorbing PVC coated polyester fabric. Under the main membrane, the dome is attached with elastic ropes. The stiffness of this support is chosen so soft, that under wind deformation the tension changes only slightly.

Ten façade columns support the foyer arch, and are at the same time the structure for an ETFE cushion cladding. These columns carry only downward forces resulting from the arch. During uplift, slotted holes allow the deformation, and help to avoid tension in the base points of these columns.

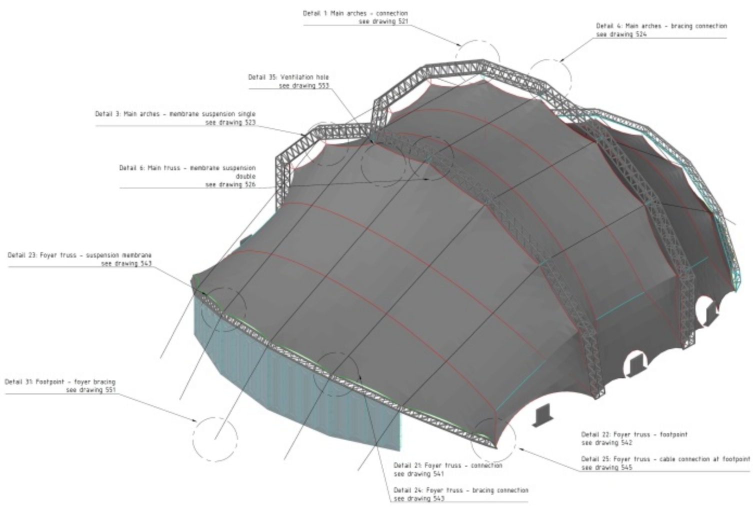

Figure 2: isometric view from front

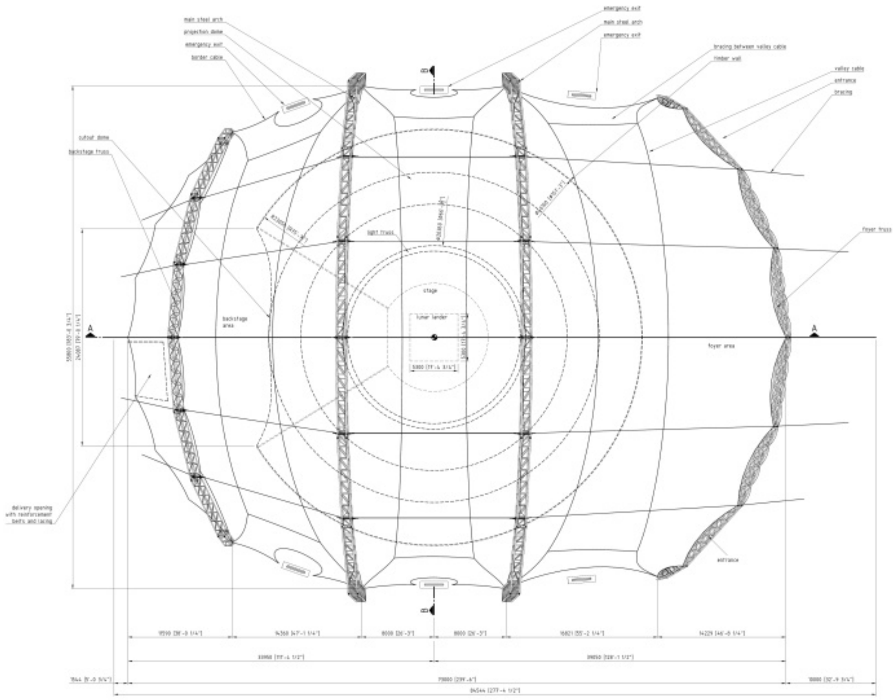

Figure 3: plan view

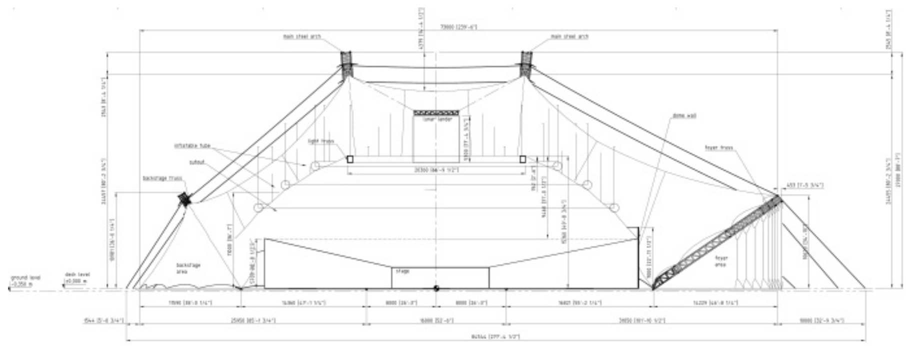

Figure 4: longitudinal section

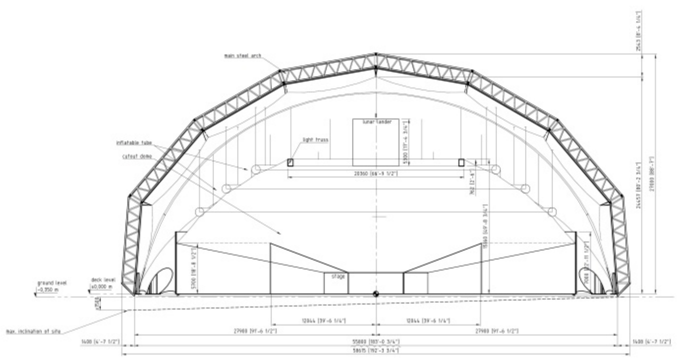

Figure 5: cross section

2.1 Tent structure

The main membrane, with a surface area of 4900 m², hangs under the four main arches. Under the arches, the membrane has joints made of twin cables. The loads of the 73 m long tent structure are mainly carried by the two central arches. These main arches have a span of 55.8 m and a height of 27 m. The smaller foyer- and backstage arches have much more inclination, and end in a height of 11m.

