German Pavilion Montreal 1967

Frei Otto

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Background

General Information

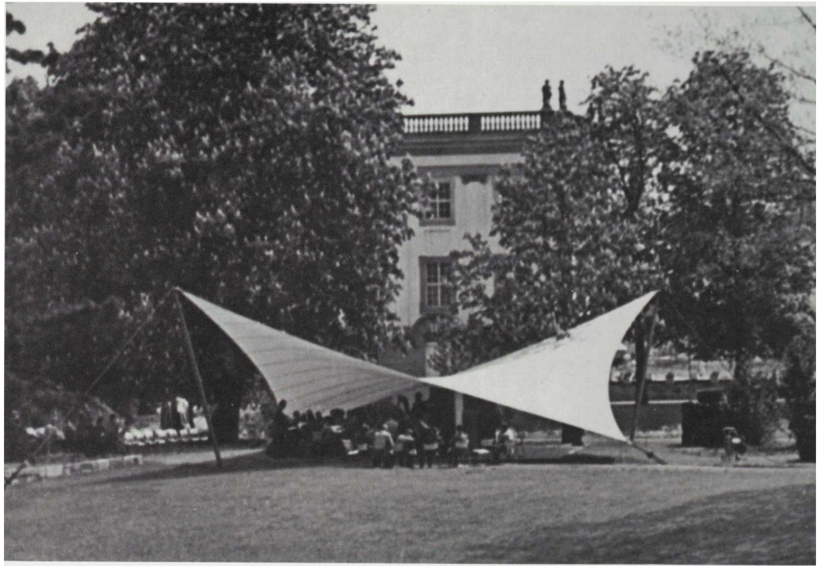
Location: Montreal, Quebec, Canada
Use: fair or trade building
Date: completed 1967
Architect: Frei Otto (other listed architects L. Medlin, H. Kies, H. Kendel, Rolf Gutbord)
Structural Engineer:

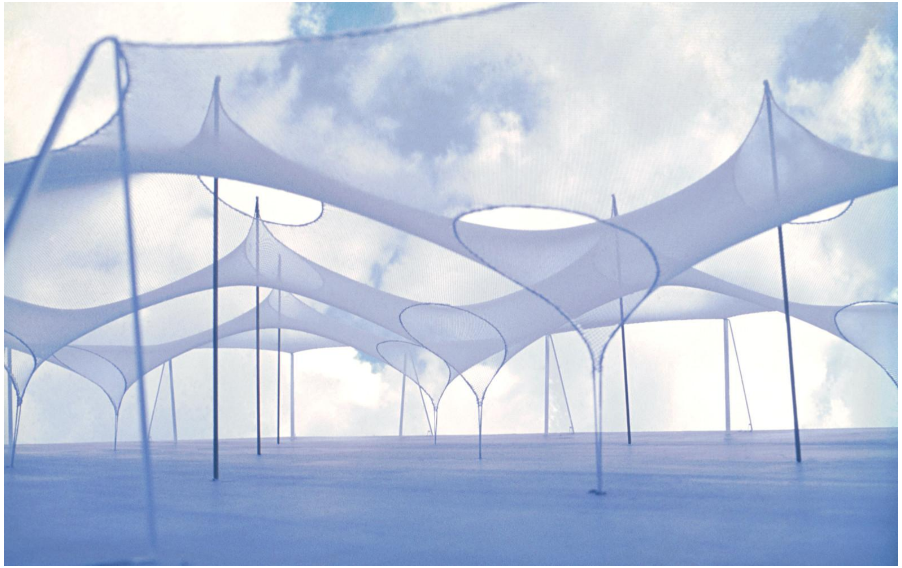
- A. Drab
- CBA Engineering Ltd.
    - K. Manniche
- Leonhardt und Andra
    - Harald Egger
    - Fritz Leonhardt

General Contractor: Dominion Bridge Company
Steel Construction: Steffens & Nolle AG
Cables: L. Stromeyer + Co.
Material Supplier: L. Stromeyer + Co. (membrane)
Client: Bundesbaudirektion

Design Constraints/Opportunities

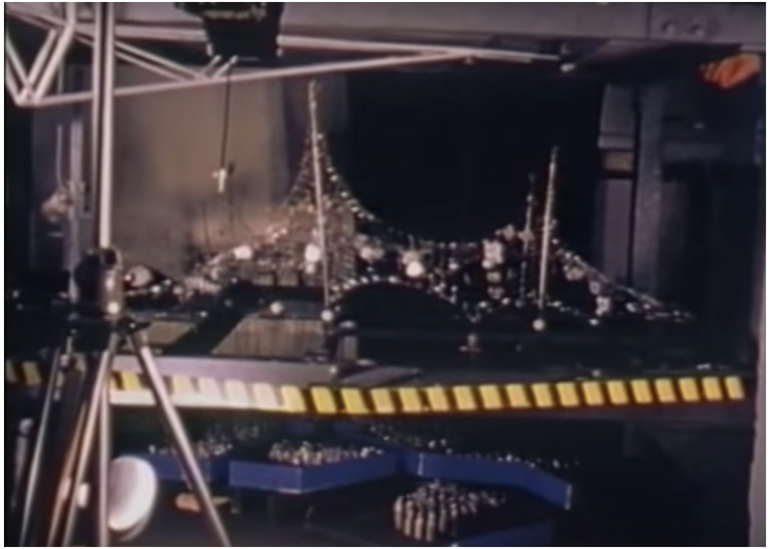
- **Personal Principles**
  - -minimal structures
  - -maximum efficiency of structure and materials,
  - -optimum utilization of the available construction energy

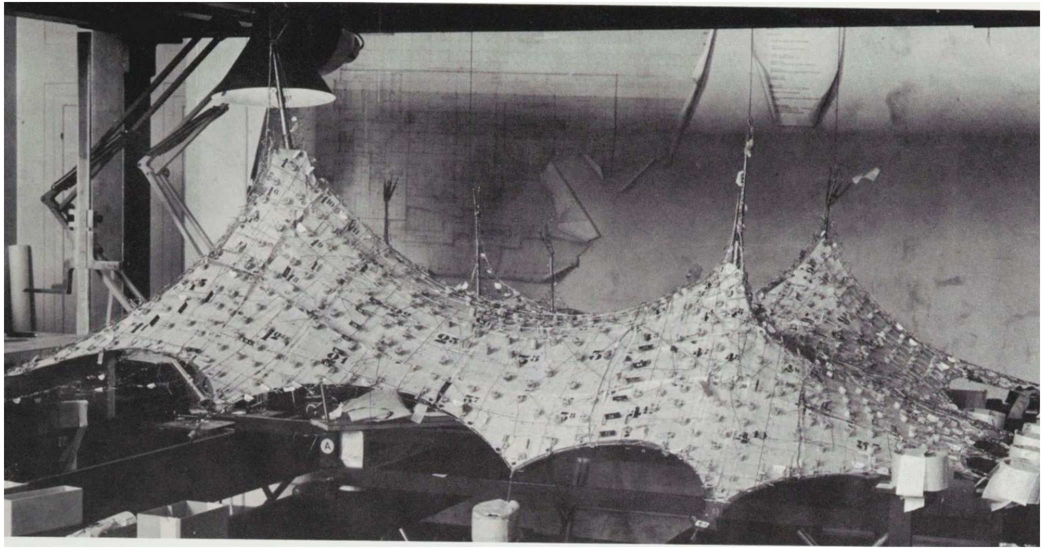




Design Constraints/Opportunities

- **Scale Translation**
  - Shape of Surface in measurement model
  - Incalculable geometry

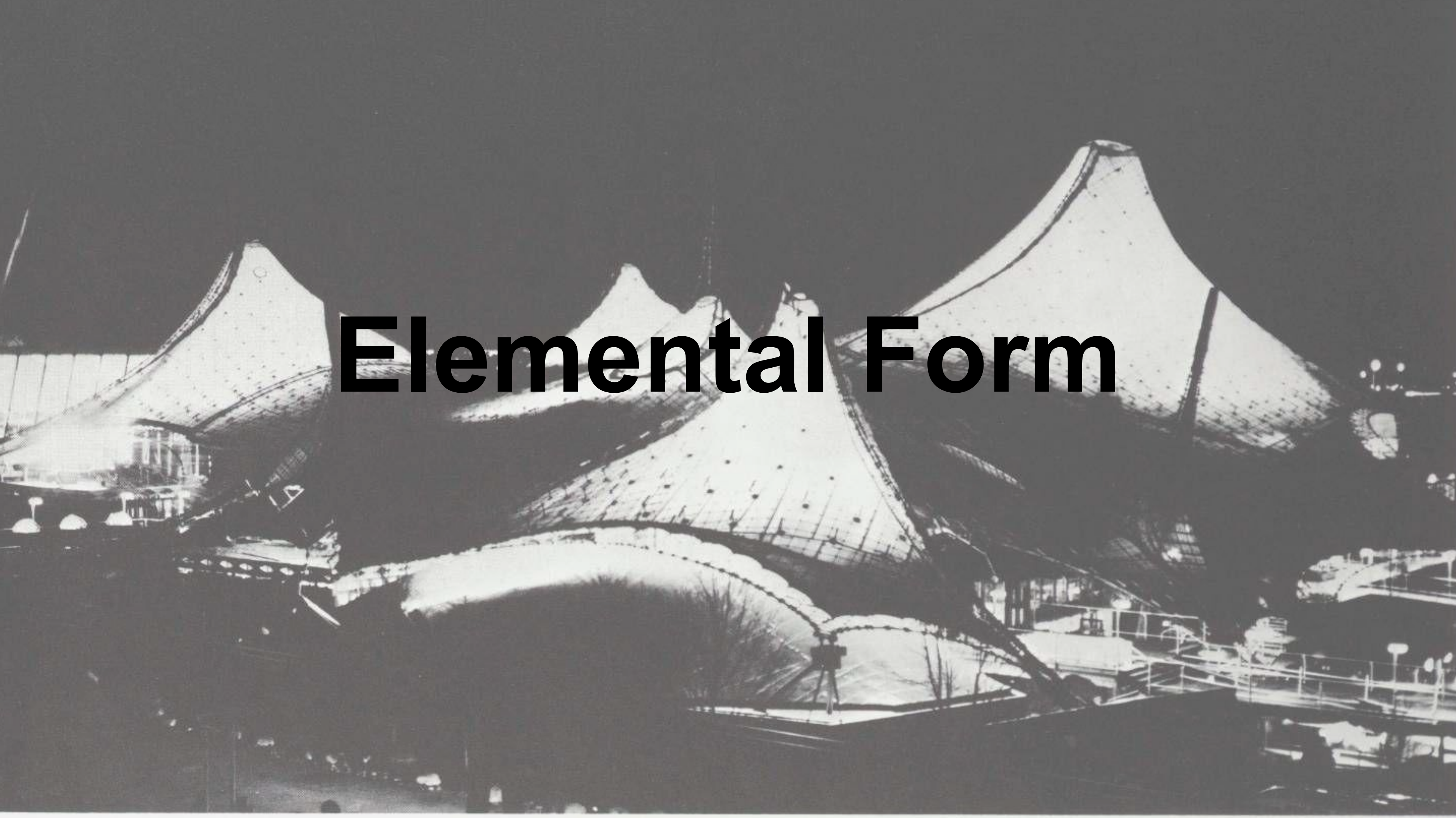




Design Constraints/Opportunities

- **Time**
  - 14 months to:
    - develop form + clarify structural details
    - fabricate building parts of structure & interior (in germany)
    - ship to montreal and assemble
  - 8 weeks to:
  - erect cable net, masts and membrane
  - 5 weeks to:
    - finish the final prestress in the cable net & membrane

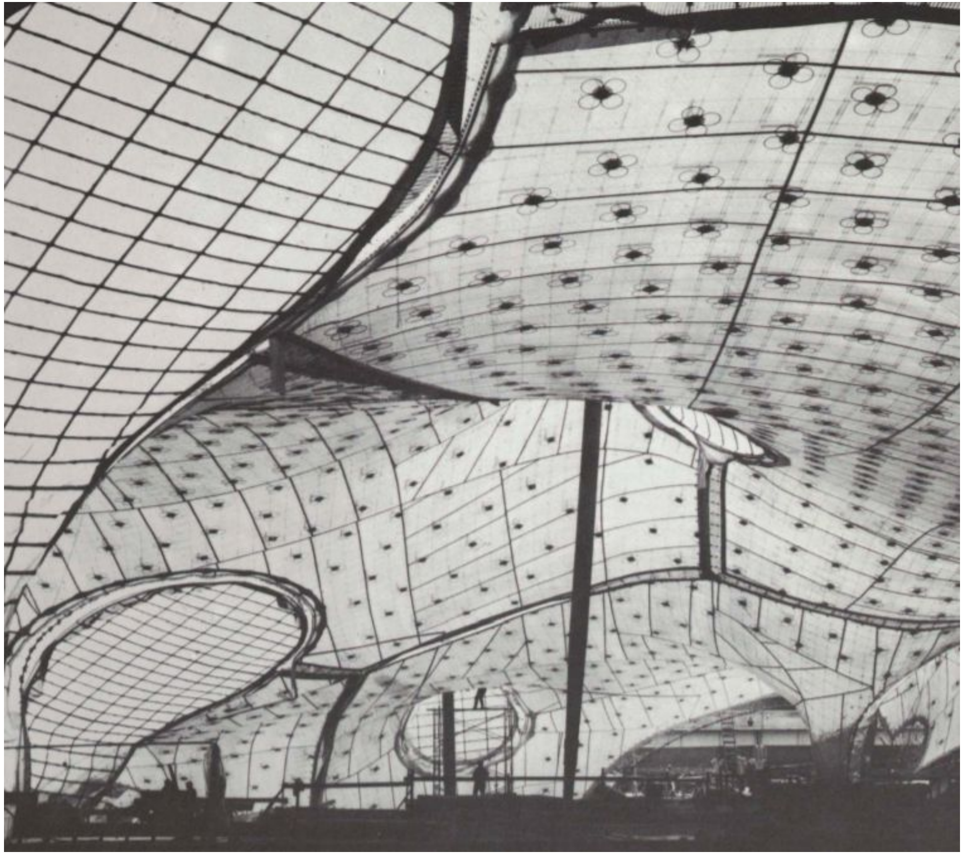
Elemental Form



Structure: Definitions

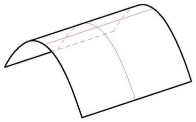
- **Membranes** are thin, flexible sheets.
  - Both simple and complex forms can be created using membranes
  - External jacking forces used to stretch the tensile membrane into shape.

- **Nets** are three-dimensional surfaces made of a series of crossed curved cables, and they are analogous to membranes.
  - German Pavilion in the 1967 Expo at Montreal was originally designed as a membrane structure, it was built as a cable net structure with the membrane as secondary cover.
  - Cable net structures mitigate fluttering due to wind loads through the positioning of cables.

