



**ARK-A3001 Design of Structures\_Basics**  
**Principle of Duality**

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Aalto University  
Department of Architecture  
Department of Civil Engineering



# Inner Forces

tension

compression

inner forces act upon material

form & inner forces are coupled

cable as tension-only structure

arch as compression-only structure

principle of duality

## ARK-A3001 Design of Structures\_Basics Form & Force

### Toni Kotnik

Professor of Design of Structures

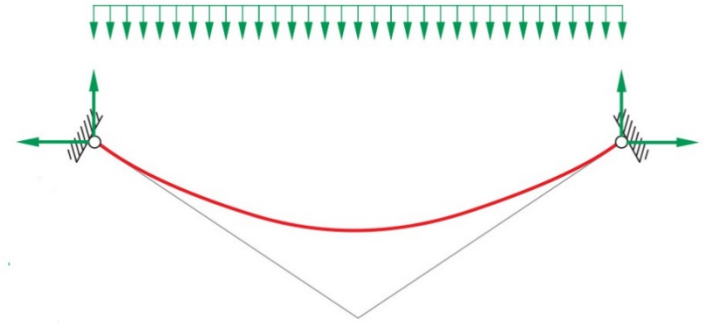
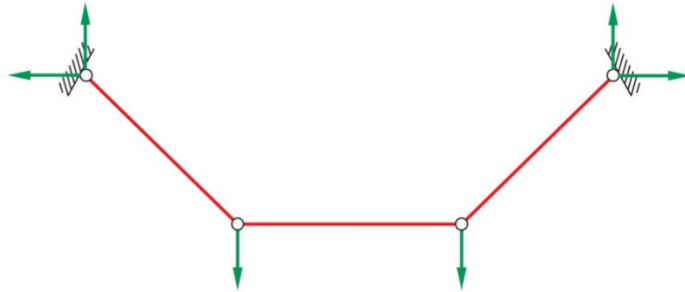
Aalto University  
Department of Architecture  
Department of Civil Engineering



# Principle of Duality

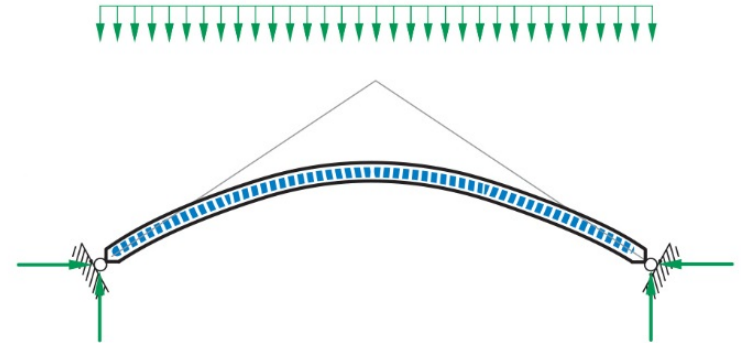
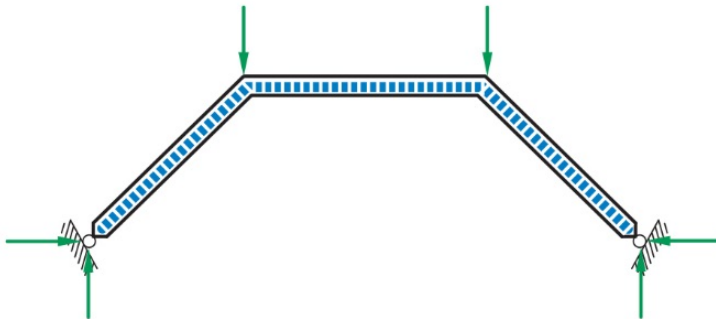
cable