The envelope is made of PVC coated polyester fabric type III. The coating is white on the outside, and matt black on the inside. Wind suction cables are just lying on the membrane. Emergency exits are integrated in the membrane saddles. The membrane of the foyer ends with large catenary cable, and allows so a comfortable access to the neighbouring VIP building. A large ring cable in the backstage membrane collects all membrane forces, and allows so the access with trucks.

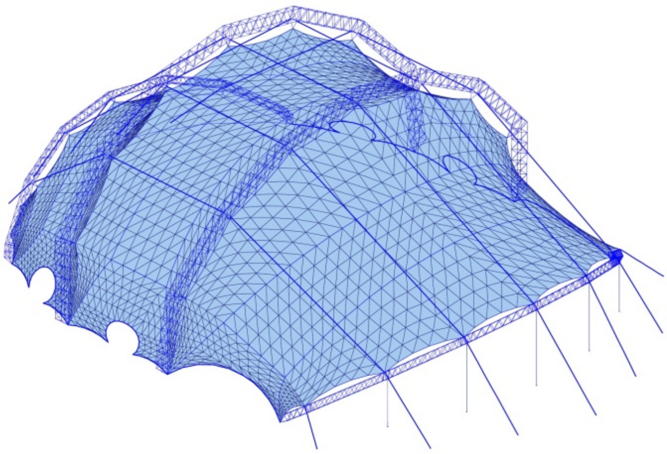

Figure 6: numerical model main structure

2.2 Projection dome

The projection dome has a diameter of 46.1 m and a height of 15 m. In the centre, it is attached to a rigging truss with a diameter of 20 m. Towards the backstage area, the cupola has a large cut-out to allow the view to a large screen. The spherical shape is generated with the help of hanger cables, attached to annular membrane strips. The annular strips, as well as the perimeter, have polyester belts stitched to the membrane, to redistribute the nodal fixation loads in to the dome.

