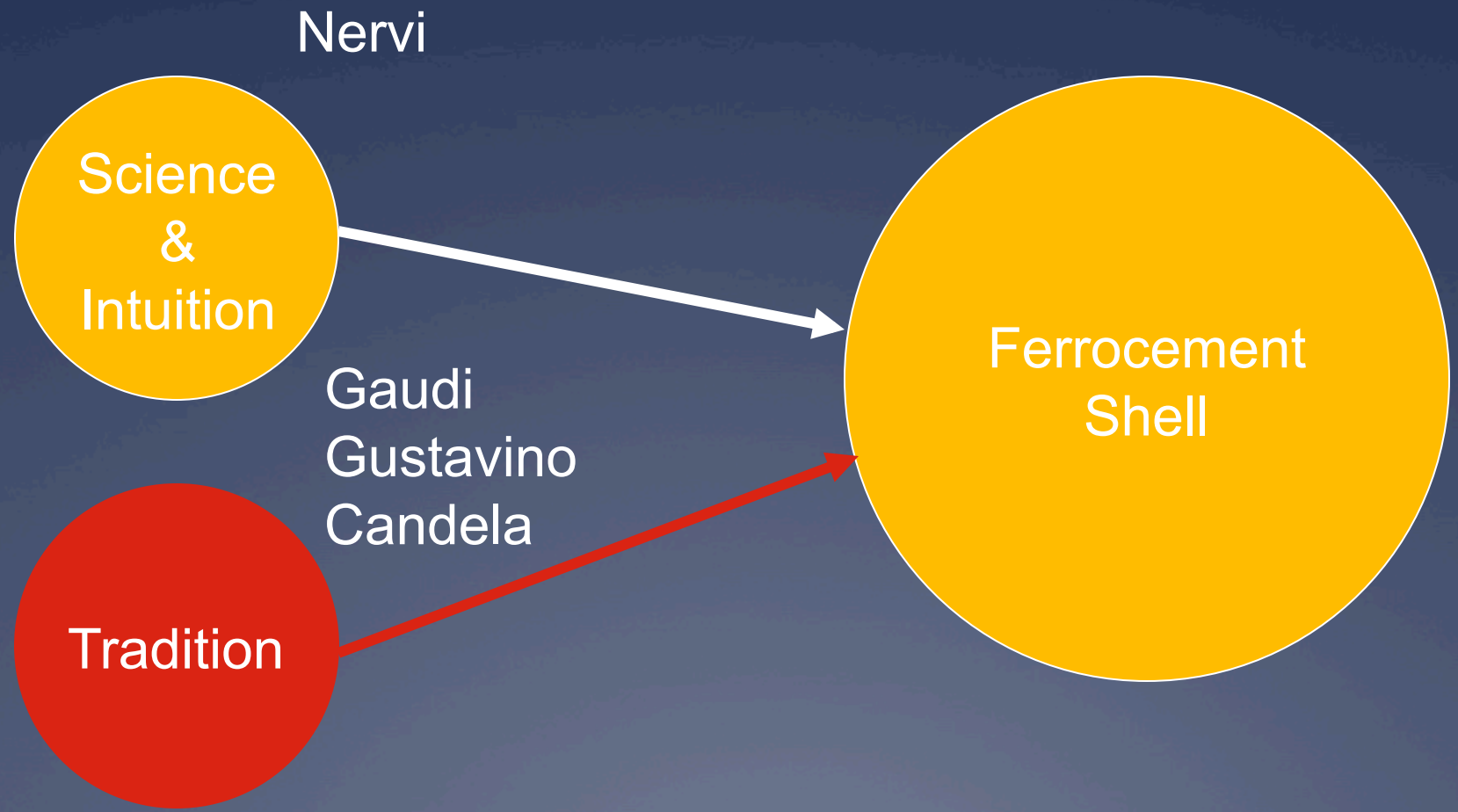
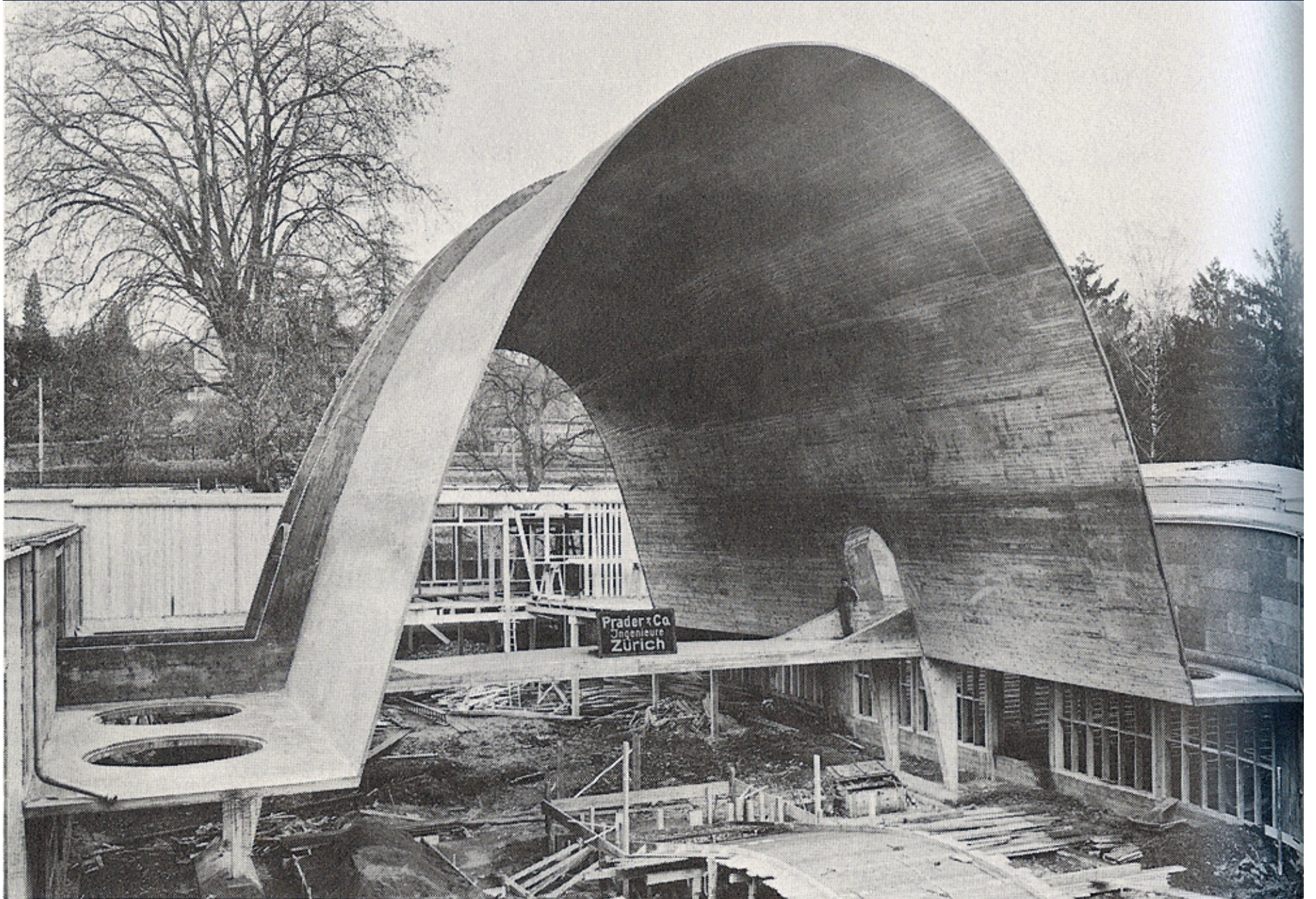


Masters of the Shell₂

The Timbrel Vault and
the road to Candela

Two paths to the shell









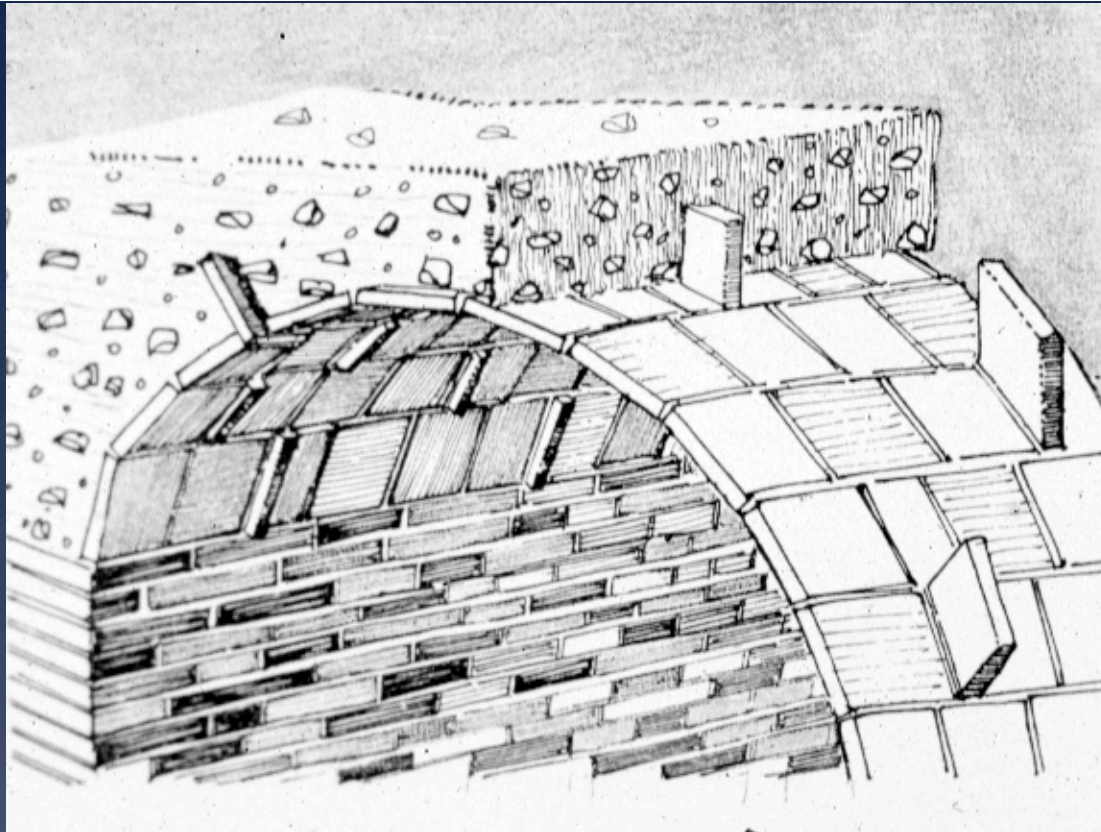


The Autonomous Community of Catalonia

- *Home of
 - *Antonio Gaudi
 - *Salvador Dali
 - *Joan Miro
 - *Junipero Serra
 - *Jose Luis Sert

Catalonia: Spanning with thin tile shells





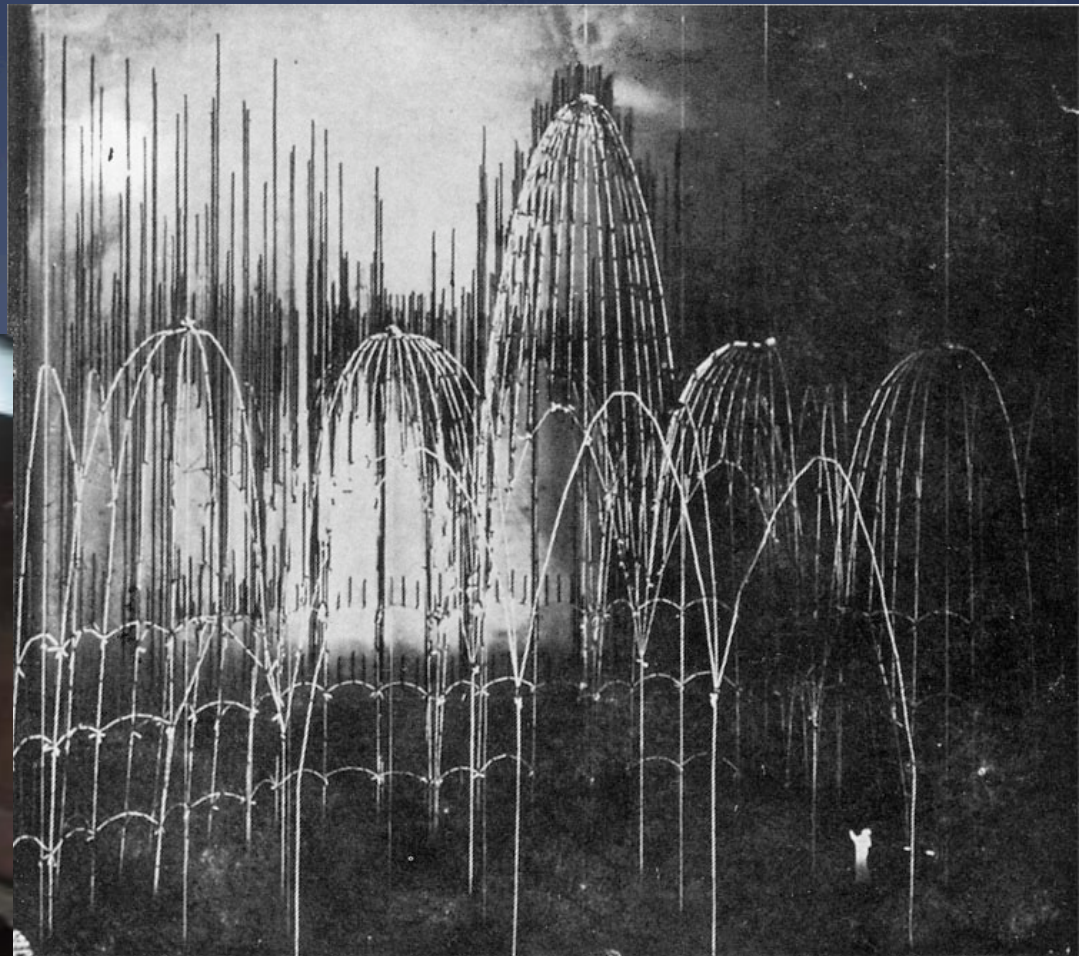
This Roman arch used thin tiles as formwork for concrete mass above. The projecting tiles acted as ties, connecting the concrete to the tile...so was the thin shell just an extension of this tile arch technique?

This is very similar to the 1" thick tile vaults found in subways, and churches built through the 1930's by the Rafael Gustavino Company of New York. Gustavino's vaults were commonly used for ceilings in large spaces and could span up to 60 feet carrying 400 lbs per s.f.!

