

A black and white photograph showing a construction worker from the side and slightly from behind. The worker is wearing a light-colored hard hat with a dark band, a high-visibility safety vest over a light shirt, and blue jeans. They are standing on a metal ladder or scaffolding, reaching up towards a large, curved concrete structure that appears to be under construction or repair. The concrete has several vertical and horizontal cracks. The background is dark and out of focus.

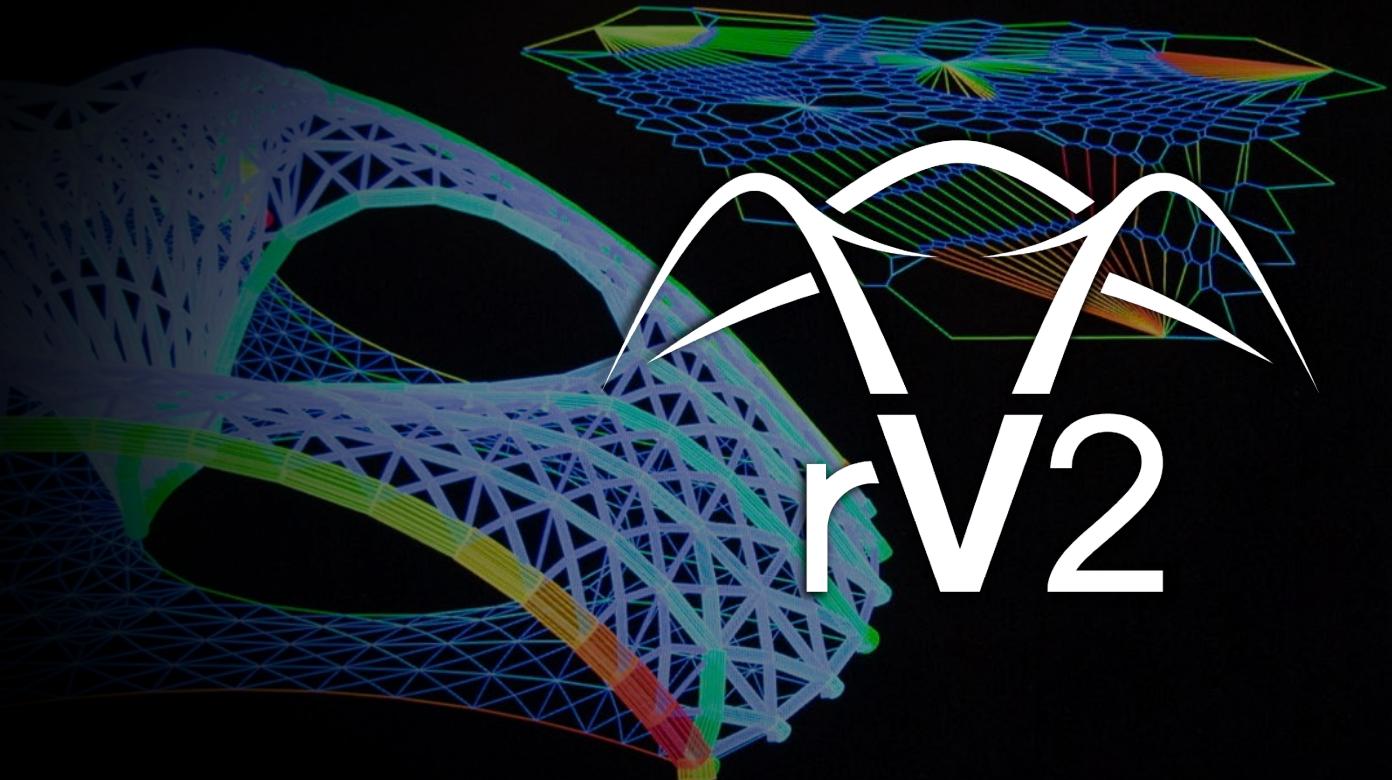
063-0606-22L : Computational Structural Design II
Structurally-informed Materialisation

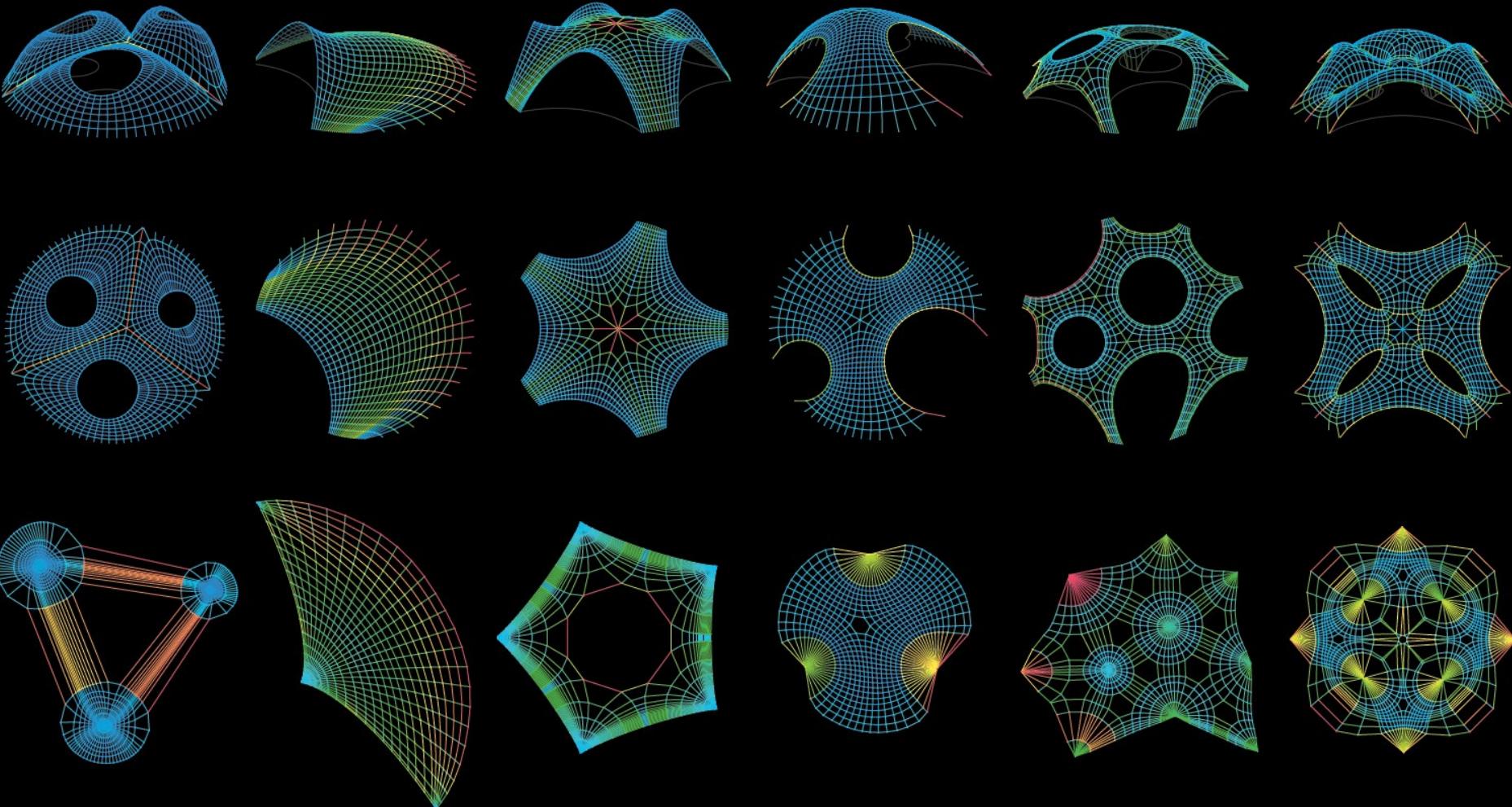
Lecture 2

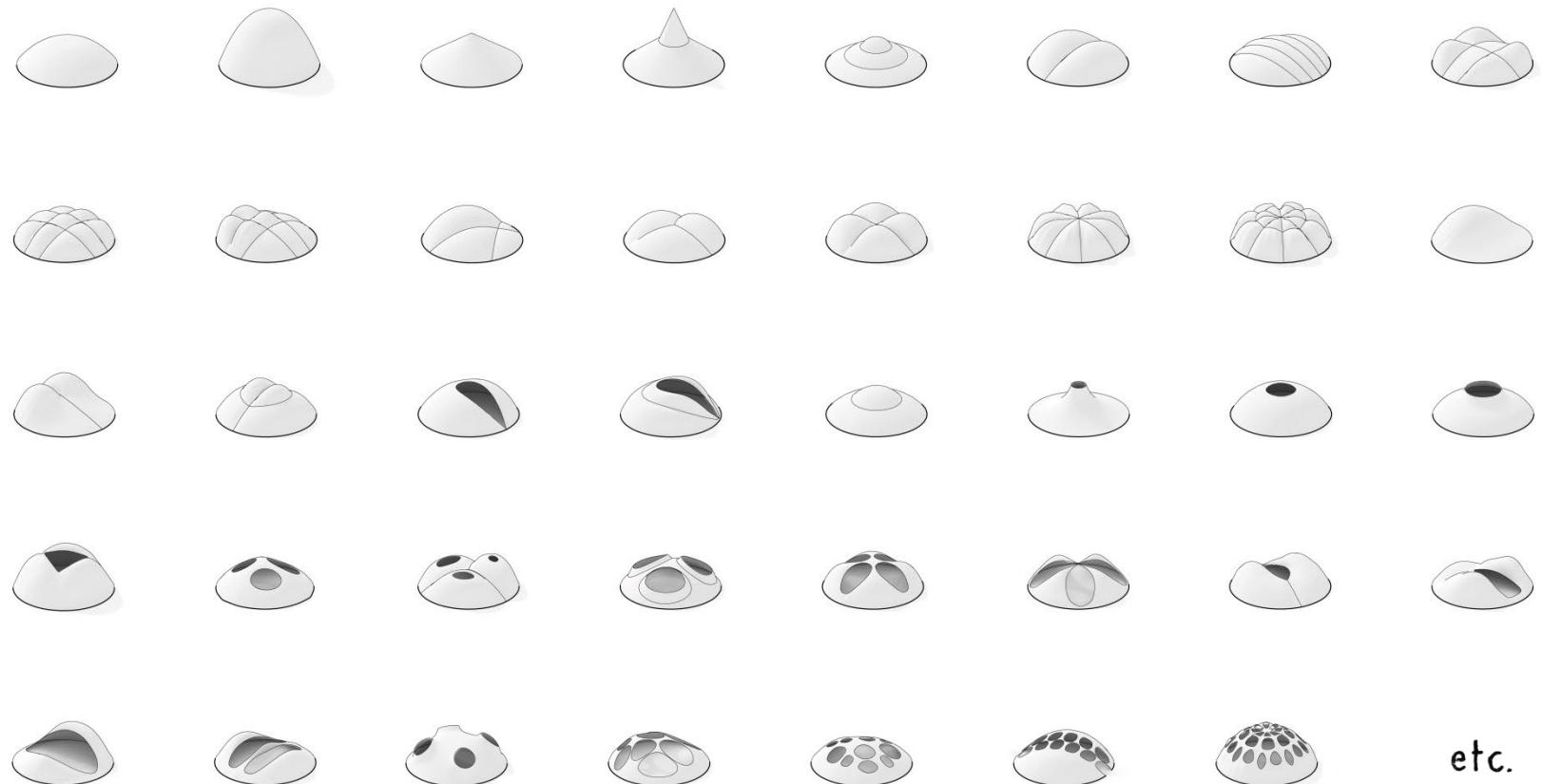
Materialisation of Funicular Shell Structures

Thursday, March 31st, 2022

Dr. Juney Lee













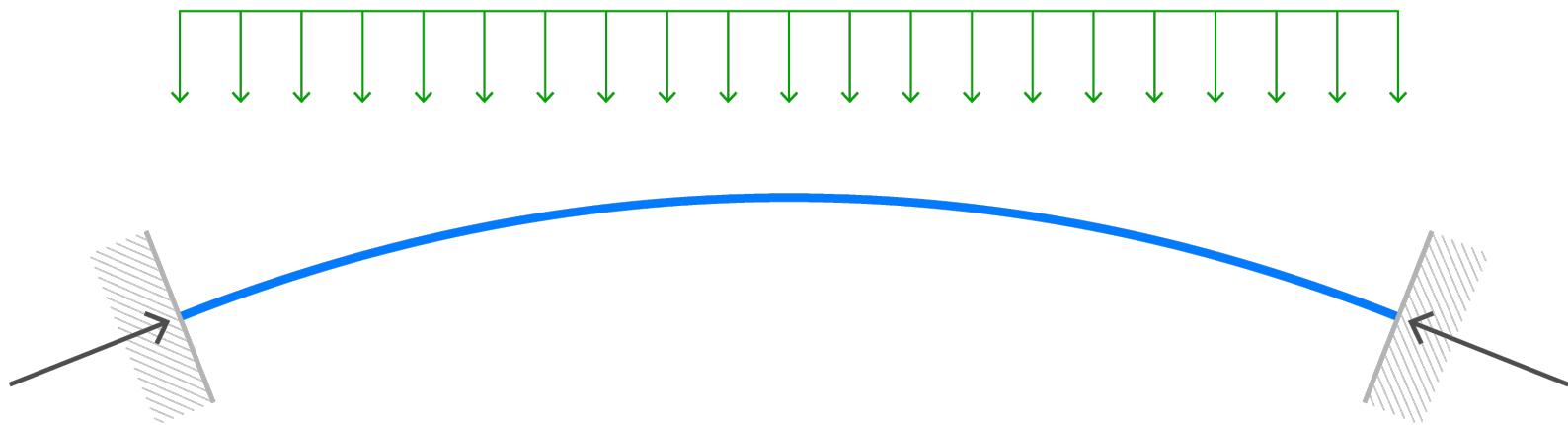


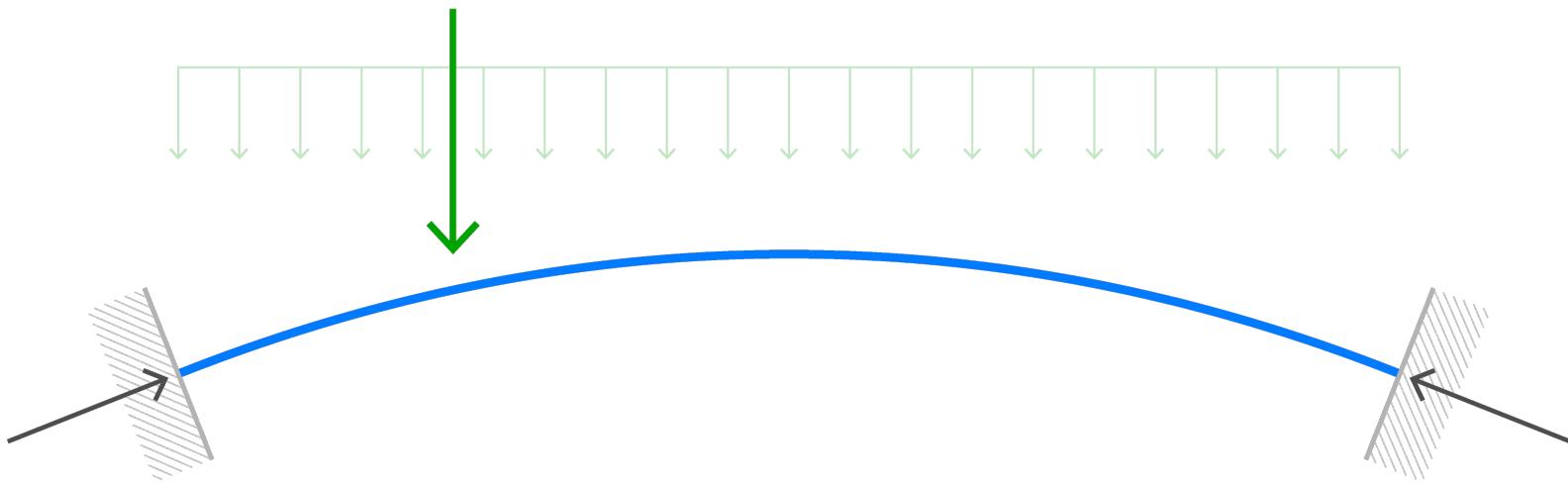
Physical Form Finding Models. | Isler Archive

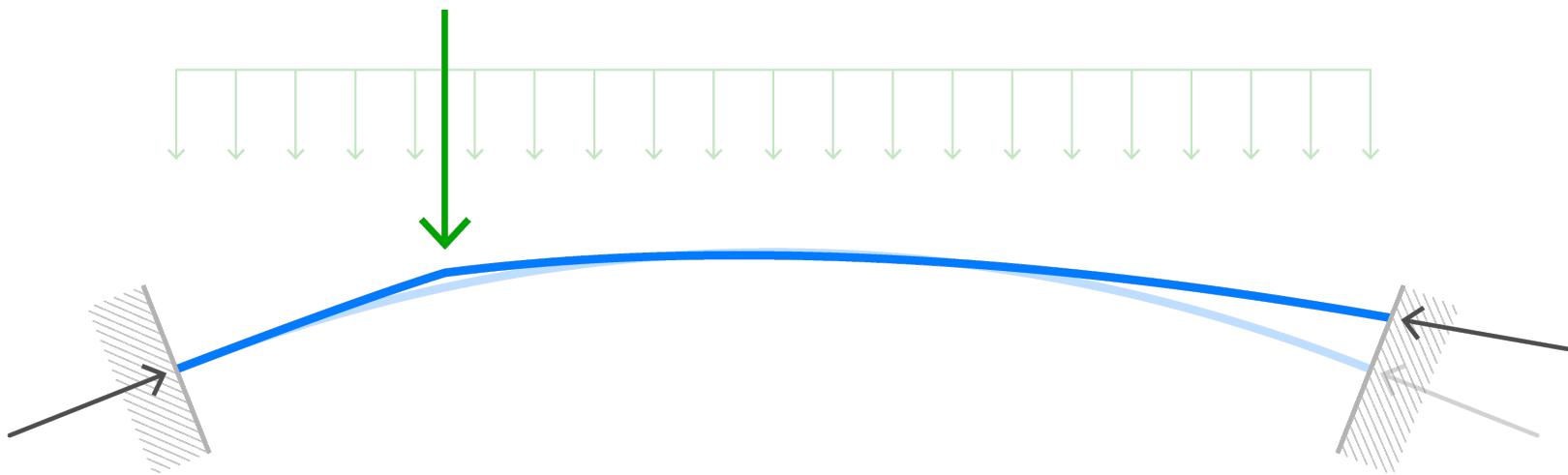


Tankstelle Deitingen Süd, Schweiz, 1968, Ing.: Heinz Isler | solothurnerzeitung.ch