The membrane is a light PVC coated membrane with micro perforation, which absorbs approximately 65% of the sound. The colour of the coating is a light grey and good for the projection. With the hanger cables, the dome is attached to the main membrane. The roof has a large deformation under wind load, therefore the hangers have to be very soft, in order to compensate this deformation with only few changes in the prestress. Polyester ropes, combined with a spring system, anchor the hanger forces in the perimeter wall. At the main membrane pulleys redirect the ropes. The springs are made of long elastic ropes. Depending on the local deformation and prestress, three different types of spring systems had been fabricated.

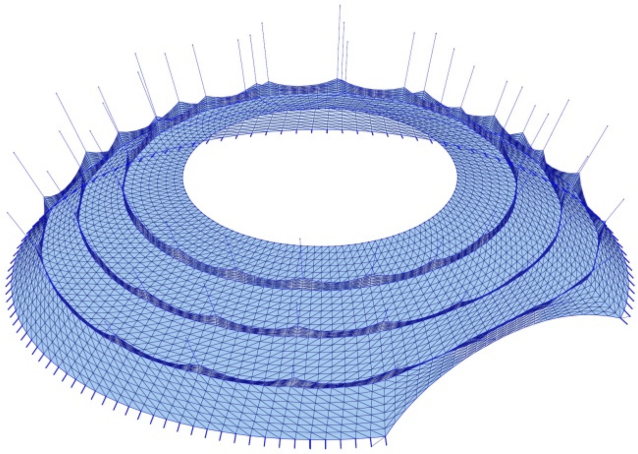

Figure 7: numerical model dome membrane

2.3 Foyer façade

Under the foyer arch, columns are integrated in the main structure. At top and bottom of these columns cross beams are attached. These cross beams carry additional columns to get a reasonable spacing for the ETFE system. The ETFE cushions are clamped to the top chords of the columns, and the cross beams with extruded aluminium profiles. The air supply is distributed from the foyer arch on top of the cushions, and exhaust valves are at the lower end towards the outside.

The cushions are double layer with 250 microns thickness. The outer layer is fritted, the inner layer is clear ETFE.

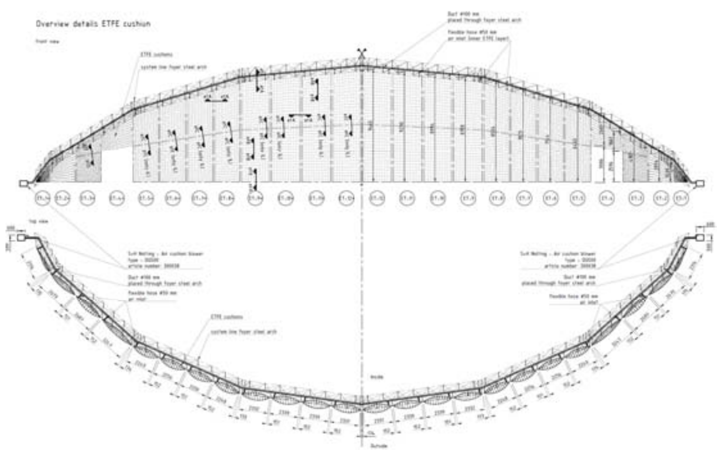

Figure 8: ETFE foil façade

3 ANALYSIS

For the analysis of the complete tent structure the software TL_form and TL_Load has been used, a software developed especially for tensile structures, by Professor Mike Barnes in Bath, UK. For formfinding and analysis the method of the dynamic relaxation[2] is applied in a geometrically nonlinear process.

3.1 Applied Loads

In addition to the self-weight of the structure, service loads for the rigging (sound and light) and the moon lander has been applied with a total weight of 135 kN. The membrane structure is not supposed to be used in winter. The wind load is determined according to ASCE/SEI 7-10[3] with a basic wind speed of 100 mph, which corresponds to 44.7 m/s. The distribution of the wind load is shown on in the following figure, including an additional inner pressure. For the verification under seismic load the location Los Angeles has been applied.