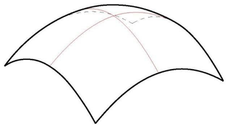


Forms of Curvature

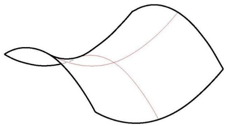
- Curvature:
  - Planar: both axes are straight.
  - Monoclastic: curvature on one axis is straight while the other curves.
  - Doubly curved:
    - Synclastic: both axes curve in the same direction
    - Anticlastic: both axes curve, but in different directions.
      - The most basic anticlastic structures are saddles, defined by alternating high and low points and connected with either straight or curved edges
      - More complex freeform structures also possible



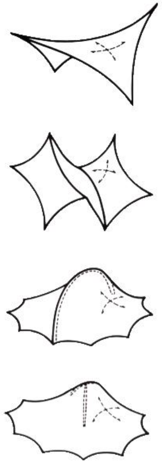
monoclastic



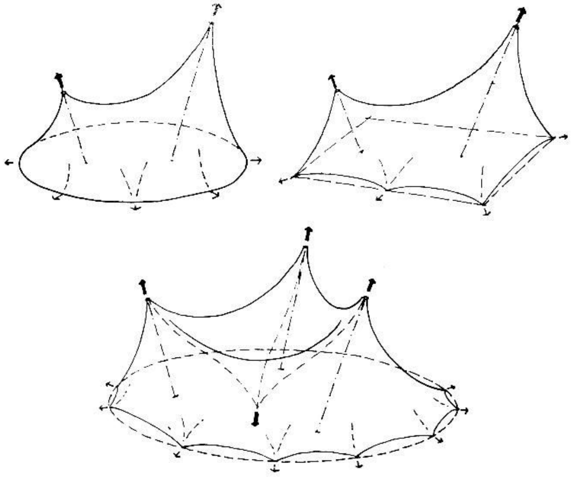
synclastic



anticlastic



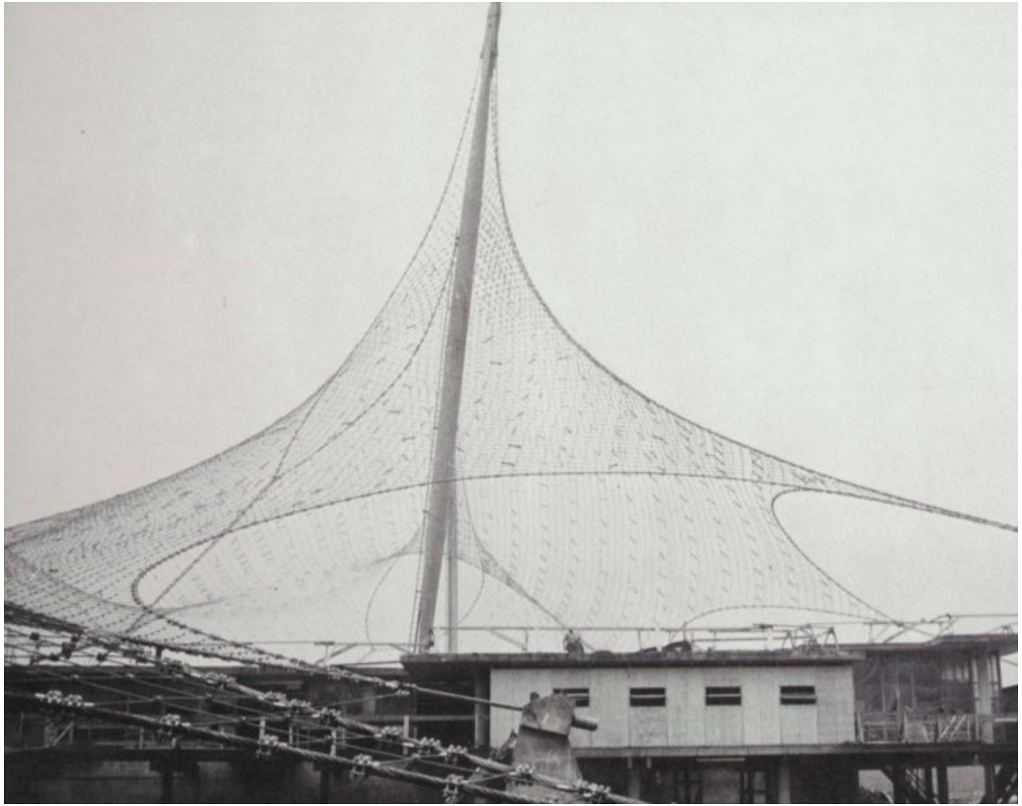
Types of anticlastic forms



composite anticlastic forms

Anticlastic Forms

- Anticlastic membrane structures are resistant to external loads by virtue of their form
        - possible to build structures that cover large areas with a minimum quantity of material
        - In anticlastic structures, surface curvature provides structural stability and stiffness to the tensioned membranes.
        - Smaller radius = more stability
    - The tensile forces necessary to ensure stability can be high, resulting in sizeable supporting structures required to transfer loads to the foundations.

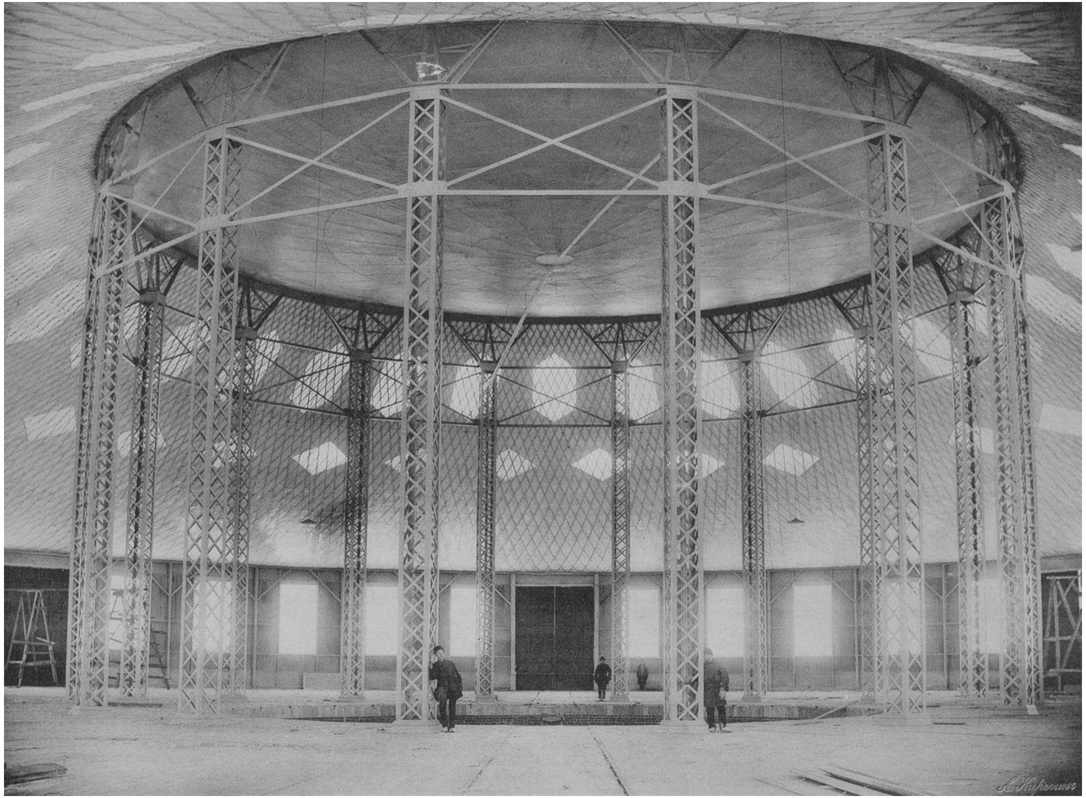


Development of Tensile Membranes

- Membrane structures in the form of tents extends back to prehistory.
- But the use of membrane surfaces in modern construction did not begin in earnest until the second half of the 20th century.
- It was mainly the engineers and architects in the circle around the German architect Frei Otto contributed to the widespread development of wide-span membrane structures. (Tensile Surface Structures : A Practical Guide to Cable and Membrane Construction).
- The German Pavilion in the Expo in Montreal 1967, is widely credited with popularizing the use of membrane structures on such a large scale.

Tensile Structures: Early History

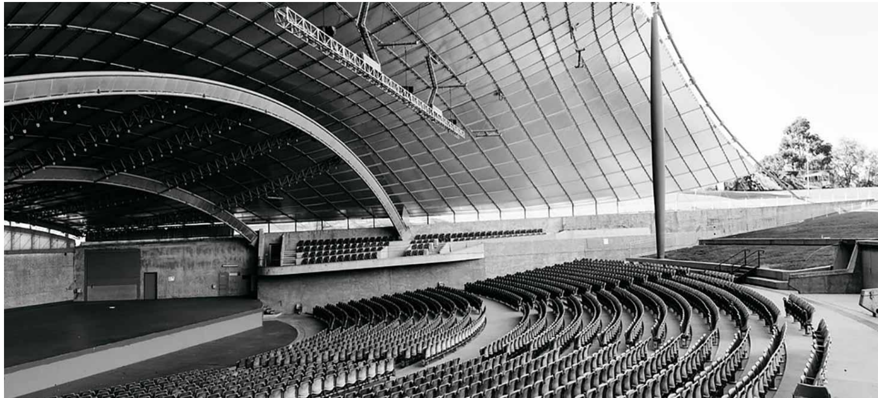
- The development of modern tensile structures began in the design of suspension bridges beginning in the early 19th century.
- It was not, however, until much later that the principles of suspension construction was integrated into building design.
- Among the first to develop practical calculations of stresses and deformations in tensile structures was Russian engineer Vladimir Shukhov, whose pavilions for the Nizhny Novgorod Fair of 1896 are often credited with being the first use of a metal membrane roof.



Shukhov’s pavilion for the Nizhny Novgorod Fair of 1896

Tensile Structures: ca. 1950

- Despite the material efficiency promised by lightweight tensile structures, the fact that suspension systems are very flexible perpendicular to the line of the cable made them unsuitable for long-span structures.
- In 1952 the structural engineer Severund and architect M Nowicki developed a means of supplying out of place stiffness to a grid of steel cables in the J.S. Dorton Arena in Raleigh
    - parallel cables stabilized with an orthogonal set of steel cables that was pulled taut and formed a saddle shape.
- Sidney Myer Music Bowl, built in 1959 by Australian architect Barry Patten, also influenced Otto's work in Montreal.



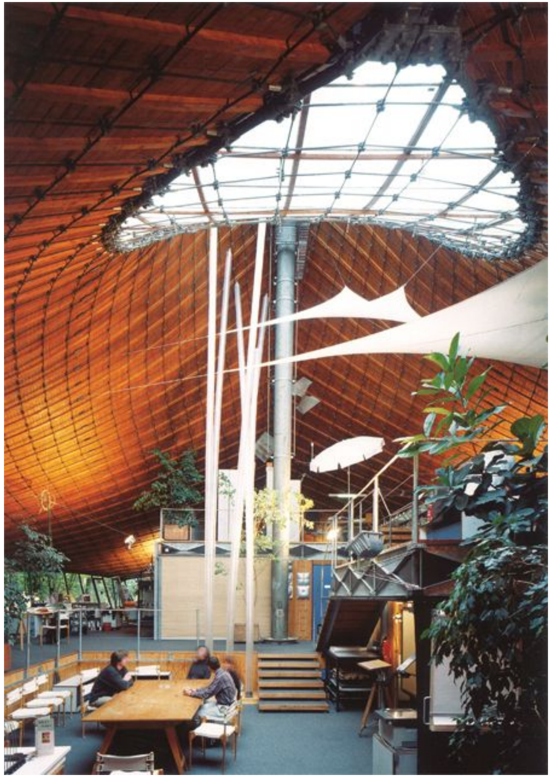
Modern Examples of Tensile Structures

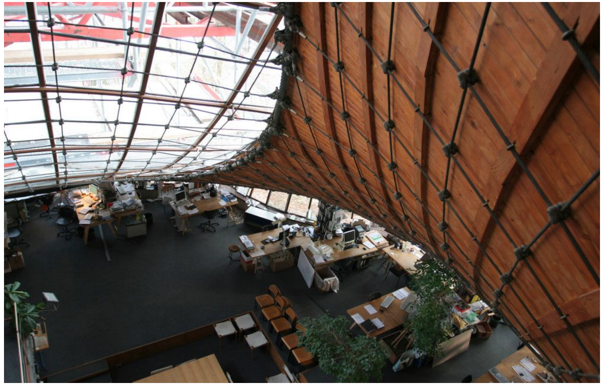
Millennium Dome, Richard Rogers and Buro Happold, 2000

