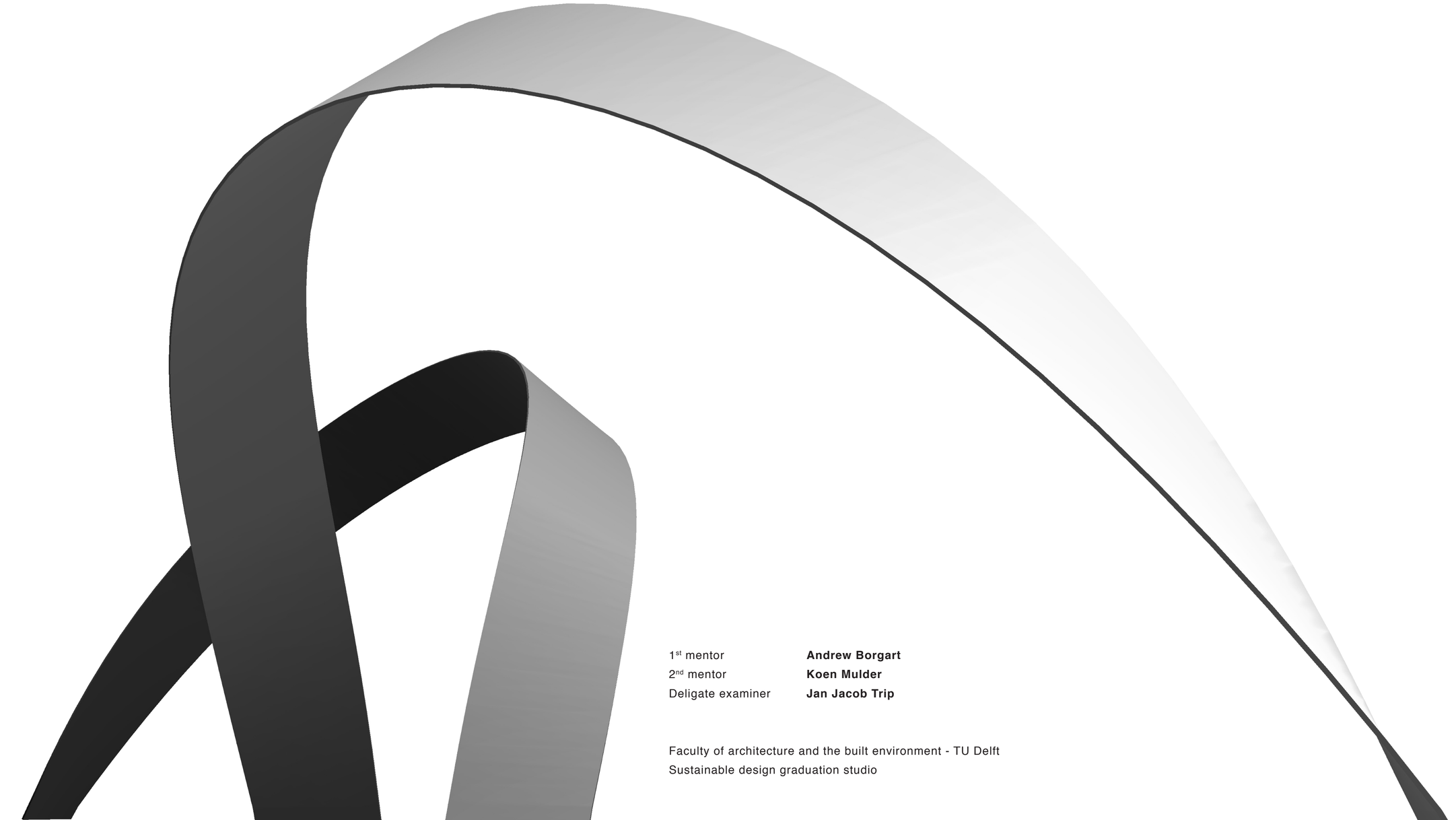
Graduation presentation

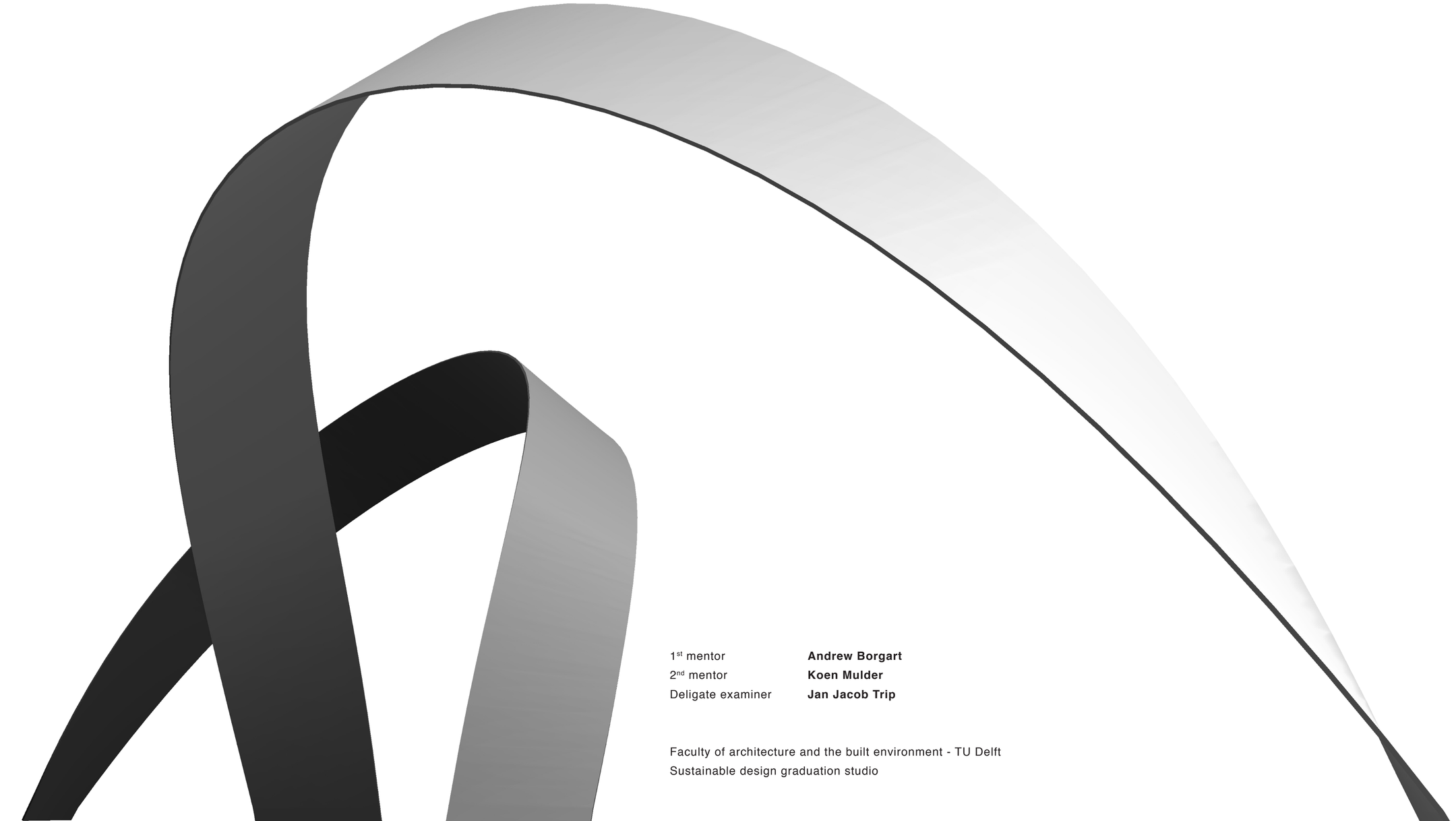
Bart-Jan van der Gaag, July 5th, 2018



1st mentor	**Andrew Borgart**
2nd mentor	**Koen Mulder**
Deligate examiner	**Jan Jacob Trip**

Faculty of architecture and the built environment - TU Delft
Sustainable design graduation studio

Exploiting Active-Bending for double curved structures



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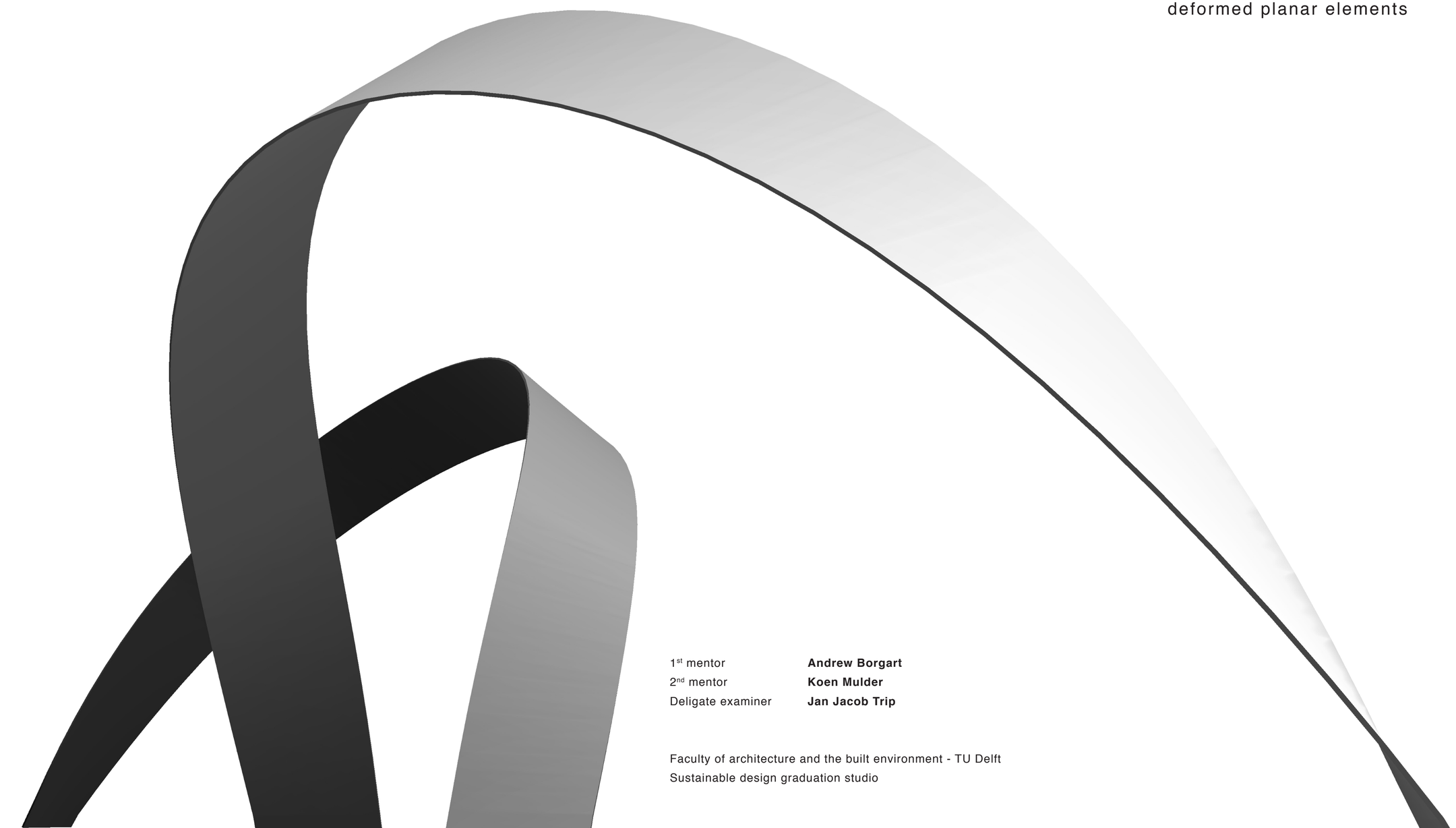
Exploiting Active-Bending for double curved structures

Research in self-supporting double-curved structure composed of elastically deformed planar elements



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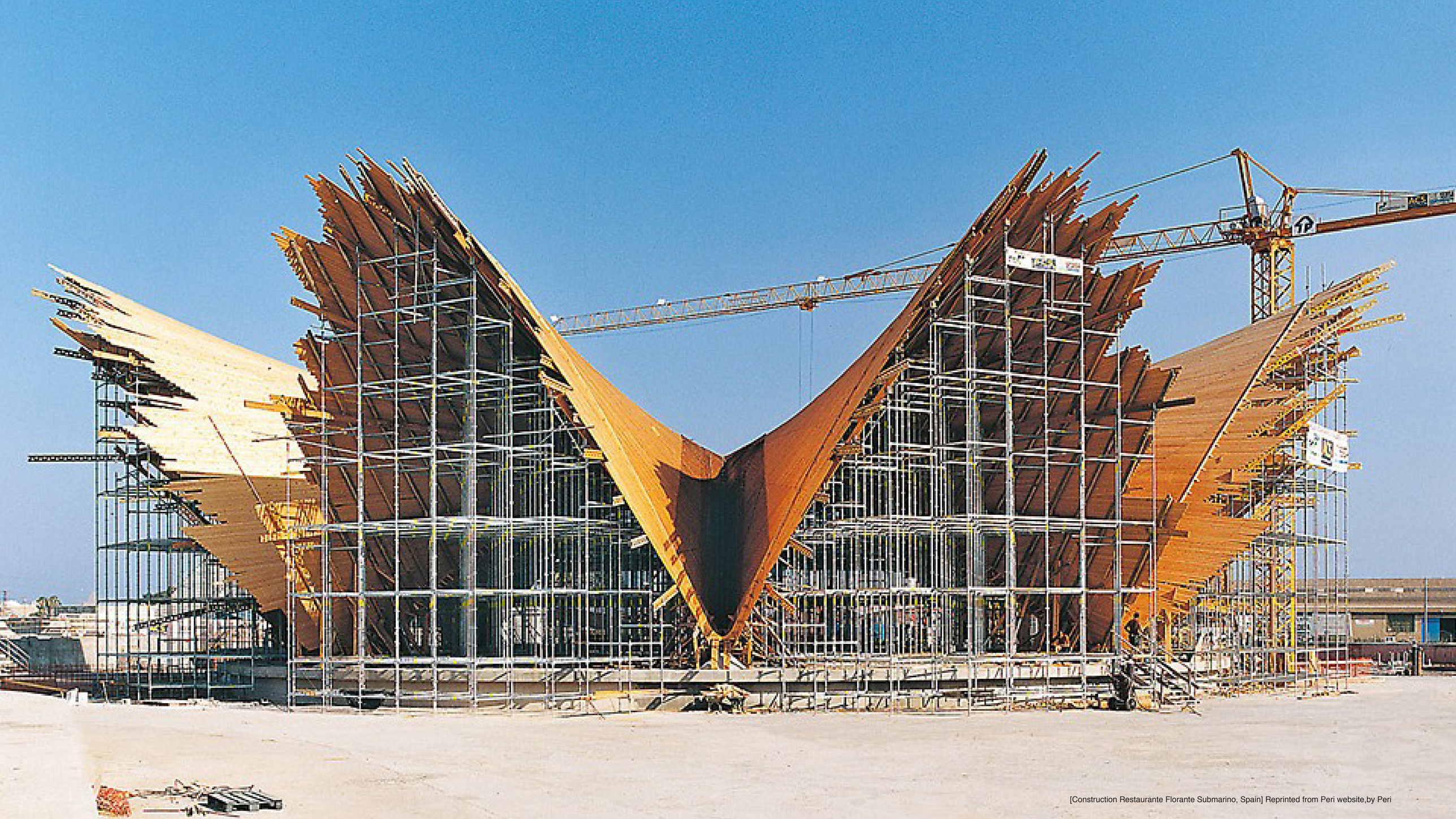
Content

Double curvature in architecture

[The restaurant of L'Oceanografic in Valencia, Spain as viewed from across the water.] Reprinted from Wikipedia website, by David Iliif, 2007

[Heydar Aliyev Center, Zaha Hadid Architects] Reprinted from Archdaily website, 2017, by Iwan Baan

[Details of construction of Kaohsiung Centre for the Arts by Mecanoo] Reprinted from floornature website, 2017, by Christian Richters



[Construction Restaurante Florante Submarino, Spain] Reprinted from Peri website,by Peri

[Heydar Aliyev Center, Zaha Hadid Architects] Reprinted from pinterest website, 2016

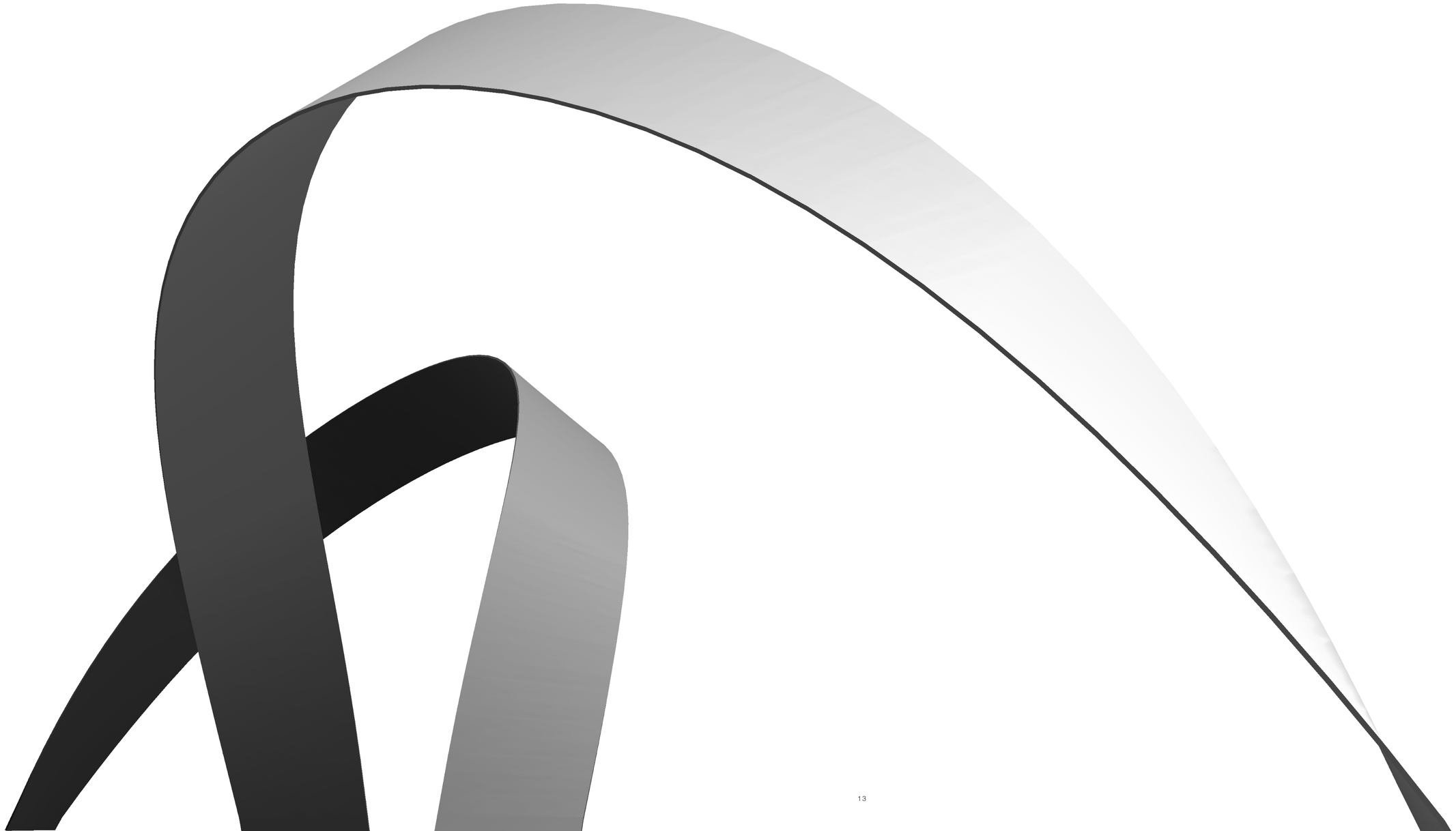
Double curved architecture

- Complex and custum structures and construction methods

- Labour intensive

- Expensive

What is Active-Bending ?



What is Active-Bending ?

Large **elastic deformation** to create **curved** structures from initially **planar** elements

History

Oca, amazonion basin, Brazil

Mudhif houses, Southern Iraq swamps

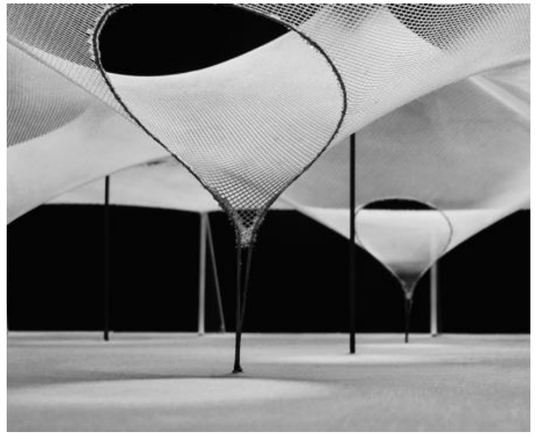
Yamut, Iran

History

Construction methods from vernacular architecture, use of available materials

20th century

Economic construction method for double curved shell structures, lack of alternatives



German pavilion-study model

Multihalle

Main station Stuttgart

20th century

Economic construction method for double curved shell structures, lack of alternatives

Current research

Formation processes based on material behaviour

Research pavilion - 2010

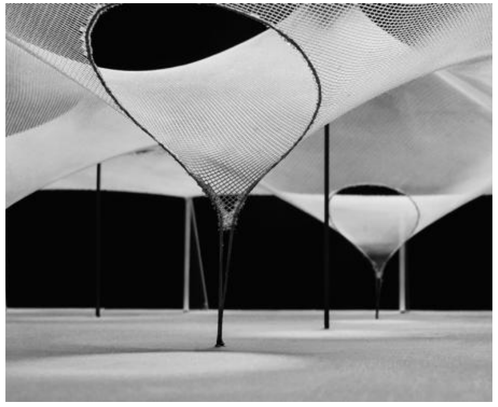
Berkeley weave-research pavilion

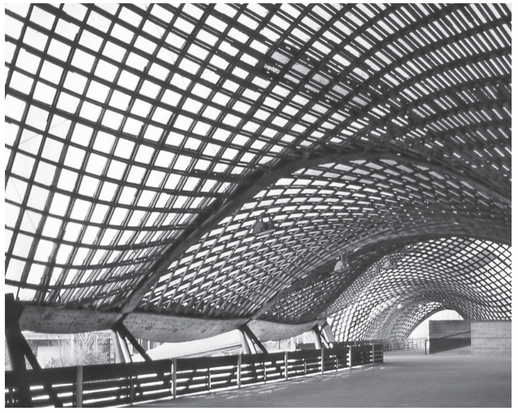
Active-bending structure - torsion research model

Current research

Formation processes based on material behaviour





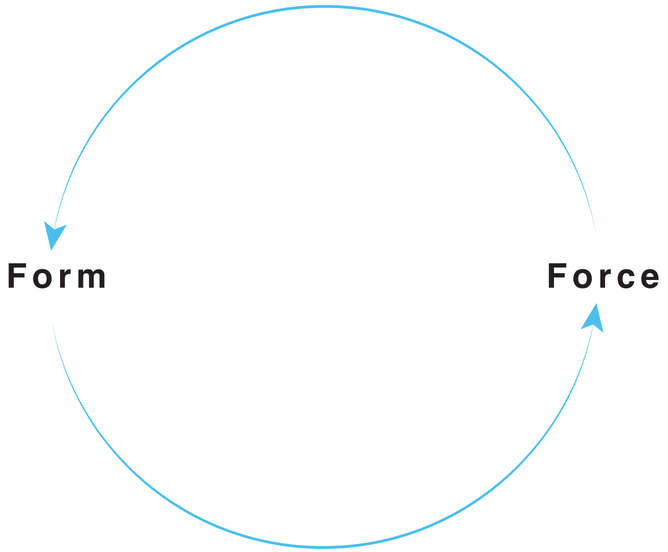


Form

Force

Active-bending motivation

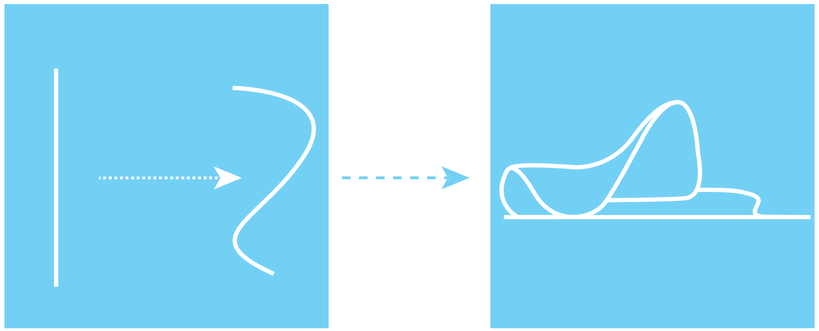
Curved geometries



Influenced by pre-stress

Common use of active bending

Building approach



Complex curved geometries

Research aim

Double curvature is both the tool and the goal

Create an active-bending structural system

Structural system

Structure

Form

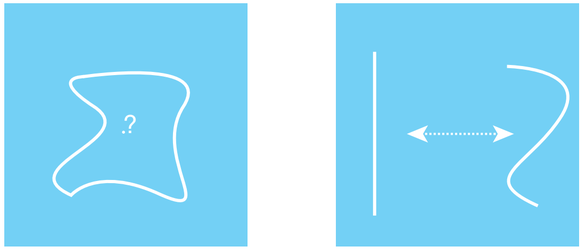
Form

How to measure double curvature?

Form

How to measure double curvature?

Relation double curvature surface - planar plate elements?



Structure

What happens structurally in the bending process of a plate?

Structure

What happens structurally in the bending process of a plate?

What is the extent of deforming planar plate elements?

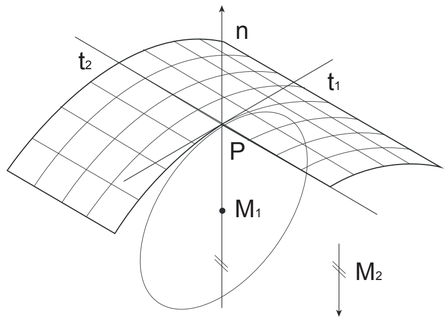
Main research question

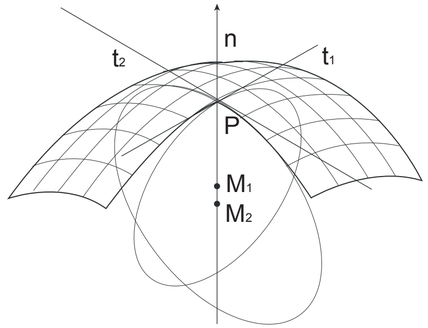
‘How can double curvature be exploited in a structure composed of elastically deformed planar elements?’

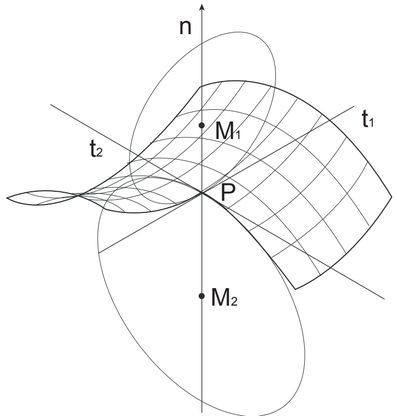
Research

How to measure surface curvature?

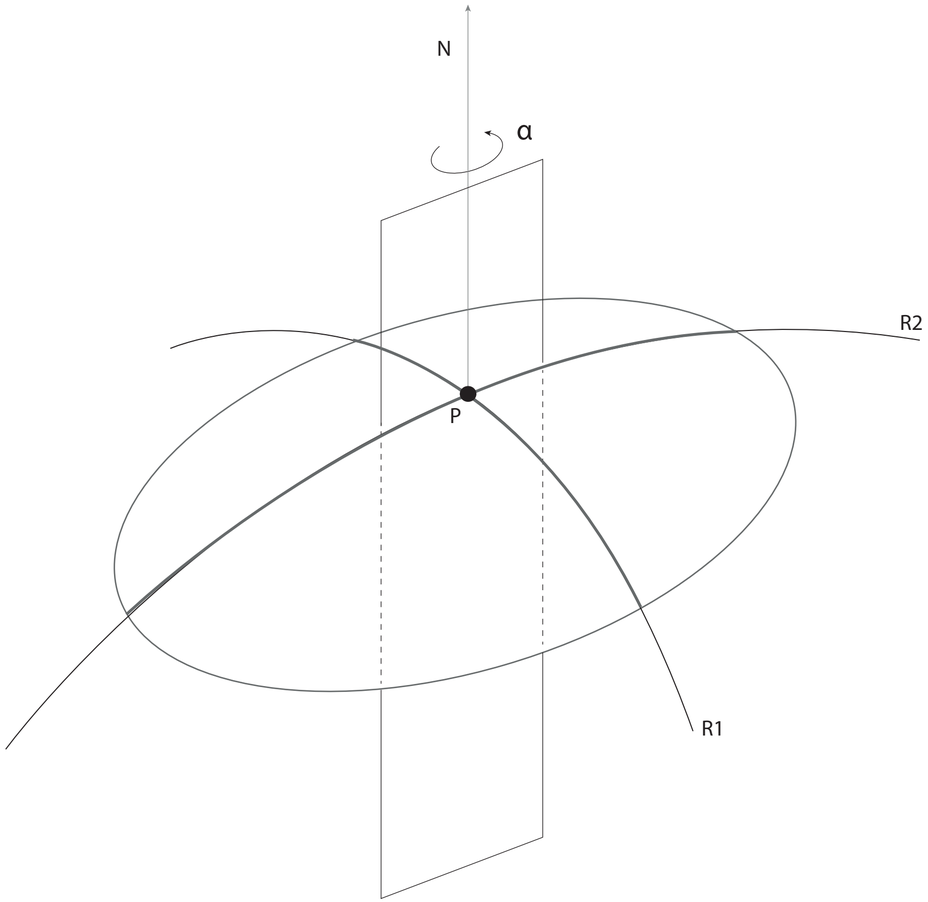
Gaussian curvature

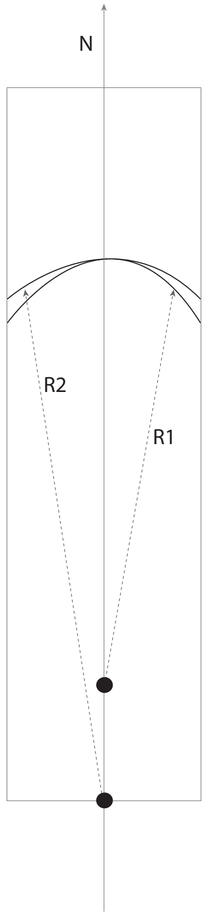




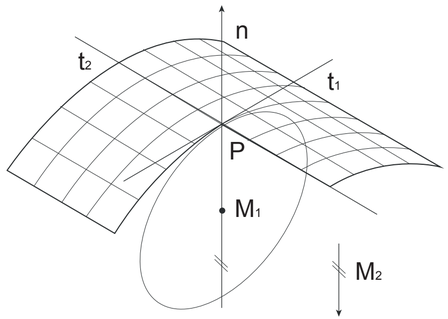


Product of principle curvatures





Product of principle curvatures



Monoclastic

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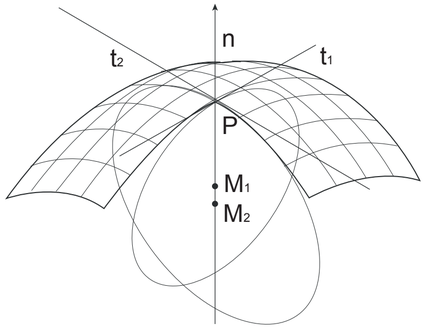

Synclastic

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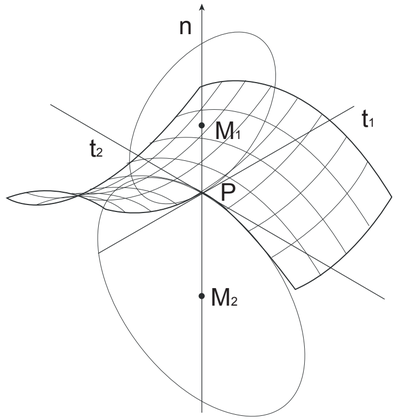
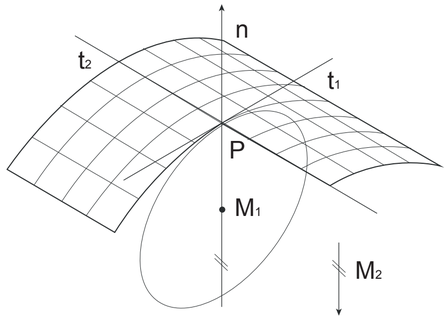


Anticlastic

K<0

Developable



Monoclastic

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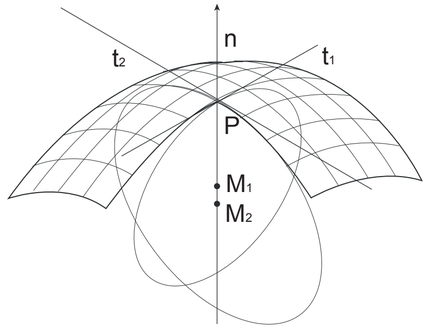

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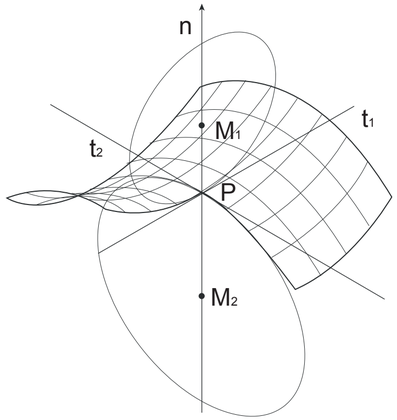
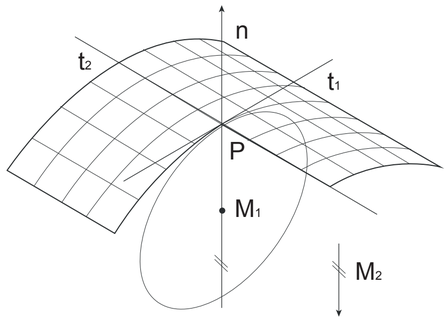


Anticlastic

K<0

Developable

Non-developable



Monoclastic

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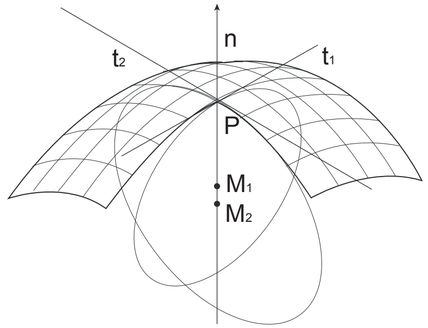

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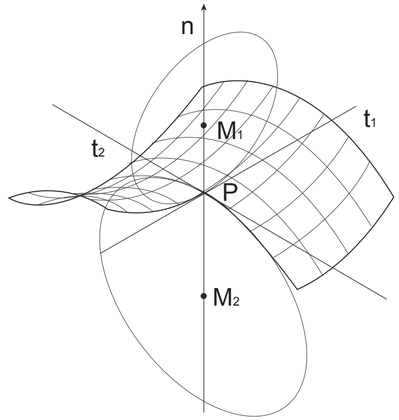
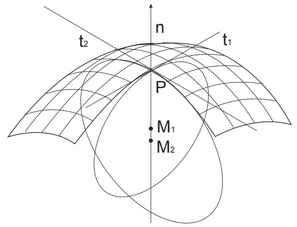


Anticlastic

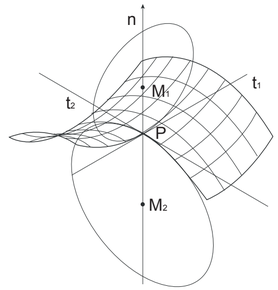
K<0

Elastic deformation

Plastic deformation



Synclastic



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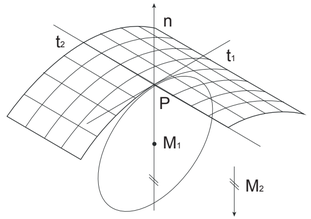