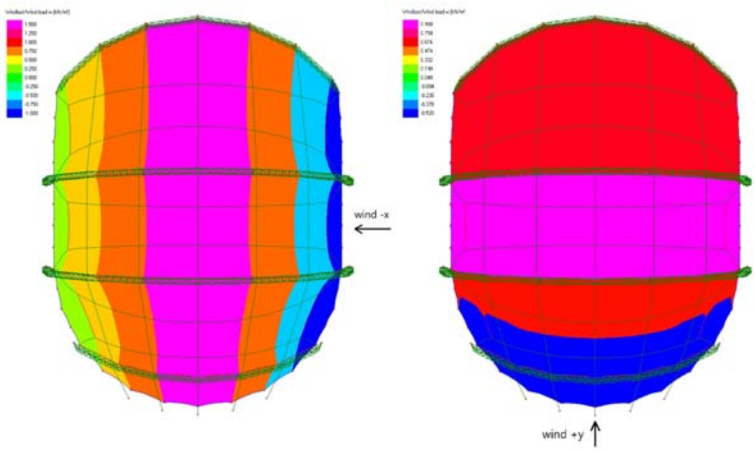

Figure 9: wind load in transversal and longitudinal direction

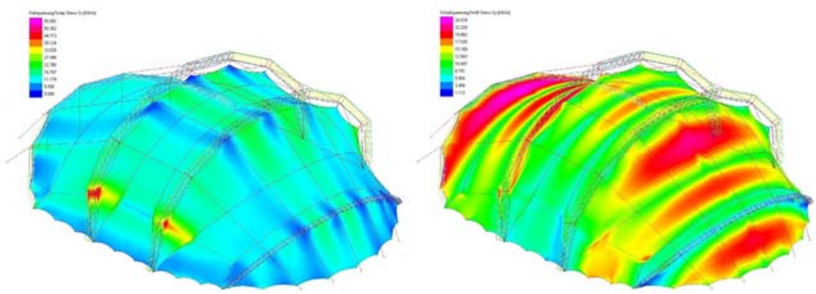

Figure 10: maximum membrane stress in warp and weft/fill direction

Neglecting local stress peaks, the maximum membrane stress is approximately 25 kN/m in both directions. At the support points, with local load concentration, the membrane is reinforced. The verification is made according to ASCE/SEI 55-104, but as well double checked with the latest draft of the future Eurocode Membrane.

4 DETAILING

4.1 Steel details

In order to minimise the different types of truss elements, attachment plates for cables and membranes have been made as loose items, attached with pins, or form fit, to cope with their individual function. The cable forces are guided through steel plates attached to the pinned connections. The membrane is suspended punctually at the ridge cables. U-shaped brackets are placed over the crossbars, and carry a V-shaped steel part, the so-called boomerang. They support he ridge cables with pin connected saddles.

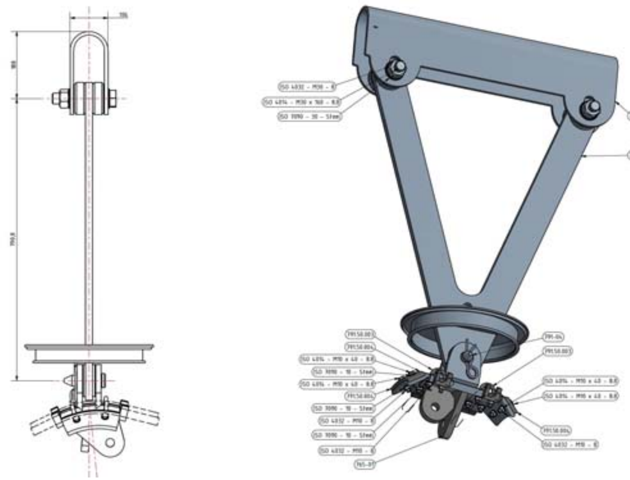

Figure 11: boomerang connection

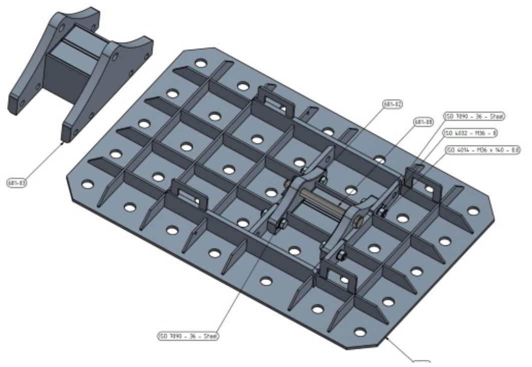

Figure 12: support plate for the main arches

The baseplates under main and secondary arches are steel plates 2200 mm long and 1500 mm wide. Steel fins stiffen the plate and activate the pegs. These steel plates can be shimmed and have two types of brackets with different levels. This allows to adjust each base point according to the level of the site. Up to 500 mm can be compensated.