only tension as  
inner forces



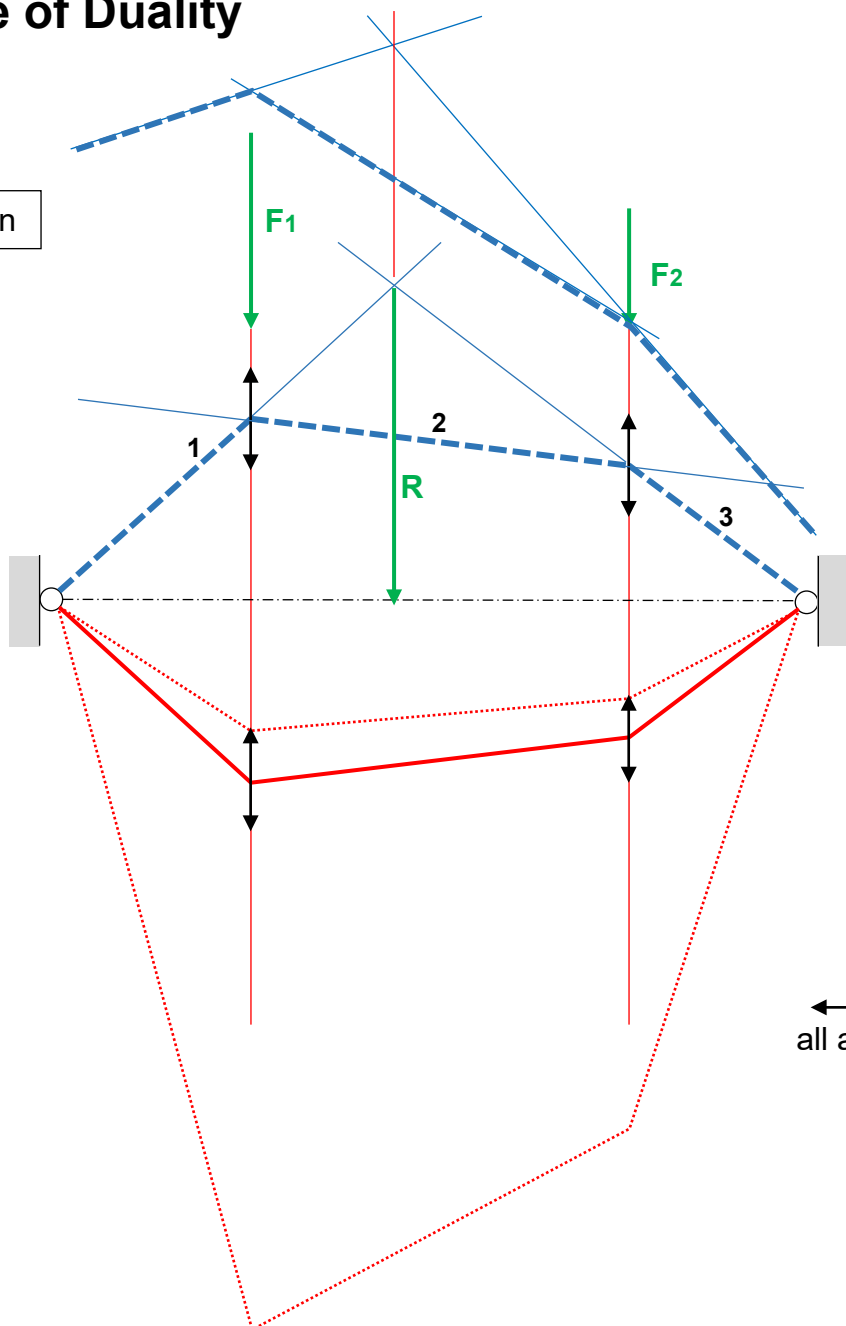
arch

only compression  
as inner forces

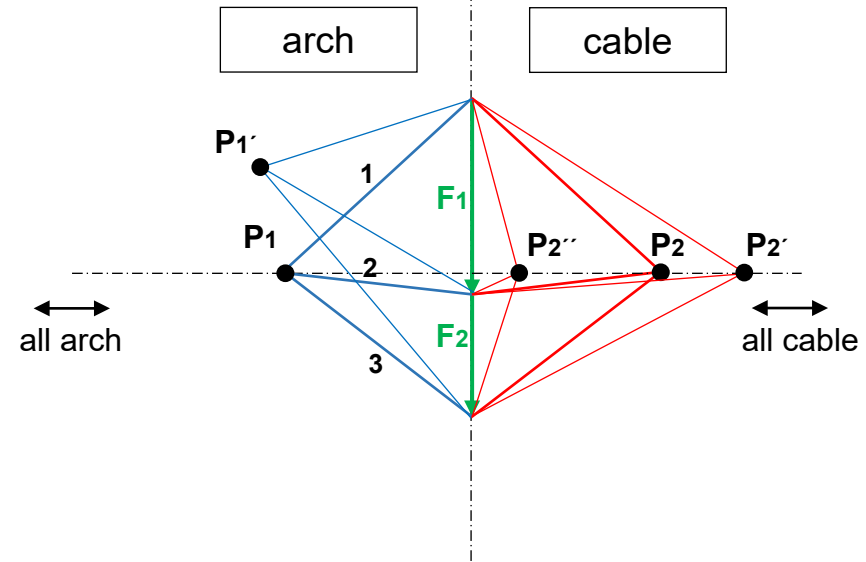


# Principle of Duality

location plan



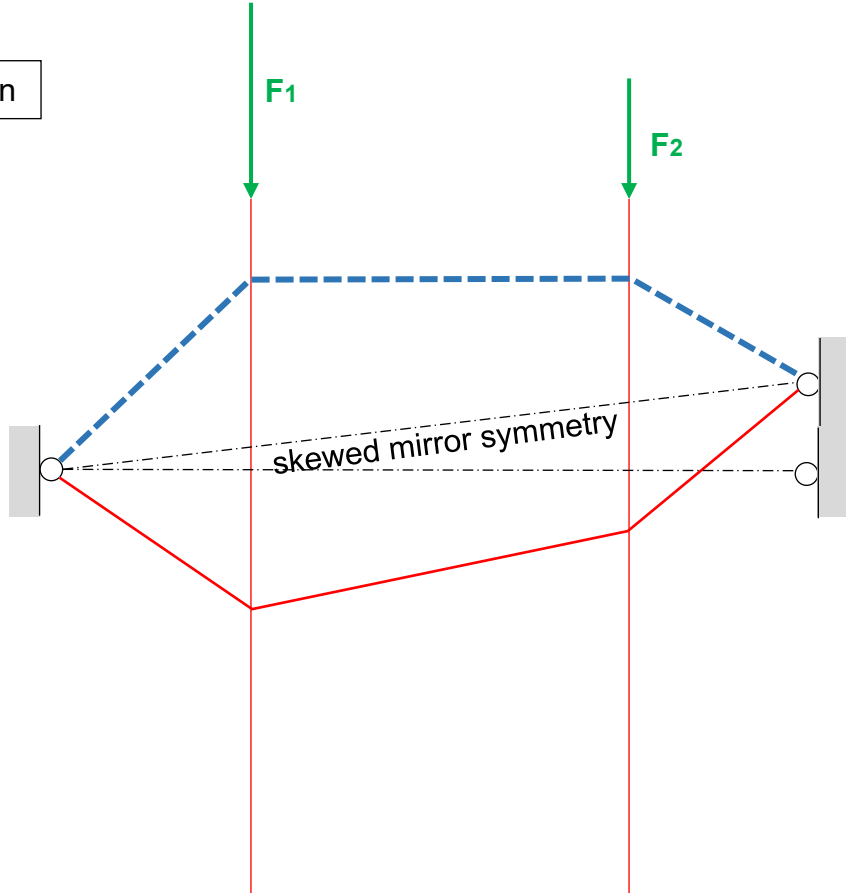
force plan





# Principle of Duality

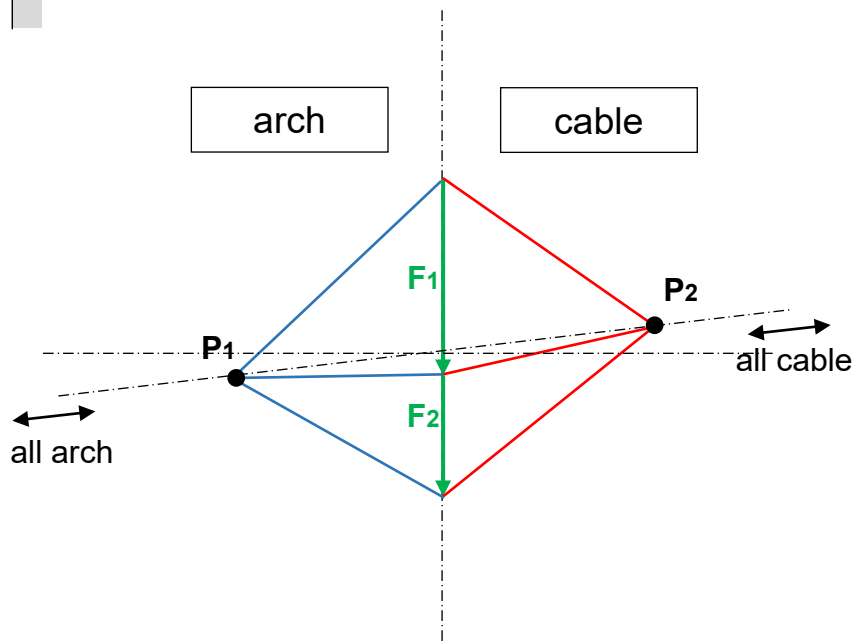
location plan



force plan

arch

cable



# Principle of Duality

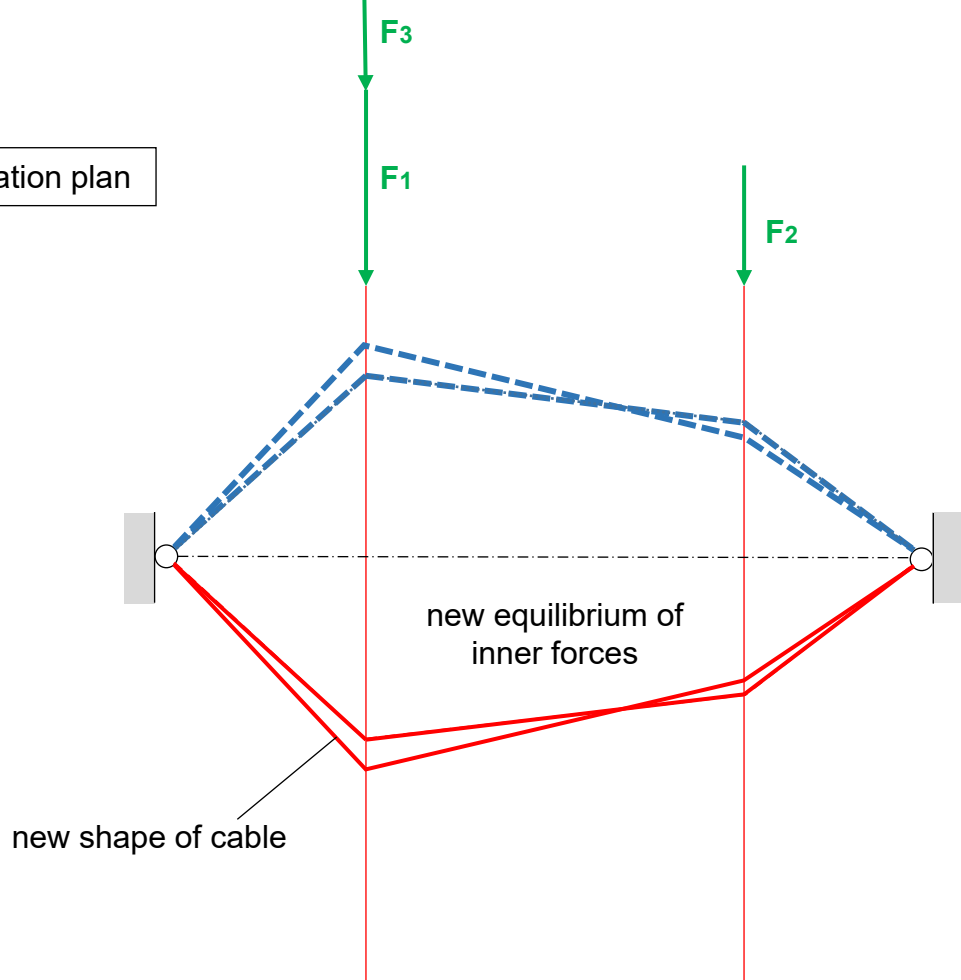


Antoni Gaudi: hanging model  
Sagrada Família, Barcelona, Spain  
around 1889

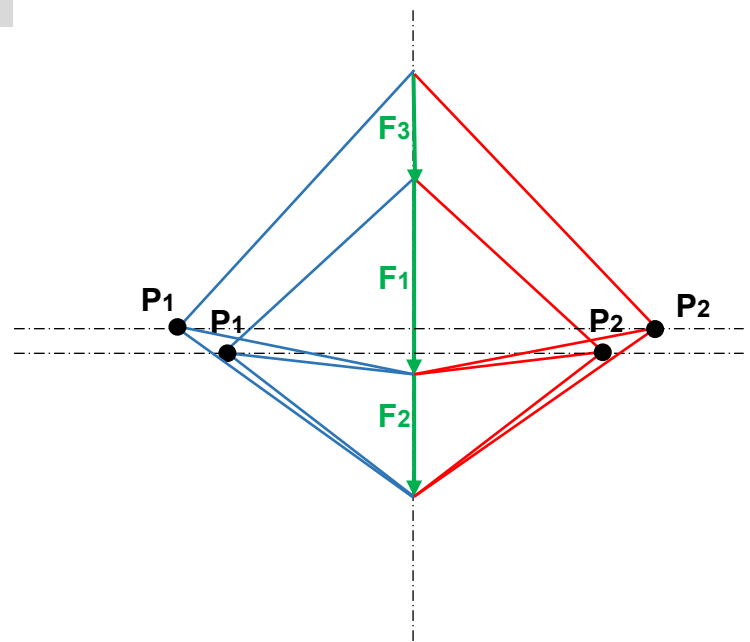


# Principle of Duality

location plan



force plan

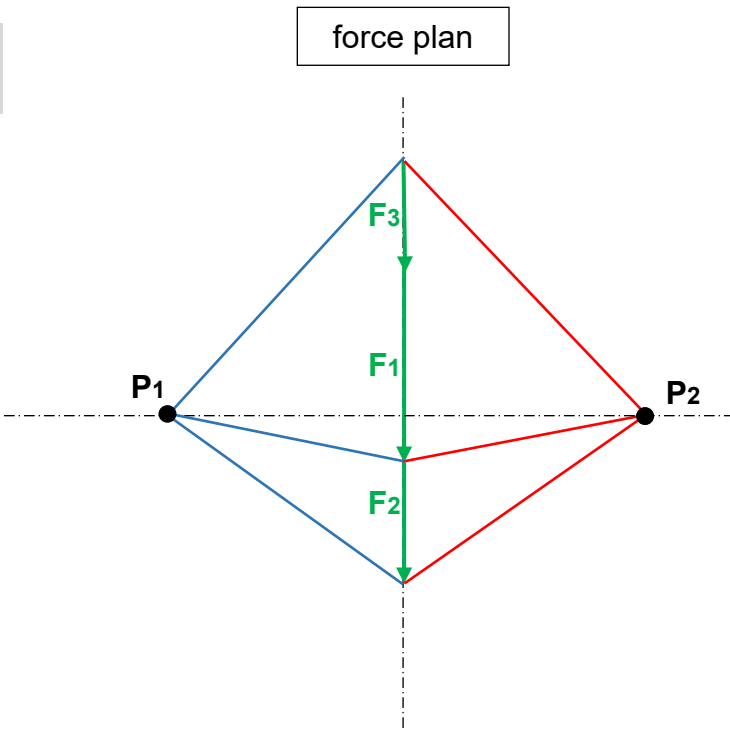
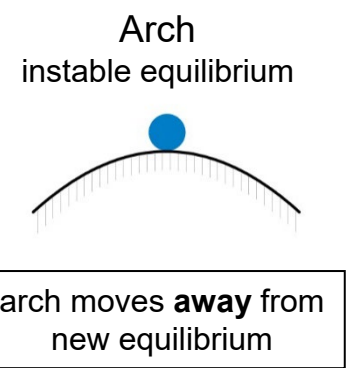
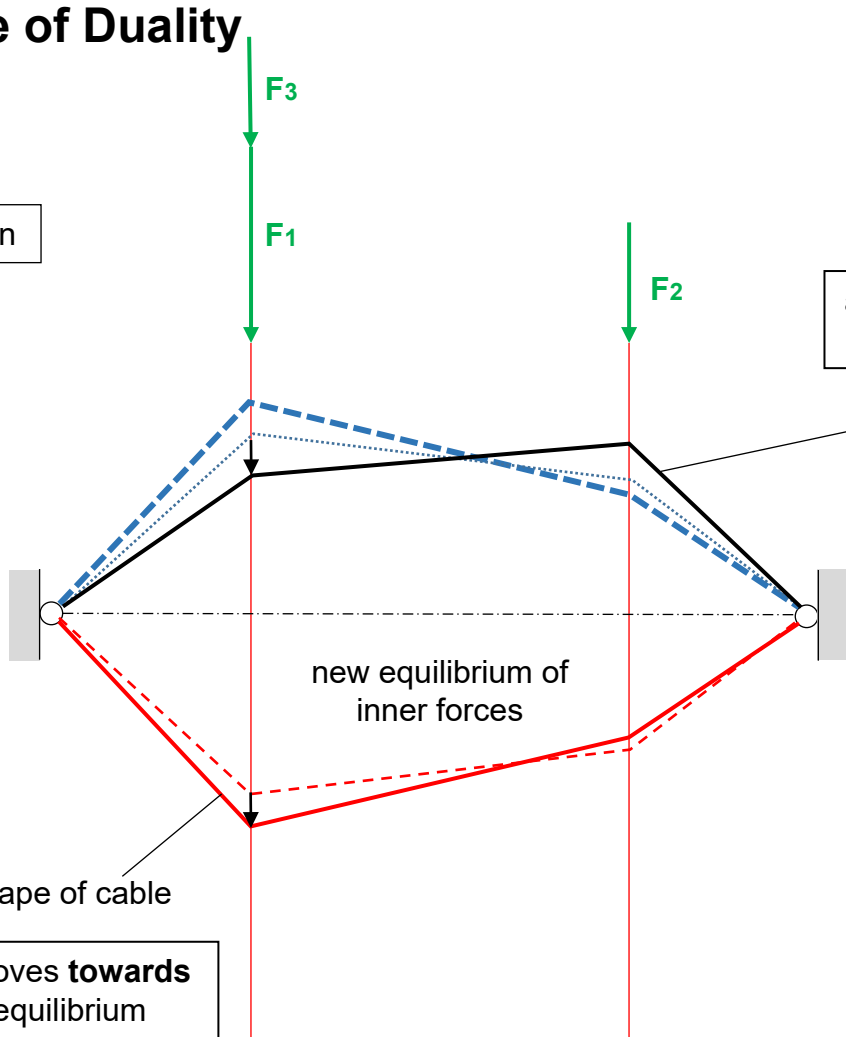