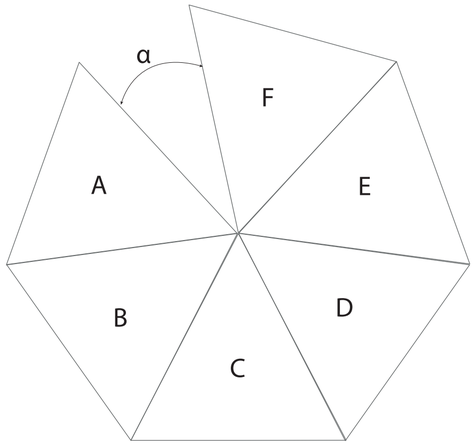
Monoclastic

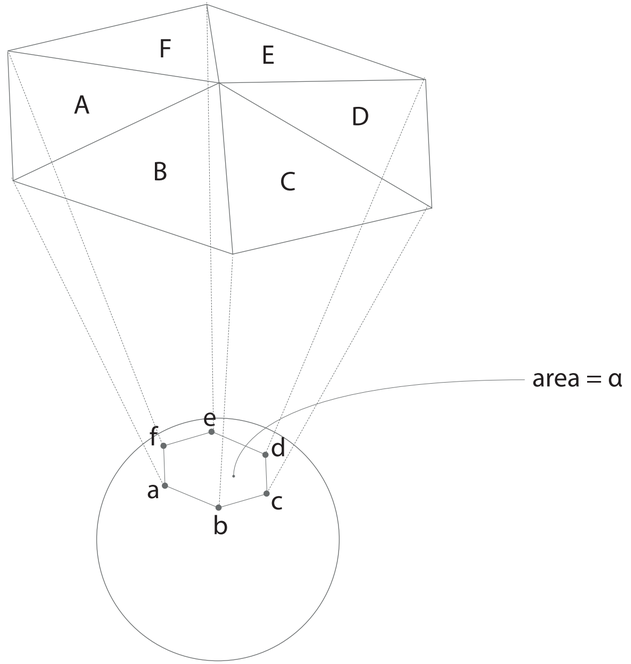
Active-bending

Rationalise non-developable to developable surfaces

Triangulation method (Calladine)

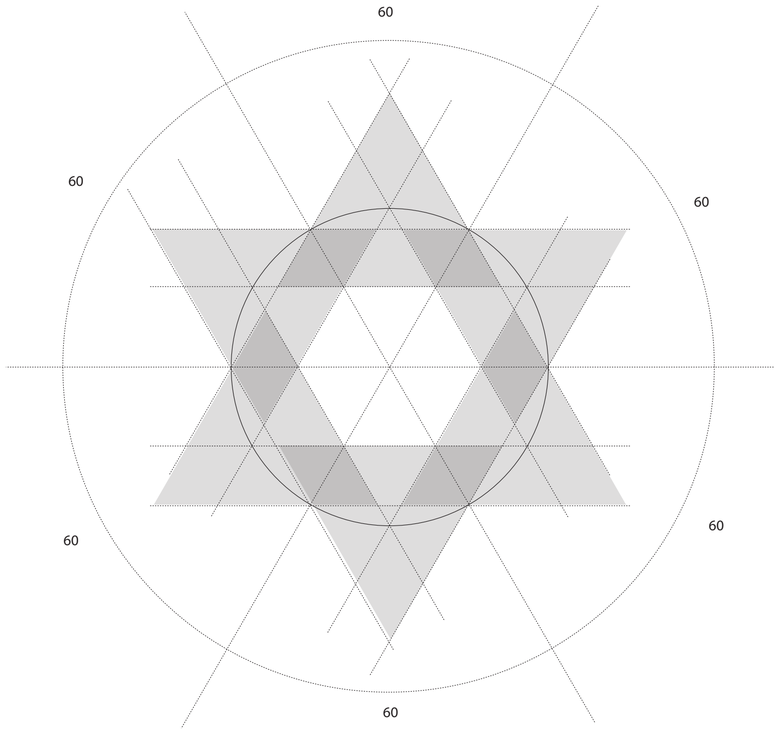
Planar surfaces represent part of sphere



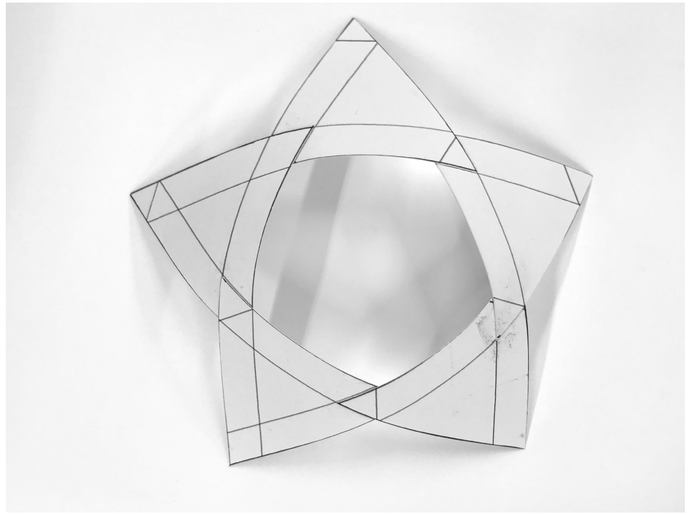


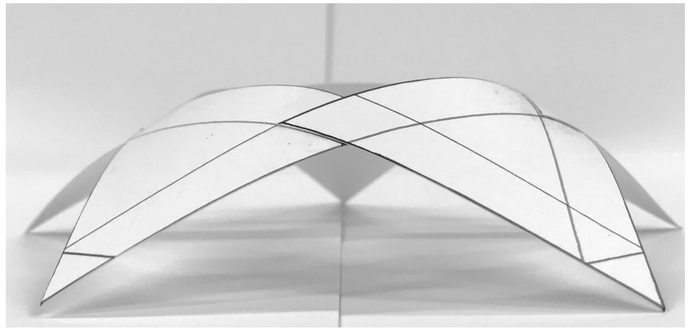
Triangulation method (Calladine)