4.2 Membrane details

The roof membrane is connected to the foyer arch with catenary cables. A flexible membrane gutter is attached under the membrane, and continues in one piece over the truss girder, being so at the same time the cladding of the truss. A heavy linear strip in the gutter keeps it in shape. The gutter drains towards the arch supports.

The main membrane panels are joined under the arches with a twin cable. These cables are placed in membrane pockets. In 500 mm steps, the twin cables are combined, and form structurally one ridge cable. A closure flap, attached on one side with a French lacing, together with a water barrier keep this joint water tight.

Attached to the roof membrane are nodal fixations with pulleys. Polyester ropes which run through these pulleys keep the projection dome under tension. These ropes are attached to the timber wall around the stage and scene. Spring elements installed in these ropes keep this fixation soft, so a deflection in the roof creates only a slight change in the prestress forces.

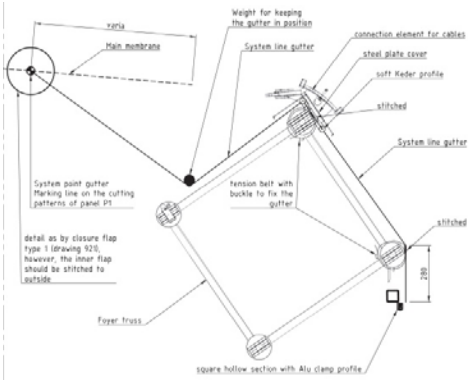

Figure 13: membrane gutter

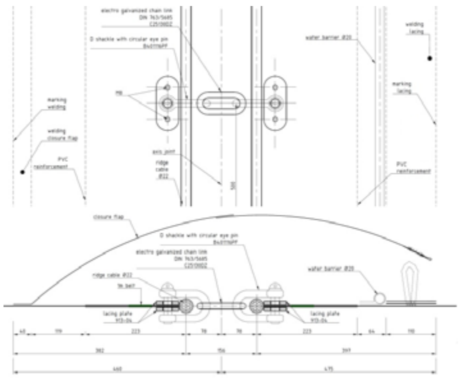

Figure 14: membrane joint

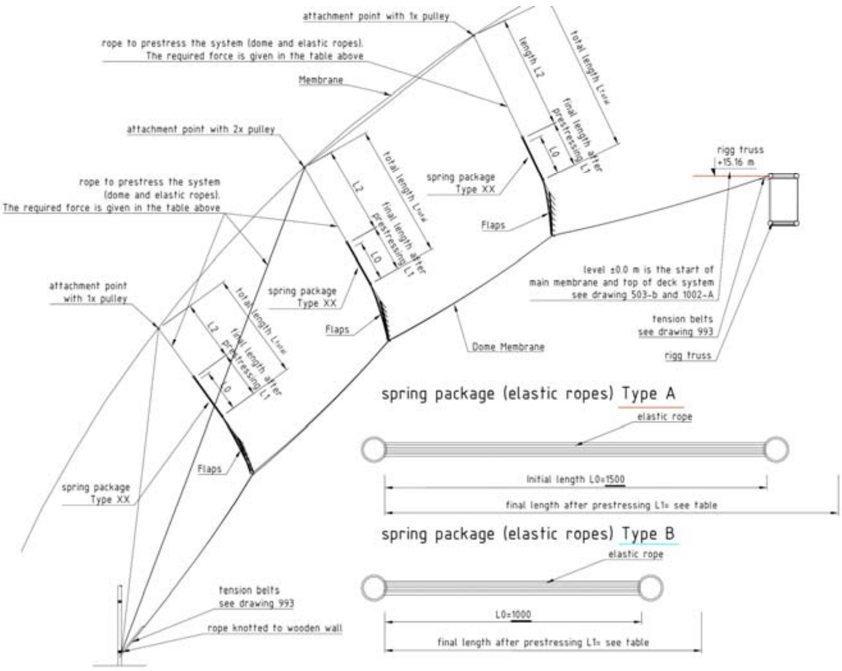

Figure 15: elastic support of the projection dome