Denver International Airport, Fentress Architects, 1994

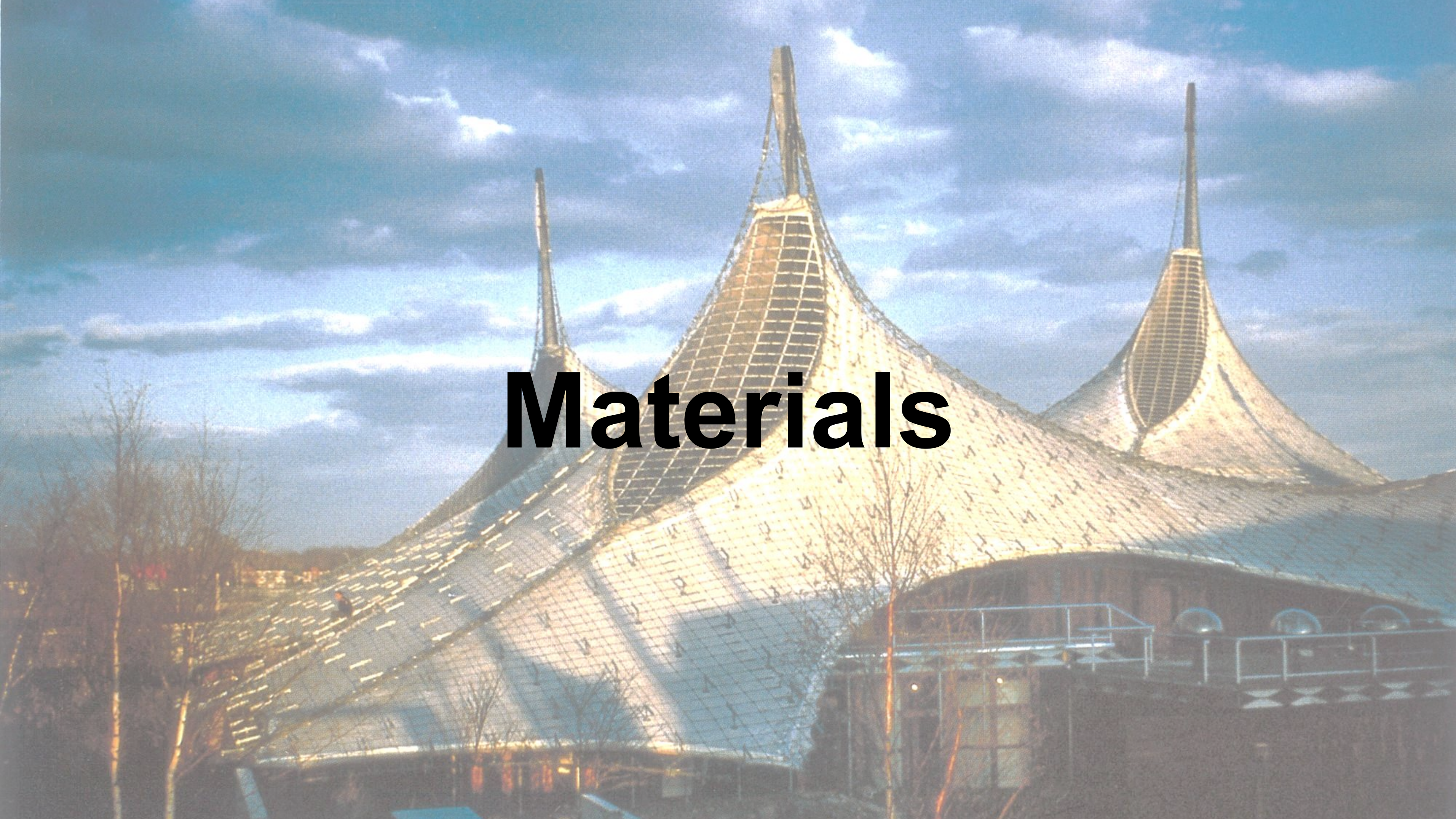
Influence

- Institute for Lightweight Surface Structures, Vaihingen Germany 1964-1967





Materials



Materials

Tensioned Canopy
- Prestressed steel cable net
- Steel masts
- Steel rope

Anchor
- Reinforced concrete guy frames
- Rock anchors

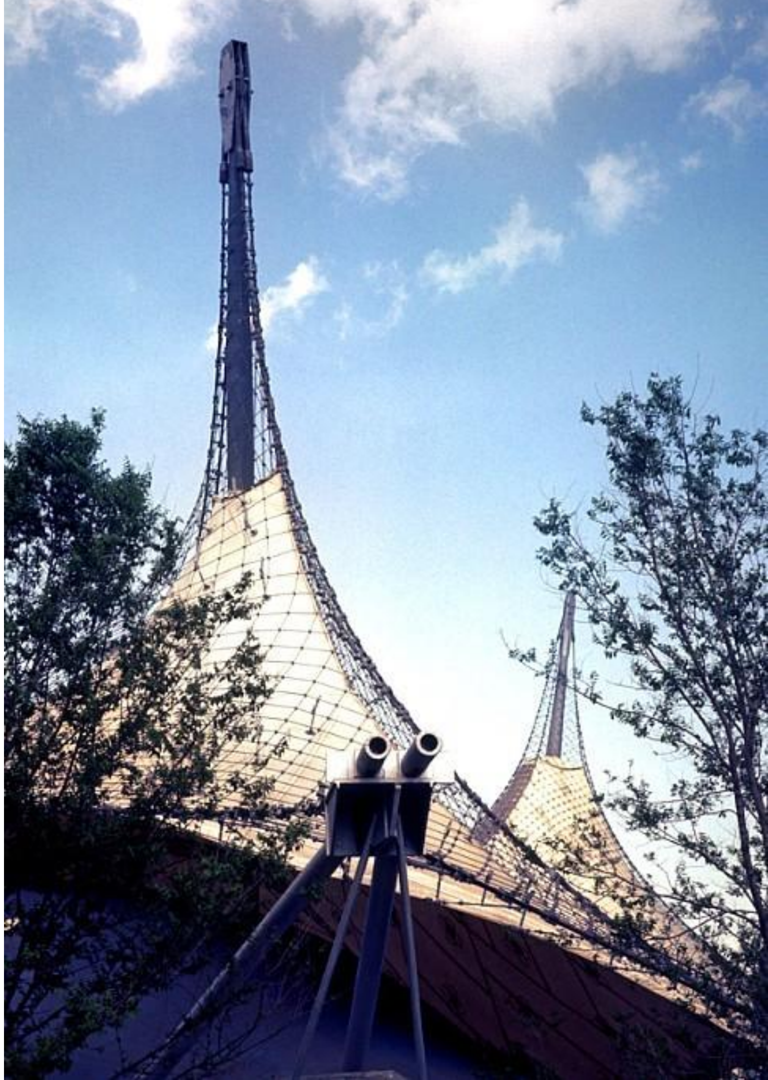
Non-structural Enclosure
- PVC-coated polyester fabric
- Astral glass (PVC)
- Wind deflecting glass walls

Interior Structure
- Steel platforms
- Plywood lattice vaults

Materials

Several factors influenced the material selection:

- *Time*
- *Durability*
- *Construction*
- *Resources*



Materials

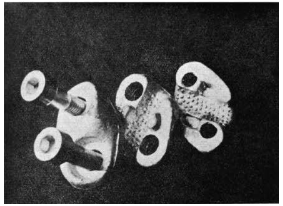
Precise engineering in tandem to material exploration was critical to the implementation of the German Pavilion.

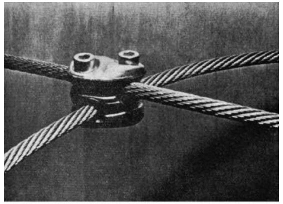
Steel cables and clamps

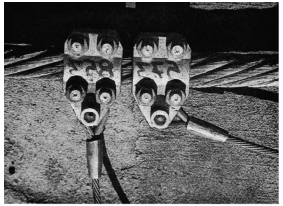
Polyester roofing film

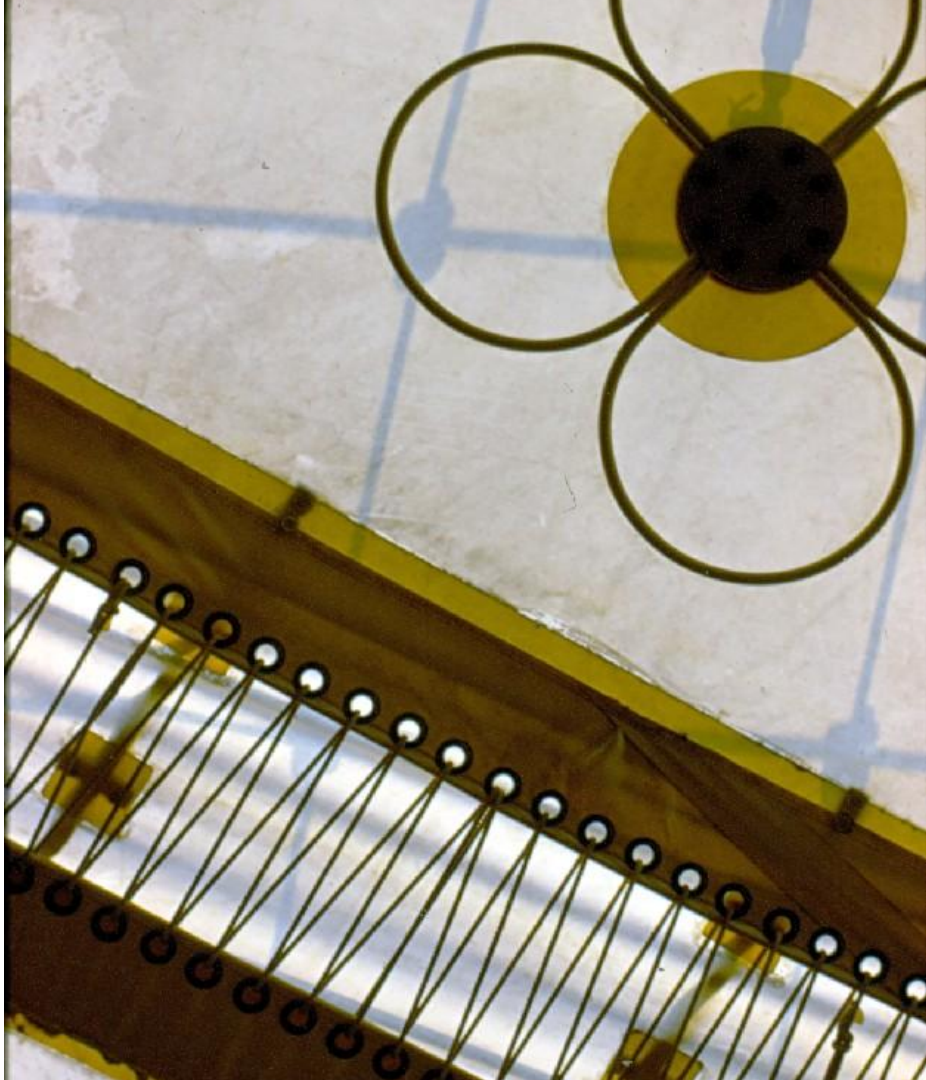
- PVC Coating
- New understandings in orthogonal anisotropic

PVC Thermoplastic Windows



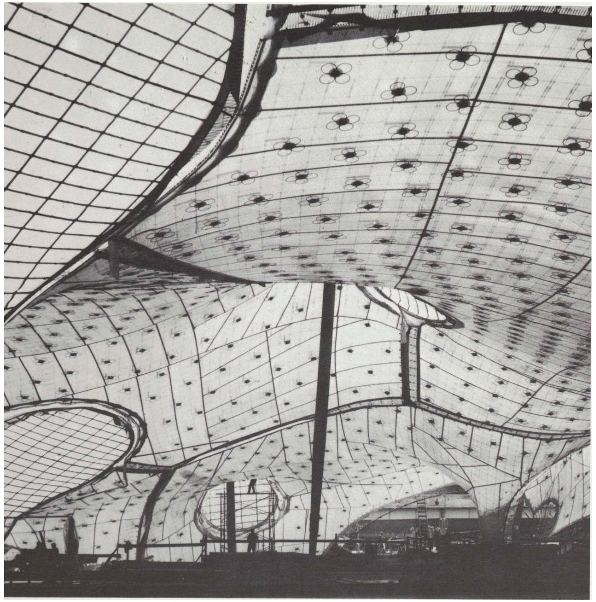






Complete Structures

Structural Types

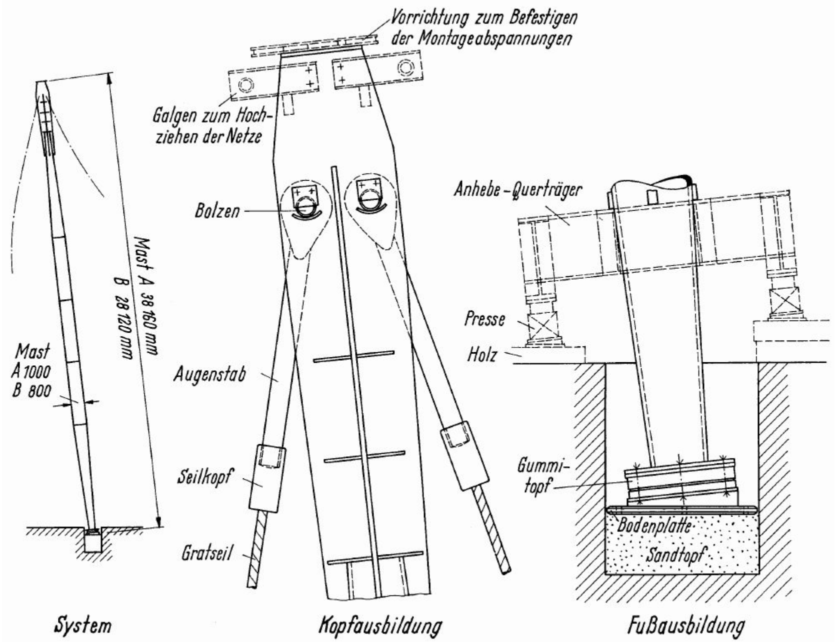


Tent

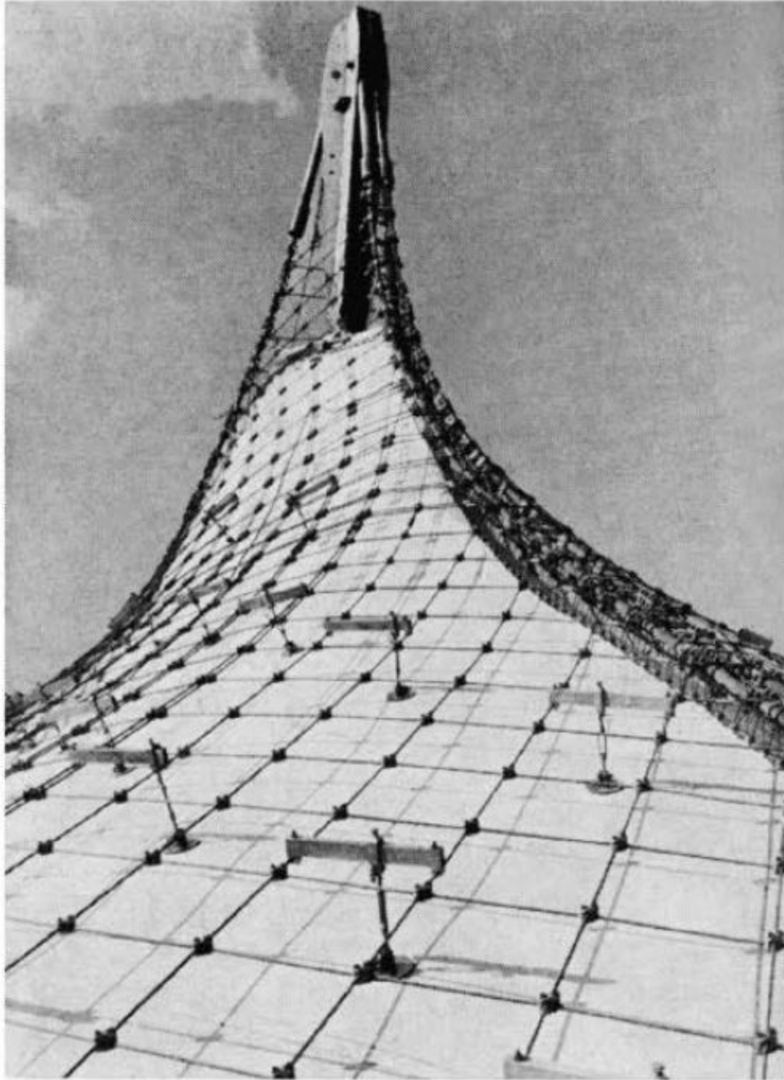
Wood Lattice

Steel Platforms

Masts

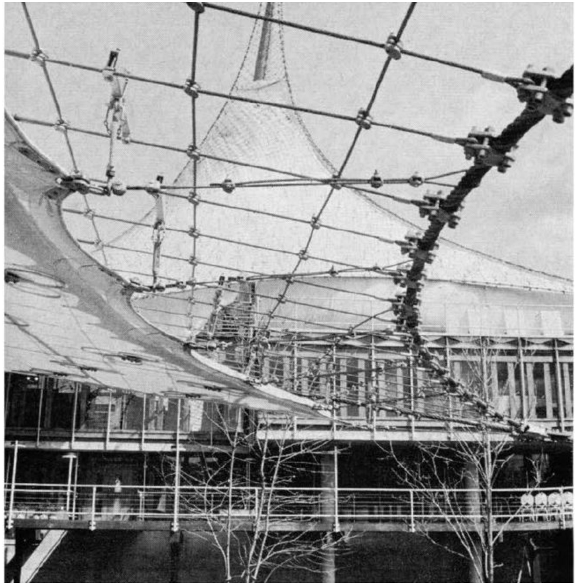


System Head Foot



Cable Net

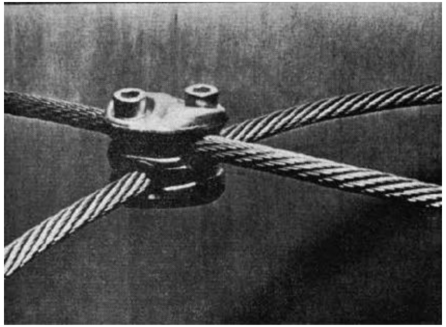
Cable Net



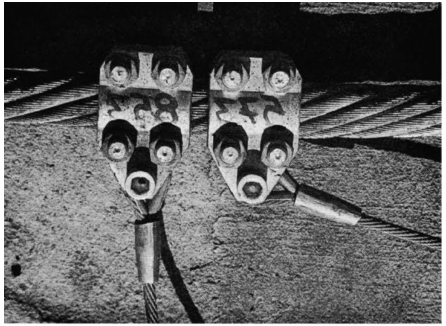
Perimeter

Guy Frame

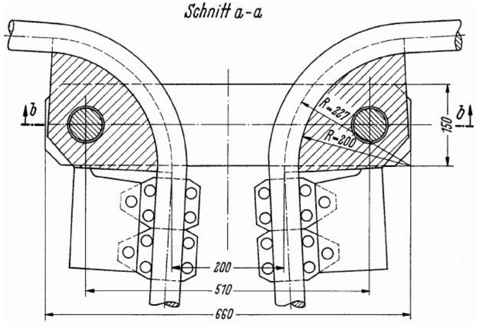
Connections



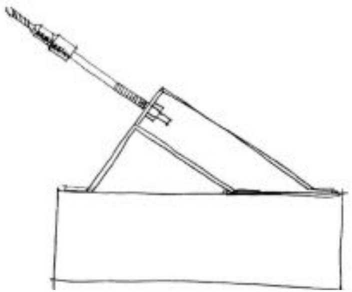
Cross clamps



Thimbles



Edge Clips



Guy Frame

Environment

Partial Control

- Glass wind screens
- Natural ventilation
- Chimney effect

Invasive Control

- Conference Room and Theater
- Wooden Lattice with plywood, insulation, and waterproofing