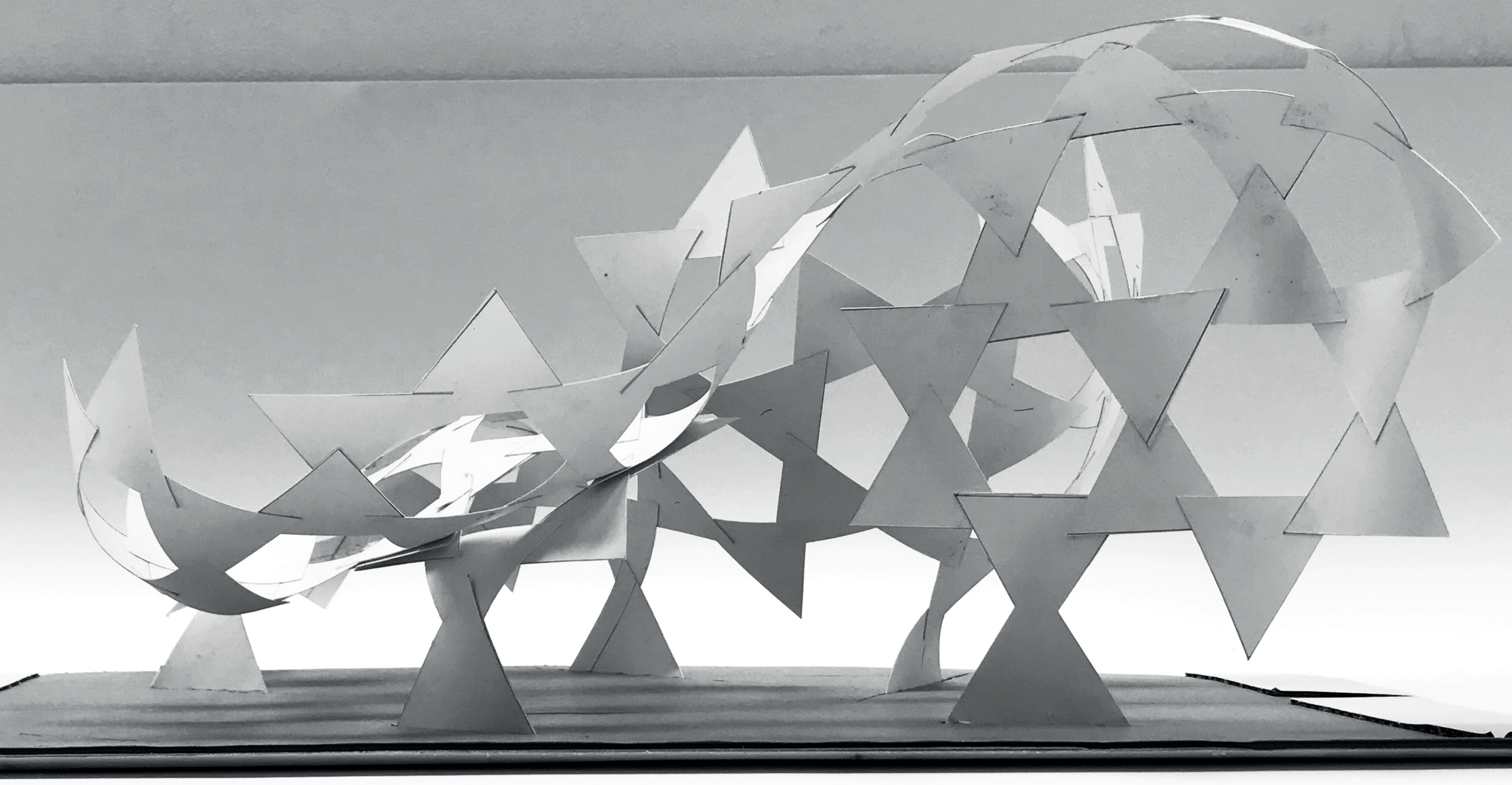
Six triangles - planar surface

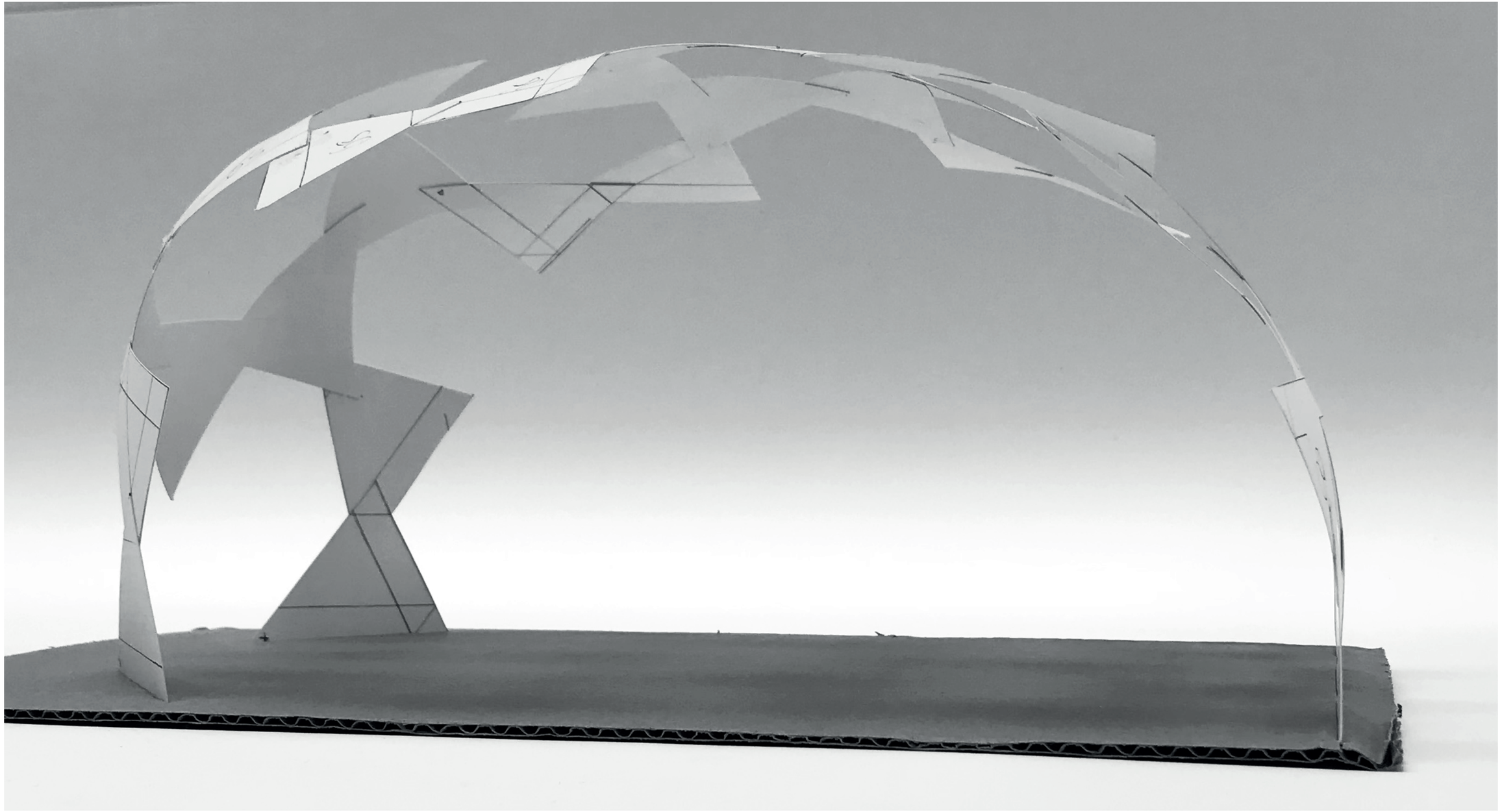


five triangles - double curved surface

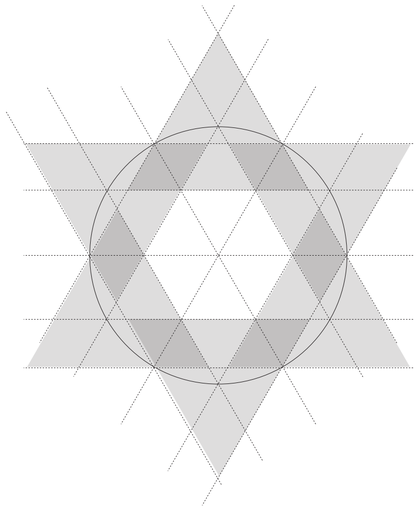


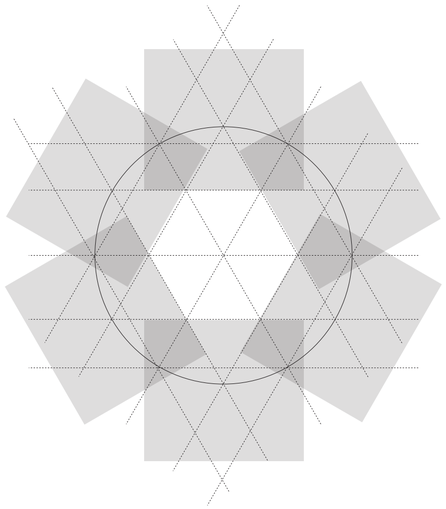


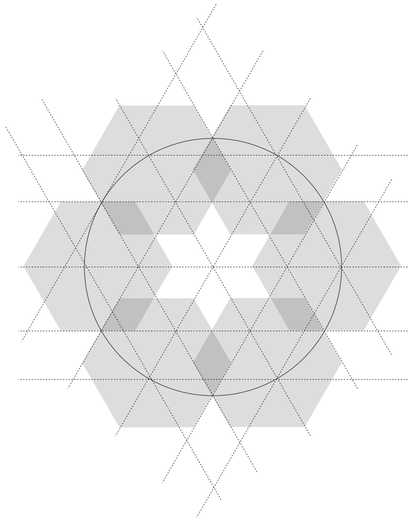




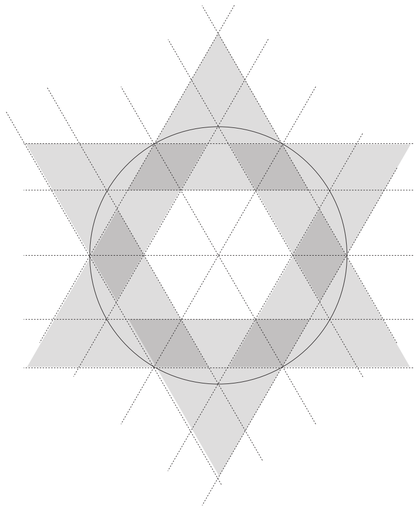
Varying geometric topology

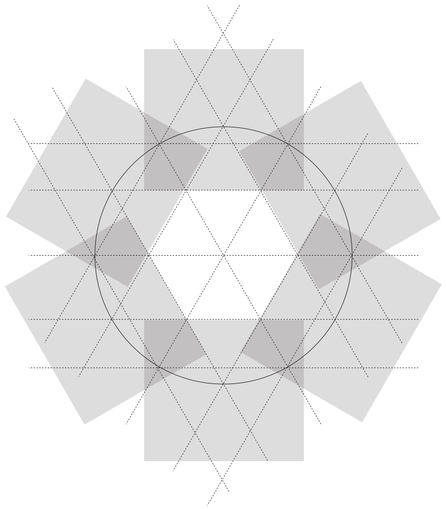


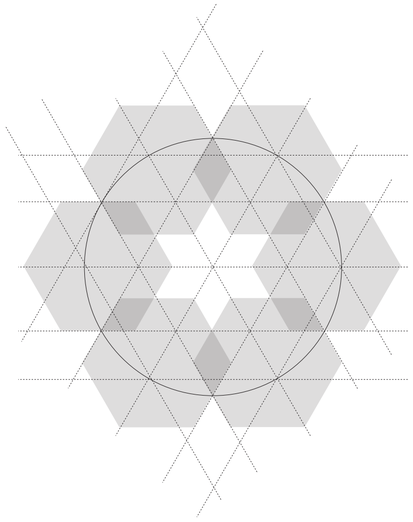


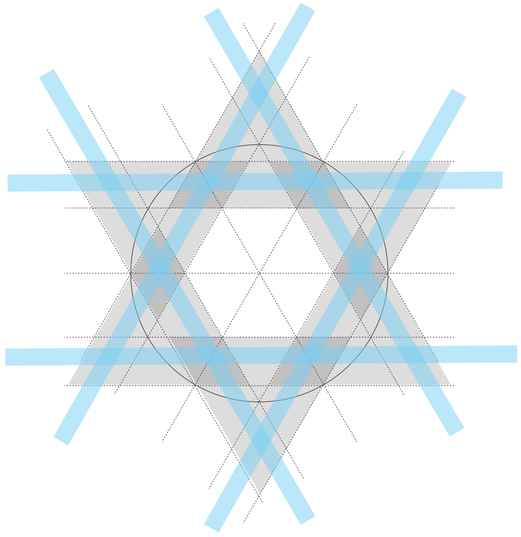


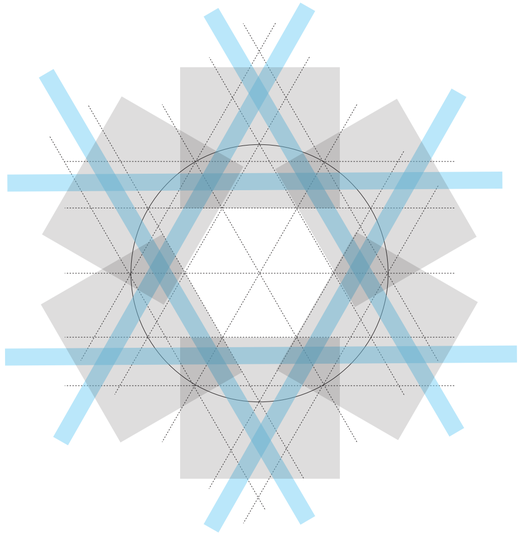
Varying geometric topology

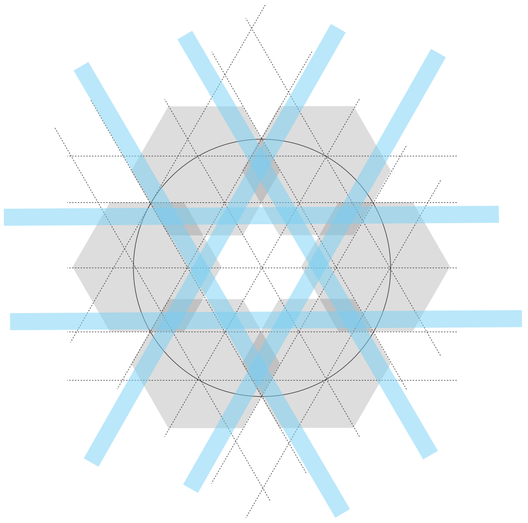


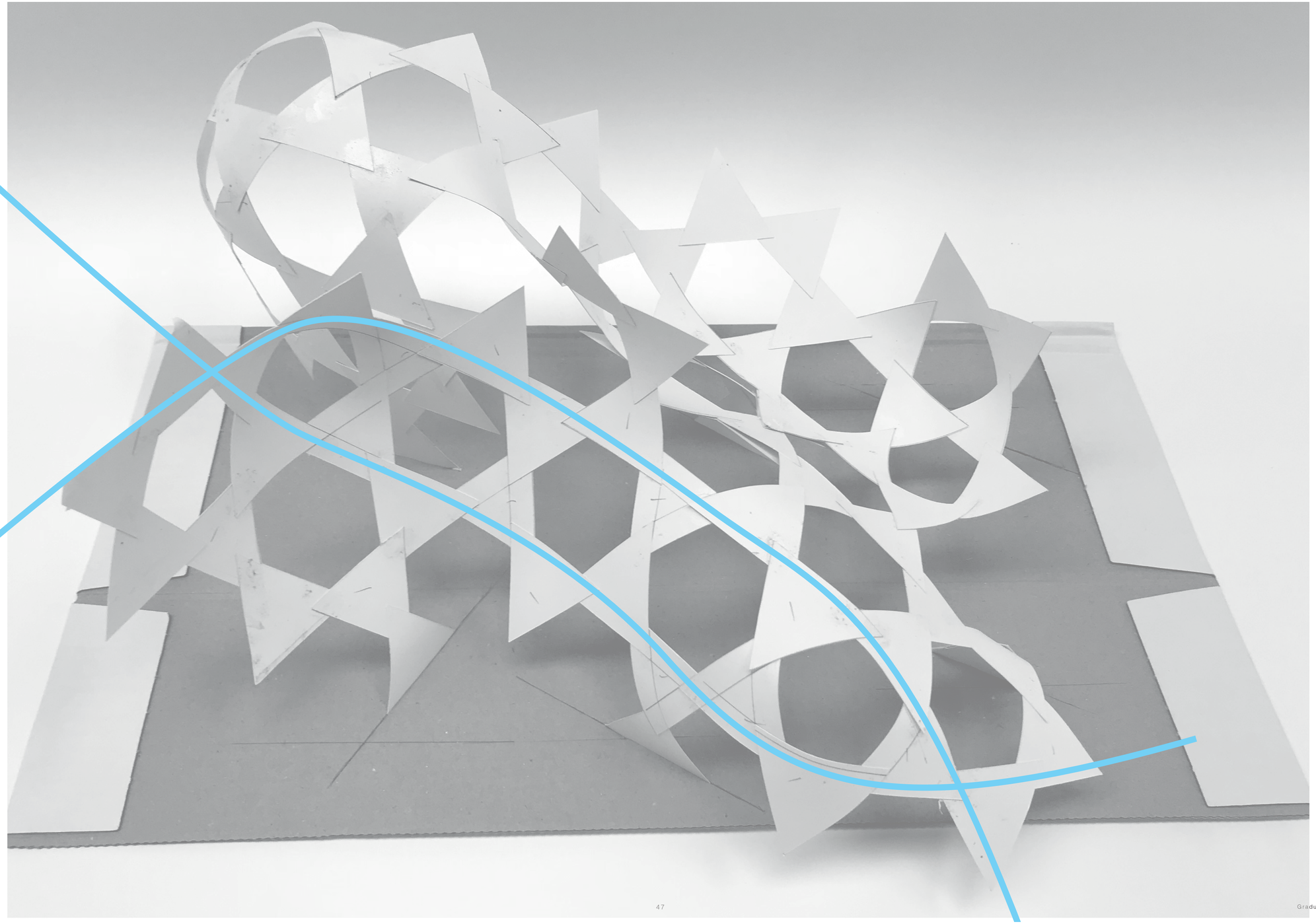


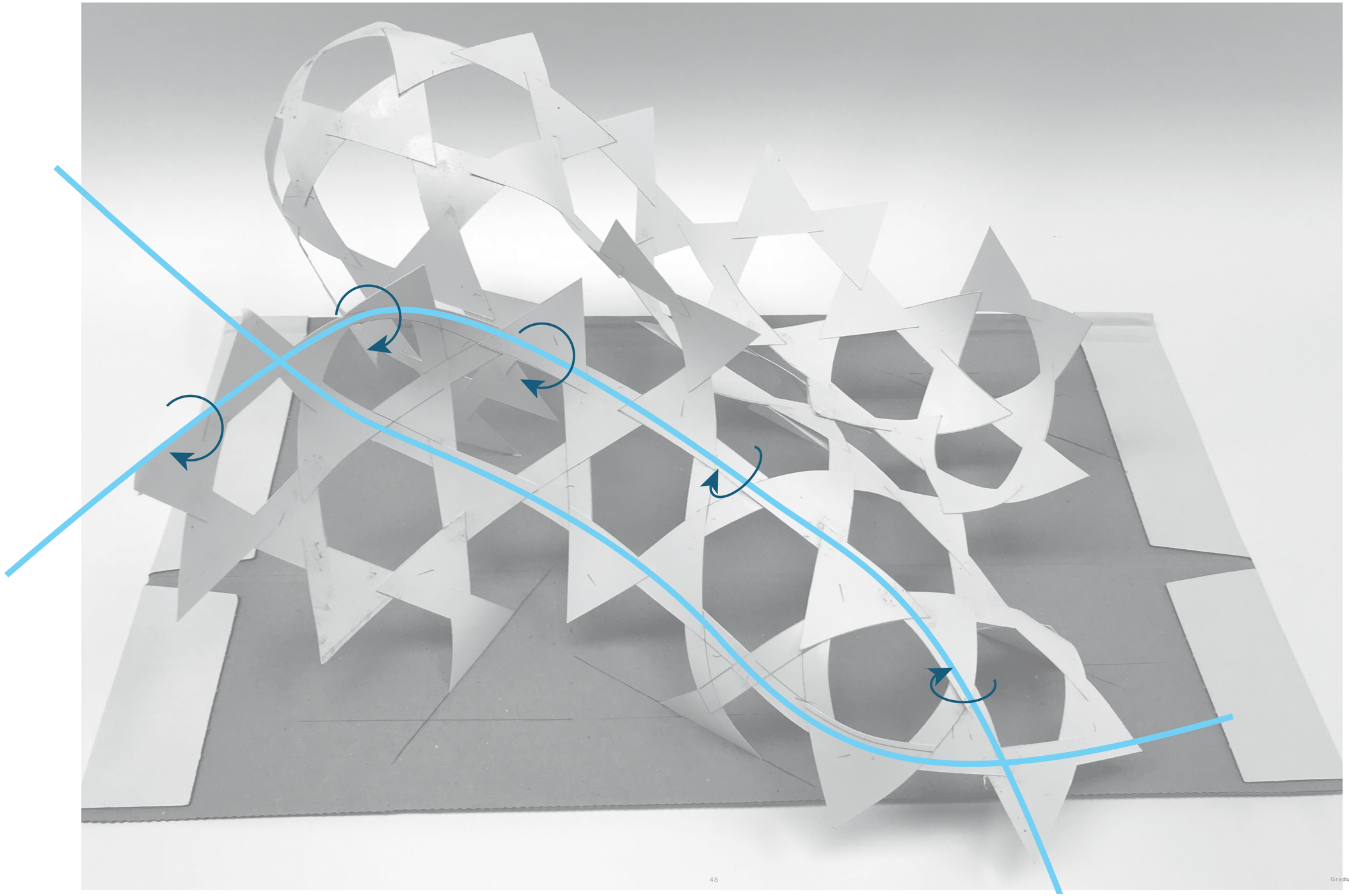




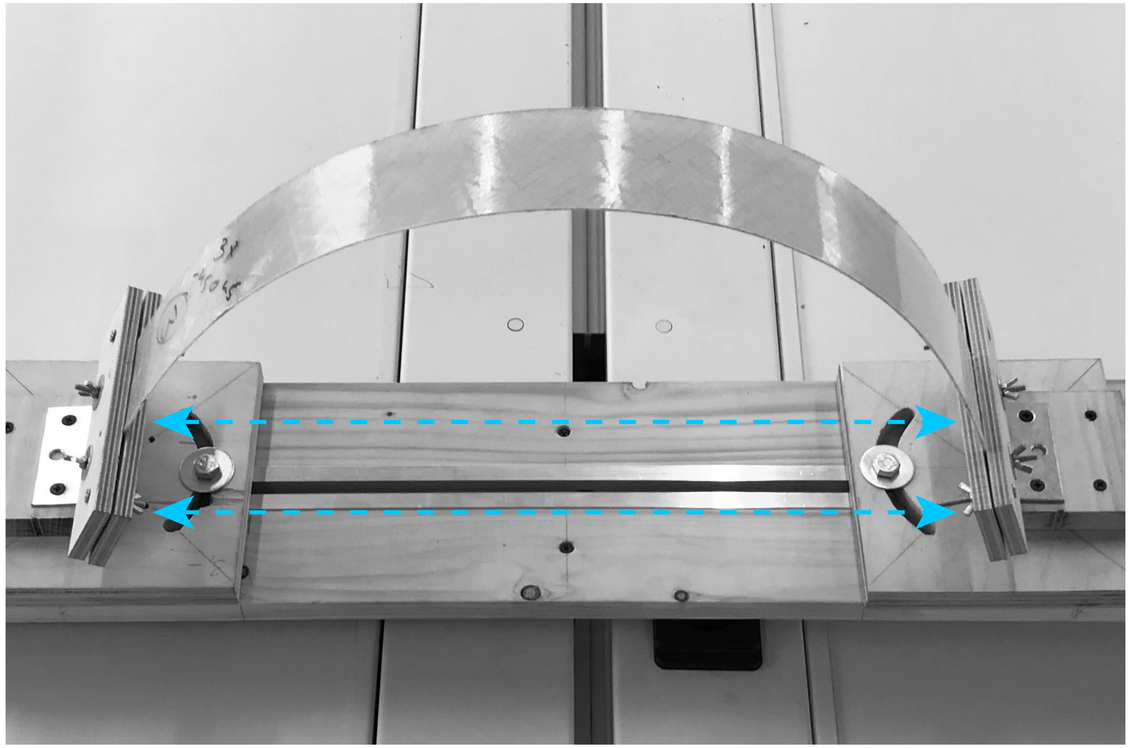






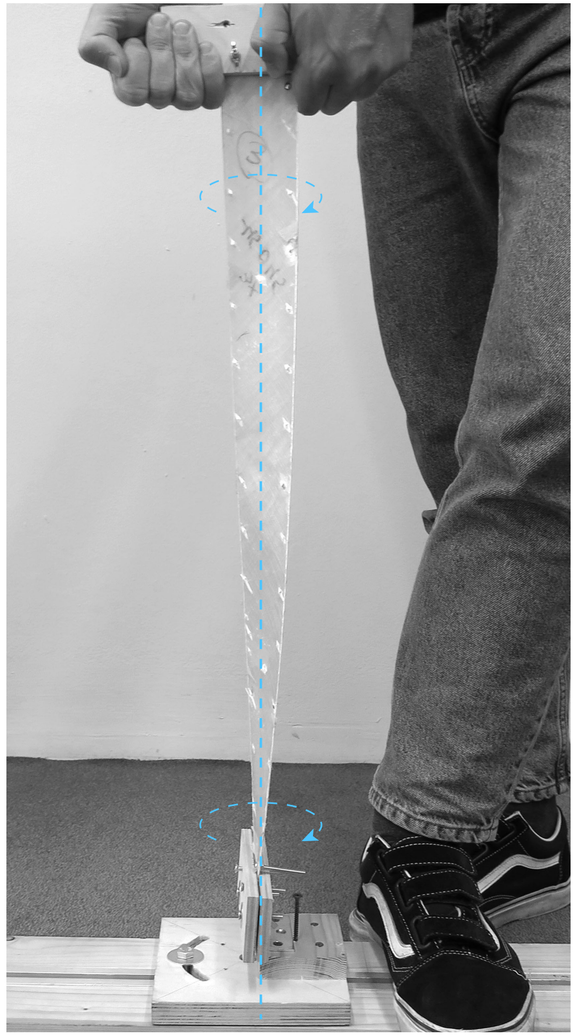


Deformation planar plate



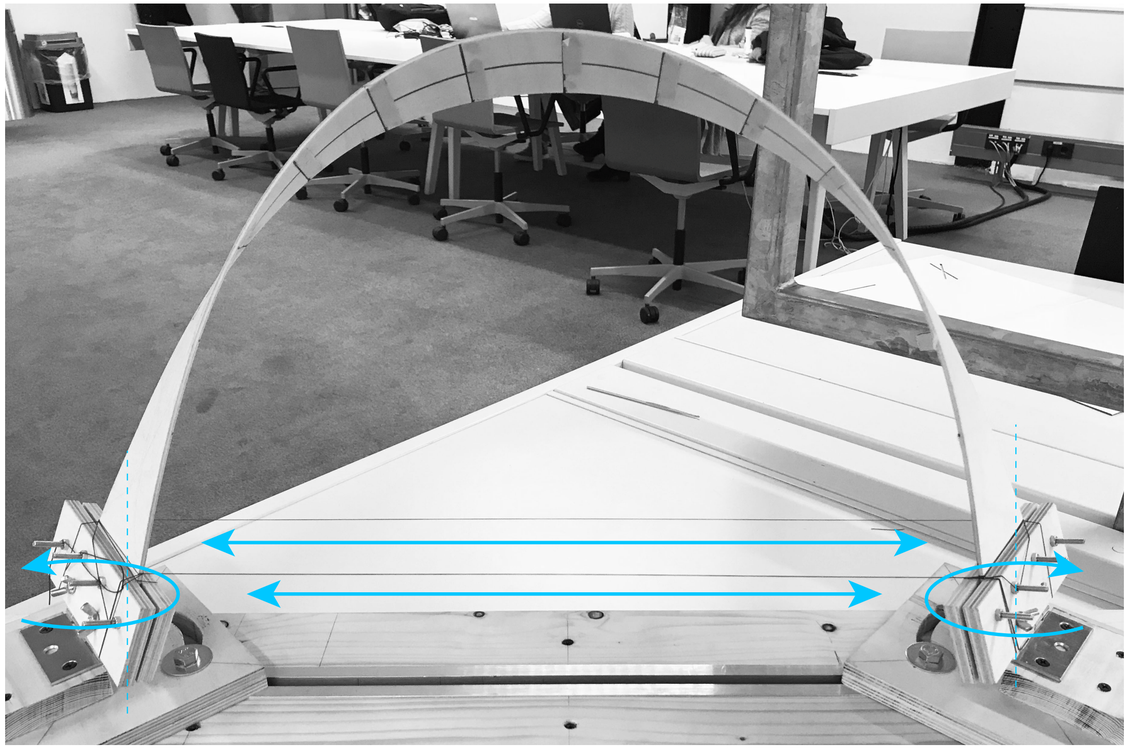
Bending

Deformation planar plate



Torsion

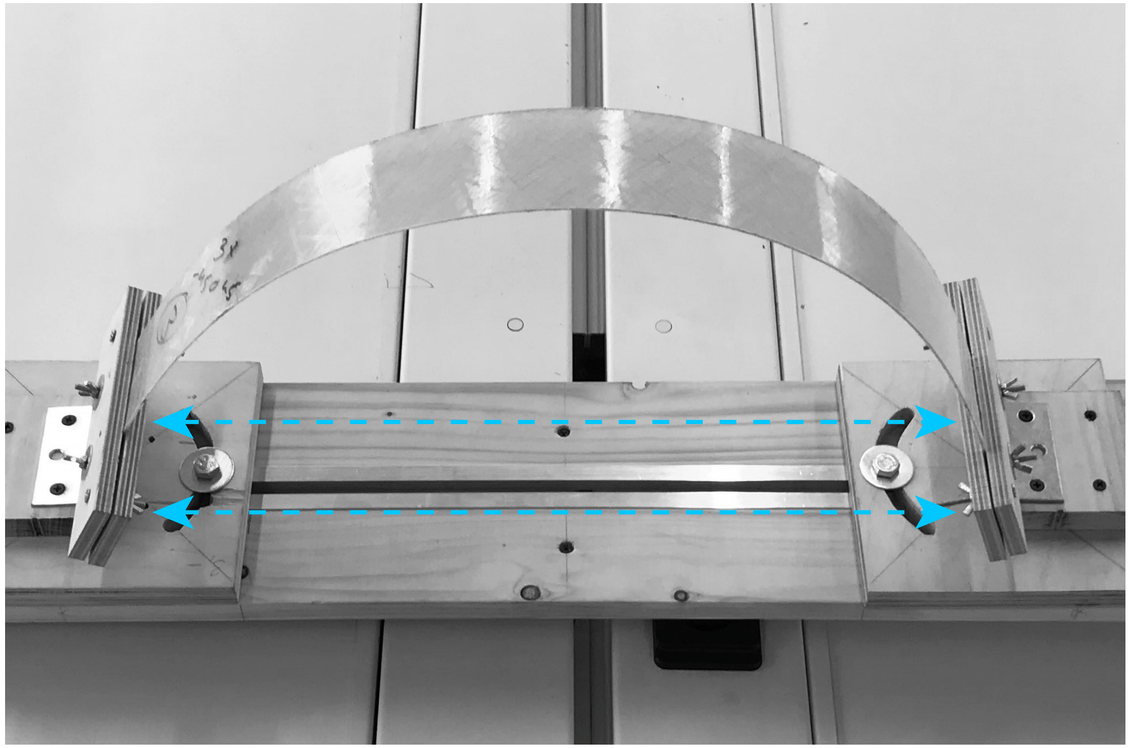
Deformation planar plate



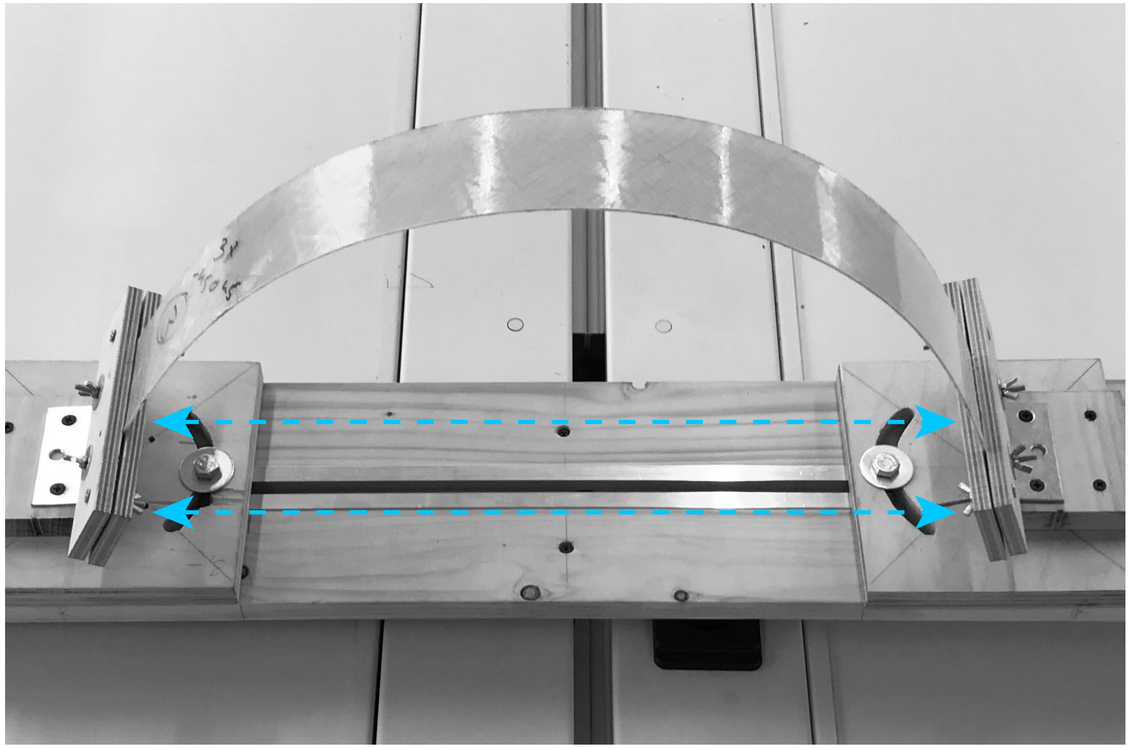
Bending and torsion combined

Theoretical framework

Bending only



Bending only



Relate curvature to bending moments in a plate

Gaussian curvature

1

$$k_1 \cdot k_2 = k_{xx} \cdot k_{yy} - k_{xy}^2$$

Principle curvature **1** and **2**
Measure of **Gaussian** curvature

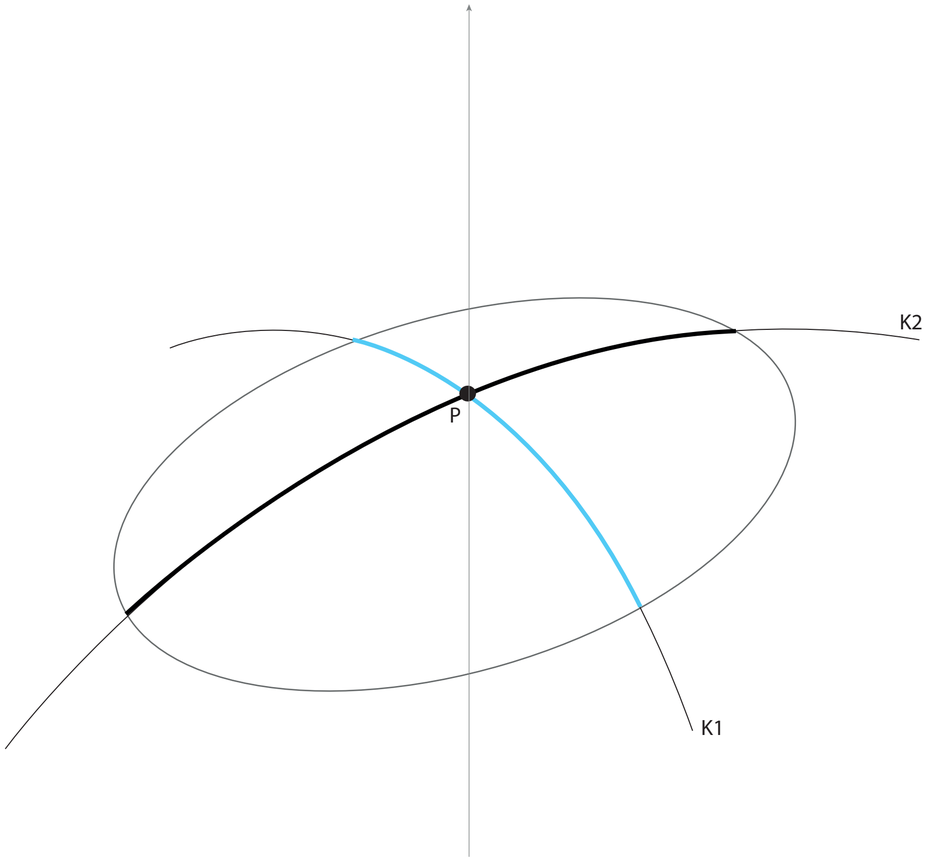
Curvature **X** direction
Bending

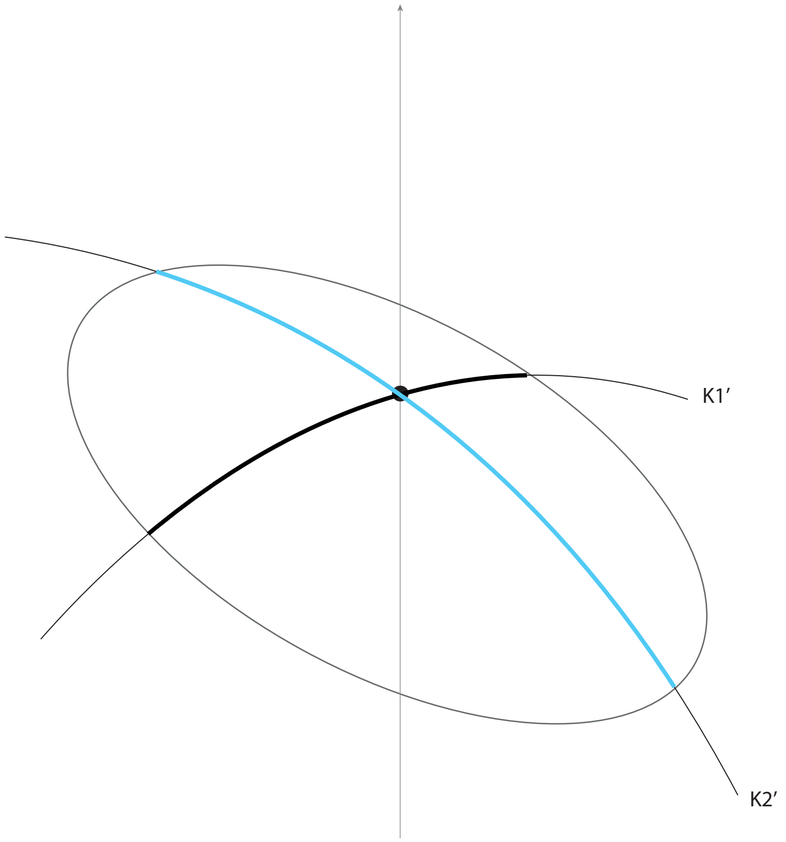
Curvature **Y** direction
Bending

Curvature **XY** direction
Torsion

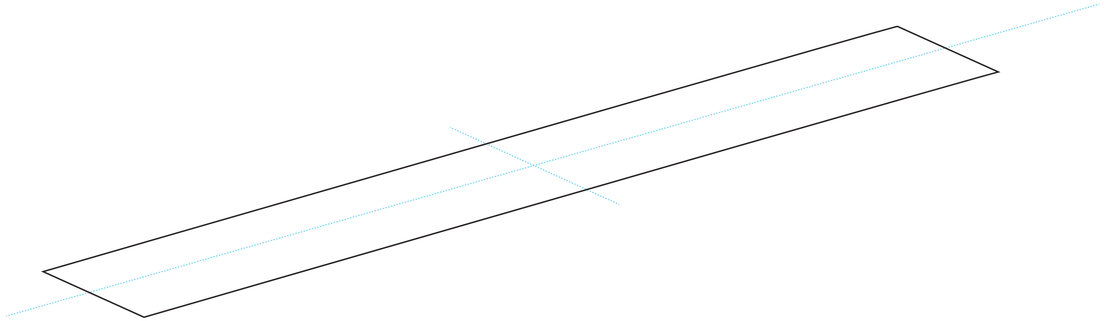
Gaussian curvature

2

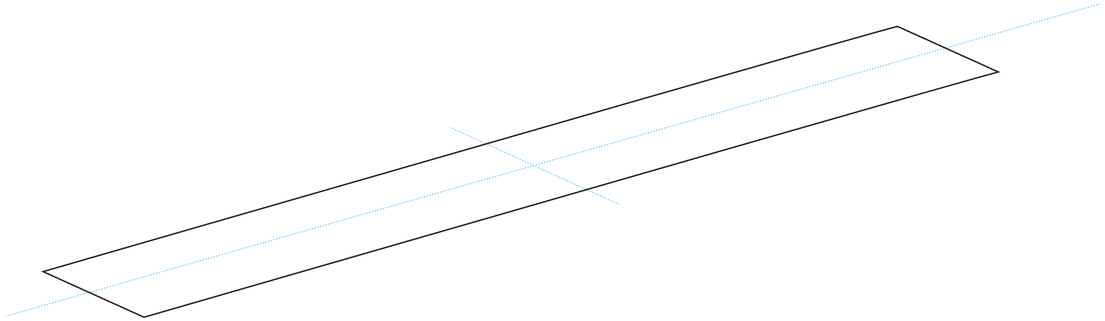




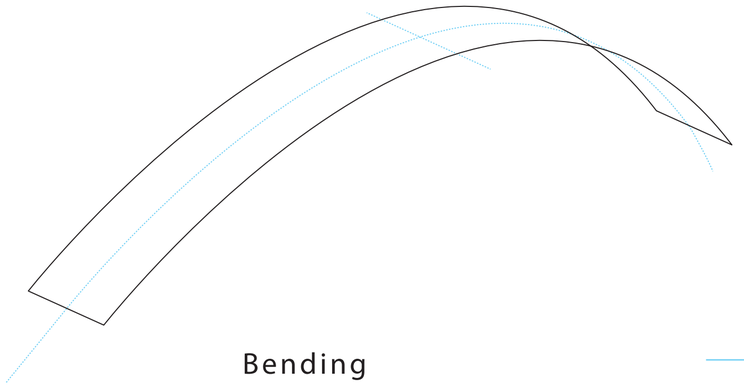
K1 * K2 = **K1' * K2'**



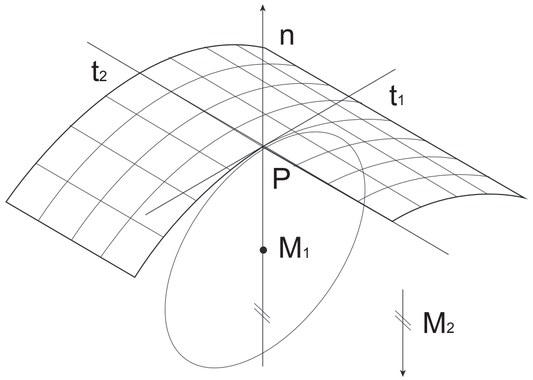
Planar surface → Gaussian curvature = 0



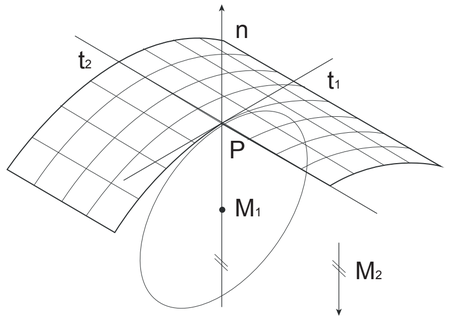
Planar surface → Gaussian curvature = 0



Bending → Gaussian curvature = 0

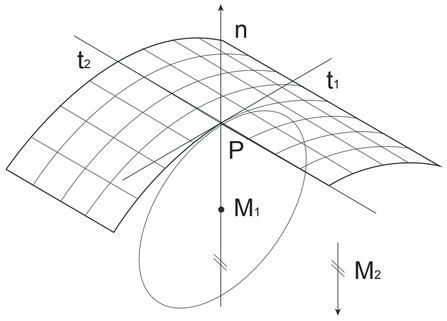


Pure geometric



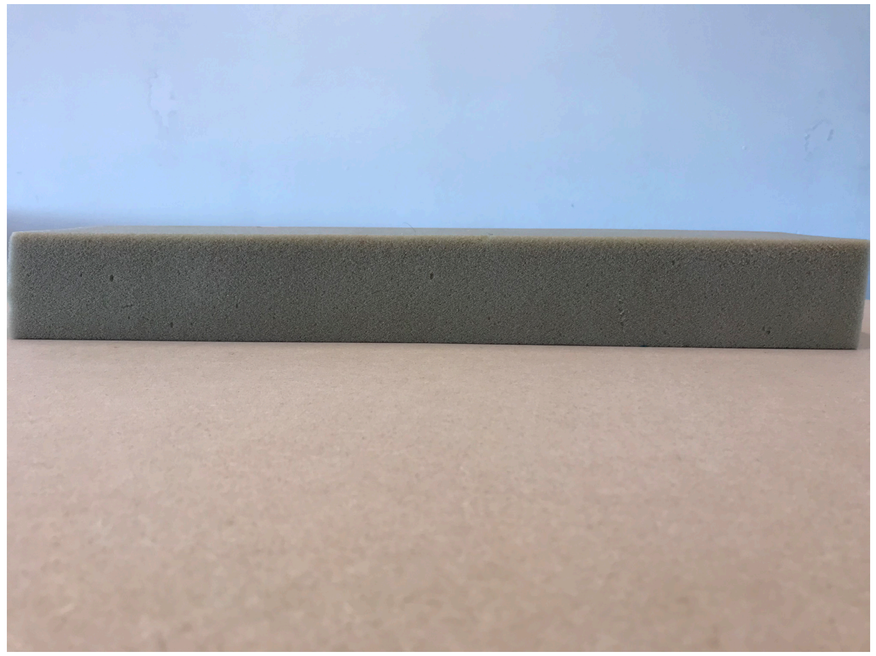
Monoclastic

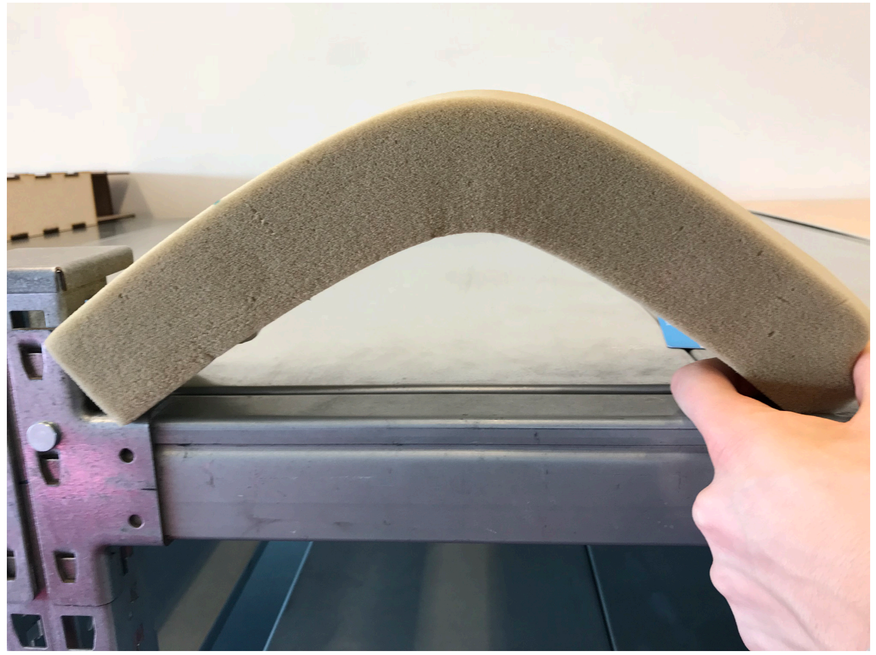
K=0

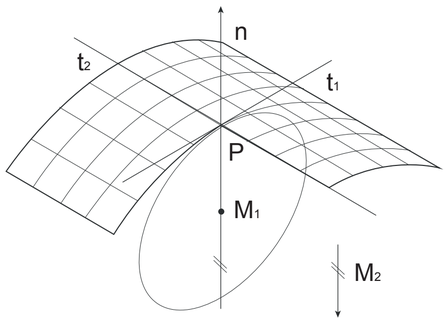


Monoclastic

K=0

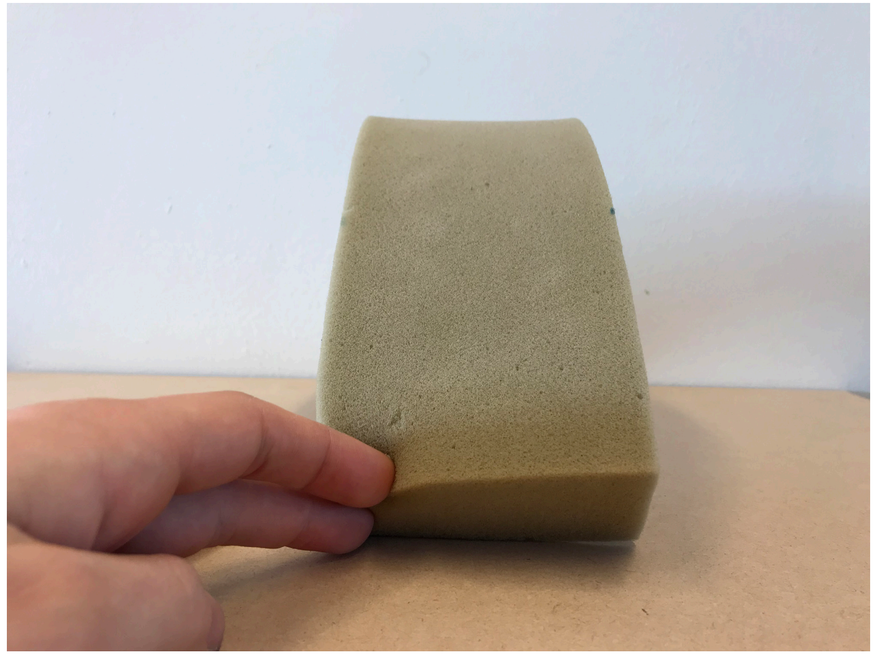


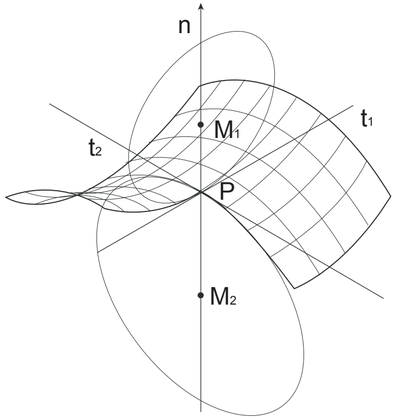




Monoclastic

K=0





Anticlastic

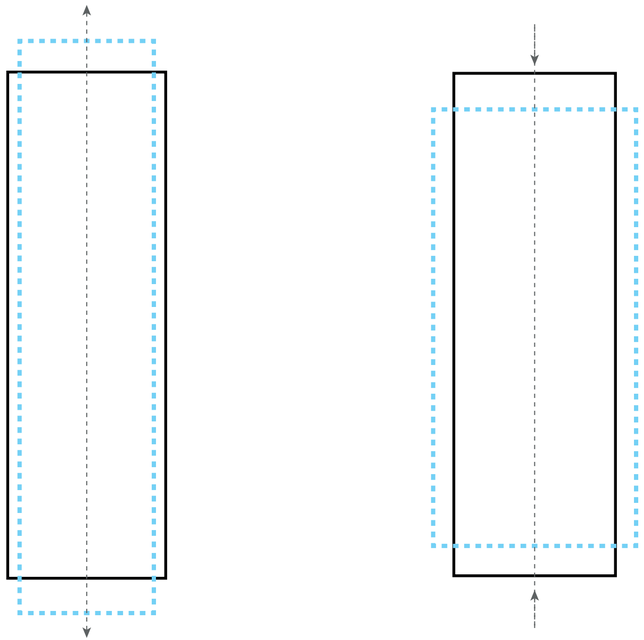
K<0

$$\nu = -\frac{\epsilon xx}{\epsilon yy}$$

ν Poisson's ratio

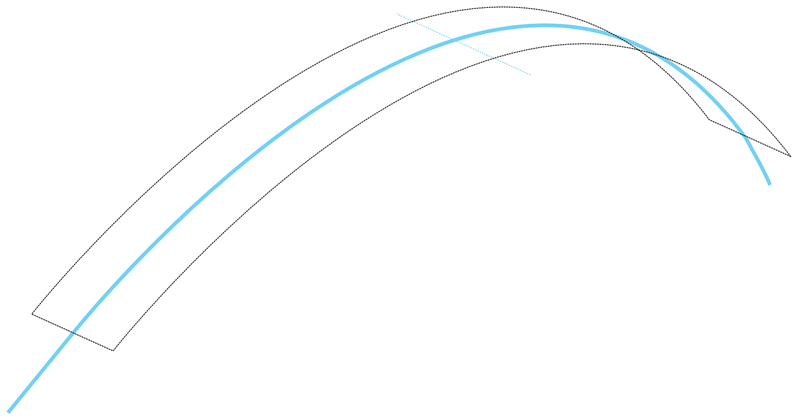
$$\nu = -\frac{\epsilon xx}{\epsilon yy}$$

v Poisson's ratio

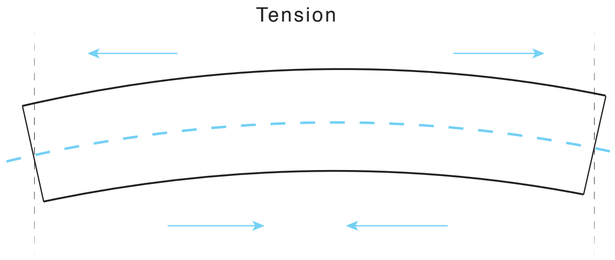


Tension Compression

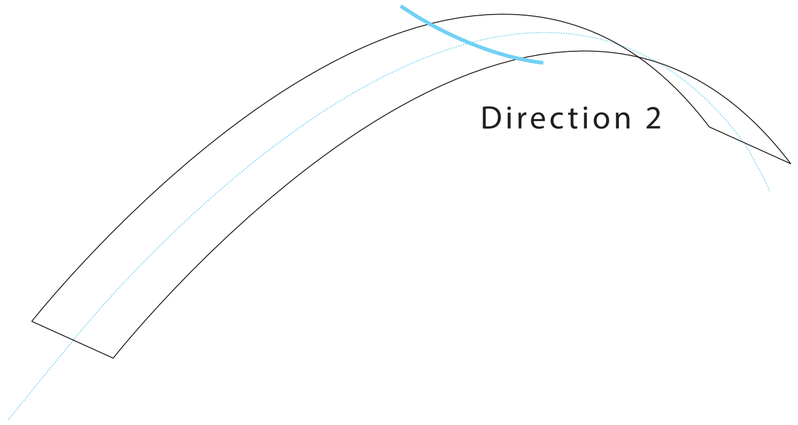
Input curvature

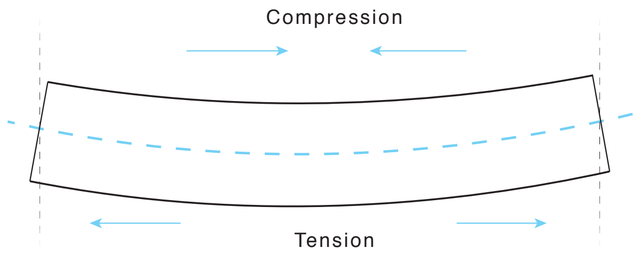


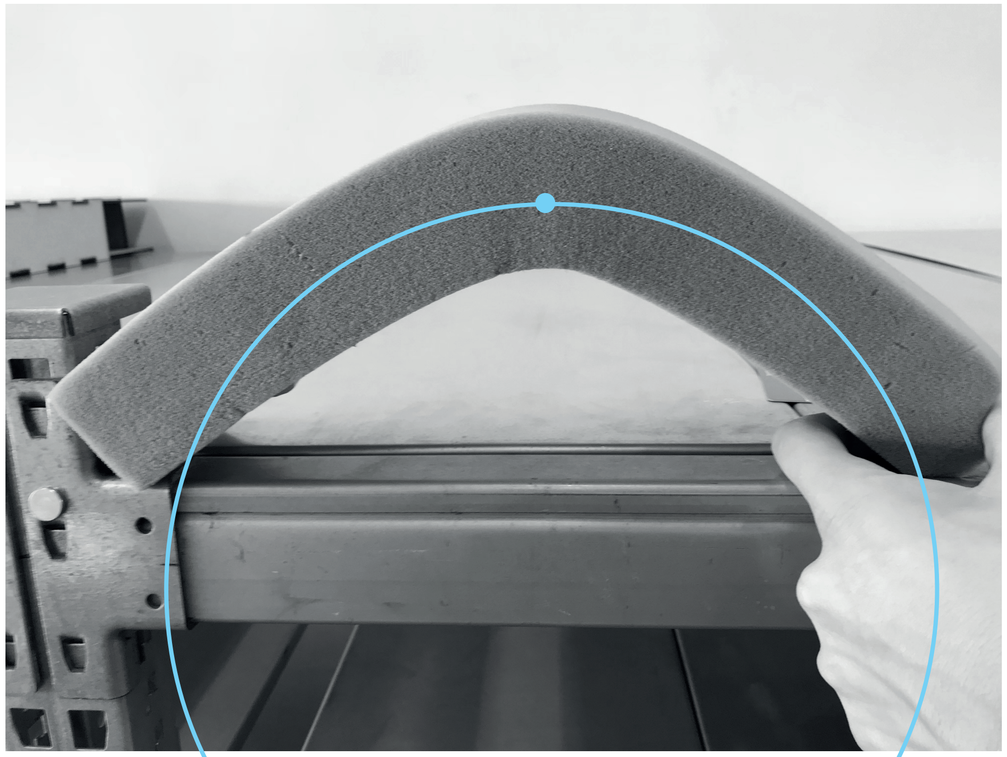
Direction 1



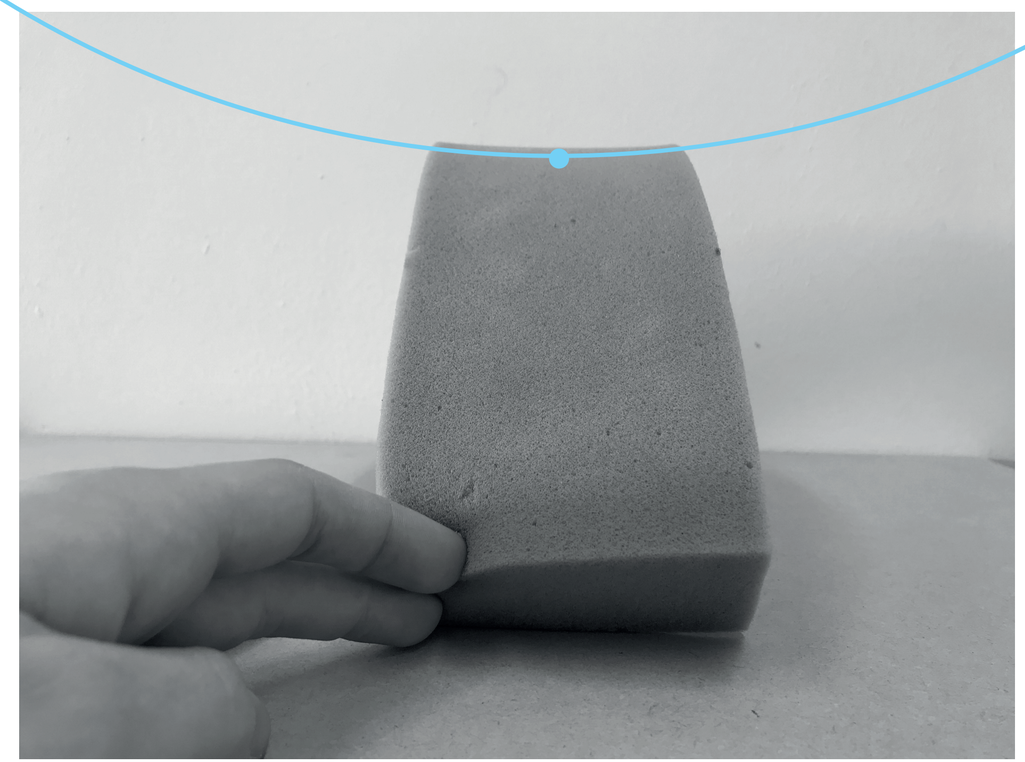
Output curvature





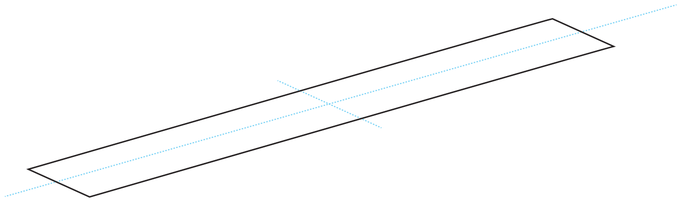


Input radius 1

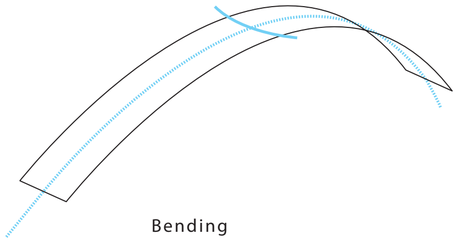


Output radius 2

Bending deformation

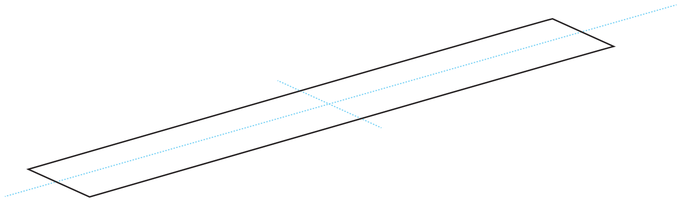


Planar surface

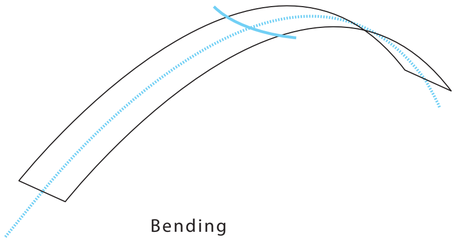


Bending

Bending deformation

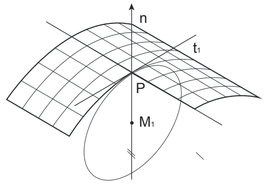


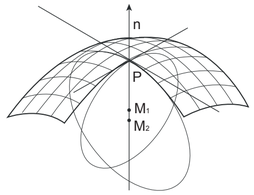
Planar surface

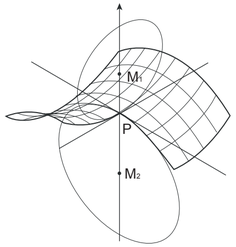


Bending

Gaussian measure







Bending deformation

Planar surface

Bending

Gaussian measure

Moment curvature relation

$$M_x = D(\kappa_x + \nu\kappa_y)$$

$$M_y = D(\kappa_y + \nu\kappa_x)$$

$$M_{xy} = D(1 - \nu)\,\kappa_{xy}$$

D	Bending rigidity
ν	Poisson's ratio
κ_x	Curvature x
κ_y	Curvature y

Bending deformation

Planar surface

Bending

Gaussian measure

$$k_1 \cdot k_2 = k_x \cdot k_y - k_{xy}^2$$

Moment curvature relation

$$M_x = D(\kappa_x + \nu\kappa_y)$$

$$M_y = D(\kappa_y + \nu\kappa_x)$$

$$M_{xy} = D(1 - \nu)\,\kappa_{xy}$$

D	Bending rigidity
ν	Poisson's ratio
κ_x	Curvature x
κ_y	Curvature y

Gaussian measure

$$k_1 \cdot k_2 = k_x \cdot k_y - k_{xy}^2$$

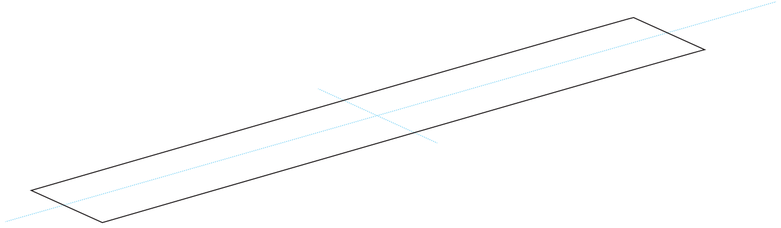
$$M_x = D(\kappa_x + \boldsymbol{\nu}\kappa_y)$$

$$M_y = D(\kappa_y + \boldsymbol{\nu}\kappa_x)$$

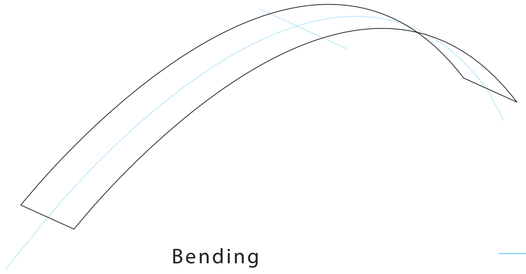
$$M_{xy} = D(1 - \boldsymbol{\nu})\,\kappa_{xy}$$

$$k_1 \cdot k_2 = D(\kappa_x + \boldsymbol{\nu}\kappa_y) \cdot D(\kappa_x + \boldsymbol{\nu}\kappa_y) - D(1 - \boldsymbol{\nu})\,\kappa_{xy}^2$$