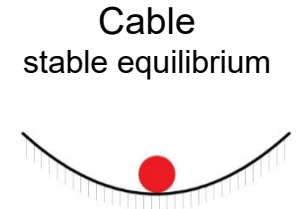


# Principle of Duality

location plan

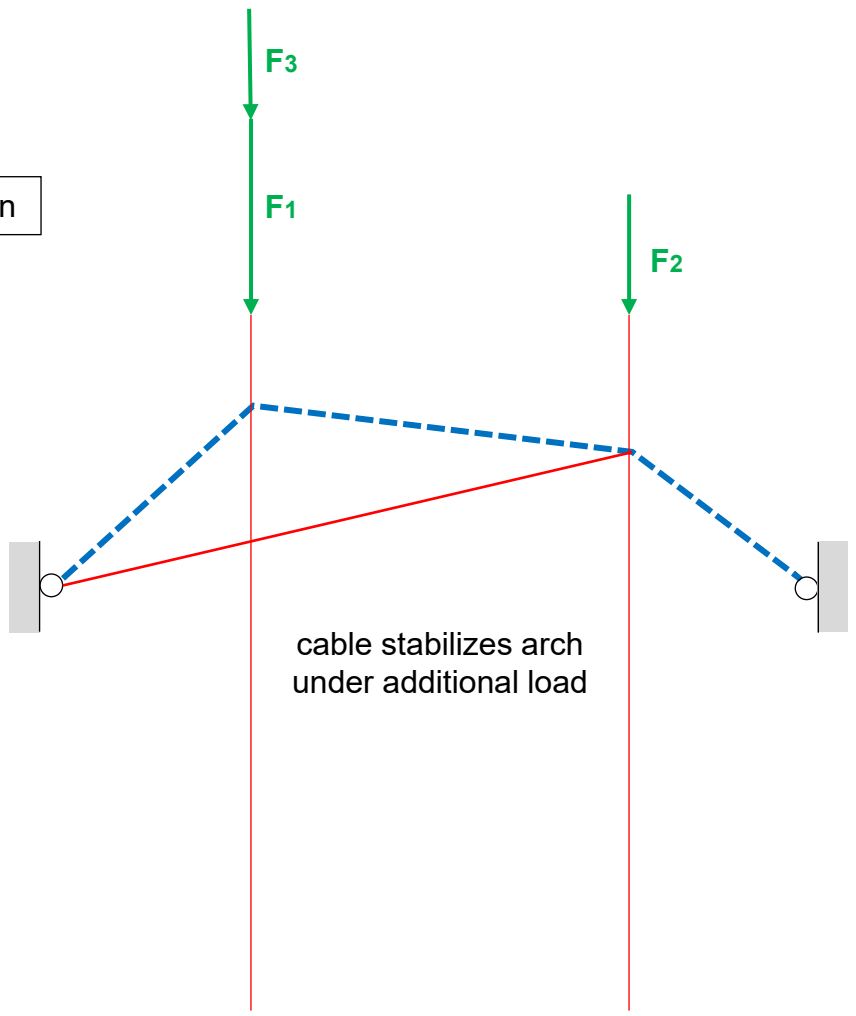


cable moves **towards** new equilibrium

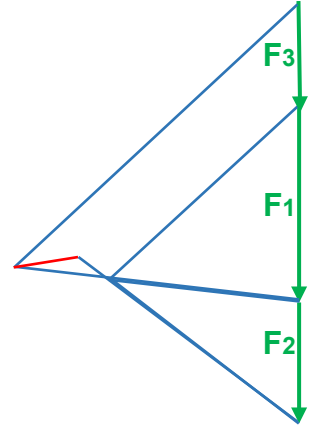


# Bracing

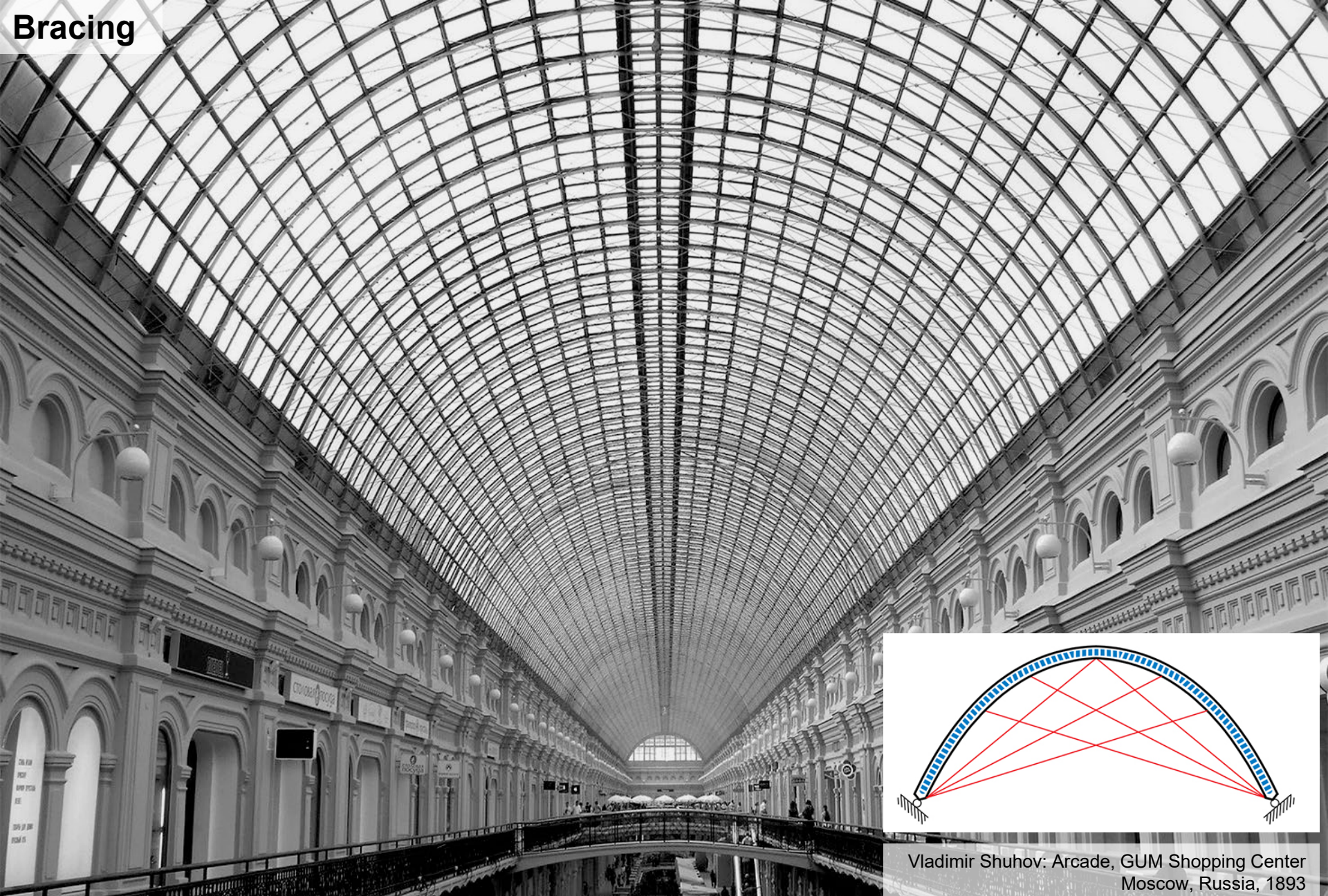
location plan



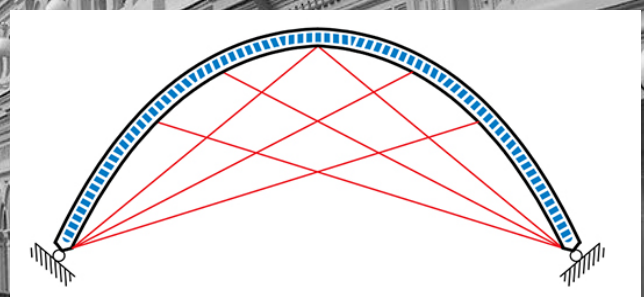
force plan







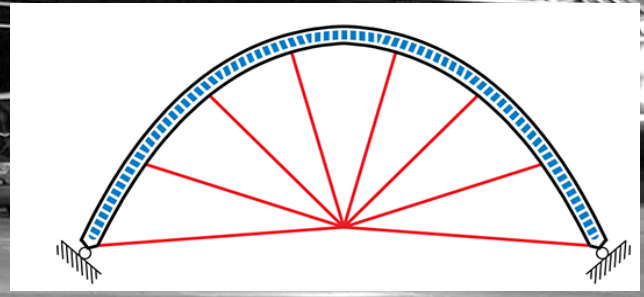
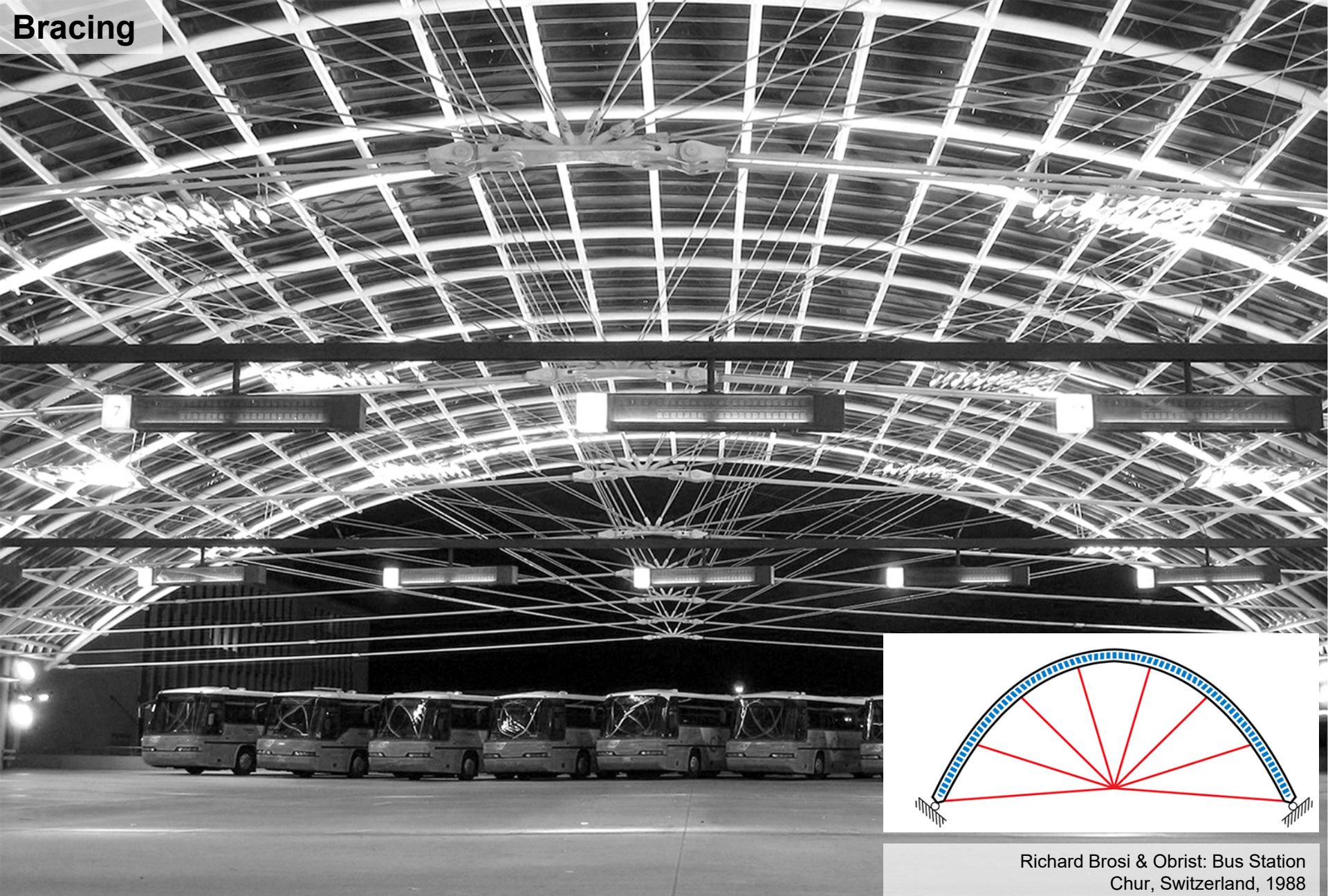
# Bracing



Vladimir Shuhov: Arcade, GUM Shopping Center  
Moscow, Russia, 1893



# Bracing

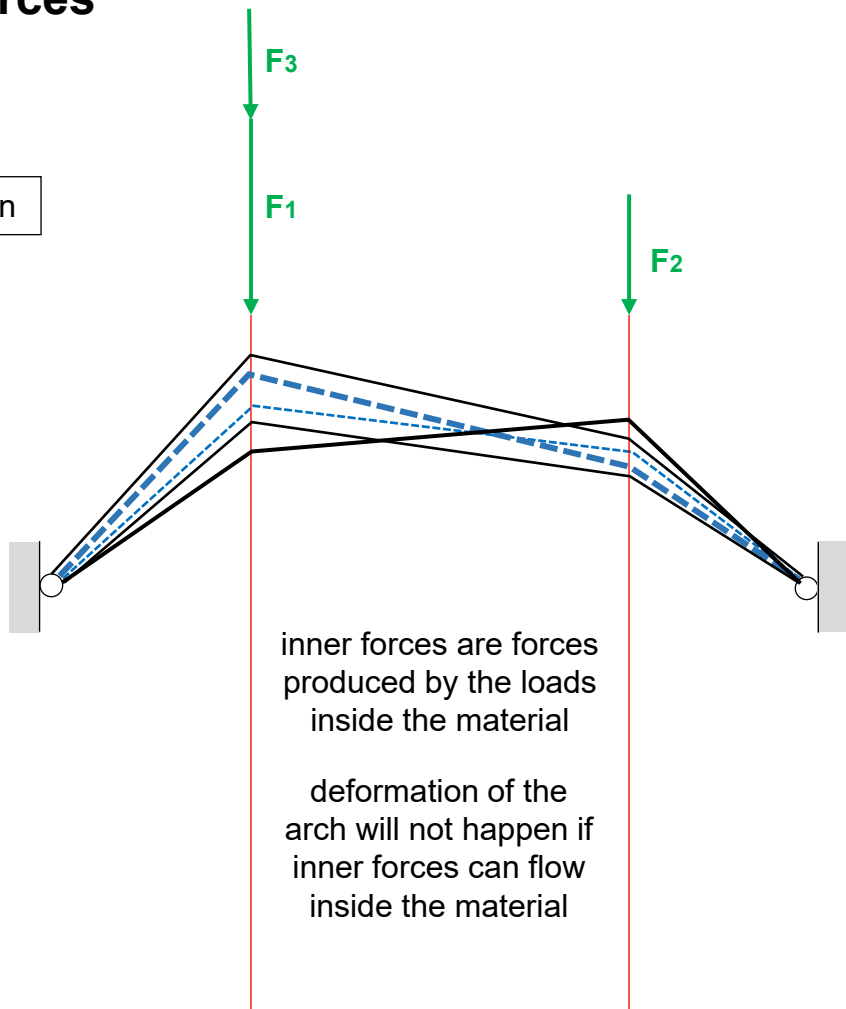


Richard Brosi & Obrist: Bus Station  
Chur, Switzerland, 1988



# Inner Forces

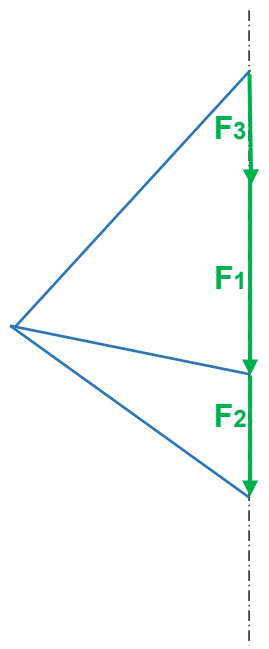
location plan



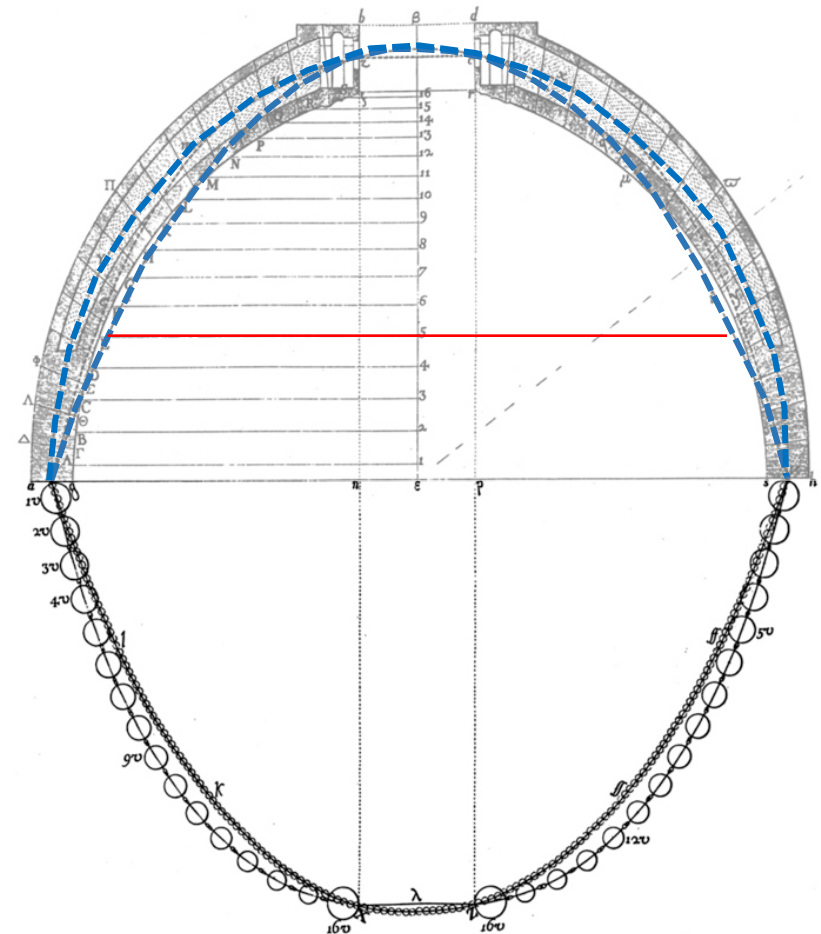
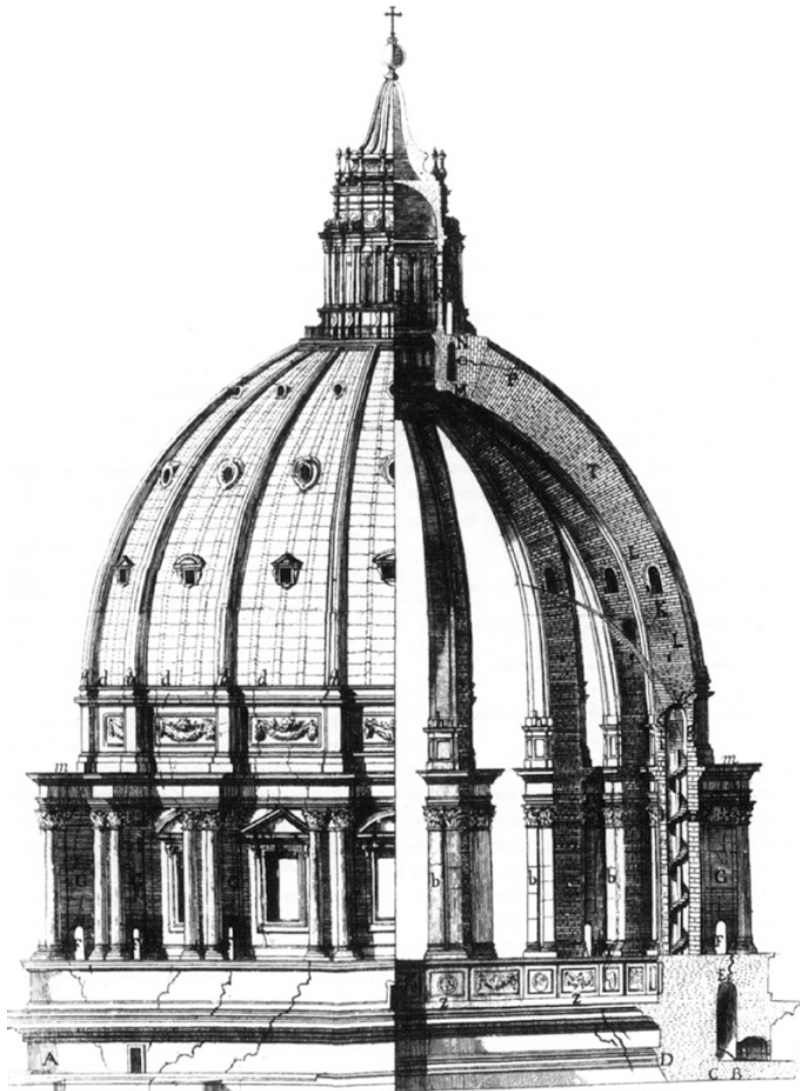
inner forces are forces produced by the loads inside the material