Exterior

- Water resistant polymer fabric

Consequence of Form

Theory vs. Reality

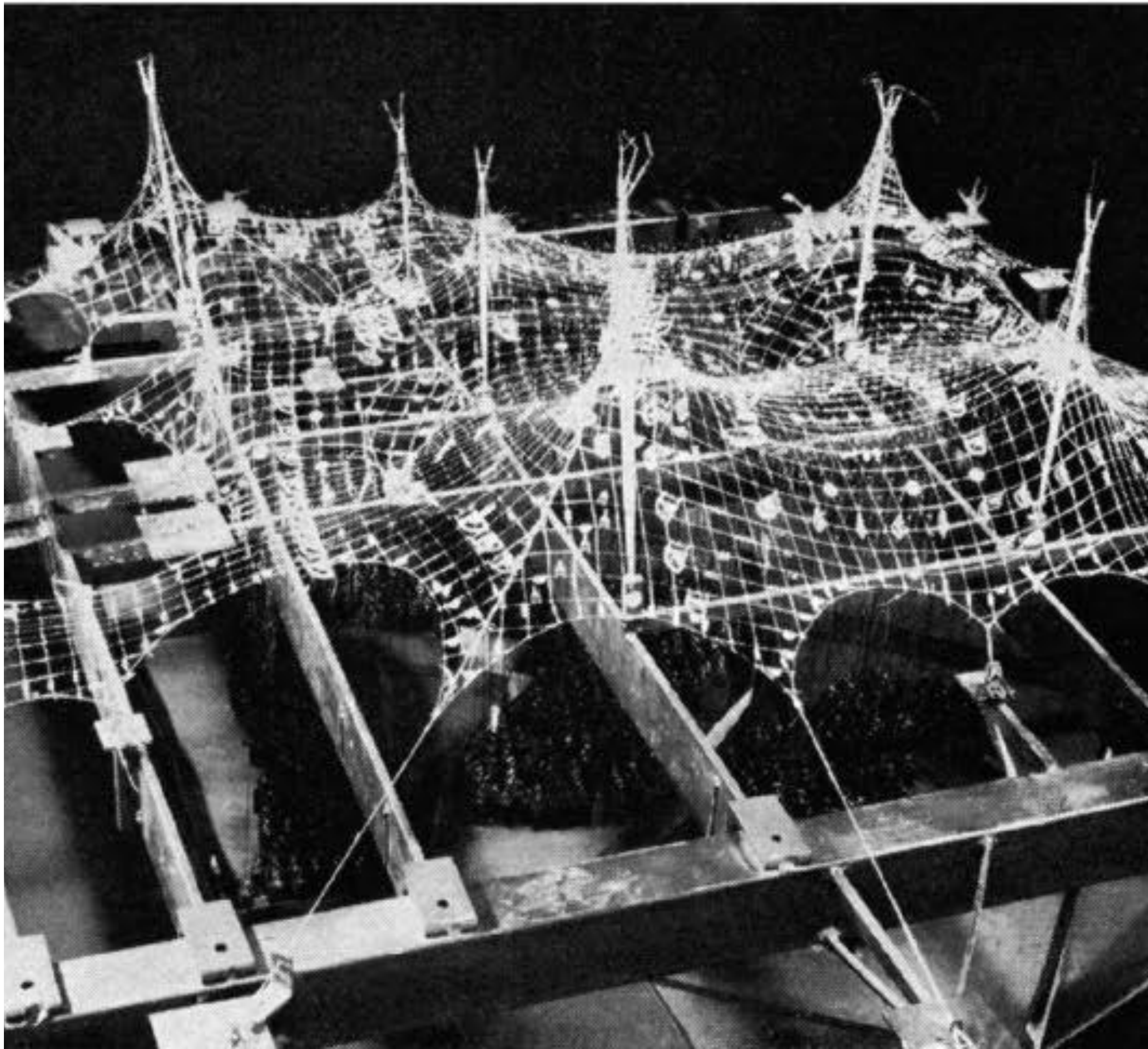
- Difference in surface forms between model and building
- Doubling of Cable Network
- Limited effect overall

Susceptibility of the Lightweight

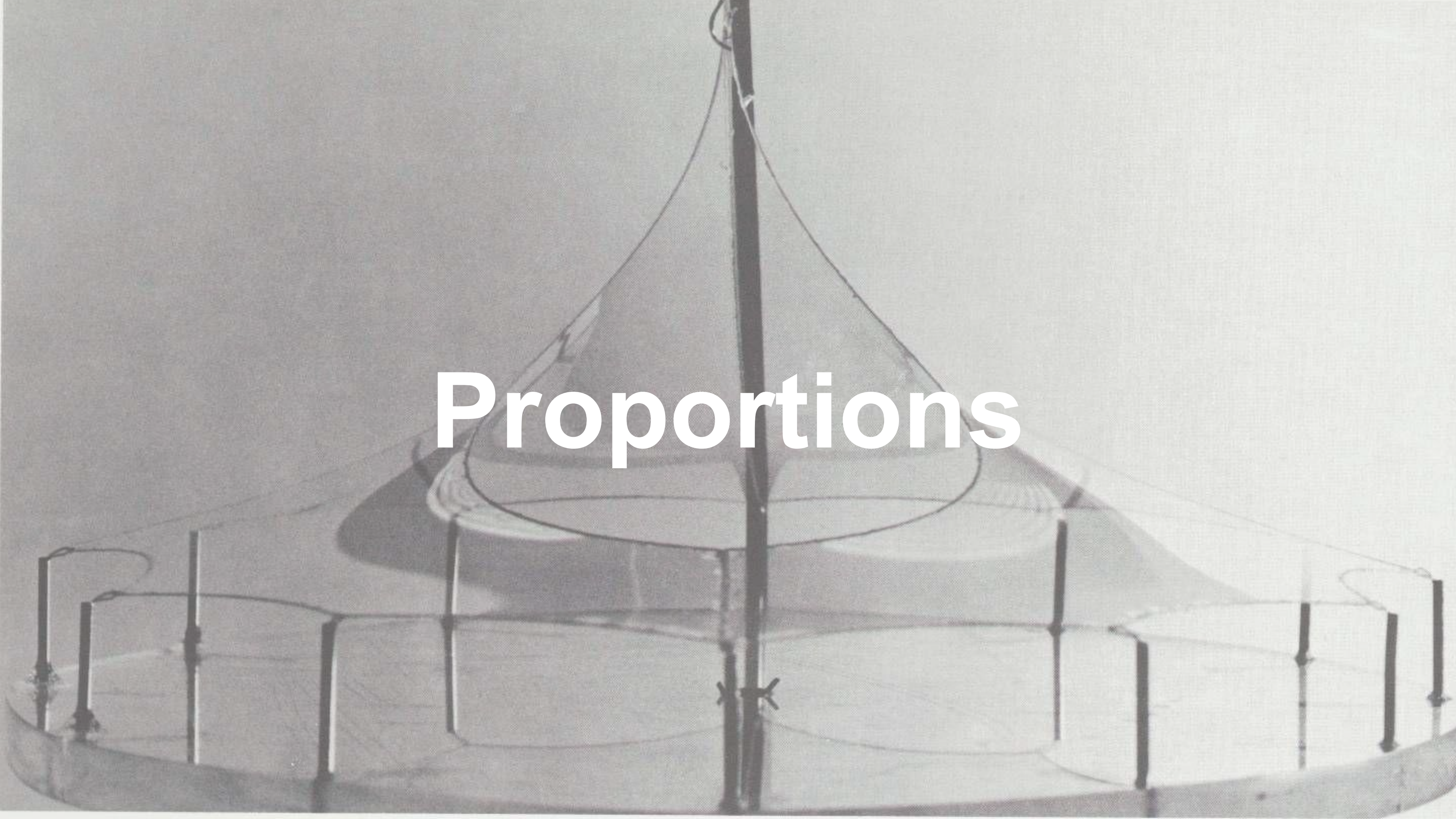
- Geometries create high tensions
- High wind and snow loads

Structural Failure

- 1972 partial collapse
- Demolition



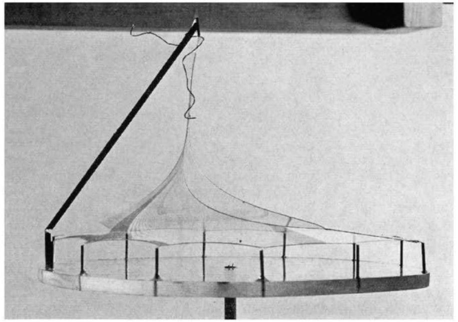
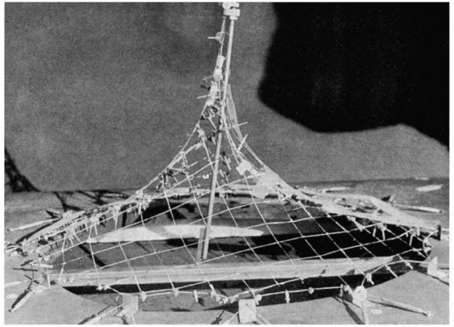
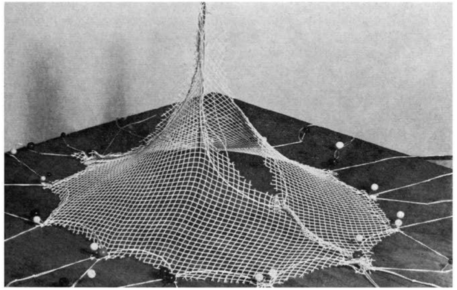
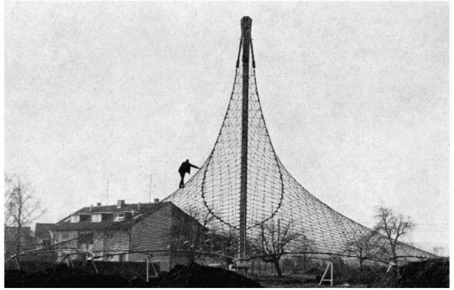
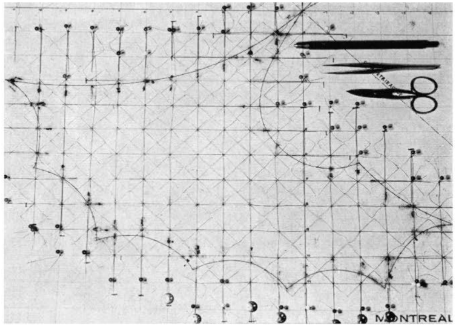
Proportions



Proportions

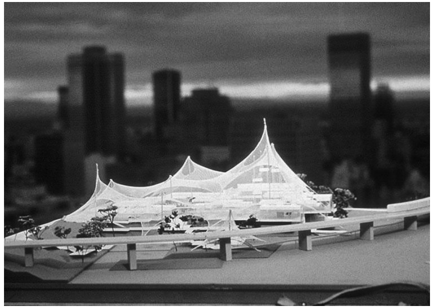
Span-to-Depth Ratio
The maximum length of the pavilion is 427 ft and the maximum width is 345 ft, with a span-to-depth ratio of 1.23.

Secondary Design Constraints
The canopy is supported by eight steel masts. While platforms within the pavilion act as breaks, the design must account for buckling.

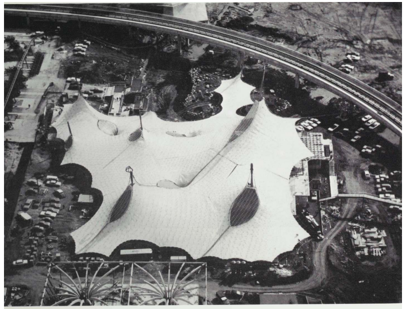
Proportions

Otto was able to create large free-span structures by separating the structure (steel cable net) from the cladding (polyester fabric). Tents, which use fabric as both the structure and cladding, cannot be built as large.

