Prestressed Stone Panels: La Sagrada Familia

MICRO PROJECT

SCIENCE AND ENGINEERING OF NATURAL STONES AND GLASS

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Supervisor: Tim Wagner

Basílica de la Sagrada Família

by Antonio Gaudi
Barcelona, Spain

- “Catalan Modernisme”: combining Gothic and Art Nouveau
- Gaudi’s Goal: creating a visual representation of Christian beliefs
- UNESCO World Heritage Site
- Over 4.5 million tourists per year (2017)
- Construction begin: 1882 (ongoing)

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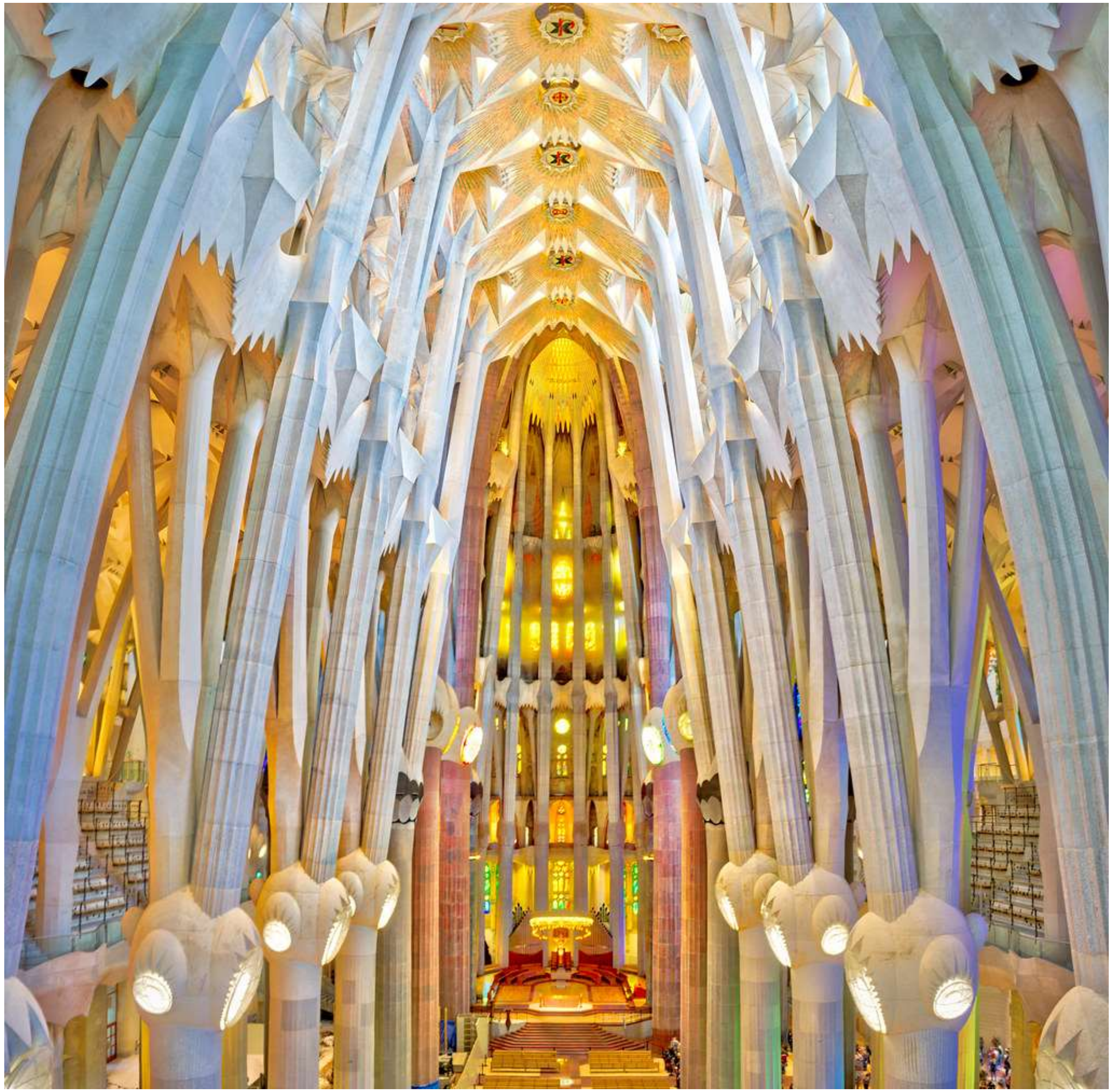
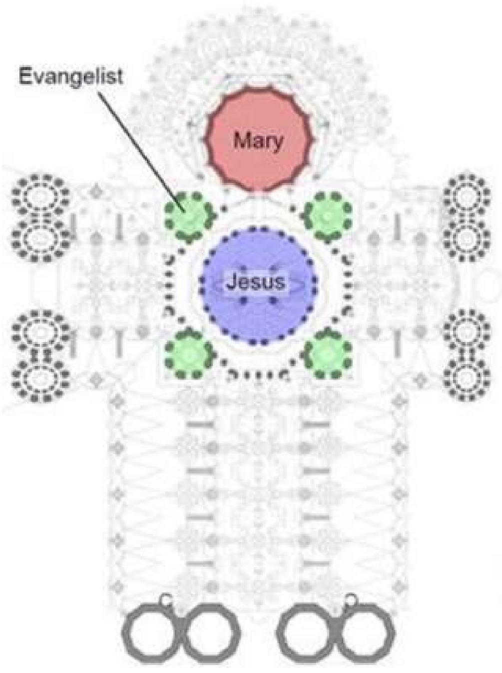
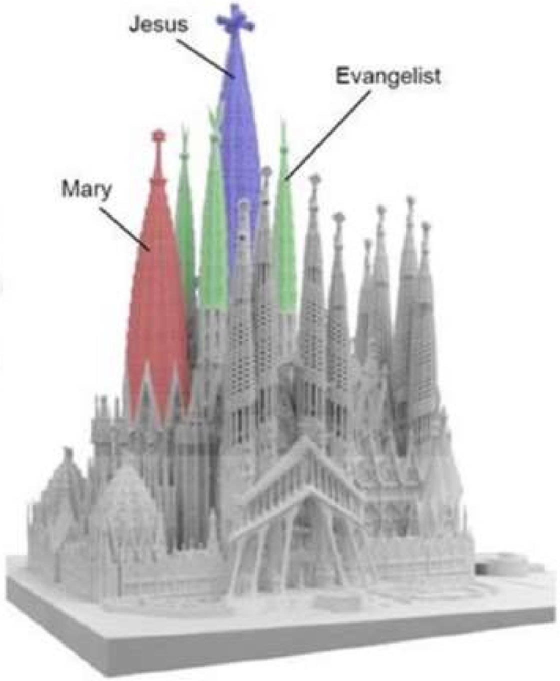