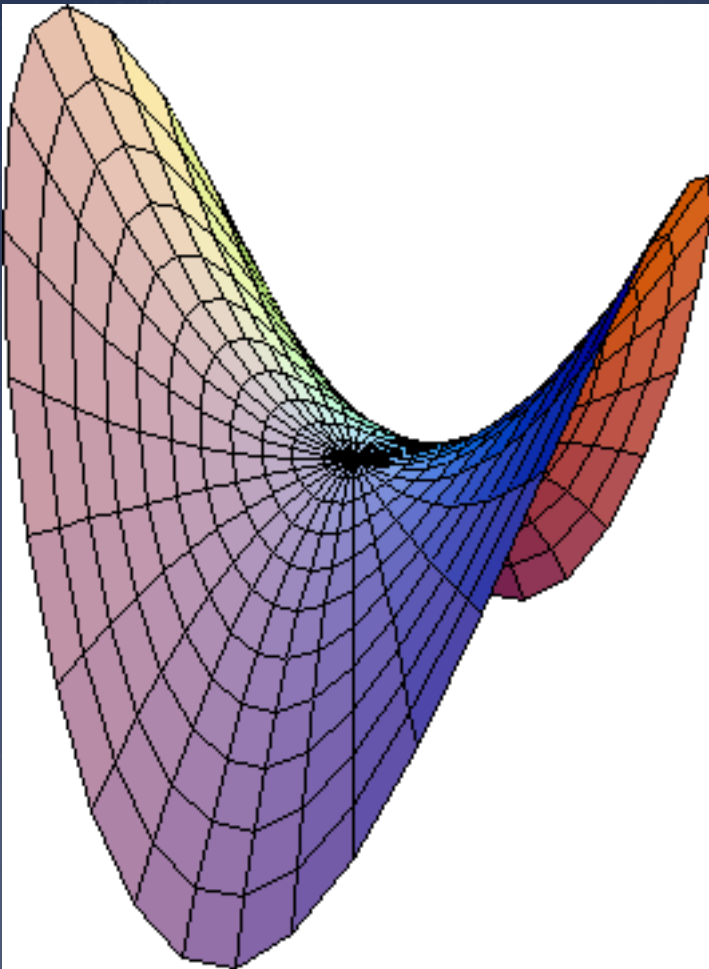
Antonio Gaudi

Design-Build

- * Guell Chapel
1908
- * Stereostatic
models of forces

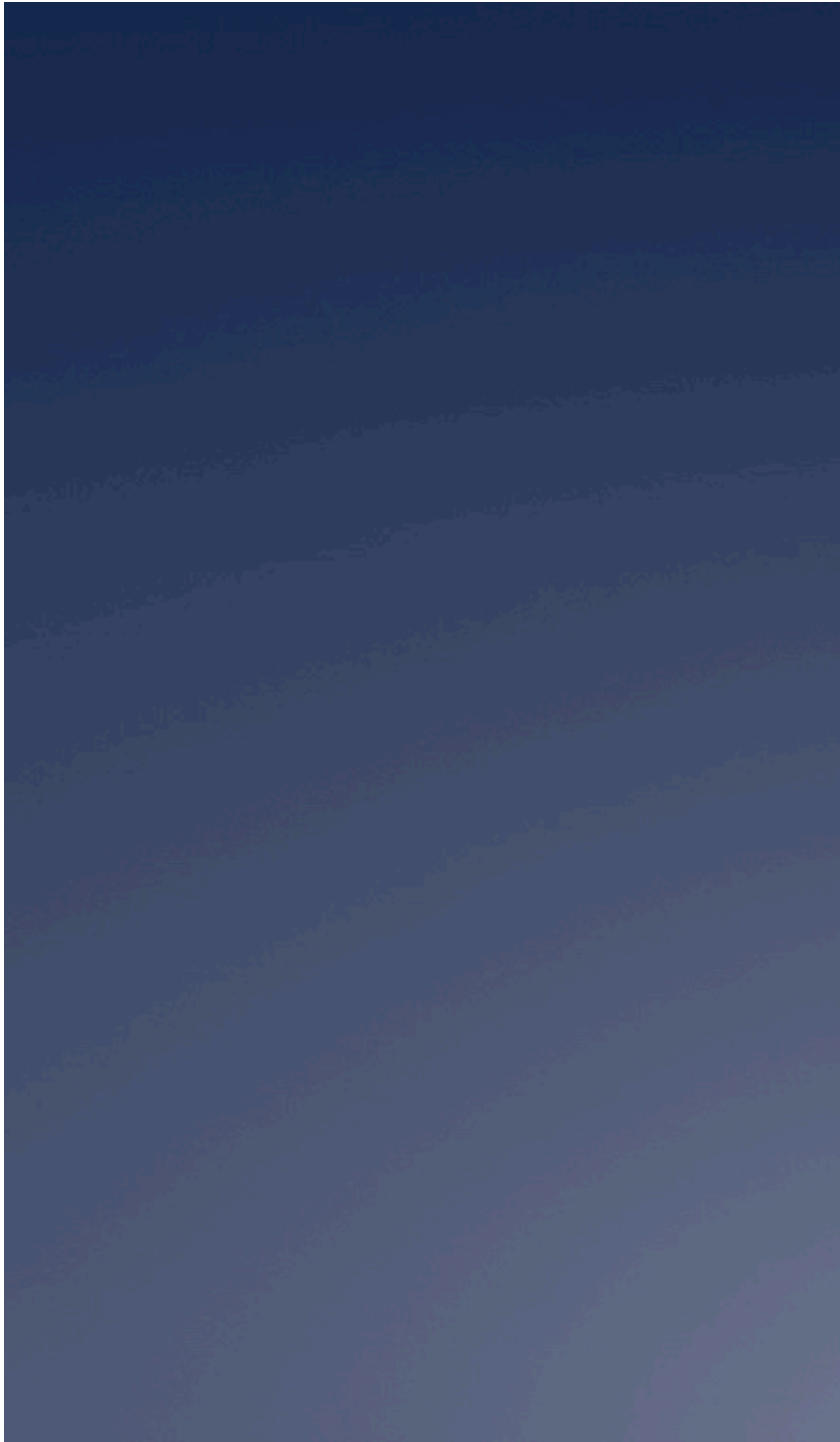


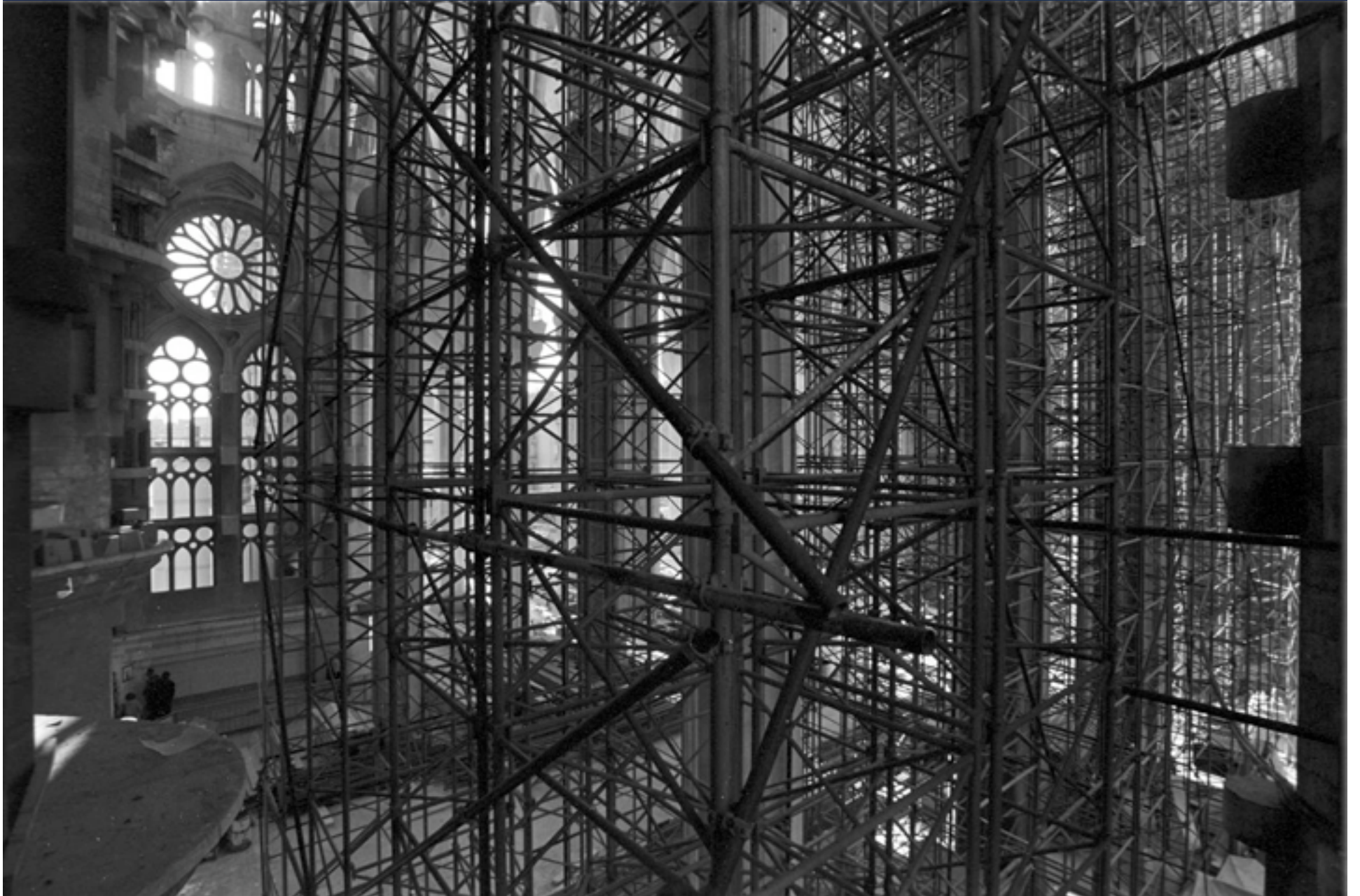
Gaudi (like Vladimir Shukov) finds
Saddle shapes,
give strength in two
directions



Hyperbolic paraboloid: a doubly-ruled surface

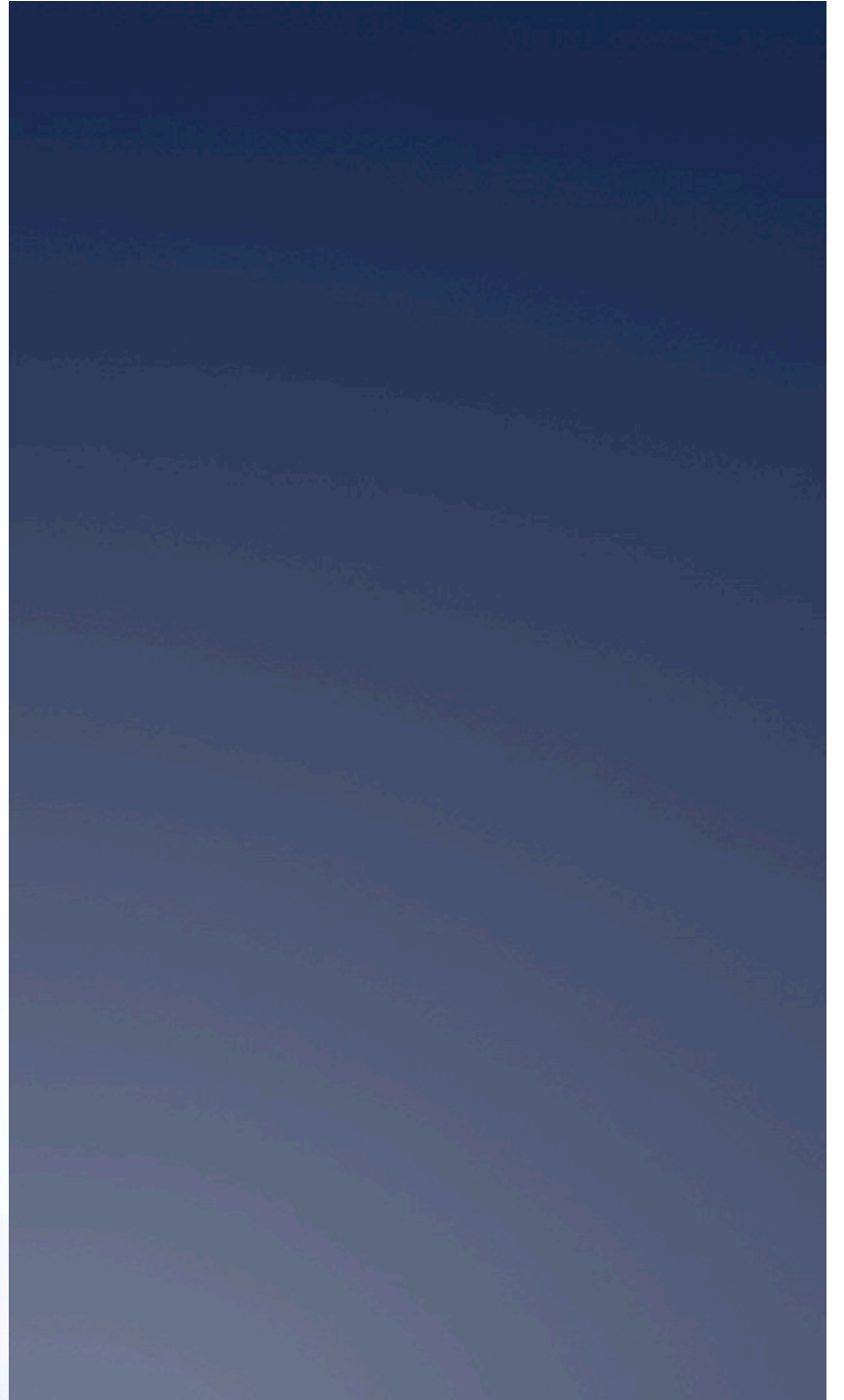


















Change requires innovation

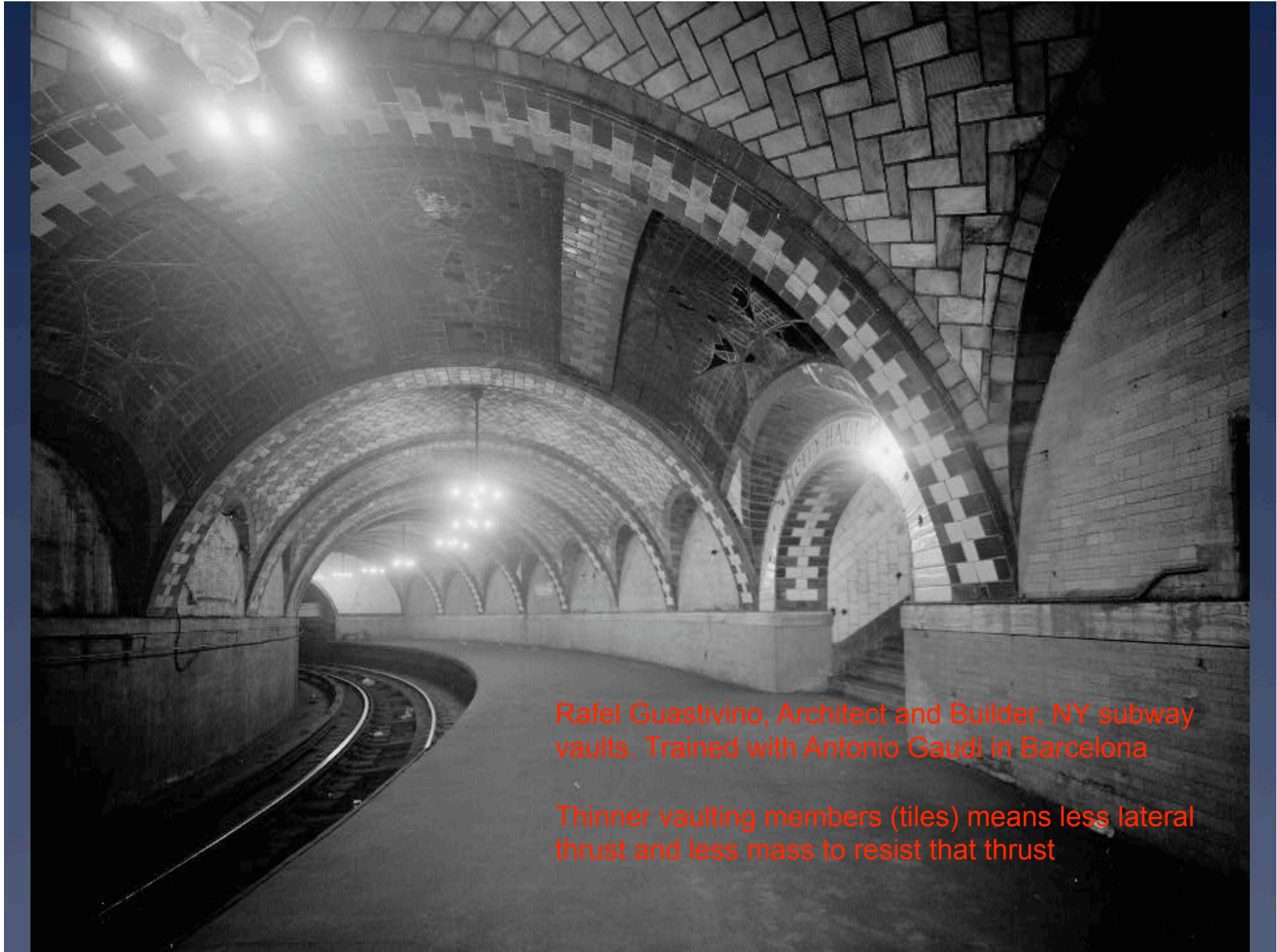


● Rafael Gustavino
Builder at the
Boston Public
Library
construction site

Charles McKim designs
this first “free” lending
library built by a major
American City.

Needs to house
700,000 volumes in
changing configurations

Needs flexible space
not cast iron columns



Rafel Guastivino, Architect and Builder, NY subway vaults. Trained with Antonio Gaudi in Barcelona

Thinner vaulting members (tiles) means less lateral thrust and less mass to resist that thrust



Timbrel loosely translates to Tambourine

- * Laminated tile at edge, single tile in center



Gustavino Patents...tradition?

947,177.

APPLICATION FILED JULY 31, 1904.

Patented Jan. 18, 1910.

2 SHEETS—SHEET 1.

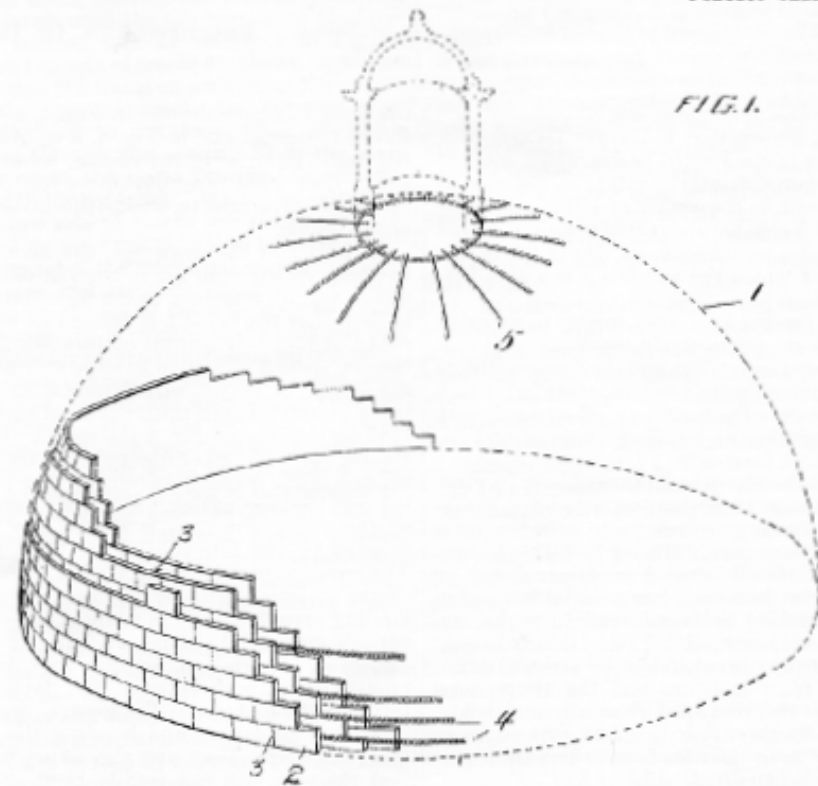
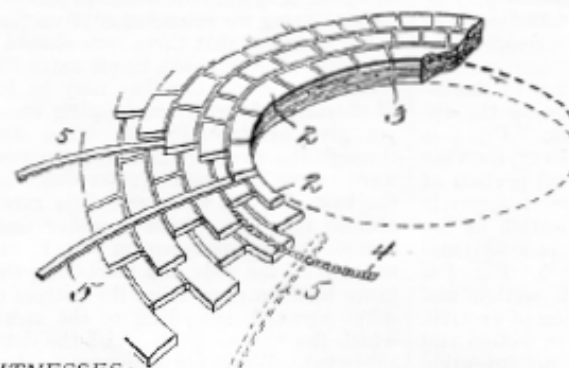


FIG. 2.



WITNESSES.

M. F. Keyler.
D. C. Praddock.

INVENTOR

Rafael Gustavino

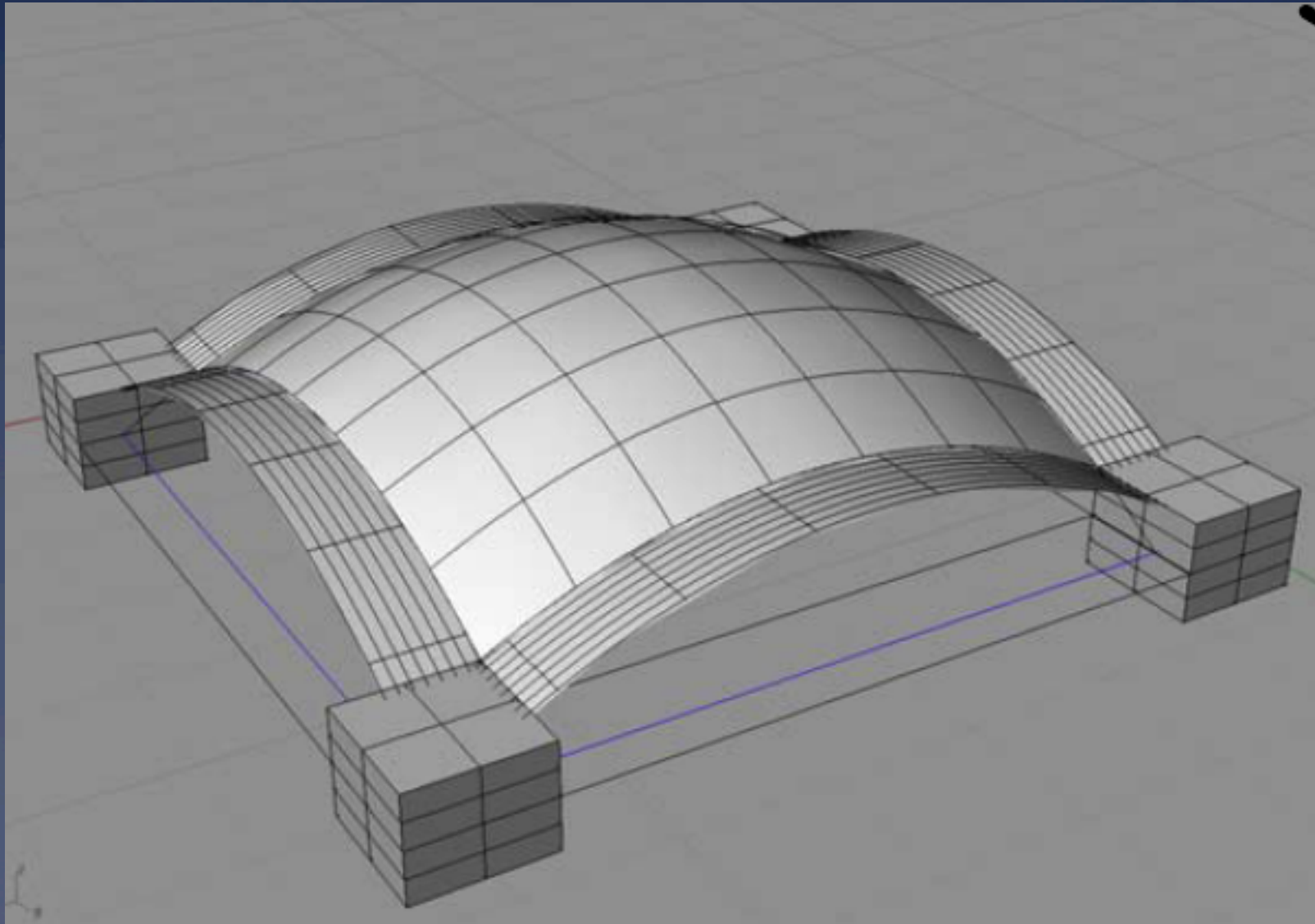
BY

Henry M. Brigham
Attorney

MIT, research by building



Computer Analysis first ... this IS MIT afterall...