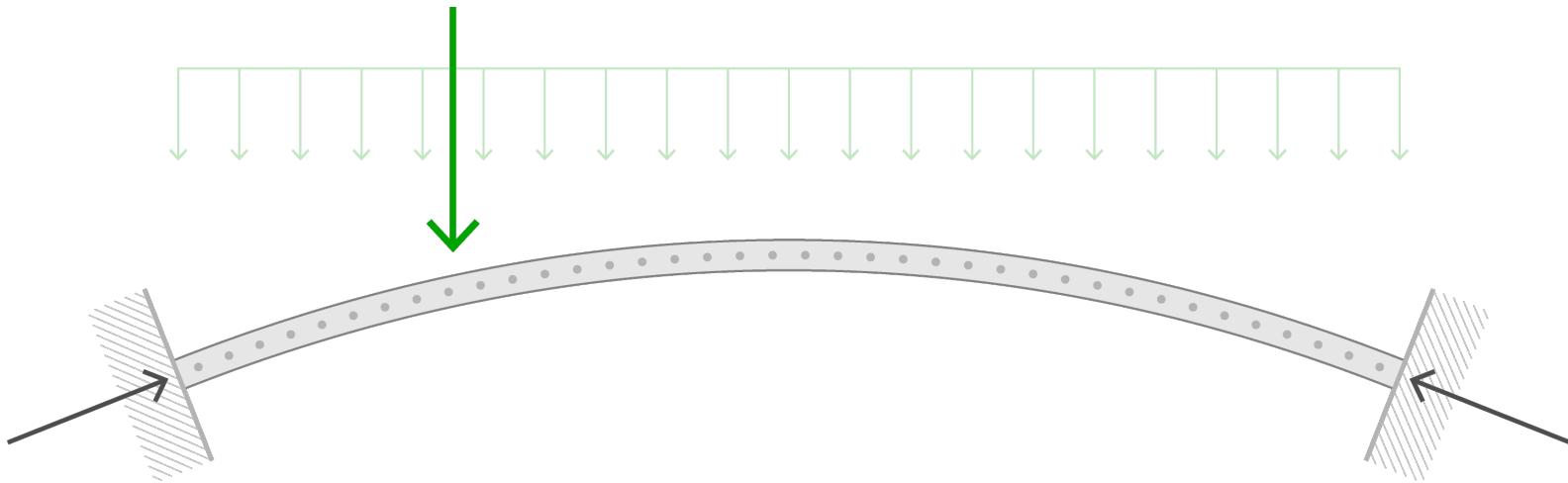
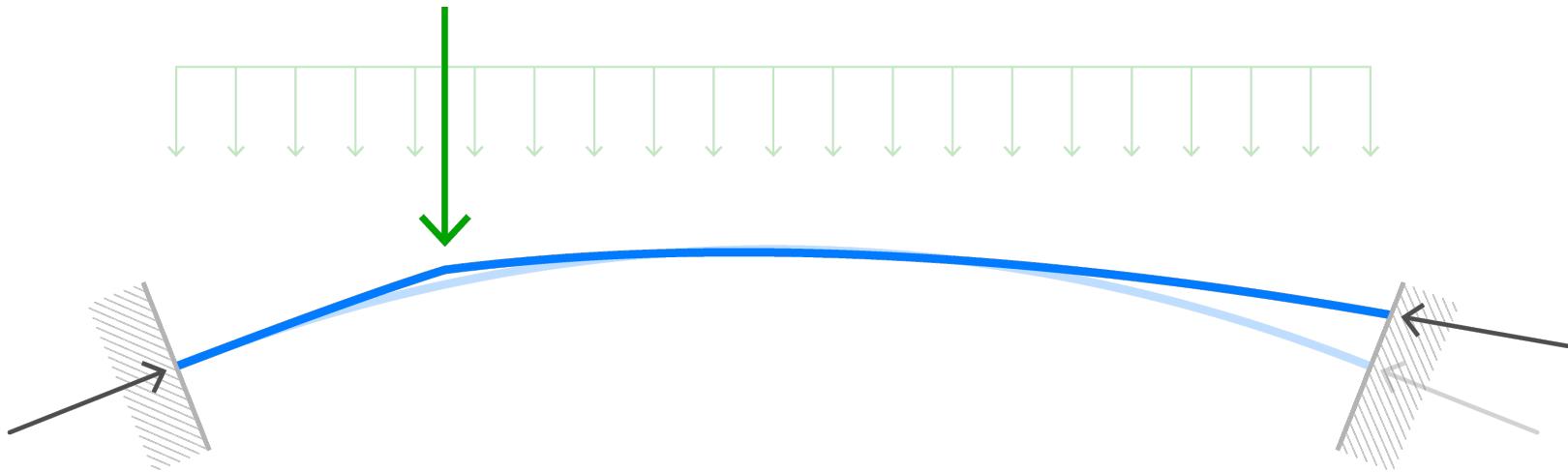
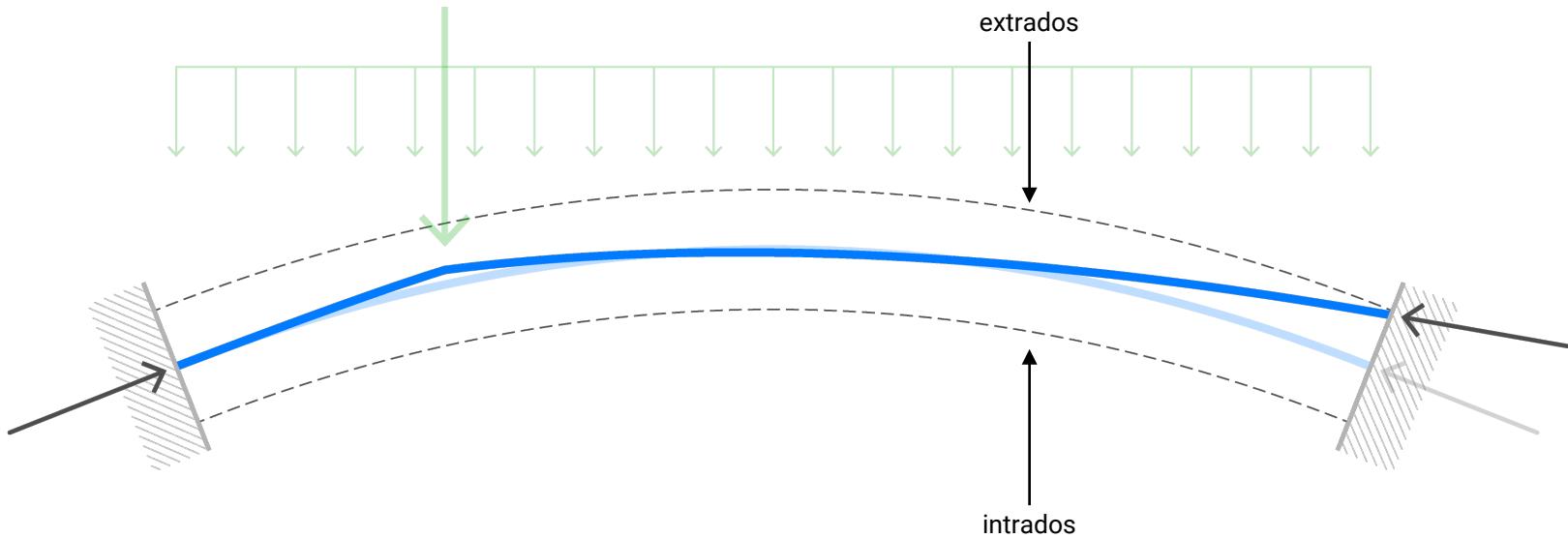


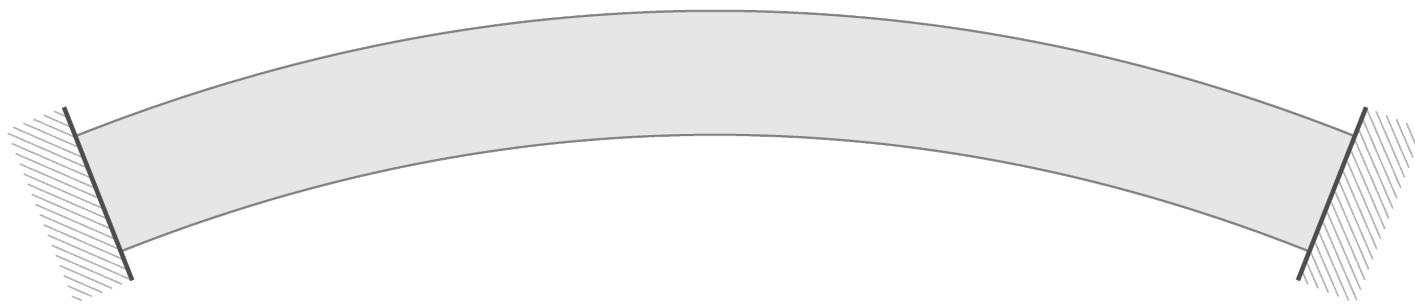


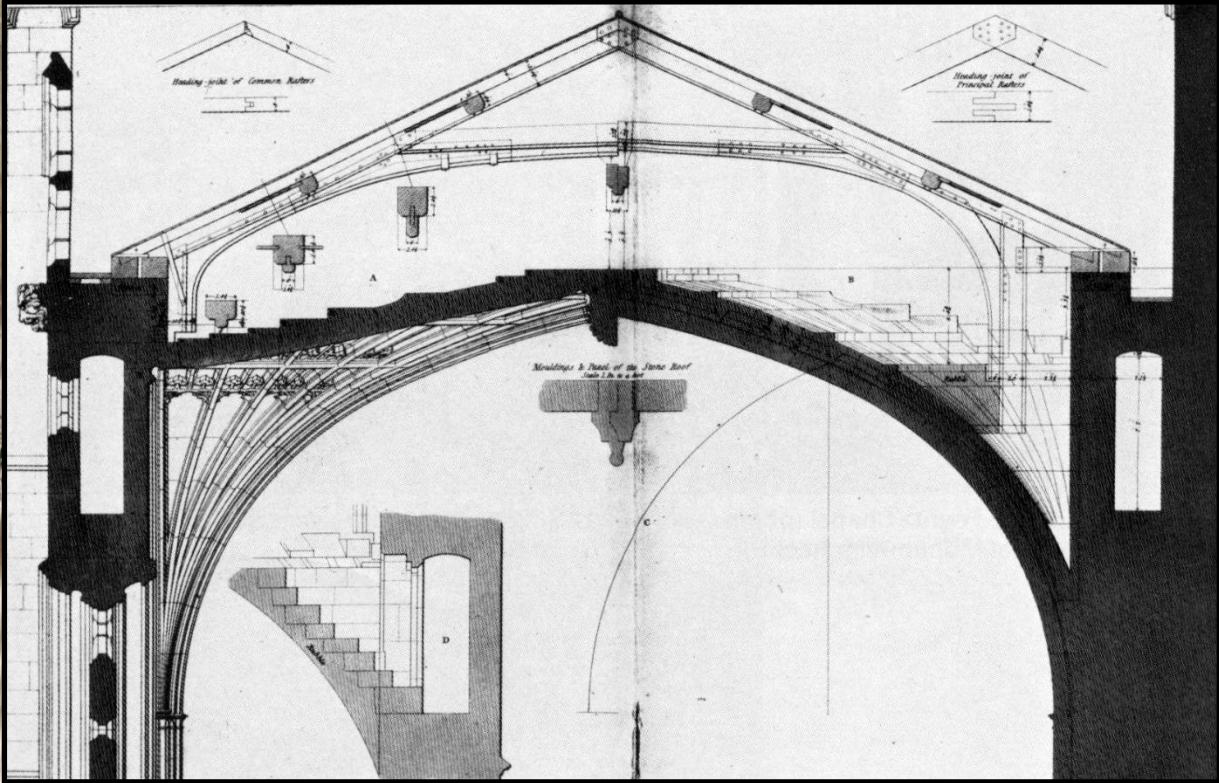


Photo: Alexander Eisenschmidt

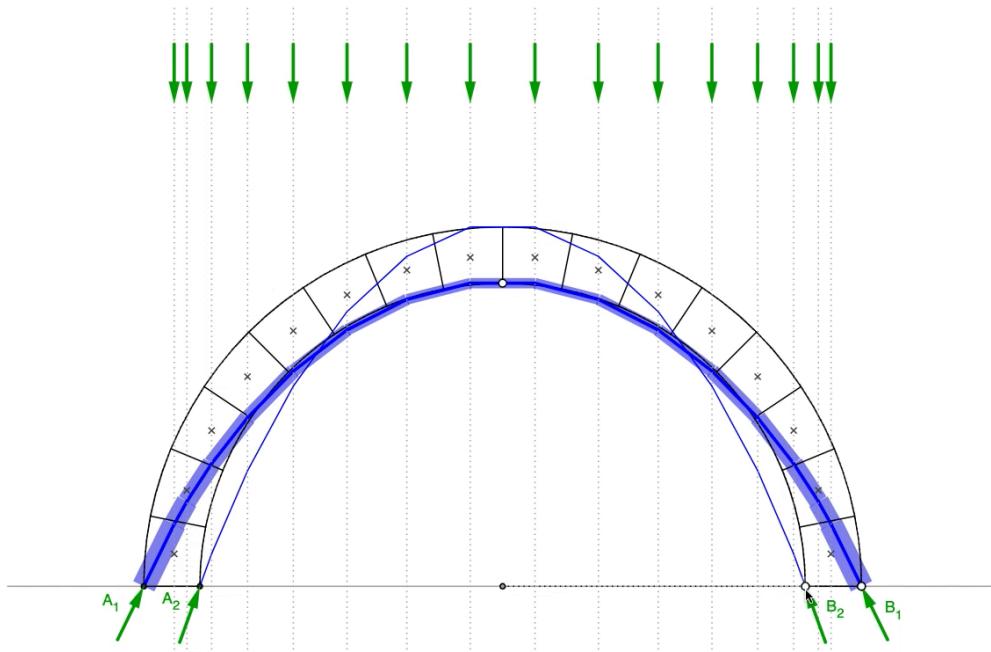




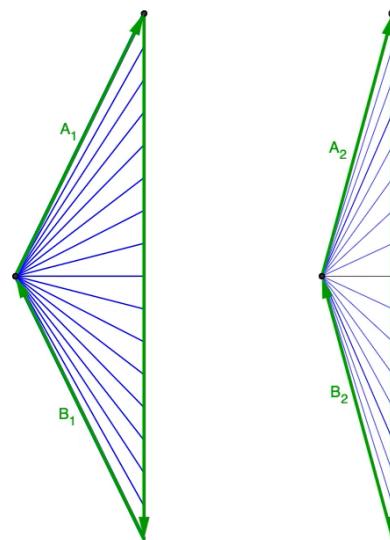




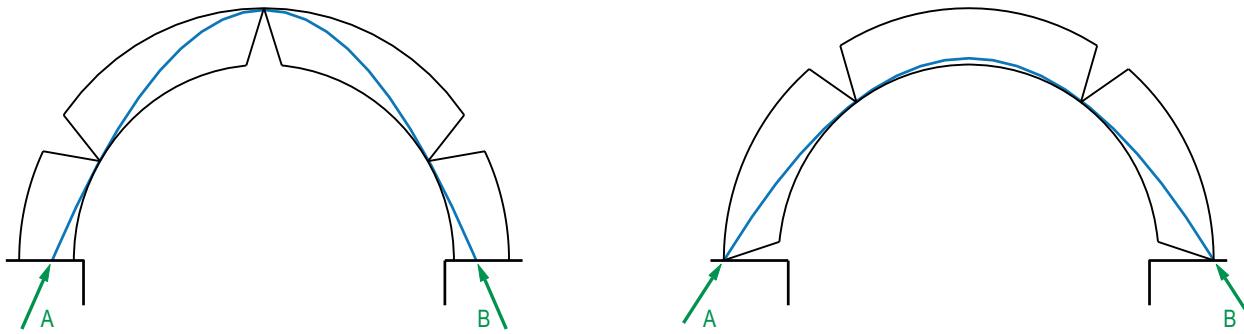
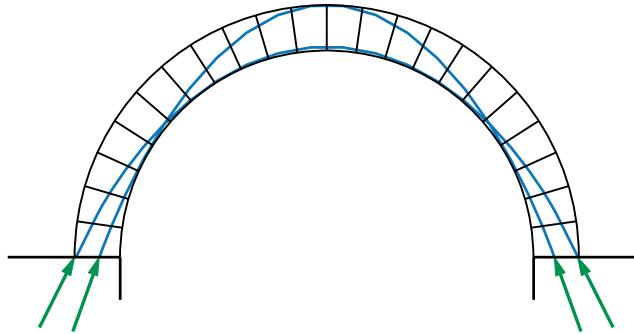
Form Diagram



Force Diagram

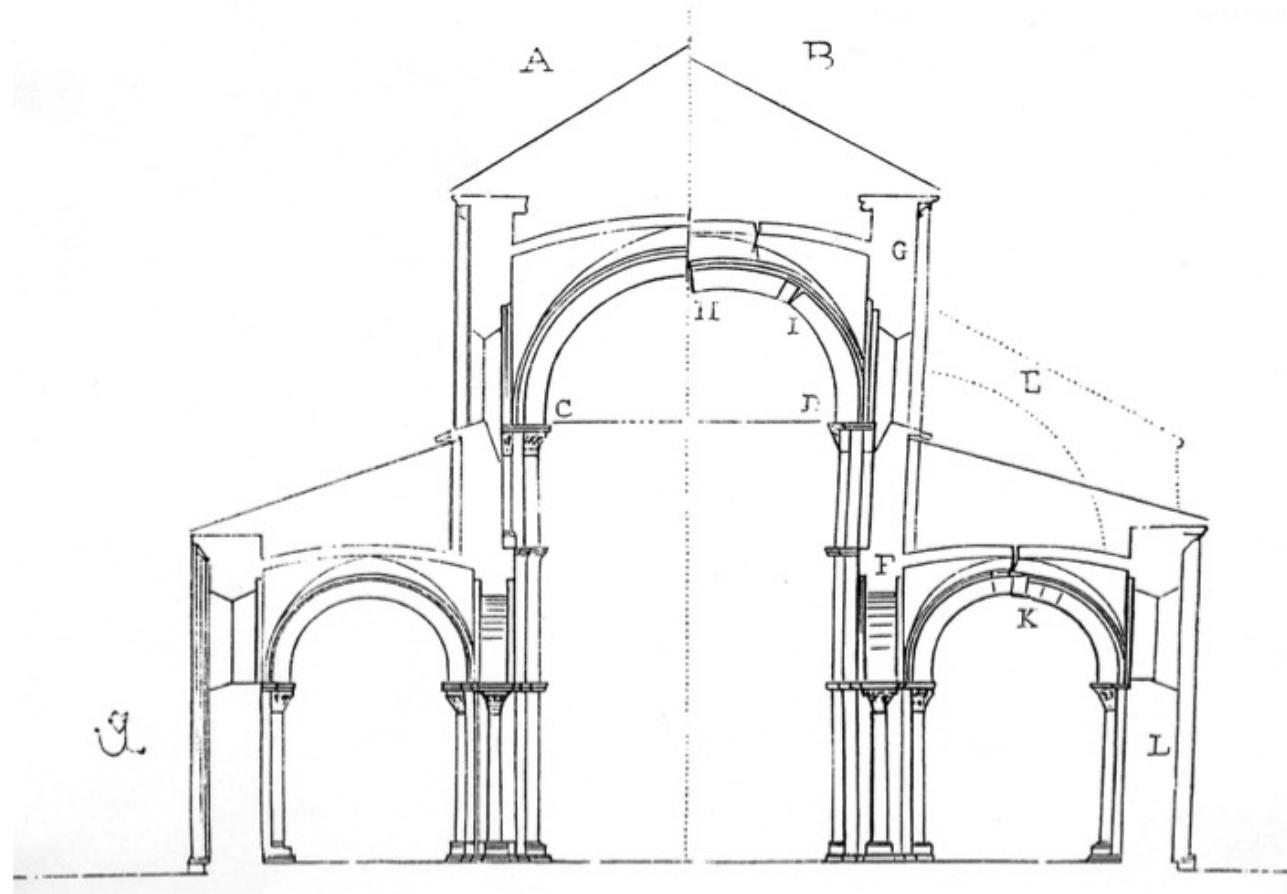


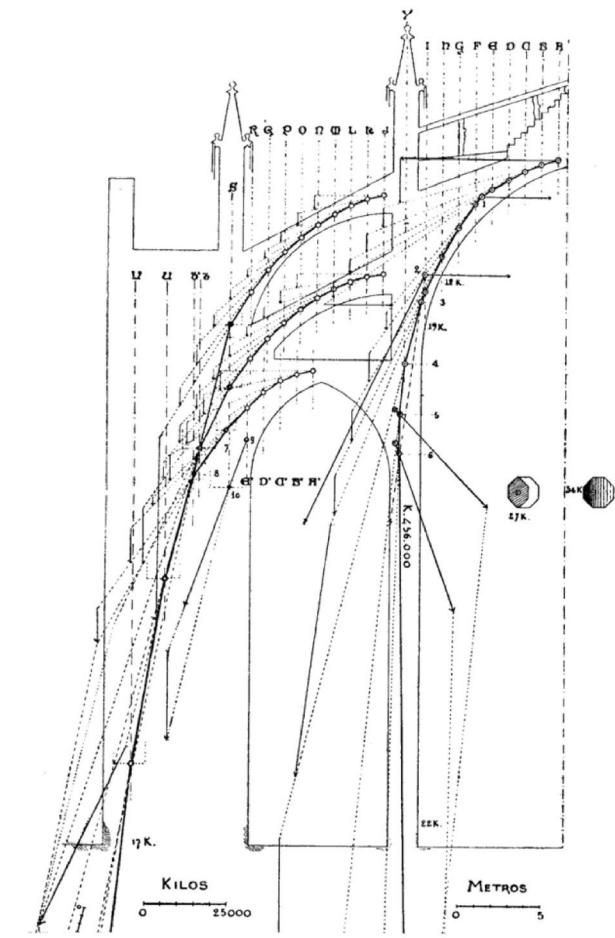
Note: The thrust line has to be contained within the bounding geometry for the arch to be stable.