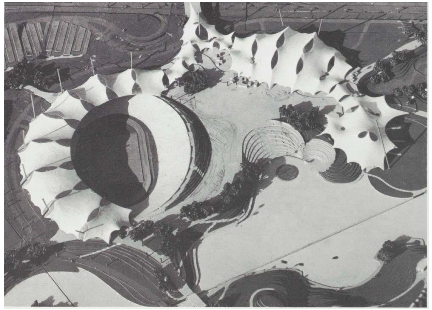


Structural Model

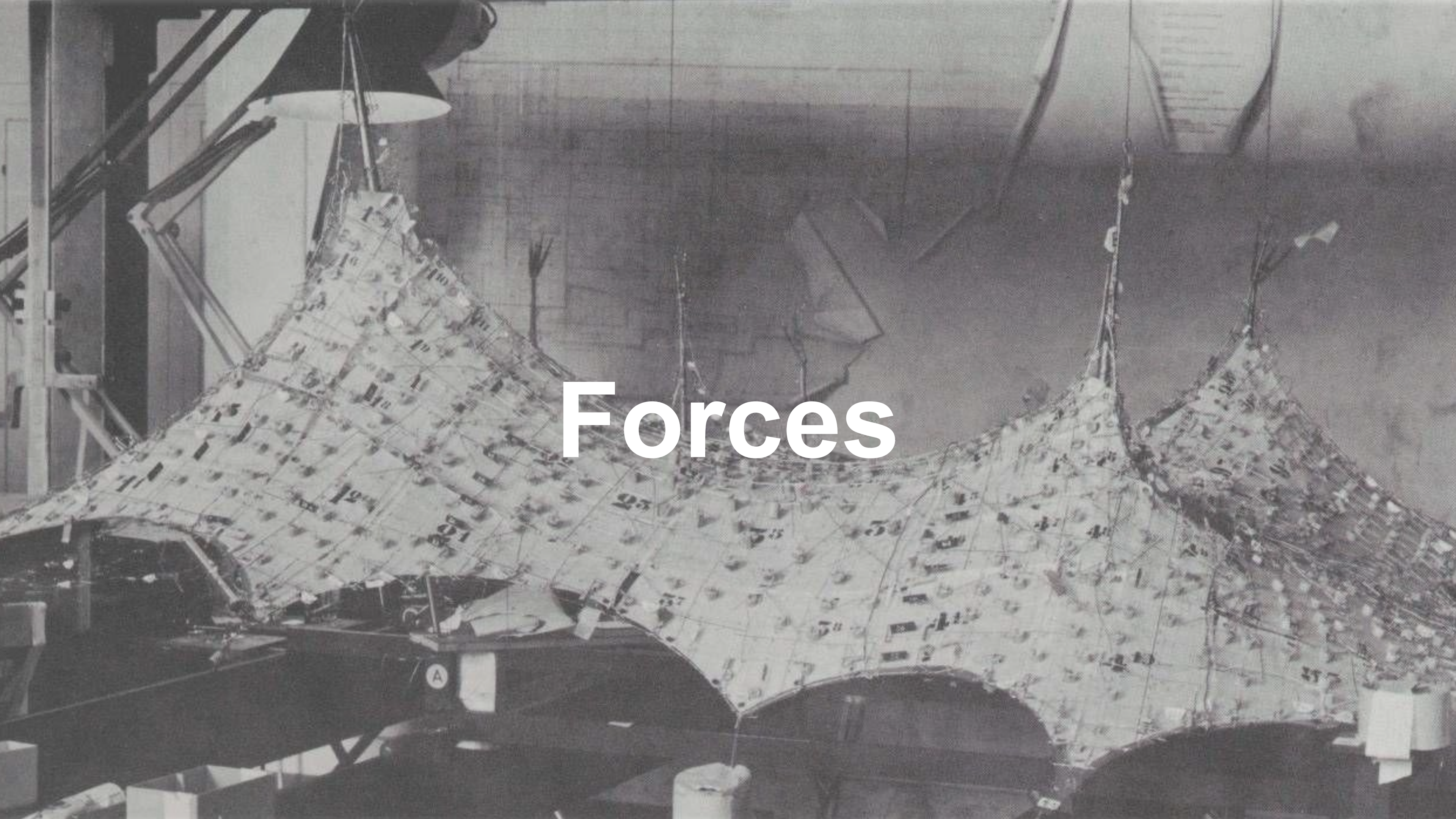
Institute for Lightweight Structures



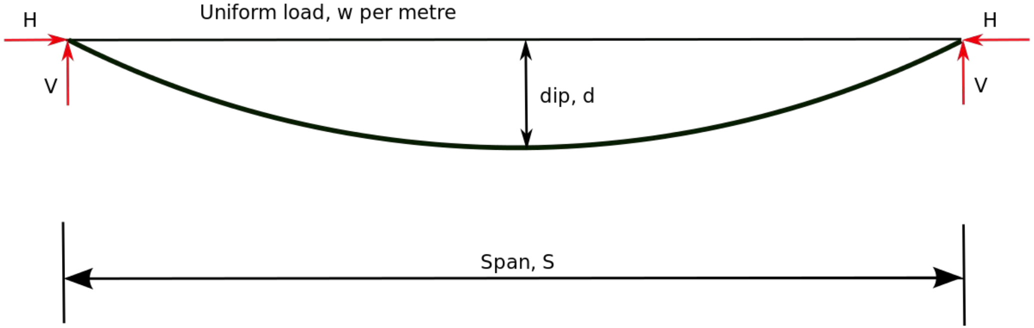
German Pavilion

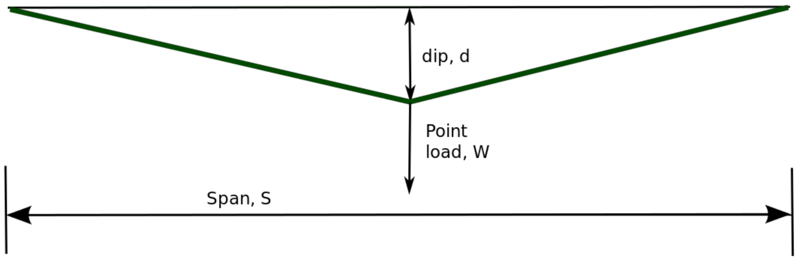


Munich Olympic Stadium


Forces

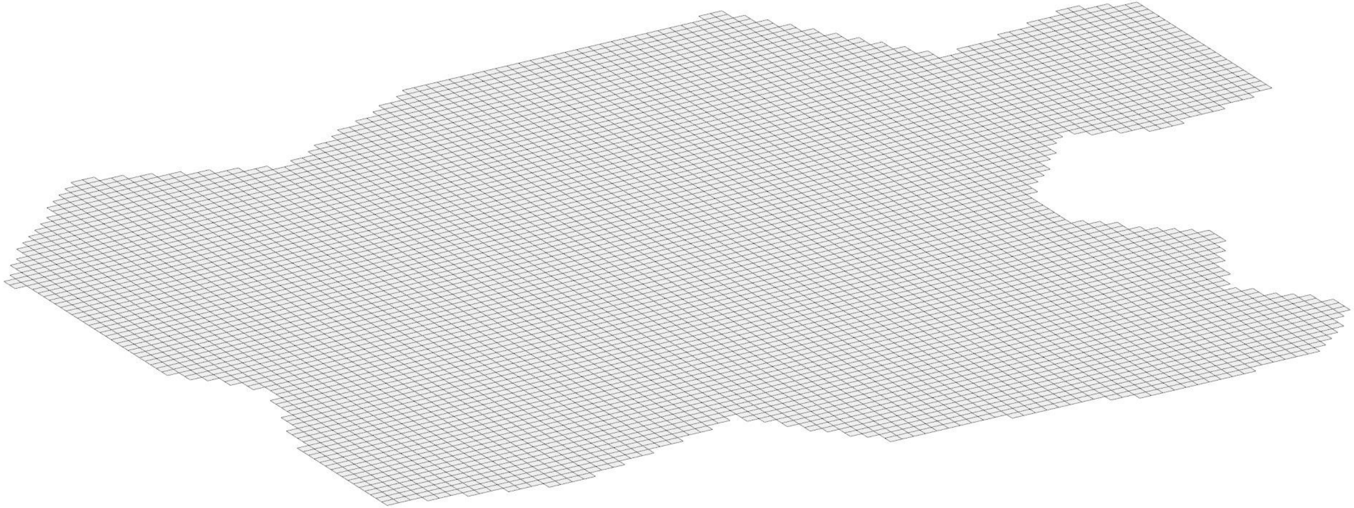
Typical behavior





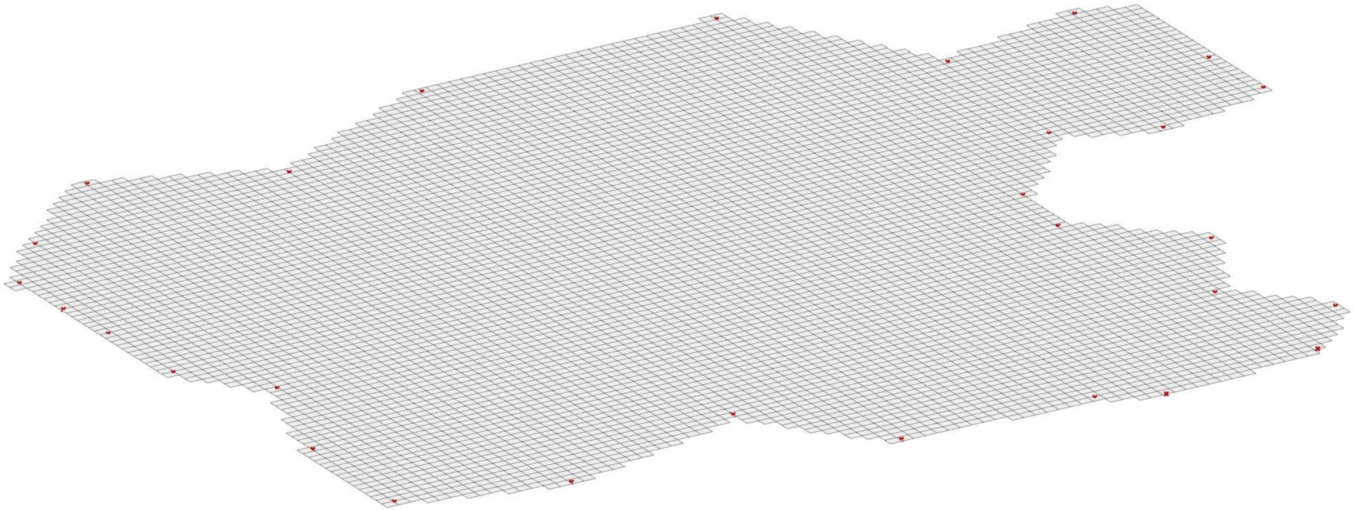
Form

Initial Mesh Surface



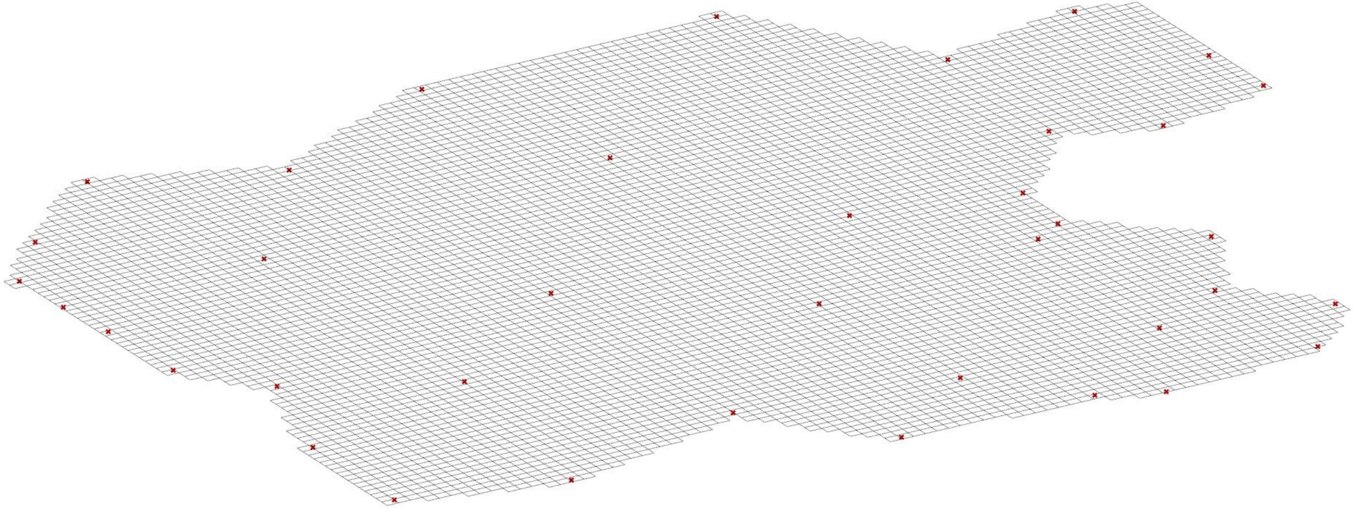
Form

Establish Perimeter Anchor Points



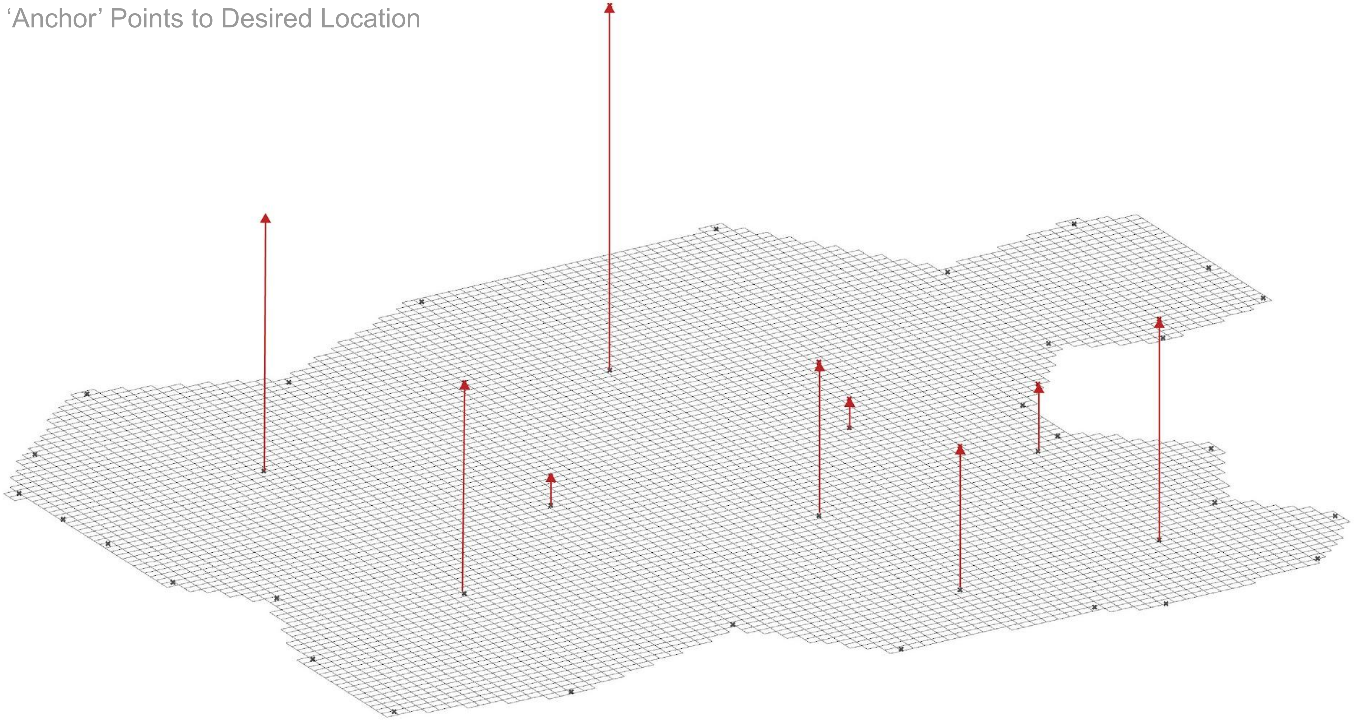
Form

Identify Central ‘Anchor’ Points



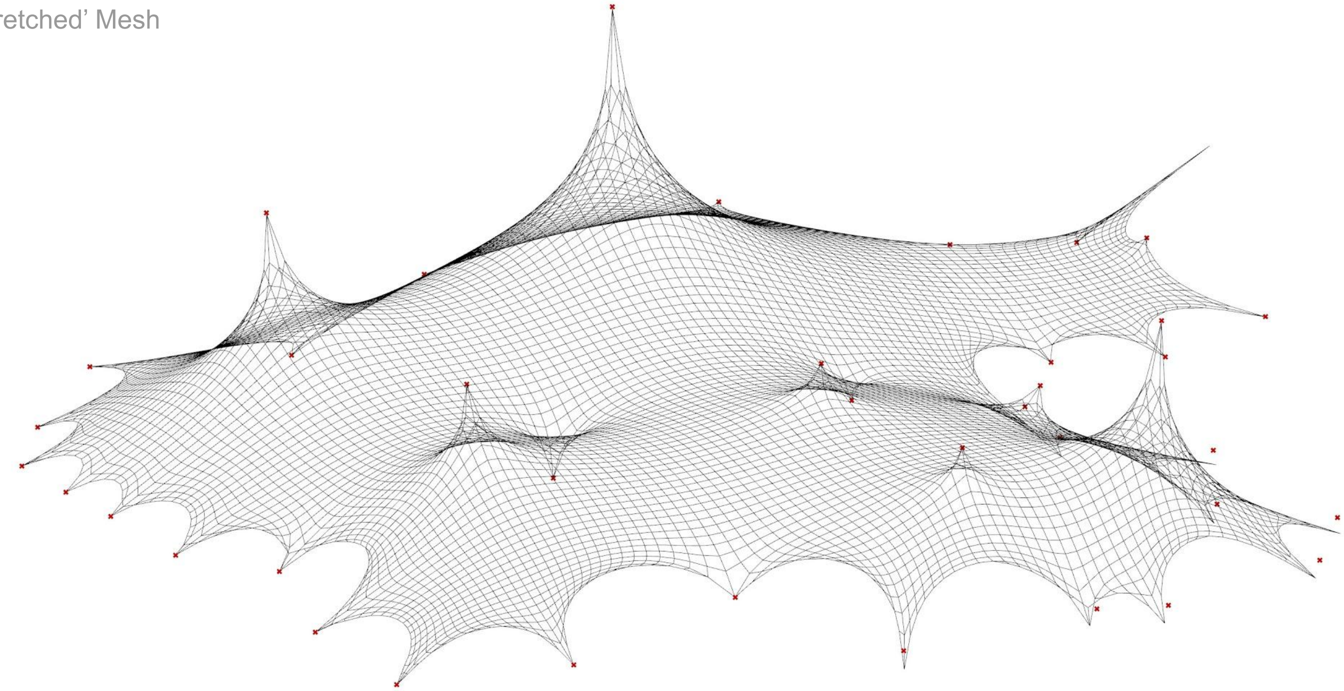
Form

Move Central ‘Anchor’ Points to Desired Location



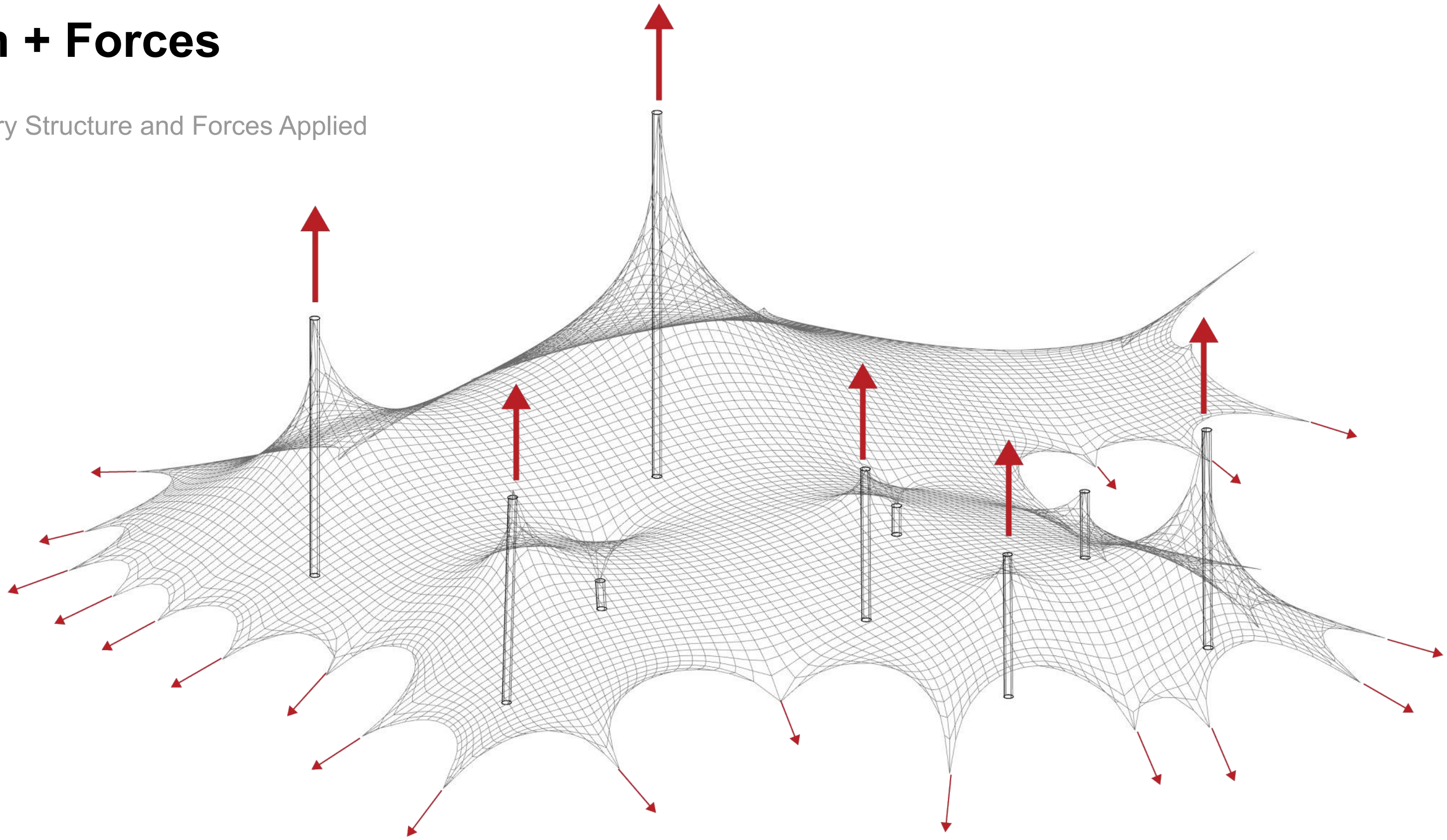
Form

Resultant ‘Stretched’ Mesh



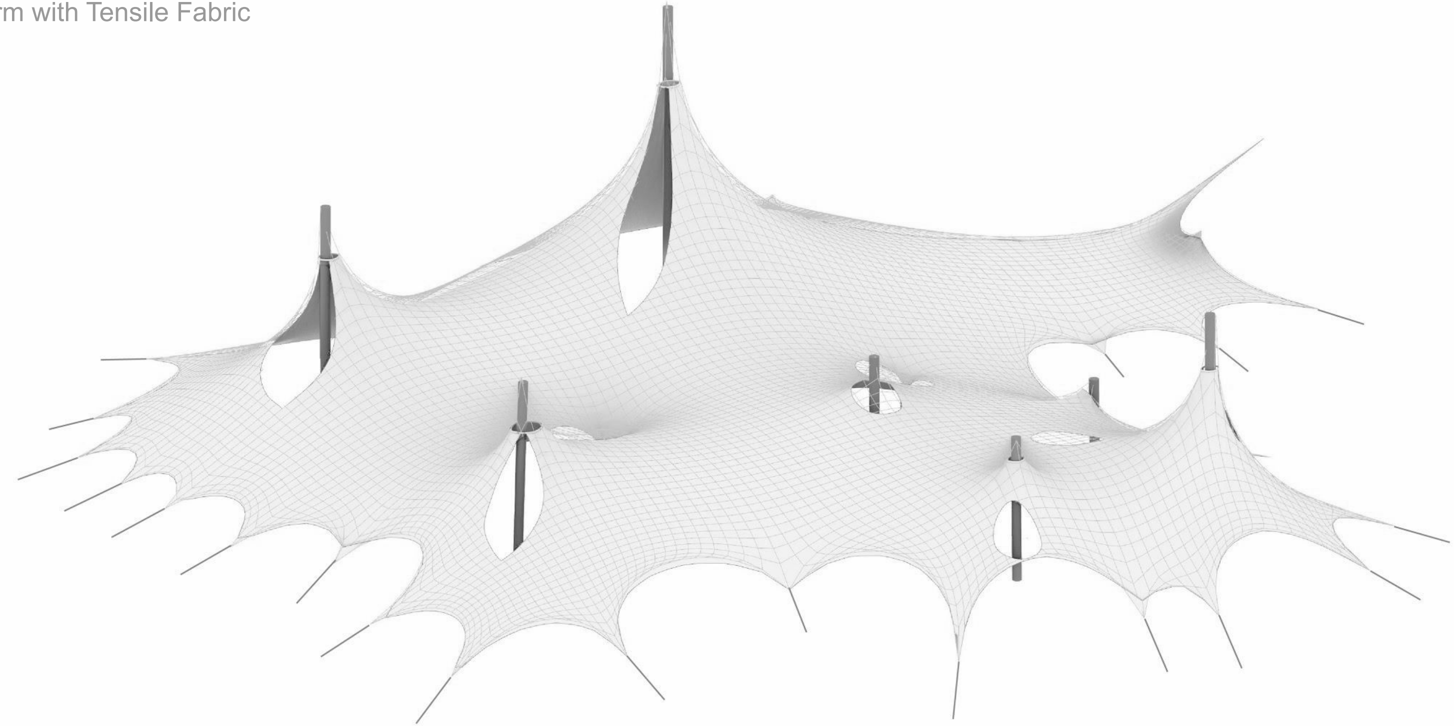
Form + Forces

Secondary Structure and Forces Applied



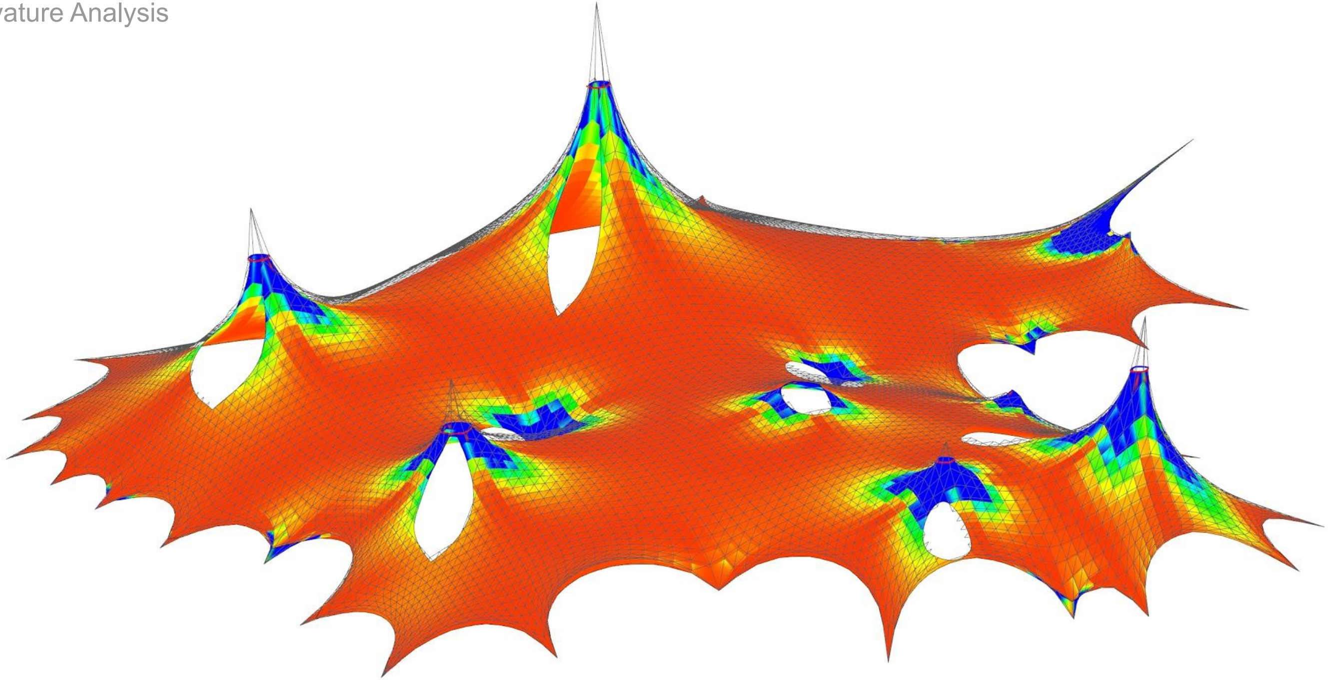
Form + Forces

Final Form with Tensile Fabric



Form + Forces

Gaussian Curvature Analysis

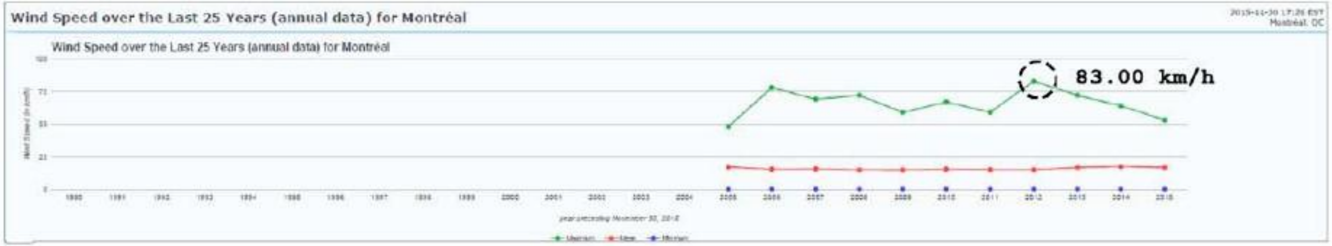