The Project Today

- Main Involved Companies: Basílica de la Sagrada Família; Arup; BMF Consulting
- Planning and Construction of the remaining 6 towers
- Largest Tower: 90 m
- Making it the largest Church in the World: 172,5 m total height
- Project requirements:
  - Overtake Gaudi's vision
  - Stone surface from the in- and outside
  - Major constraint: limited load capacity of the supports



Plan view



3D view

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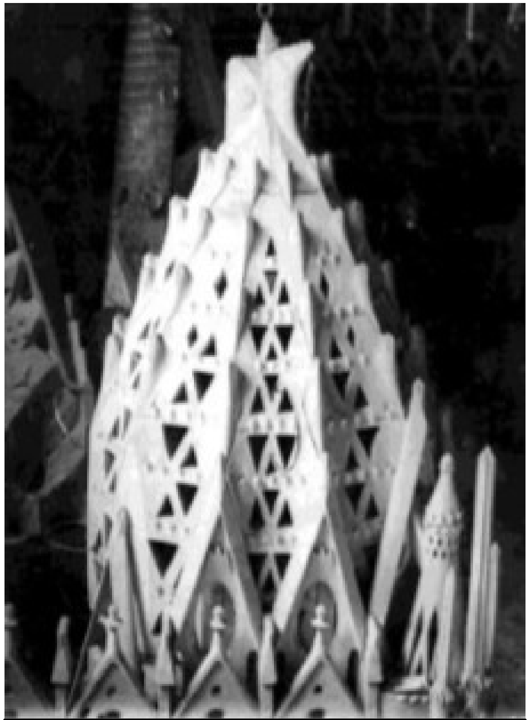


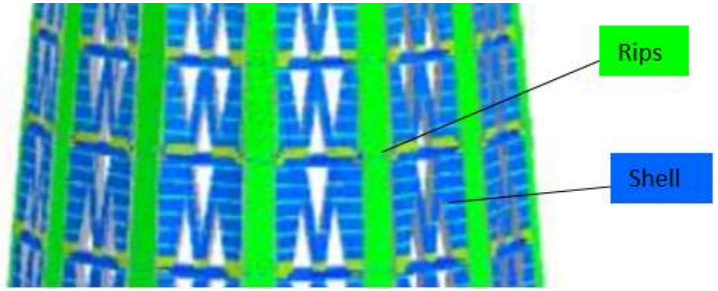
1:25 plaster model built by Antonio Gaudi

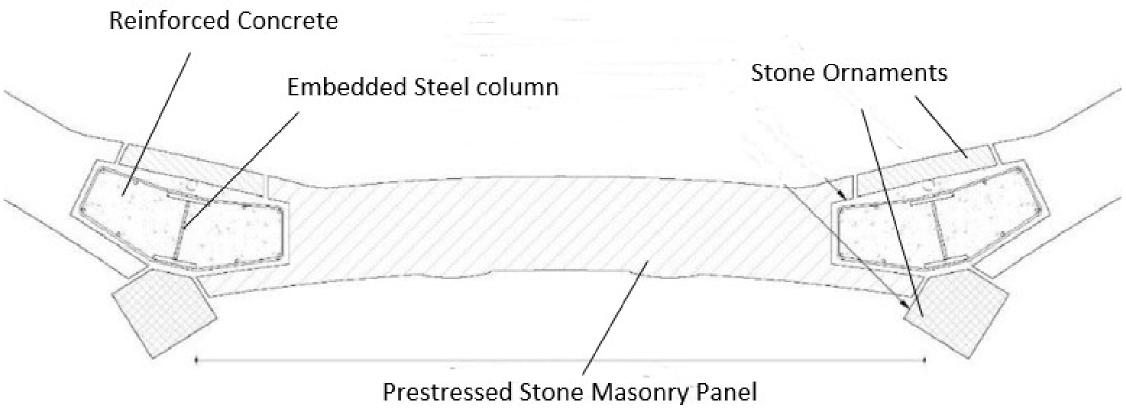
Content

Mary Structural model

The Structural Concept: Prestressed Stone Masonry composite shell

- **Shell:** Prestressed Masonry Stone Panels
- **Rips:** Reinforced Concrete with embedded steel column with
- **Stone ornaments:** stone masonry