Build perimeter arch centering



Soak



Mix plaster of Paris





Butter the
tile

Two laminations at edge arches





Lamination
at 90
degrees to
substrate

Perimeter arches first



Single layer infill, butter, place, hold and it sticks!



Groin forms for guides, not structural support



All done



From below





$6 \times 6 = 36 \text{ s.f.}$

8 people at 130 lbs =
1,040 pounds

$1040/36 = 28 \text{ psf}$

...probably more like
65 psf as the people
are standing in the
middle 4 feet

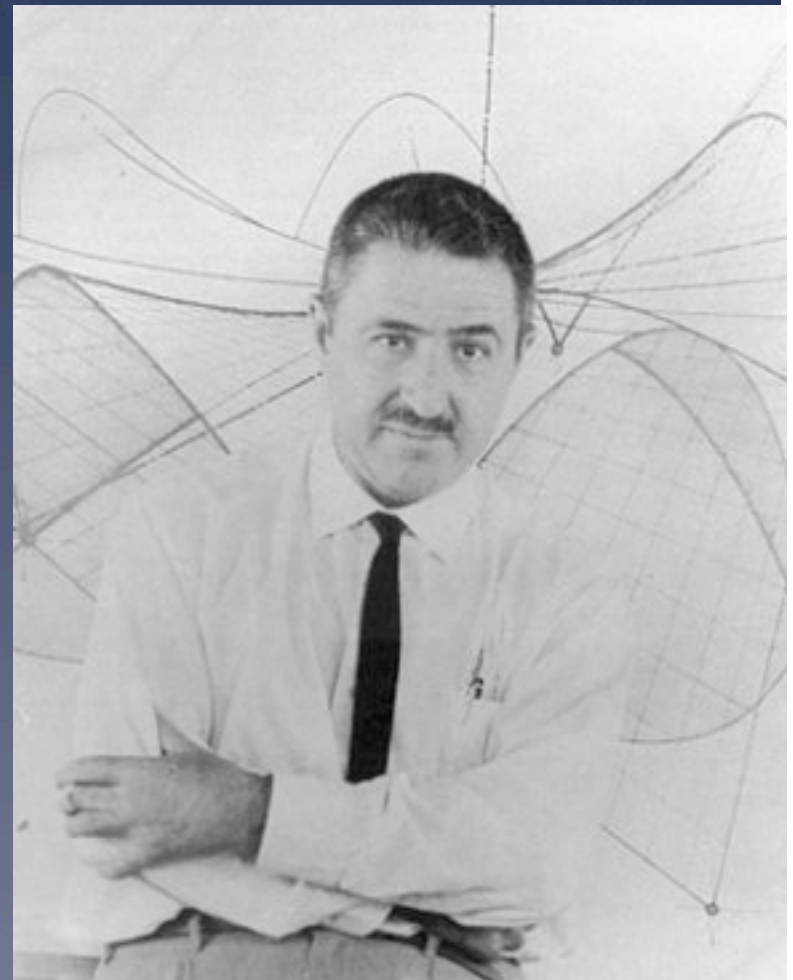
not bad for some tile,
plaster and unskilled
masons working one
weekend

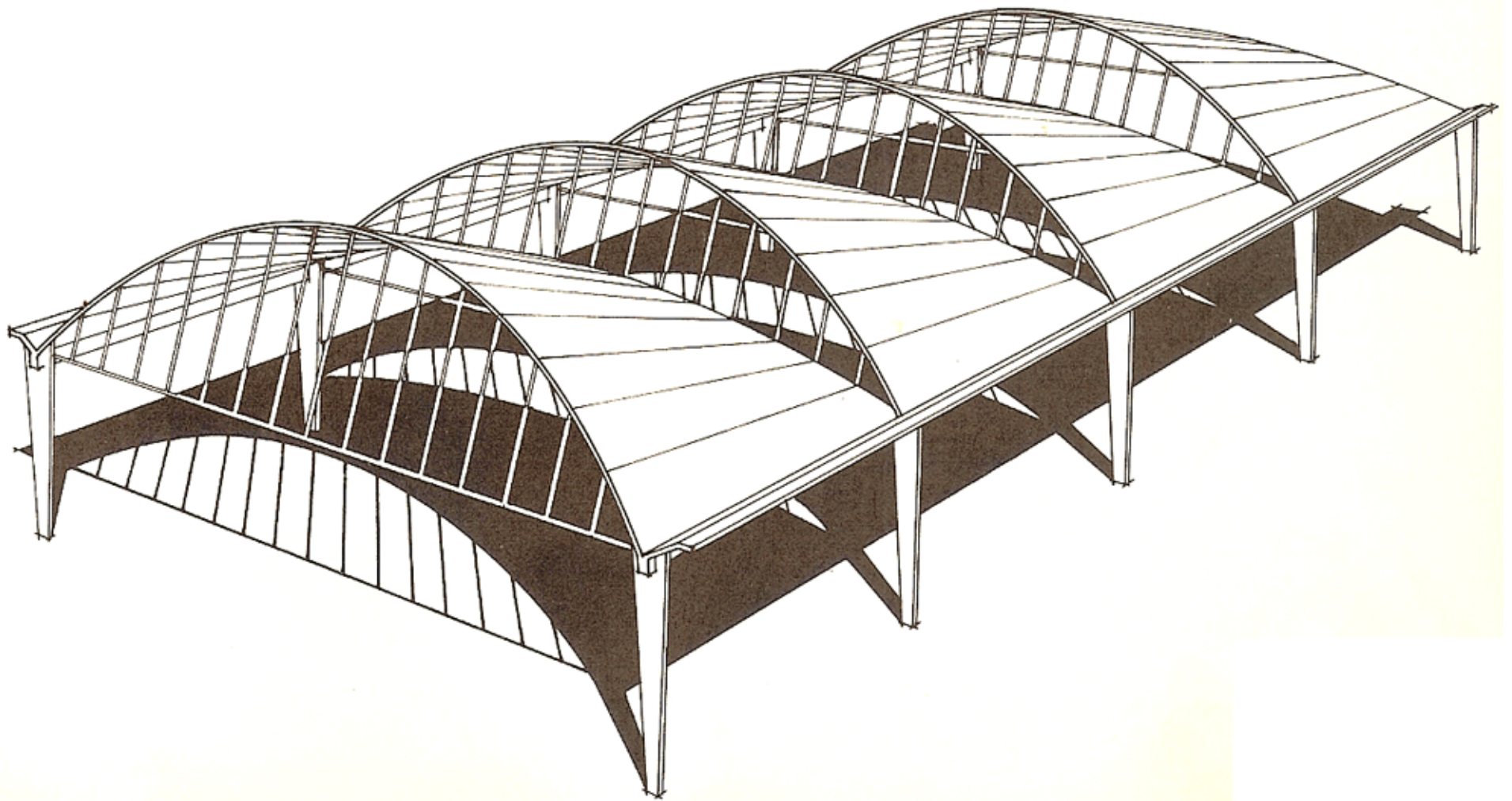
So Gaudi, teaches Gustavino

- * Gustavino, the builder, shows architects and engineers what thin tile vaults and domes can do in Boston, New York & Chicago in the late 1800's / early 1900's
- * Maillart and Nervi set the standard for minimal material, maximum efficiency in the 1920's through the 1940's
- * That sets the stage for Felix Candela (1910-1997)

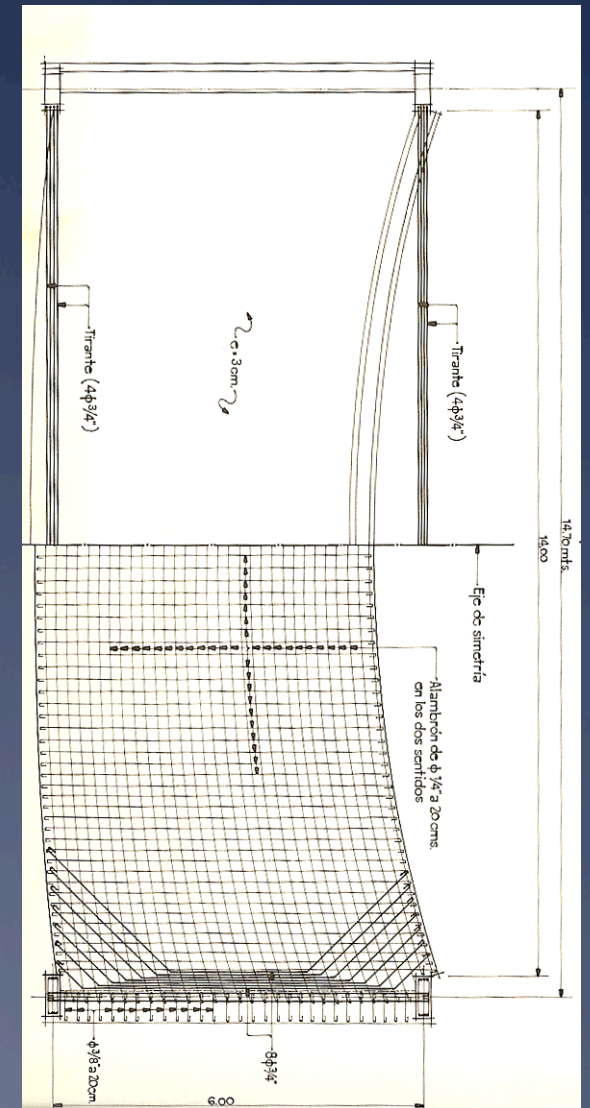
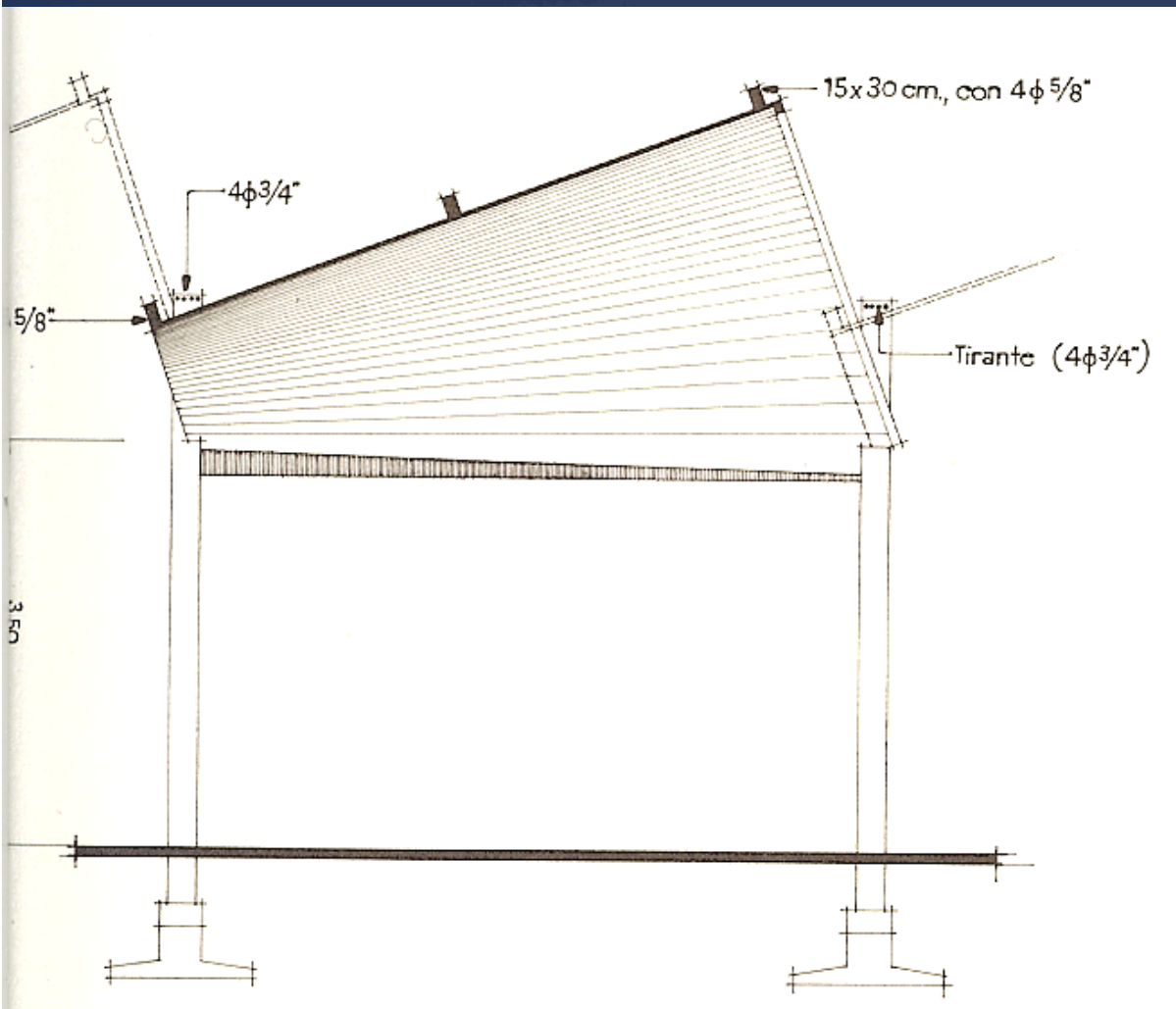
Felix Candela

- * Born in Spain, 1910
- * Grandfather is Sergeant of the Palace Bodyguards
- * Spanish National Ski Champion 1932
- * Member of Spanish National Champion Rugby Team 1934
- * Recreational Rock Climber
- * Joined the Republican Army 1936 to defend the government against the military coup led by Francisco Franco
- * Becomes Captain of Army Engineers
- * Franco wins, Candela is POW at the concentration camp near Perpignan
- * Society of Friends (Quakers) sponsors a few hundred (out of 70,000) POW's to emigrate. Candela's name is called, he gets to emigrate to Mexico.