Form + Forces

Typical Loads

Parámetros climáticos promedio de Montreal (Aeropuerto Internacional Pierre Elliott Trudeau) 1981-2010 [ocultar]

Mes	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic	Anual
Temperatura máxima absoluta (°C)	13.9	15.0	25.6	30.0	34.7	35.0	35.6	37.6	33.5	28.3	21.7	18.0	37.6
Temperatura máxima media (°C)	-5.3	-3.2	2.5	11.6	18.9	23.9	26.3	25.3	20.6	13.0	5.9	-1.4	11.5
Temperatura media (°C)	-9.7	-7.7	-2.0	6.4	13.4	18.6	21.2	20.1	15.5	8.5	2.1	-5.4	6.8
Temperatura mínima media (°C)	-14.0	-12.2	-6.5	1.2	7.9	13.2	16.1	14.8	10.3	3.9	-1.7	-9.3	2.0
Temperatura mínima absoluta (°C)	-37.8	-33.9	-29.4	-15.0	-4.4	0.0	6.1	3.3	-2.2	-7.2	-19.4	-32.4	-37.8
Precipitación total (mm)	77.2	62.7	69.1	82.2	81.2	87.0	89.3	94.1	83.1	91.3	96.4	86.8	1000.3
Lluvias (mm)	27.3	20.9	29.7	67.7	81.2	87.0	89.3	94.1	83.1	89.1	76.7	38.8	784.9
Nevadas (cm)	49.5	41.2	36.2	12.9	0.02	0.0	0.0	0.0	0.0	1.8	19.0	48.9	209.5
Días de precipitaciones (≥ 0.2 mm)	16.7	13.7	13.8	12.9	13.6	13.3	12.3	11.6	11.1	13.3	14.8	16.3	163.3