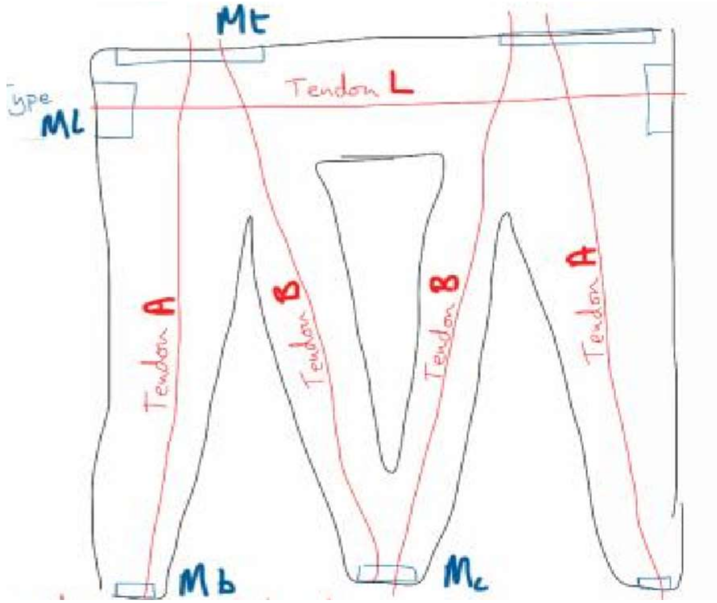


Prestressed Stone Masonry Panel

- Steel tendons are tensioned

  → compress stone masonry

Steel Tendons Arrangement



Prestressed Stone Masonry Panel

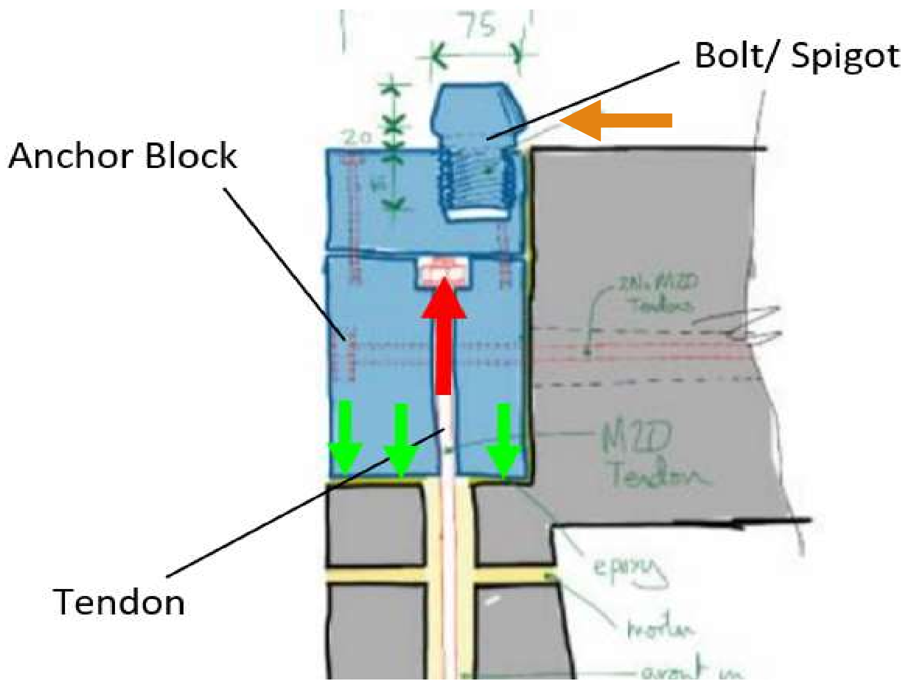
- Steel tendons are **tensioned**

  → **compresses** stone masonry

- Anchor Blocks: distribute tension force from tendon into stone, without local overstressing