deformation of the arch will not happen if inner forces can flow inside the material

force plan



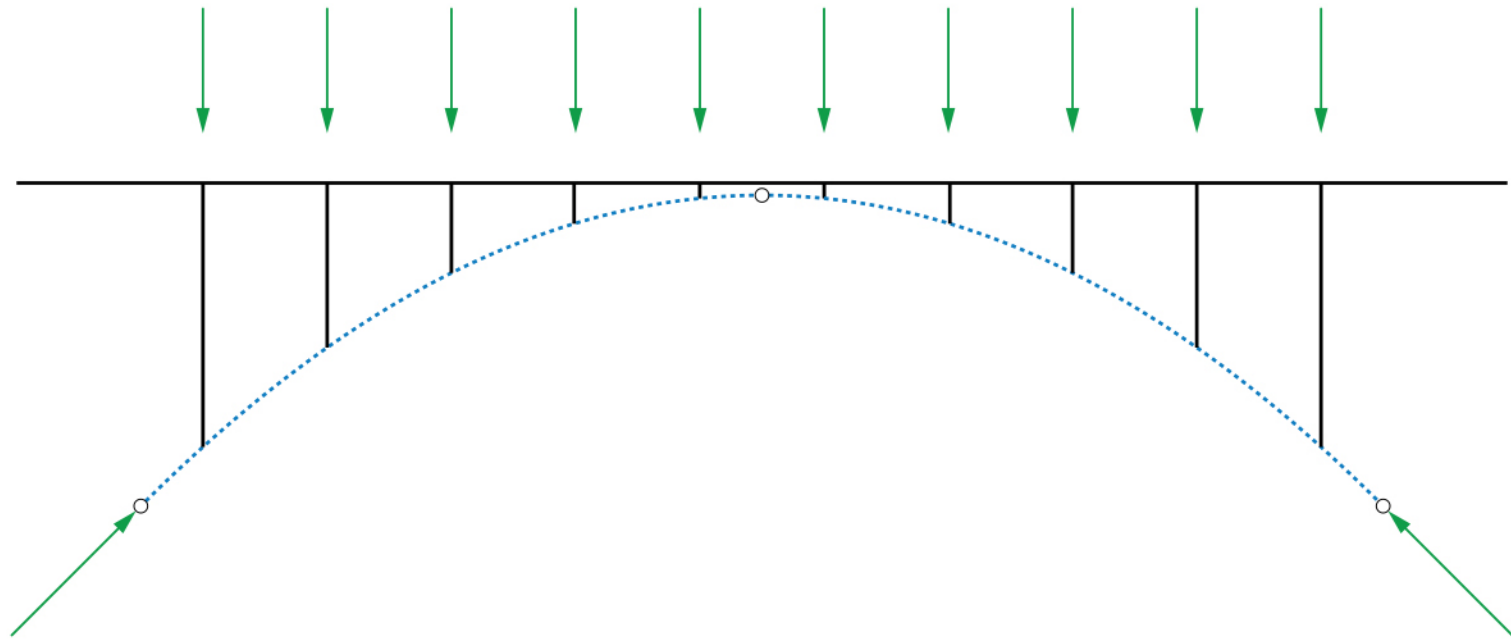
# Inner Forces



Giovanni Poleni: analysis of structural behaviour of  
cuppola of St. Peter, Rome, Italy, 1748

# Inner Forces

design method

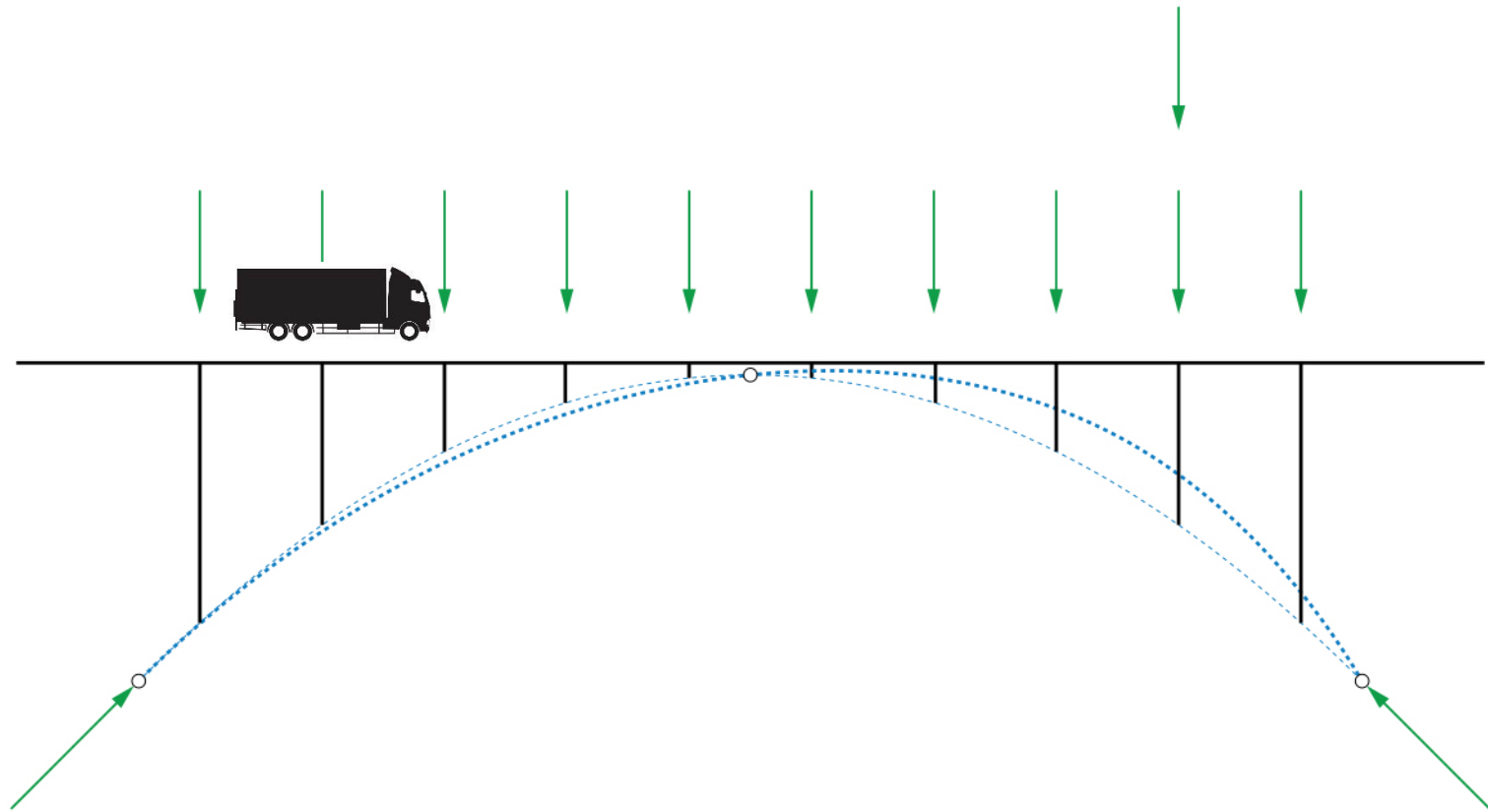


Robert Maillart: Salginatobel Bridge  
Schiers, Switzerland, 1930



# Inner Forces

design method

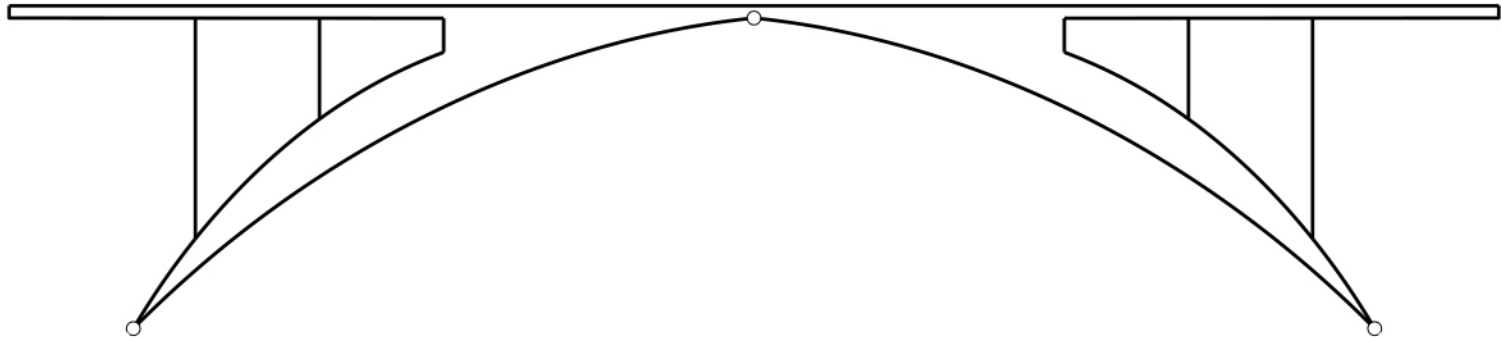


Robert Maillart: Salginatobel Bridge  
Schiers, Switzerland, 1930

# Inner Forces

design method

overlay of inner force flow of  
all possible load conditions ...



... in order to define the geometry  
of the structural element

Robert Maillart: Salginatobel Bridge  
Schiers, Switzerland, 1930

# Inner Forces

design method



Robert Maillart: Salginatobel Bridge  
Schiers, Switzerland, 1930



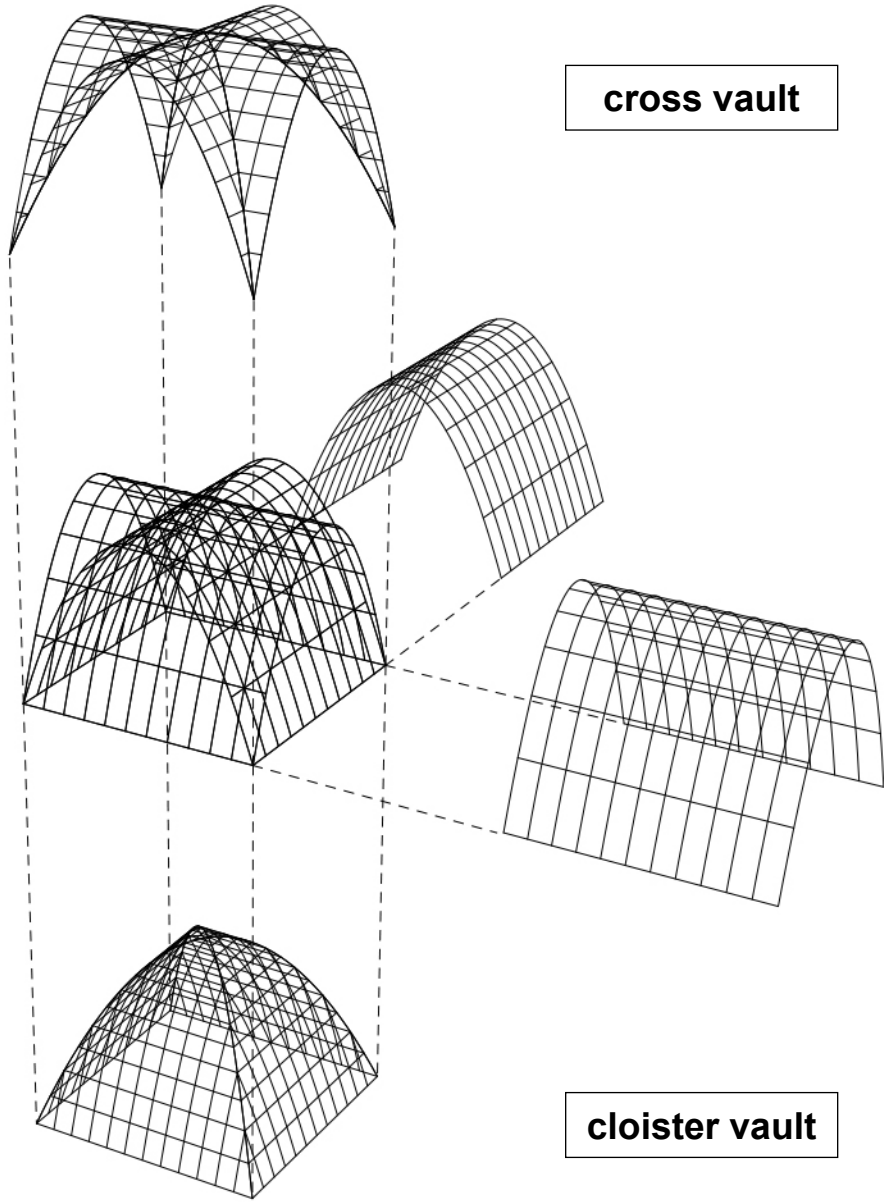
# Inner Forces

design method



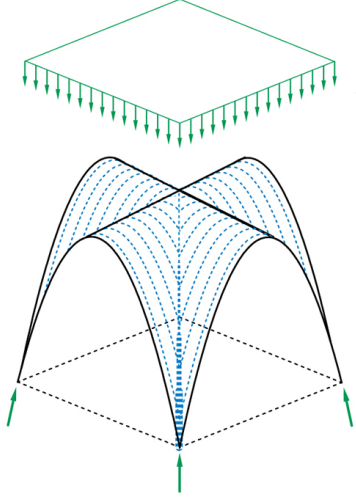
Sir Horace Jones: Tower Bridge  
London, UK, 1894