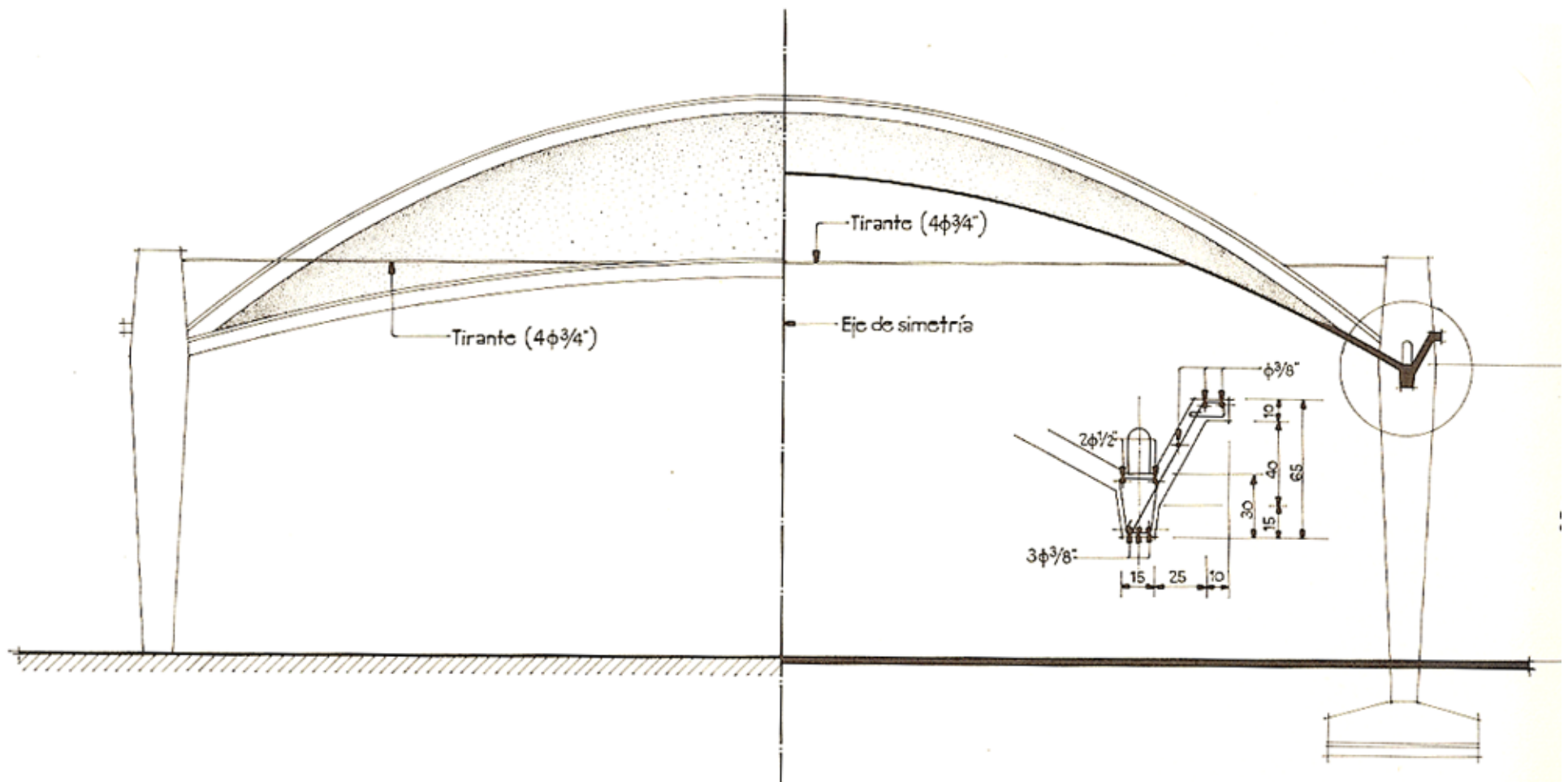




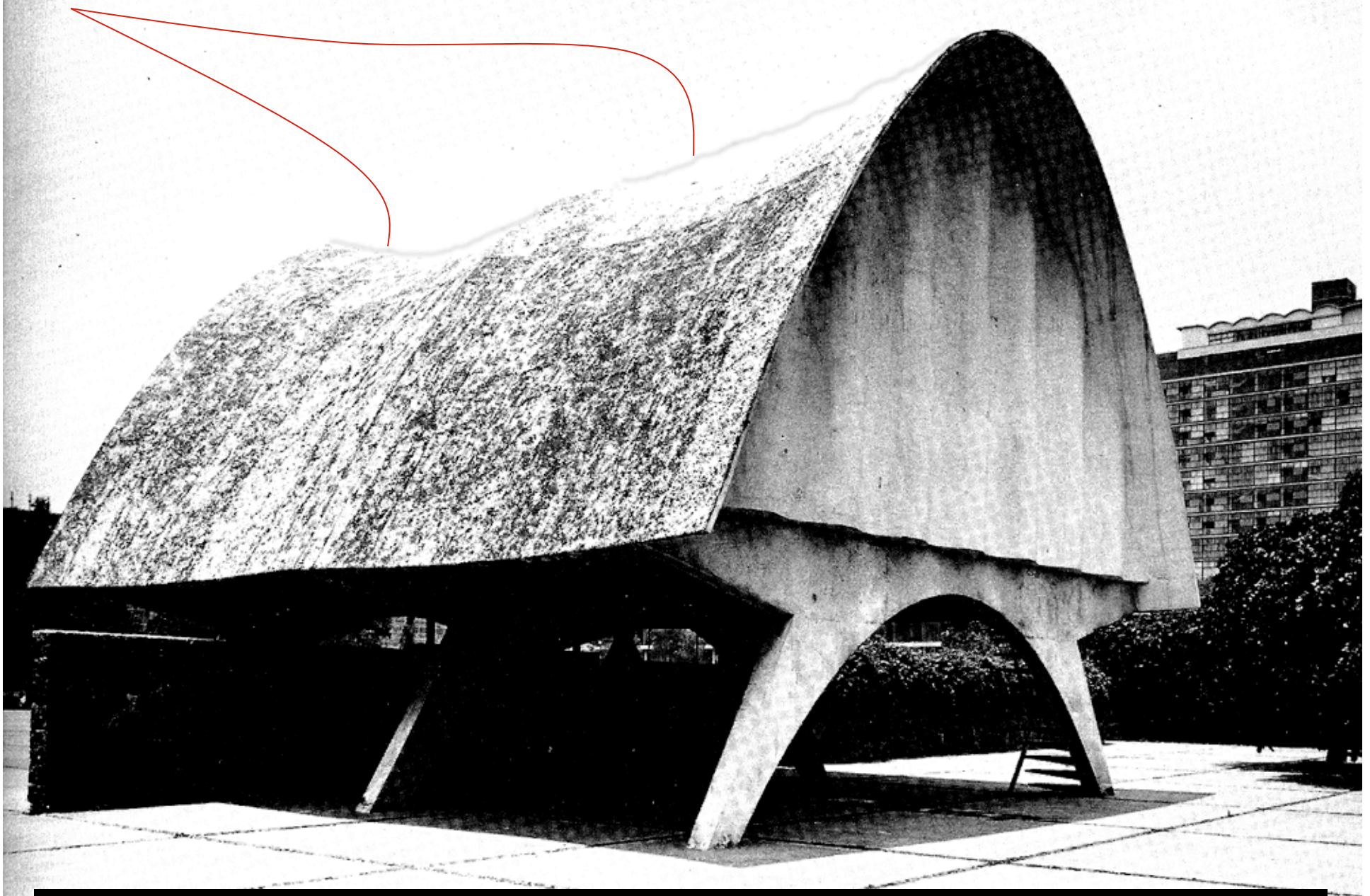
Not Nervi...fewest ribs possible



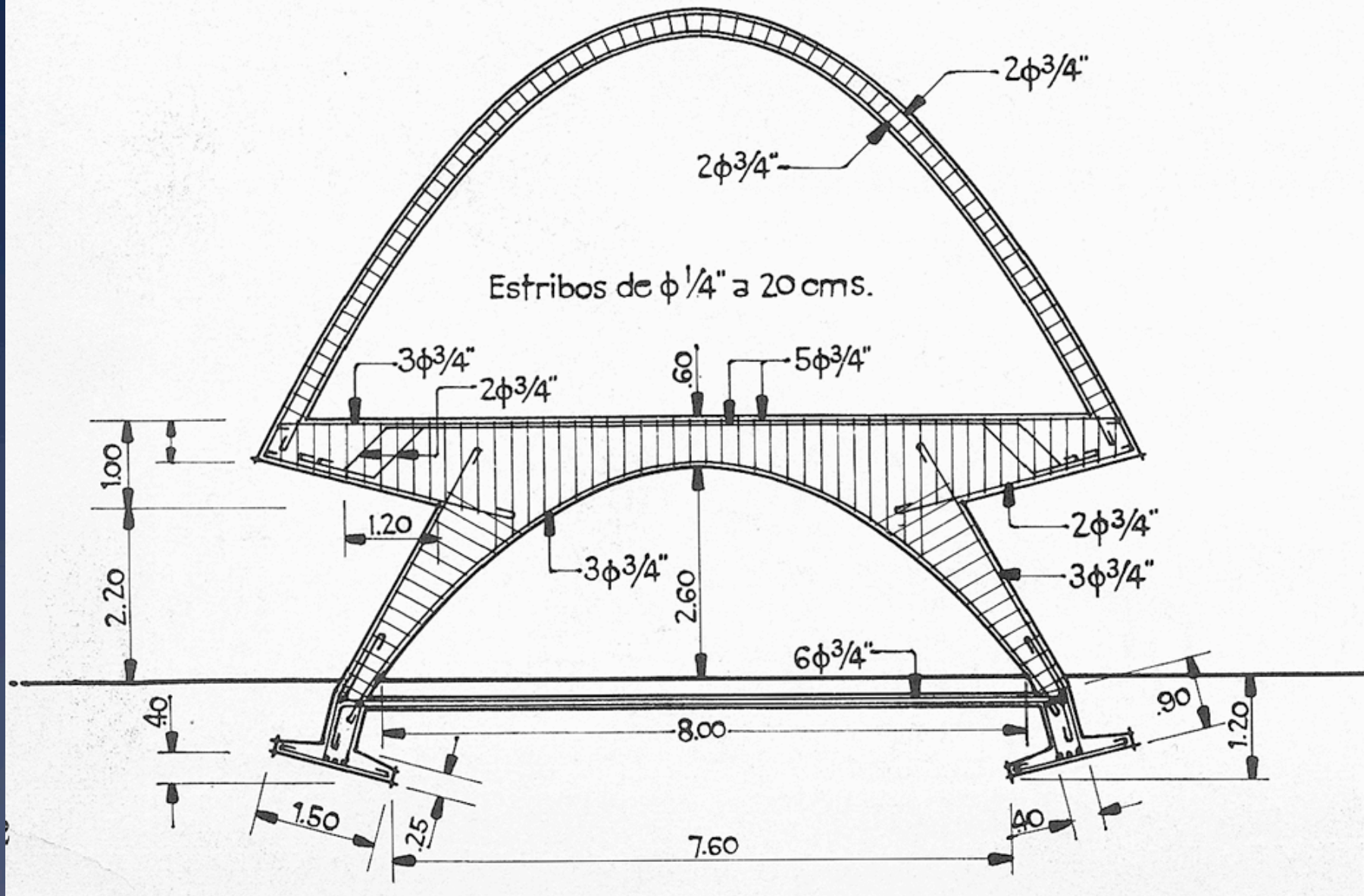
Like the catalan vault of
Gustavino, thicken edges, thin center



Two “hypar” hyperbolic paraboloid shells, doubly curved surfaces for stability



1951 Cosmic Ray Pavillion, structure could not be more than 5/8" thick

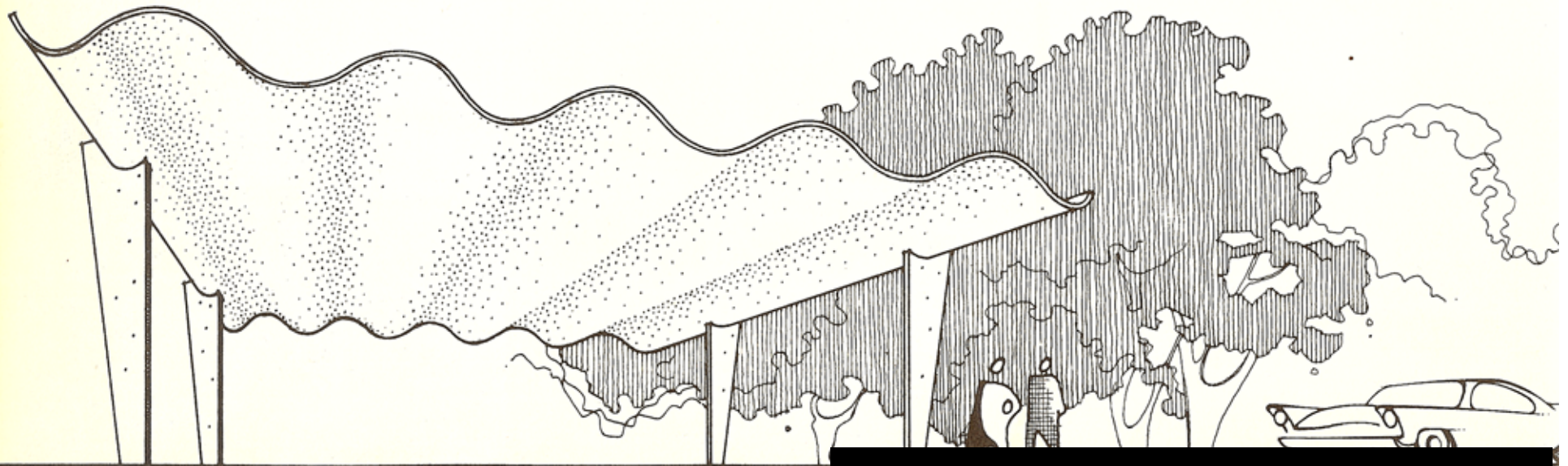


* Third-Party reviewers asked the Candela Brothers Builders for calculations...there were none...a few pages of explanation were prepared



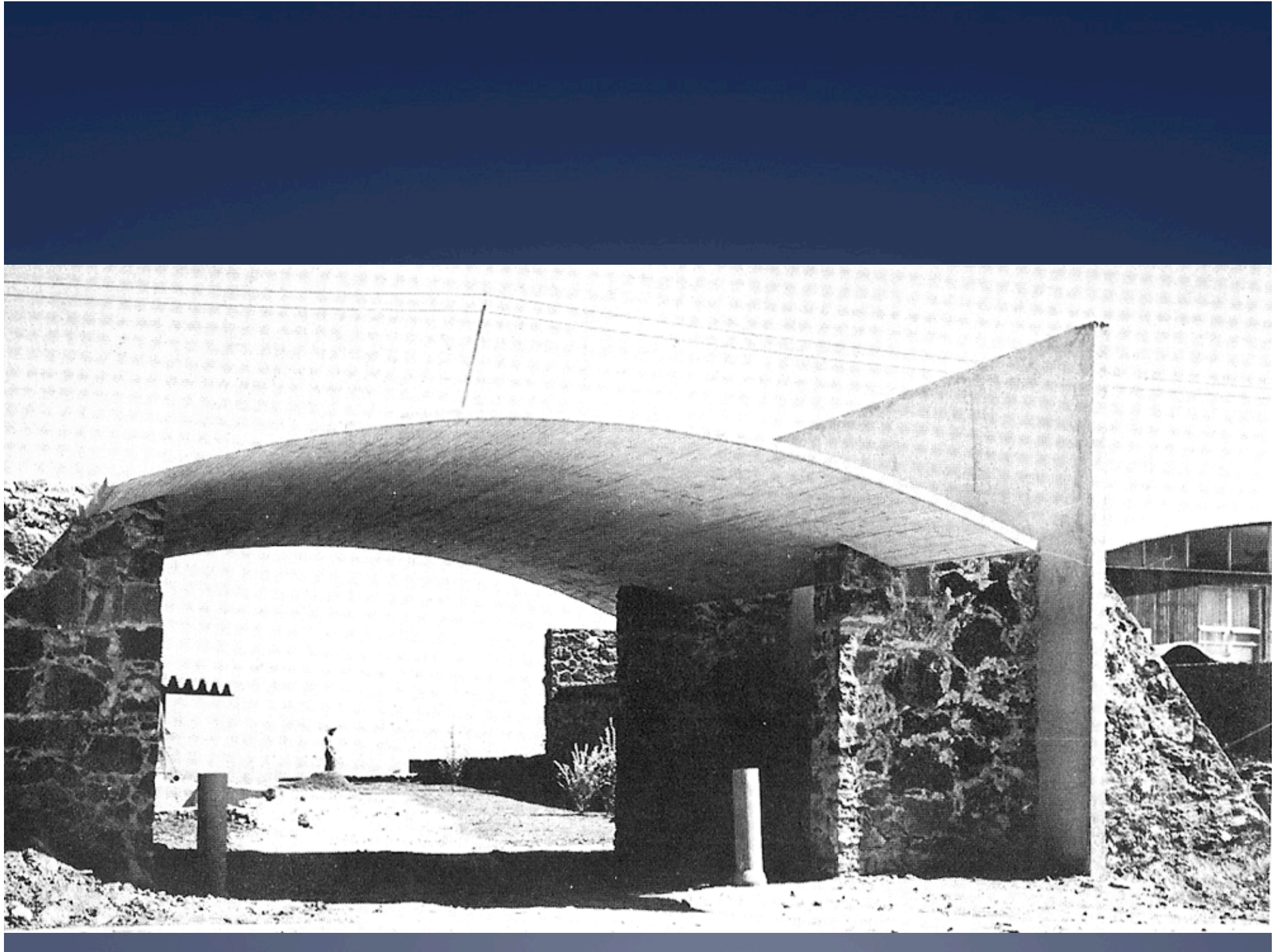
1/2 inch t&g flooring for form, 1/8 (no. 1) rebar, no aggregate larger than 1/4"