- Bolts: Provide horizontal **shear** resistance between two panels

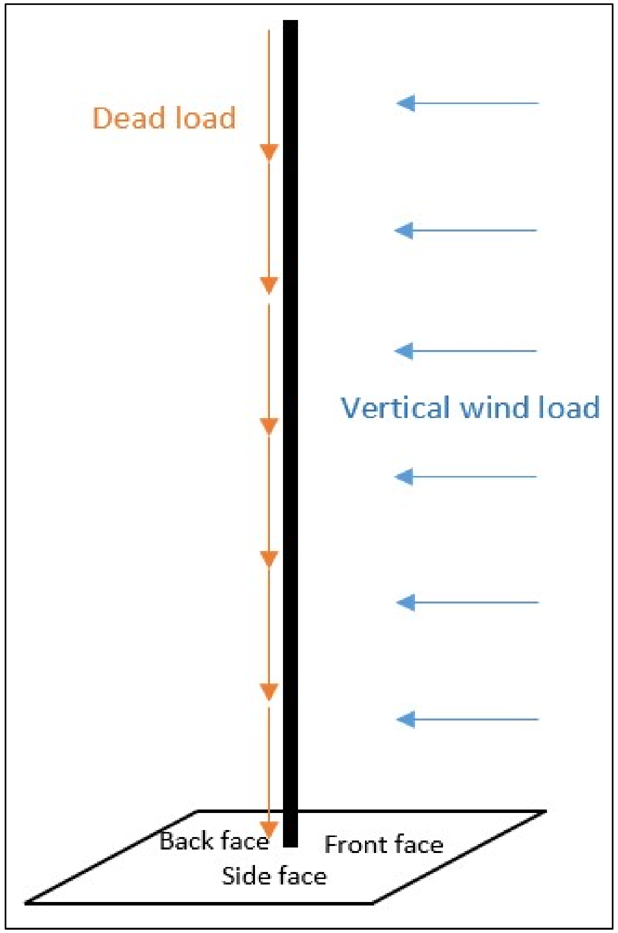
Anchor block Detail with bolt



Structural Analysis

WITHOUT PRESTRESSING

Critical Load Case: Wind and Dead Load



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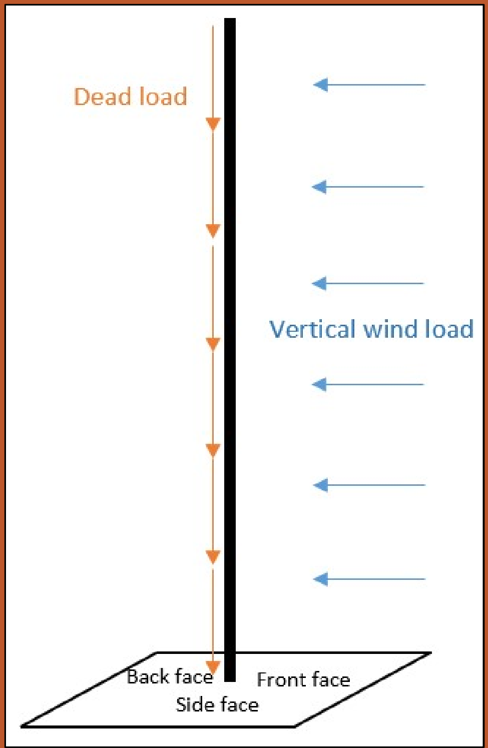
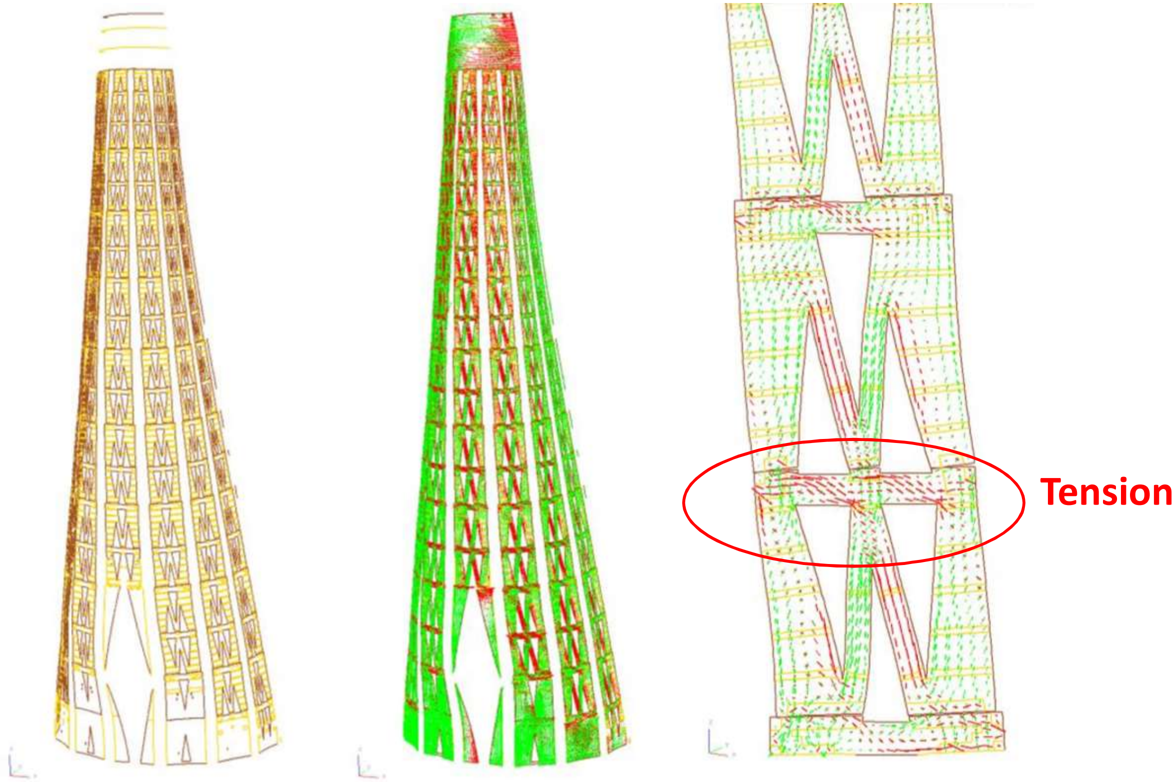


Global Normal Force

- transferred from panel to panel down the shell in compression
- Mathematically derived curvature (not funicular) → hoop tension