4.3 Cutting pattern

The main membrane consists of four panels. The largest panel is towards the foyer arch, and has a surface area of 1700 m². To optimise the handling during the fabrication, the large panels have been fabricated in two halves, and the final seam was made towards the end of the fabrication. The panels have been cut in parallel strips, with slight radial corrections on both sides, so that a more homogeneous appearance was achieved.

The compensation was determined with biaxial tests, considering the stress in predominant loadcases. In warp direction the membrane was not compensated, while in weft direction a compensation of 2.8% was applied. Near the ridge cables the compensation was reduced to comply with the strain of the wire ropes.

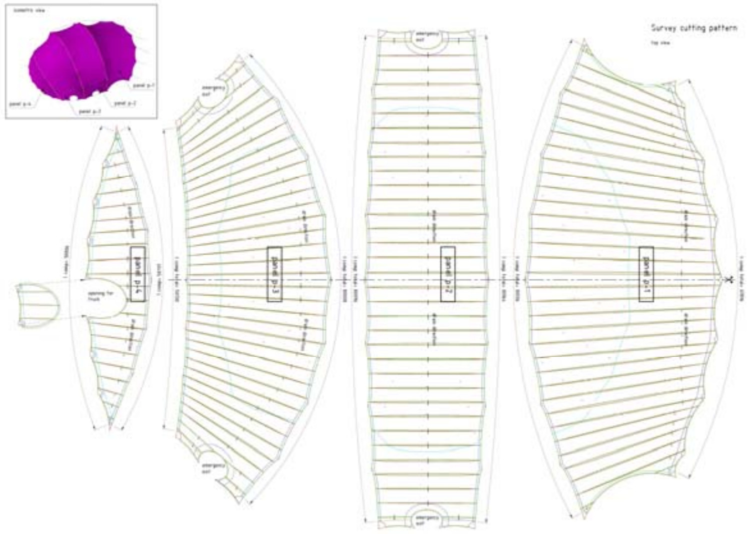

Figure 16: cutting pattern layout main membrane

The projection dome is made of a very light material, with a very low prestress level. The dome is cut in radial direction, the borders have polyester belts, stitched to the membrane. The garland strips to tension the dome are made of white PVC polyester fabric, with welded and with stitched seams. Projection tests have been made to choose the weld detail with the least visual impact.