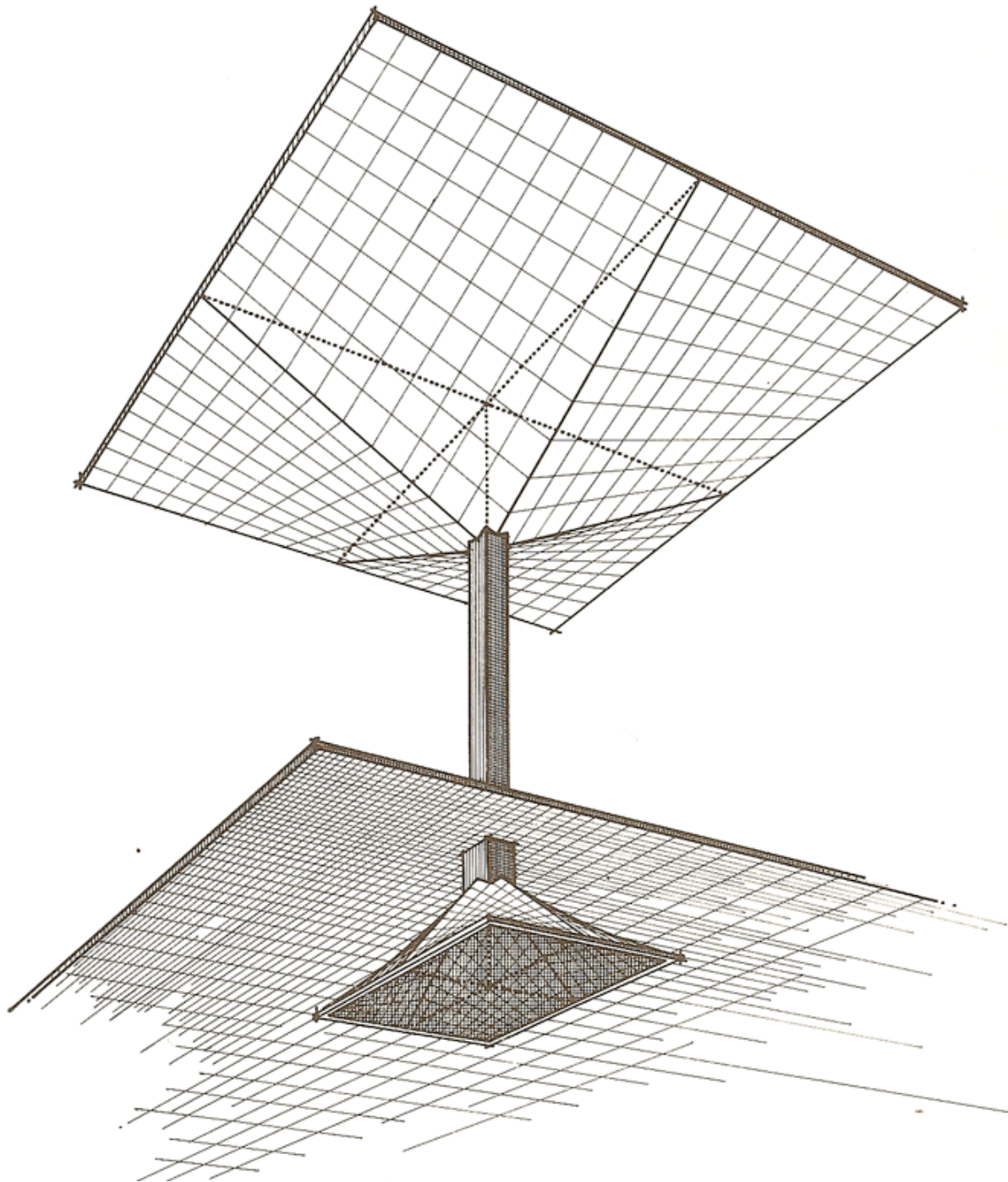
Shop as corrugated plate



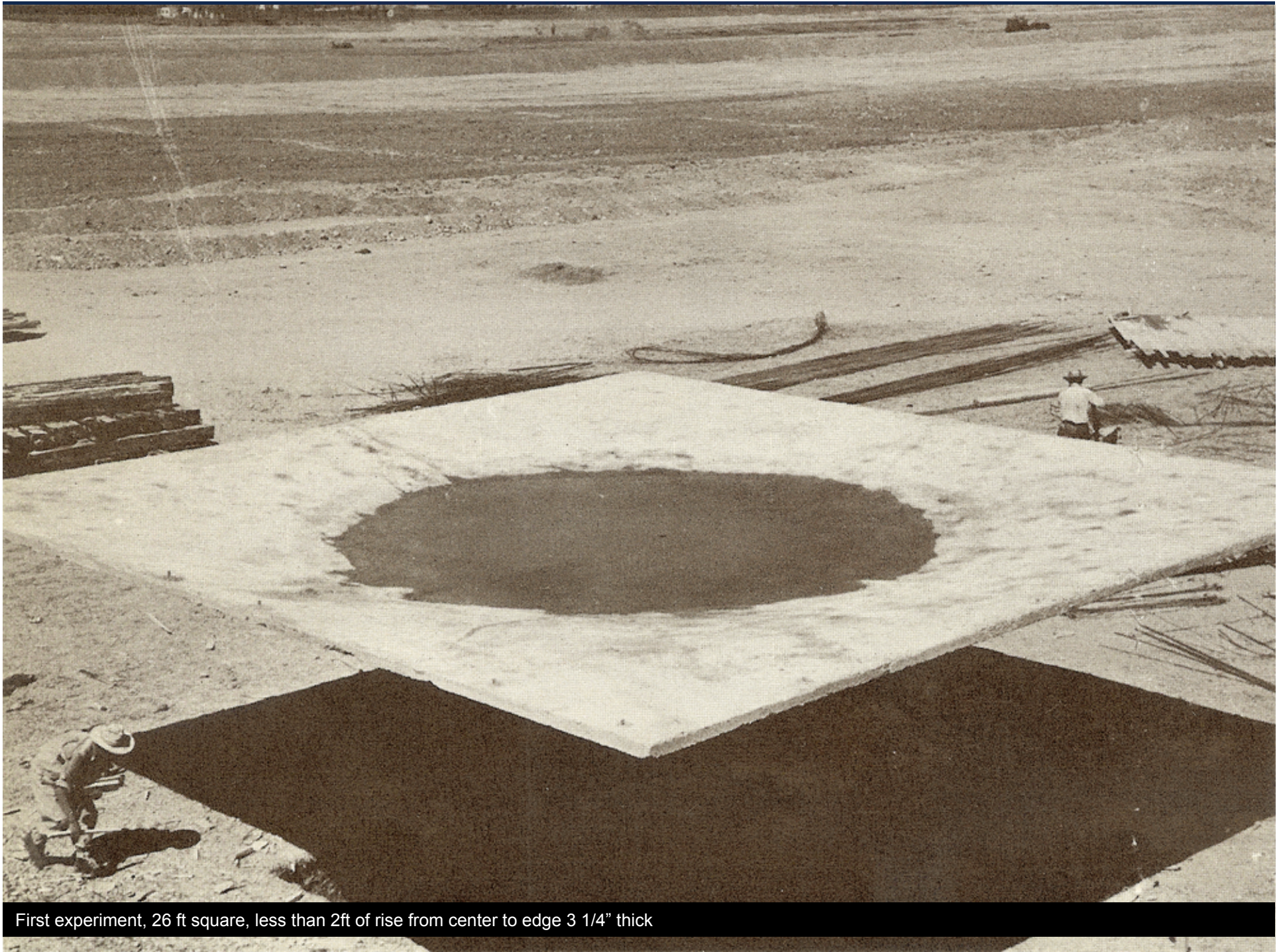
1951 Ras-Martin Flower Shop



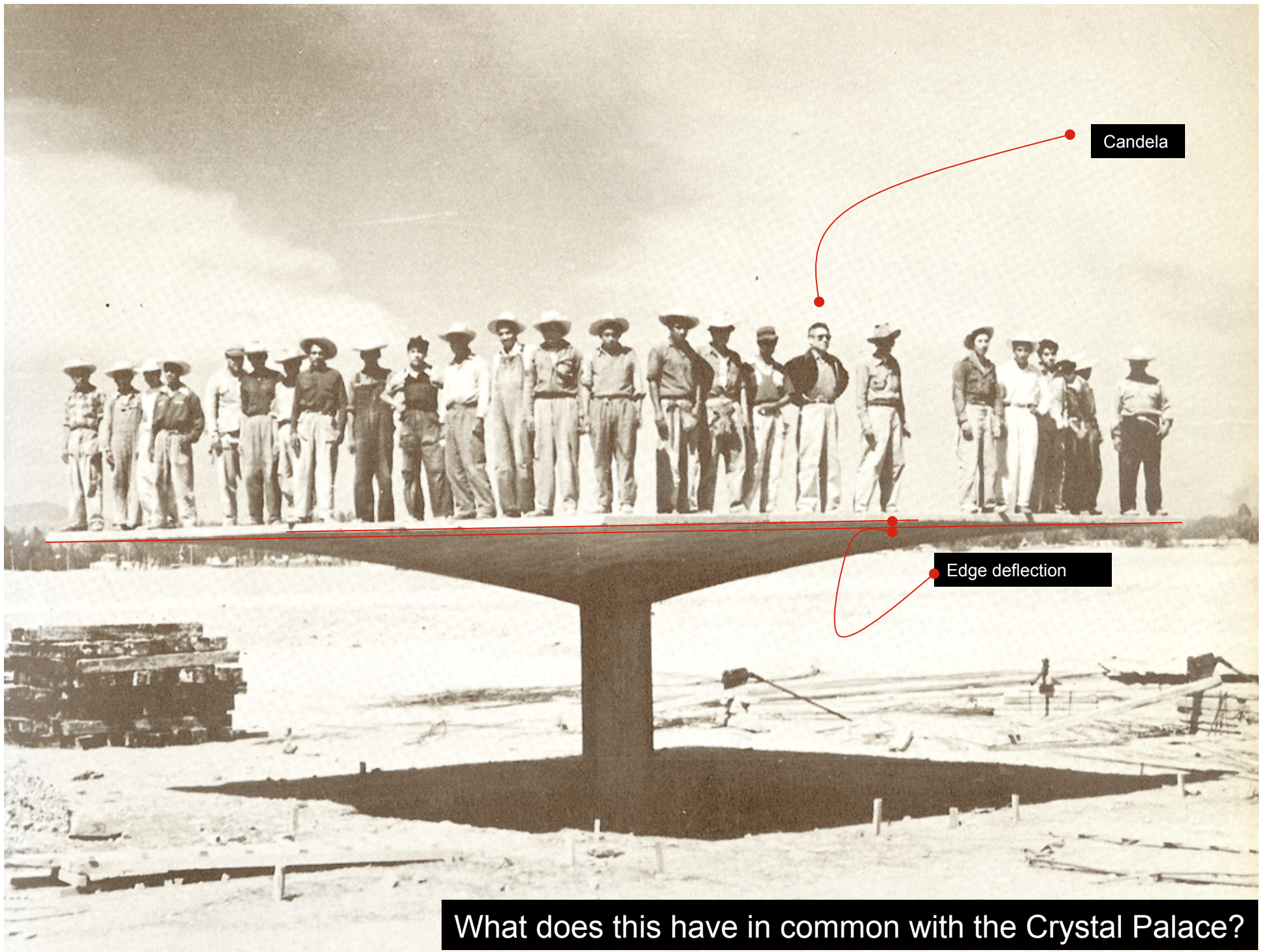




Hyperbolic
paraboloid
umbrella
experiments
1952-53



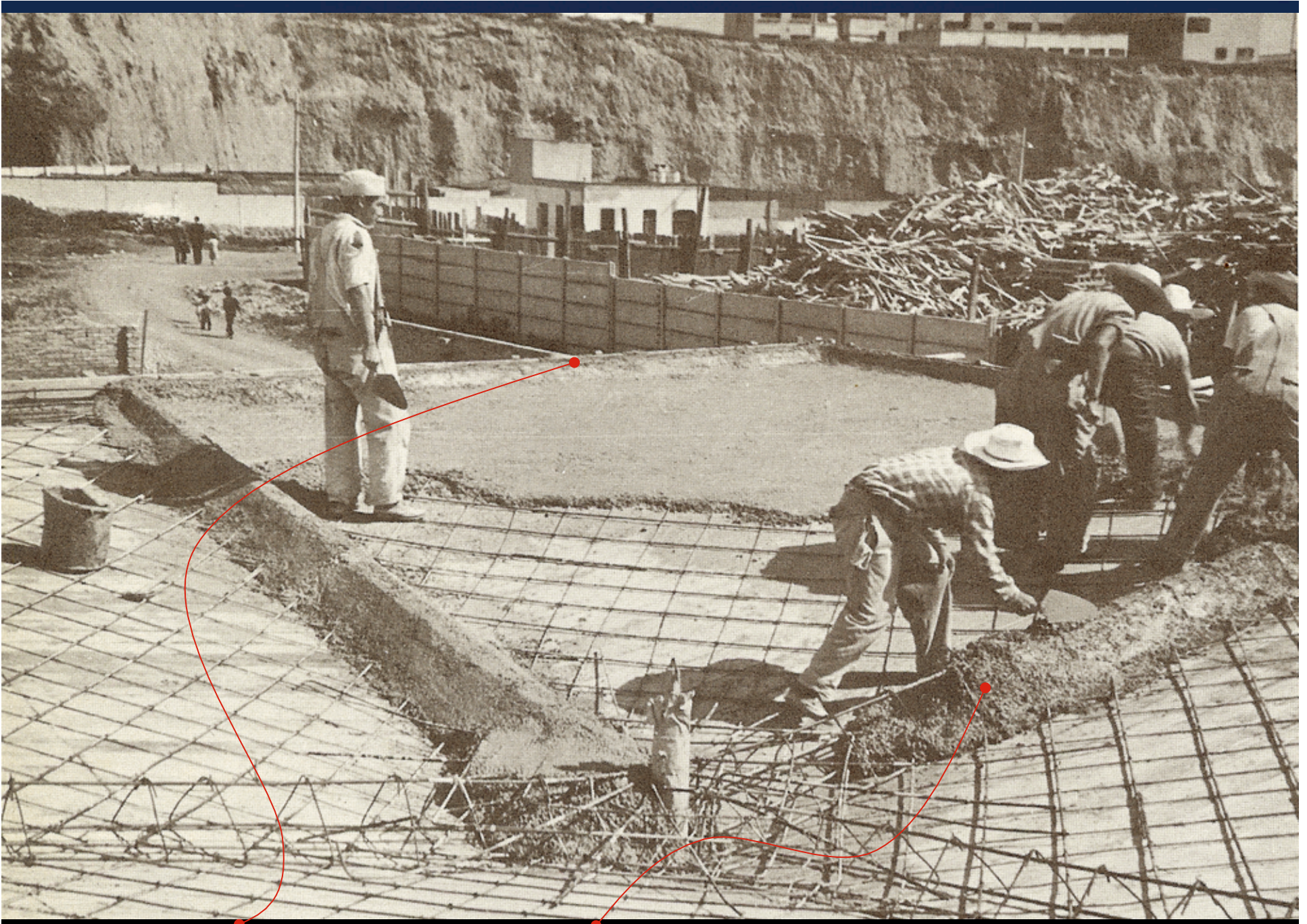
First experiment, 26 ft square, less than 2ft of rise from center to edge 3 1/4" thick



Candela

Edge deflection

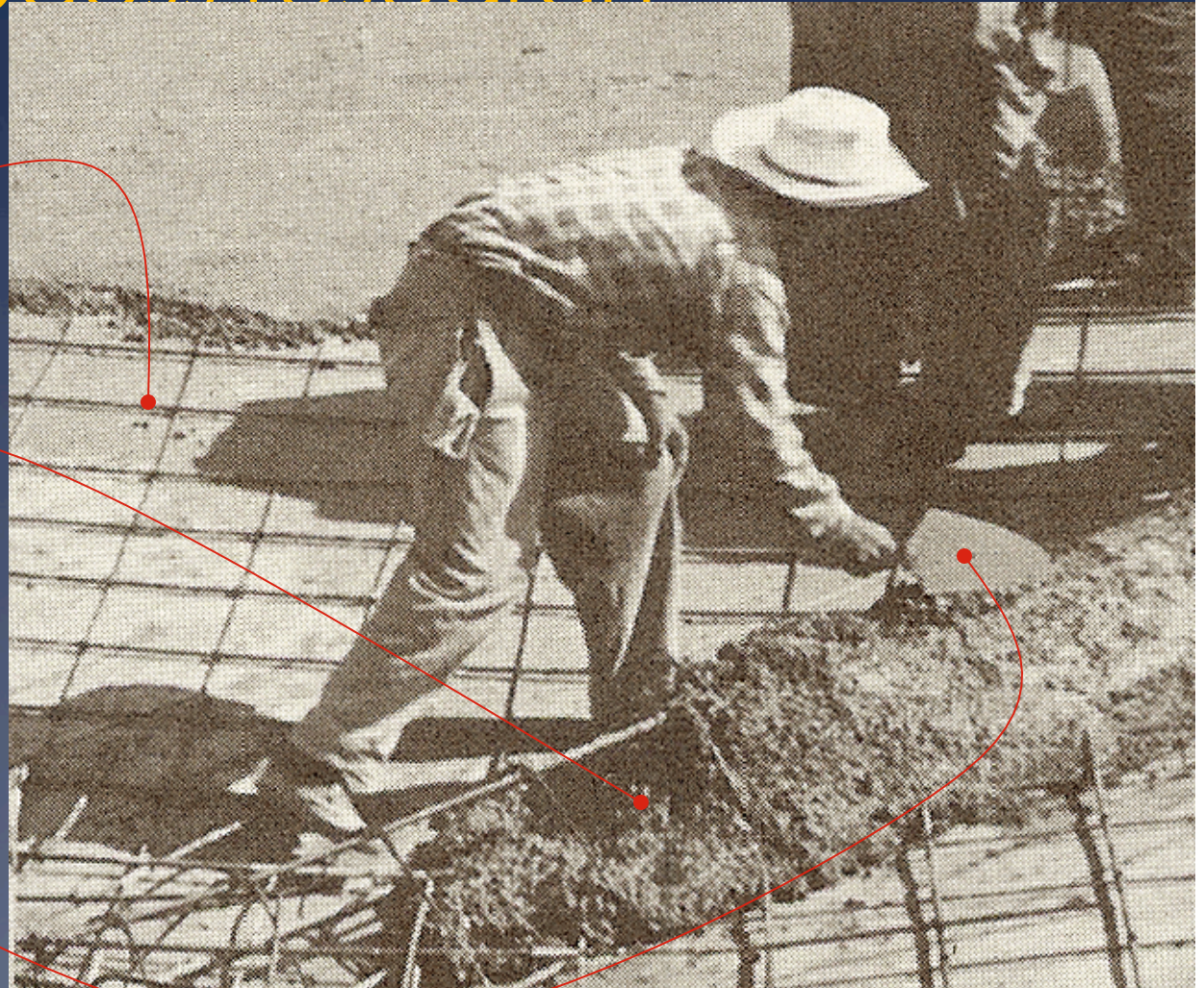
What does this have in common with the Crystal Palace?



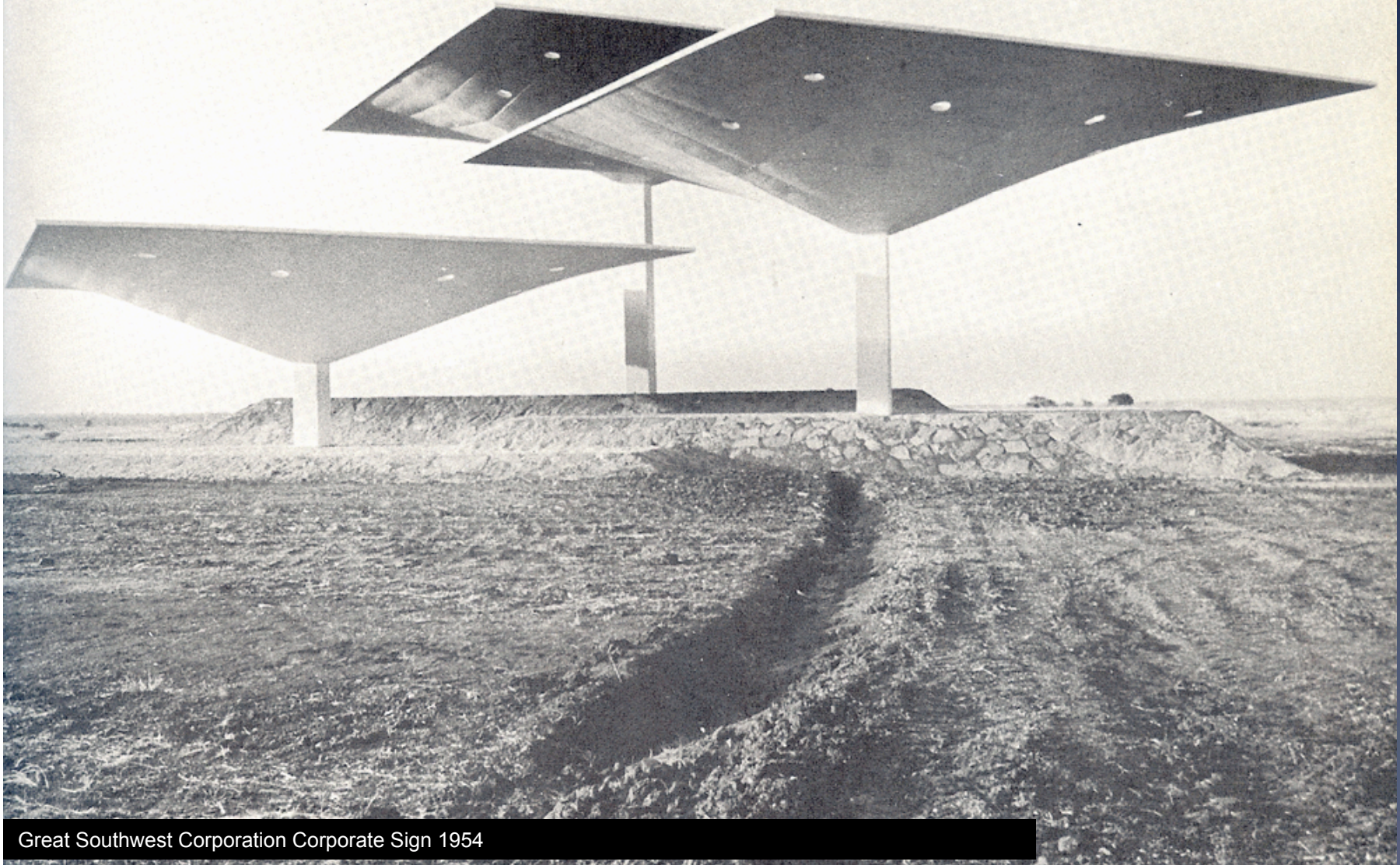
Next experiment edge beam and built-up beams at surface intersections