The Taq Kisra, Ctesiphon, Iraq (6th century)

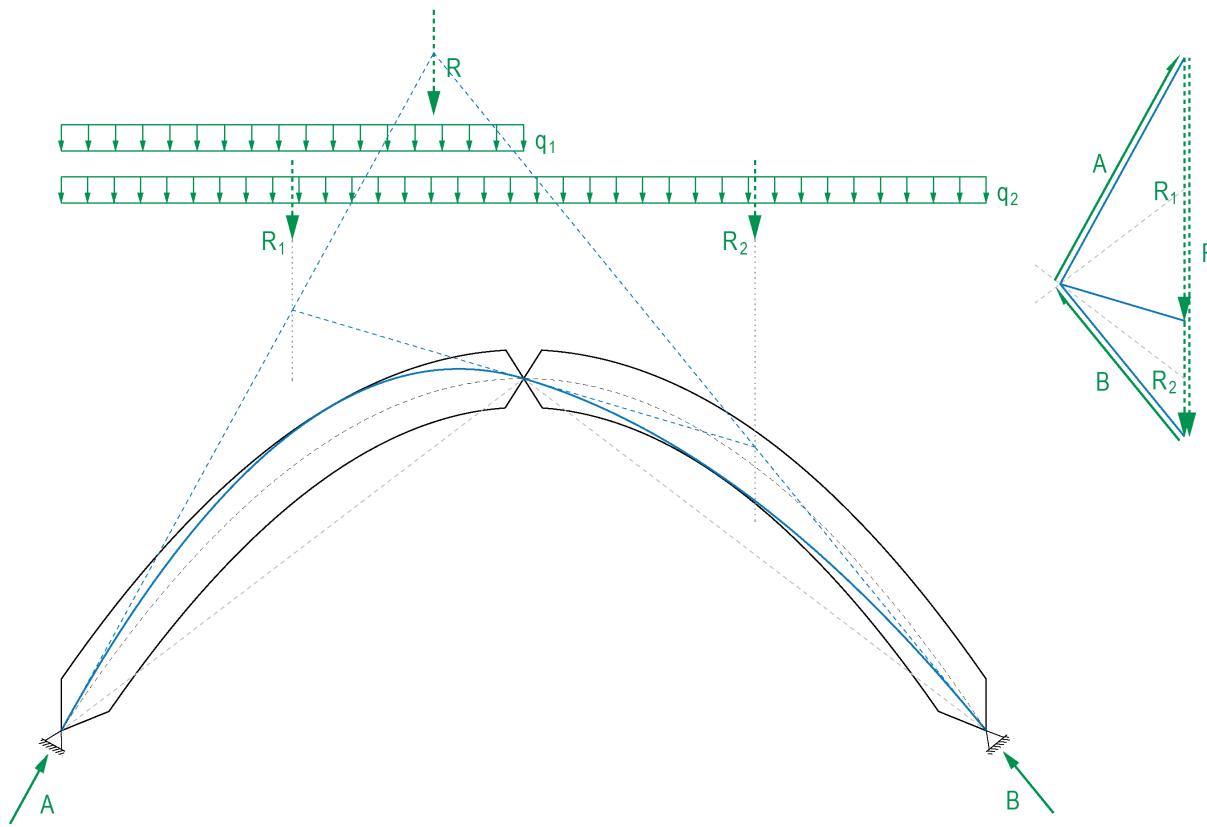




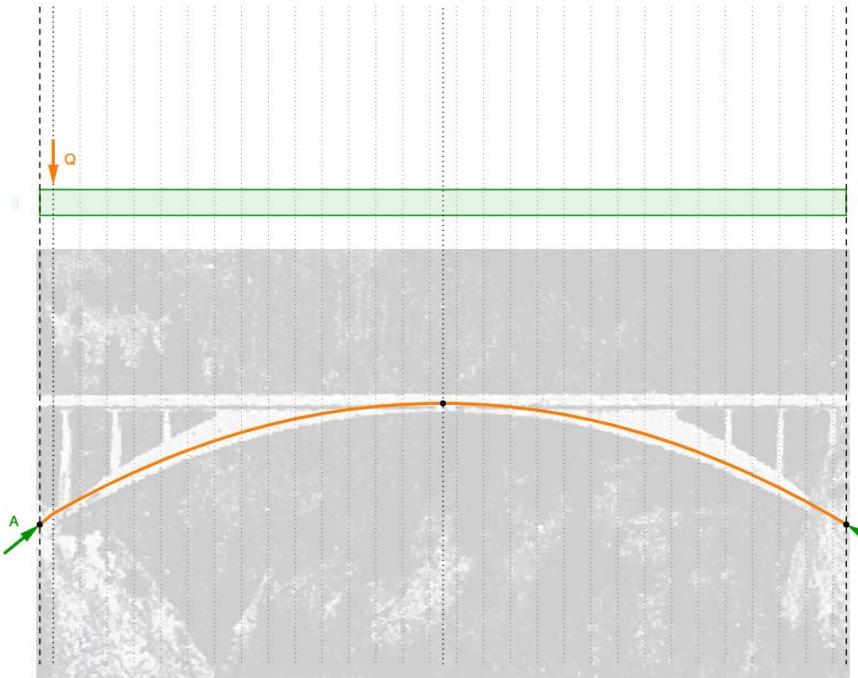


Saignatobel Bridge, Switzerland | Robert Maillart (1914)

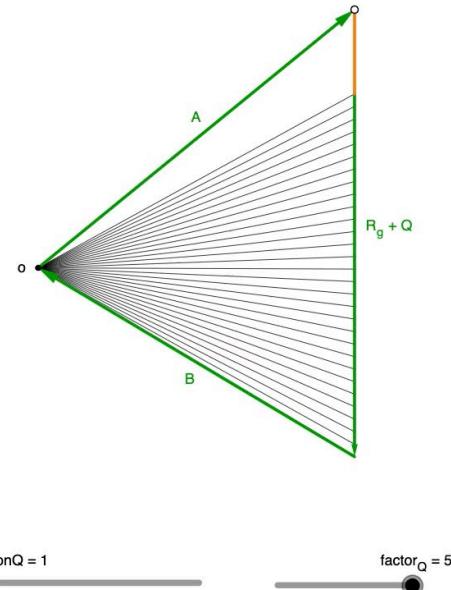
Photo: Robert Maillart Archives

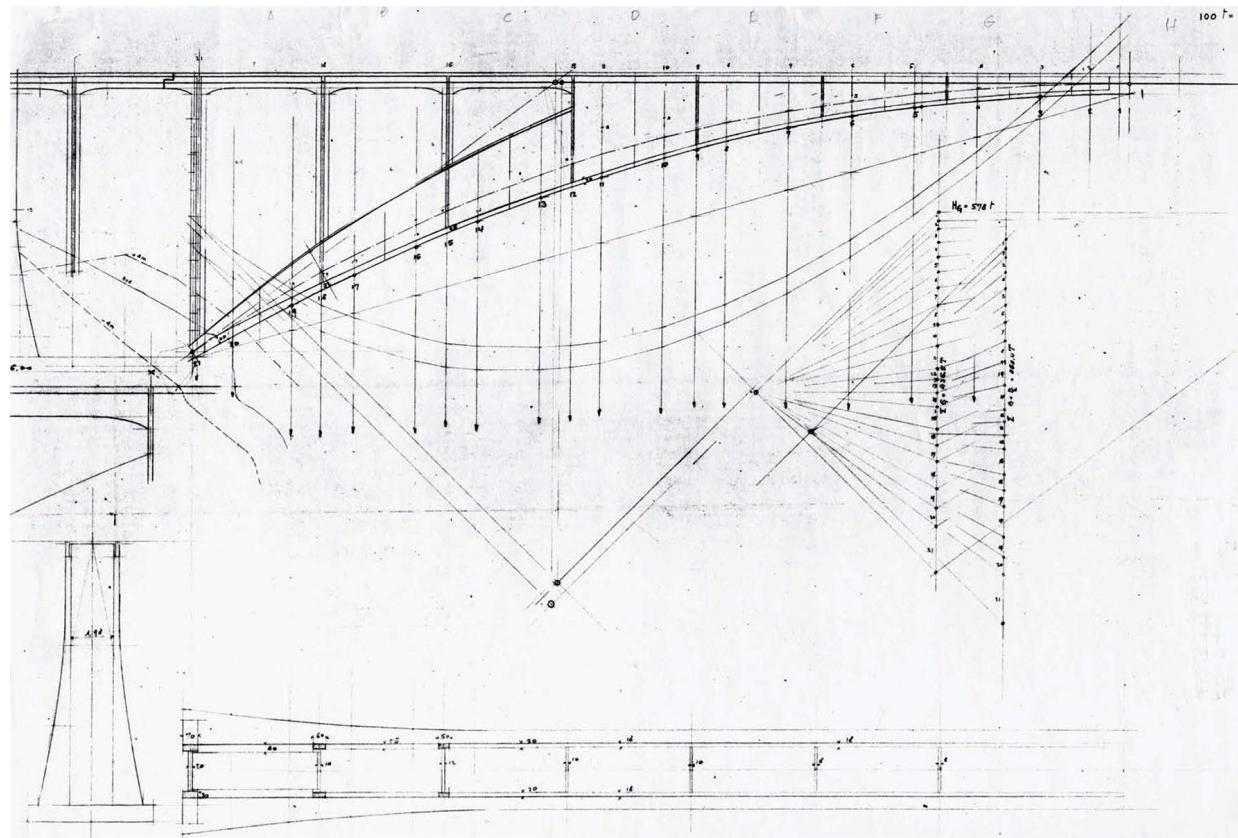


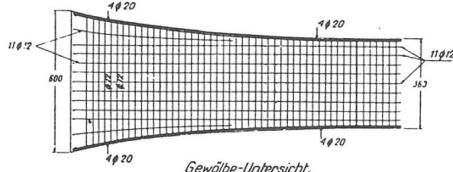
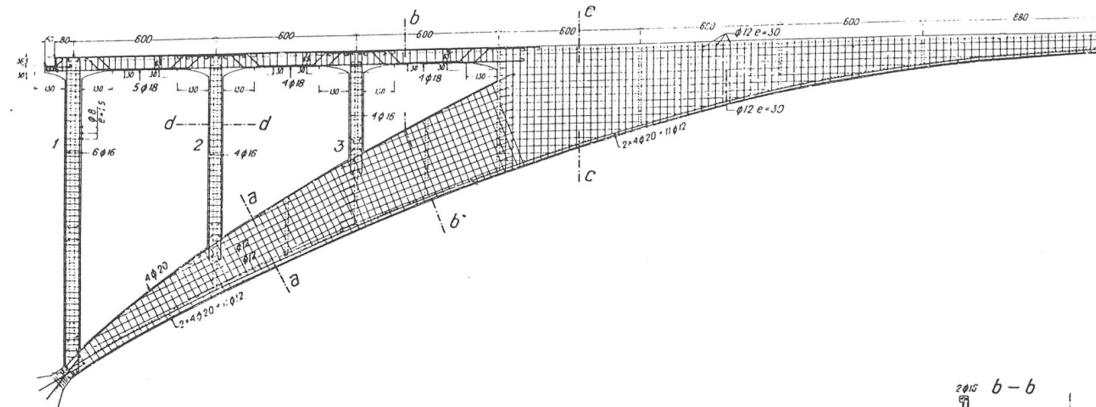
Form Diagram



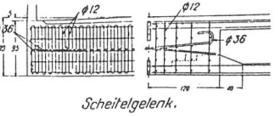
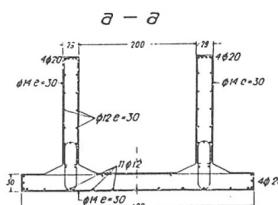
Force Diagram



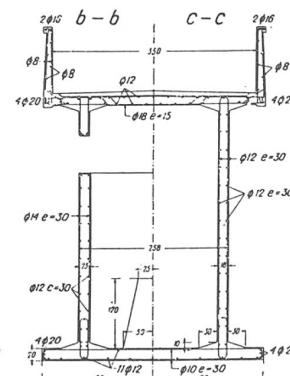




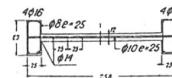
Gewölbe-Untersicht.



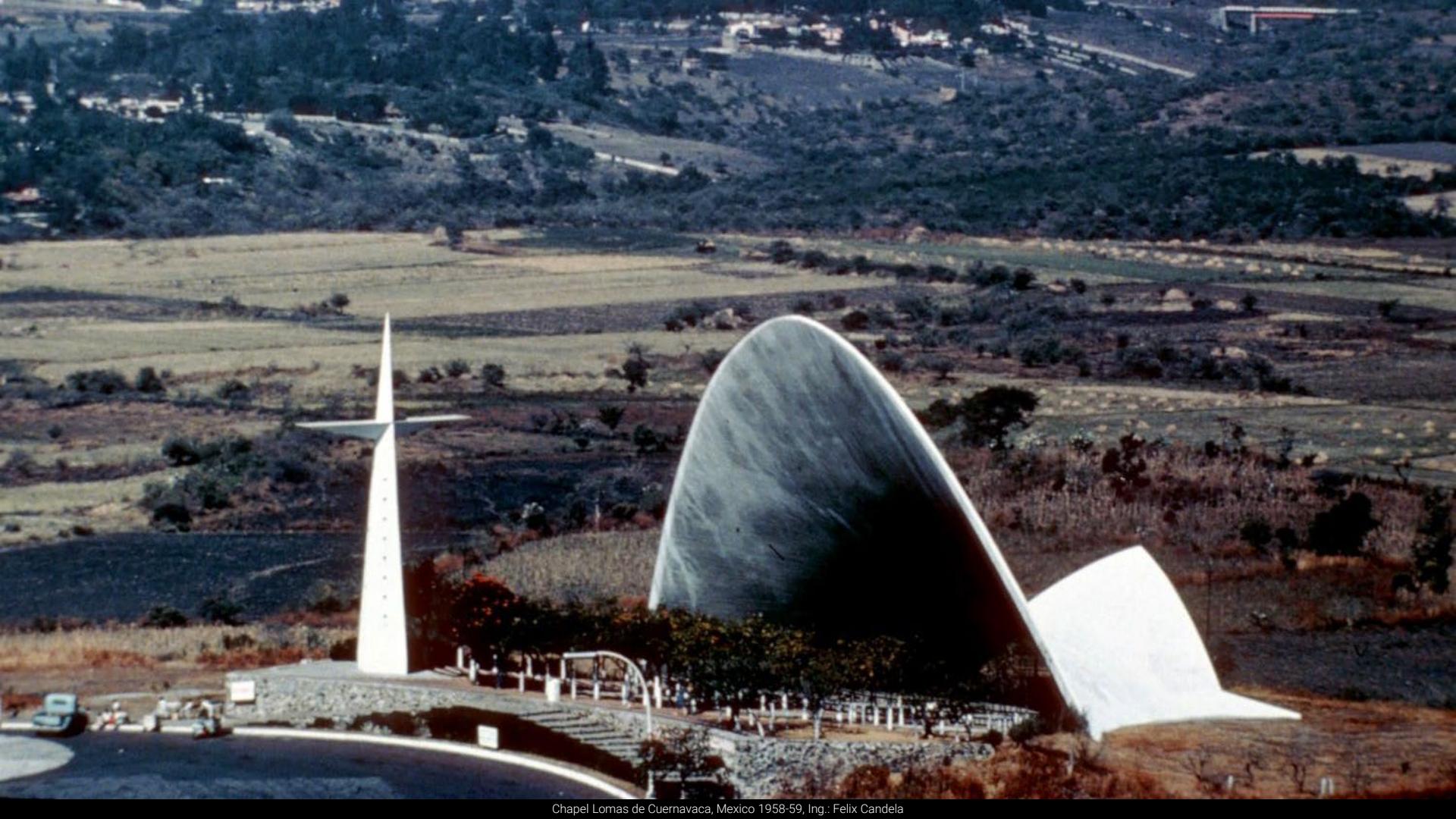
Scheitelgelenk.



d - d







Chapel Lomas de Cuernavaca, Mexico 1958-59, Ing.: Felix Candela



Chapel Lomas de Cuernavaca, Mexico 1958-59, Ing.: Félix Candela



© Iwan Baan

Rolex Learning Center, EPFL | SANA (2010)



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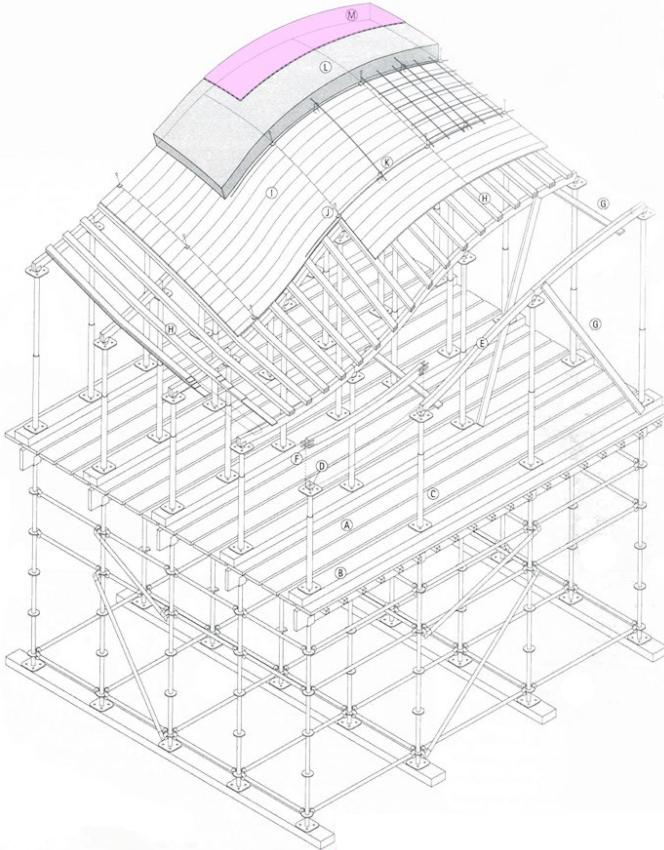


Alain Herzog, © Fabian Scheurer / desinoproduction



Kakamigahara crematorium, Toyo Ito (2006) | Photo: Iwan Baan

A. Piso elevado de trabajo formado con estructura de andamios y tablones de madera.
 B. Durmiente de madera para apoyo de puentes.
 C. Puntal regulable en altura.
 D. Pinza para soporte de vigas.
 E. Viga de madera compuesta por dos tableros contrachapados de 100x25 mm cortada en taller.
 F. Pieza metálica para unión atornillada entre las piezas de la viga.
 G. Tabla para arrastamiento.
 H. Correas cada 25 cm formadas por la superposición de 5 listones de 75x12 mm encolados entre sí.
 I. Superficie de hormigonado formada por tablas de 150 mm de anchura.
 J. Separador para armadura inferior.
 Marca el espesor total a hormigonar.
 K. Separador para armadura superior.
 L. Losa de hormigón armado con 20 cm y capa de mortero de regularización.
 M. Pintura impermeabilizante de poliuretano con 3 mm.

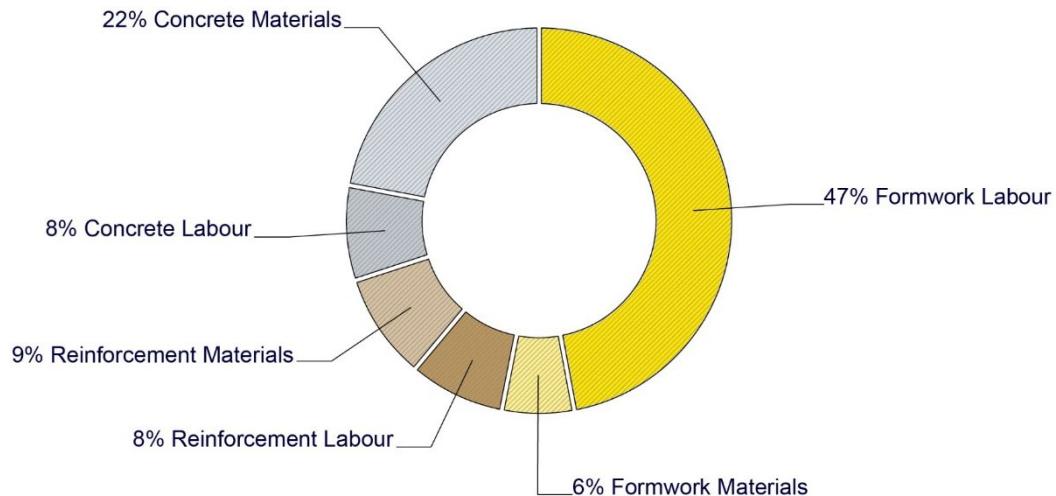


Ramon Muñoz © Toyo Ito



Kakamigahara crematorium, Toyo Ito (2006) | Photo: Iwan Baan

Cost of concrete formwork





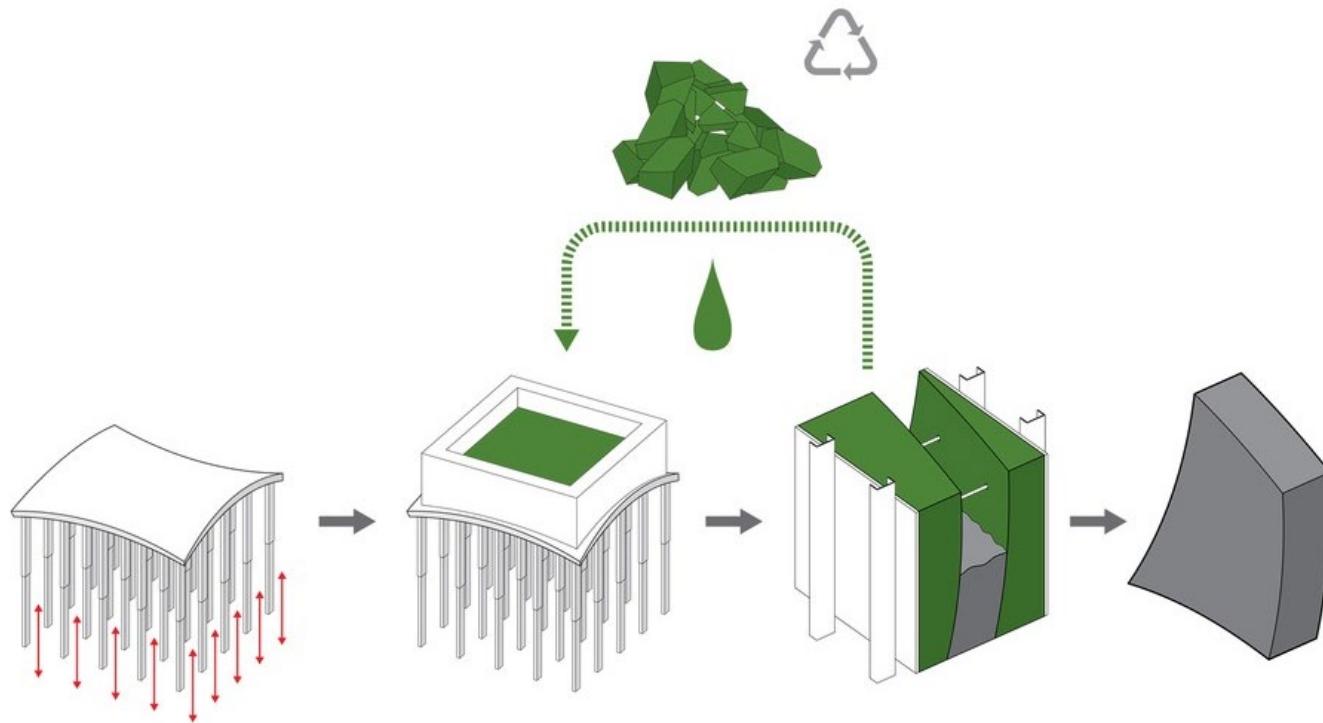
TailorCrete demonstrator, Superpool, Danish Technological Institute (2014)