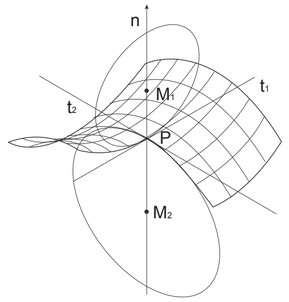
Geometric Gaussian measure with material properties



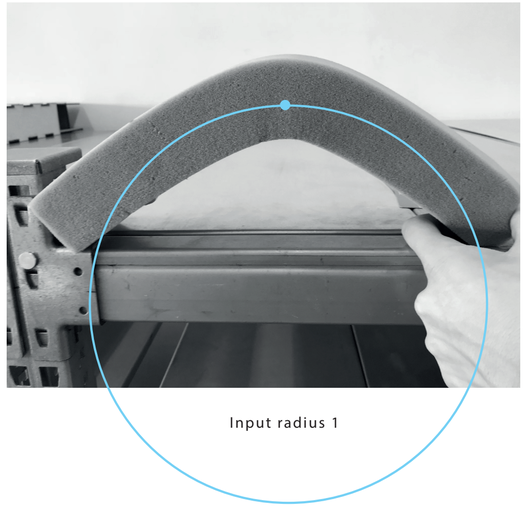
Planar surface → Gaussian curvature = 0



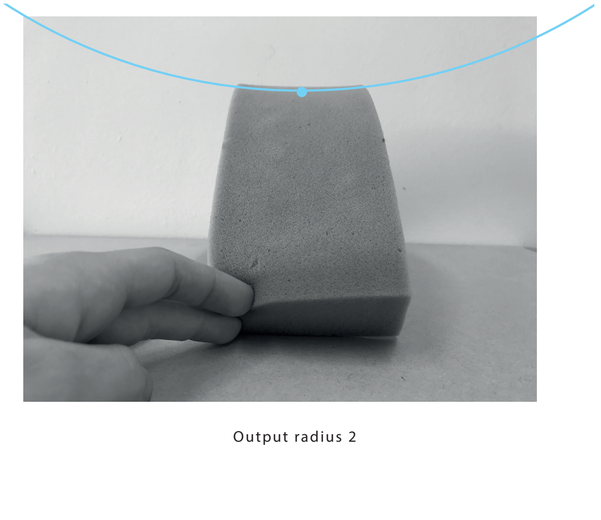
Bending → Gaussian curvature **≠ 0**



Calculate ouput radius



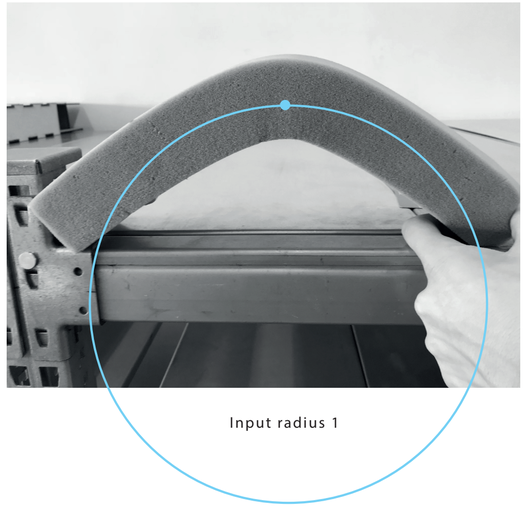
Input radius 1



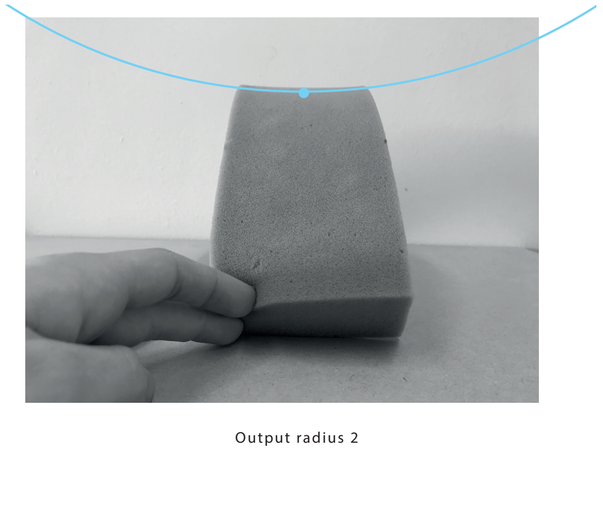
Output radius 2

Relation bending & torsion curvatures

Geometric Gaussian measure with material properties



Input radius 1

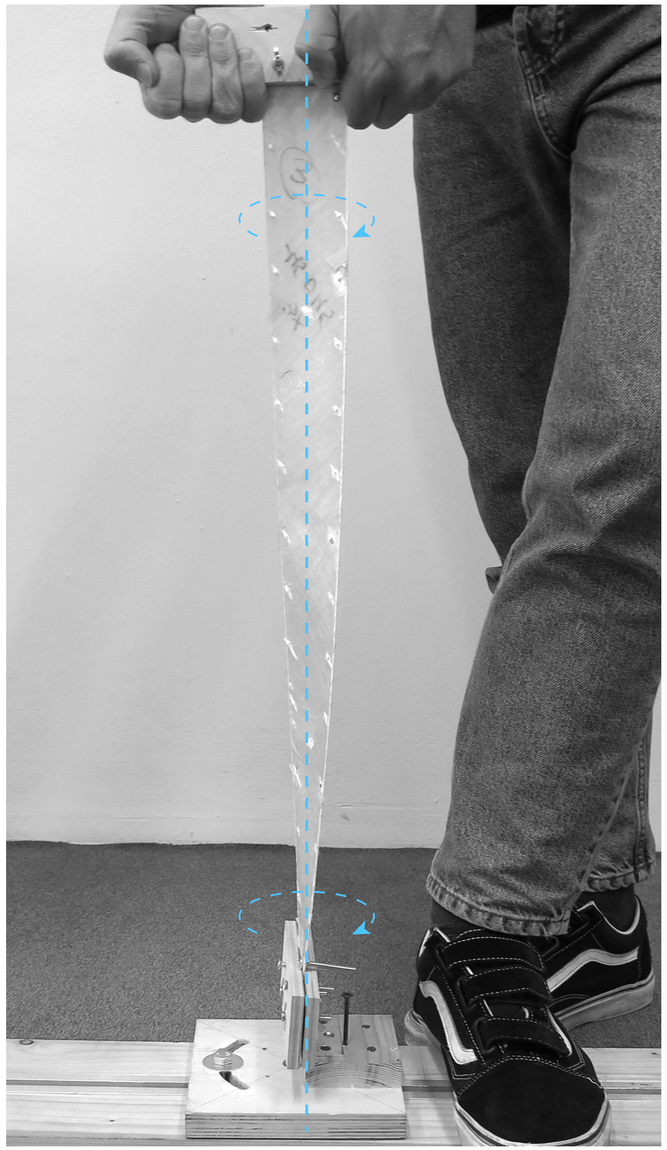


Output radius 2

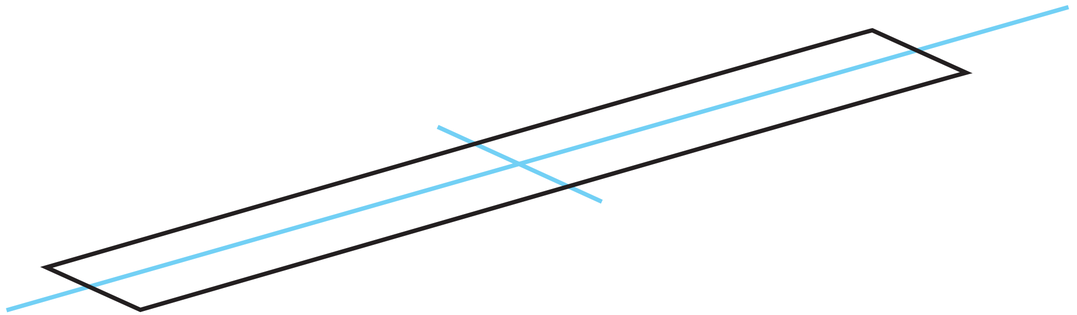
Relation bending & torsion curvatures

Relation bending and shear stress

Torsion

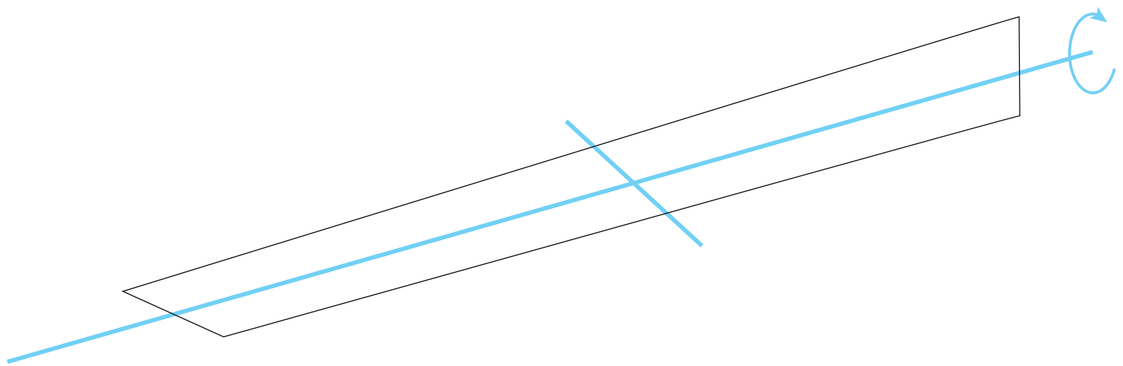


Torsion



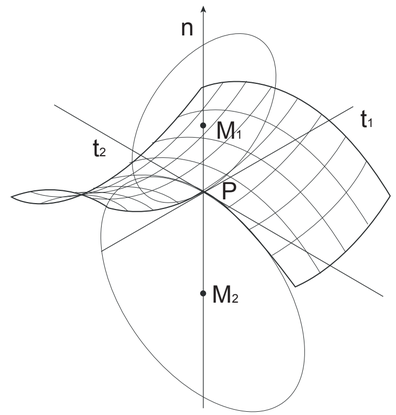
Planar surface

$K_1 \cdot K_2$

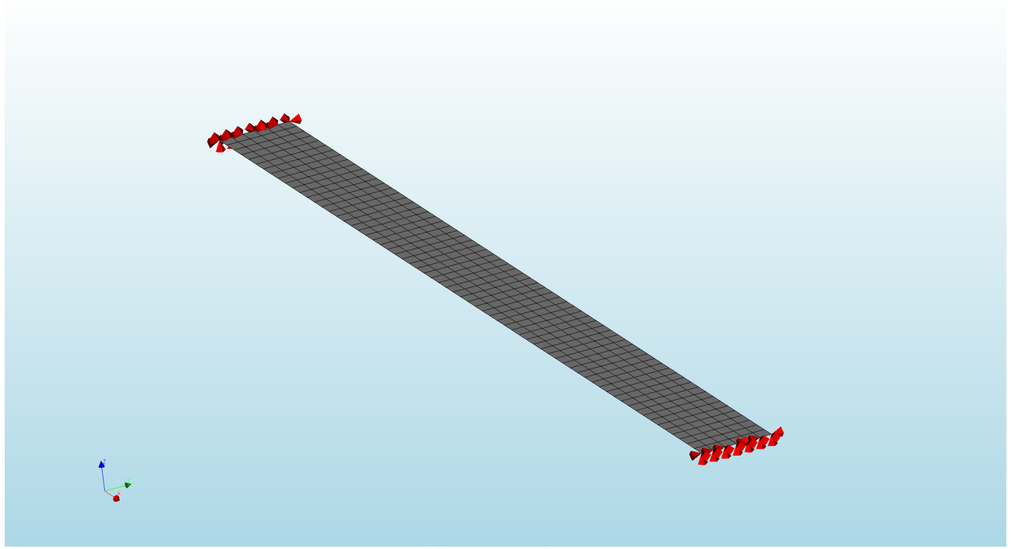


Torsion

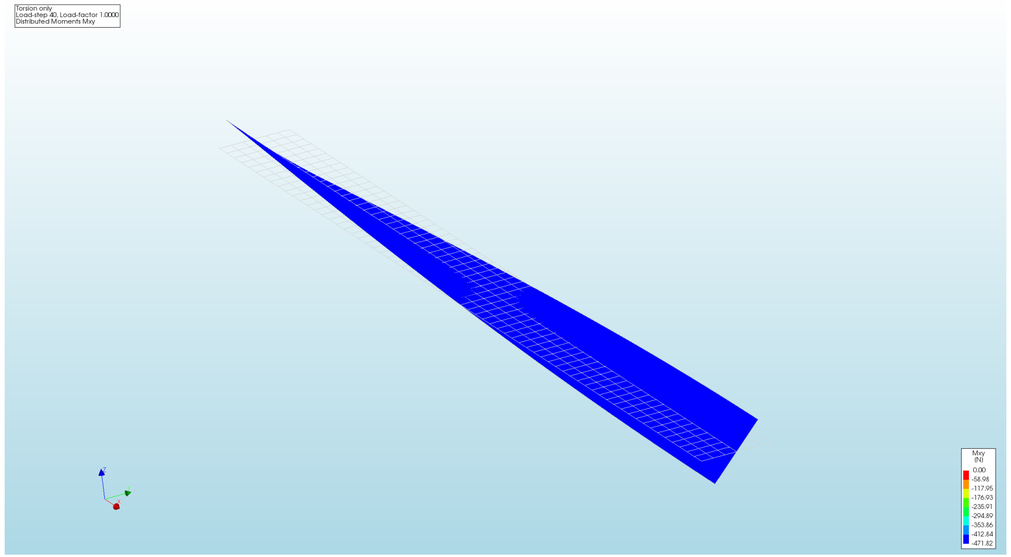
$K_1' \cdot K_2'$



Stiffening effect torsion

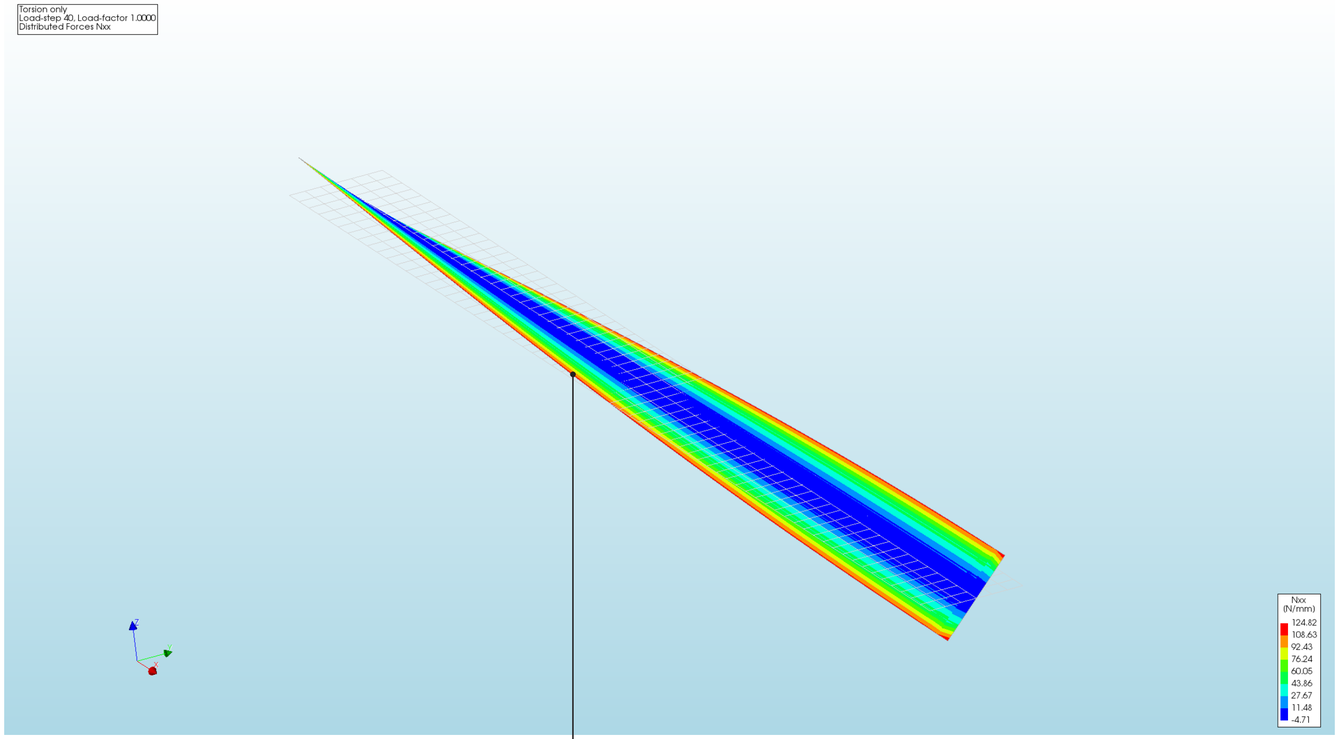


Planar plate



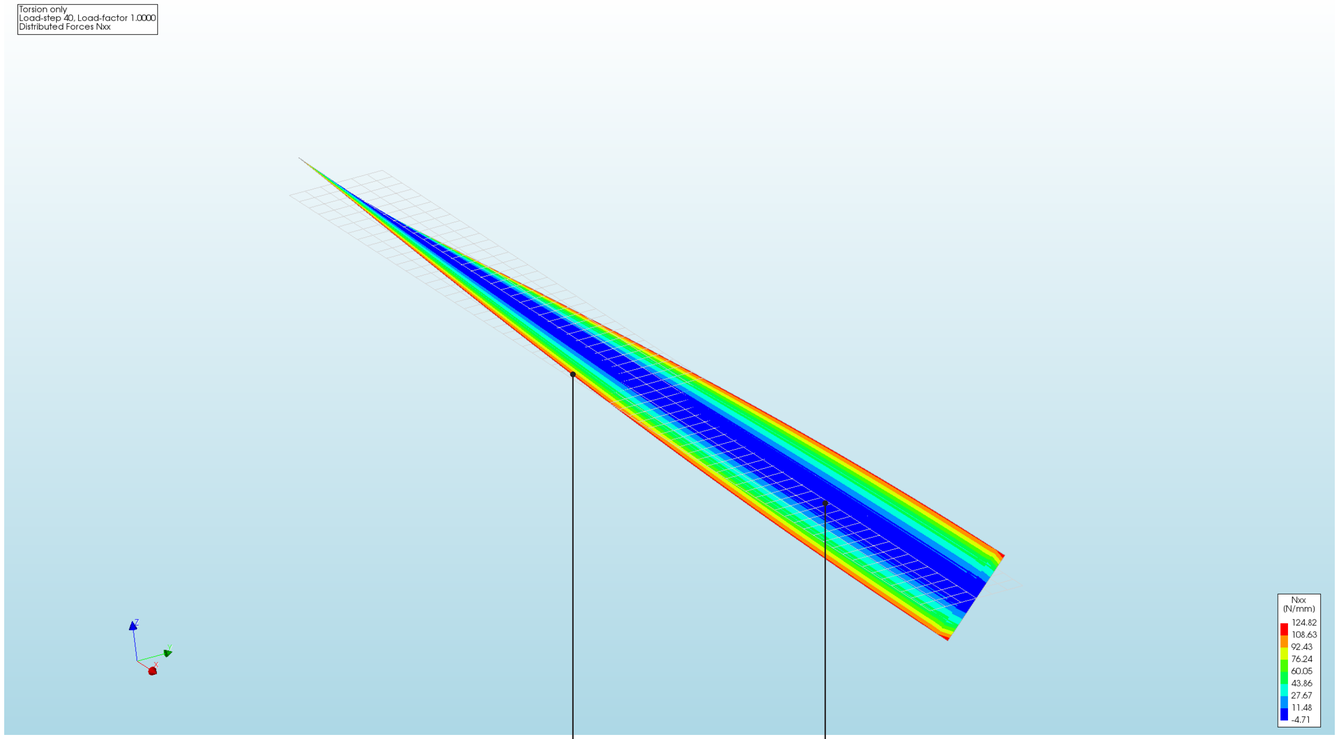
Torsional displacement

Stiffening effect torsion

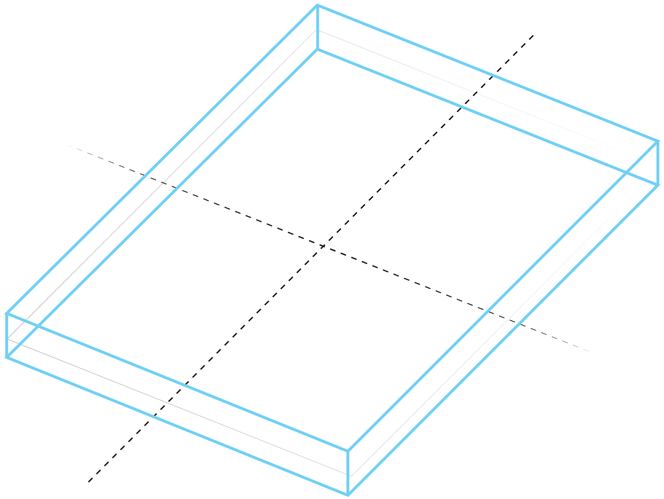


Increased tensile stress

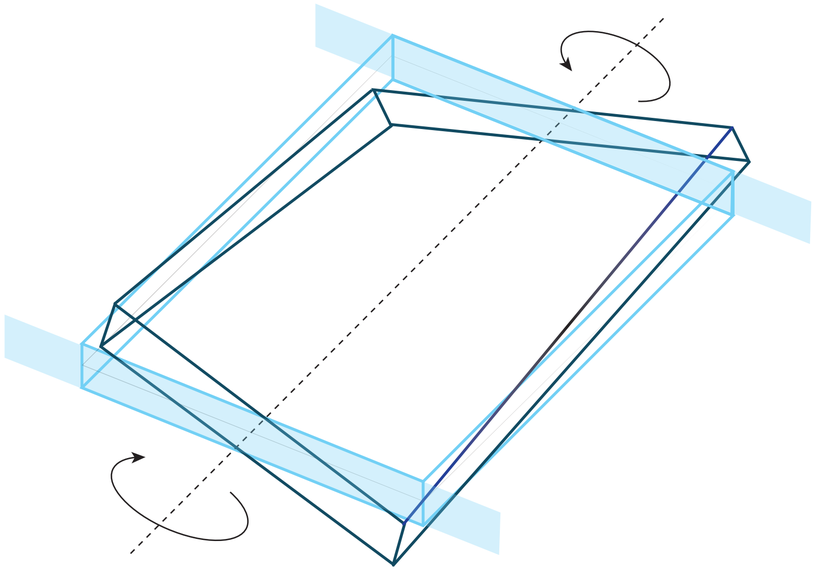
Stiffening effect torsion



Stiffening effect torsion

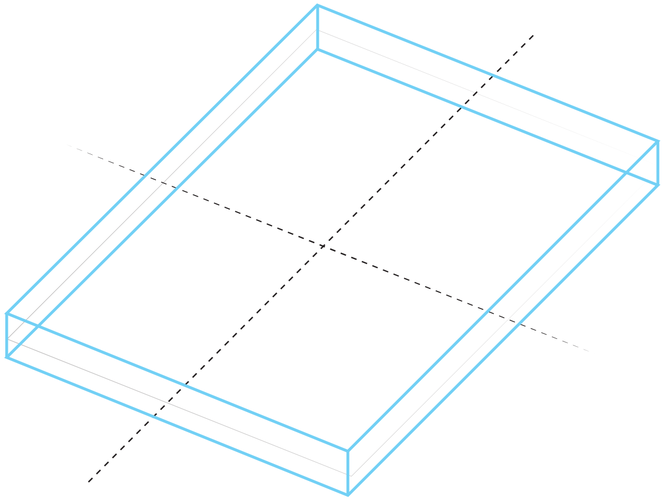


Planar plate

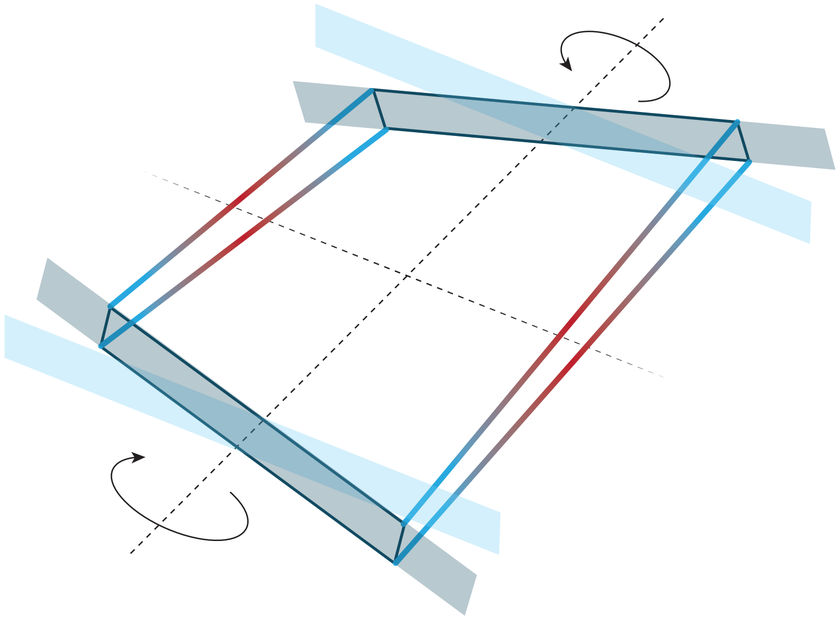


Torsion

Stiffening effect torsion



Planar plate

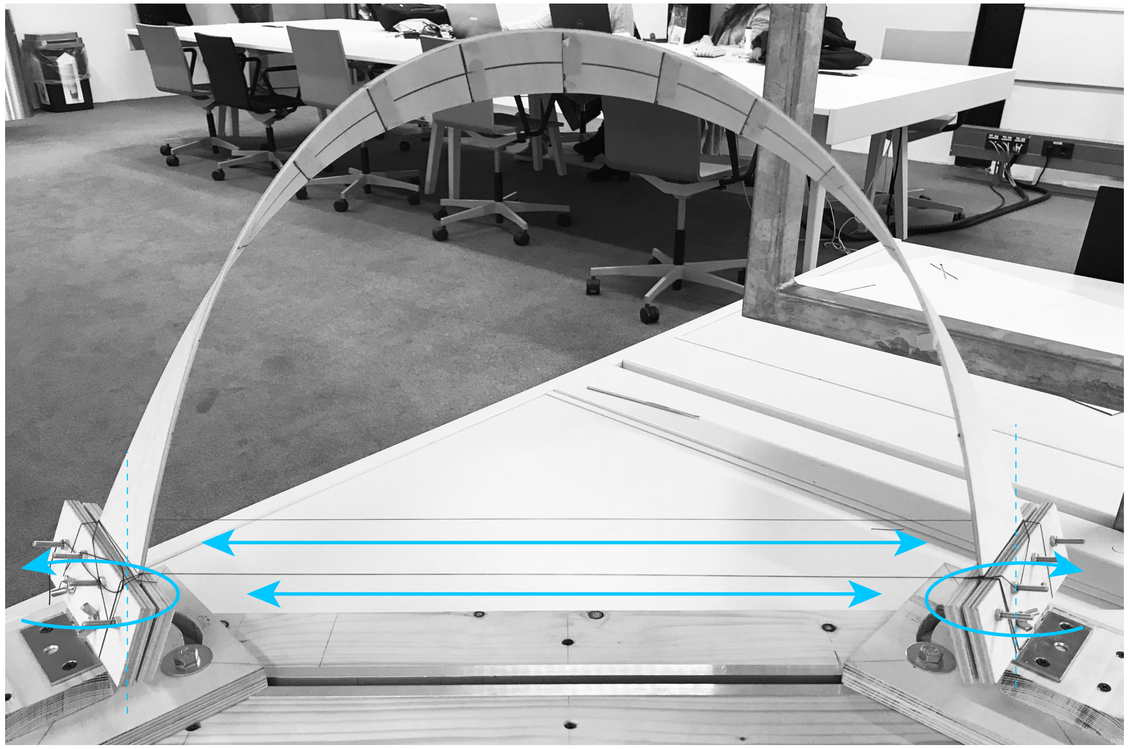


In-plane fixation

Prevent warping

Increased tensile stresses

Deformation planar plate



Bending and torsion combined

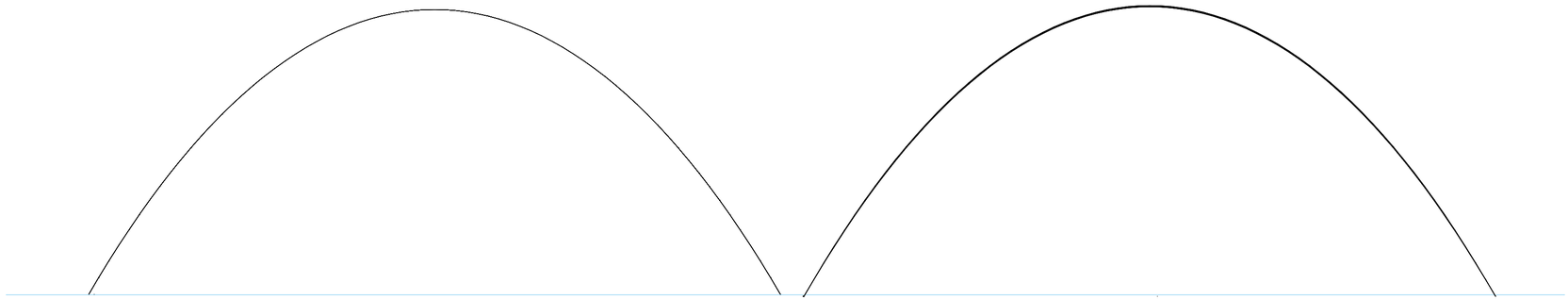
Leading parameter in bending and torsional deformation

Poisson’s ratio

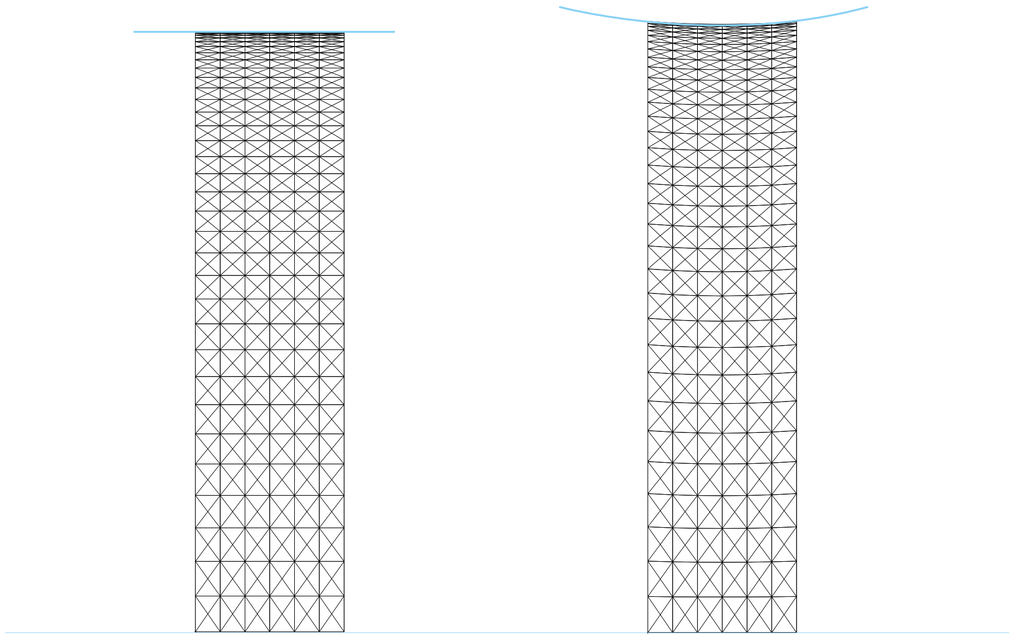
$$\nu = -\frac{\epsilon xx}{\epsilon yy}$$