Experiments were structural and process research

- * 1/8" rebar
- * Low wcr concrete
- * Place and shape with trowel not float

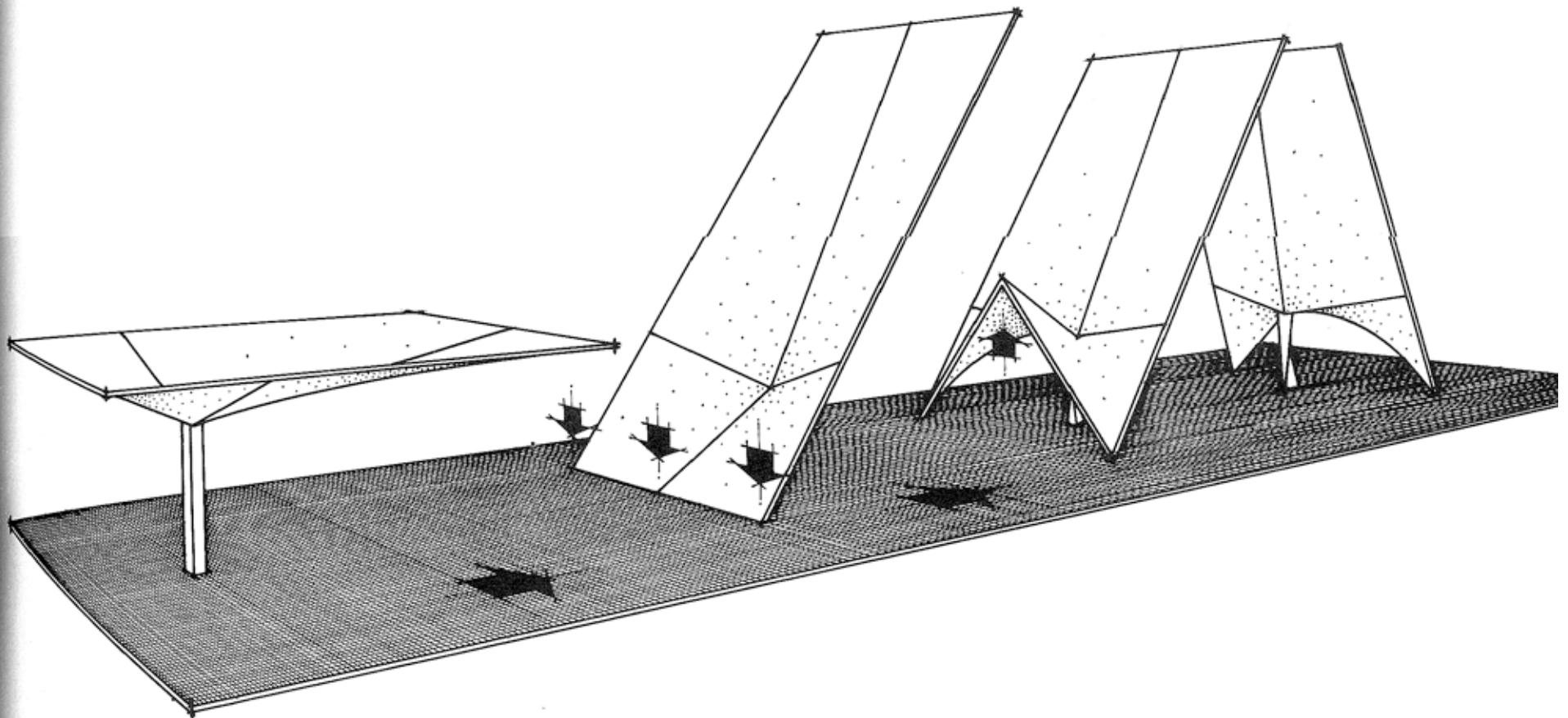


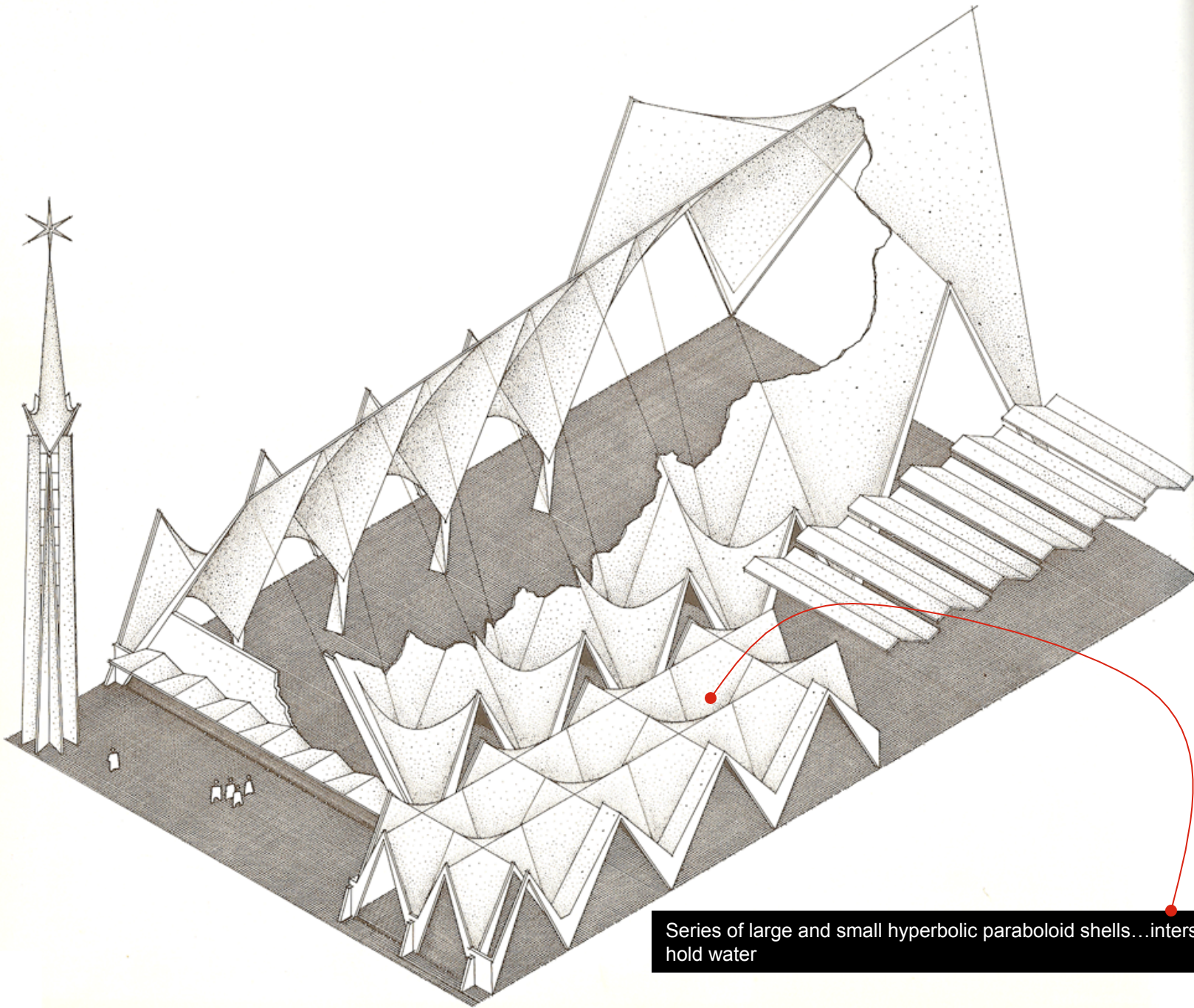
Signs of the future



Great Southwest Corporation Corporate Sign 1954

From umbrella to sidewall





Series of large and small hyperbolic paraboloid shells...intersections might hold water



Steep hp
forms
require
more
toeboard
s



High-Early strength concrete, low wcr, buckets passed up from one level to another. Trowel to shape top surface of shell

HP umbrellas also need to plan for water



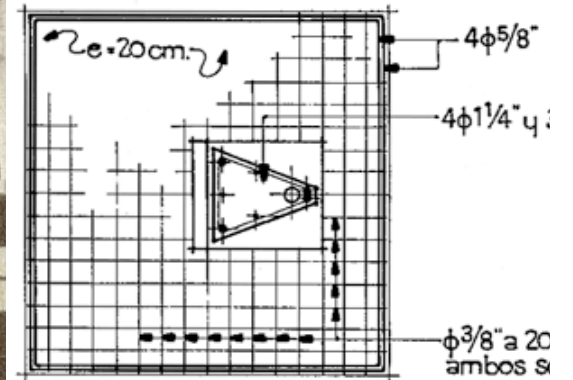
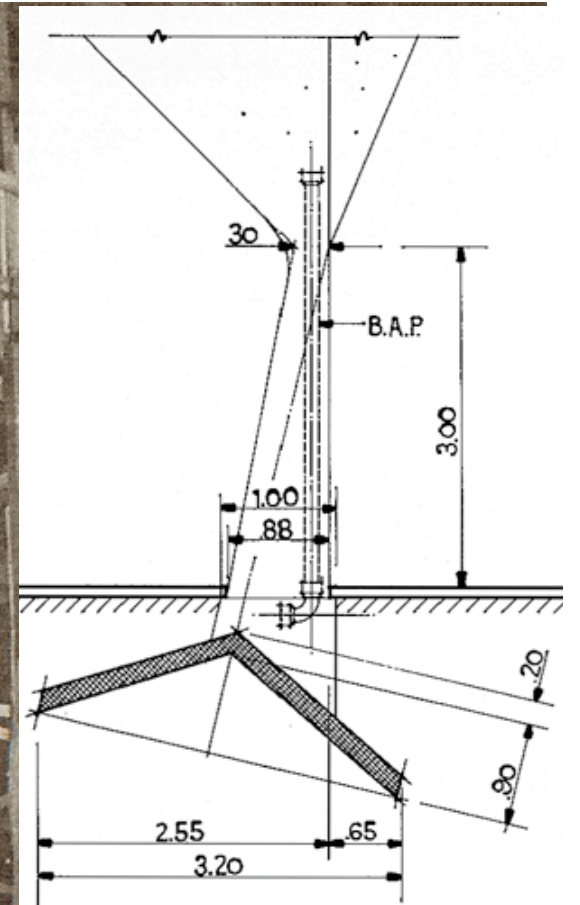
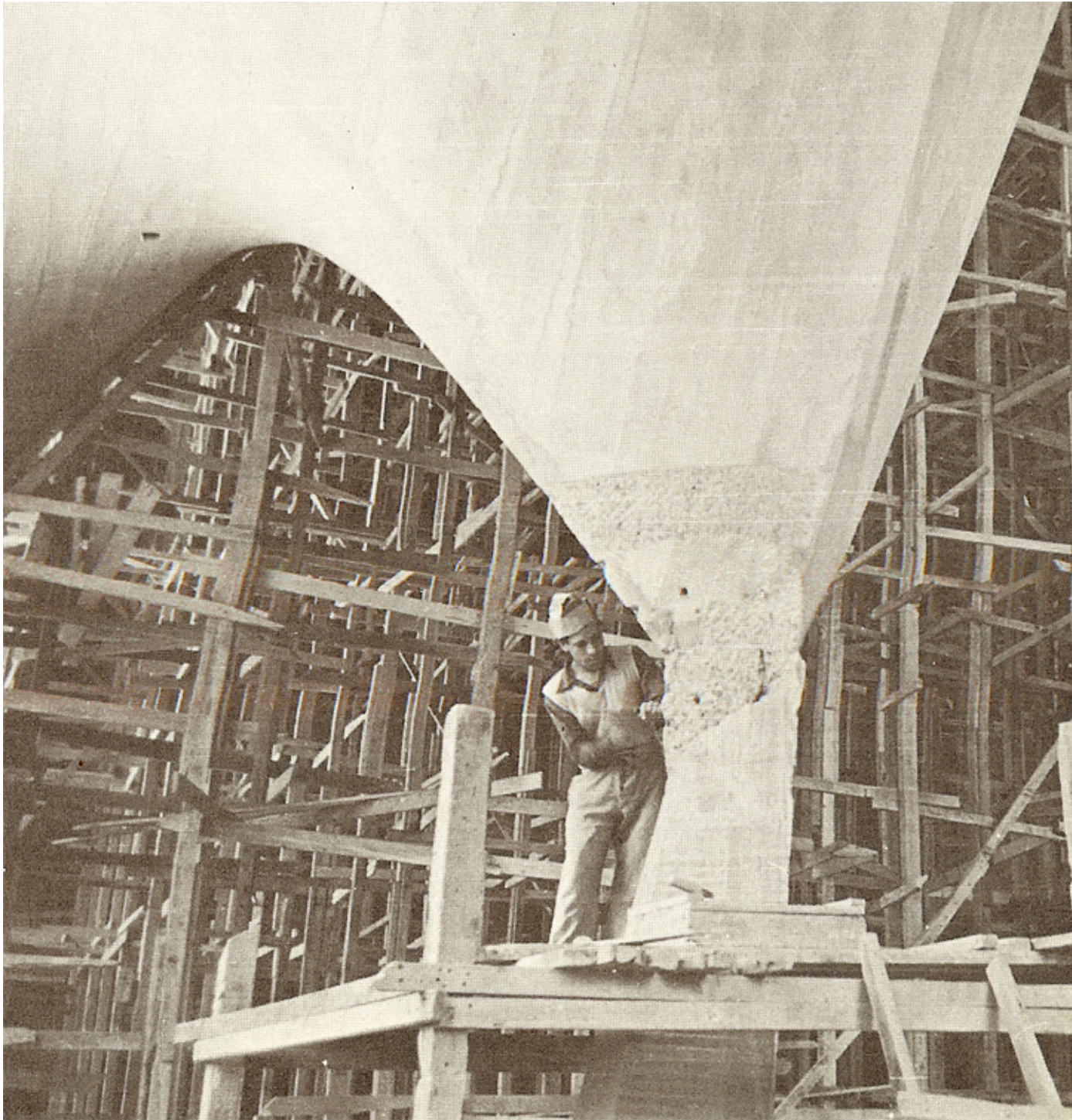






Photo: Structurae.de, Isono

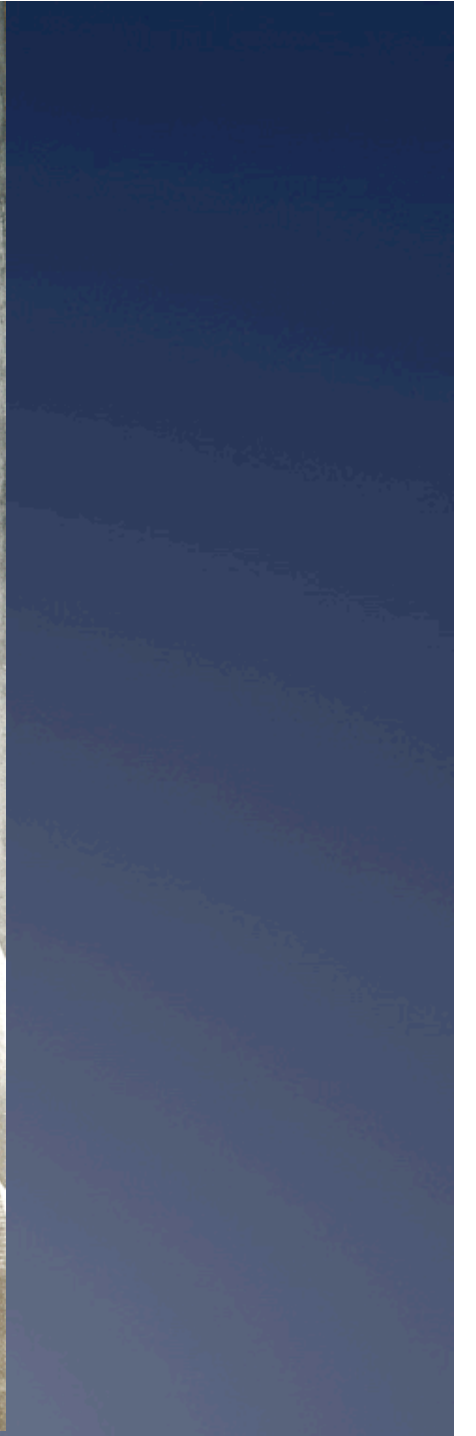
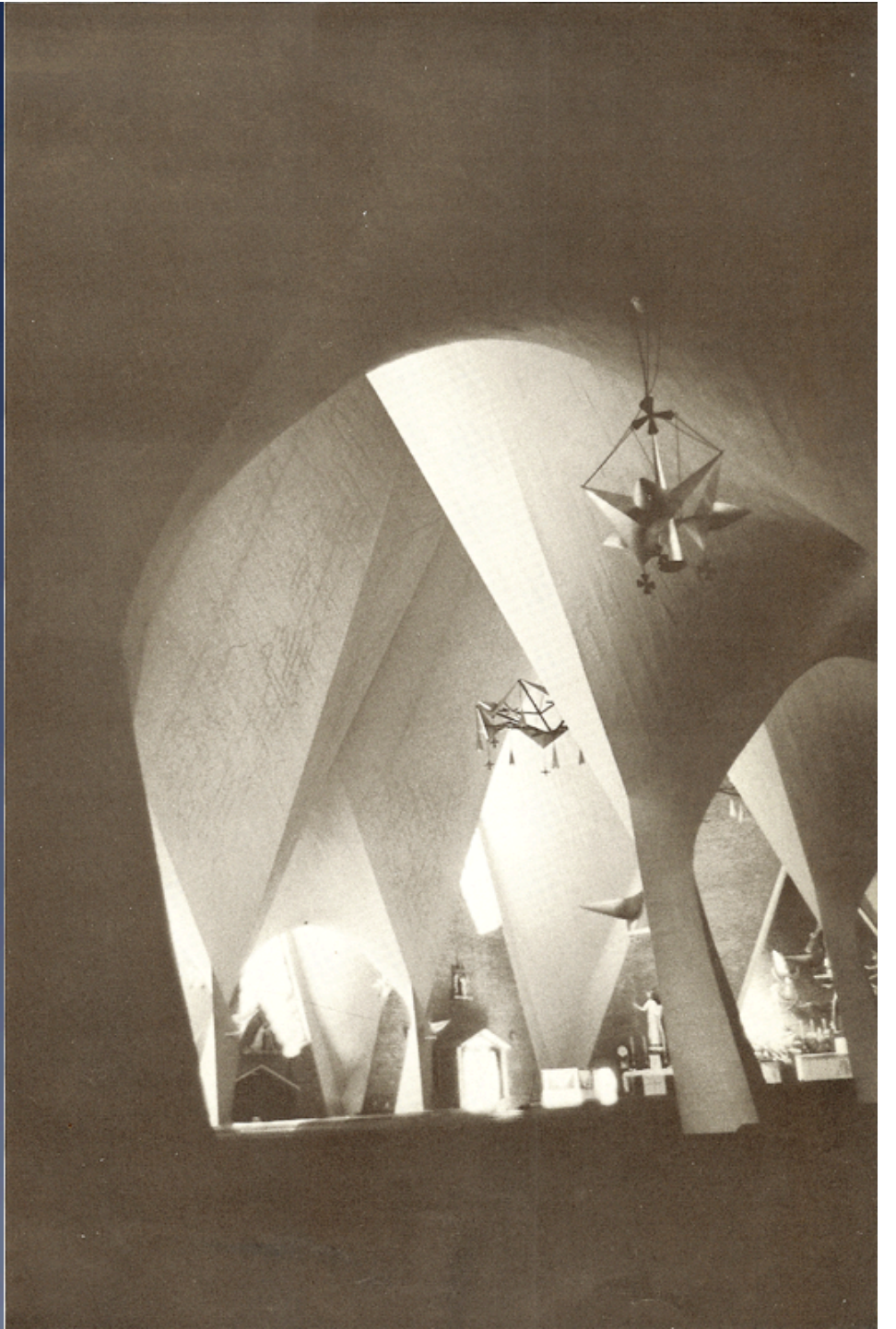