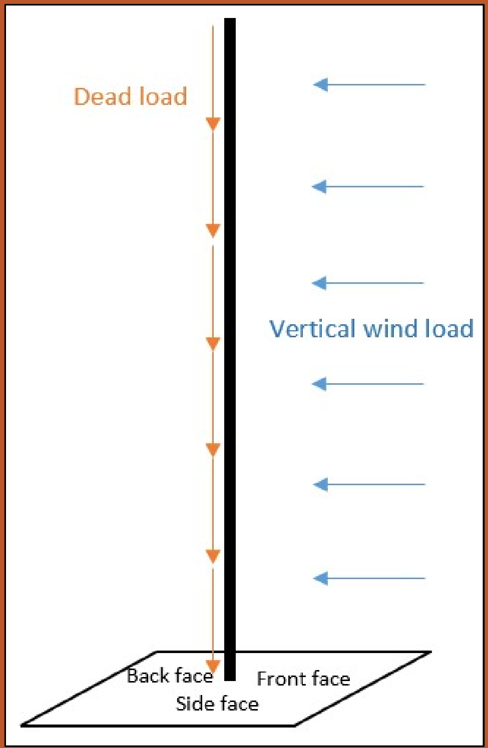


Deflected shape   Principal Stresses   Principal Stresses

Structural Analysis

Critical Load Case: Wind and Dead Load

WITHOUT PRESTRESSING



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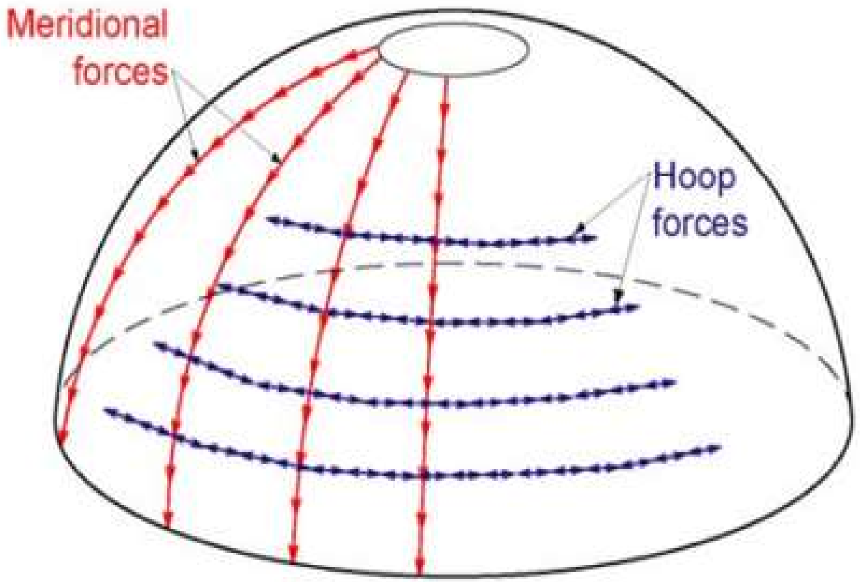

Structural Analysis

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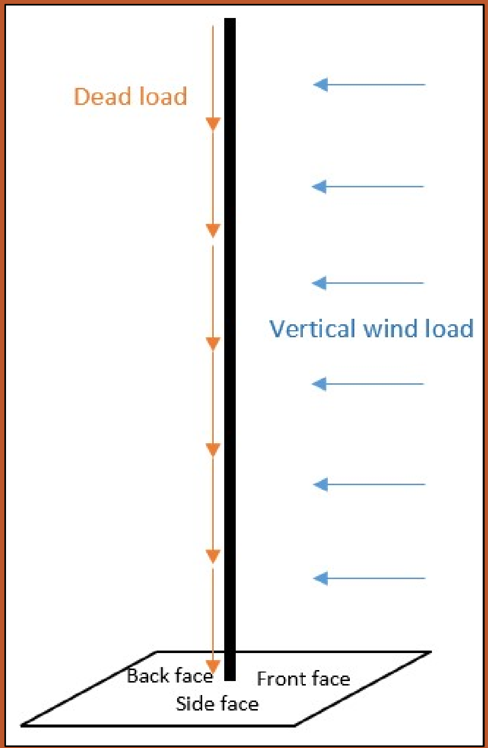
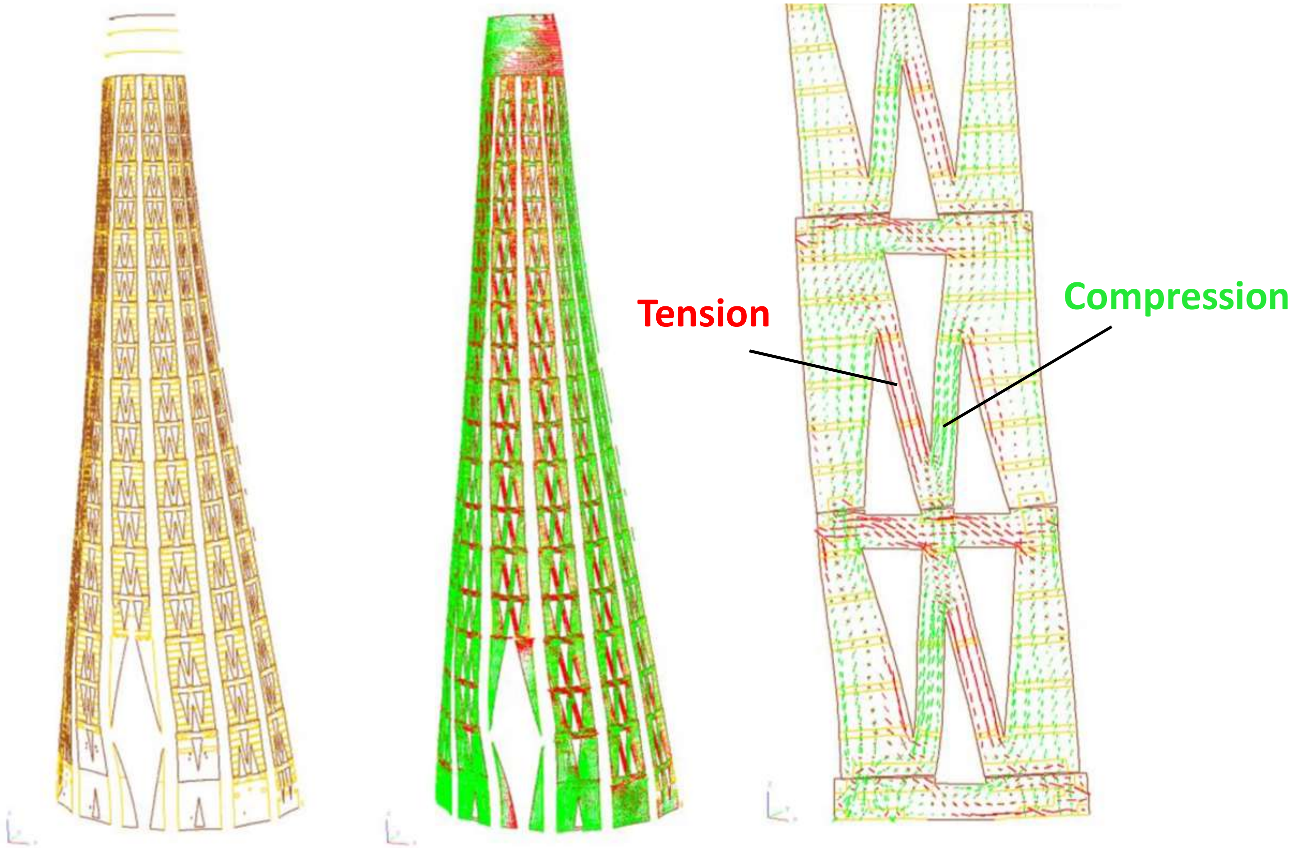