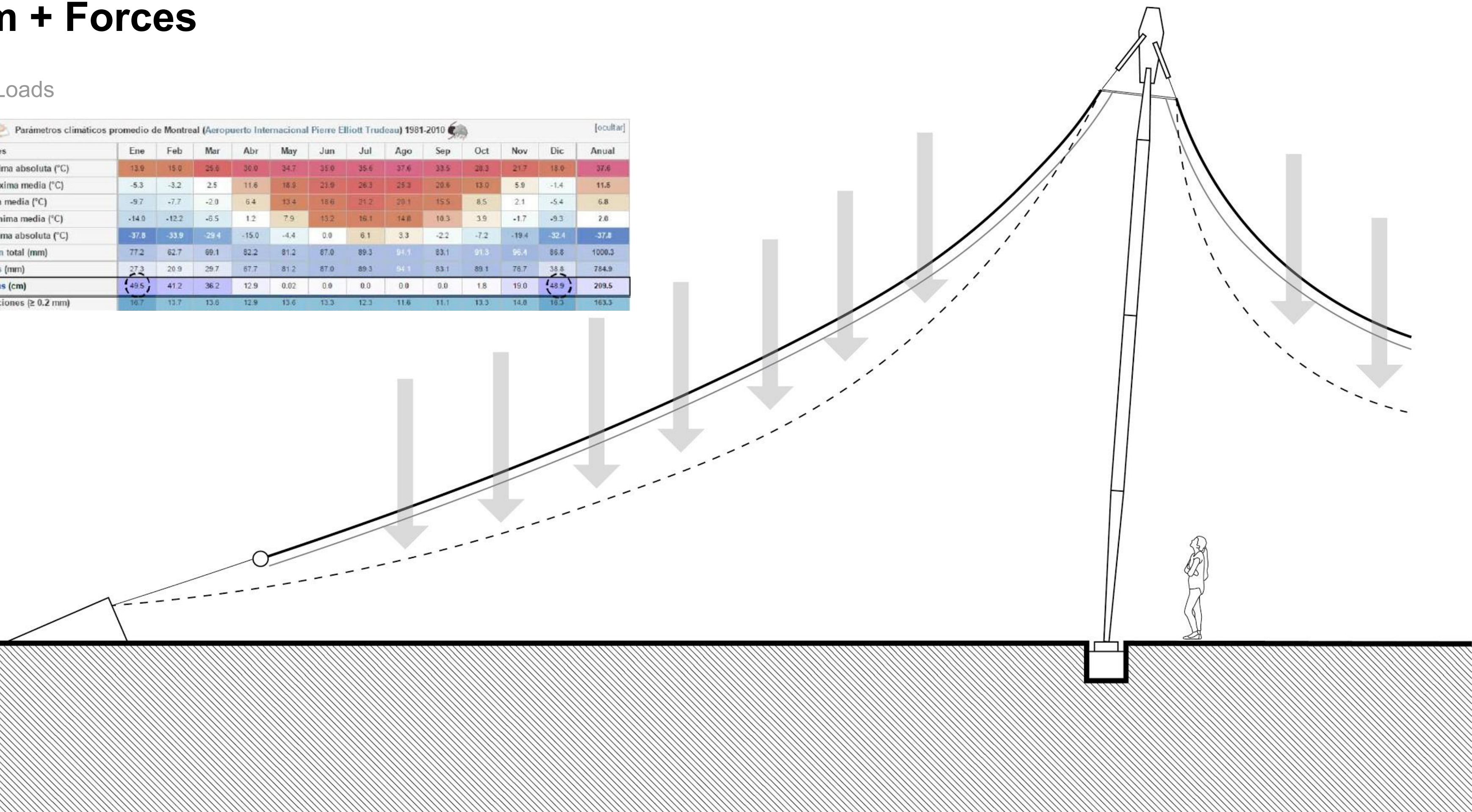


Form + Forces

Typical Loads

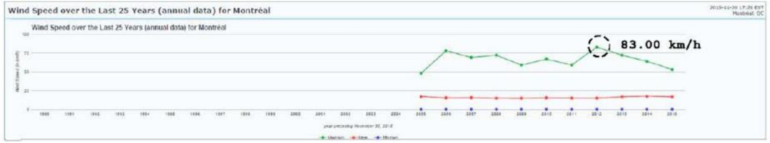
Parámetros climáticos promedio de Montreal (Aeropuerto Internacional Pierre Elliott Trudeau) 1981-2010 [ocultar]

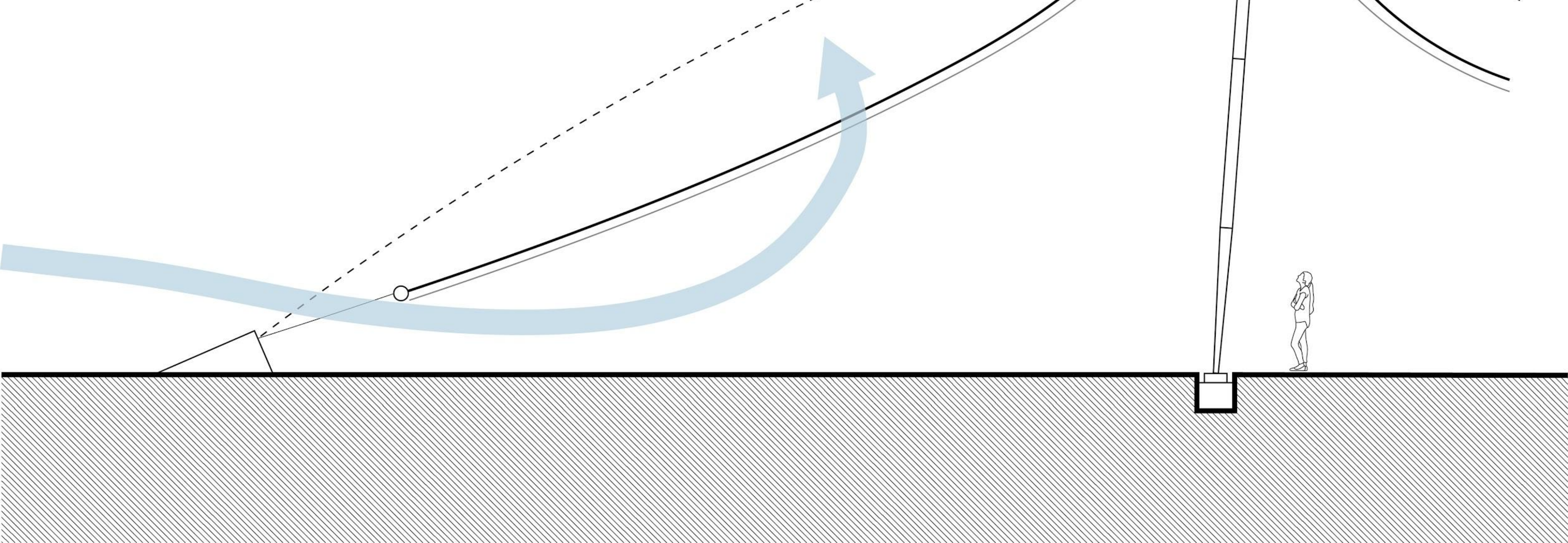
Mes	Ene	Feb	Mar	Abr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic	Anual
Temperatura máxima absoluta (°C)	13.9	15.0	25.6	30.0	34.7	35.0	35.6	37.6	33.5	28.3	21.7	18.0	37.6
Temperatura máxima media (°C)	-5.3	-3.2	2.5	11.6	18.9	23.9	26.3	25.3	20.6	13.0	5.9	-1.4	11.5
Temperatura media (°C)	-9.7	-7.7	-2.0	6.4	13.4	18.6	21.2	20.1	15.5	8.5	2.1	-5.4	6.8
Temperatura mínima media (°C)	-14.0	-12.2	-6.5	1.2	7.9	13.2	16.1	14.8	10.3	3.9	-1.7	-9.3	2.0
Temperatura mínima absoluta (°C)	-37.8	-33.9	-29.4	-15.0	-4.4	0.0	6.1	3.3	-2.2	-7.2	-19.4	-32.4	-37.8
Precipitación total (mm)	77.2	62.7	69.1	82.2	81.2	87.0	89.3	94.1	83.1	91.3	96.4	86.8	1000.3
Lluvias (mm)	27.3	20.9	29.7	67.7	81.2	87.0	89.3	94.1	83.1	89.1	76.7	38.8	784.9
Nevadas (cm)	49.5	41.2	36.2	12.9	0.02	0.0	0.0	0.0	0.0	1.8	19.0	48.9	209.5
Días de precipitaciones (≥ 0.2 mm)	16.7	13.7	13.6	12.9	13.6	13.3	12.3	11.6	11.1	13.3	14.8	16.3	163.3