Influence geometry and stiffness

Influence Poisson’s ratio bending geometry

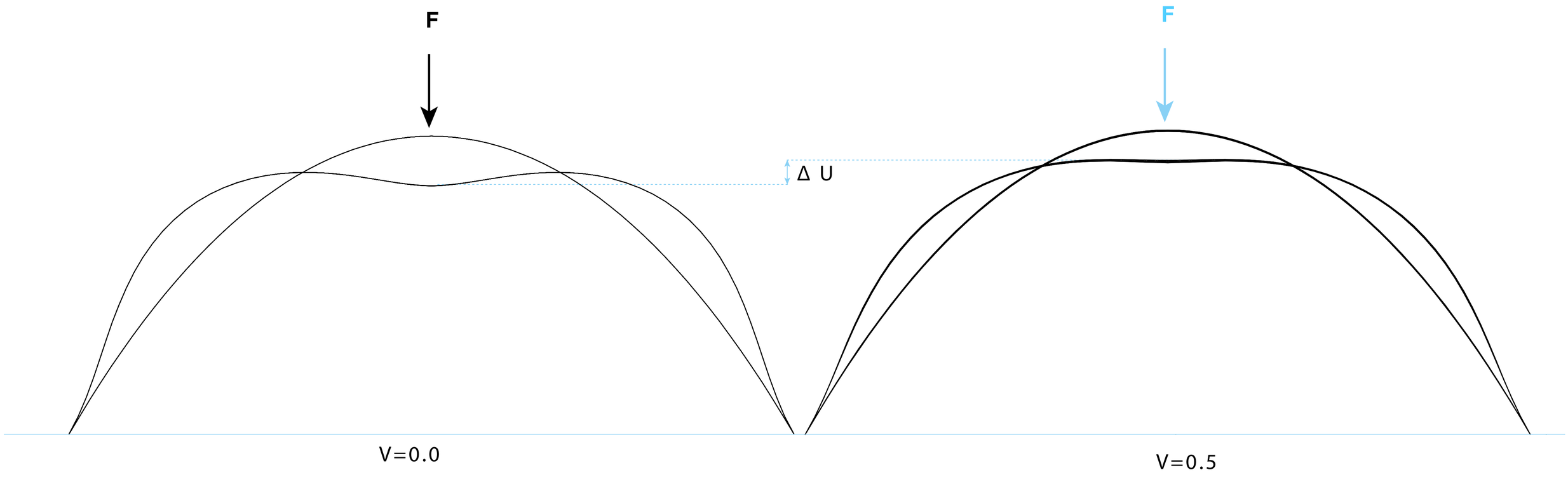


V=0.0 V=0.5

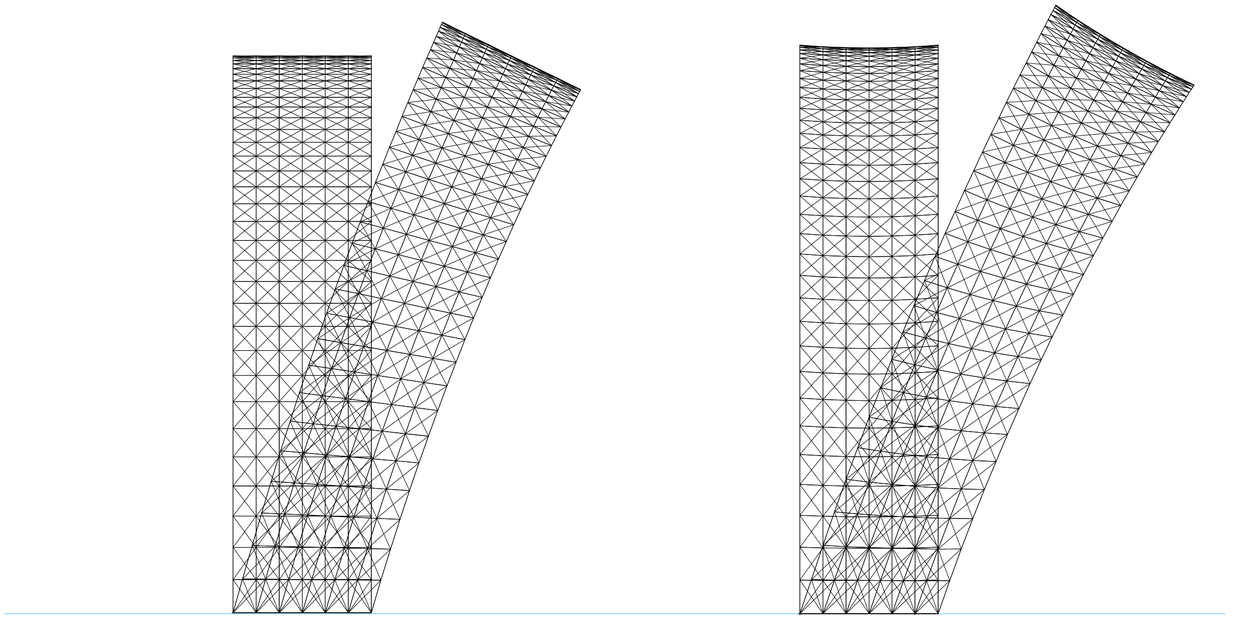


V=0.0 V=0.5

Load deflection diagram bending geometry



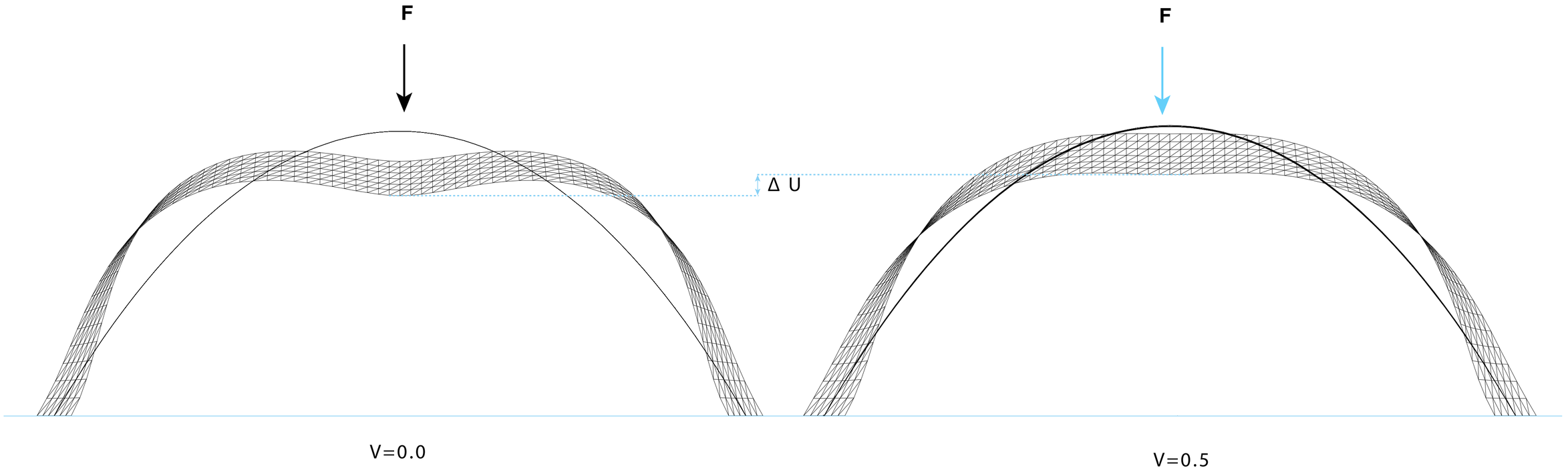
Influence Poisson’s ratio torsional geometry



V=0.0

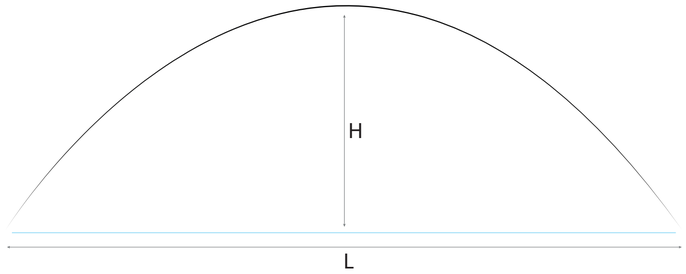
V=0.5

Load deflection diagram bending and torsion geometry



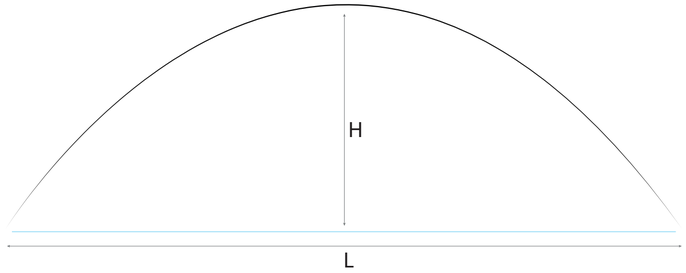
Structural and architectural design variables

Design parameters bent and twisted arch

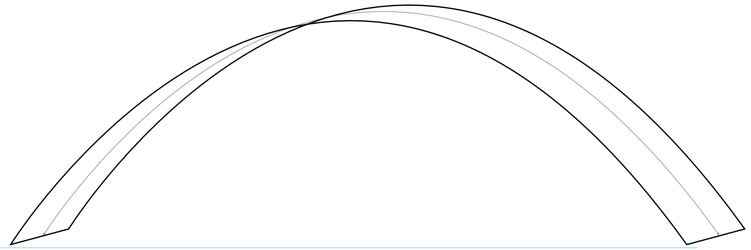


Height and width

Design parameters bent and twisted arch

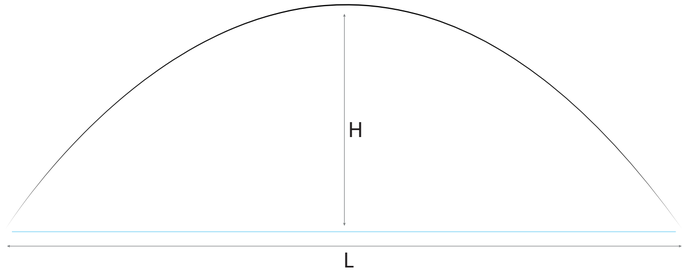


Height and width

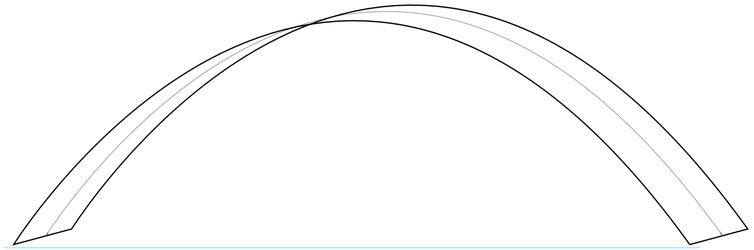


Thickness

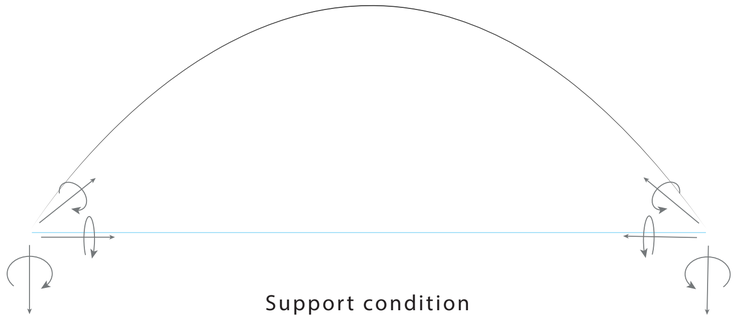
Design parameters bent and twisted arch



Height and width

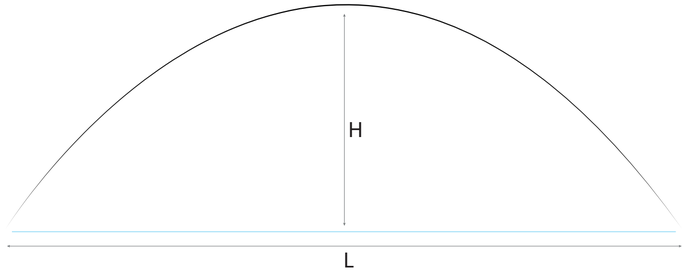


Thickness

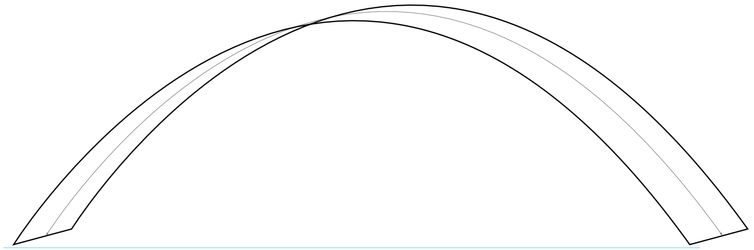


Support condition

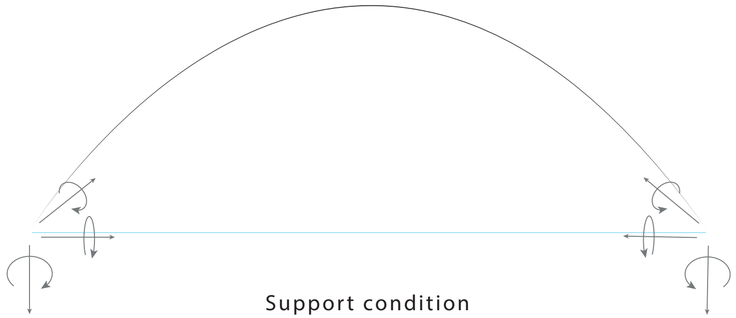
Design parameters bent and twisted arch



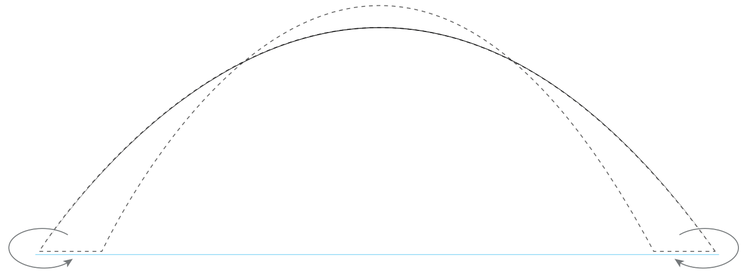
Height and width



Thickness

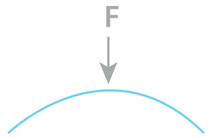


Support condition



Torsional displacement

Material selection



Form creation

Structural capacities

High **flexibility**

High **stiffness**

Low energy

Heavy loads

Large deformation

Small deformation

Material requirements

Material database

1 Flexural strength[MPA]
Youngs modules [GPA]

2 Poisson’s ratio > 0.3

3 Tensile strength > 200 MPA

4 Filler / reinforcement form:
UD QI laminate lay-up
Long fiber > 5mm
Woven fabric

5 UV-resistance

6 Strain < 1%

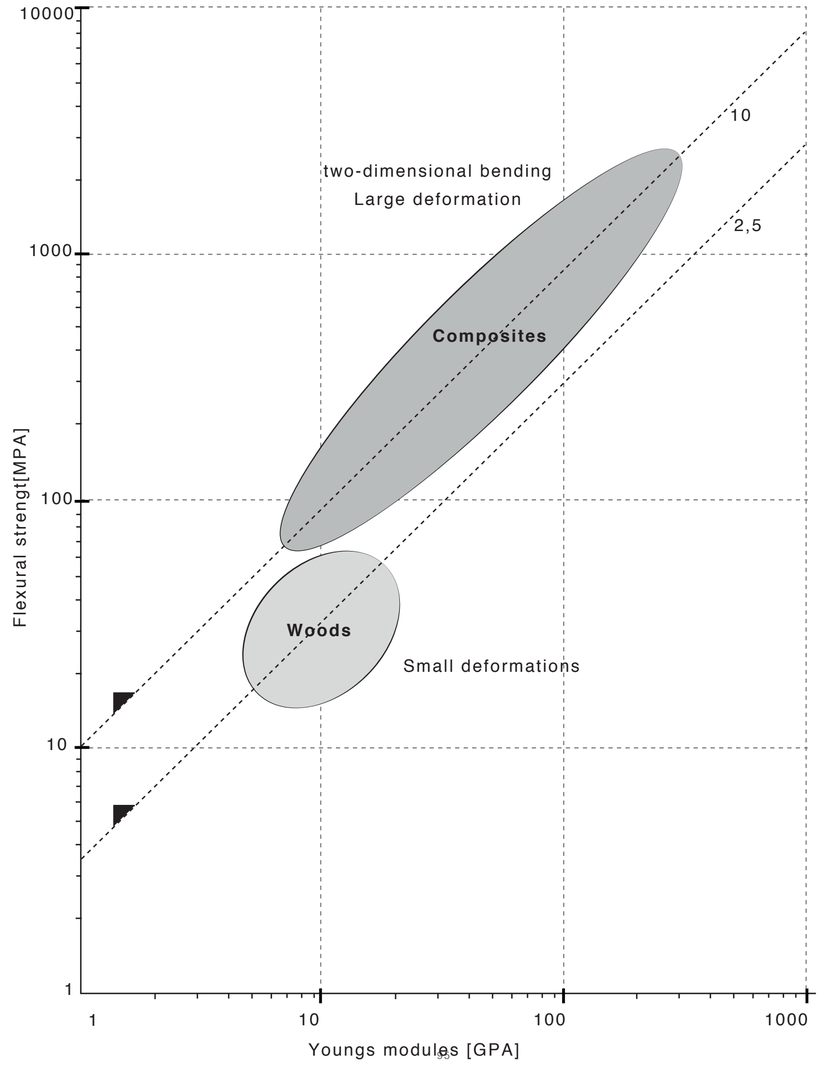
7 Lowest weight

8 Production process

Suitable materials

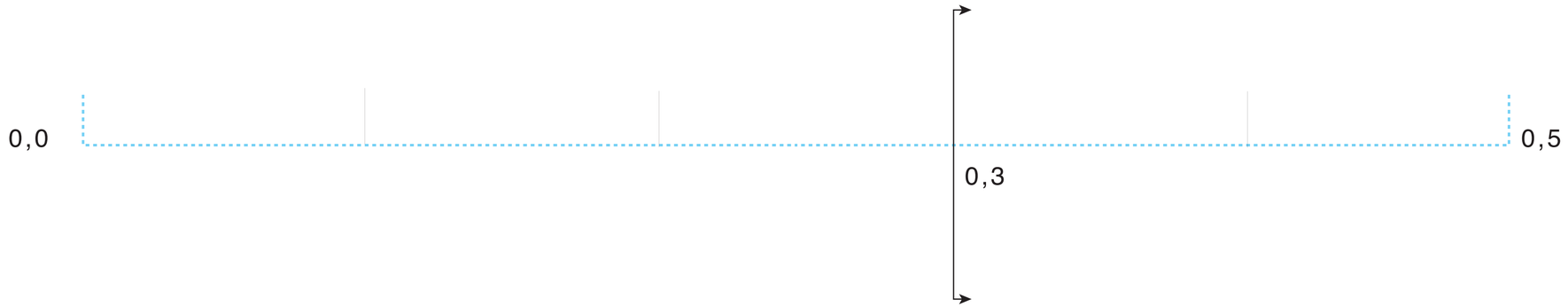
Material parameters

1 Flexural strength[MPA] Youngs modules [GPA]



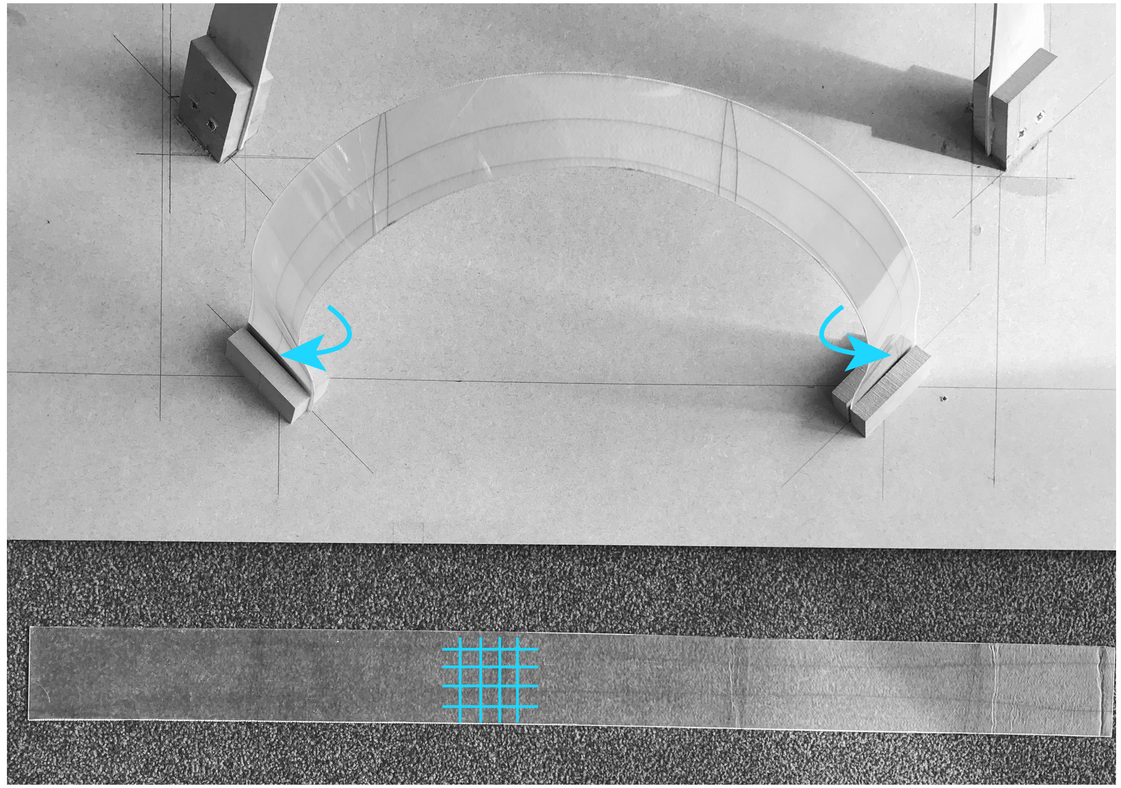
Material parameters

2 Poisson’s ratio > 0.3



Material parameters

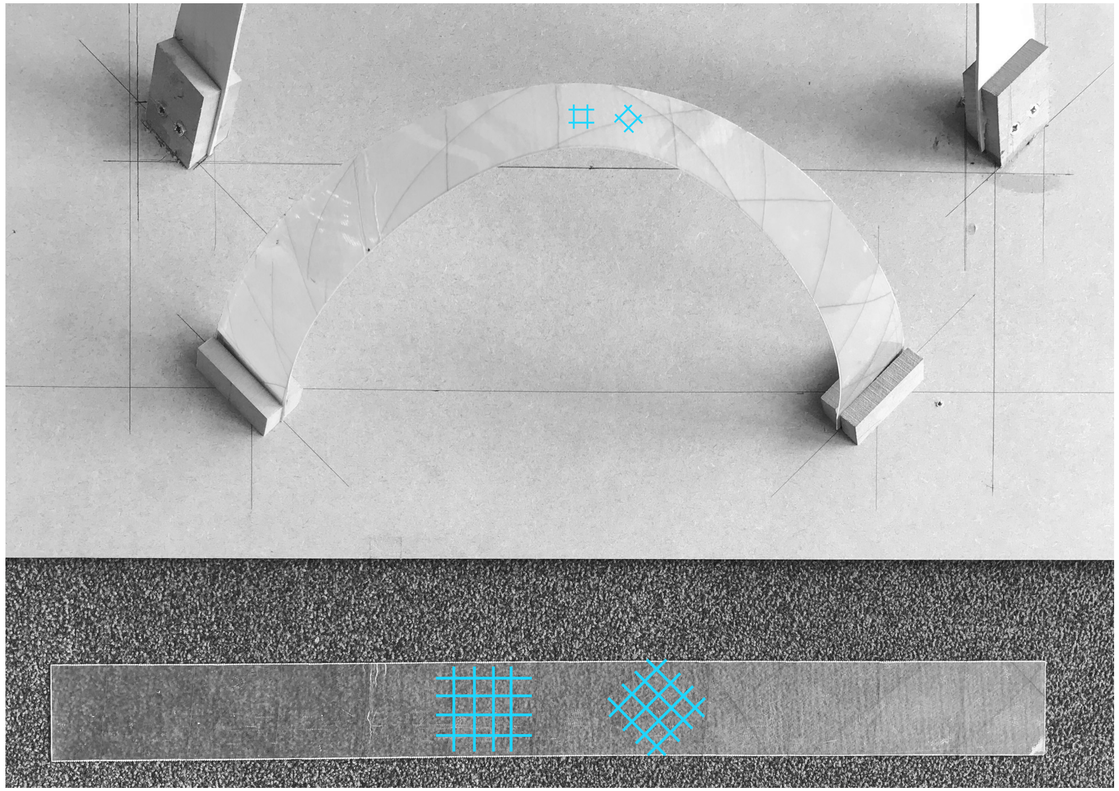
4 Filler / reinforcement form:
UD QI laminate lay-up
Long fiber > 5mm
Woven fabric



Uni directional

Material parameters

4 Filler / reinforcement form:
UD QI laminate lay-up
Long fiber > 5mm
Woven fabric



Quasi isotropic

Material parameters

Material database

1 Flexural strength[MPA]
Youngs modules [GPA]

2 Poisson’s ratio > 0.3

3 Tensile strength > 200 MPA

4 Filler / reinforcement form:
UD QI laminate lay-up
Long fiber > 5mm
Woven fabric

5 UV-resistance

6 Strain < 1%

7 Lowest weight

8 Production process

Suitable materials

Material	Tensile strength [MPA]	Poisson's ratio	Shear strength [MPA]	Youngs Modulus [GPA]	Flexural strength [MPA]	σ[MPA]/ E[GPA]
Epoxy SMC (65% long glass fiber)	267,00	0,33	153,00	22,40	476,00	21,25
Epoxy SMC (55% long carbon fiber)	278,00	0,31	198,00	60,60	607,00	10,01
Epoxy S-glass fiber(UD prepreg, QI-layup)	504,00	0,31	-	21,00	121,00	5,76
Epoxy Carbon fiber (woven prepreg, QI-layup)	649,00	0,34	-	48,20	649,00	13,46

	Material	Tensile strength [MPA]	Poisson's ratio	Shear strength [MPA]	Youngs Modulus [GPA]	Flexural strength [MPA]	σ[MPA]/ E[GPA]
	Epoxy SMC (65% long glass fiber)	267,00	0,33	153,00	22,40	476,00	21,25
Carbon	**Epoxy SMC** (55% long carbon fiber)	278,00	0,31	198,00	60,60	607,00	10,01
	Epoxy S-glass fiber(UD prepreg, QI-layup)	504,00	0,31	-	21,00	121,00	5,76
Carbon	**Epoxy Carbon fiber** (woven prepreg, QI-layup)	649,00	0,34	-	48,20	649,00	13,46

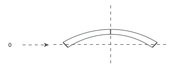
	Material	Tensile strength [MPA]	Poisson's ratio	Shear strength [MPA]	Youngs Modulus [GPA]	Flexural strength [MPA]	σ[MPA]/ E[GPA]
S-Glass	**Epoxy SMC** (65% long glass fiber)	267,00	0,33	153,00	22,40	476,00	21,25
	Epoxy SMC (55% long carbon fiber)	278,00	0,31	198,00	60,60	607,00	10,01
S-Glass	**Epoxy S-glass fiber**(UD prepreg, QI-layup)	504,00	0,31	-	21,00	121,00	5,76
	Epoxy Carbon fiber (woven prepreg, QI-layup)	649,00	0,34	-	48,20	649,00	13,46

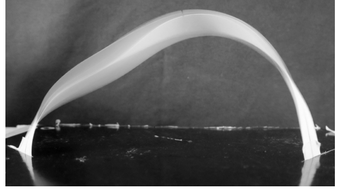
Structural analyses

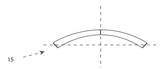
Non - linear structural analyses

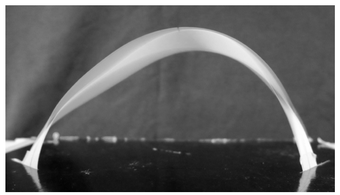
Wind simulation - Low youngs modulus

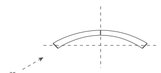
Front

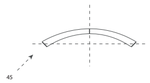


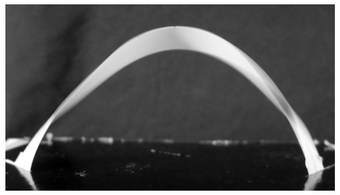


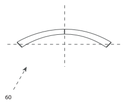


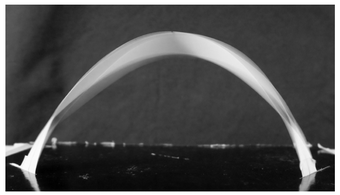


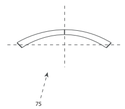


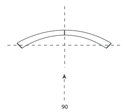


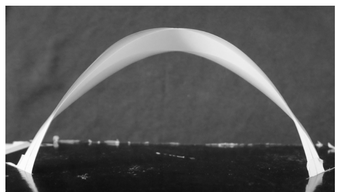












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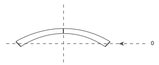

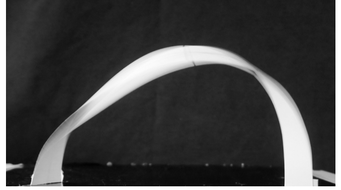

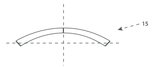

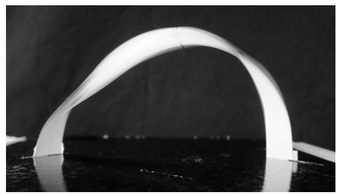

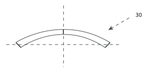

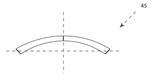

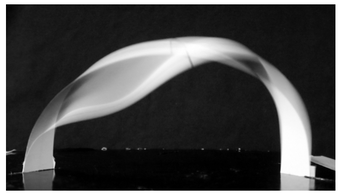

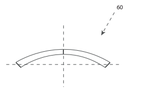

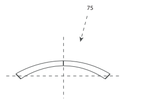

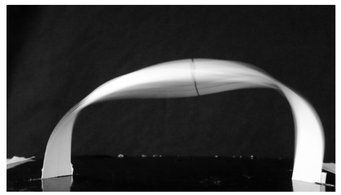

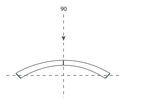

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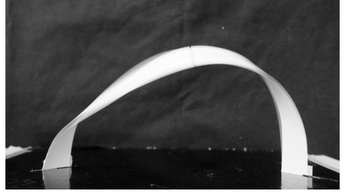

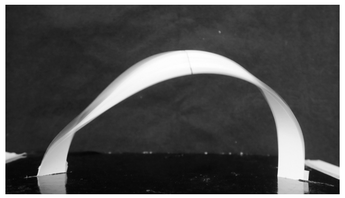

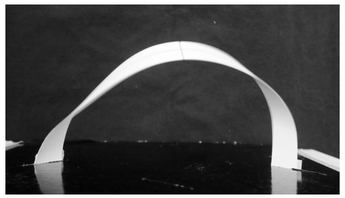

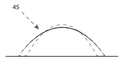

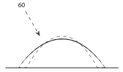

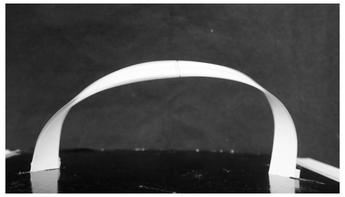

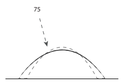

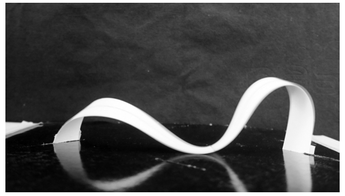

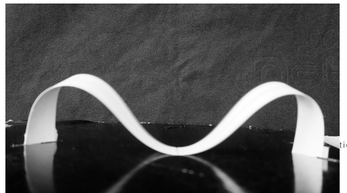

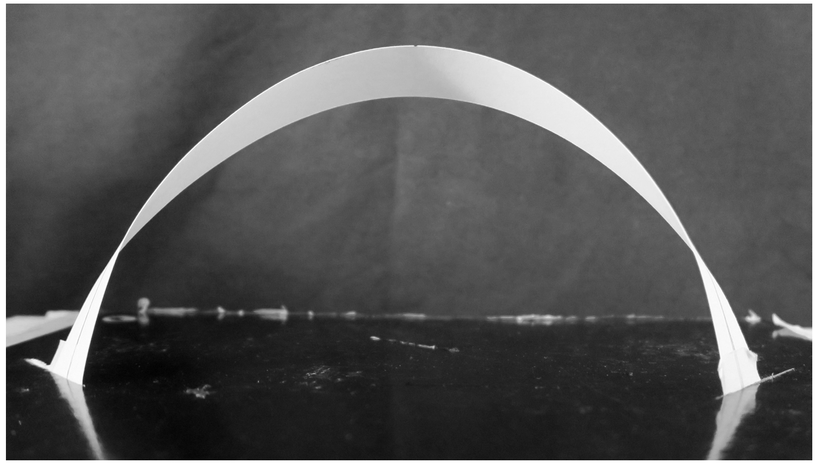

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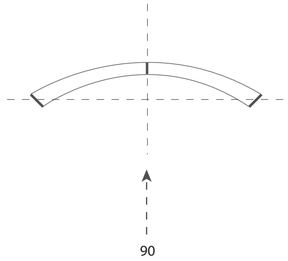

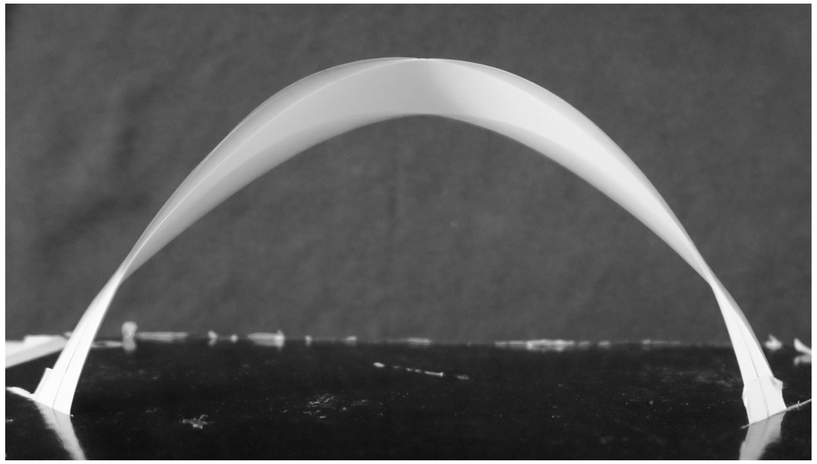

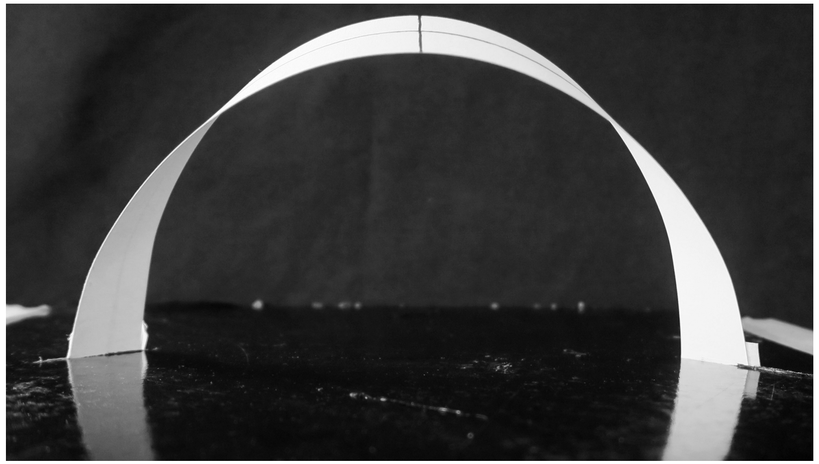

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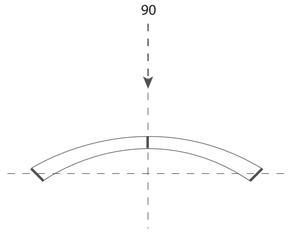