Robotic EPS foam milling



Odico, Robotic hot-wire and hot-blade cutting





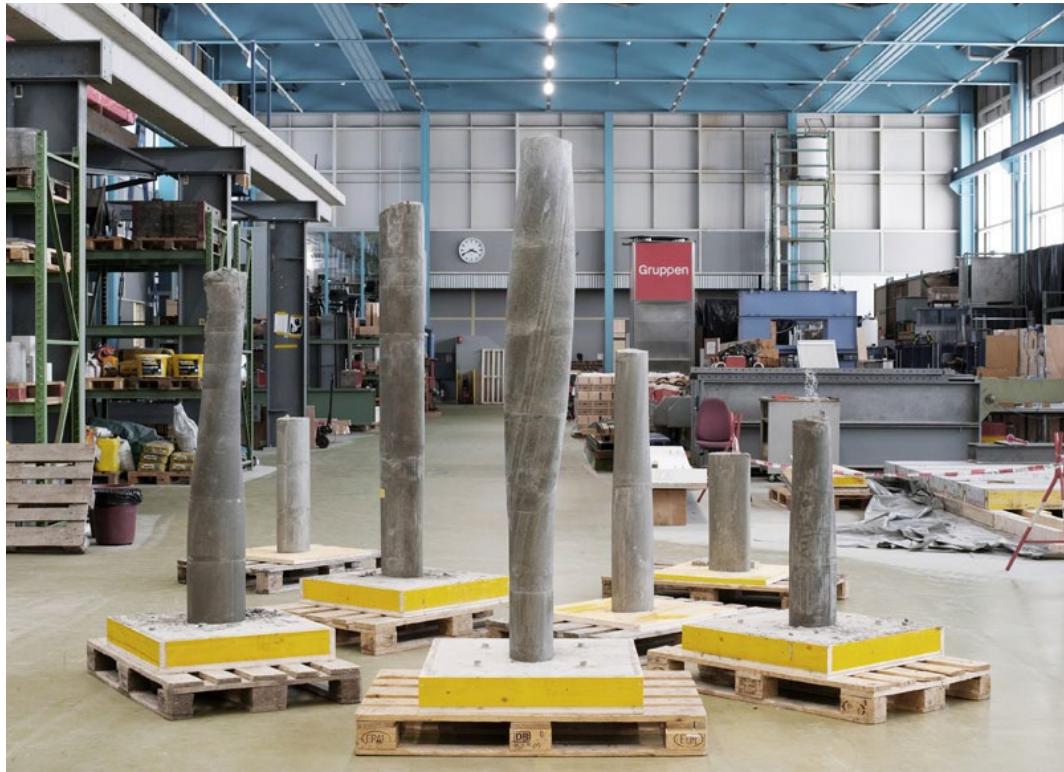
TailorCrete, Gramazio Kohler Research, ETH Zurich (2009-2013)



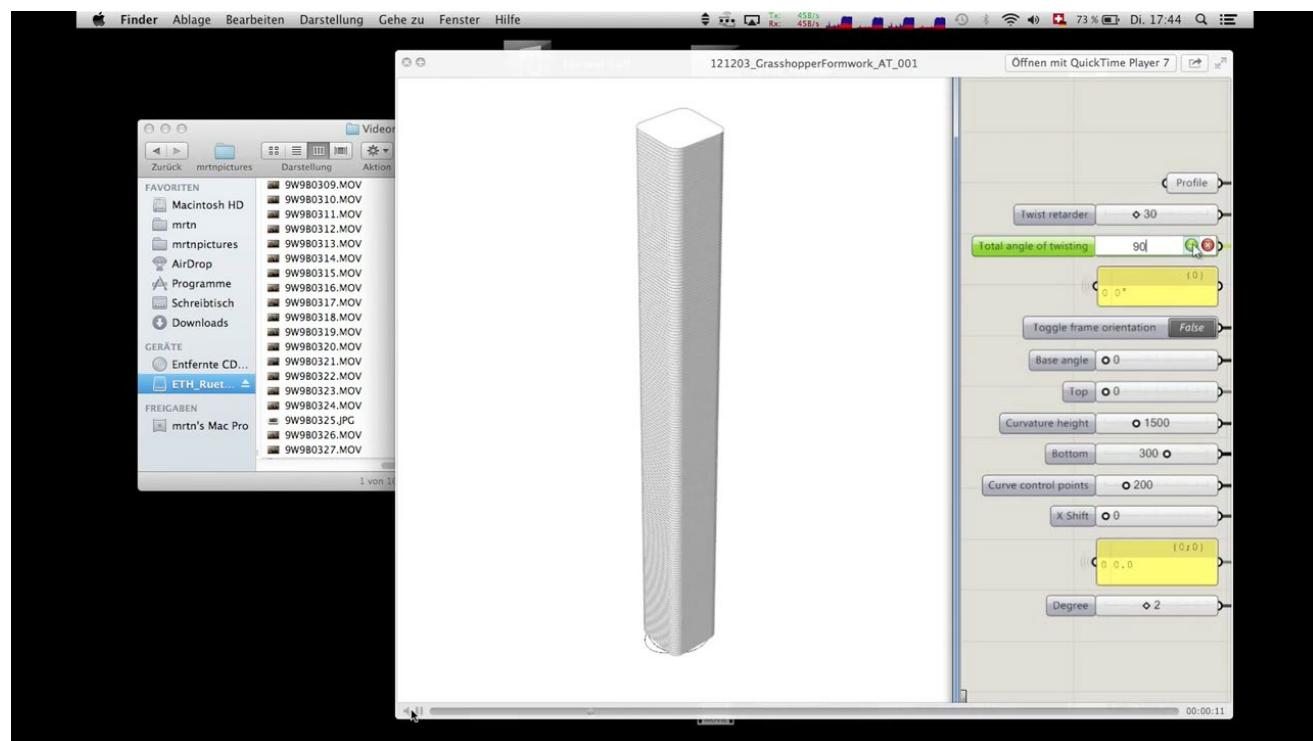
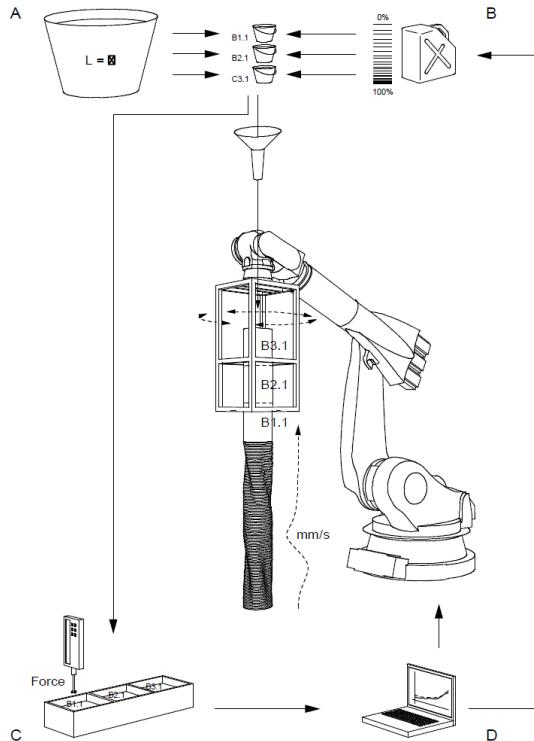
Palazzetto dello Sport, Rome, Italy, 1957 | Pier Luigi Nervi

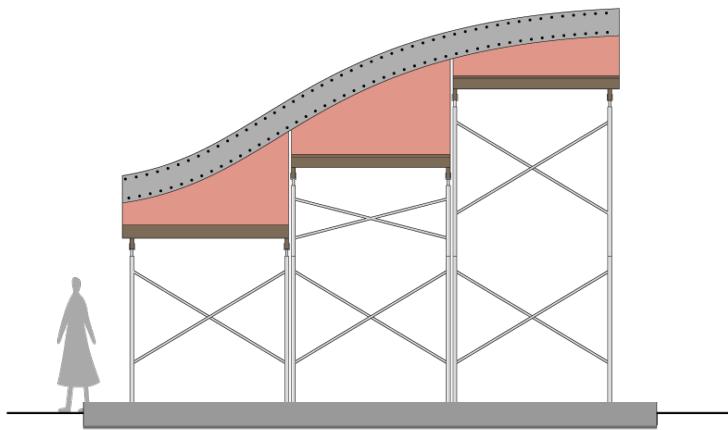


Palazzetto dello Sport, Rome, Italy, 1957 | Pier Luigi Nervi

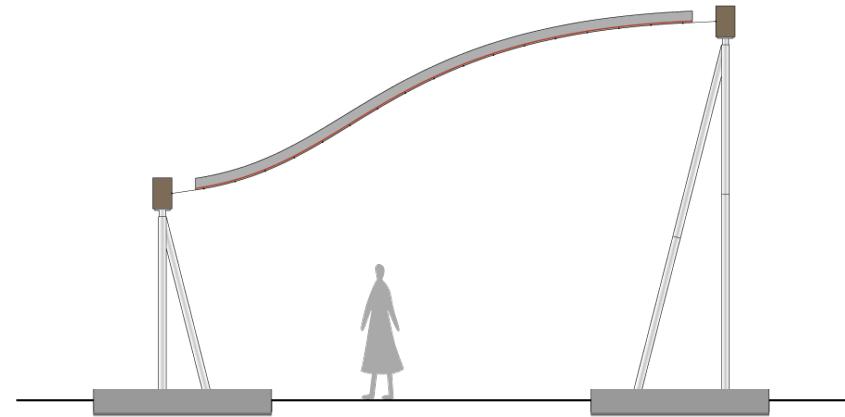


Smart Dynamic Casting - Gramazio Kohler Research, ETH Zurich (2012-)

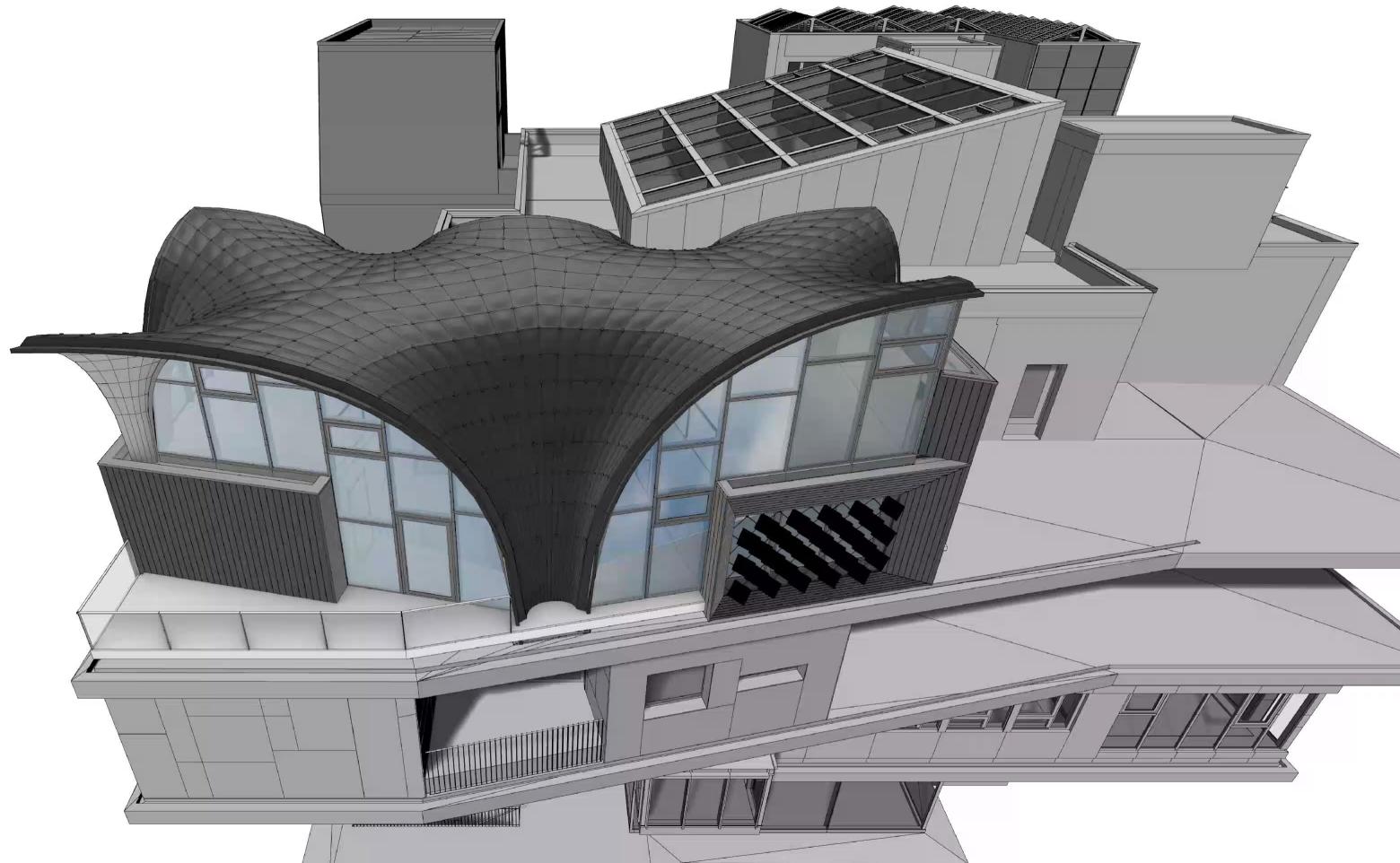




Traditional rigid formwork



Lightweight flexible formwork



HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)



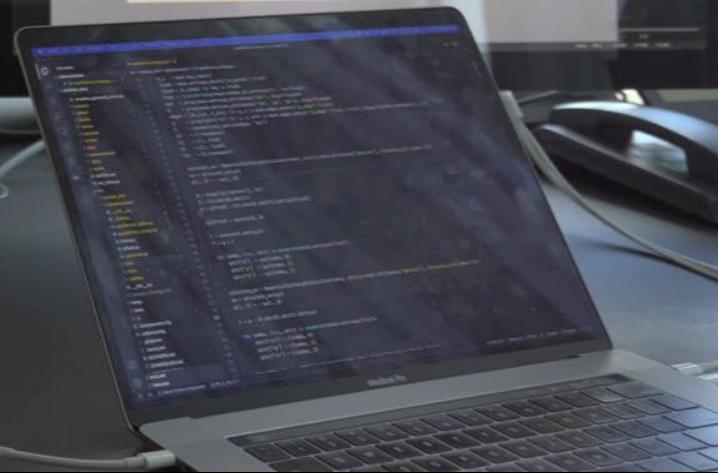
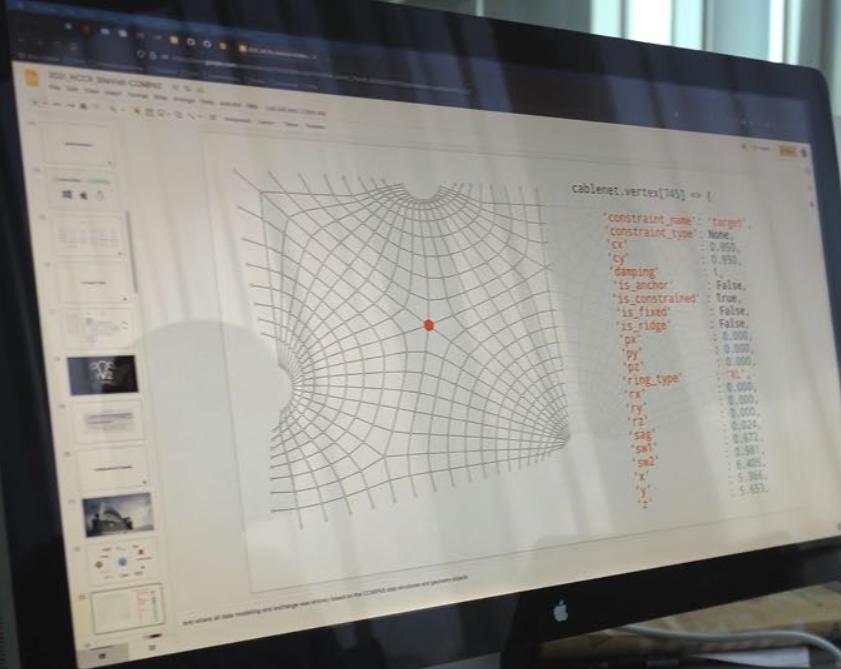


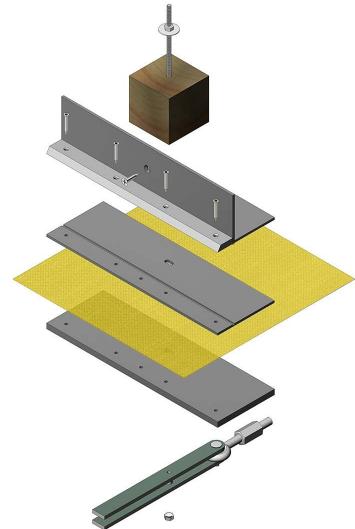
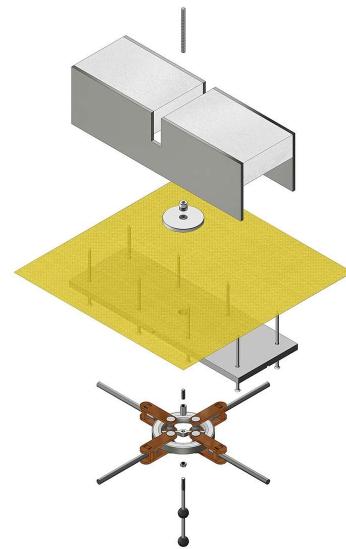
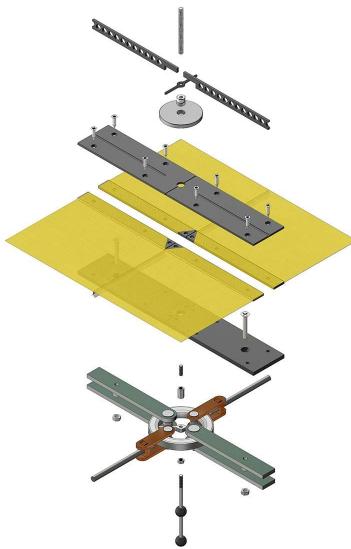
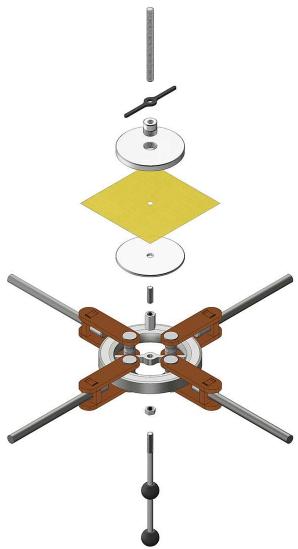
HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)