Form + Forces

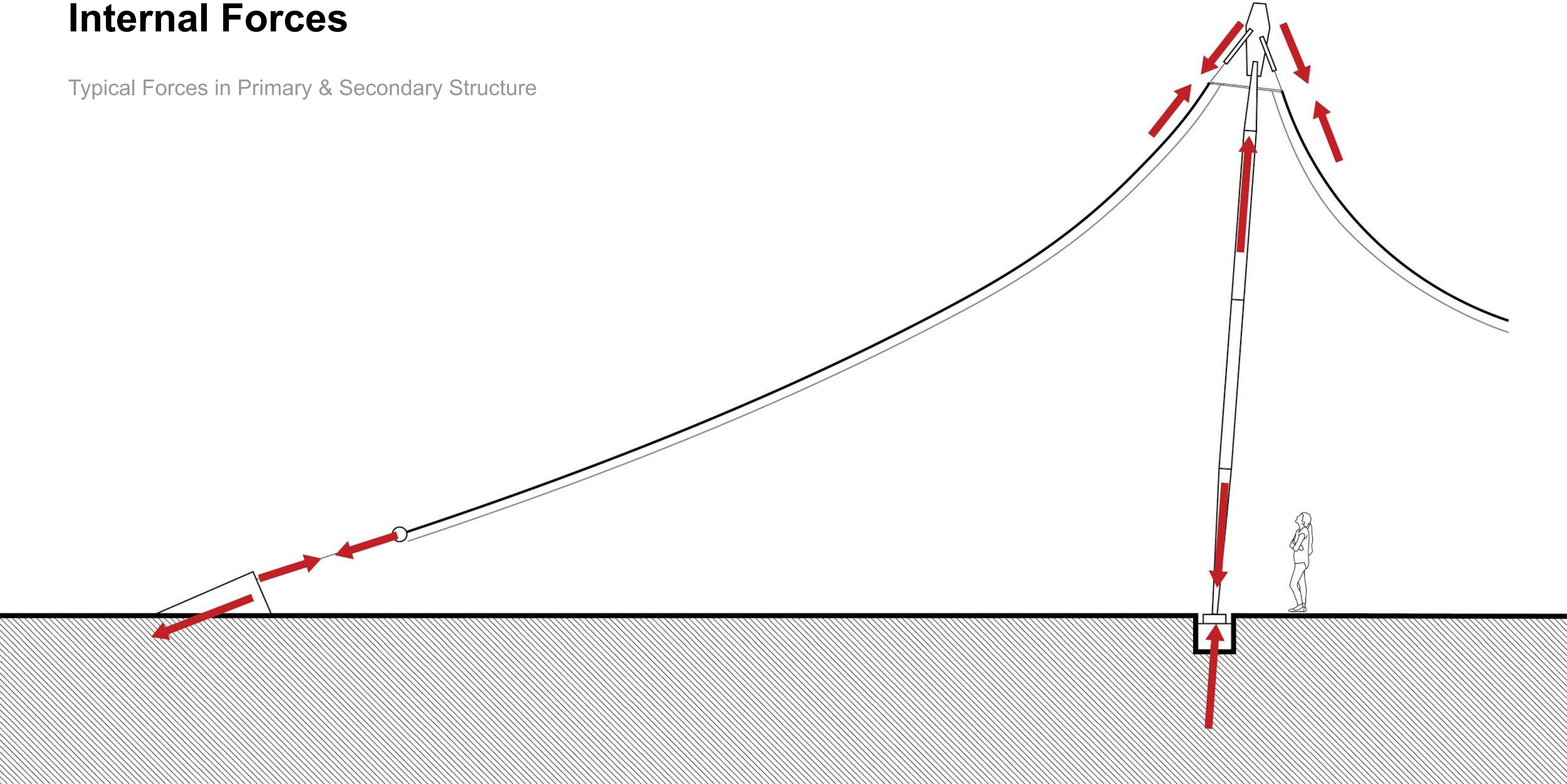
Typical Loads





Internal Forces

Typical Forces in Primary & Secondary Structure

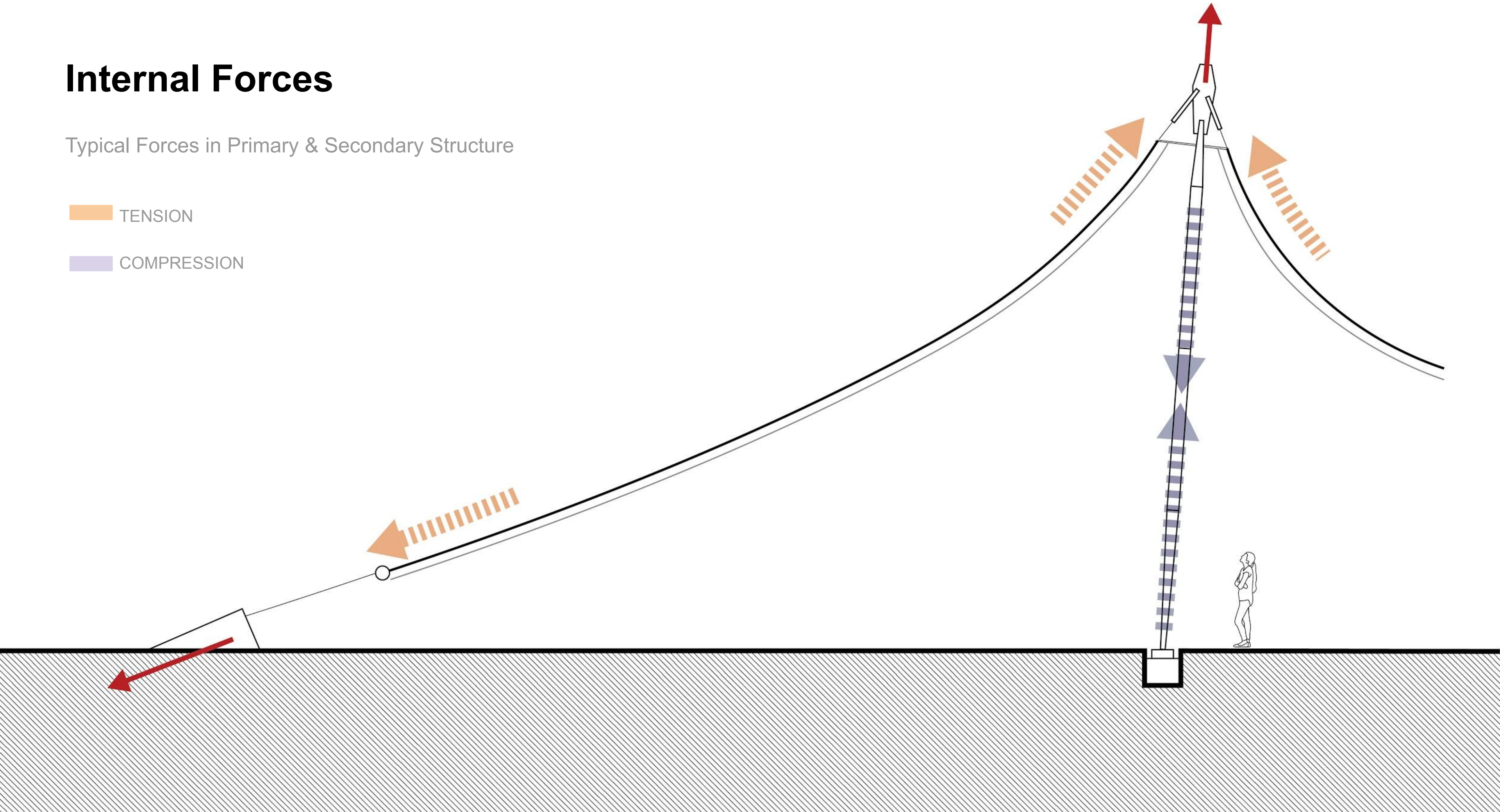


Internal Forces

Typical Forces in Primary & Secondary Structure

TENSION

COMPRESSION

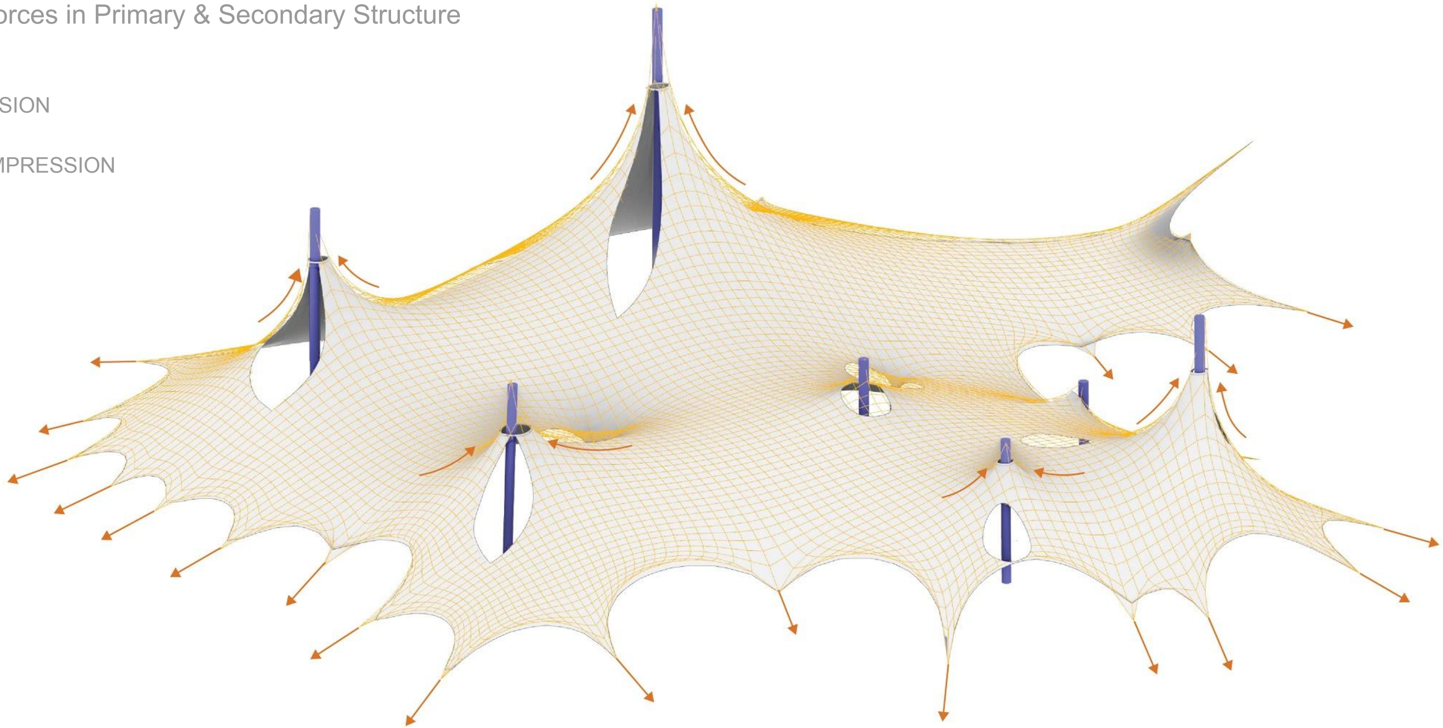


Internal Forces

Typical Forces in Primary & Secondary Structure

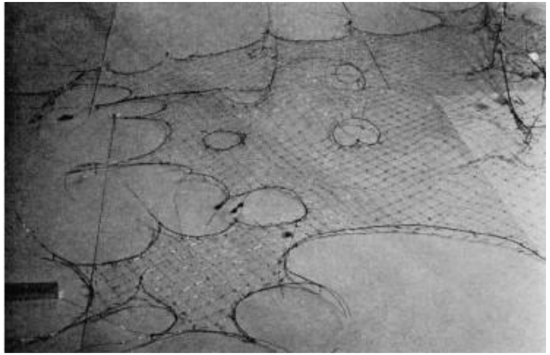
TENSION

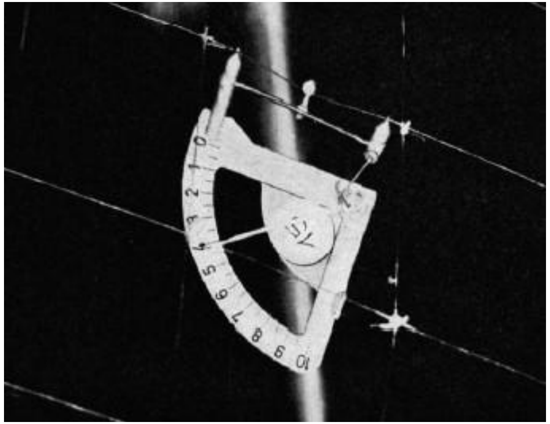
COMPRESSION

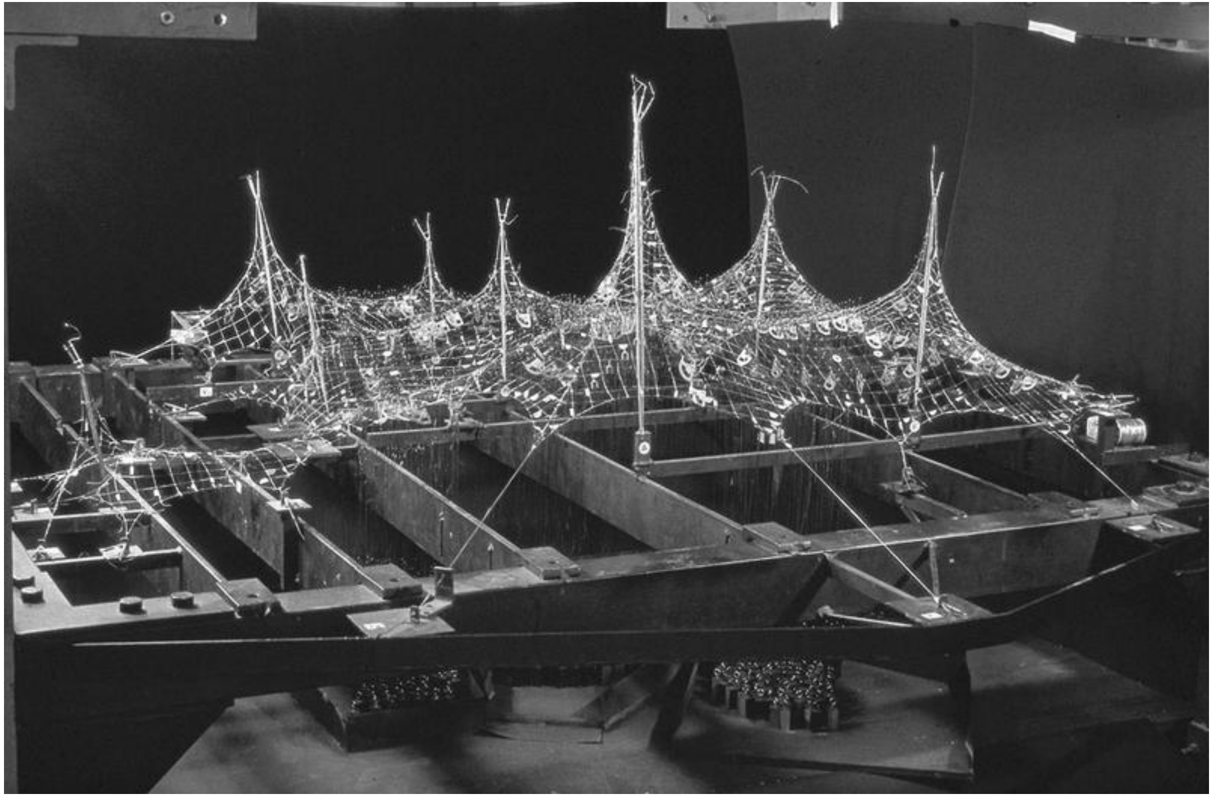


Reality

Physical Modeling for Form Finding





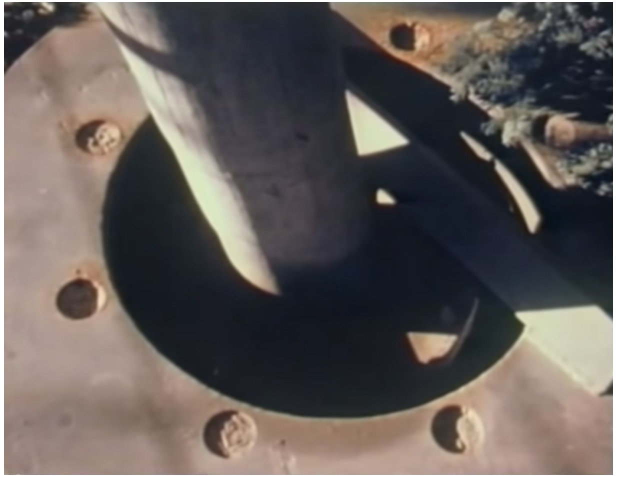
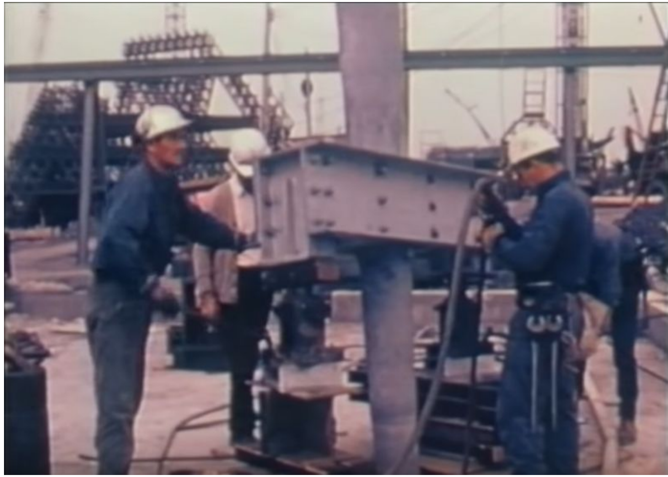


Reality

Physical Modeling for
Form Finding

0:39 - 1:40

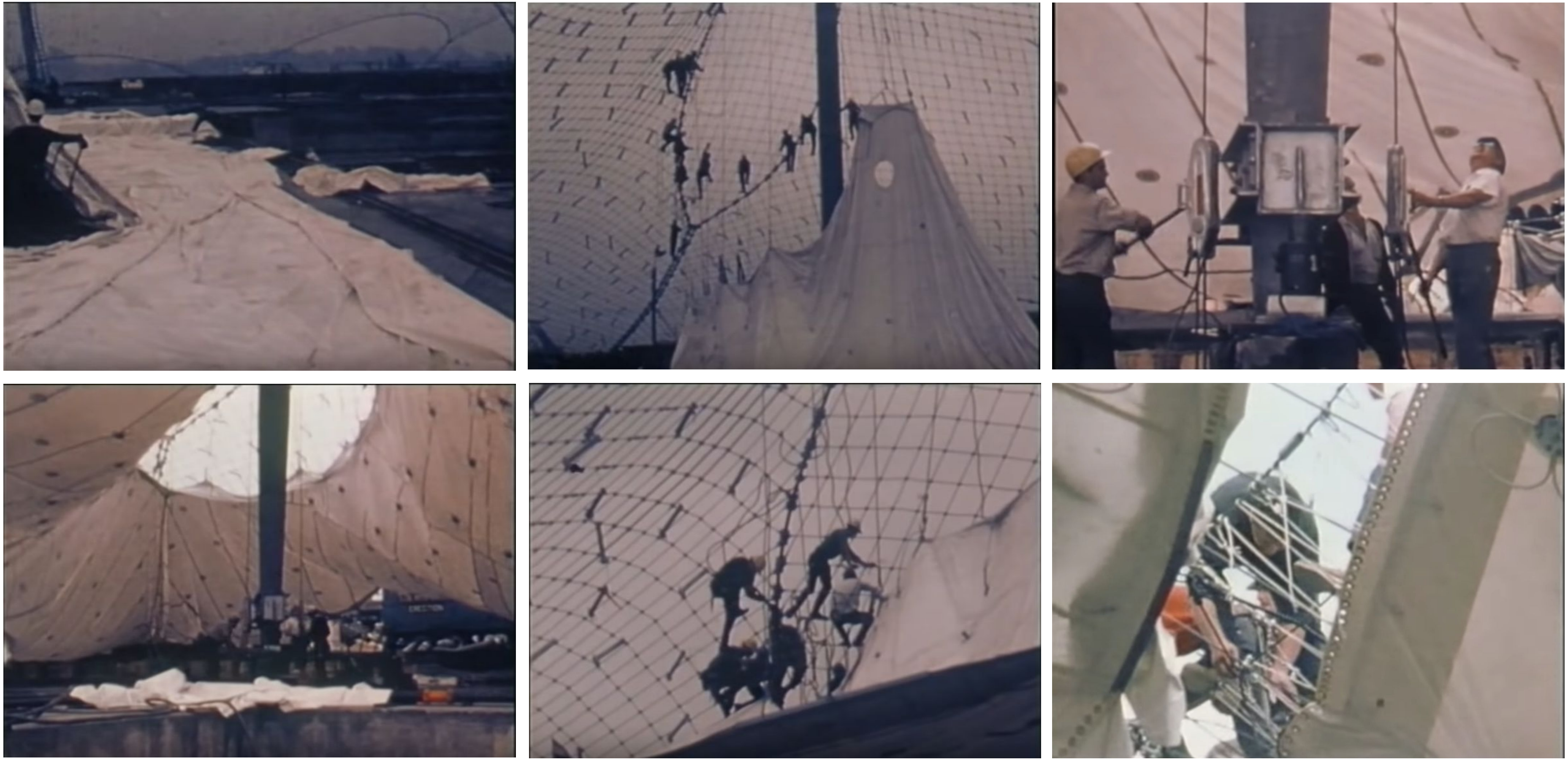
Construction

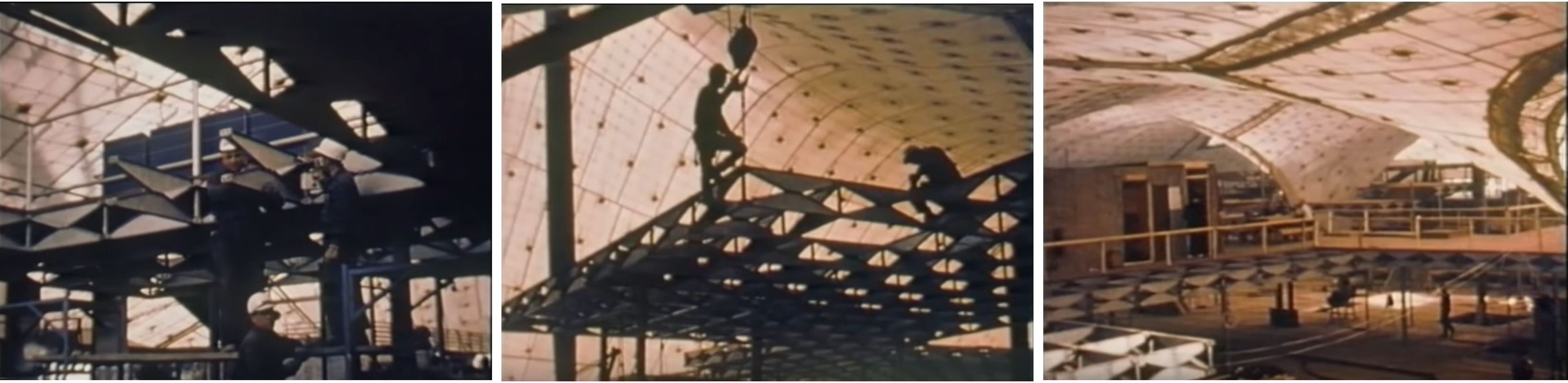
Installation of Masts

Assembly of Cable Net

Assembly of Wood Lattice



Assembly of Membrane



Assembly of Interior Structure