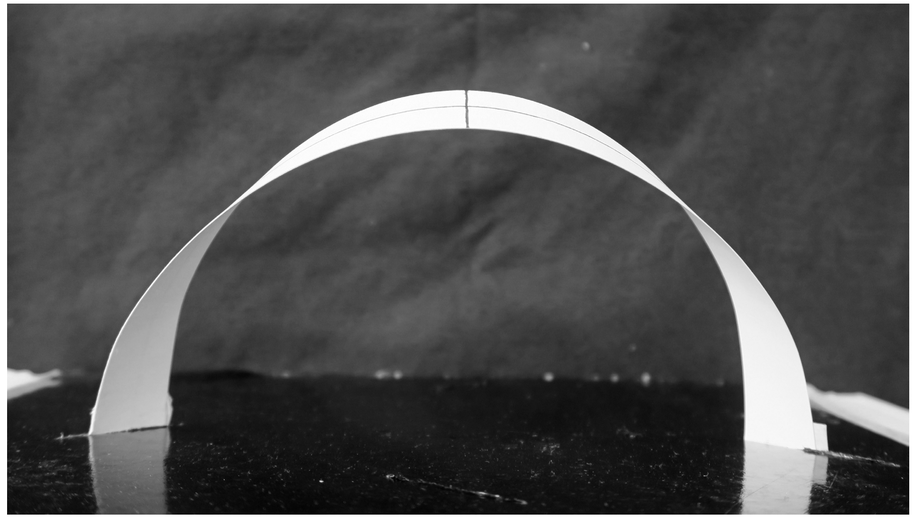

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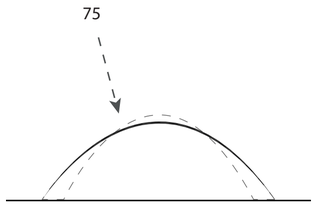
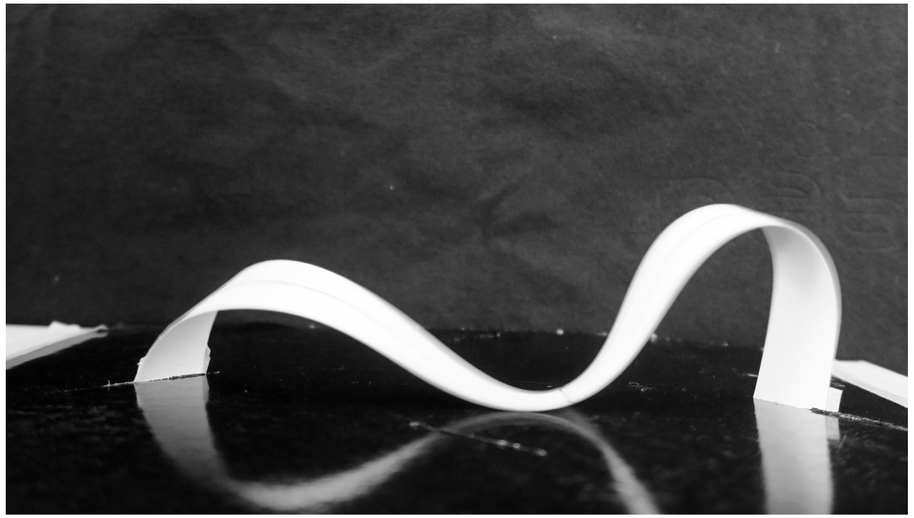
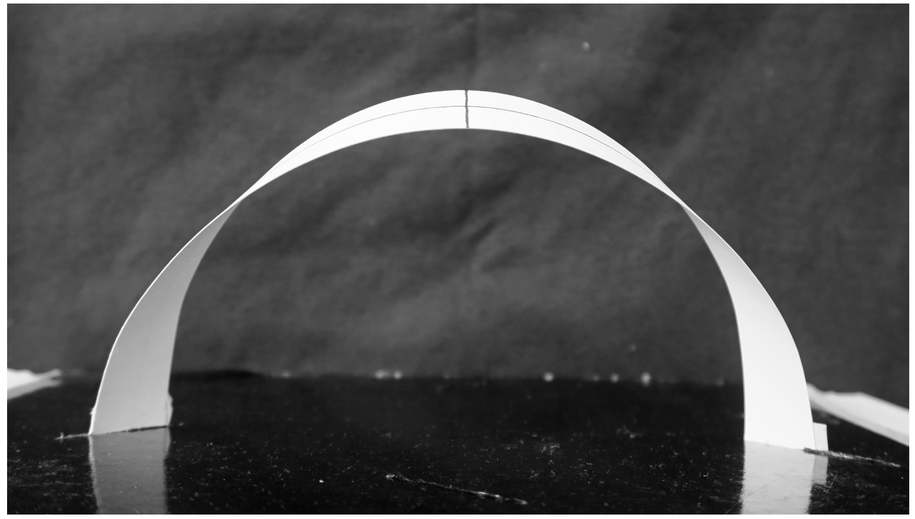
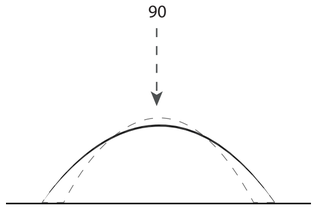
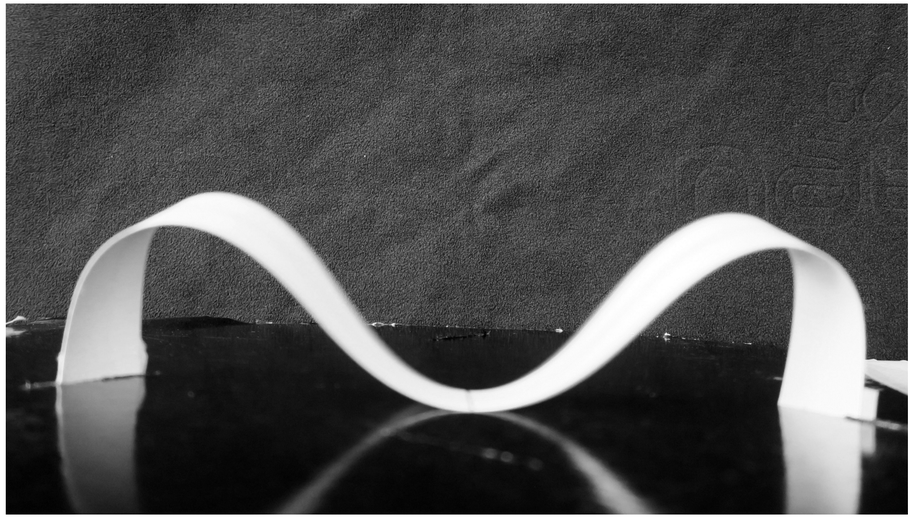


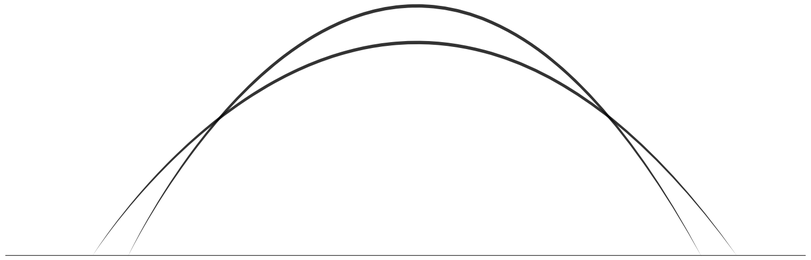




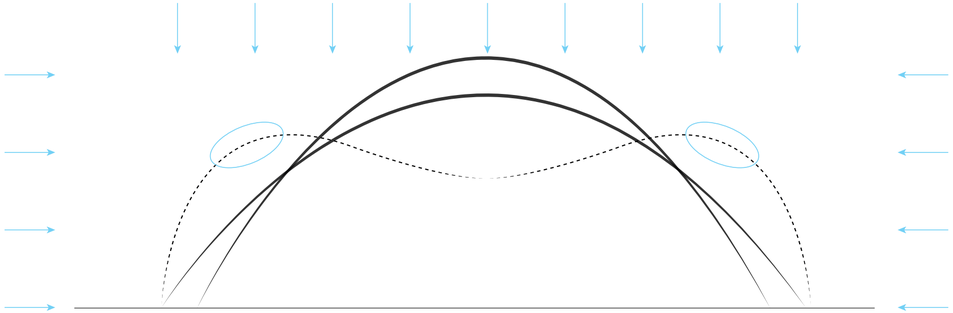




Weak areas in bent and twisted arch

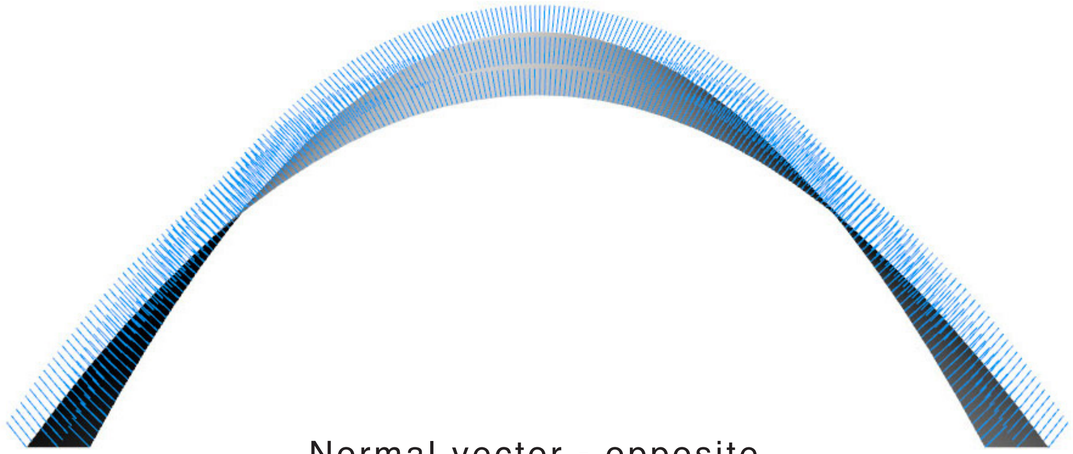


Original shape

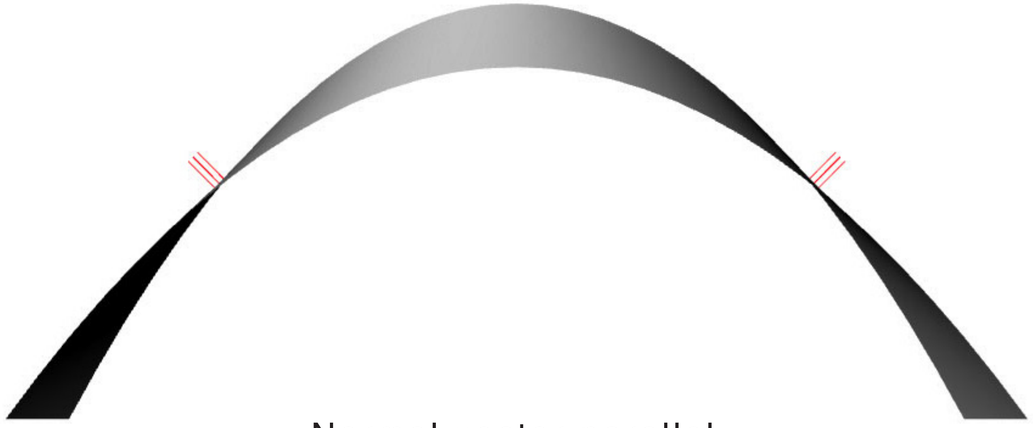


Locally increased curvature

Vector plot



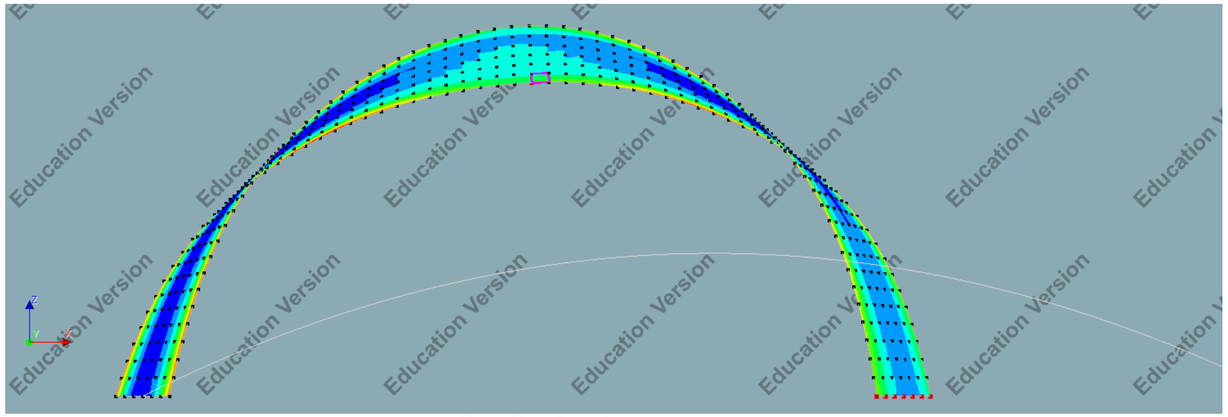
Normal vector - opposite



Normal vector parallel

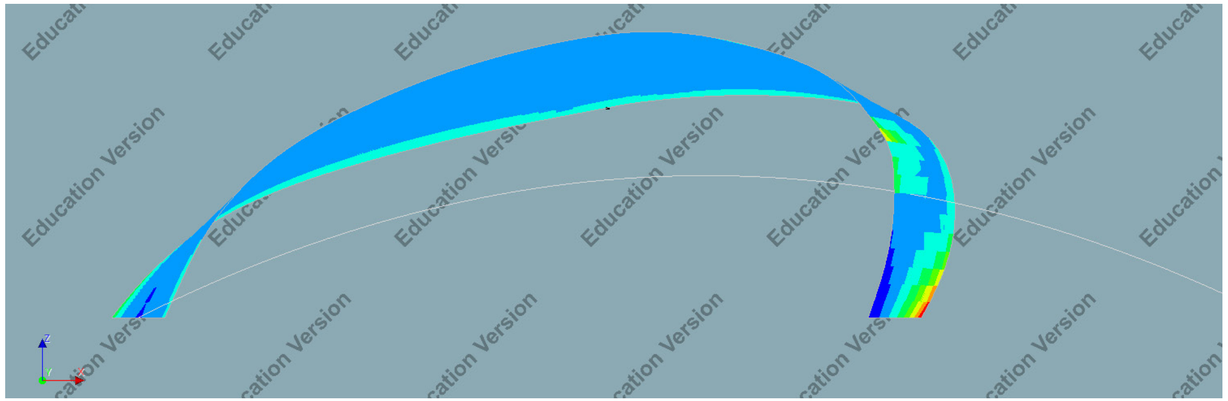
Load - deflection diagram

Epoxy SMC (55% long carbon fiber)



Epoxy SMC (65% long glass fiber)

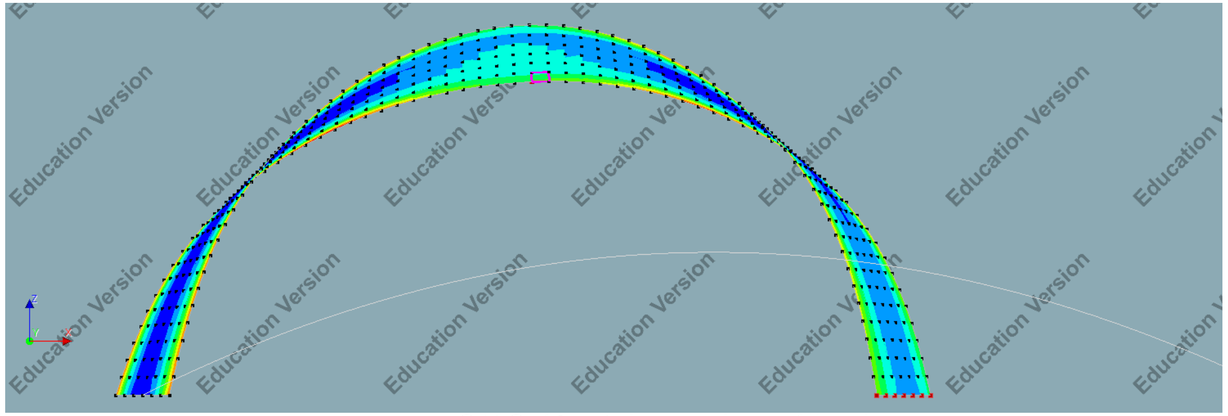
Epoxy Carbon fiber (woven prepreg, QI-layup)



Epoxy S-glass fiber(UD prepreg, QI-layup)

Load - deflection diagram

Epoxy SMC (55% long carbon fiber)



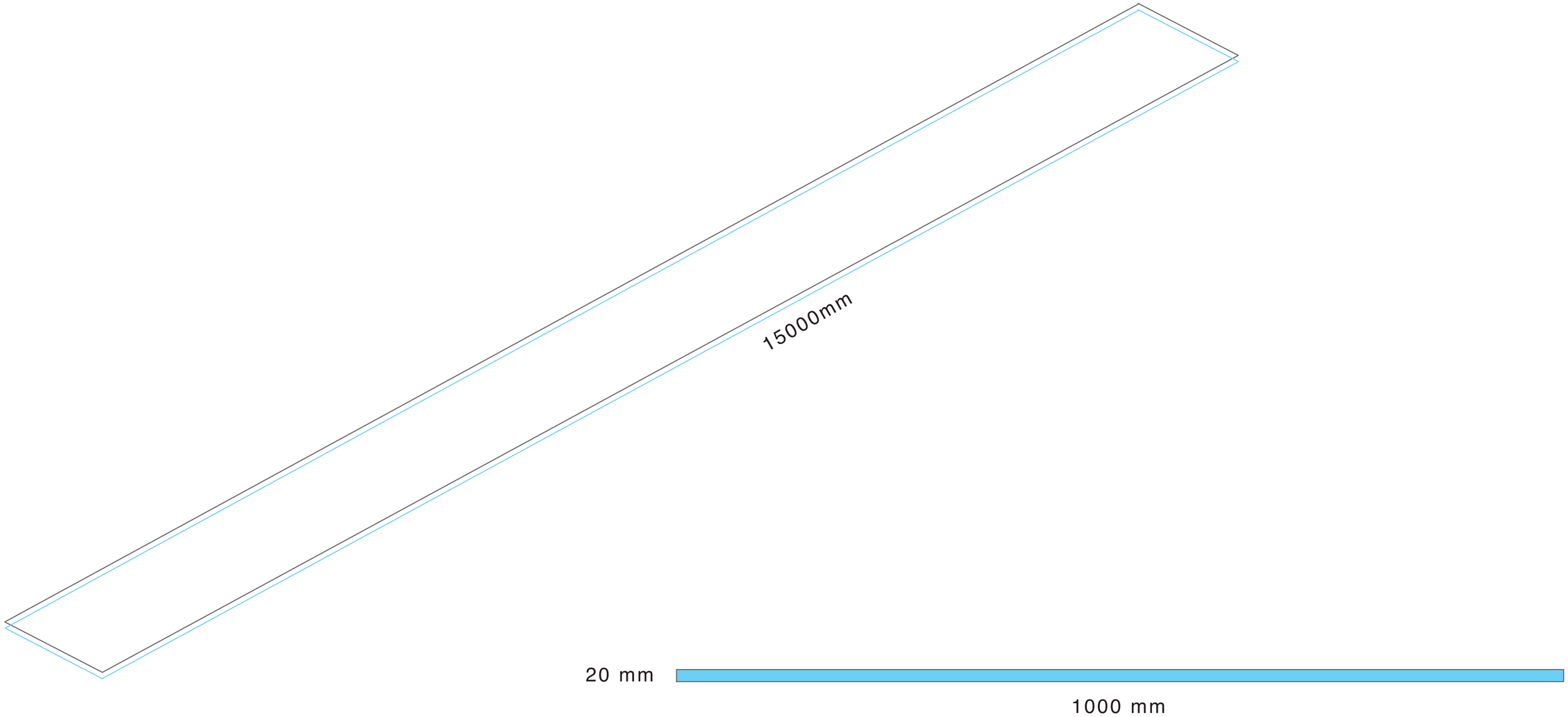
Epoxy SMC (65% long glass fiber)

Epoxy Carbon fiber (woven prepreg, QI-layup)

Epoxy S-glass fiber(UD prepreg, QI-layup)

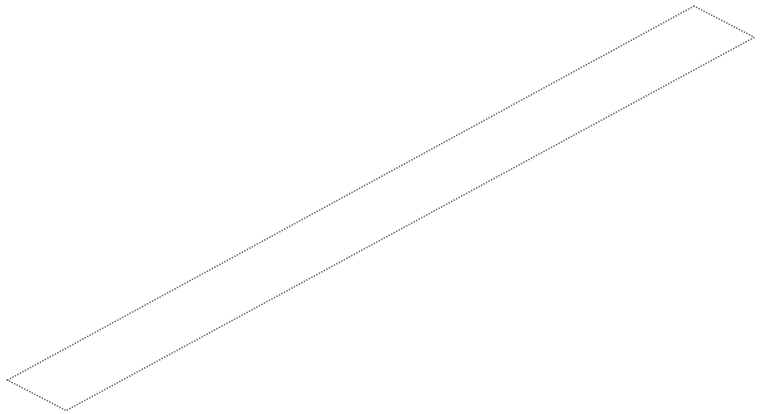
Epoxy SMC (65% long glass fiber)