Global Shear

→ resisted locally by compression and tension in the inclined mullions



Deflected shape   Principal Stresses   Principal Stresses

Functionality of Prestressing

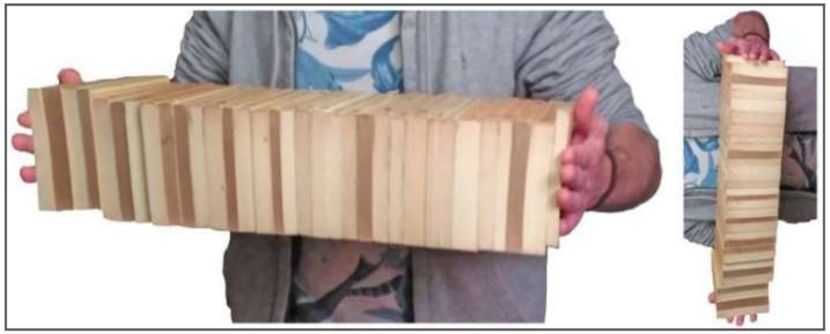
- Un-prestressed Masonry has low tensile strength

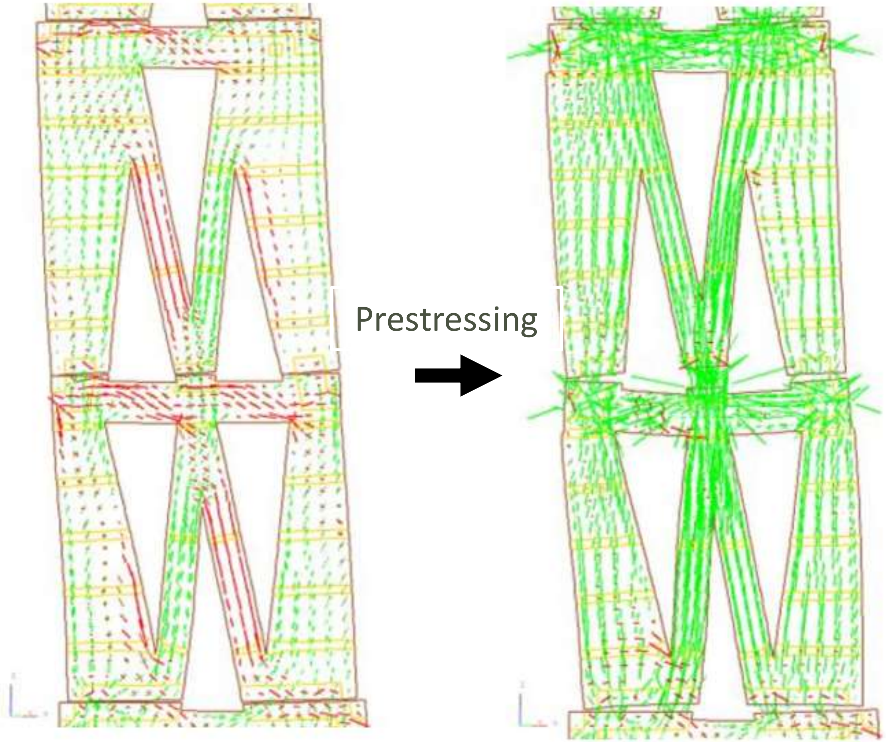
  → insufficient capacity to carry the tensile stresses

- high prestress forces, so all tensile stresses can be compensated

  → Pure Compression state

  →increase in shear strength





Un-Prestressed Masonry   Prestressed Masonry

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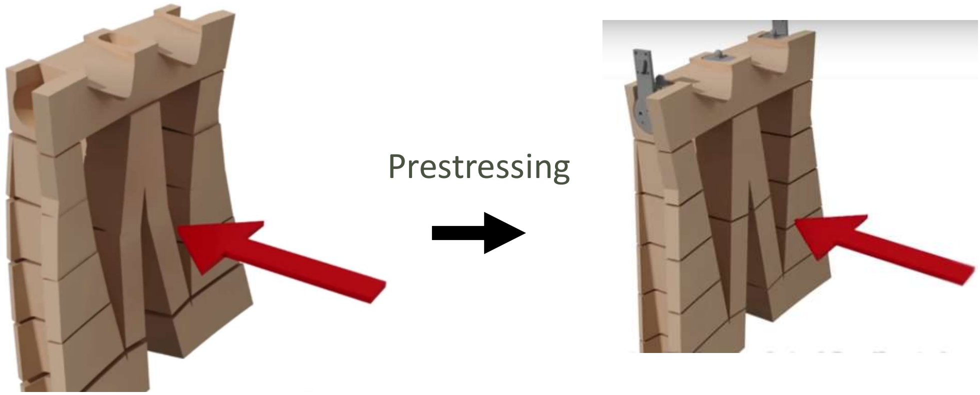