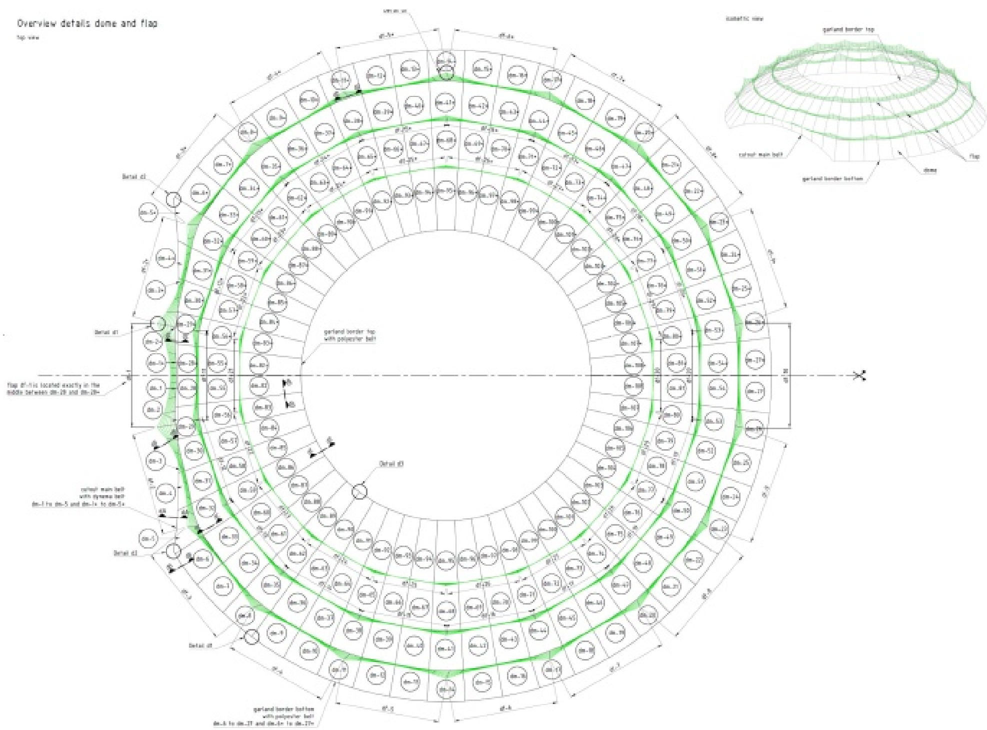

Figure 17: cutting pattern layout projection dome

5 FABRICATION

The steel structure has been fabricated in three different shops around the world. The membrane steel and pegs came from Italy, boomerang elements and adjustable support have been fabricated in Canada, and the truss girders came from Singapore. The girders are duplex coated. The length of 12 m required large zinc outlets, which were not feasible in the slender profiles used. Therefore, the pin connections were welded after galvanizing.

Figure 18: Main girder before galvanisation

Membranes and foils came from Germany, France and Italy, and have been processed in Italy, as well as the structural cables.

6. INSTALLATION

The arches have been laid to the ground beside the levelled support points. A special installation tool guides the pin connection in the correct position. Once the pin is installed, the arches are lift up to the final inclination, where it was fixed with temporary cables. As soon as more arches were in place, the final cables have been attached where it was possible.

Figure 19: arch installation Figure 20: Membrane joint

Then the membrane panels are unrolled and spread out. The valley cables are connected, and the saddle elements attached. Together with the boomerang elements the membrane is lifted up with electric winches, which are installed in the truss girders. Once up, the boomerang elements are pinned to the connection detail under the arches. After that the membrane is tensioned towards all the lateral anchoring points.

Figure 21: lifting of the main membrane

Figure 22: Foyer with ETFE façade

Figure 23: view during the day

6. CONCLUSION

With one year for design, fabrication and installation, a temporary structure with enormous dimensions has been realised. Through continents and time zones the project has been coordinated and designed. To integrate the touring capability in all the details was a huge challenge, in these dimensions. Realising temporary foundations with the loads of this project, as well as ETFE cushions in a travelling tent were further challenges to be solved.

But the effort was worth it. In time for the inauguration in July 2019 in Pasadena, the temporary theatre was up and operating. With the dimensions and the architecture, it appears to be a theatre for permanent use.

PROJECT PARTICIANTS

Producer: Matthew Churchill Production Ltd. und Nick Grace Management Ltd.
Architecture: Teresa Hoskyns
Structural design: formTL ingenieure für tragwerk und leichtbau GmbH
Engineer of Record: Wiss, Janney, Elstner Associates, Inc.
Steel structure: Boon Chang Structure Pte Ltd, CORBO Engineering, Inc., Anceschi Alberto e Paolo srl
Membrane contractor: Canobbio Textile Engineering srl
Membrane and foil supplier: Verseidag-Indutex GmbH, Serge Ferrari S.A.S., Guarniflon Spa Pati Divison
Cables: FAS SpA

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[3] American Society of Civil Engineers (2010) ASCE Standard ASCE/SEI 7-10 Minimum design loads for buildings and other structures.
[4] American Society of Civil Engineers (2010) ASCE Standard ASCE/SEI 55-10 Tensile Membrane Structures

PICTURE CREDITS

Figures 1, 19, 22, 23: Matthew Churchill Production Ltd
Figures 2 to 18: formTL GmbH
Figures 10, 21: Canobbio Textile Engineering Srl