# From arch to vault

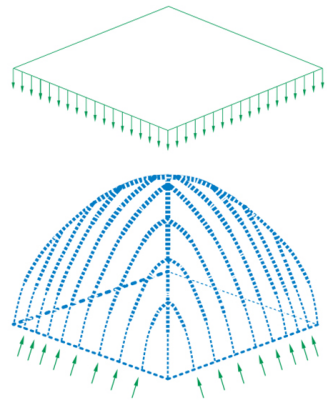


**cross vault**

intersect two barrel vaults



**barrel vault**



**cloister vault**





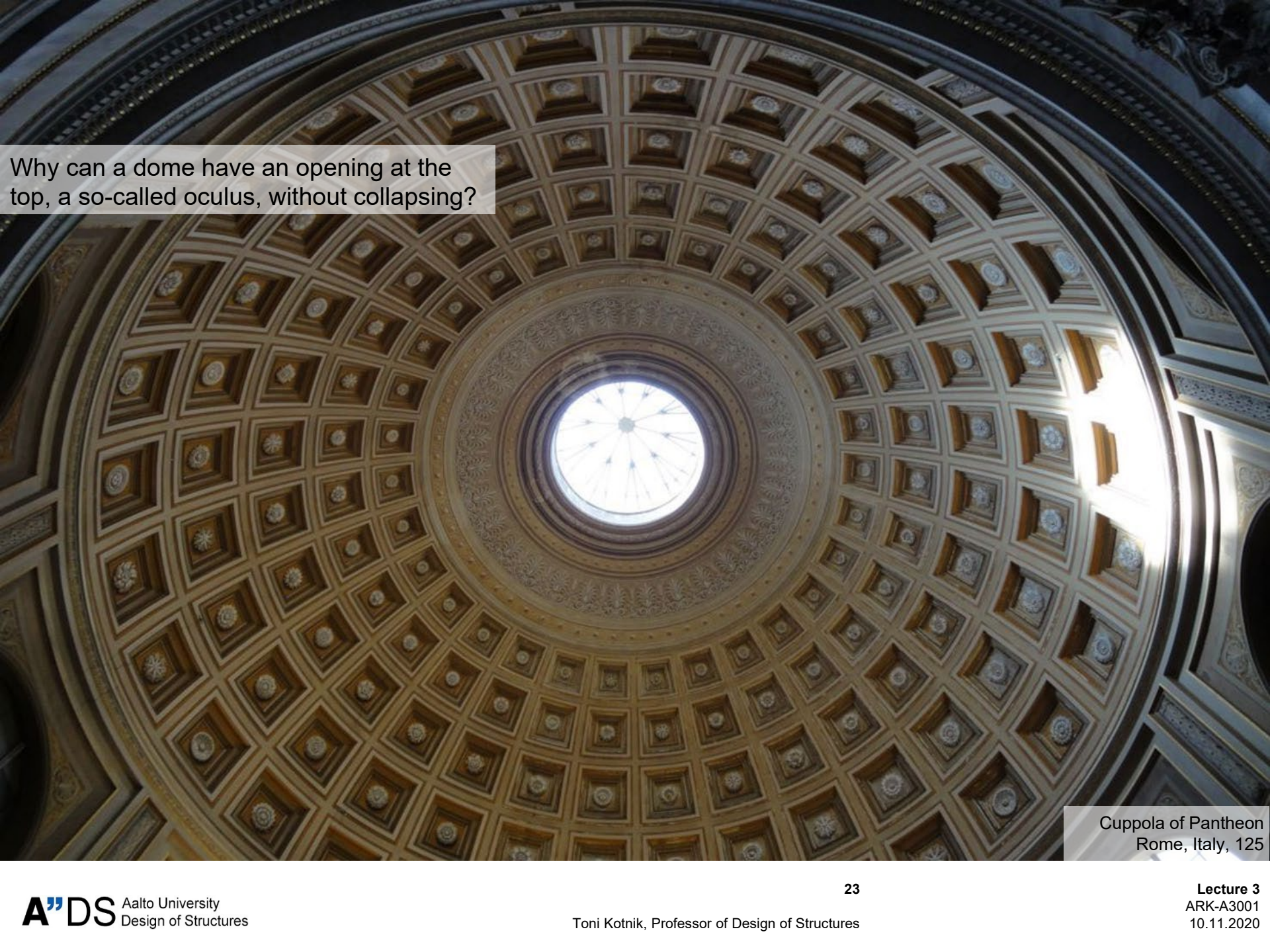
Cathedral Church of St. Mary, Salisbury, UK, 1479  
Tempio Maggiore, Rome, Italy, 1904





Filippo Brunelleschi: Cuppola of Santa Maria del Fiore  
Florence, Italy, 1418-36

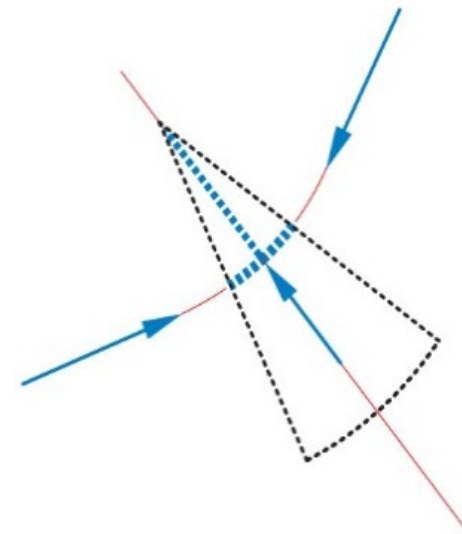
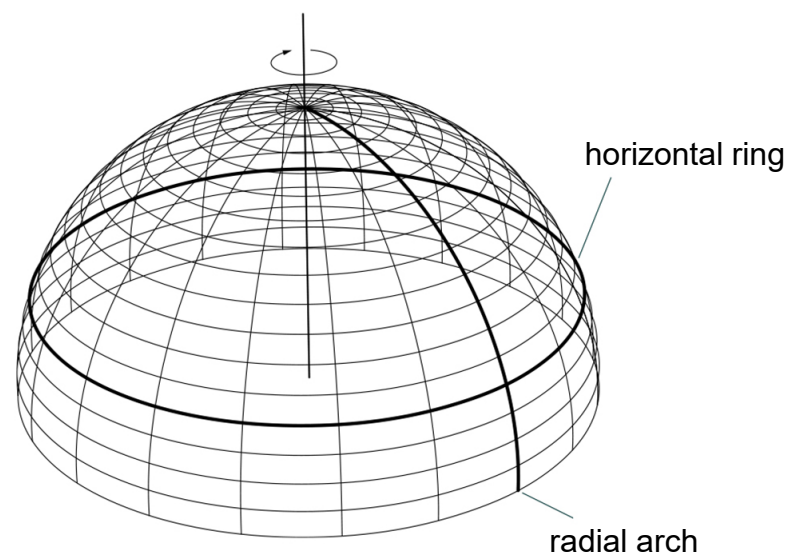
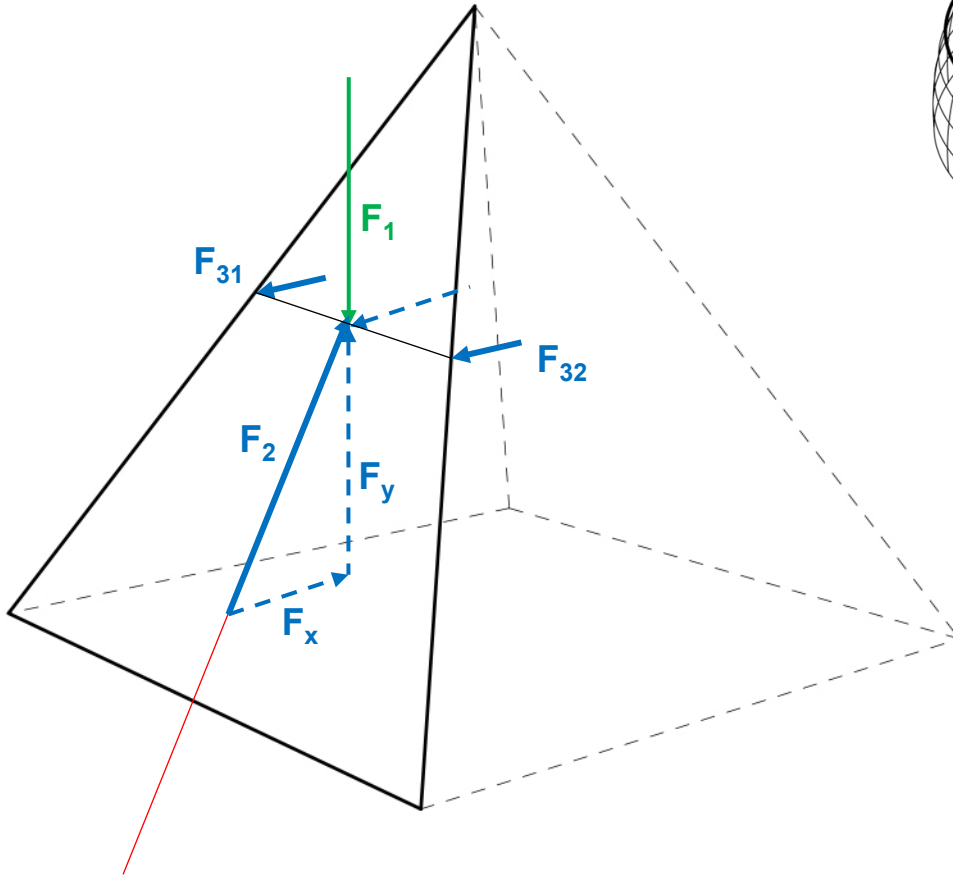




Why can a dome have an opening at the top, a so-called oculus, without collapsing?

Cuppola of Pantheon  
Rome, Italy, 125

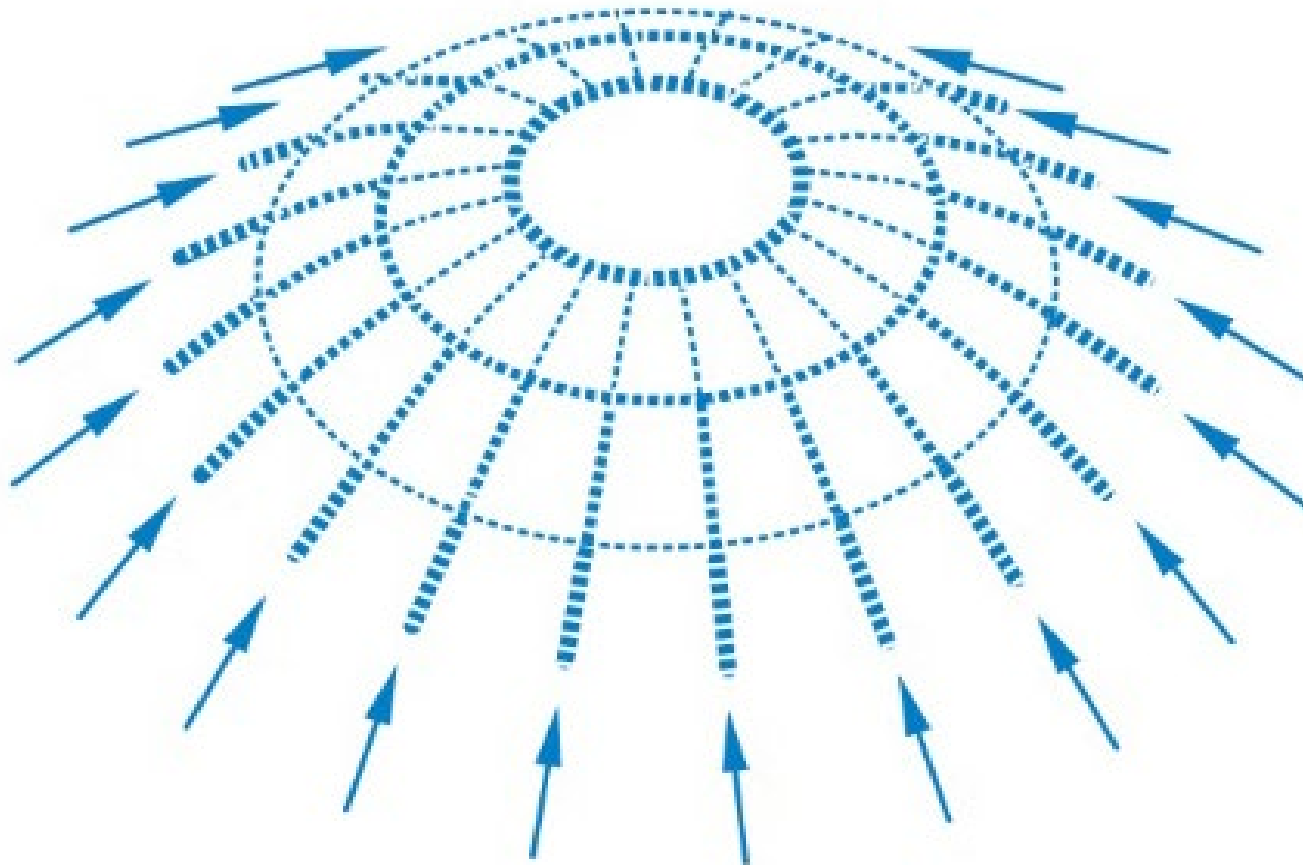
from polygon to dome



forces from arch get partially balanced by compression forces in horizontal rings