Final plate dimensions

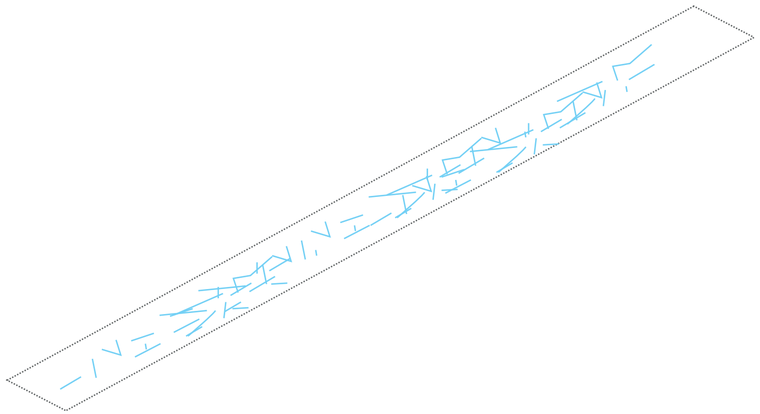


Building methodology

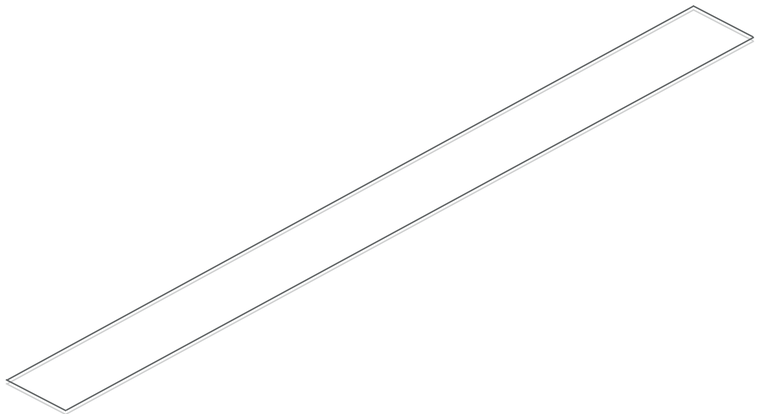
1. Planar plate



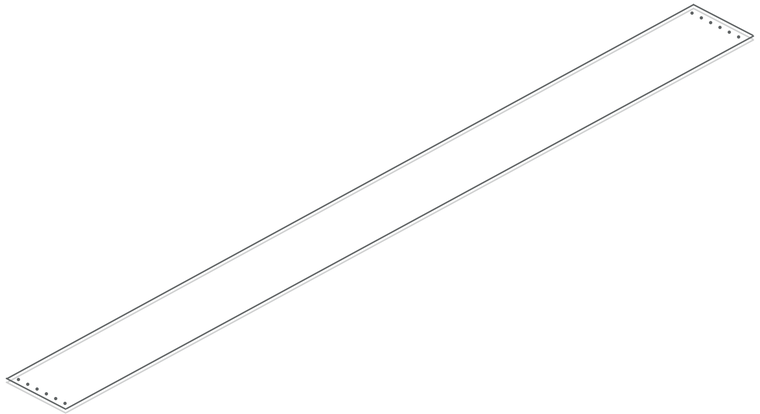
1 Epoxy resin



2 Glass fiber

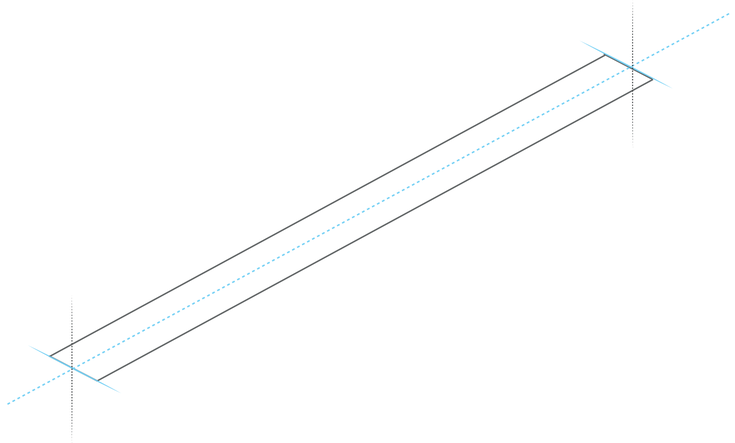


1 Hardening process

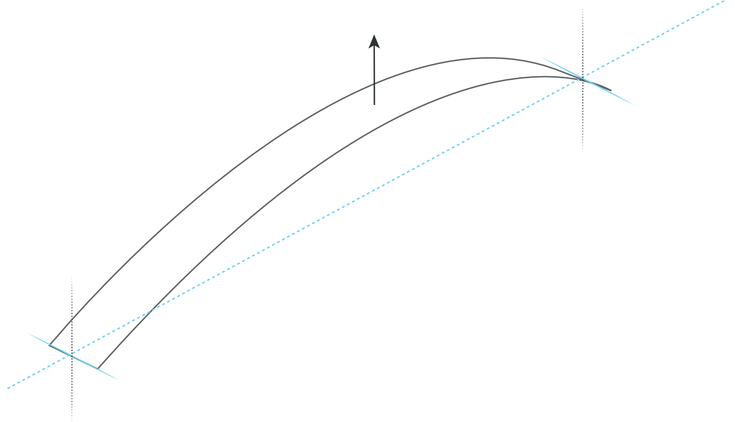


4. Drilling

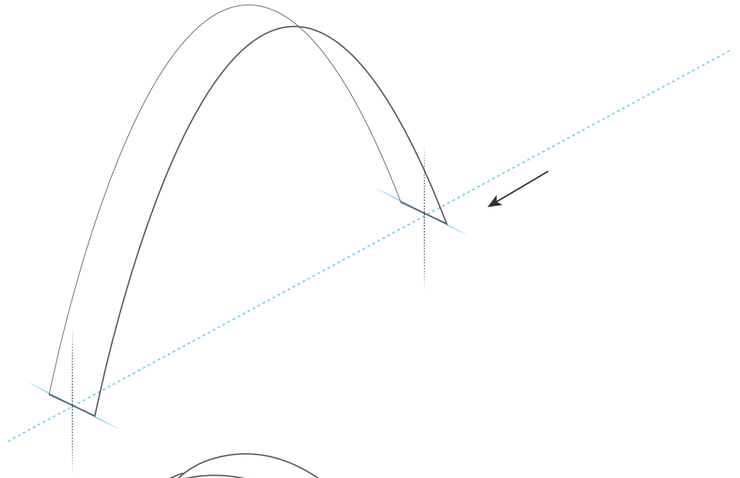
2. Bending deformation



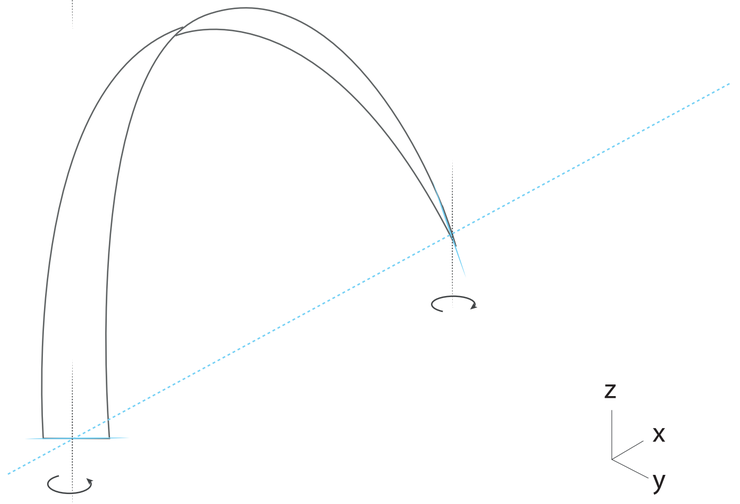
1 Planar plate



2 placement

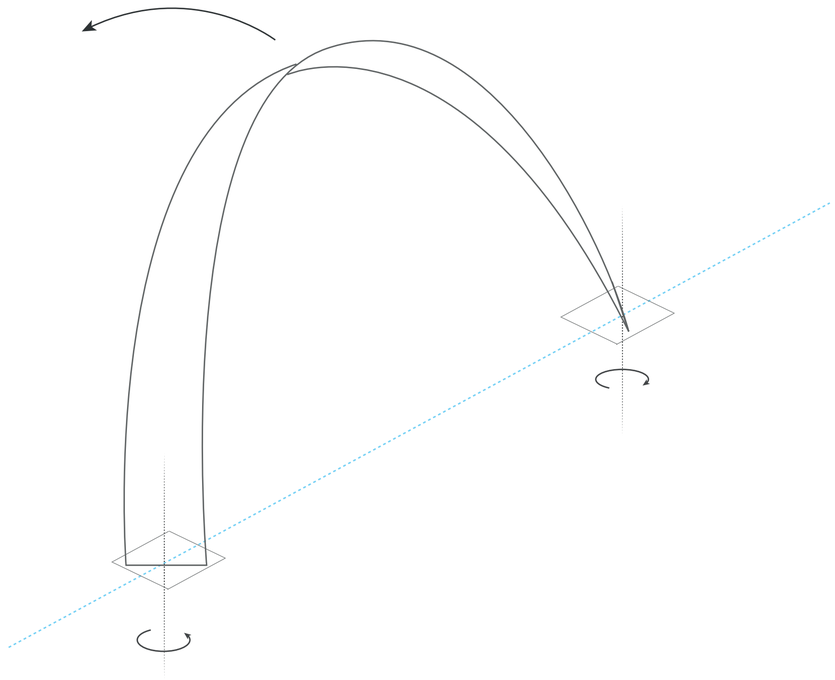


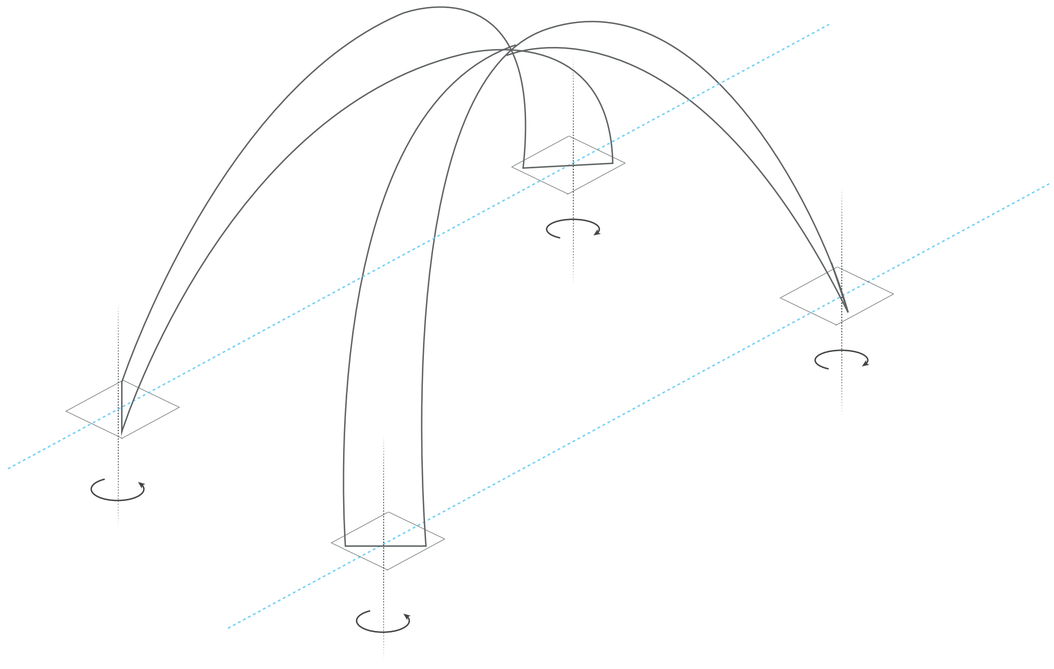
3 Bending



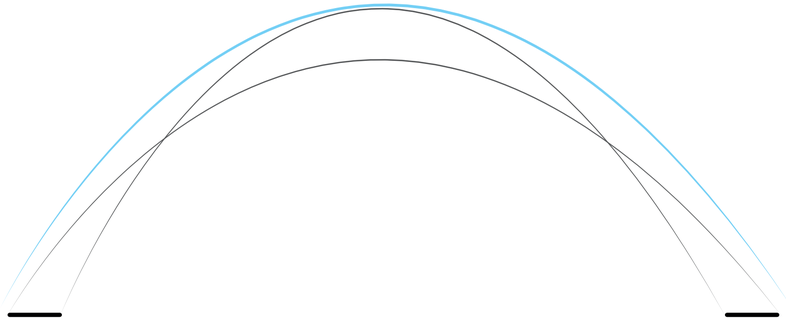
4 Torsion

3. Coupling two arches

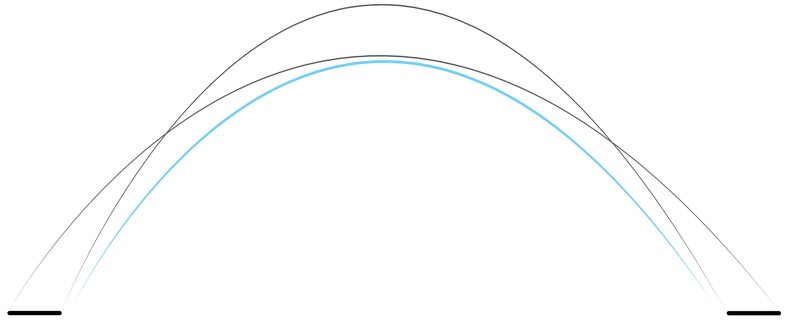




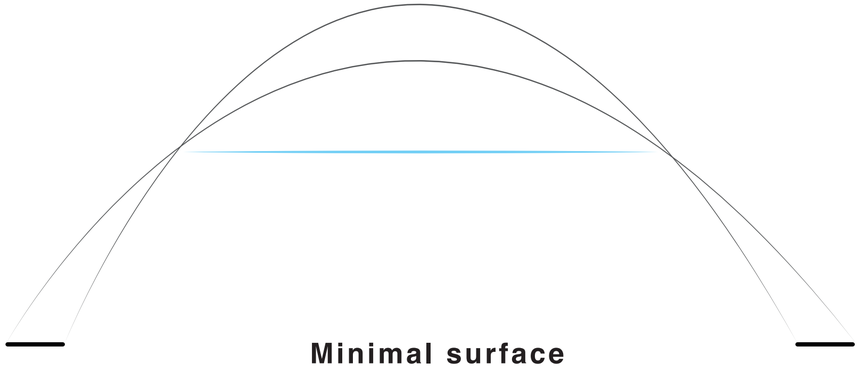
4. Membrane space enclosure



Membrane over arch

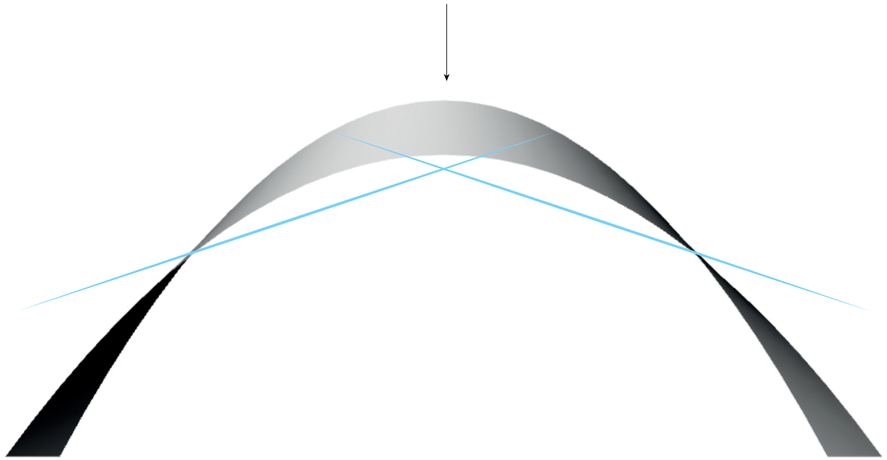


Membrane under arch

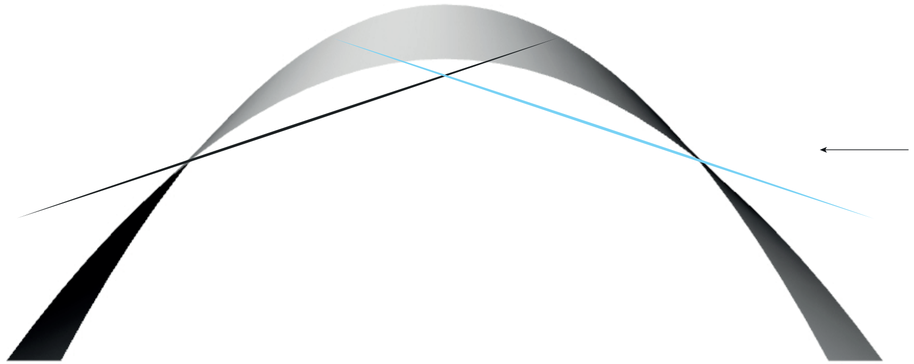


Minimal surface

Membrane space enclosure

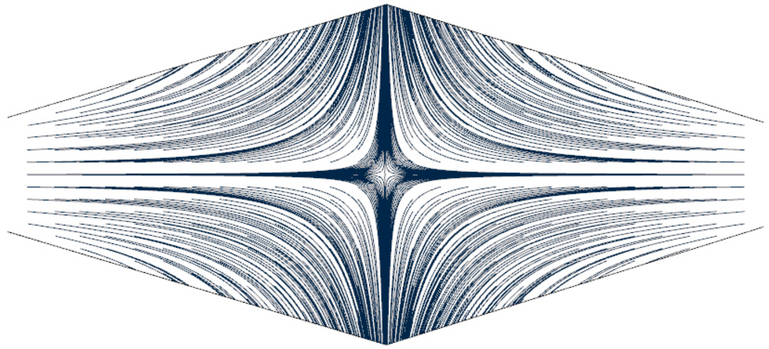


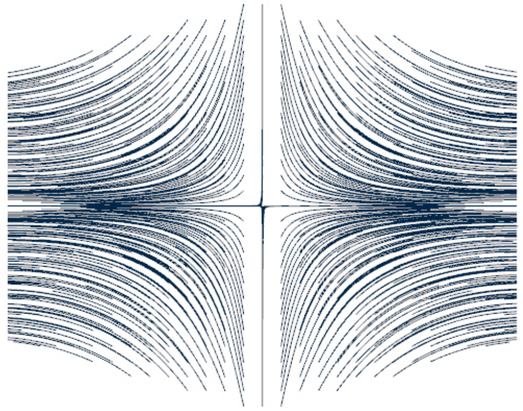
Vertical load

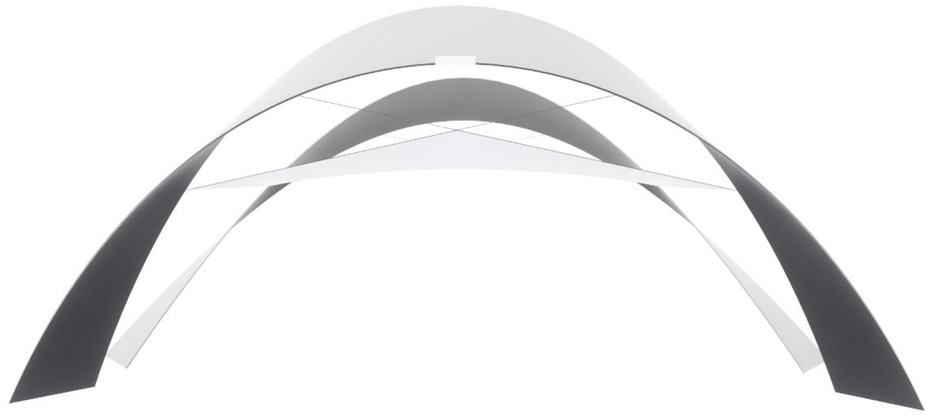


Side load

Membrane space enclosure







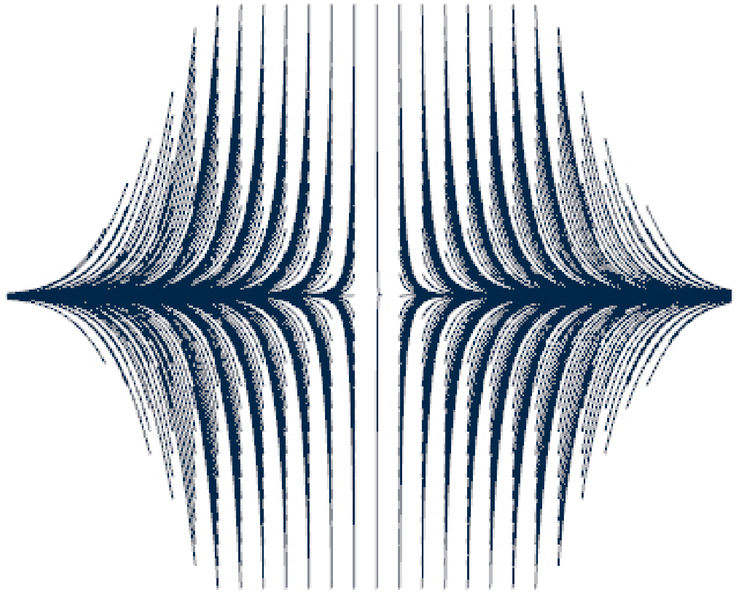
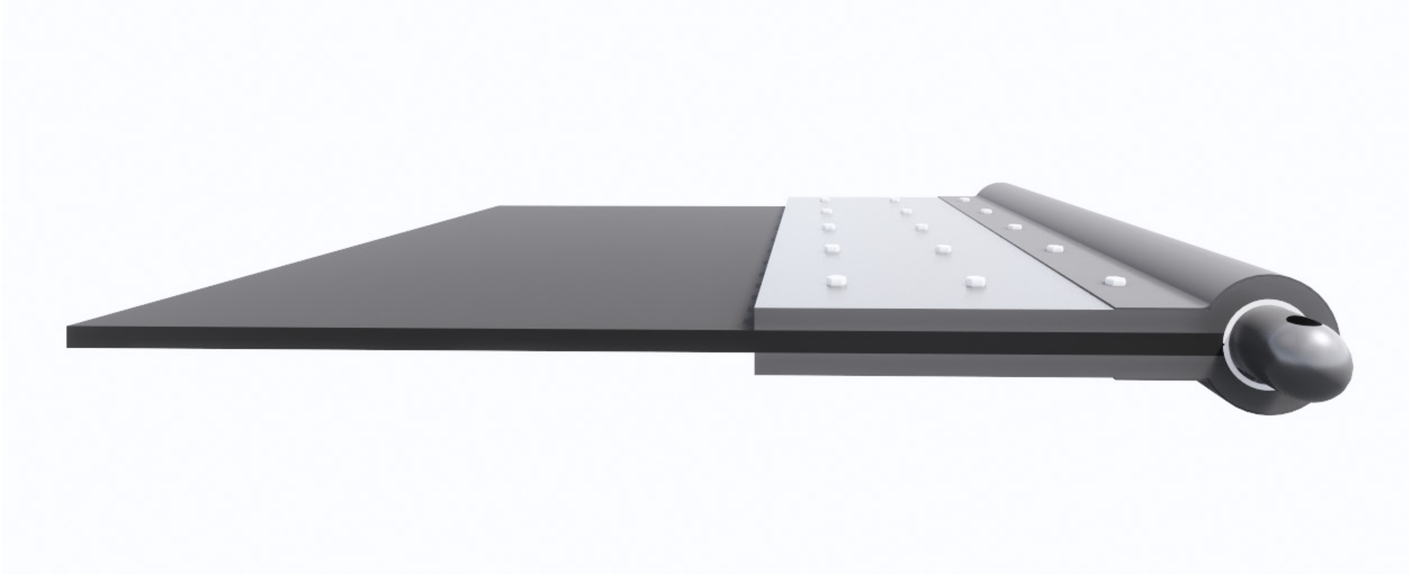
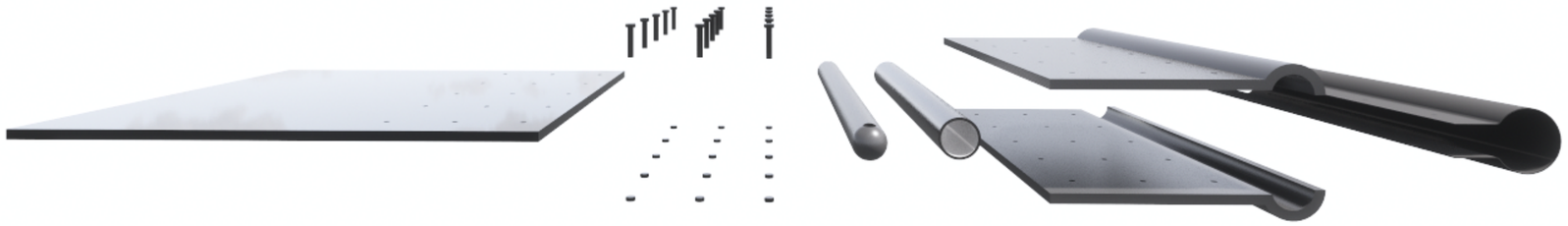