Un-Prestressed Masonry   Prestressed Masonry

Material: Natural Stone

- Primary load bearing structure

  → high strength and durability requirements

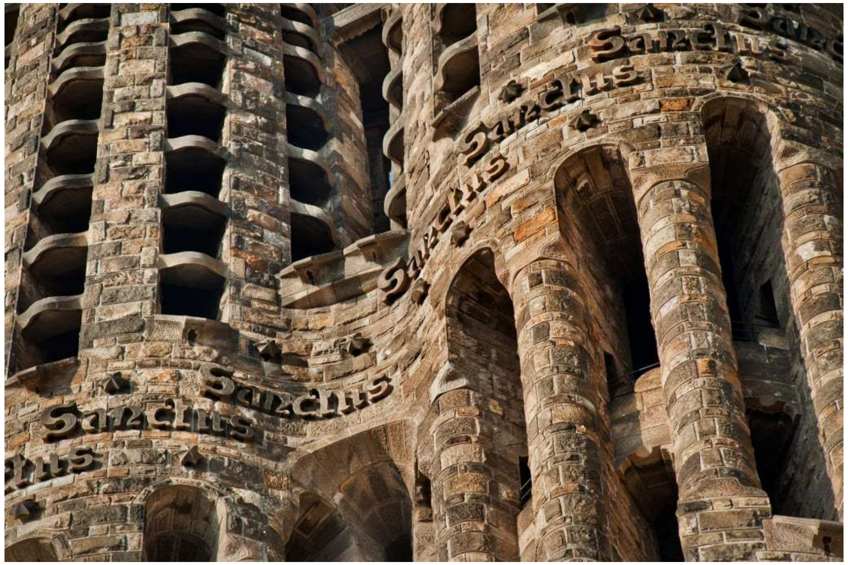
Montjuïc stone

- siliceous sandstone
- Grains: high Quartz content
- Matrix: high content of silica

  → strong pure silica tetrahedral bonds

  → High durability

Quarries closed (since 1970s)



Search for new suitable Stone

- Requirements:

Enough strength	high Durability	Visual Match	Availability of large Volume

→ To find sandstone that fulfils all of the mentioned criteria turned out to be very difficult

→ **Bottleneck of the construction**

Solution: Toasted fine-grain granites

- granite differs from its genetic standpoint
- chemically and aesthetically nearly identical to the Montjuïc stone

Enough strength ✓

high Durability ✓

Visual Match ✓

Availability of large Volume

→ suitable granites and sandstone was taken from many different quarries

«Toasted» Granite:

Granite with quartz grains of orange/brown appearance

Used Sandstone and Granite types and their quarries

Sandstone:

Beige inglés (Inglaterra)
Piedra de Cantabria (Cantabria)
Blavozy (Francia)
Montjuïc (Cataluña)
Clashac (Escocia)
St. Vicenç de Castellet (Cataluña)
Floresta (Cataluña)

Granite:

Moreno Ingemar (Galicia)
Gudiña (Galicia)
Quintana (Extremadura)
Azul Bahía (Brasil)
Pórfido (Irán)
Blanco Cristal (Madrid)
Tarn (Francia)
Basalto (Cataluña-Italia)

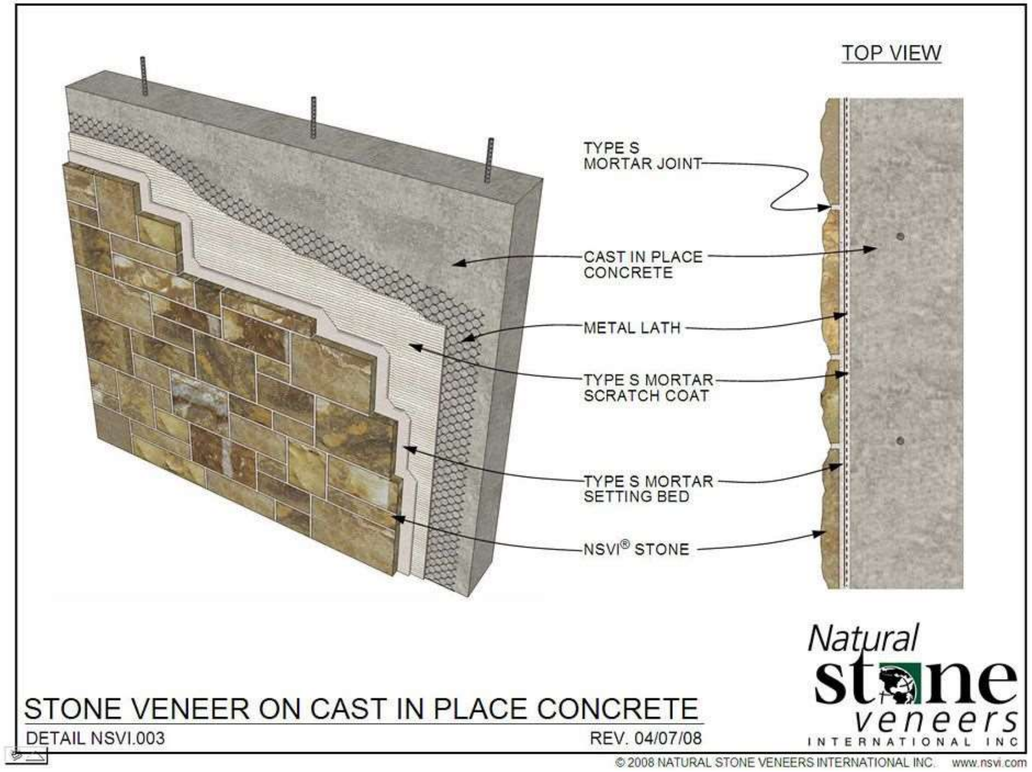
Alternative Method

Reinforced concrete structure with stone facings

- Reinforced concrete: load bearing structure
- Stone facing = architecture purpose

→increases the weight by the **factor of 2**

Too heavy for historic church



Prestressed Stone Masonry

ADVANTAGES

- Stone
  - Is Primary load bearing structure
  - Provides aspired visual stone surface
- Efficient Material usage
- Weight is within load limit of historic supports
- Prefabrication of panels
  - Acceleration of construction
  - Safer construction method
- Stone production is not energy intensive