Why can a dome have an opening at the top, a so-called oculus, without collapsing?



inner forces in dome  
under self-weight



Pier Luigi Nervi\_ Palazzetto della Sport  
Rome, Italy, 1957





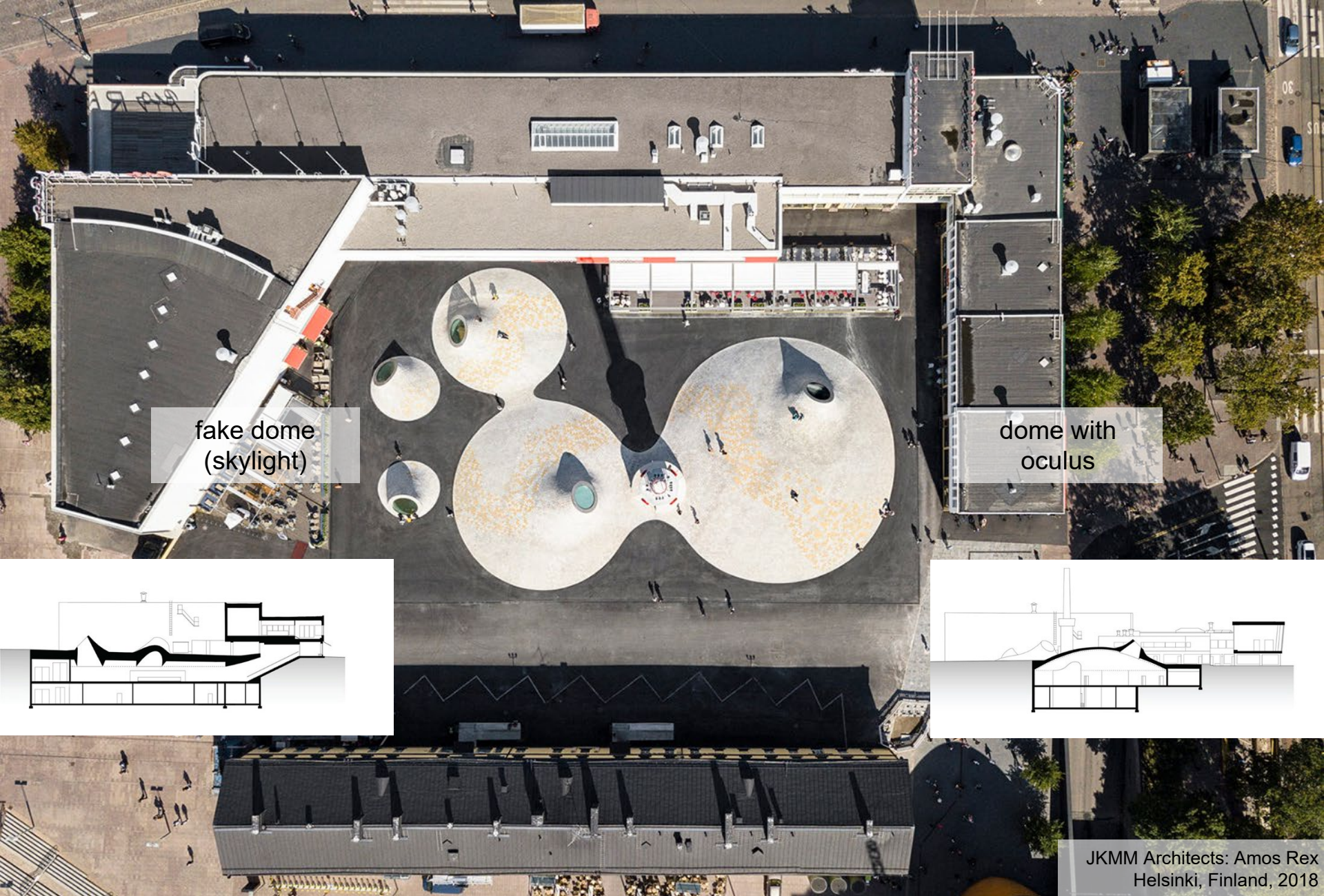
Pier Luigi Nervi\_ Palazzetto della Sport  
Rome, Italy, 1957





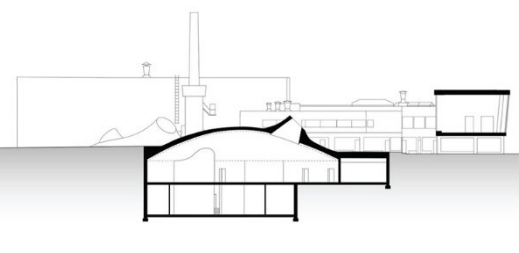
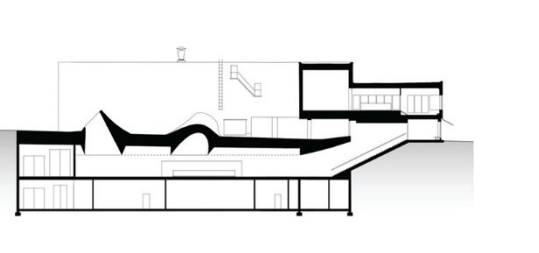
JKMM Architects: Amos Rex  
Helsinki, Finland, 2018





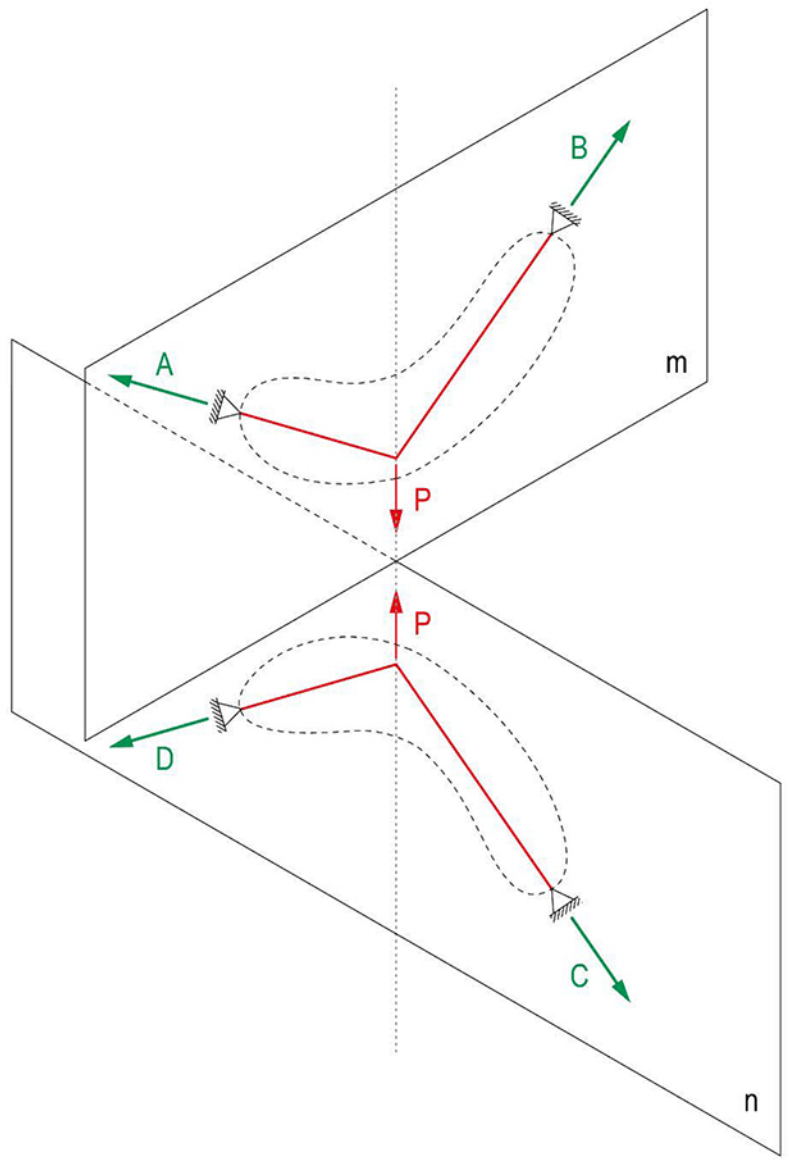
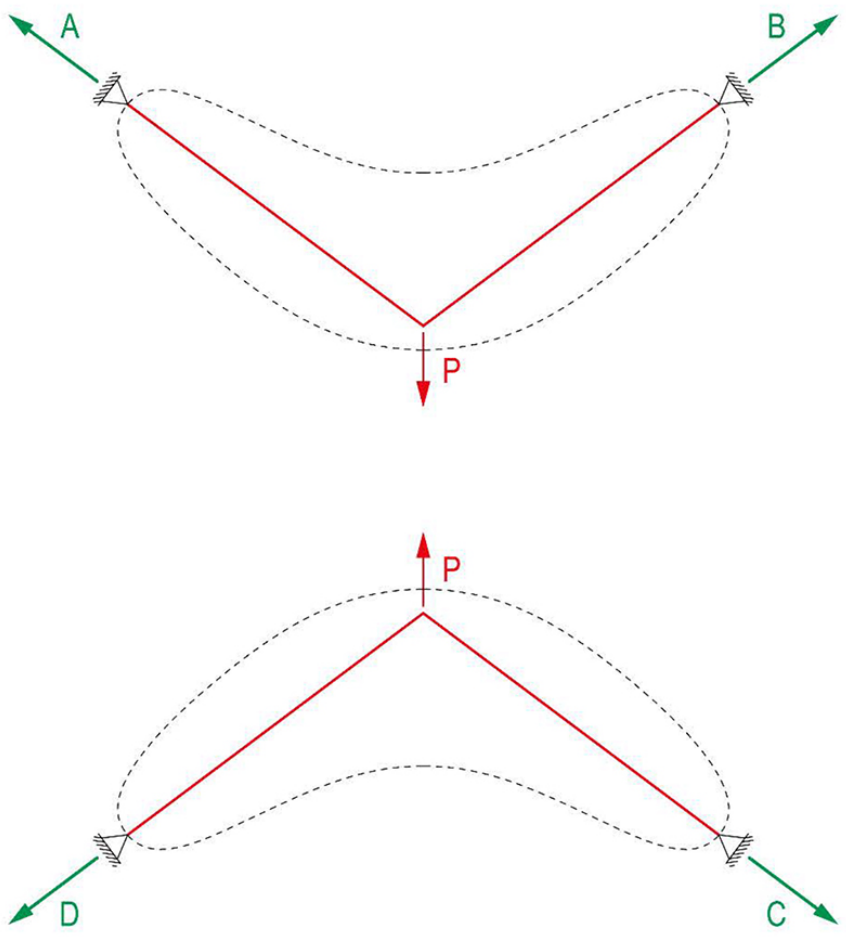
fake dome  
(skylight)

dome with  
oculus



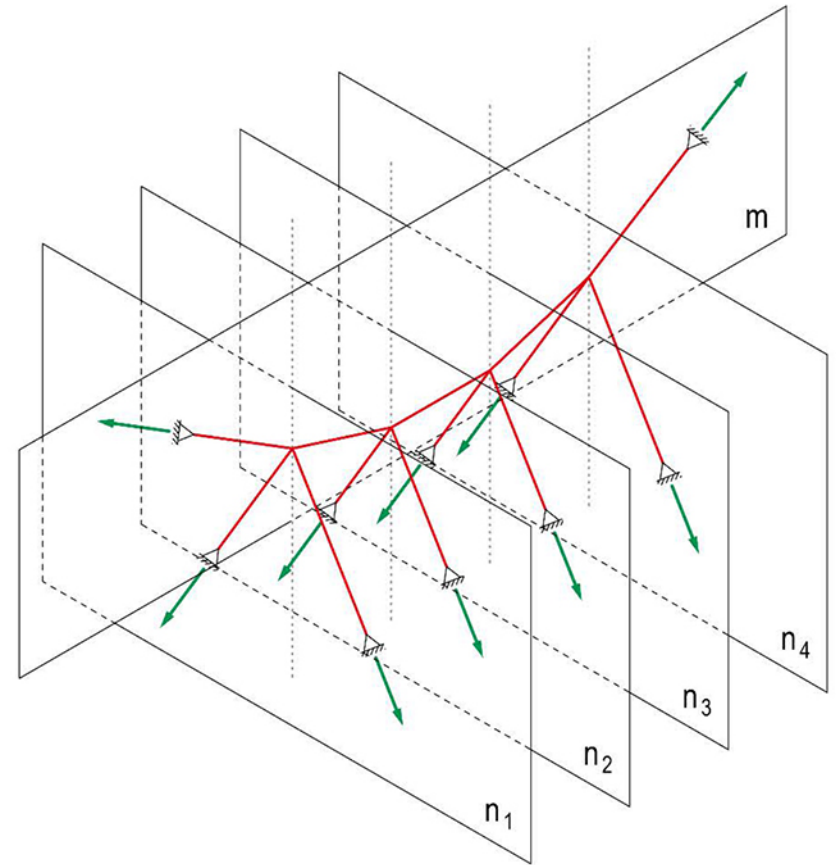
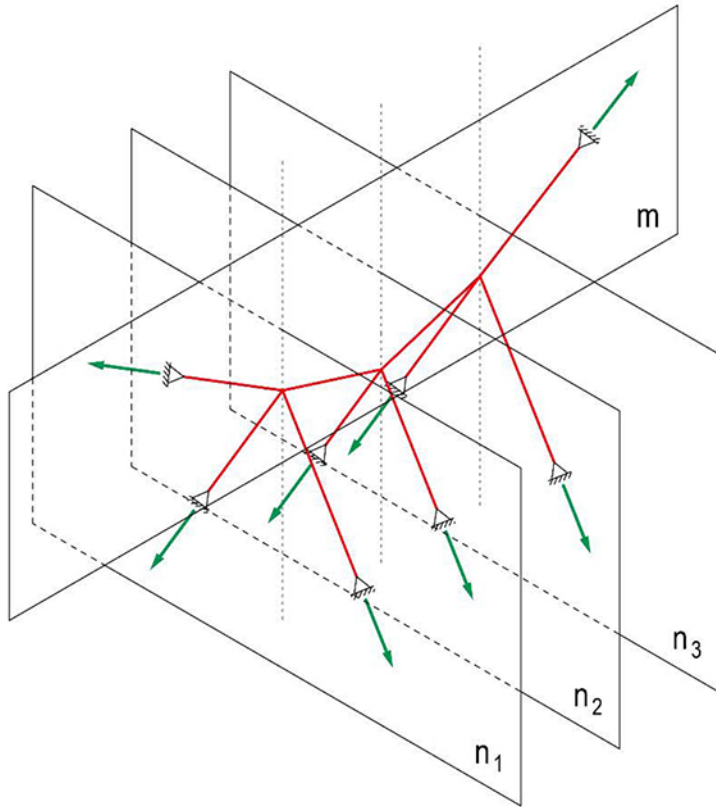
JKMM Architects: Amos Rex  
Helsinki, Finland, 2018