Photos: Juney Lee

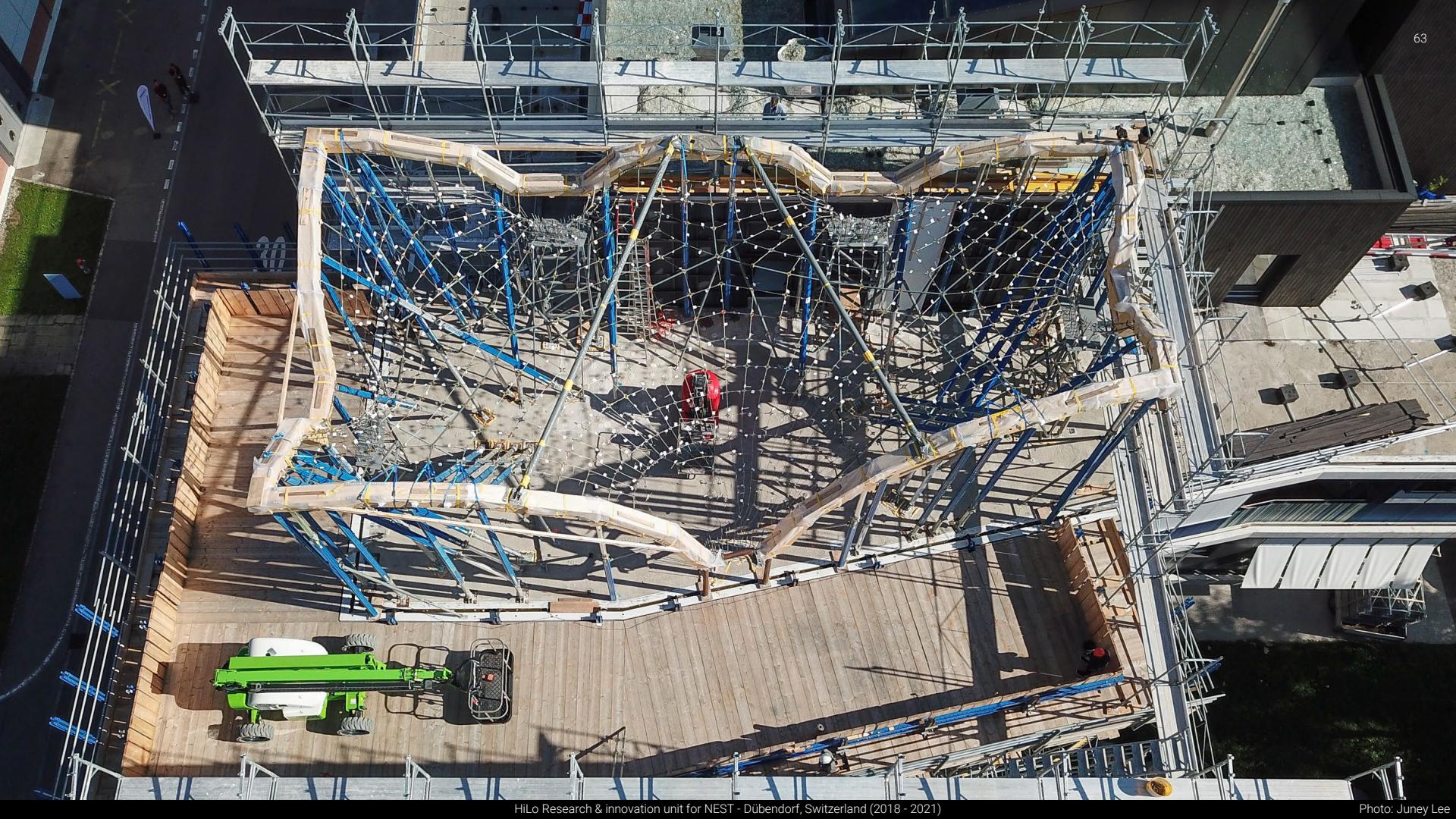








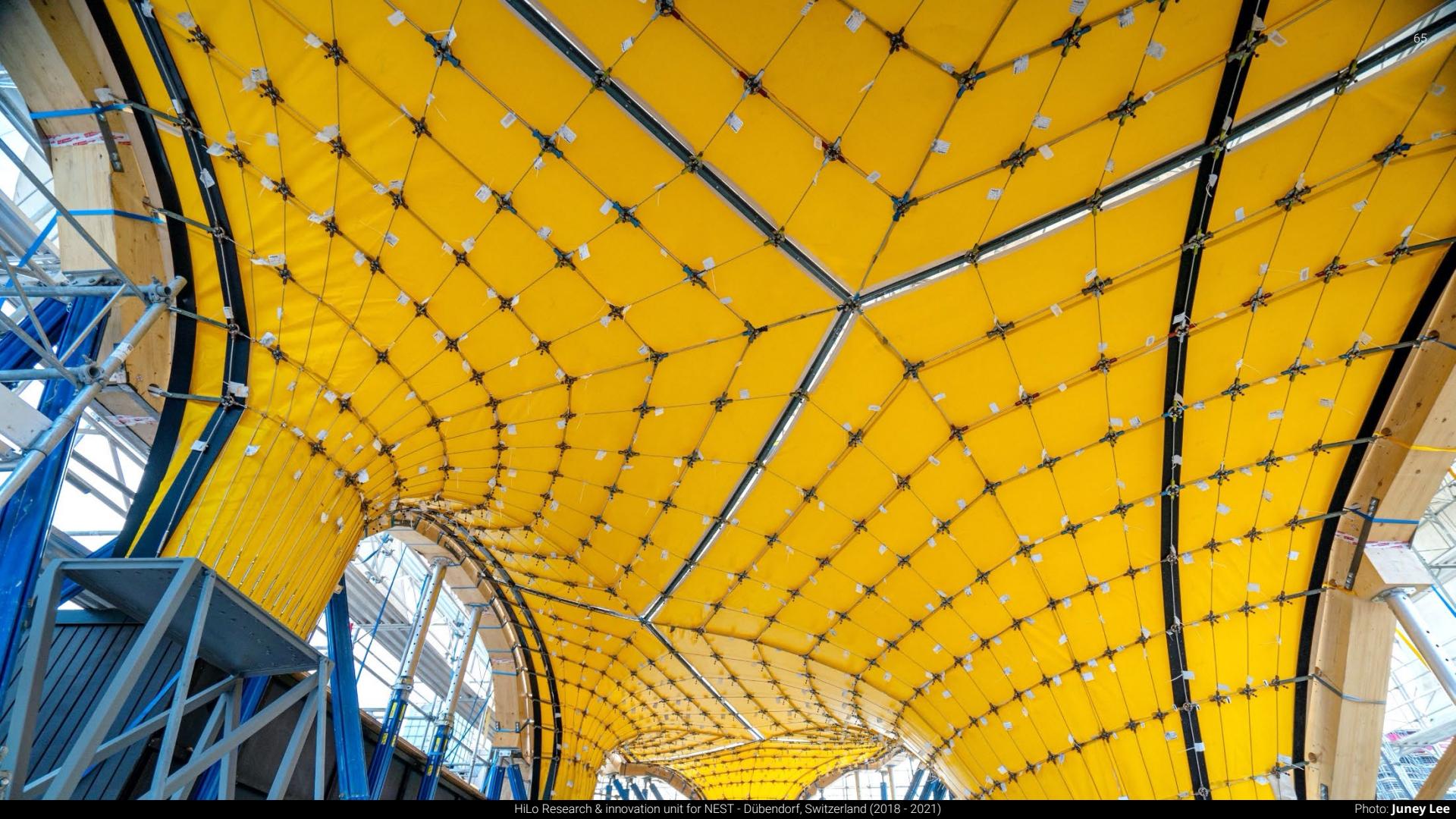




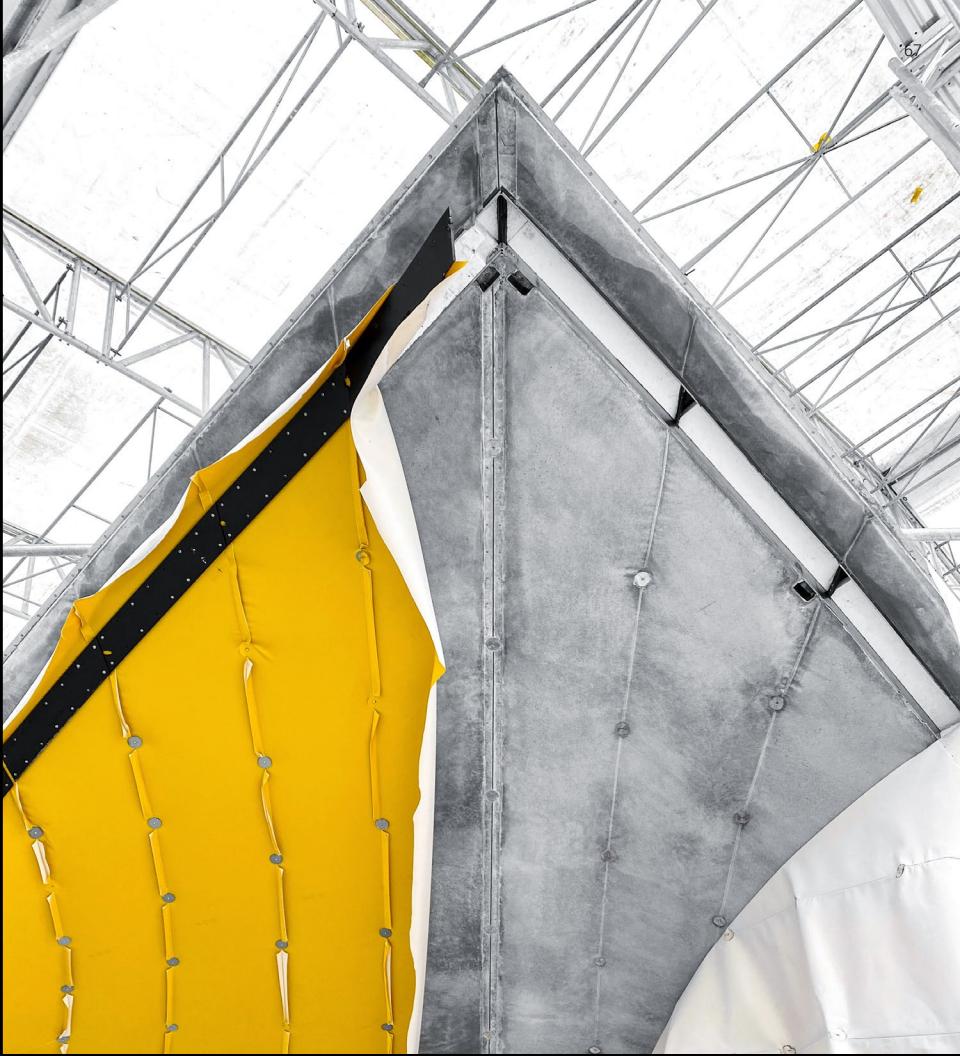
HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)

Photo: Junye Lee









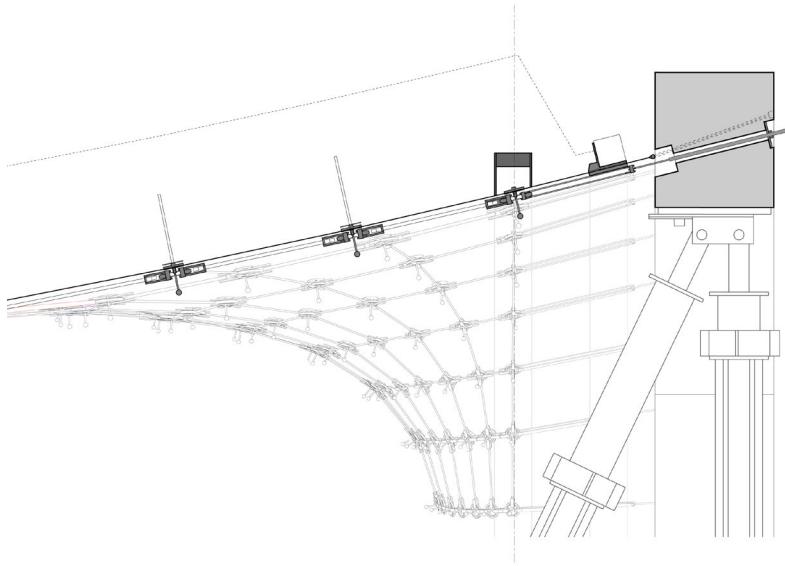
HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)

Photos: Junye Lee

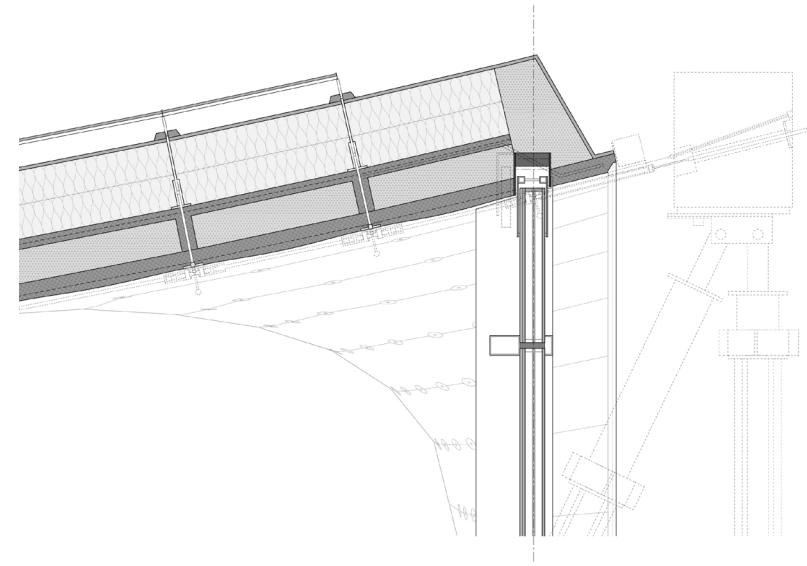


HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)

Photo: Juney Lee



Cable-net and fabric formwork

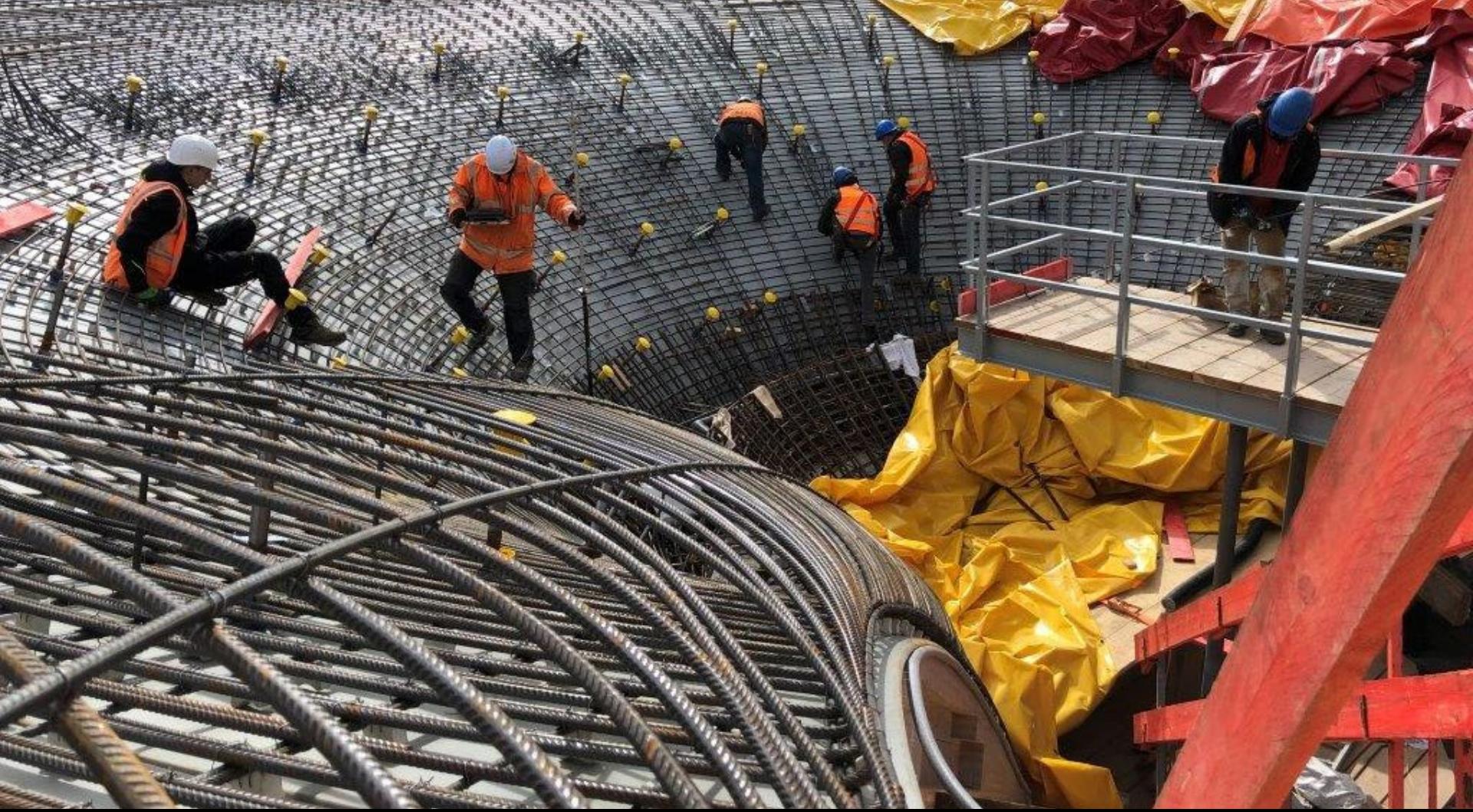


Doubly-curved, two-layered concrete shell

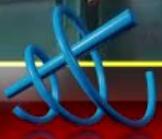


HiLo Research & innovation unit for NEST - Dübendorf, Switzerland (2018 - 2021)

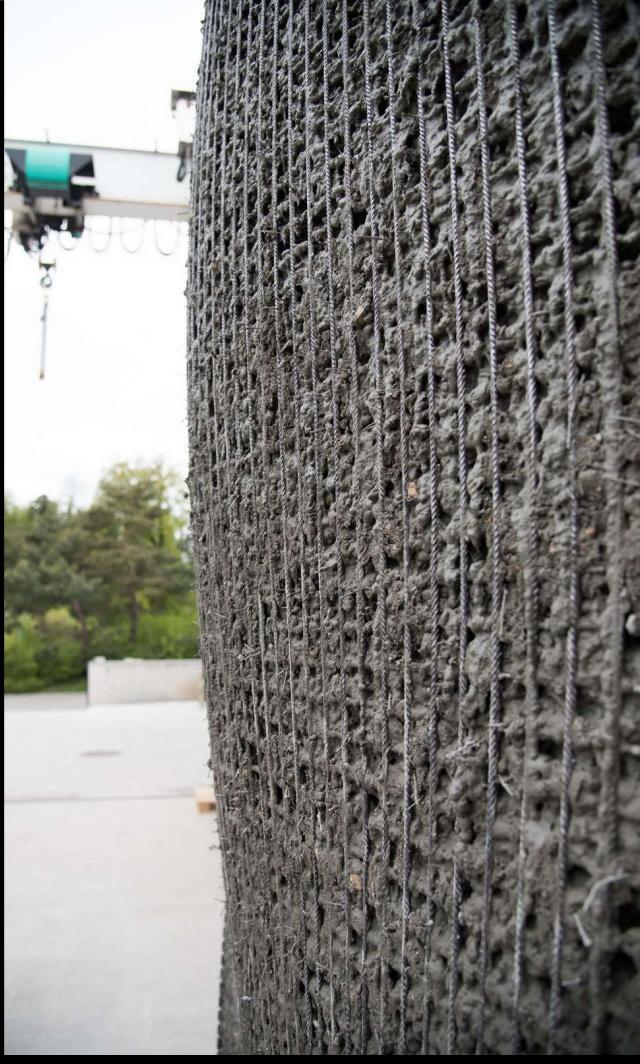
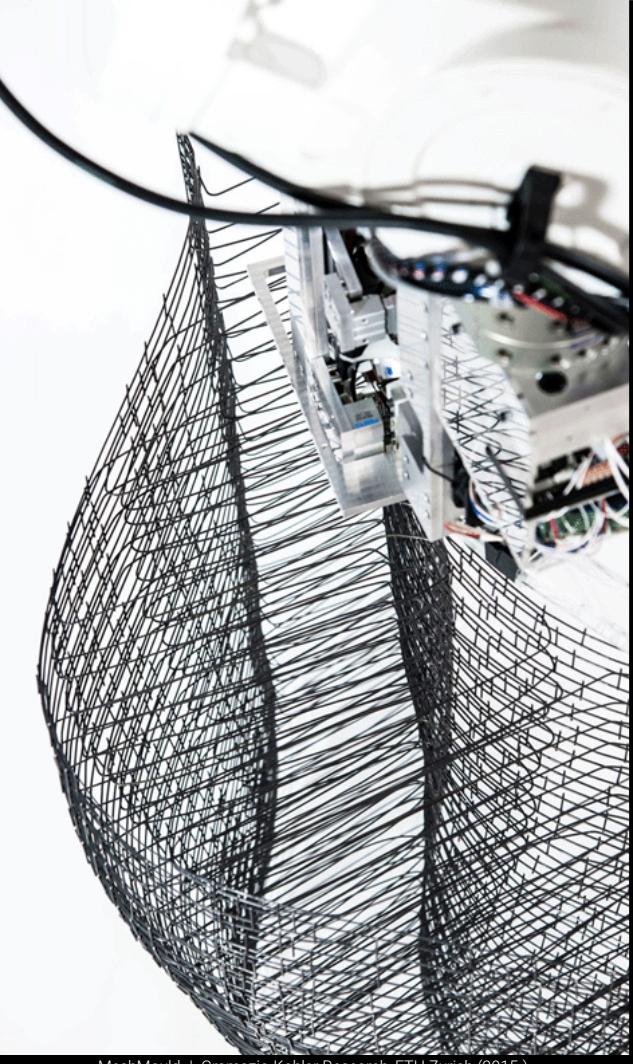
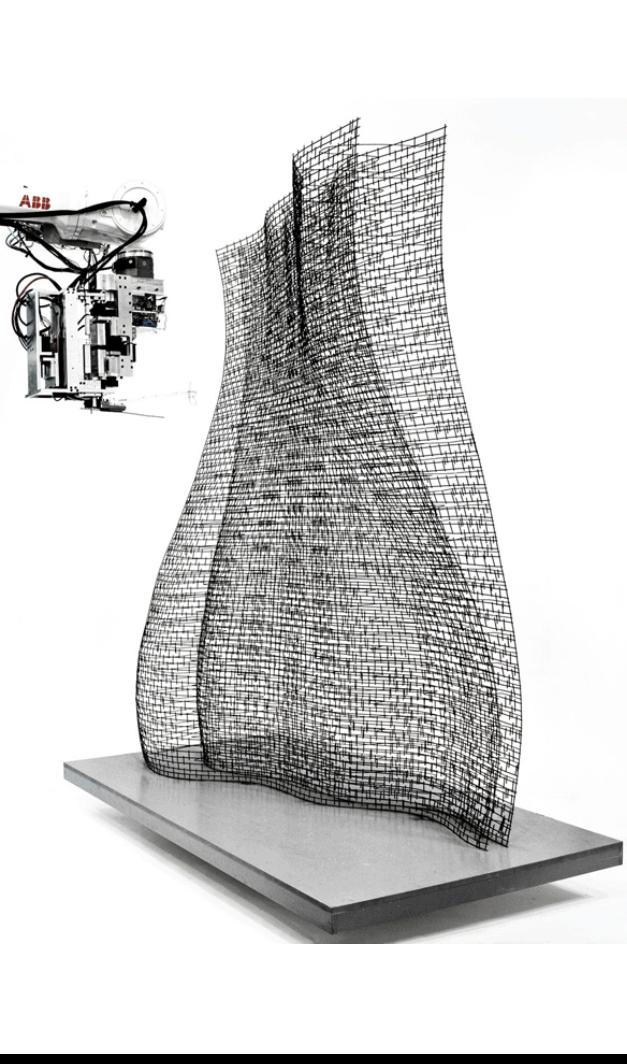
Video: Schwarz Pictures



Ingenhoven Architects, S21 (2018)