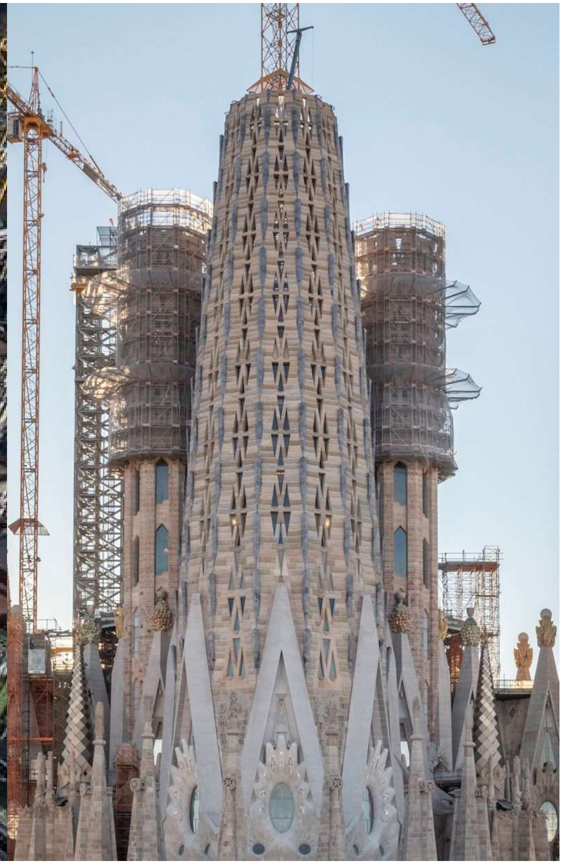
DISADVANTAGES

- Novel and rarely used method → increases planning time (testing, approvals)
- Stone is a naturally processed material → uncertainty in mechanical behavior → testing required
- Suitable Stone is hard to find -> expensive
- High CO2 Emission by transportation

Conclusion

The method was suitable for the projects goal to build the church after Antonio Gaudi's vision and to create a visual representation of Christian beliefs. Both architectural and statical constraints could be met, but it required a big budget, a lot of time, effort and resources.

Questions?



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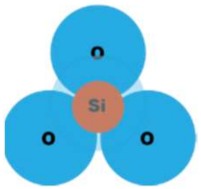
Back-Up Slide 1: Durability comparison

QUARTZ

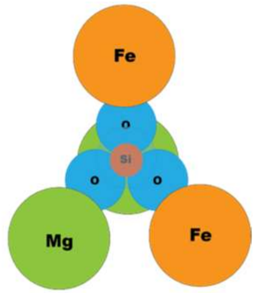
- contains pure silica tetrahedra
- each tetrahedron shares all its oxygen with other SiO_4 tetrahedra



→ forms a strong three-dimensional framework (covalent bonding)

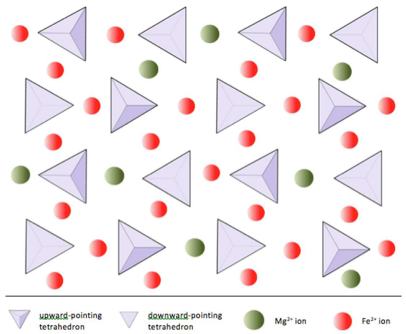
OLIVIN

- silicate tetrahedra are isolated from each other by metallic cations (such as Iron and Magnesium)



- weaker bond between the individual silica tetrahedrons and a cation

→ easily destroyed by water molecules



→olivine being much more susceptible to weathering than quartz

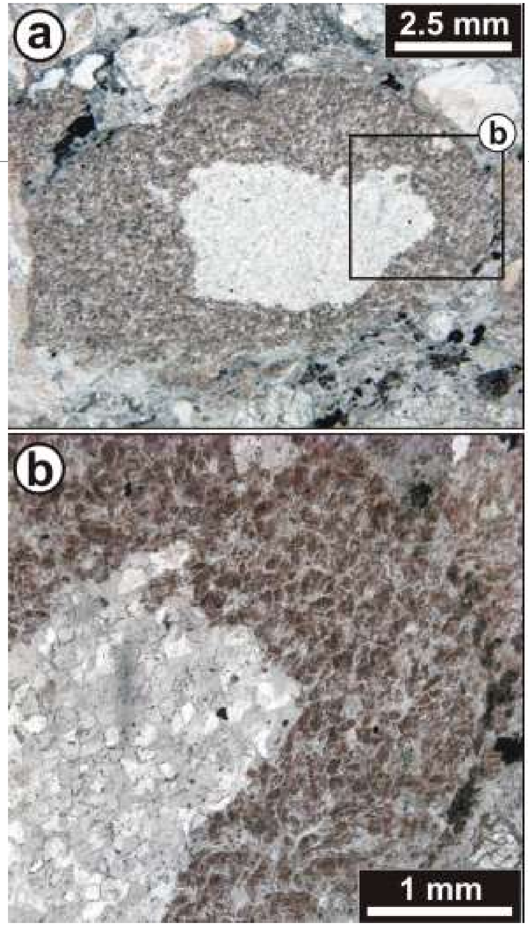
Back-Up Slide 2:Constructing one Panel

- Ashlar masonry is built using a jig
- Post-Tensioning-Technique: after the mortar reached a essential minimum strength
- Prestressed both in horizontal and vertical direction
- Prefabrication of Panels of-site and on ground level

Back-Up Slide 3: Toasted Quartz

= quartz grains of orange-brown to grayish-reddish brown appearance

which has been so far only reported in rocks affected by shock metamorphism [3, 4], is possibly related to post-shock temperatures, but the exact formation mechanism for “toasted” quartz is still unresolved.



Back-Up Slide 4: Vierendeel Bending of an Beam with an opening

In a beam with a web opening, the cross-section on the opening zone is composed by two “T” sections (top and bottom), and the shear transfer occurs by Vierendeel bending of the T-sections at the four corners of the opening. This phenomenon is exemplified in the figure.