# From cable to membrane

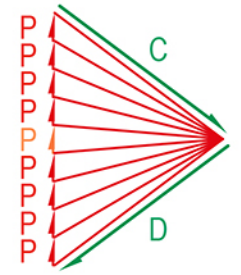
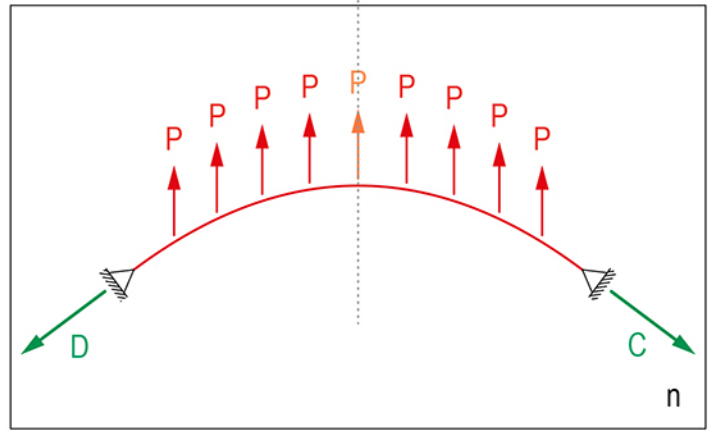
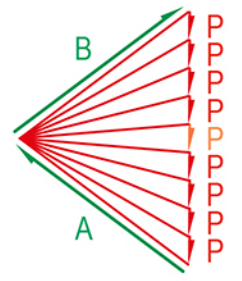
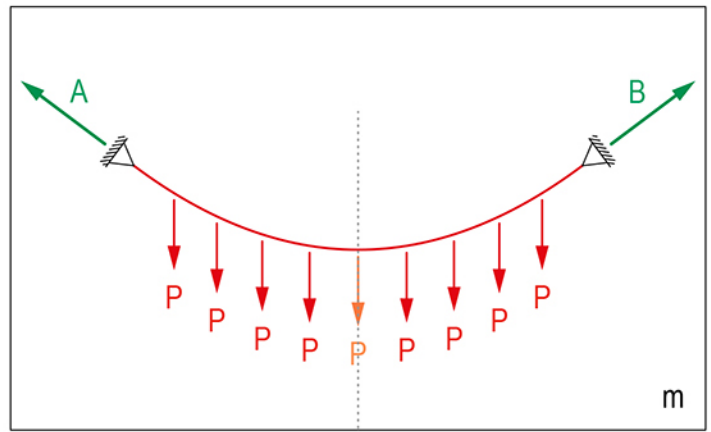
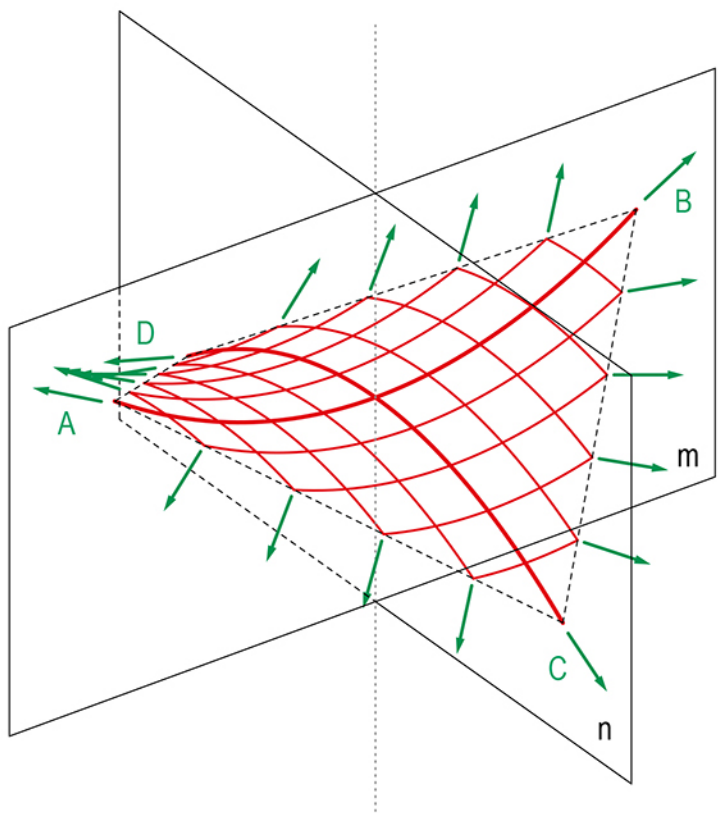




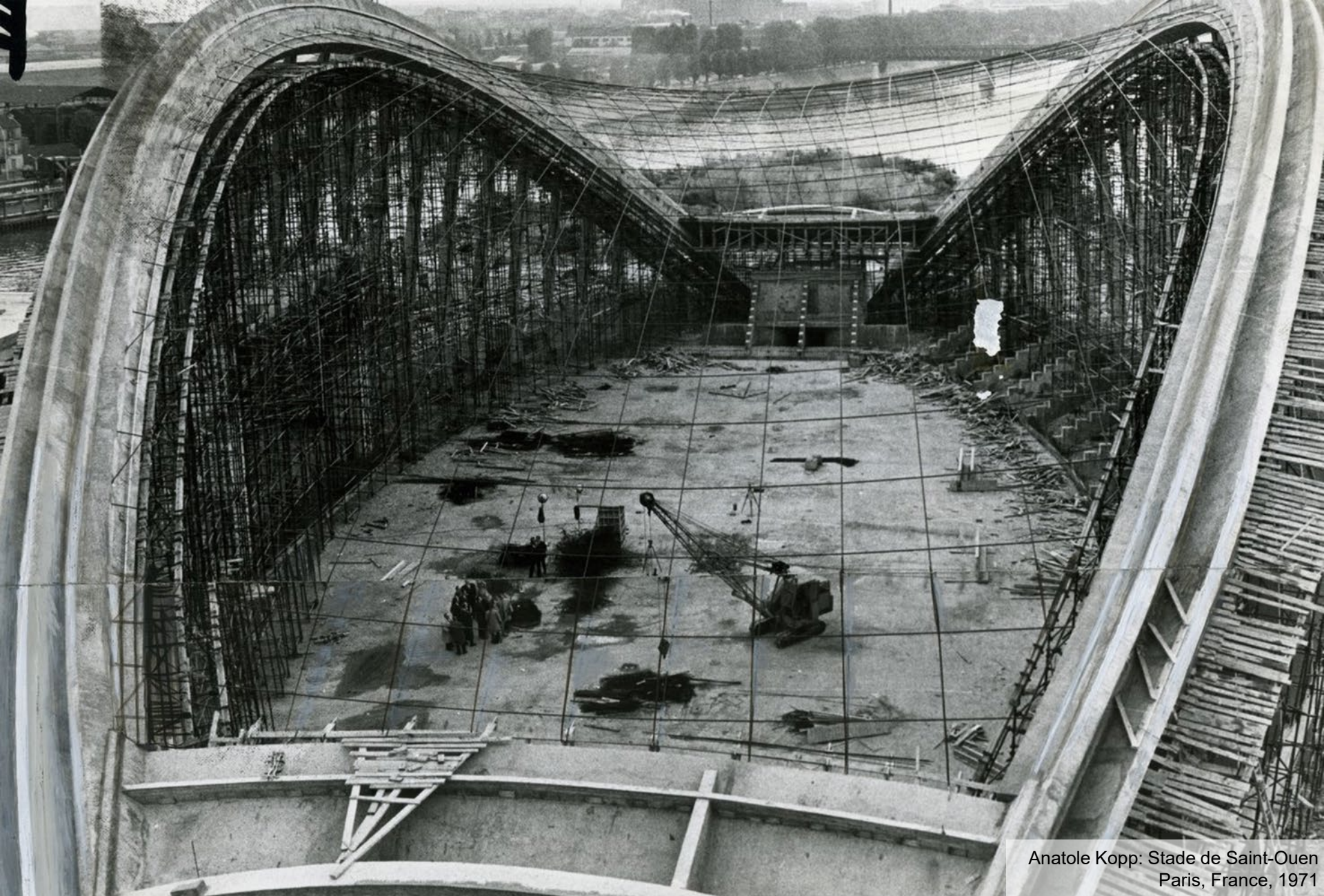
# From cable to membrane



# From cable to membrane







Anatole Kopp: Stade de Saint-Ouen  
Paris, France, 1971





Anatole Kopp: Stade de Saint-Ouen  
Paris, France, 1971





Anatole Kopp: Stade de Saint-Ouen  
Paris, France, 1971





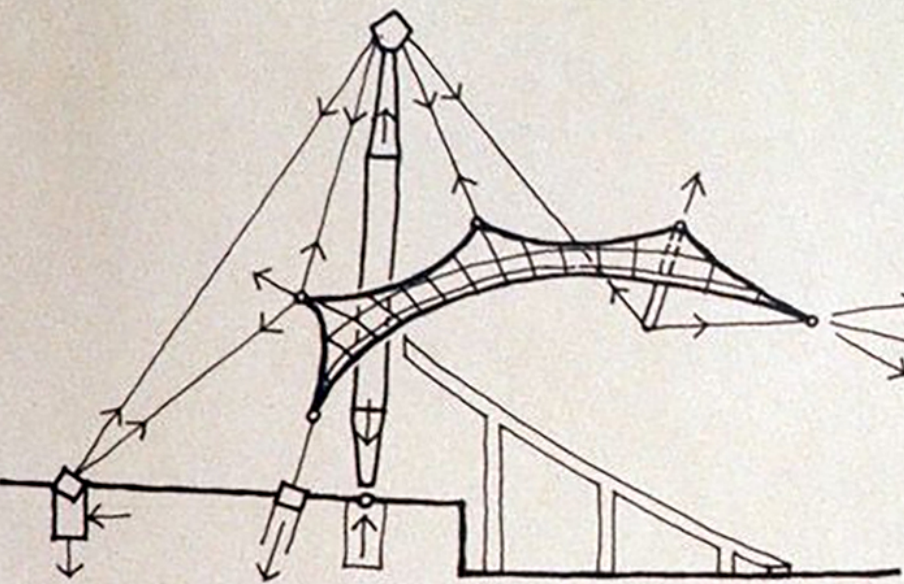
Günther Behnisch & Frei Otto: Olympic Park  
Munich, Germany, 1972



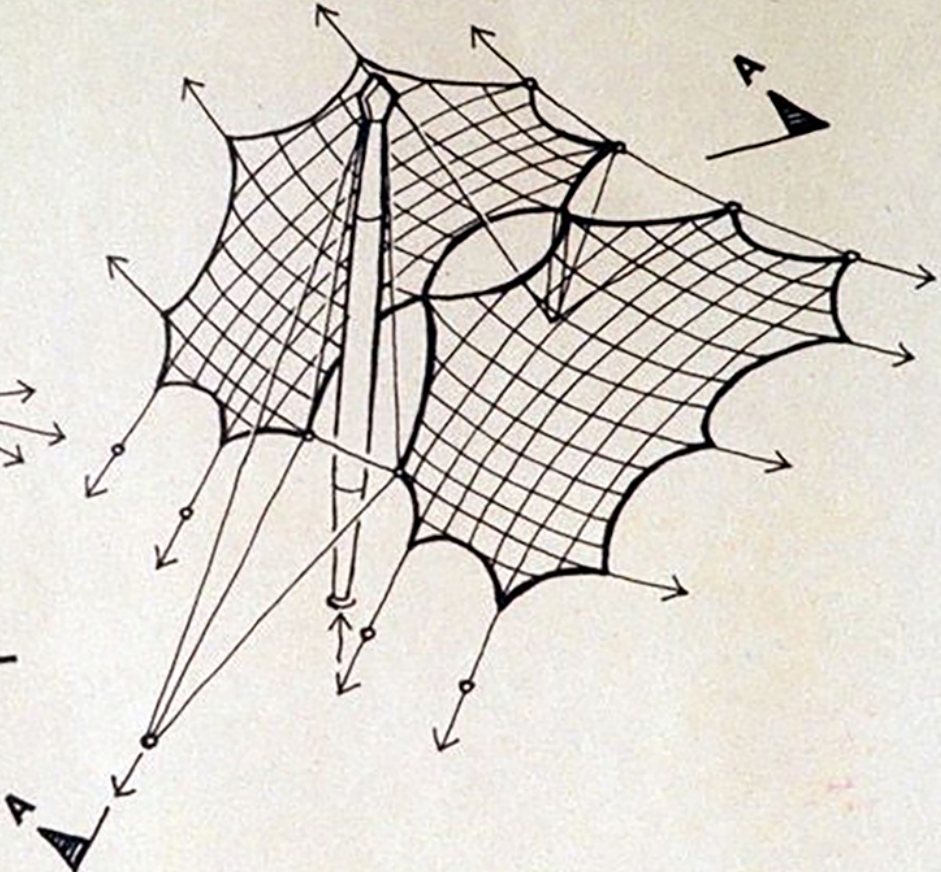


Günther Behnisch & Frei Otto: Olympic Park  
Munich, Germany, 1972





**Section A-A**



**One of the net sections**

Günther Behnisch & Frei Otto: Olympic Park  
Munich, Germany, 1972



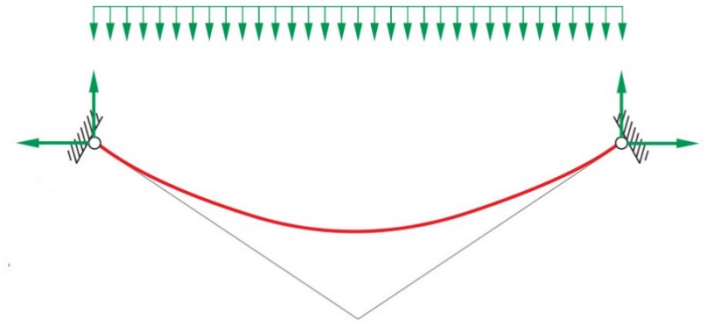
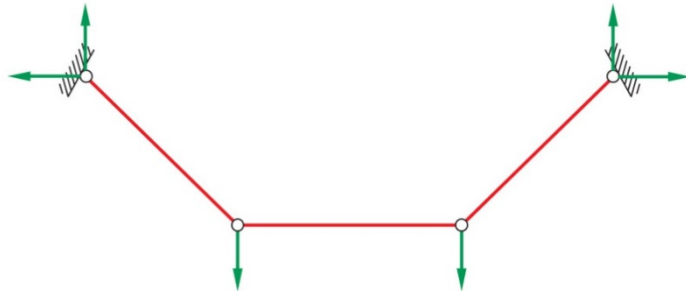