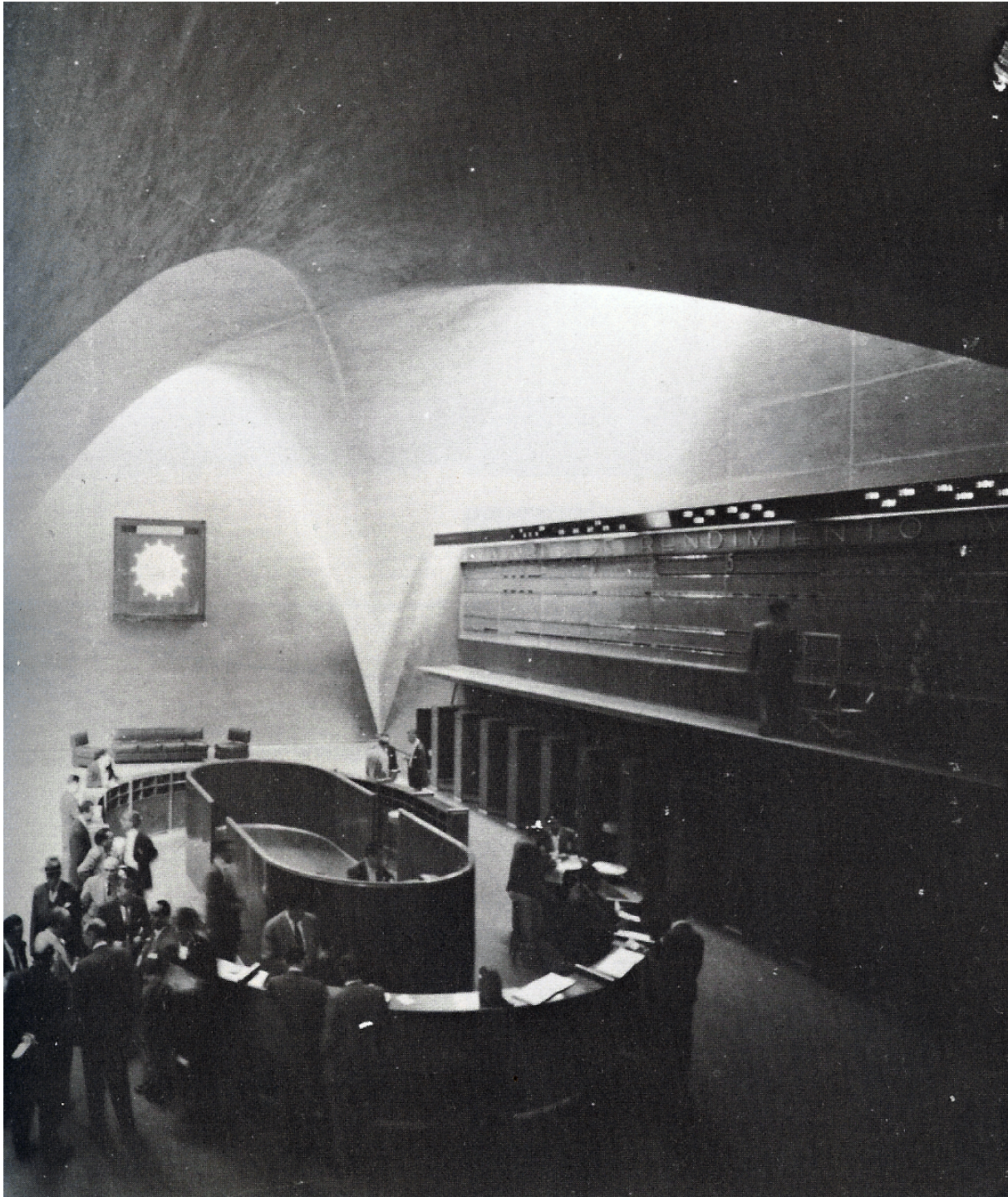


Photo: Structurae.de, Isono



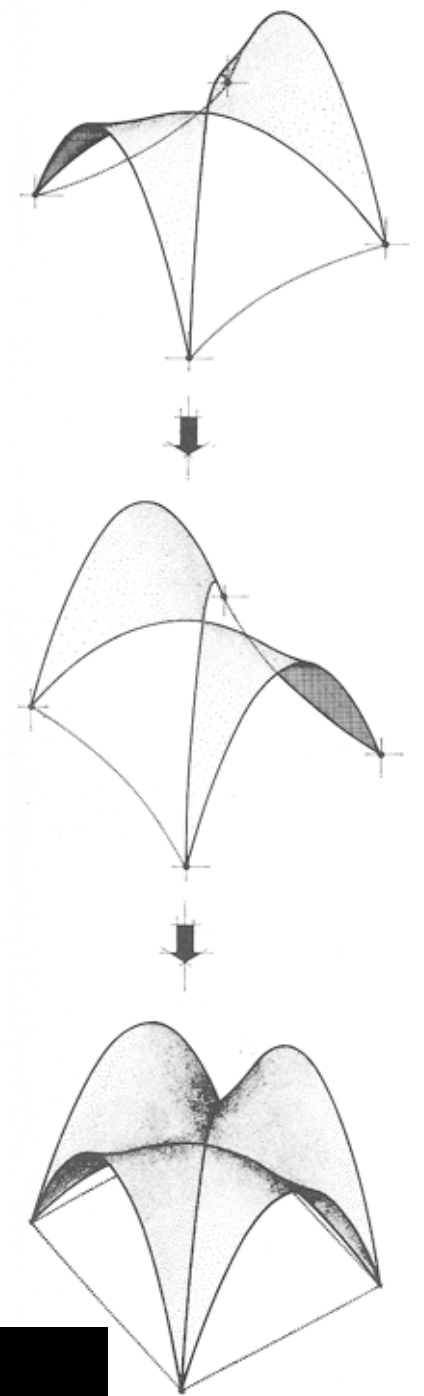


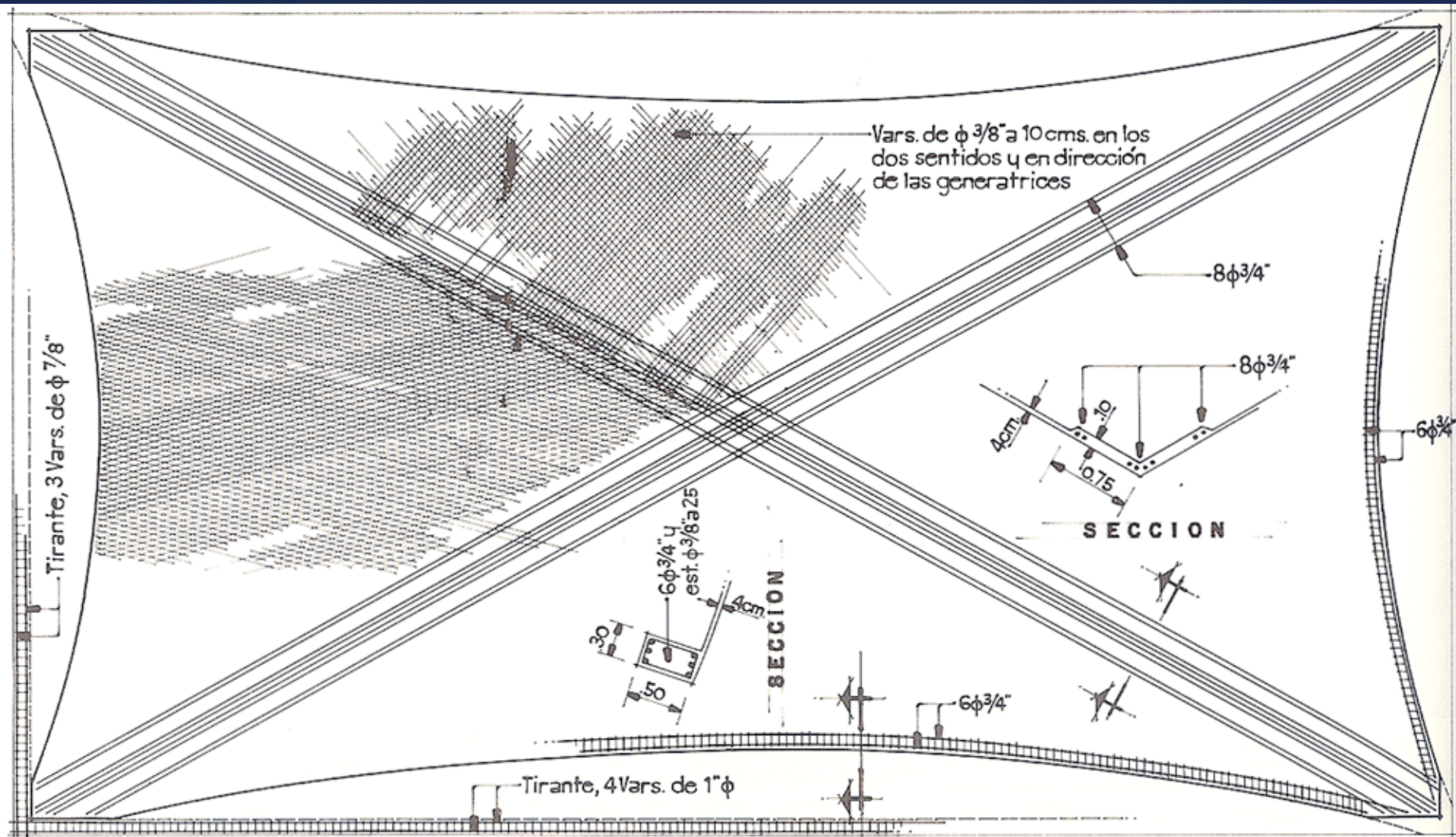




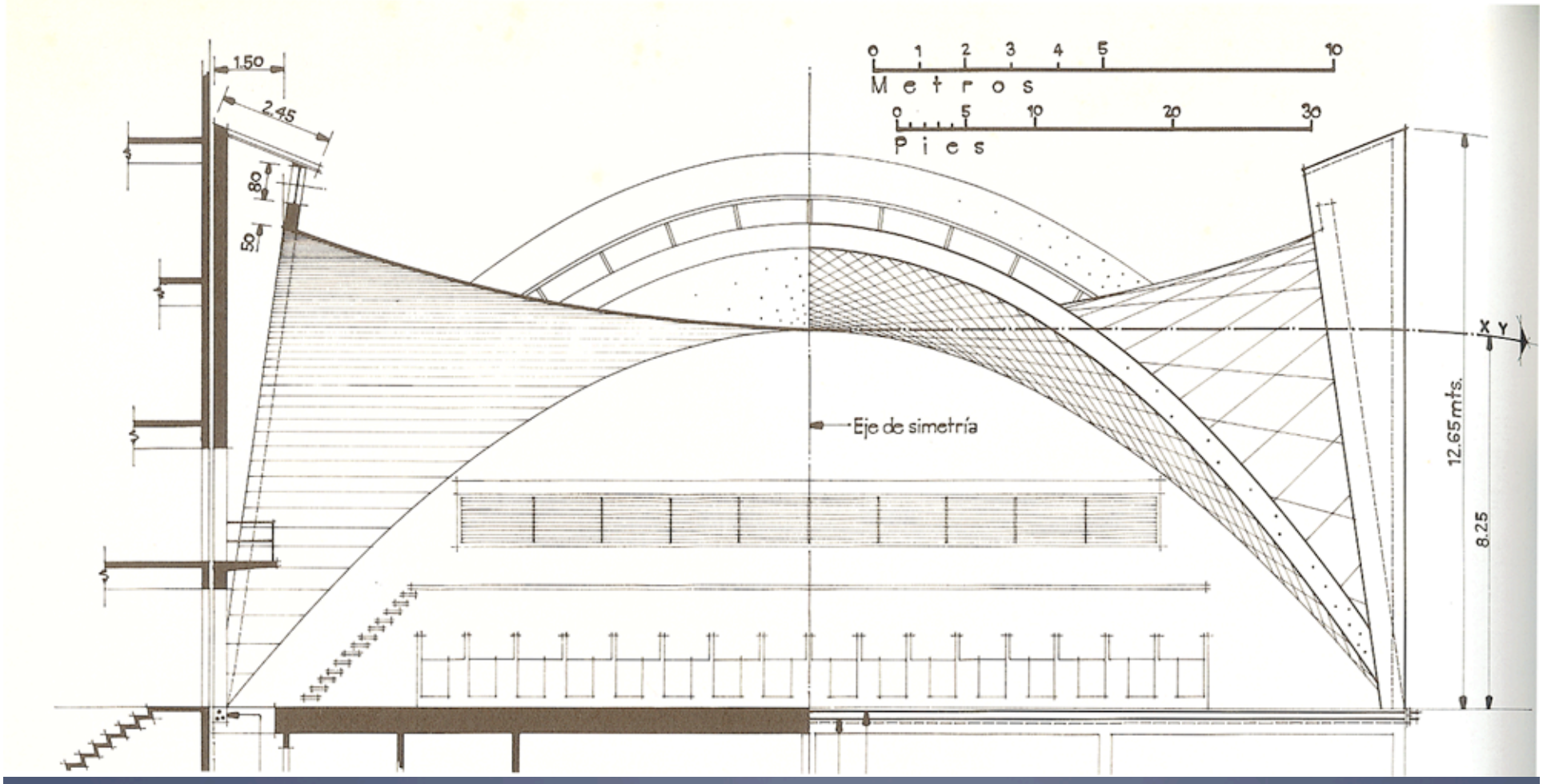
* Stock Exchange of Uruguay

* Crossed shapes rectangular not square





Calculations reveal need for thick edges, thin infill...Gustaviono's Catalan vault?

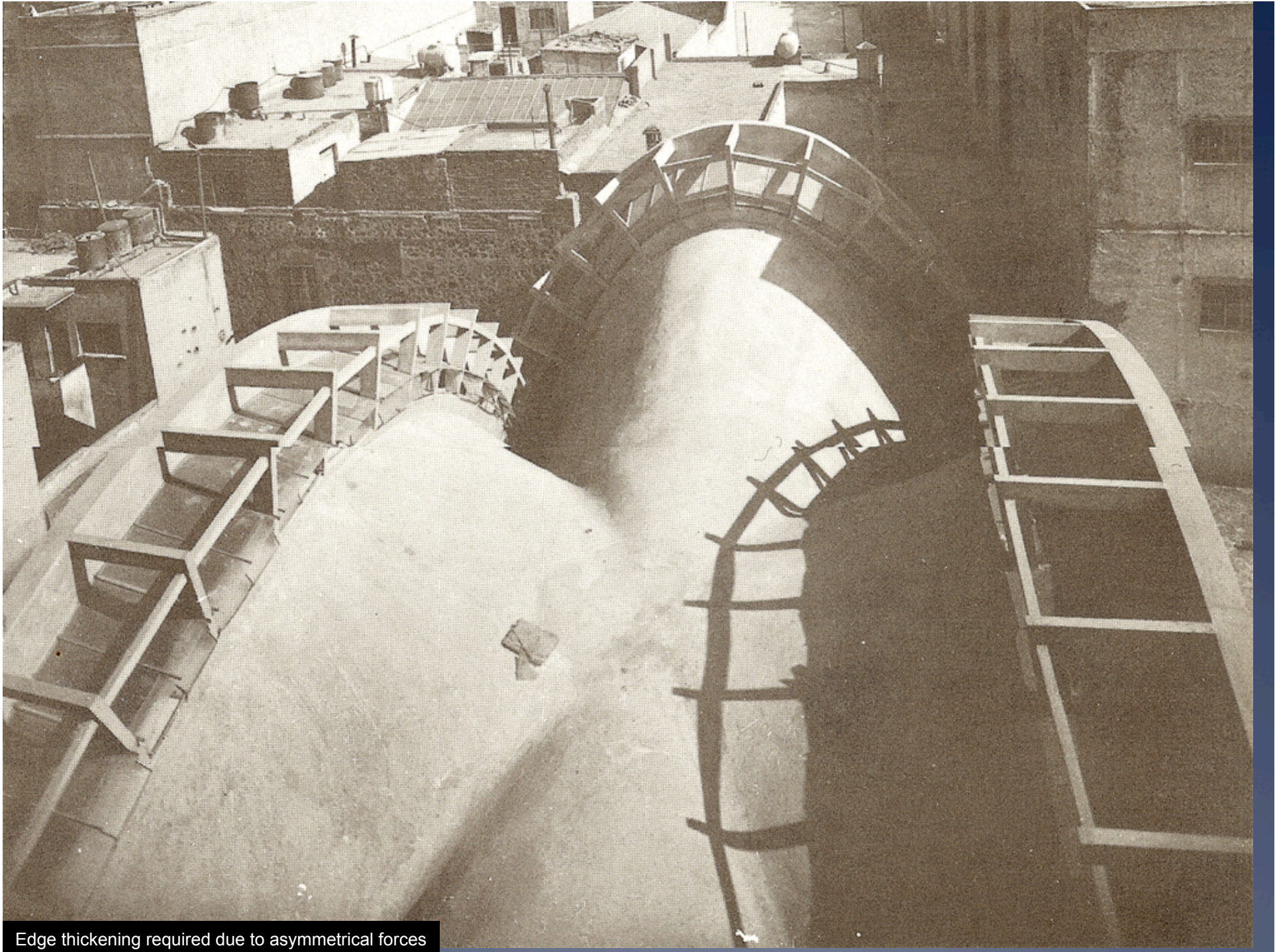




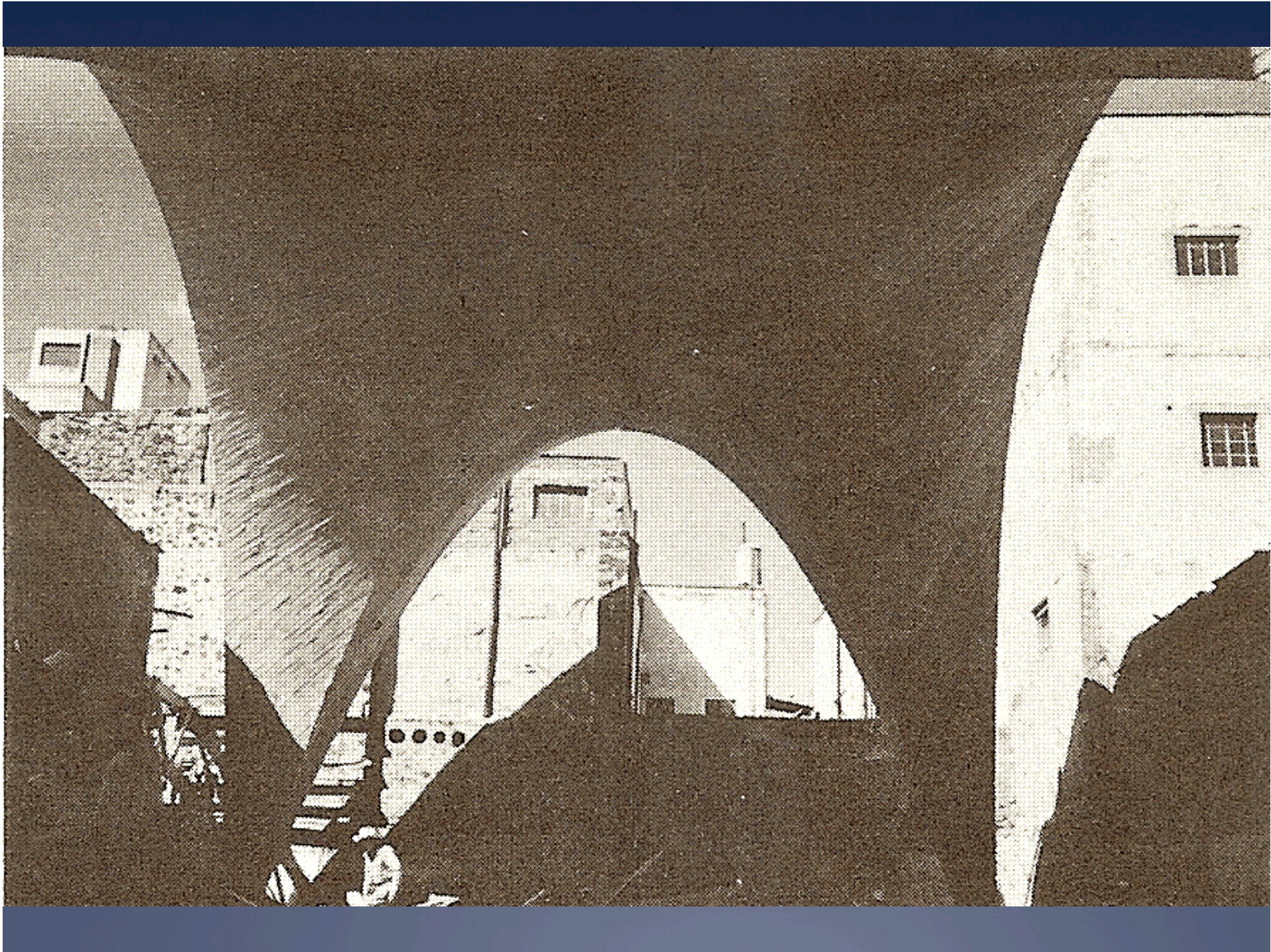
Shell intersections require additional reinforcing