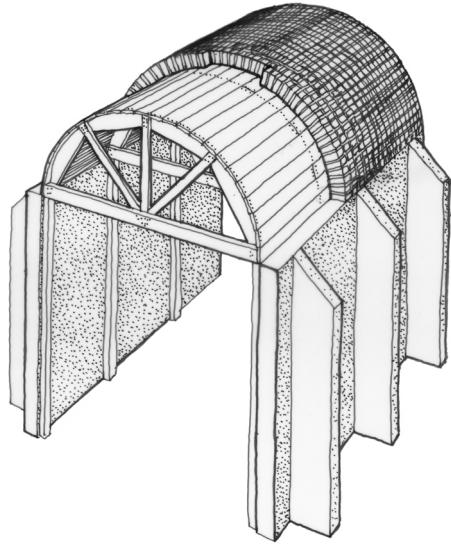
CNC Vertical Rebar Double Bender



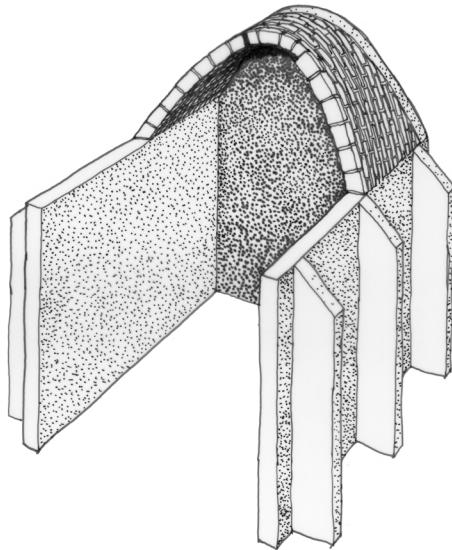
MeshMould | Gramazio Kohler Research, ETH Zurich (2015)



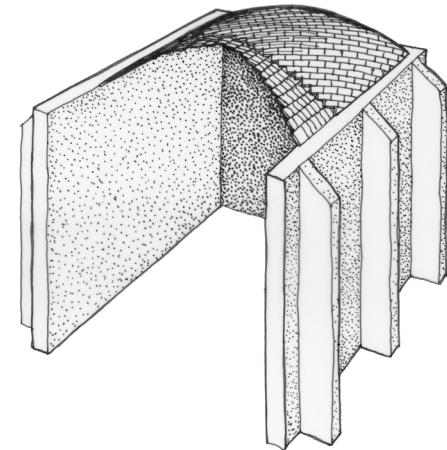
MeshMould | Gramazio Kohler Research, ETH Zurich (2015-)



Roman
semi-circular section built using formwork



Nubian
catenary section, no formwork



Catalan
catenary section, can also be shallow, no formwork



Queensborough Bridge Market, NYC | © Michael Freeman



Guastavino vaulting, Oyster Bar, Grand Central Terminal, NYC | John Ochsendorf, Michael Freeman (2013)



Church of Christ the Worker and Our Lady of Lourdes – Eladio Dieste (1958) | Photo: openbuildings.com



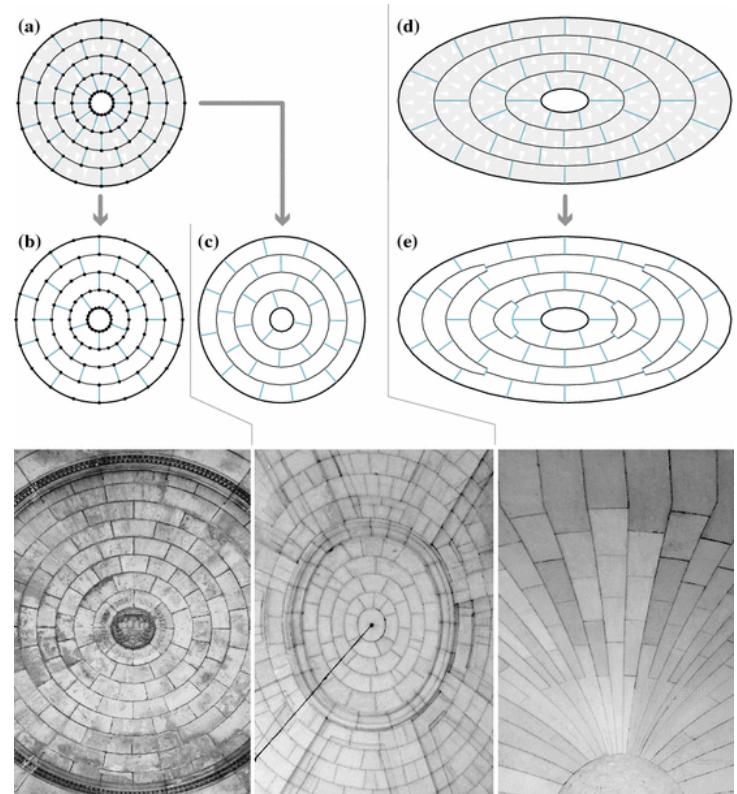
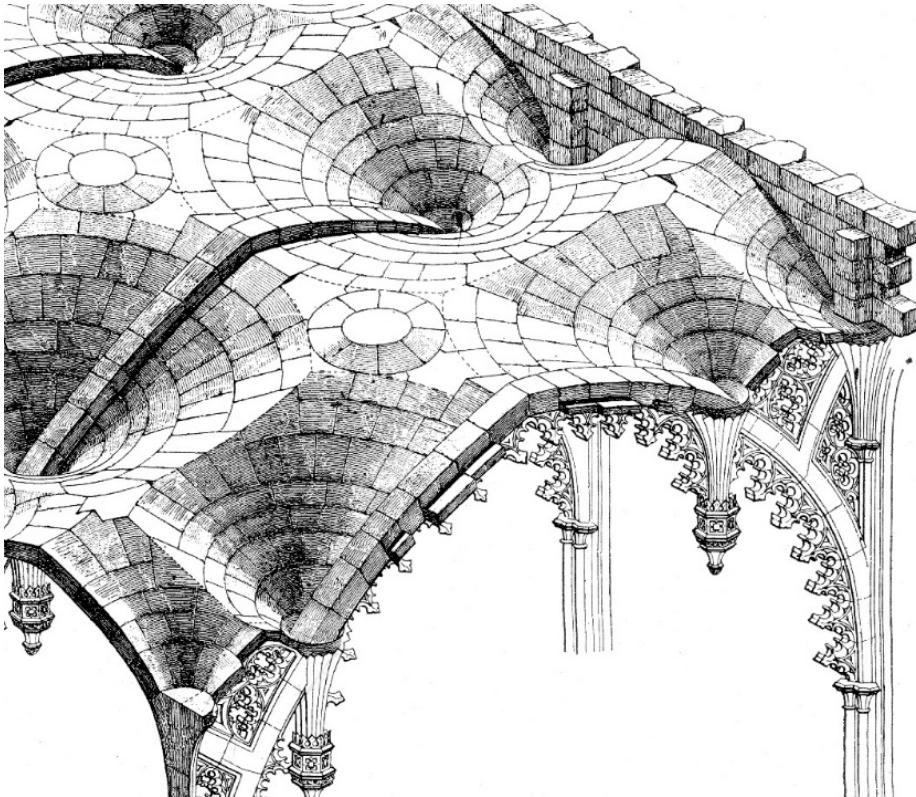
Terminal Municipal de Ómnibus – Eladio Dieste (1973) | Photo: Rafael Oliveira



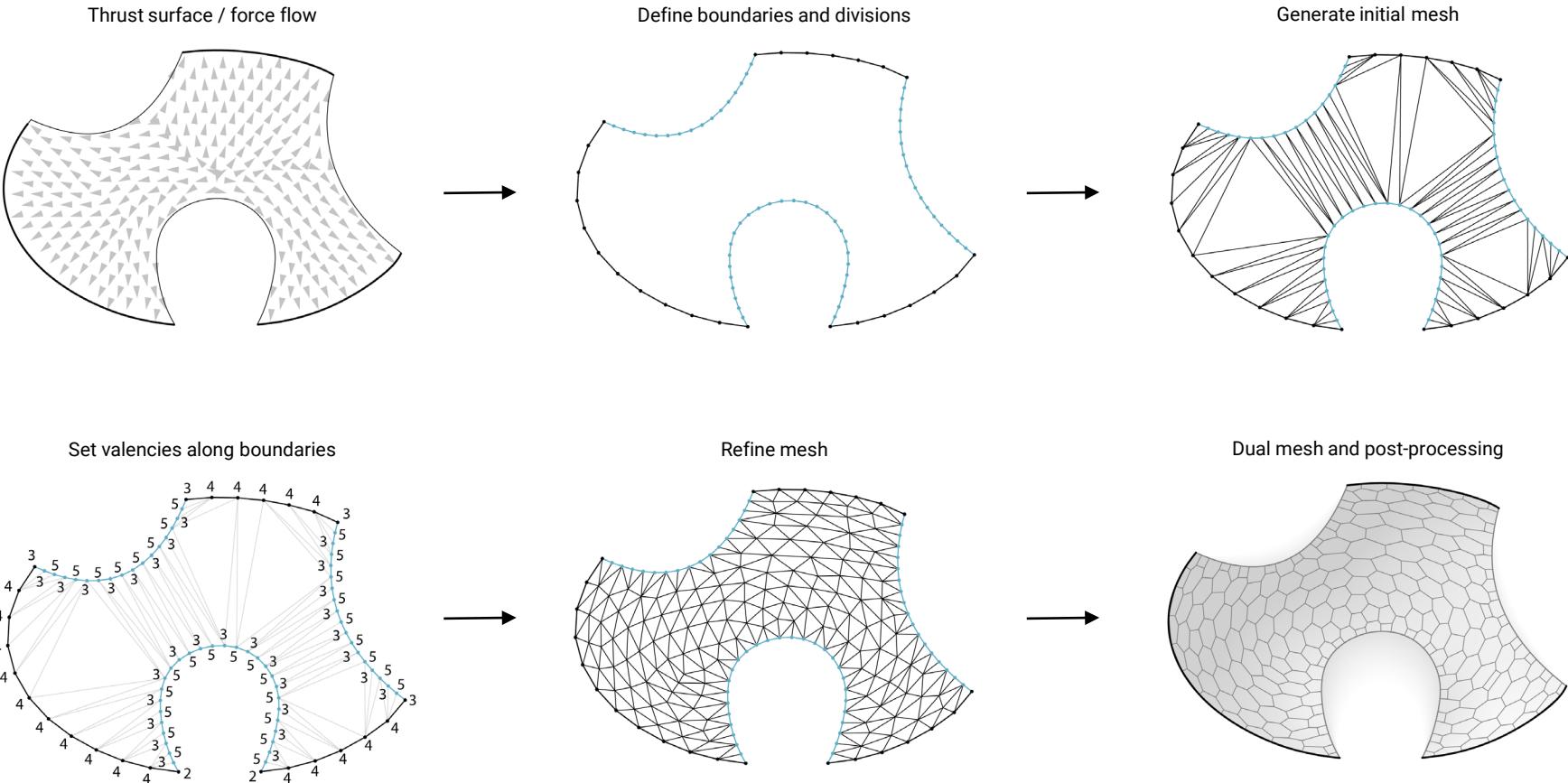
MLK Jr. Park Stone Vault - Austin, TX, USA (2010-2013)

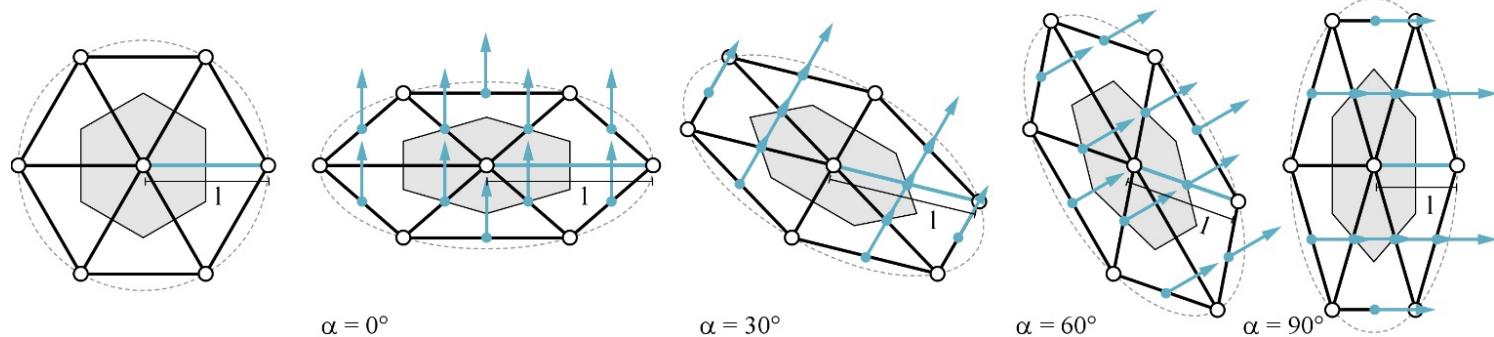
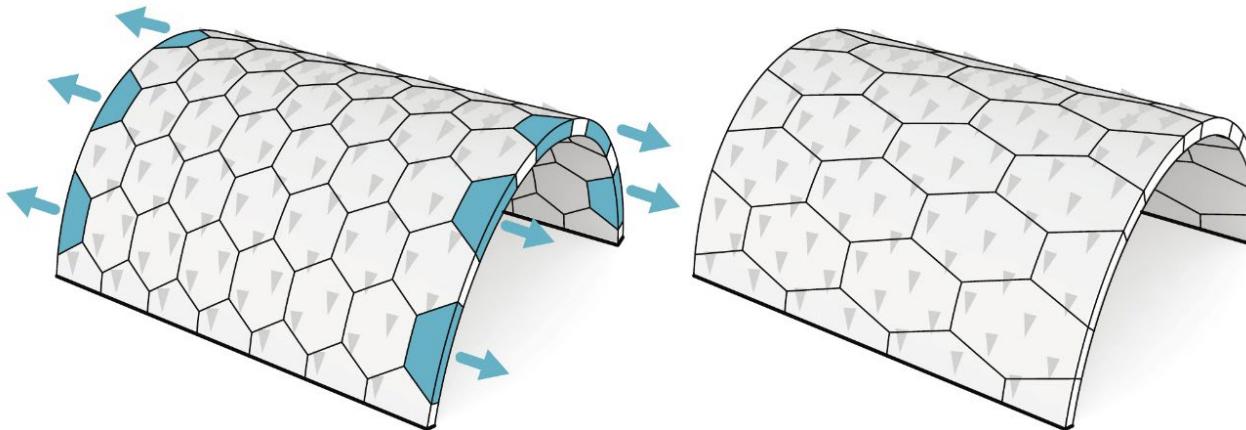


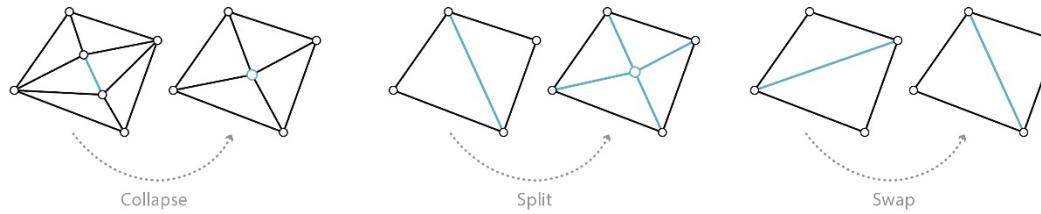
MLK Jr. Park Stone Vault - Austin, TX, USA (2010-2013)



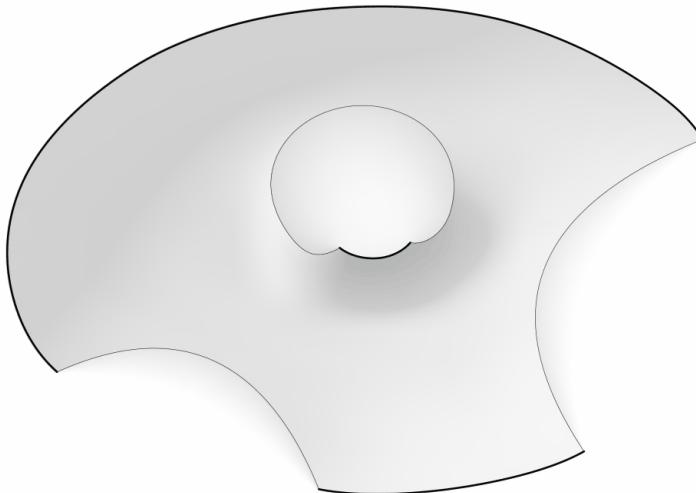
Henry VII Lady Chapel vaults (1519) Drawing: Robert Willis, 1842