Günther Behnisch & Frei Otto: Olympic Park  
Munich, Germany, 1972

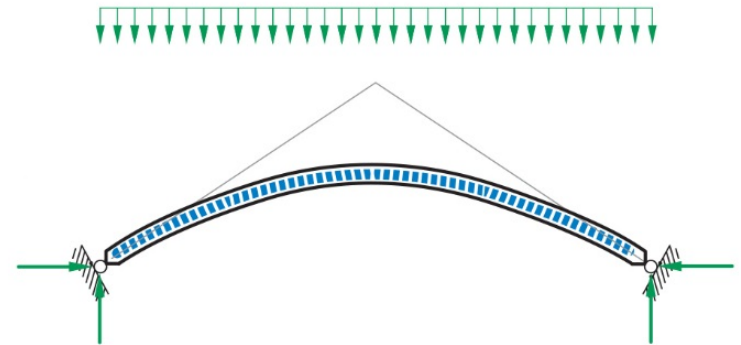
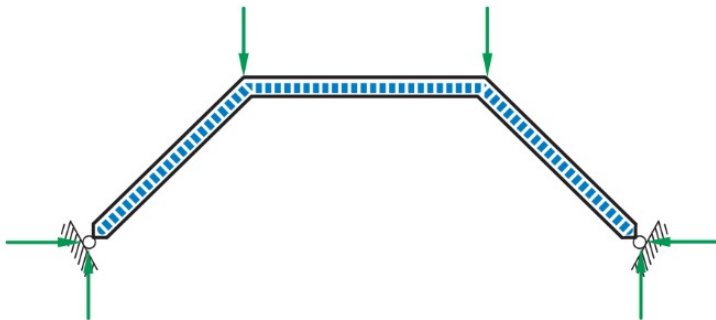


# Principle of Duality

2d cable  
3d membrane

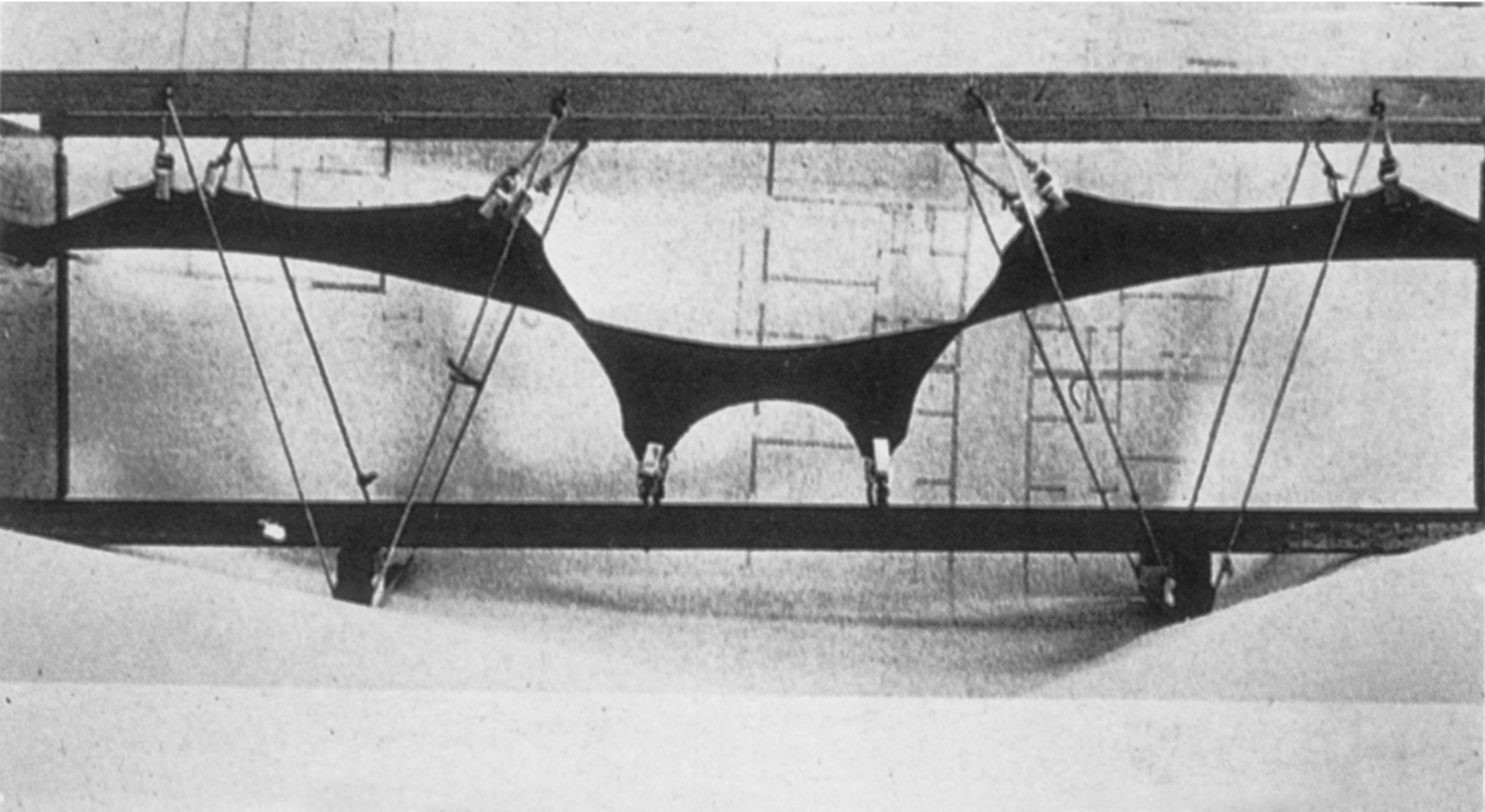


2d arch  
3d shell



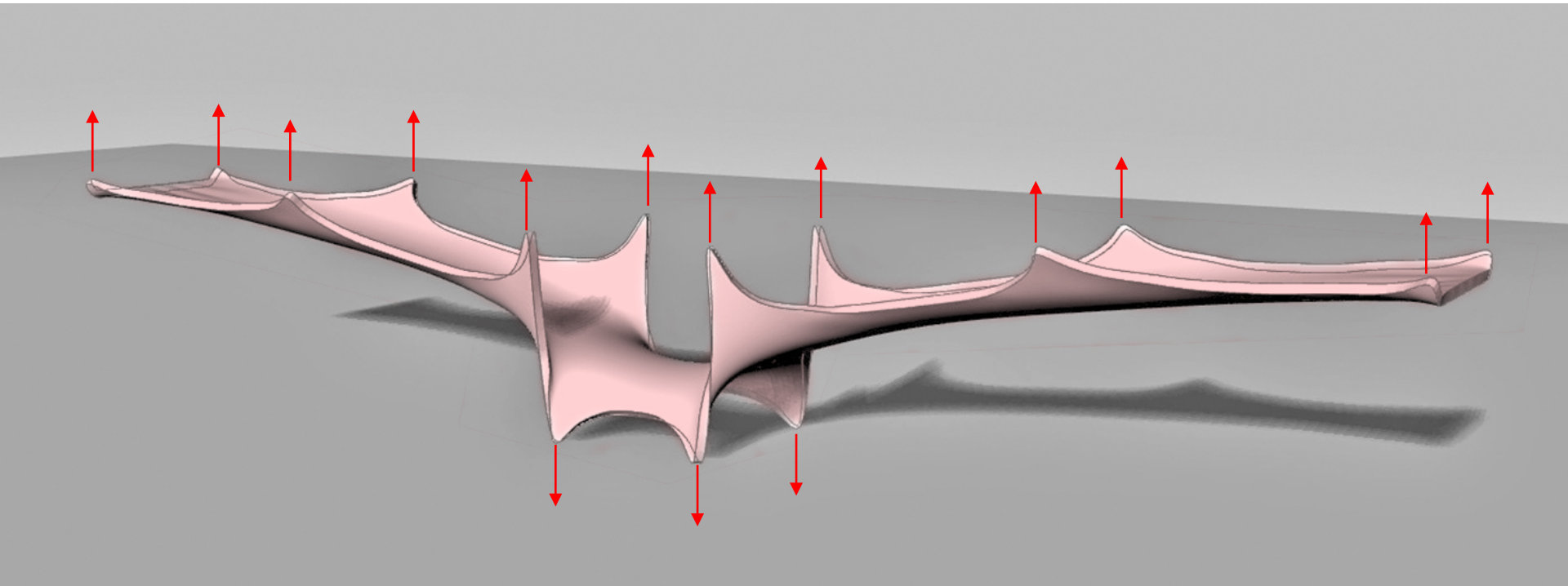


# Principle of Duality



Sergio Musmeci: membrane model of bridge  
Potenza, Italy, 1975

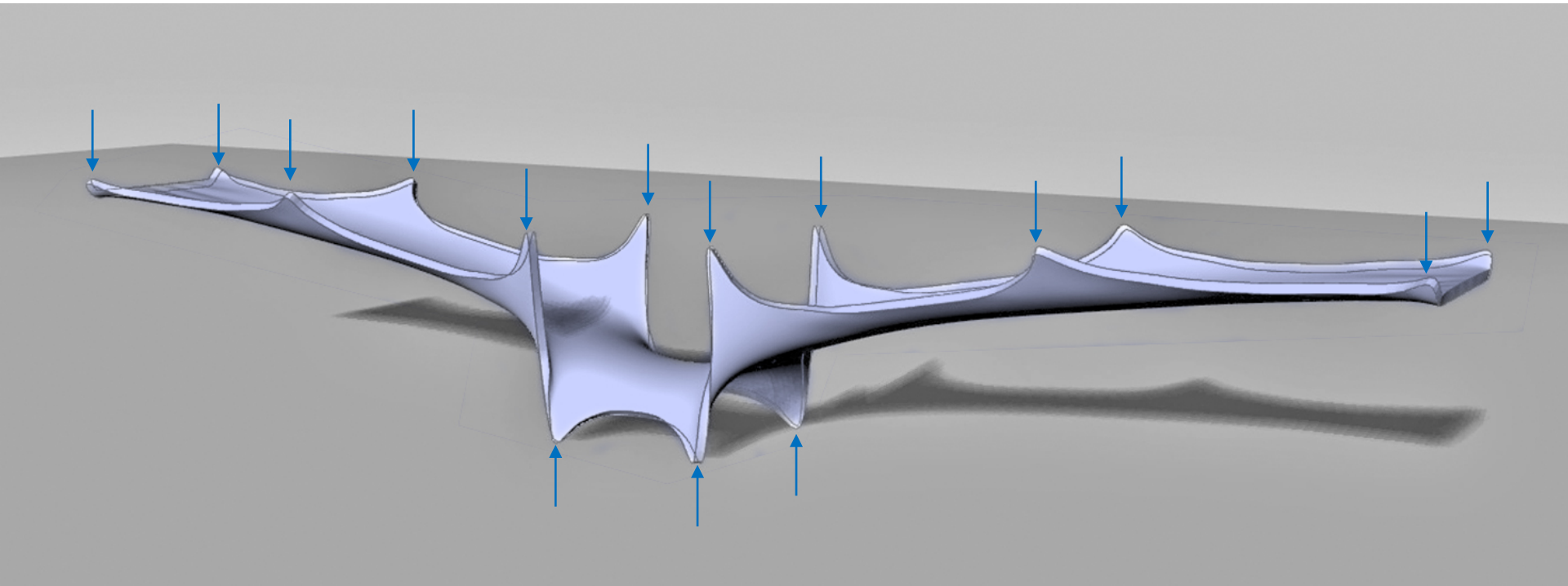
# Principle of Duality



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# Principle of Duality



Sergio Musmeci: membrane model of bridge  
Potenza, Italy, 1975



# Principle of Duality



Sergio Musmeci: Basento Bridge  
Potenza, Italy, 1975



# Principle of Duality



Sergio Musmeci: Basento Bridge  
Potenza, Italy, 1975



# Principle of Duality



Sergio Musmeci: Basento Bridge  
Potenza, Italy, 1975



## principle of duality

cable & arch

same geometric logic

different structural behaviour

bracing

design of arches

vault

membrane

## ARK-A3001 Design of Structures\_Basics Principle of Duality

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## Exercise 3.1

The design for the proposed New Norcia Cathedral in Perth by Pier Luigi Nervi was based on a modern interpretation of traditional vaulting techniques. Develop a three-dimensional model of the vaulting in Rhino and add the inner force flow into the model using density of lines as indicator of the magnitude of the inner forces (compare lecture, slide 20)



Pier Luigi Nervi: New Norcia Cathedral  
Perth, Australia, 1955



## Exercise 3.2

Construct a simple sectional drawing of the façade and use location and force plan to discuss the function and shape of the bracing visible in the Airside Center at the Zürich Airport.



Grimshaw Architects: Airside Center  
Zurich Airport, Switzerland, 2003