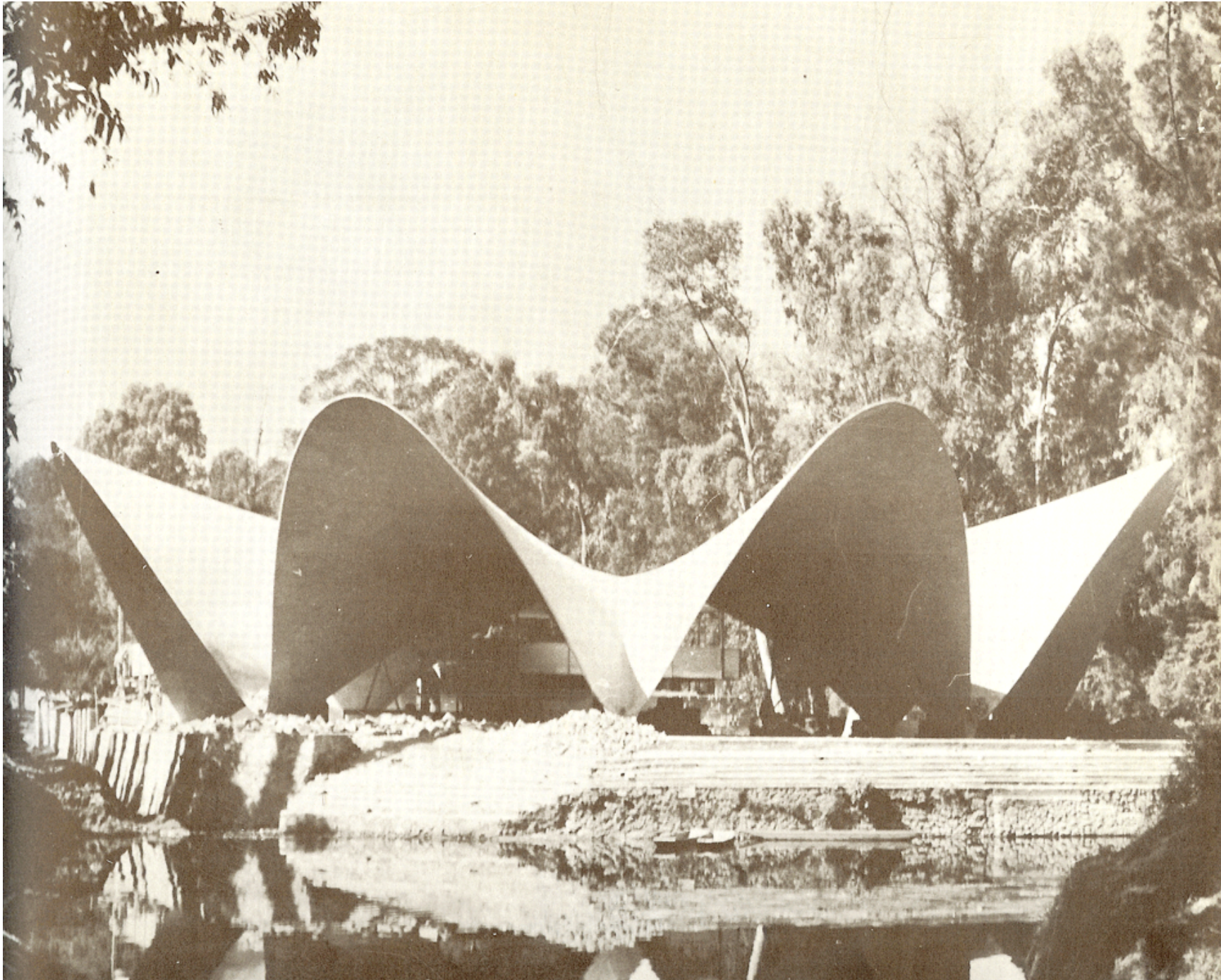


Wedge shapes in form boards



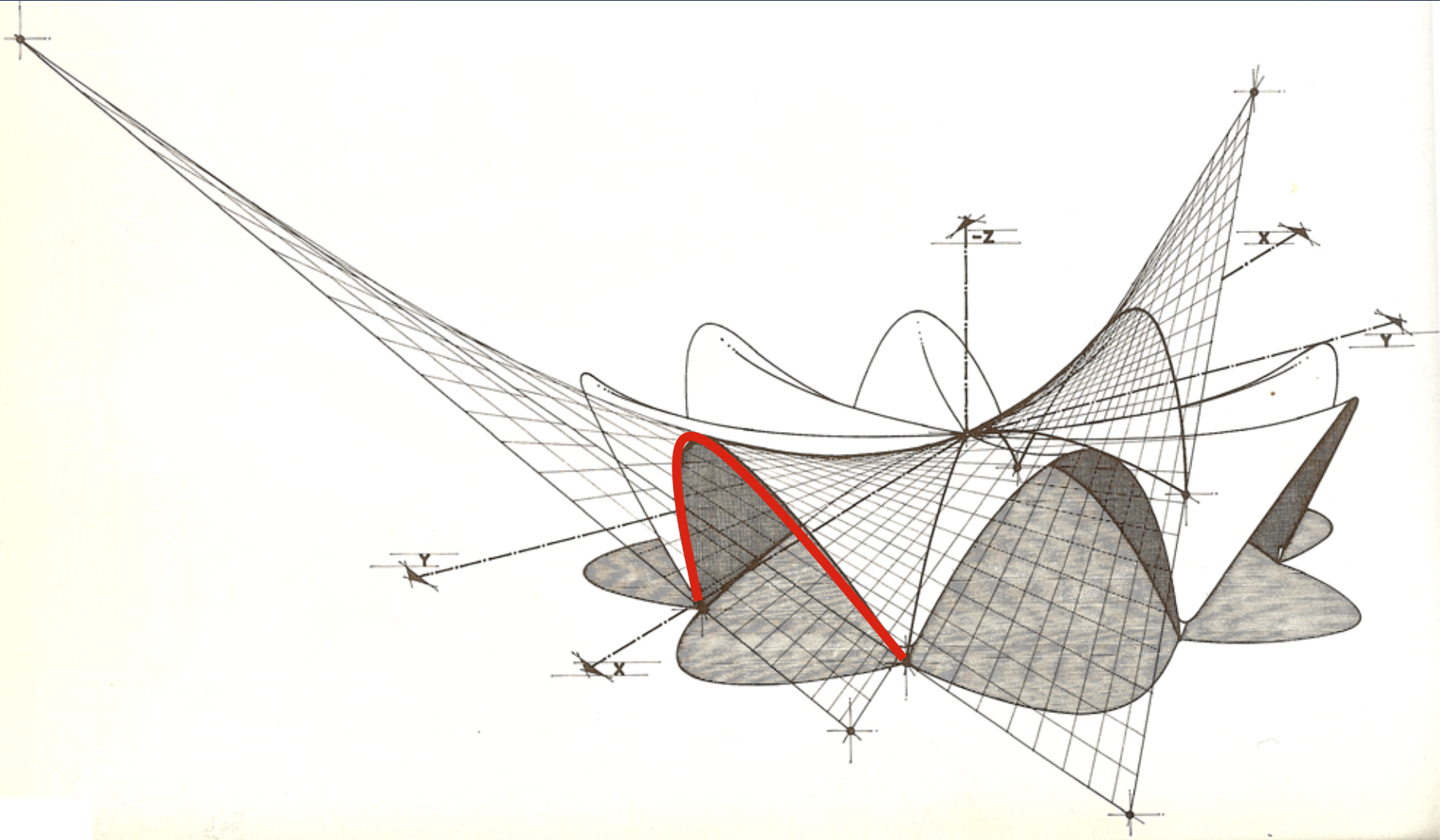
Edge thickening required due to asymmetrical forces





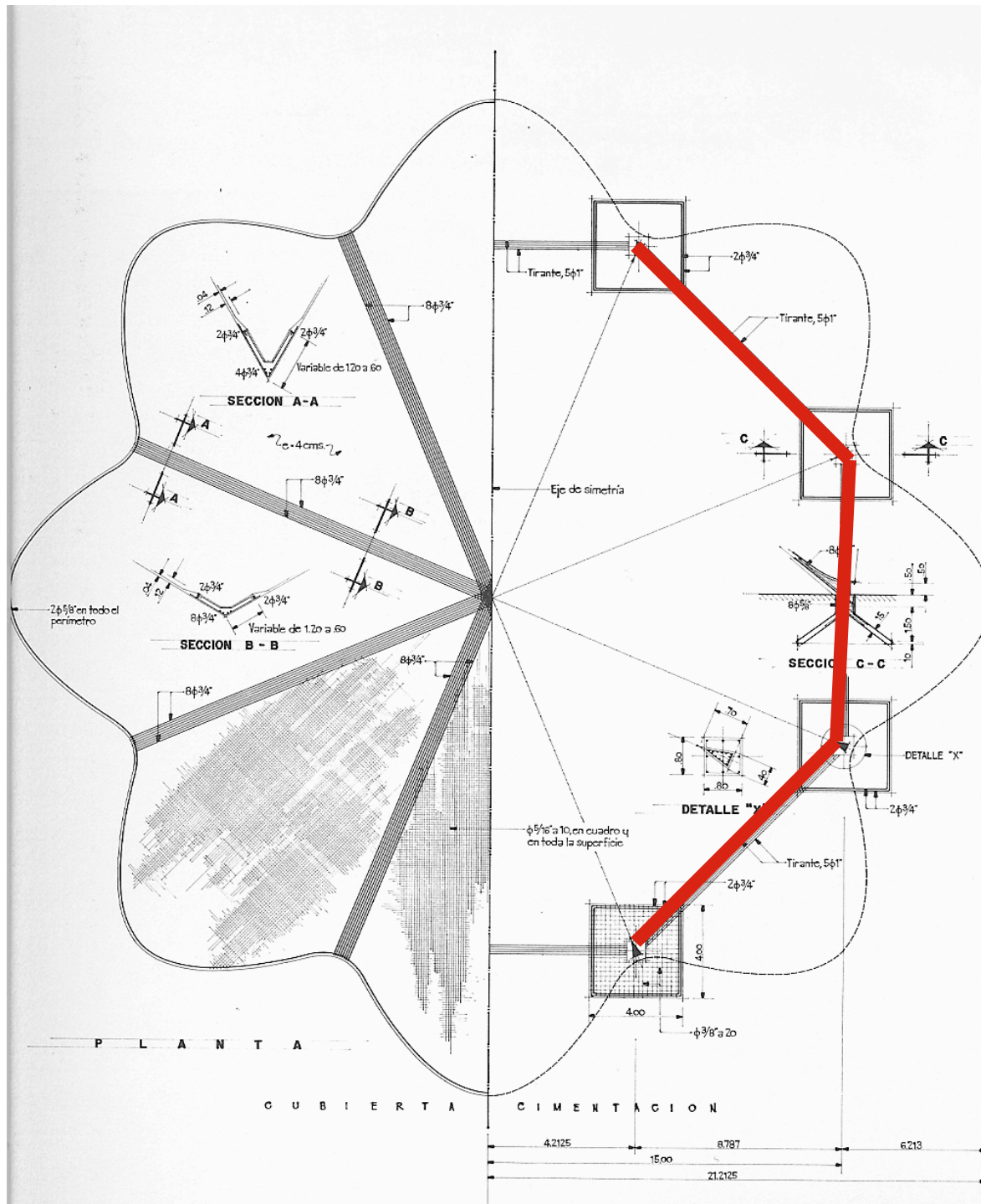
Restaurant at Xochimilco 1958. 150' span. 2-5/8" thick at edges

Symmetry & sloped arches, the key to thin, stable hp shells



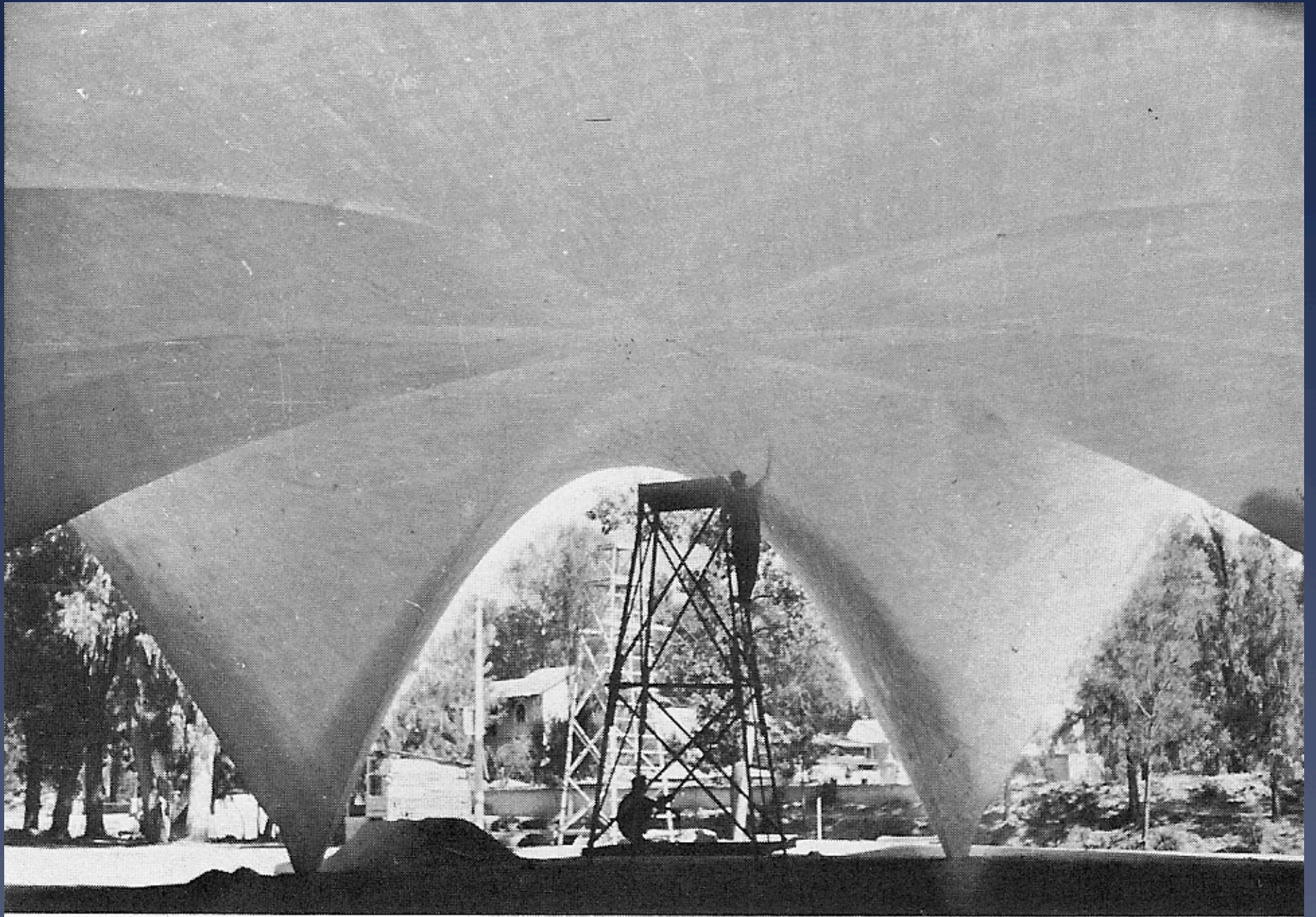
Tension ties below slab...

lesson from the Palais Des Machines?

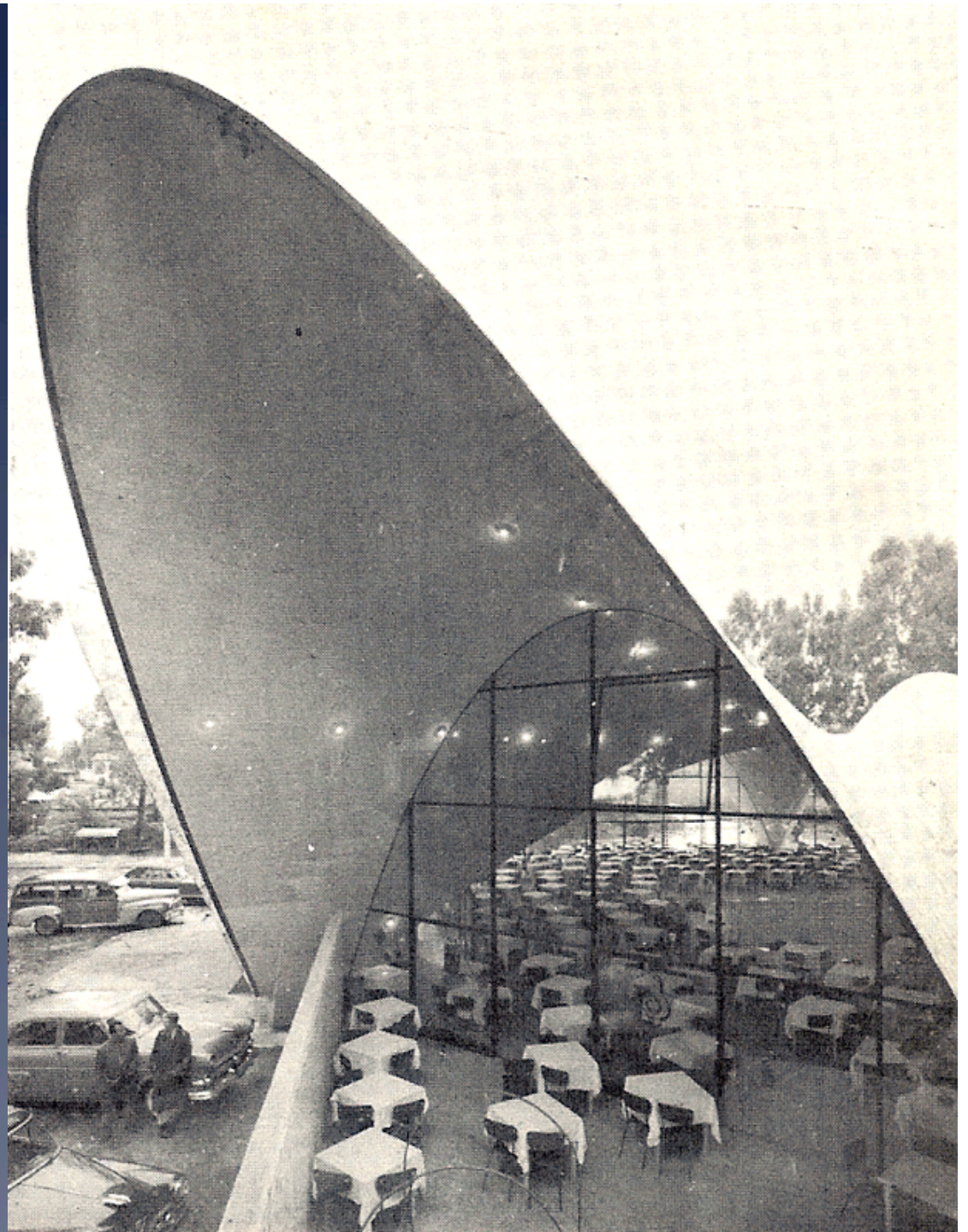


Shrinkage, not alligator cracking





* Less than 3 inches
thick at edges



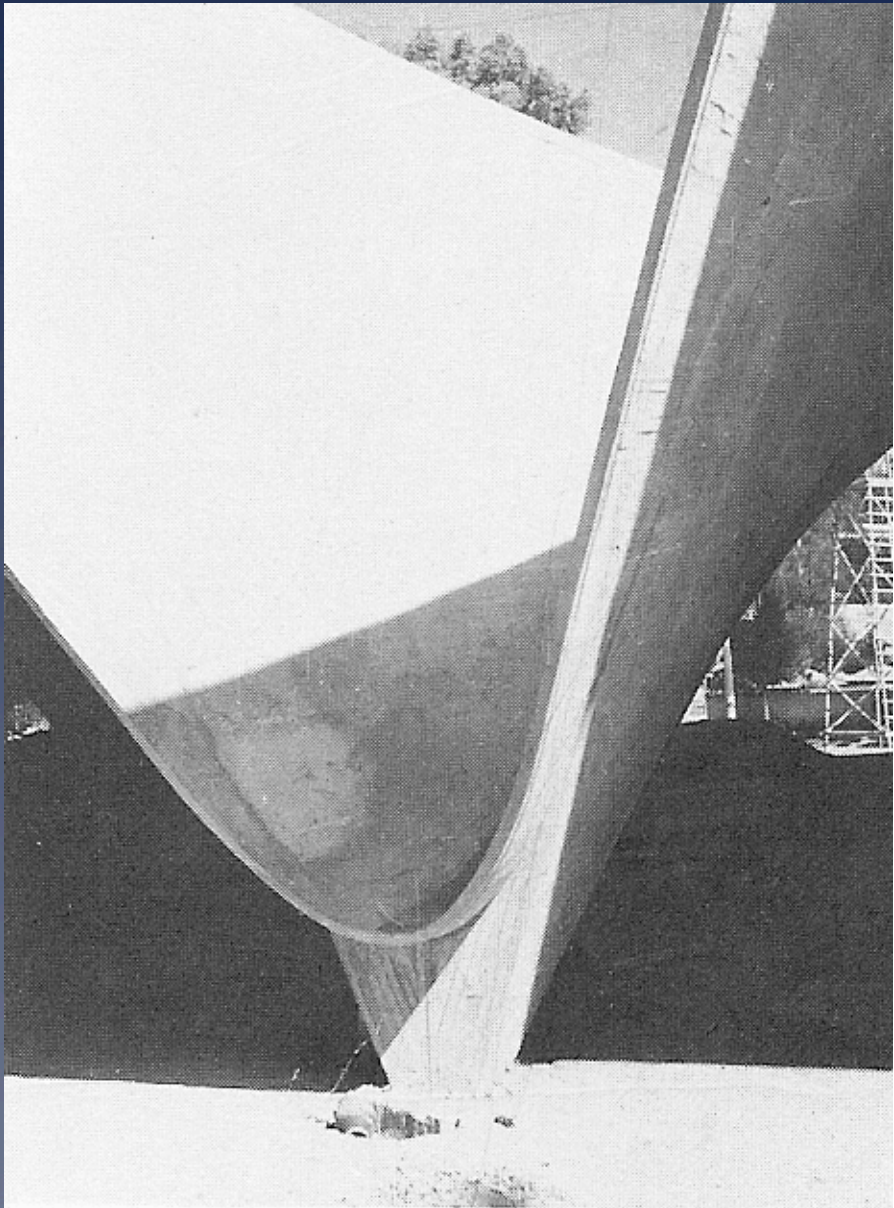




Photo: Structurae.de, Isono



Photo: Structurae.de, Isono