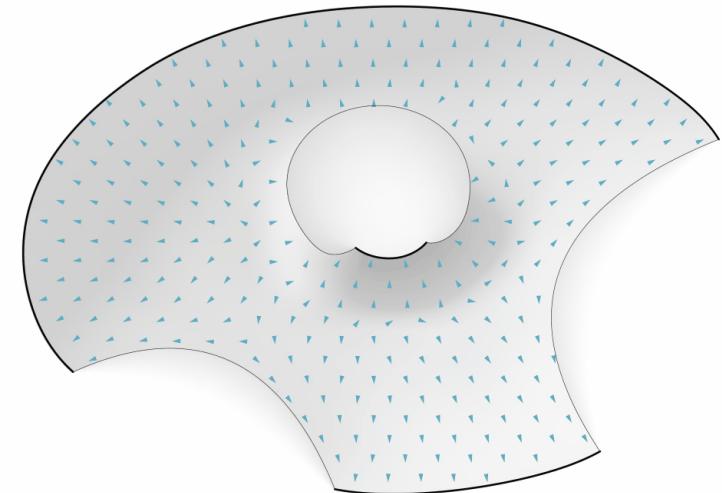


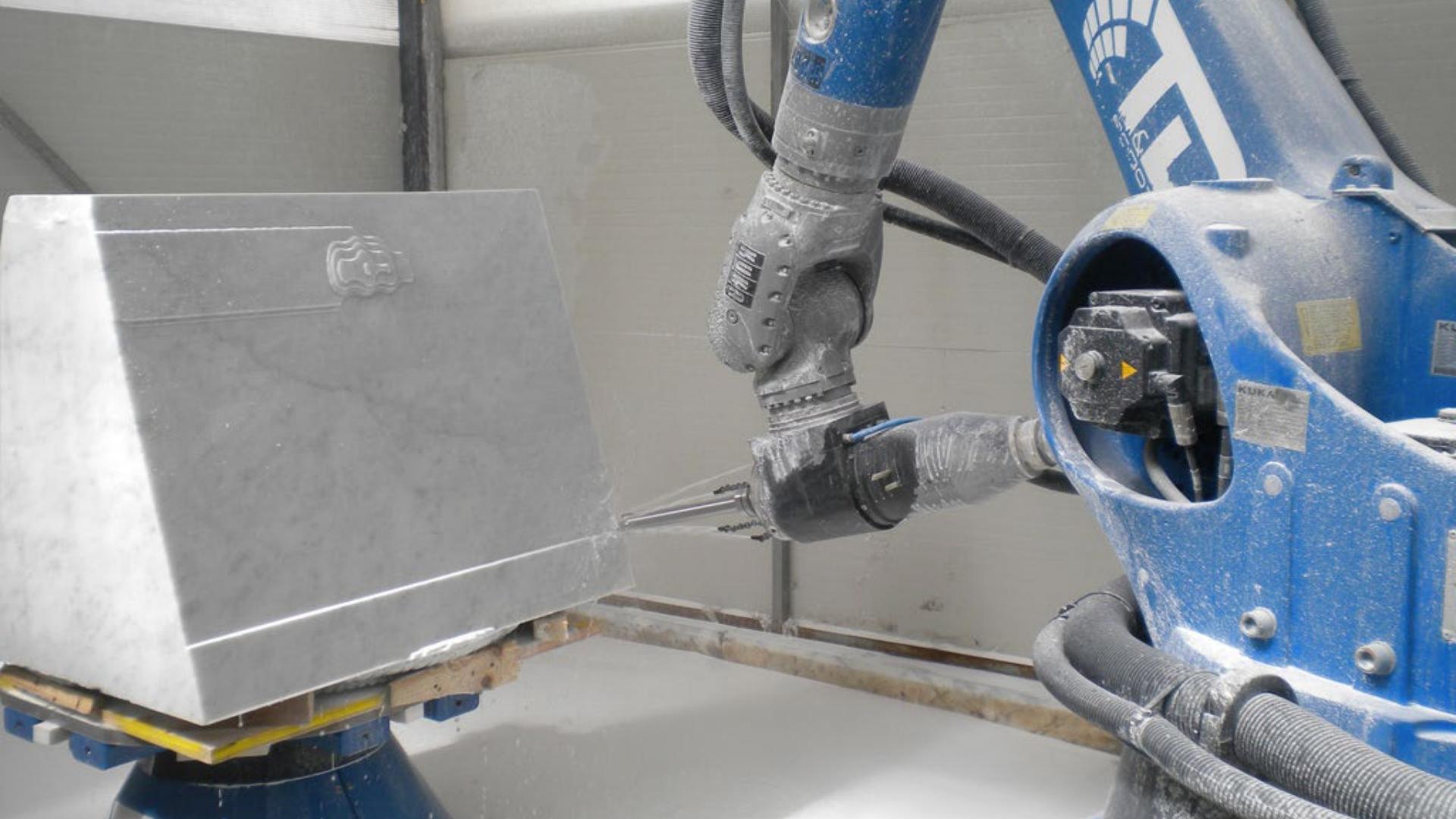


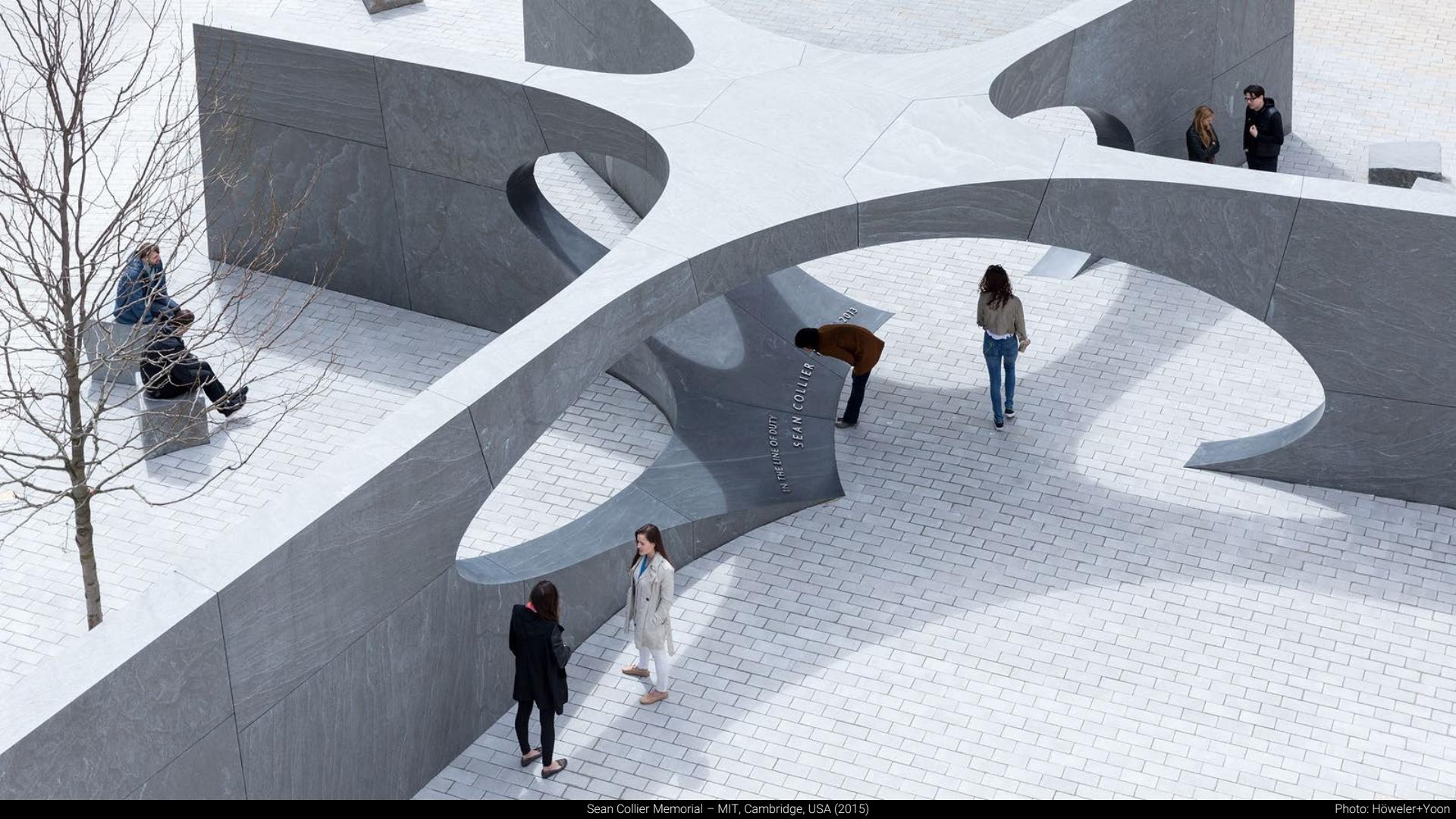
Isotropic tessellation



Anisotropic tessellation

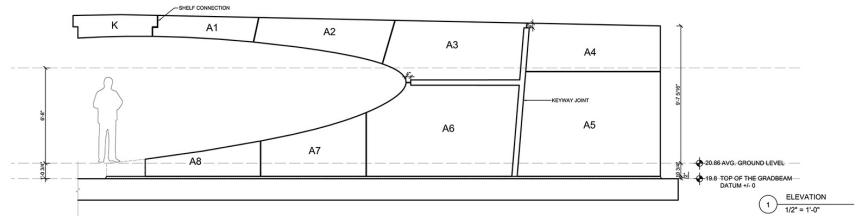
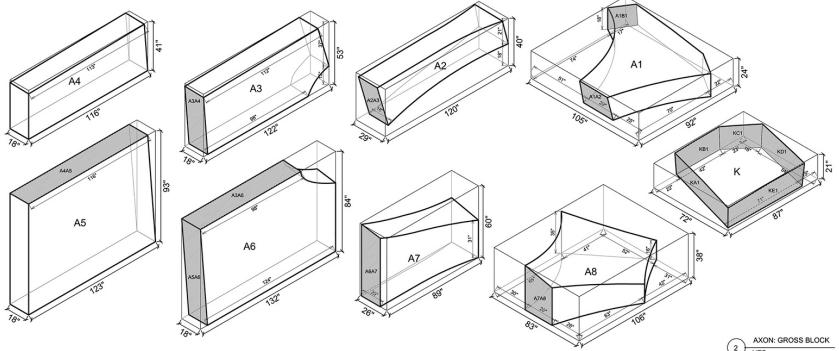
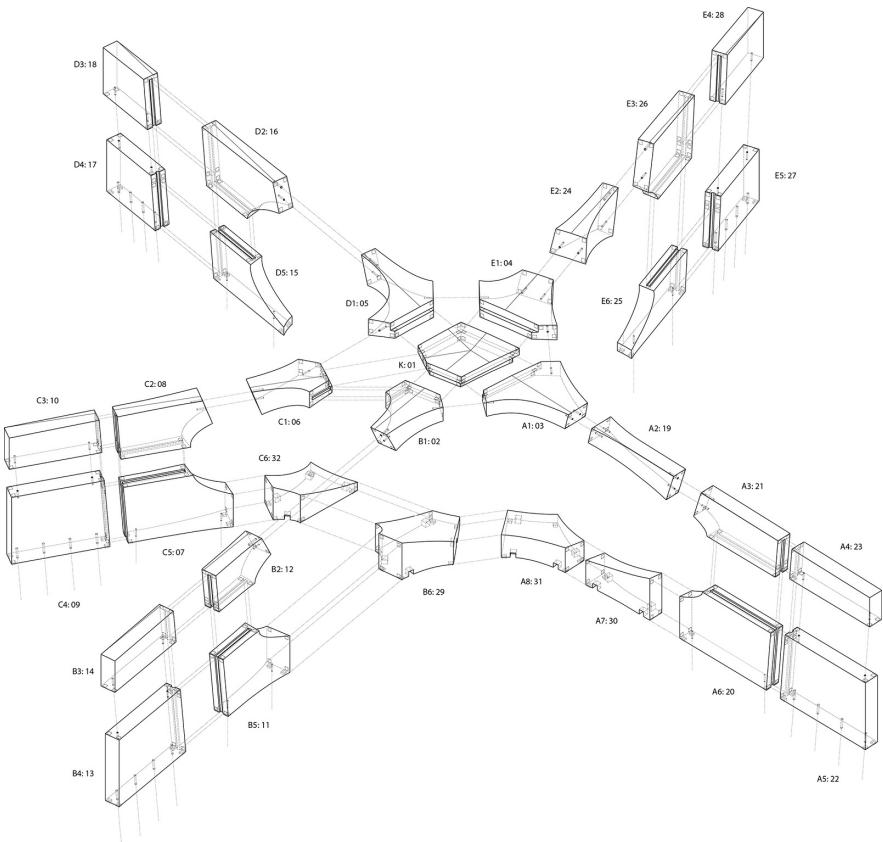






Sean Collier Memorial – MIT, Cambridge, USA (2015)

Photo: Höweler+Yoon



Sean Collier Memorial – MIT, Cambridge, USA (2015)

Images: Höweler+Yoon



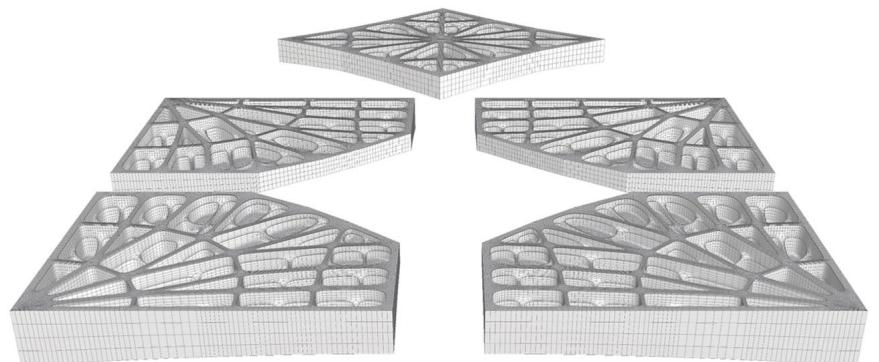
Sean Collier Memorial – MIT, Cambridge, USA (2015)



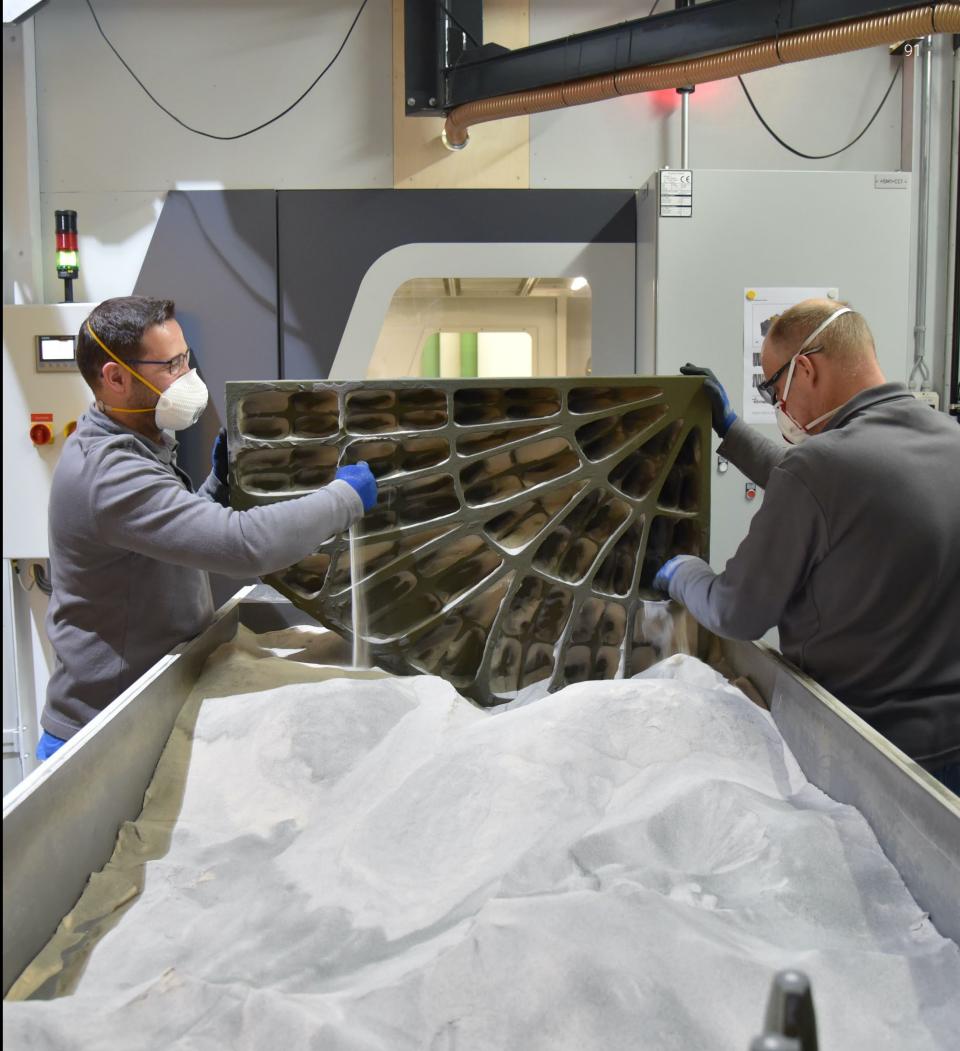
Photos: Höweler+Yoon

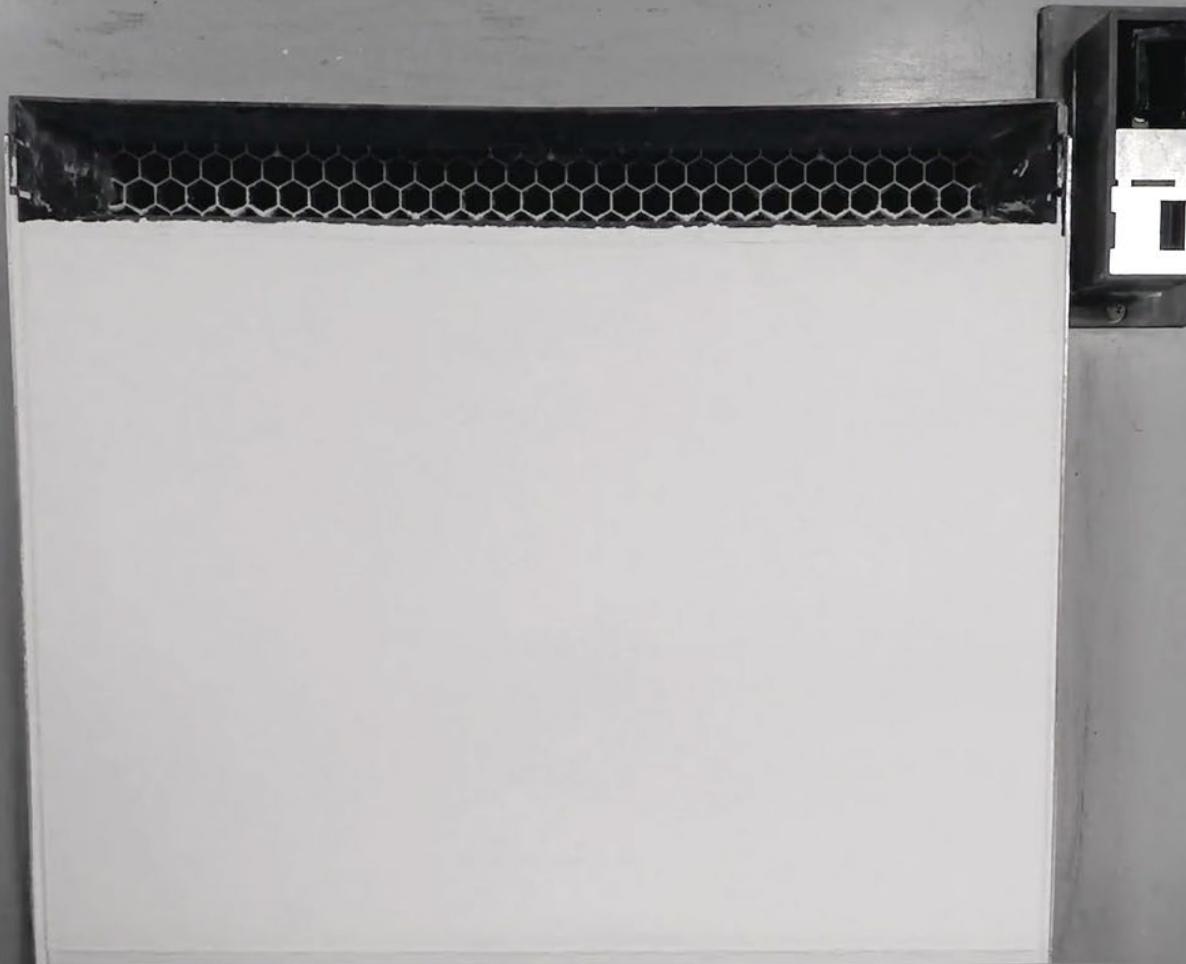


3D-printed floor system (2014 - 2018)



3D-printed floor system (2014 - 2018)

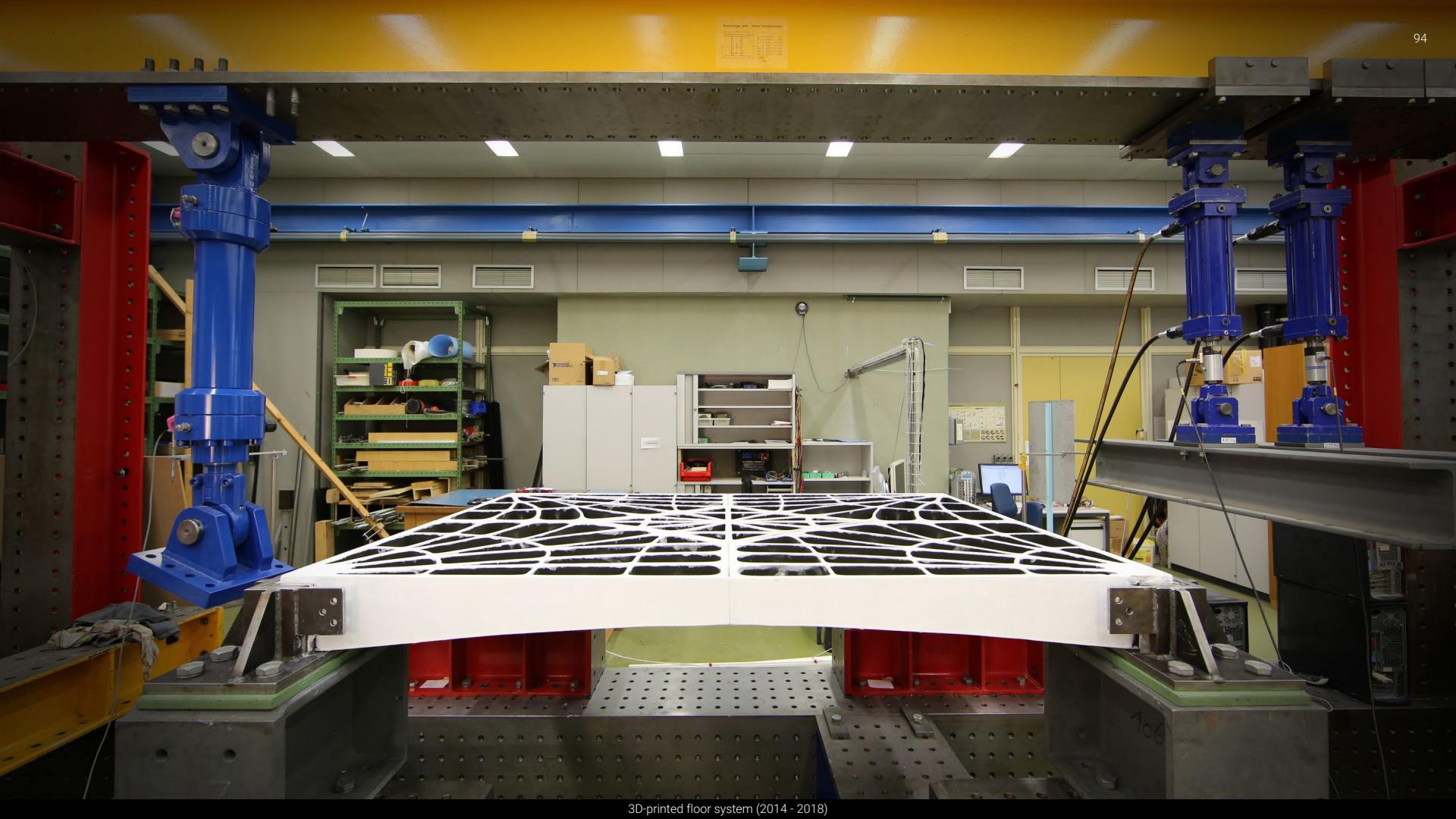




3D-printed floor system (2014 - 2018)



3D-printed floor system (2014 - 2018)



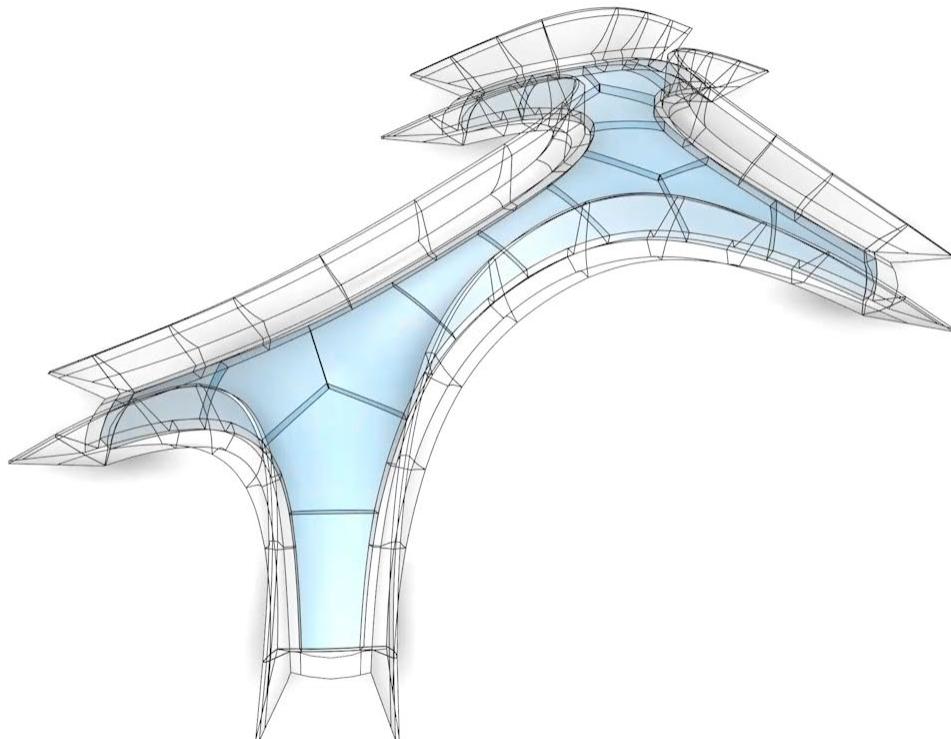


3D-printed floor system (2014 - 2018)

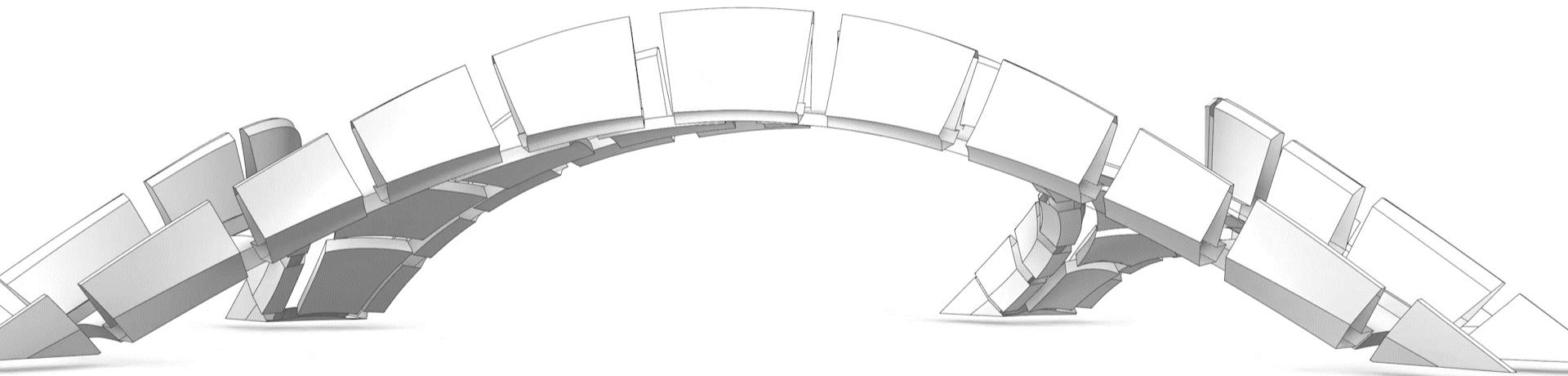


Striatus: 3D concrete printed masonry bridge - Venice, Italy (2021)

Photo: naaro



Bifurcating Deck Arches



Striatus: 3D concrete printed masonry bridge - Venice, Italy (2021)

Video editing: Zaha Hadid Architects



Striatus: 3D concrete printed masonry bridge - Venice, Italy (2021)



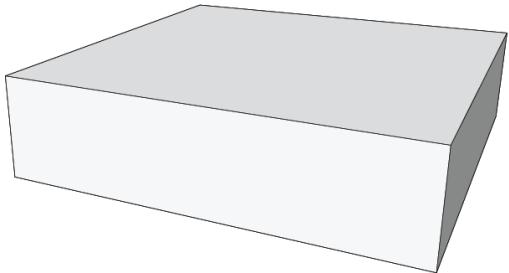
Striatus: 3D concrete printed masonry bridge - Venice, Italy (2021)

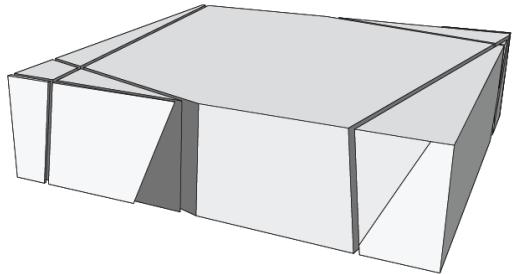
Video editing: Zaha Hadid Architects

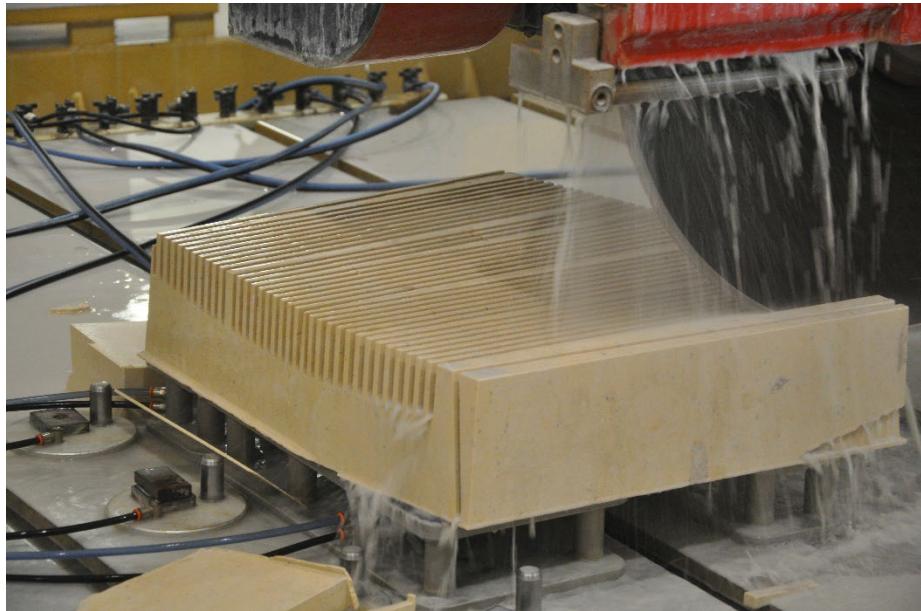
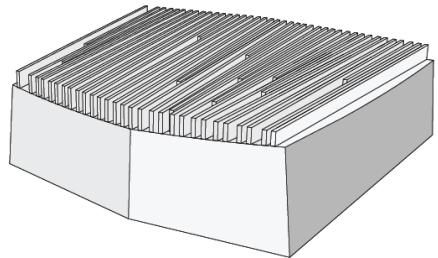


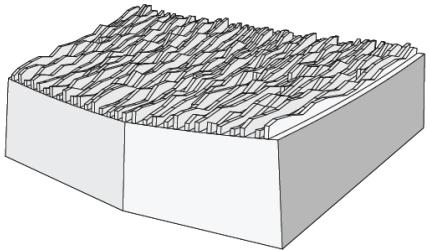
Armadillo Vault - Venice, Italy (2016)

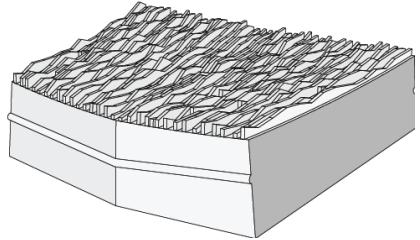
Photo: © Iwan Baan



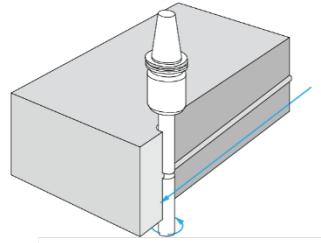
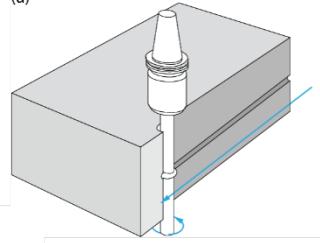








(a)





Armadillo Vault - Venice, Italy (2016)

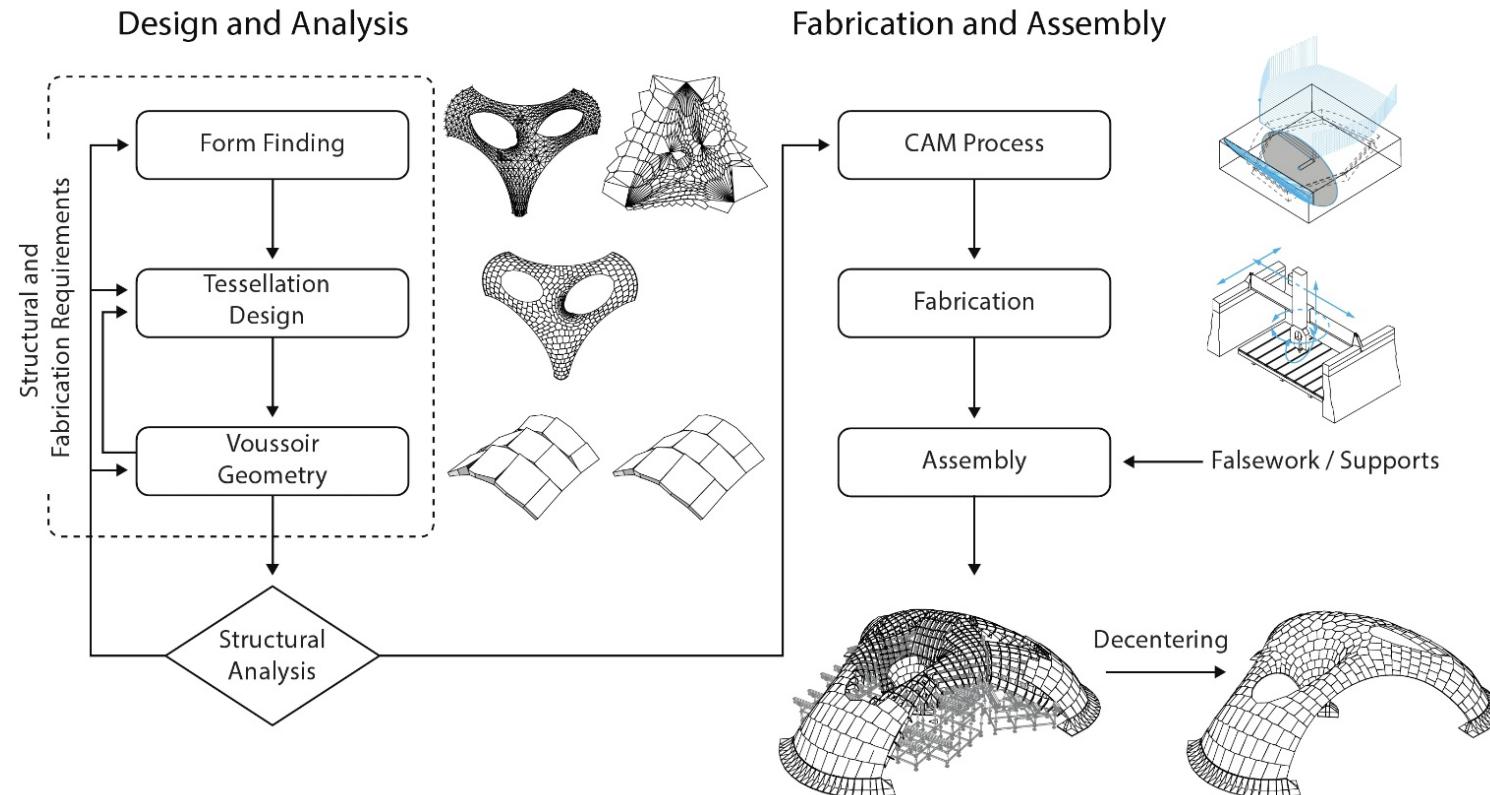
Photo: © Iwan Baan



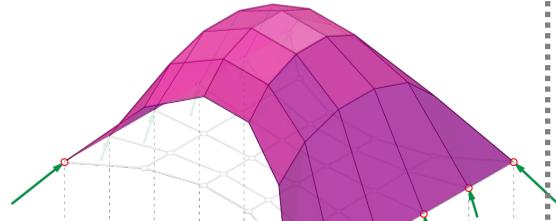
Armadillo Vault - Venice, Italy (2016)



Photos: Anna Maragkoudaki



thrust diagram data



form diagram data

```
edge (u, v): {'q': 1.0,
               'lmin': 0.0,
               'lmax': 1e+7,
               ...}

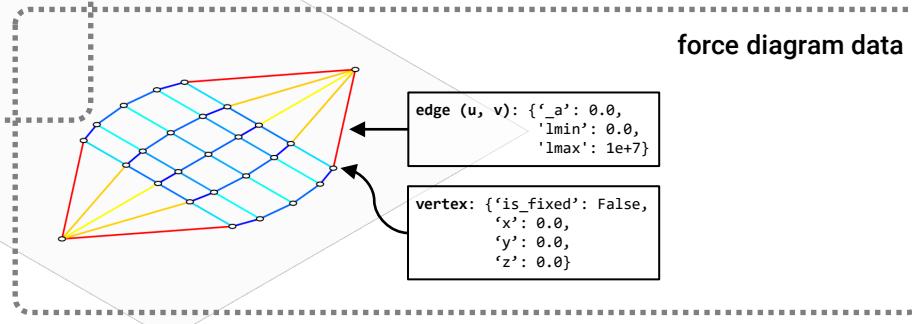
vertex: {'is_fixed': False,
          'is_anchor': False,
          'x': 0.0,
          'y': 0.0,
          'z': 0.0,
          ...}
```

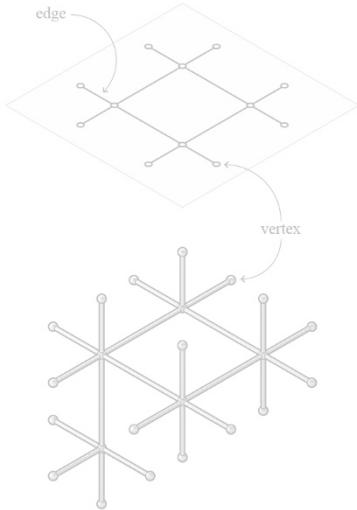


force diagram data

```
edge (u, v): {'a': 0.0,
               'lmin': 0.0,
               'lmax': 1e+7}

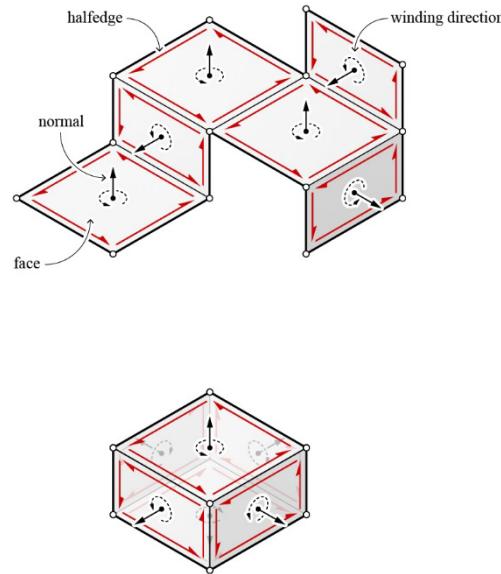
vertex: {'is_fixed': False,
          'x': 0.0,
          'y': 0.0,
          'z': 0.0}
```





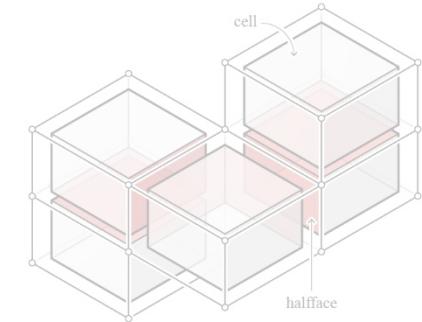
network

network of vertices



mesh

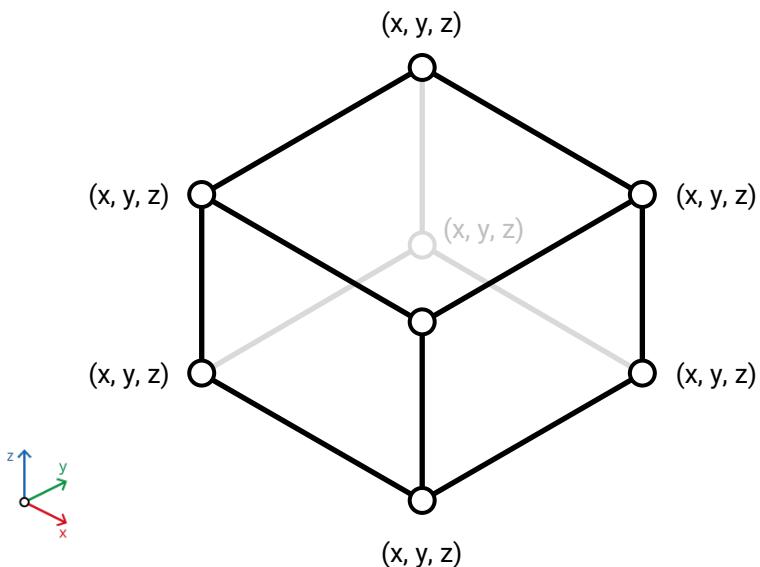
network of faces



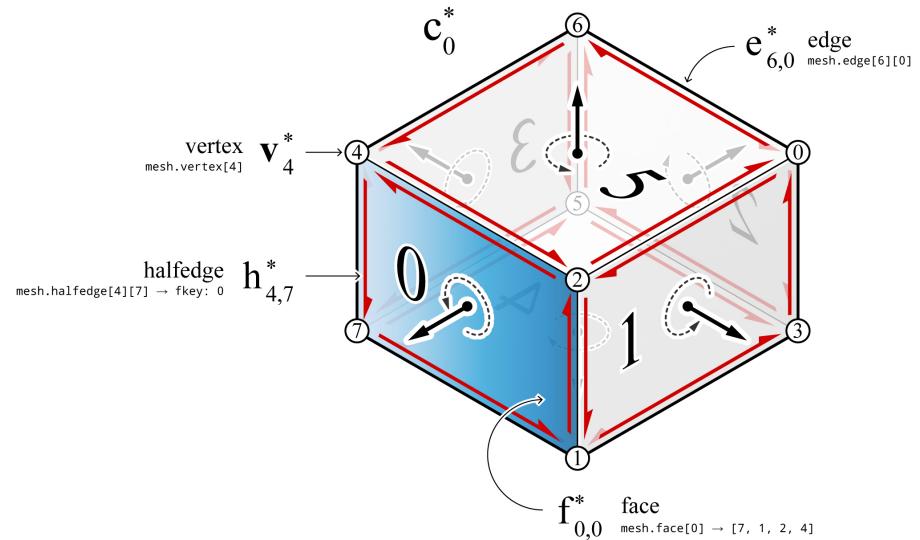
volmesh

network of cells

geometry



topology



Mesh Datastructure

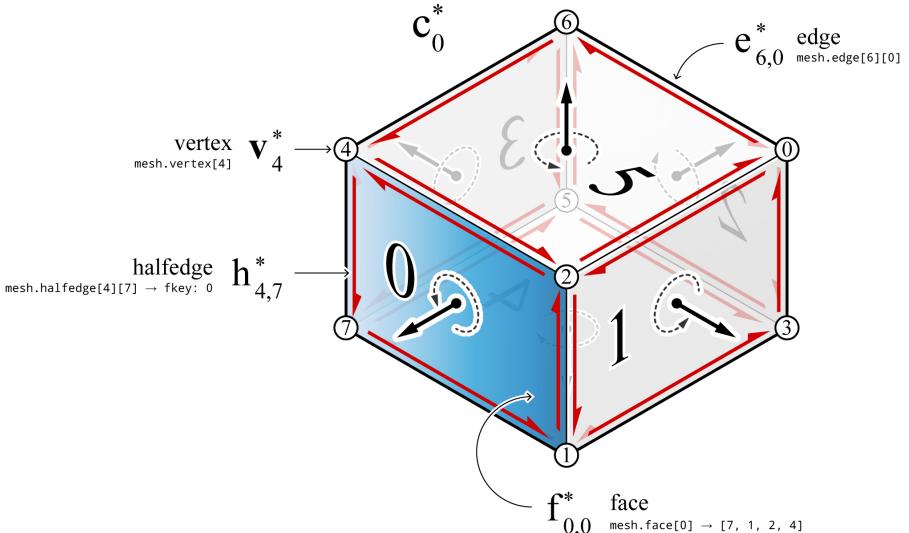
119

vertex	
vkey	attr
0: { 'x': 10.0 , 'y': 10.0 , 'z': 7.0 }	
1: { 'x': 10.0 , 'y': 0.0 , 'z': 0.0 }	
2: { 'x': 10.0 , 'y': 0.0 , 'z': 7.0 }	
3: { 'x': 10.0 , 'y': 10.0 , 'z': 0.0 }	
4: { 'x': 0.0 , 'y': 0.0 , 'z': 7.0 }	
5: { 'x': 0.0 , 'y': 10.0 , 'z': 0.0 }	
6: { 'x': 0.0 , 'y': 10.0 , 'z': 7.0 }	
7: { 'x': 0.0 , 'y': 0.0 , 'z': 0.0 }	

edge		
u	v	attr
0: { 2: {} }	7	
1: { 2: {} }	1	
2: { 4: {} }	2	
3: { 0: {} , 5: {} }	4	
4: { 7: {} , 6: {} }	0	
5: { 7: {} , 6: {} }	2	
6: { 0: {} }	1	
7: { 1: {} }	3	

face					
fkey	u	v	u	v	fkey
0: [7 , 1 , 2 , 5]	0	2	1	5	6
1: [0 , 2 , 0 , 1]	1	0	2	0	3
2: [0 , 5 , 1 , 3]	2	5	1	3	4
3: [0 , 1 , 0 , 1]	3	0	1	1	4
4: [7 , 4 , 5 , 6]	4	7	4	5	6
5: [7 , 4 , 6 , 5]	5	7	4	6	5
6: [0 , 1 , 5 , 6]	6	0	1	5	2
7: [0 , 1 , 2 , 3]	7	0	1	2	4

halfedge		
u	v	fkey
0: { 2: 1 , 3: 2 , 6: 5 }	0	2
1: { 7: 4 , 2: 0 , 3: 1 }	1	7
2: { 0: 5 , 1: 1 , 4: 0 }	2	0
3: { 0: 1 , 1: 4 , 5: 2 }	3	0
4: { 7: 0 , 2: 5 , 6: 3 }	4	7
5: { 7: 3 , 3: 4 , 6: 2 }	5	7
6: { 0: 2 , 4: 5 , 5: 3 }	6	0
7: { 1: 0 , 4: 3 , 5: 4 }	7	1



063-0606-22L : Computational Structural Design II
Structurally-informed Materialisation

<http://block.arch.ethz.ch>