Plate fixation





Composite plate

Bolt fixation

Steel sleave and
steel rotation axis

clamping

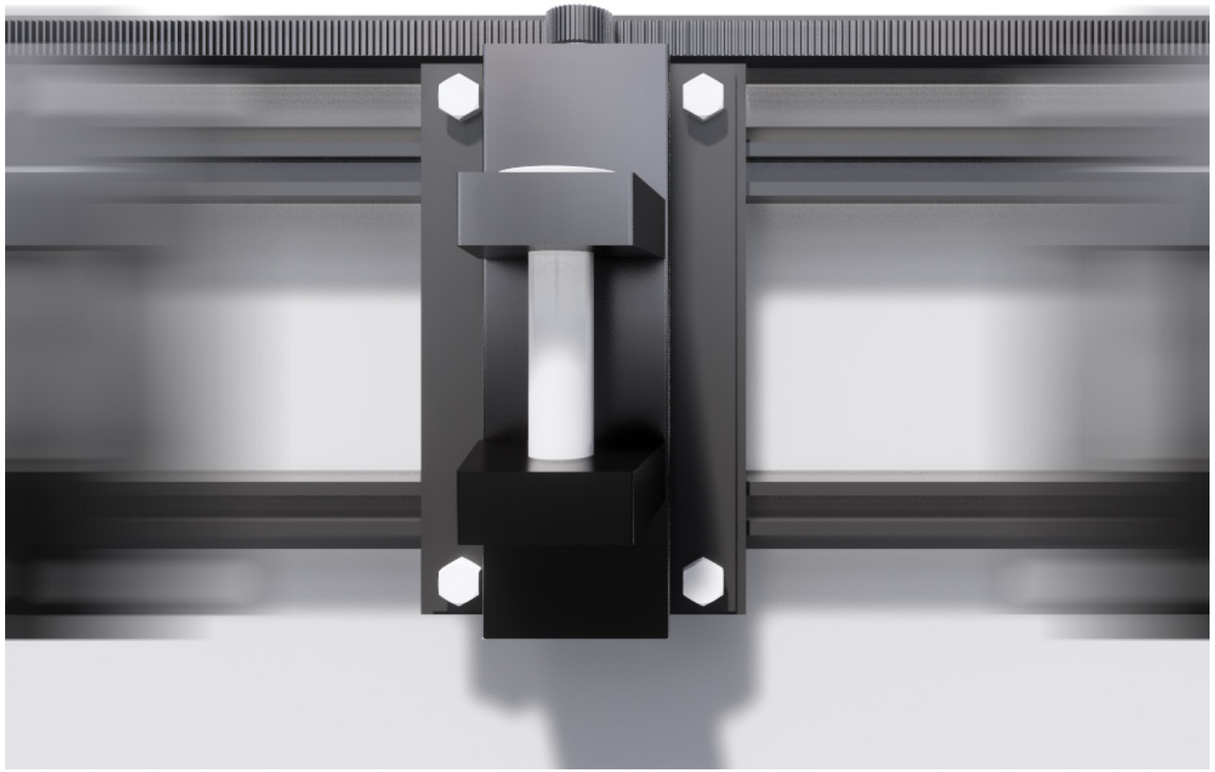
sleaved finish

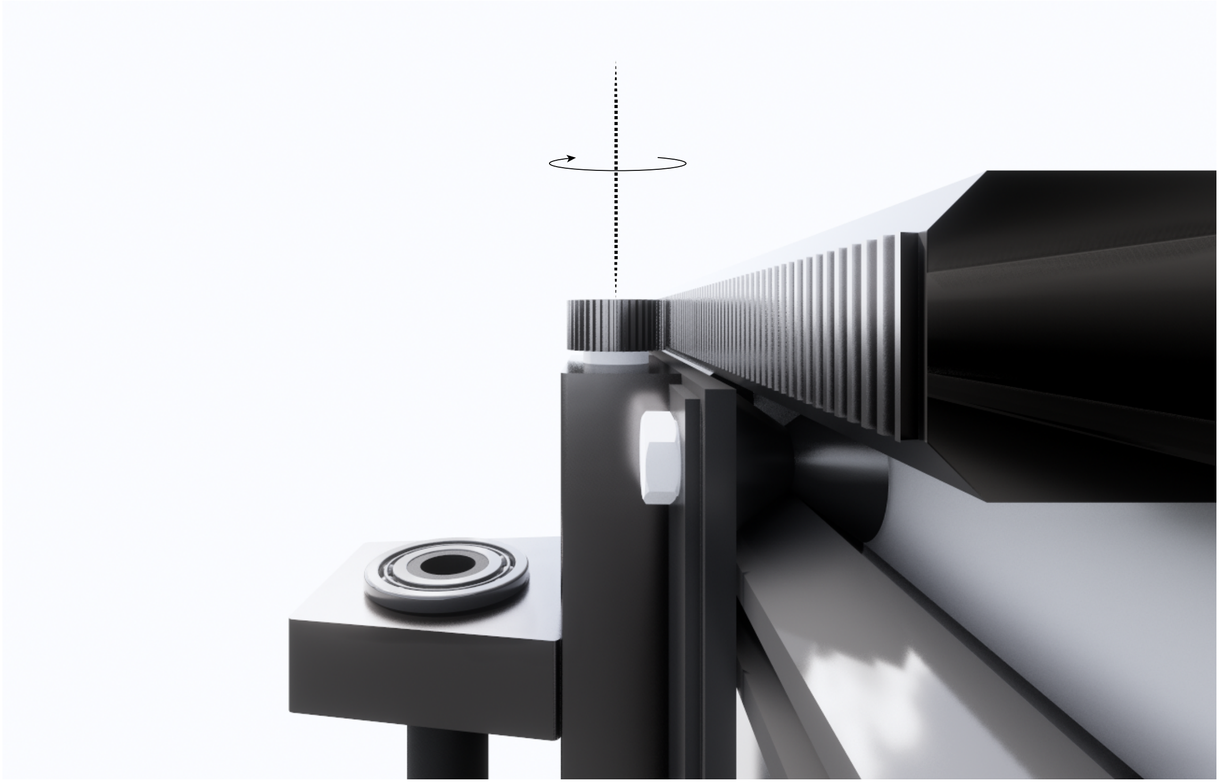
Gliding rail rotation axis

Gliding rail - mounts

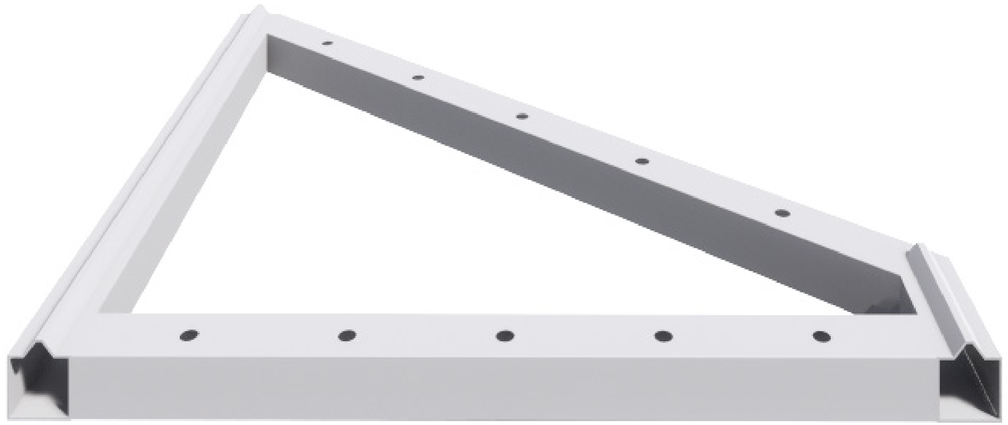
Rotation

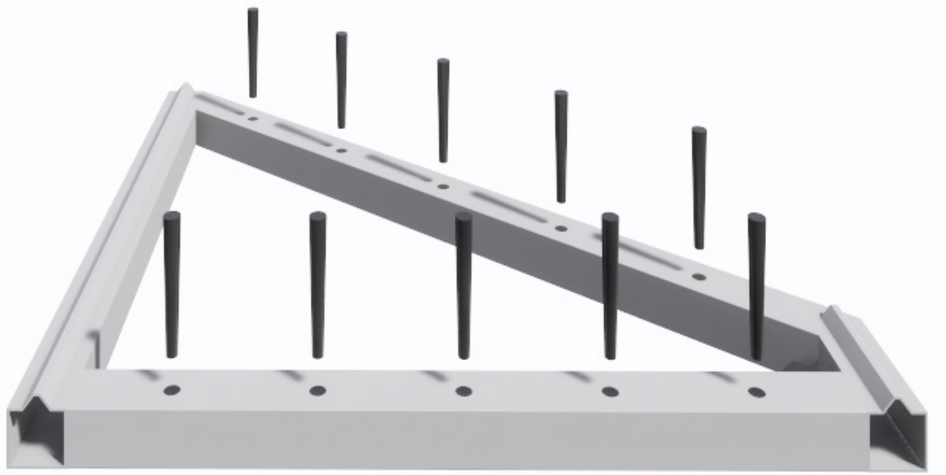
Mounting elements

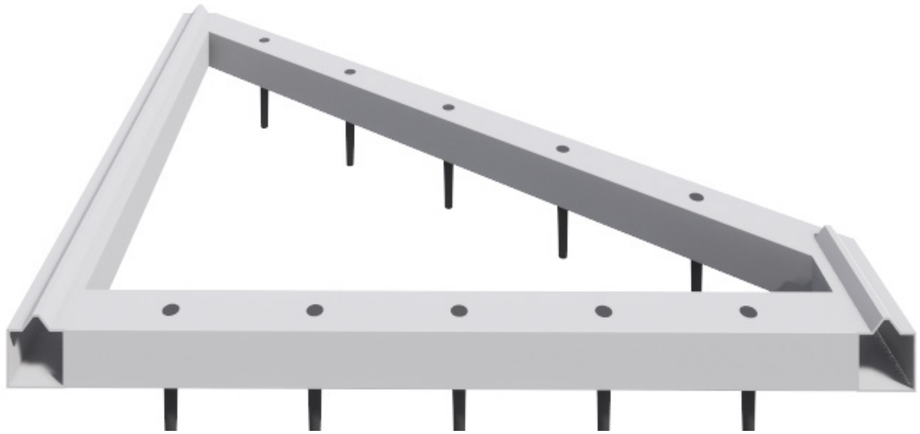


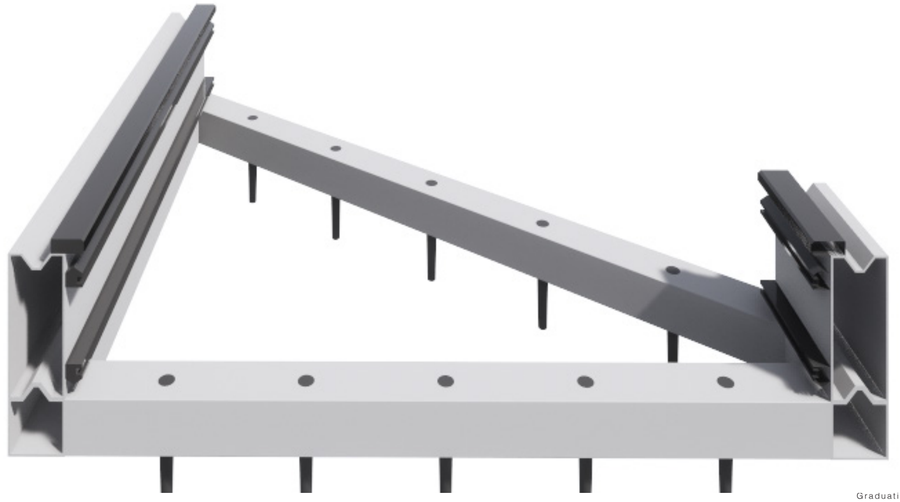


Base support arch

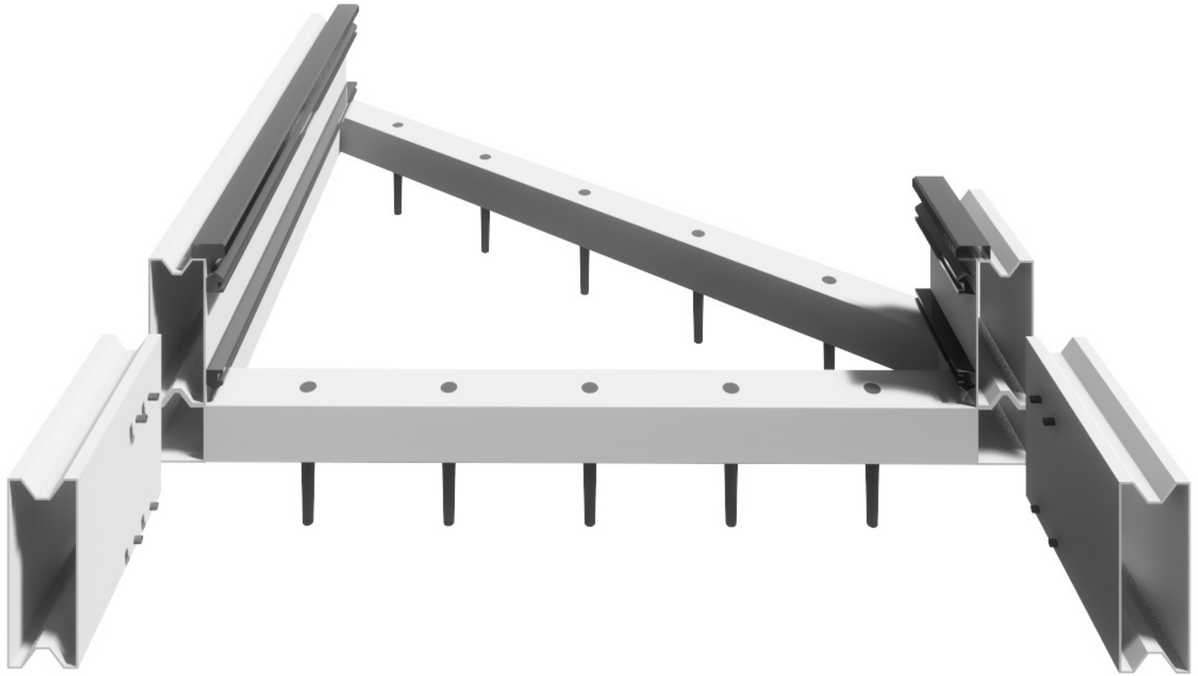








Extendable rail for bending deformation



Extendable rail for bending deformation

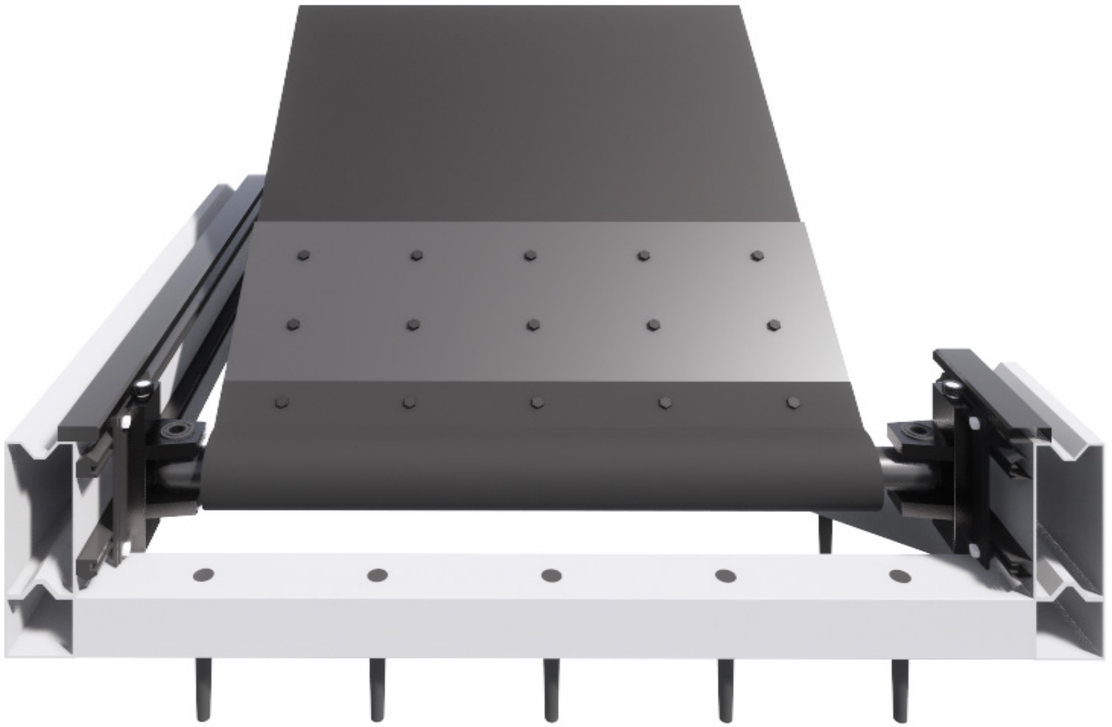
Extendable rail for bending deformation

Placement plate

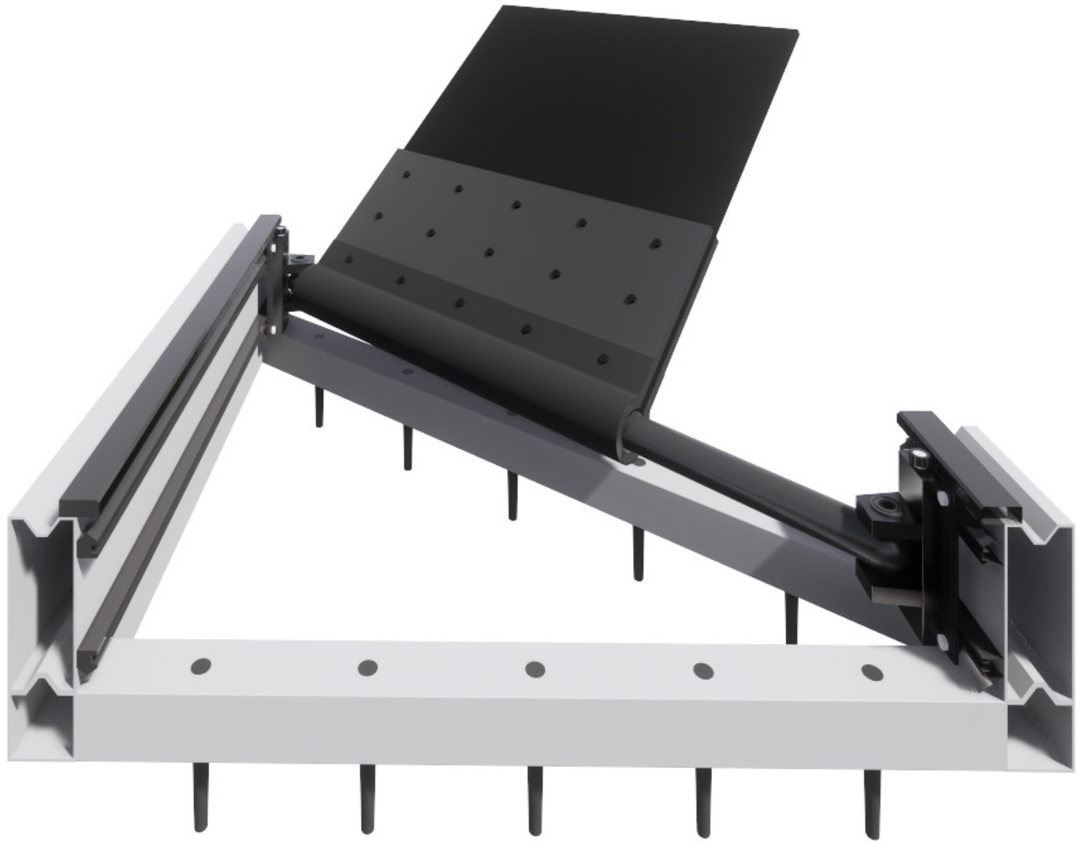
Bending process

Final position bending

Final deformation - rotation



Final deformation - rotation



Formation process sequence

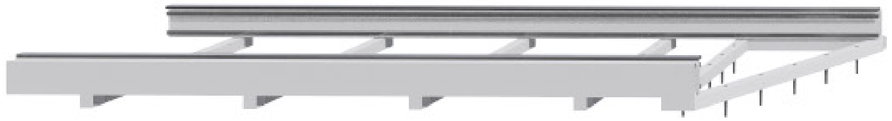
Placement supports

Formation process sequence

Extension gliding rail

Formation process sequence

Plate placement

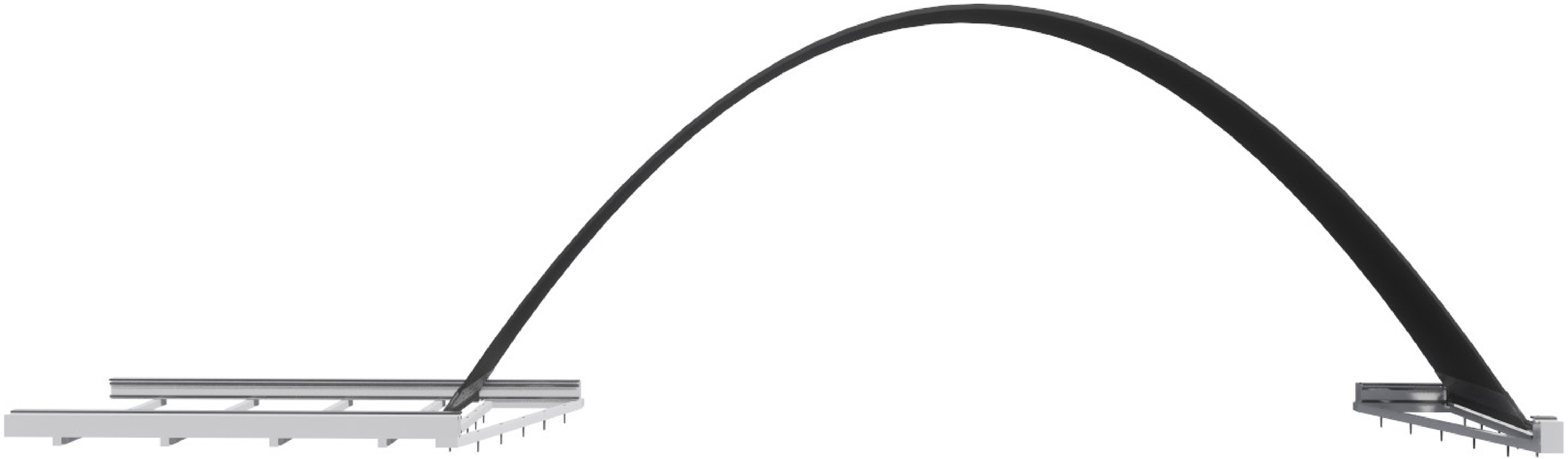


Formation process sequence

Plate placement

Formation process sequence

Bending deformation

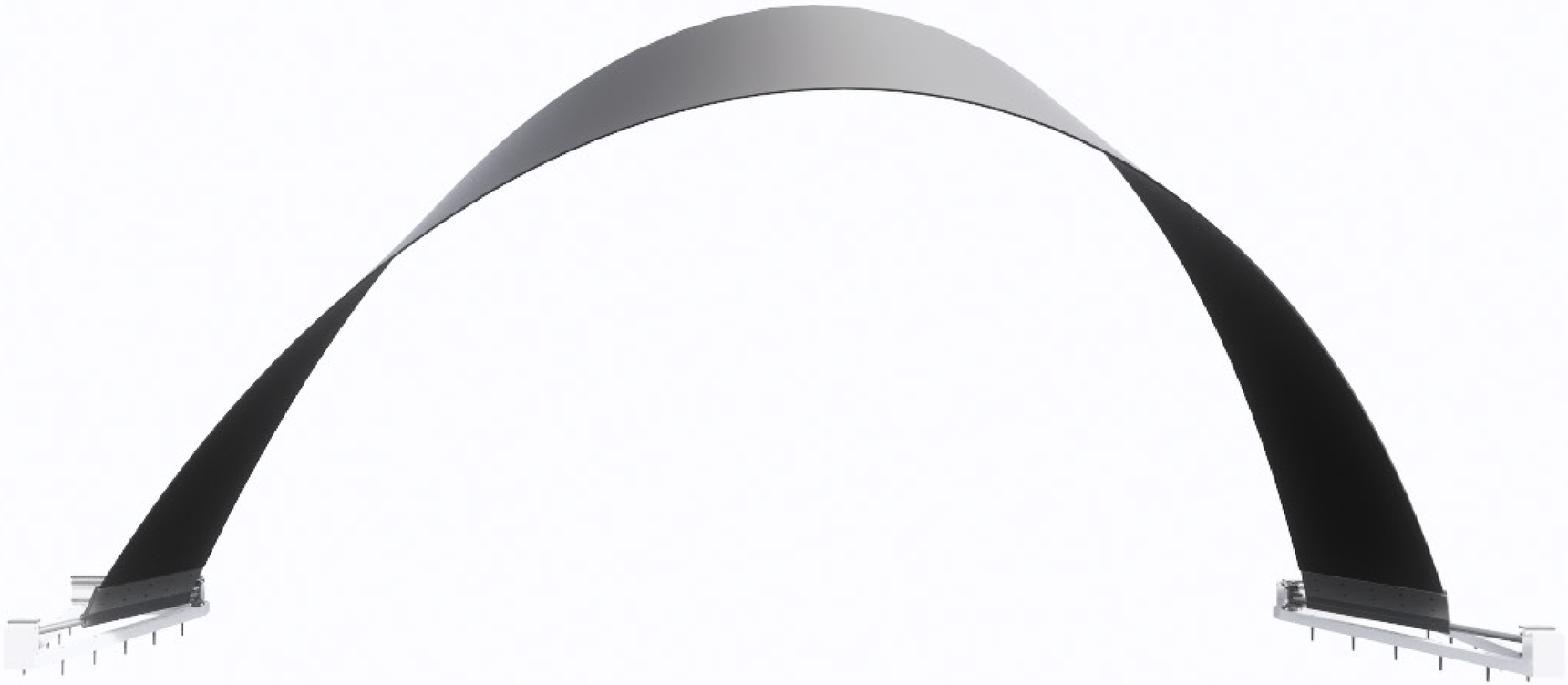


Formation process sequence

Disassemble gliding rail

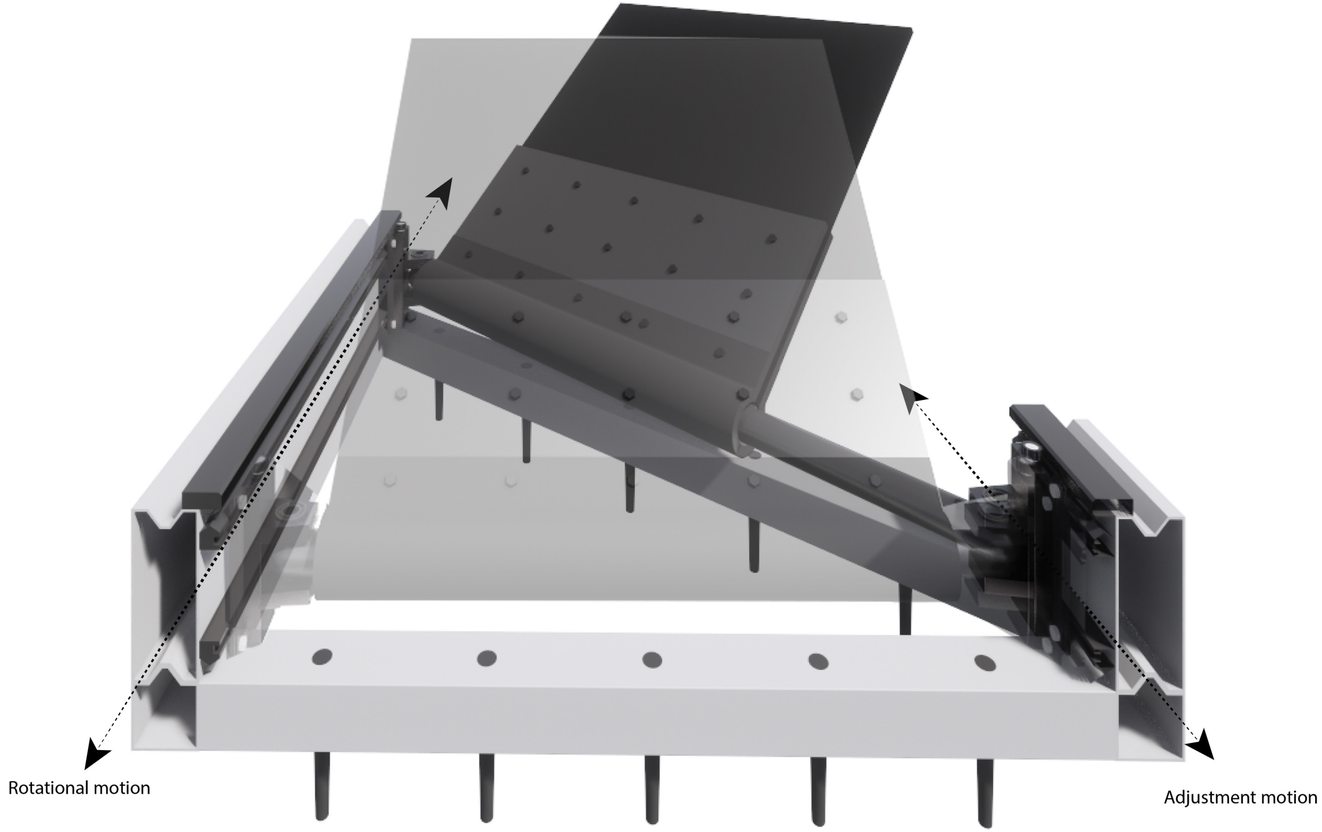
Formation process sequence

Torsional deformation



Active-bending sequence

Adjustments for coupling arches



Active-bending sequence

Adjustments for coupling arches

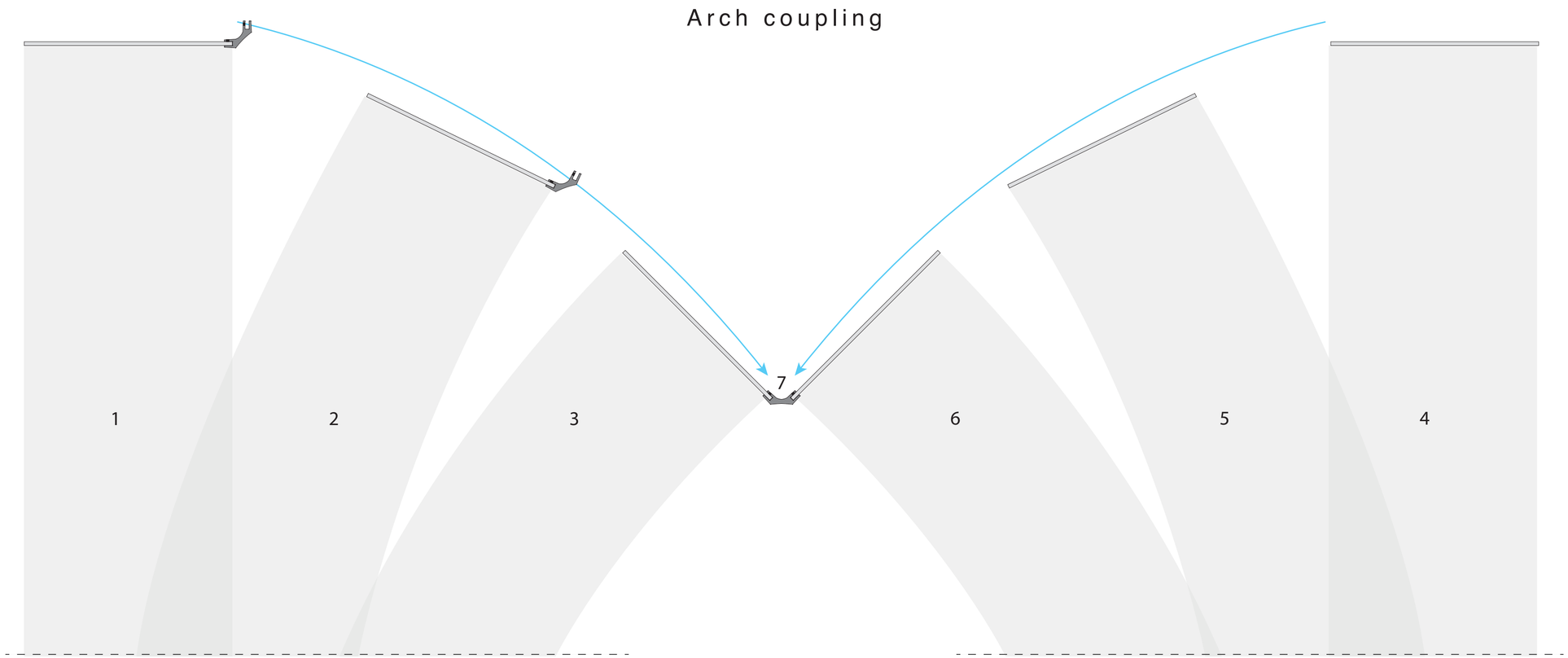
Active-bending sequence

Arch coupling

Active-bending sequence

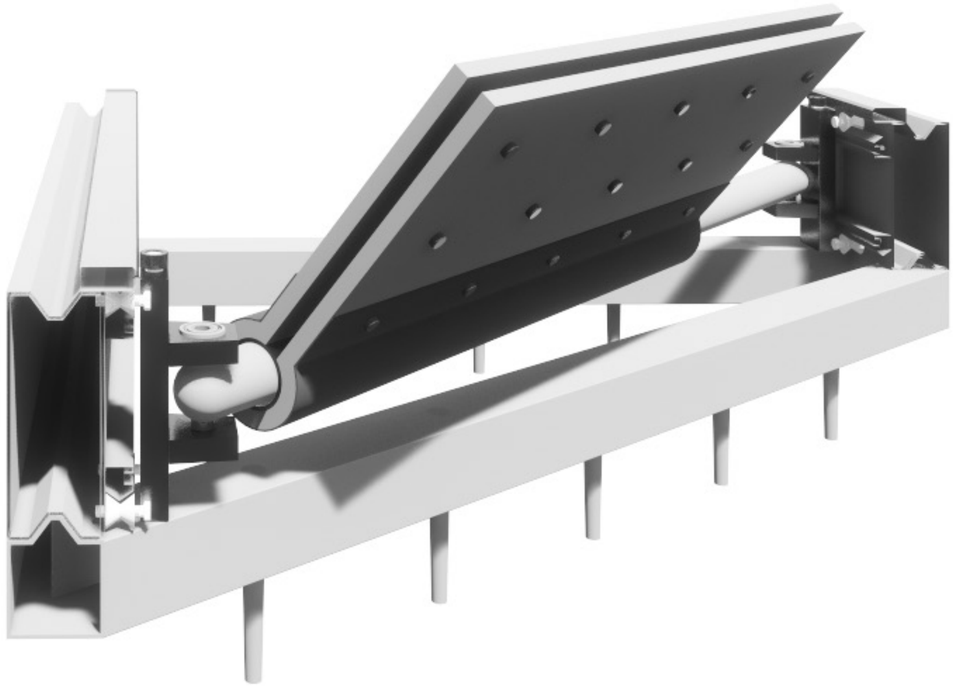
Arch coupling

Active-bending sequence

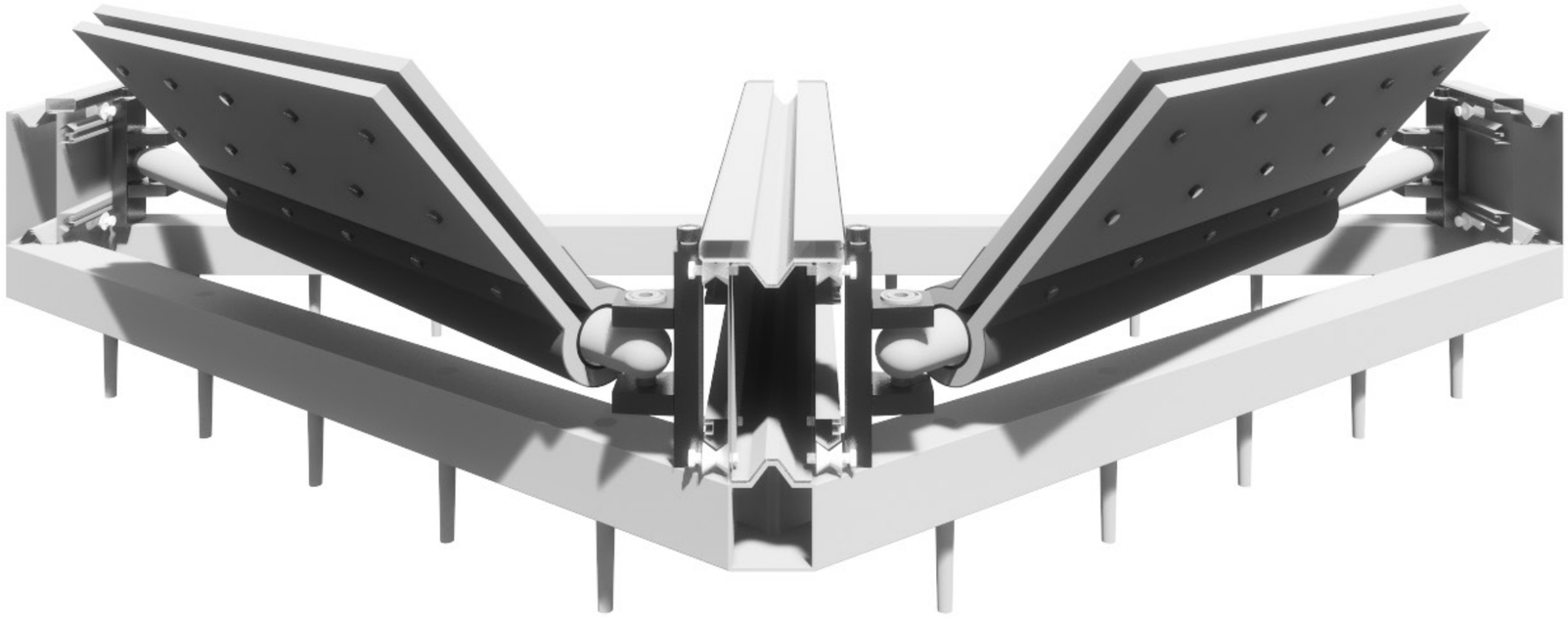


Extension abilities

One support

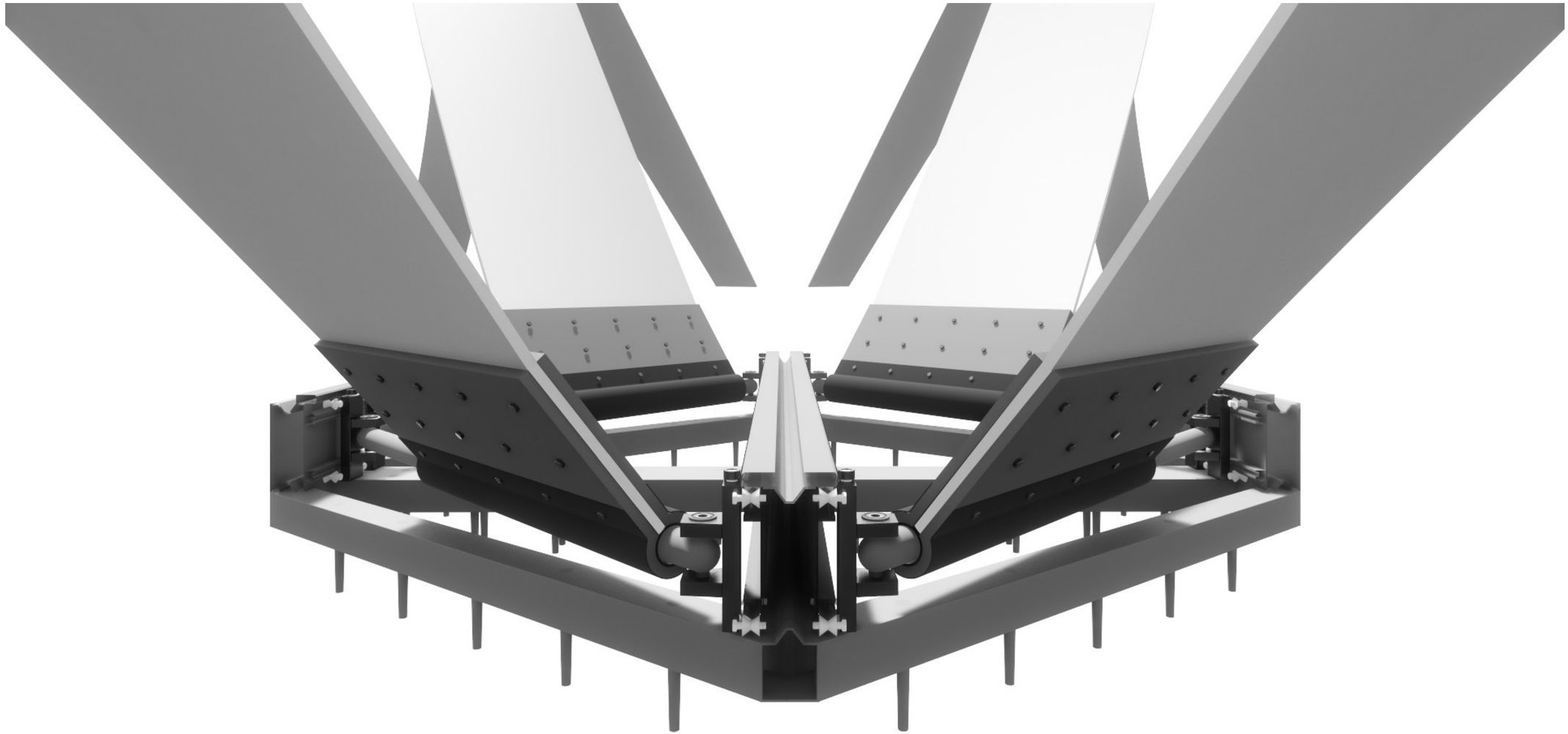


Extension abilities



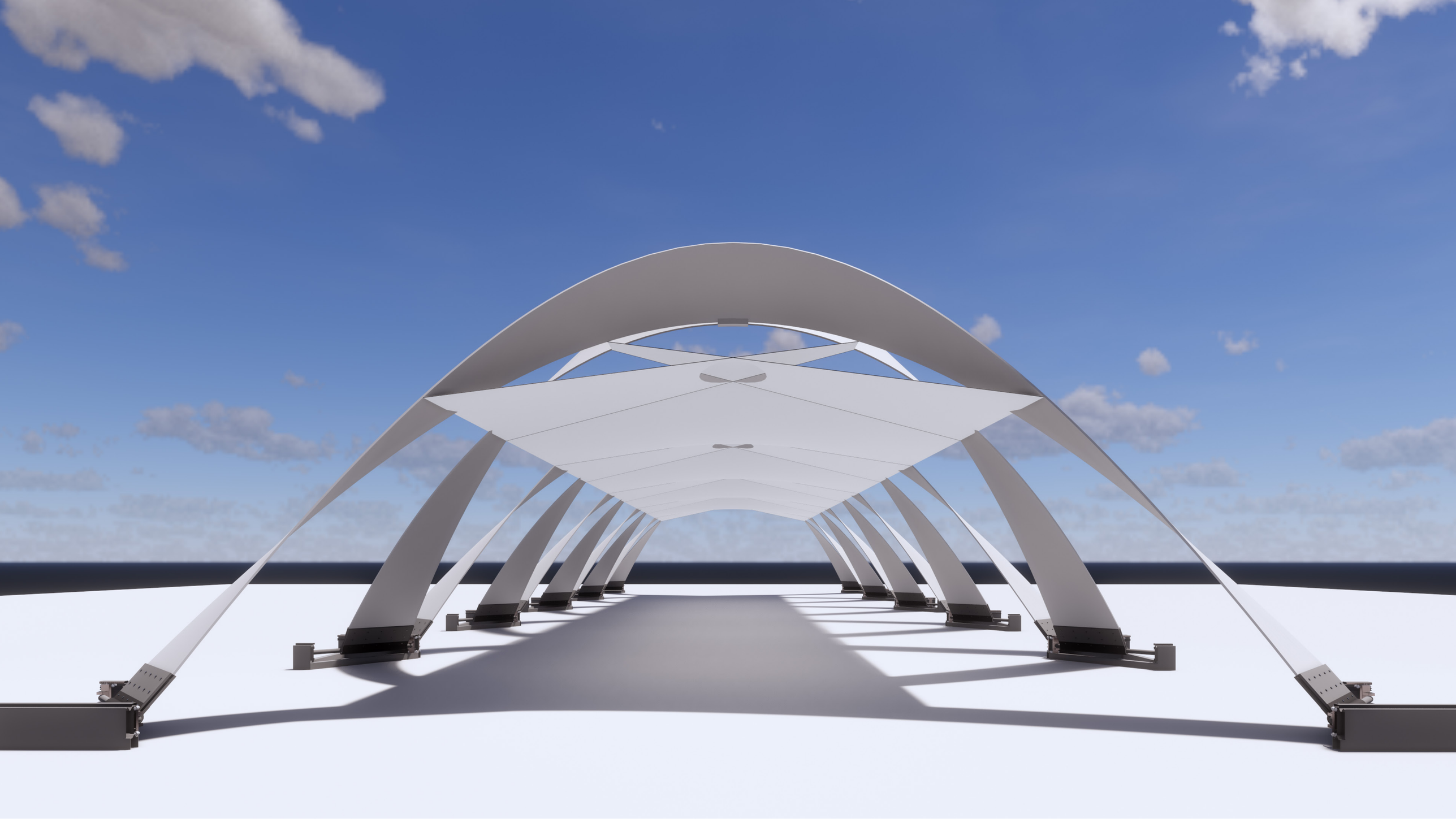
Two supports, shared middle rail

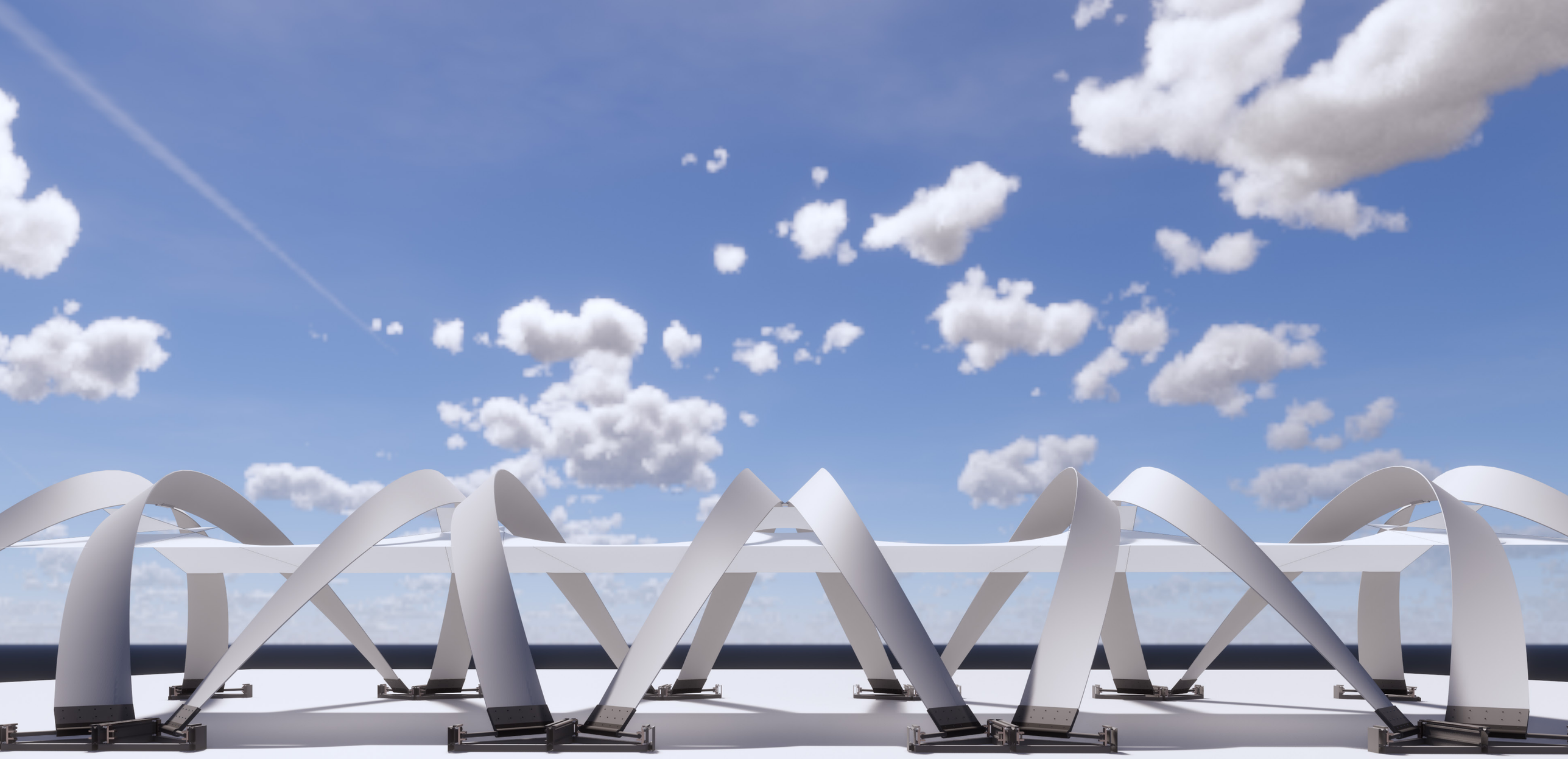
Extension abilities

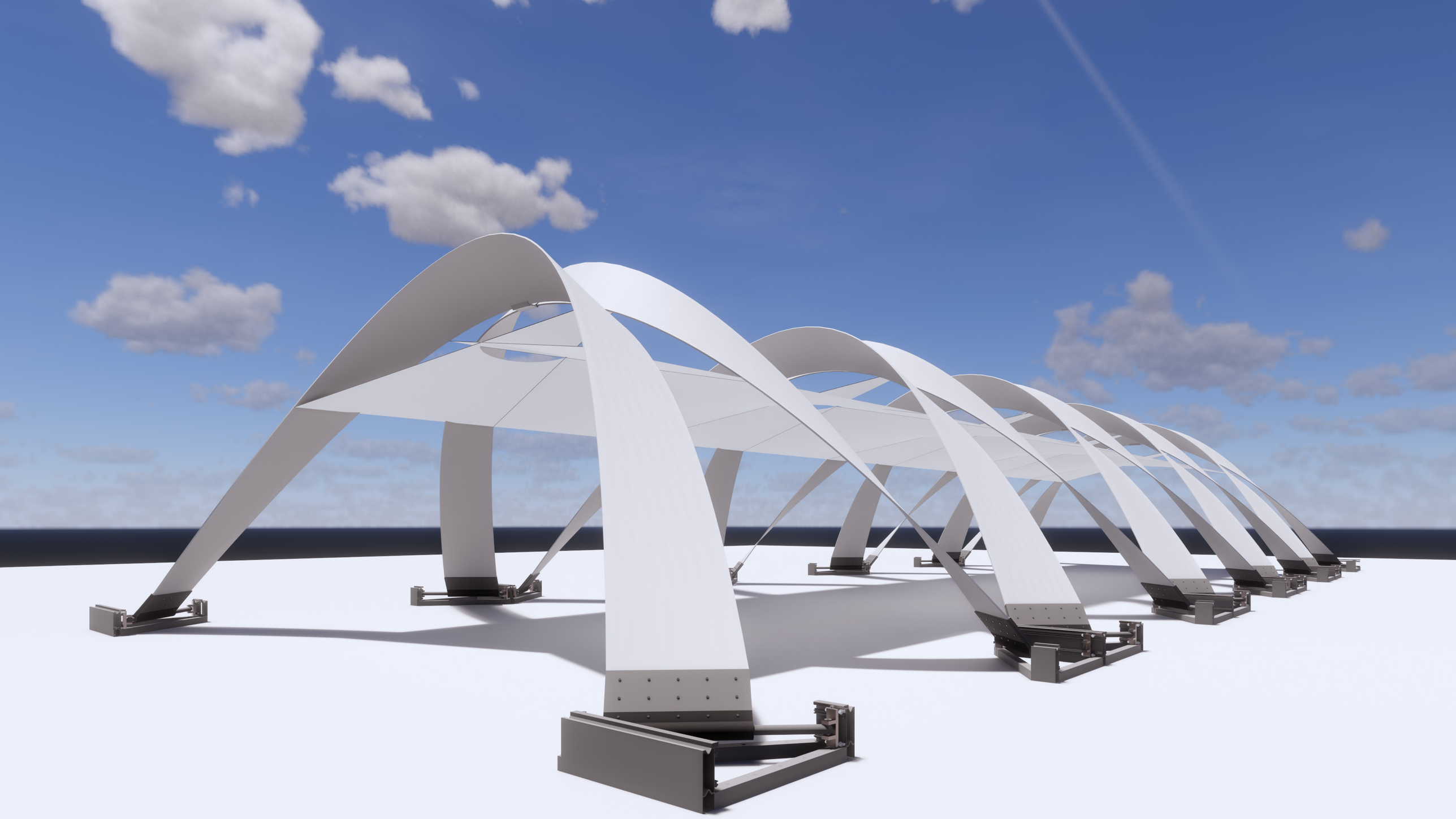


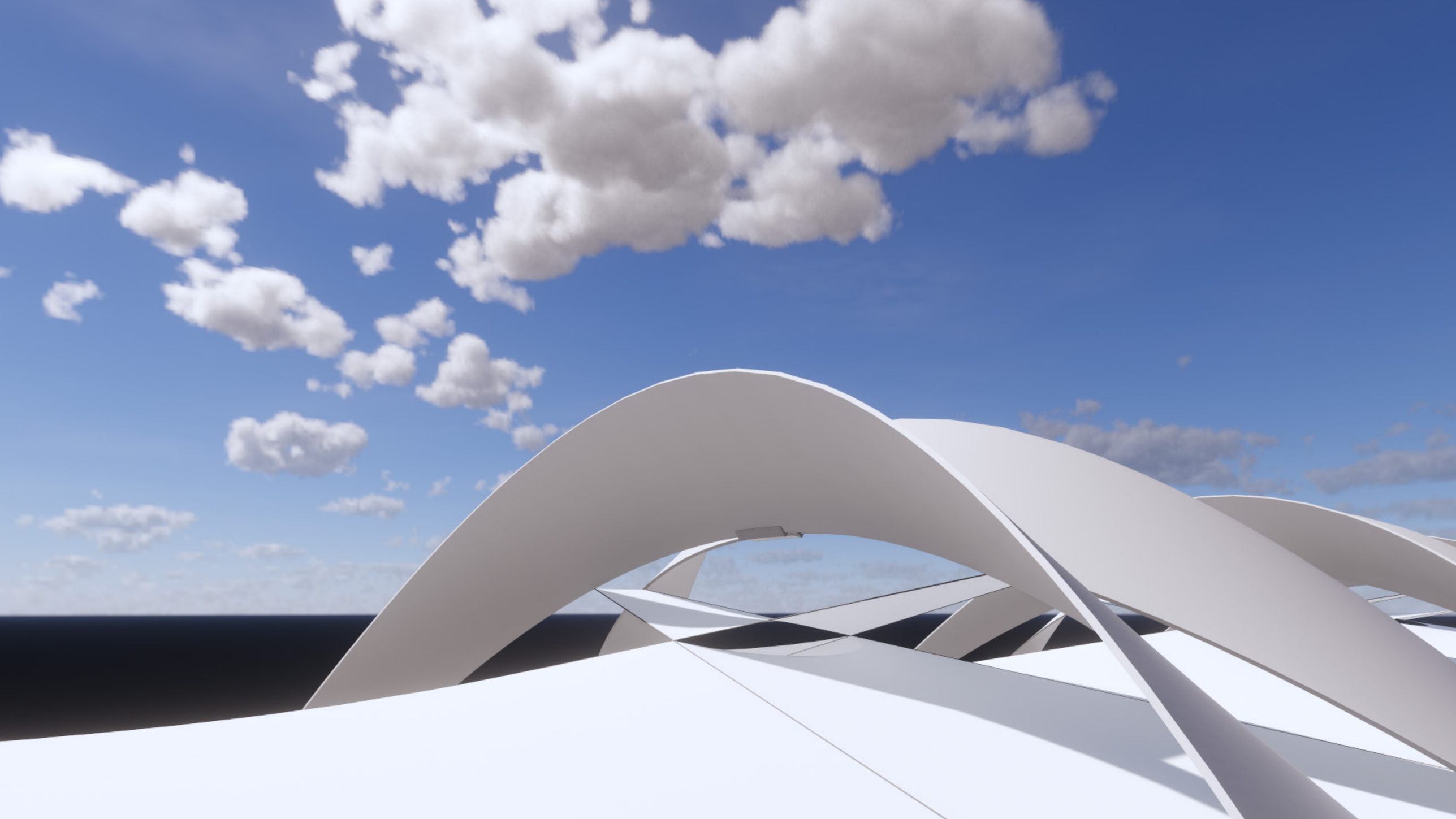
Four supports - one combined base support

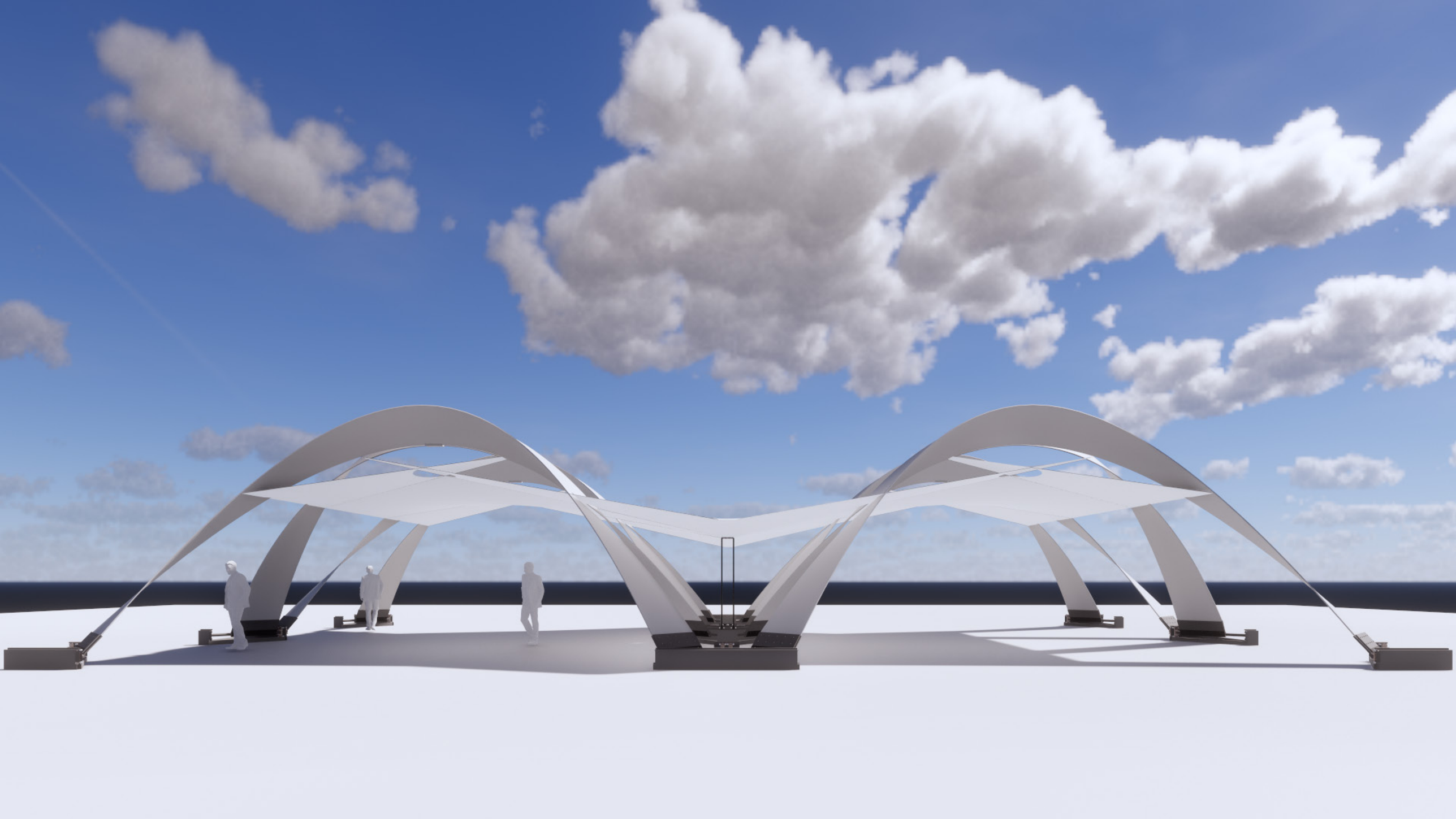
Design application

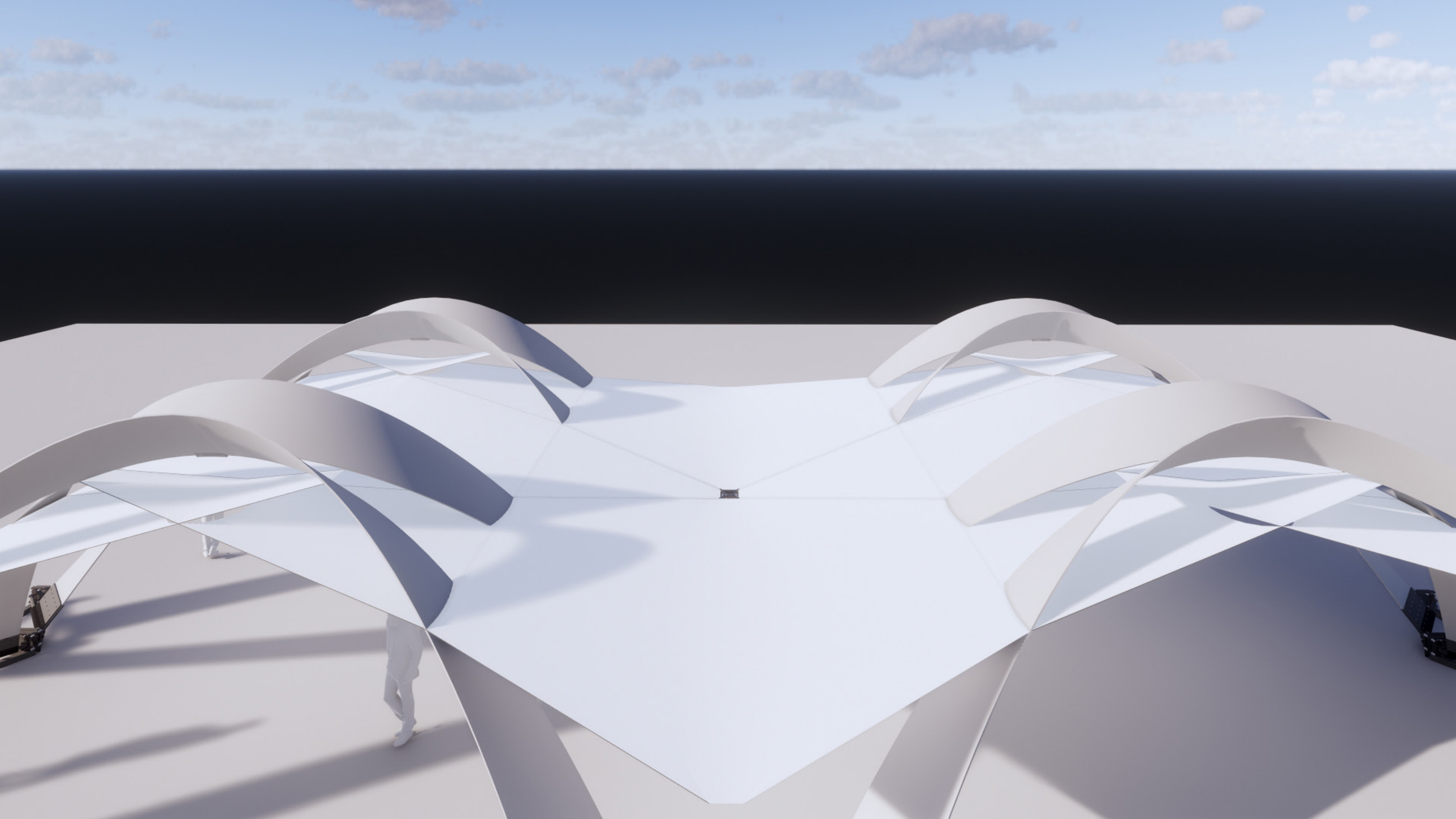


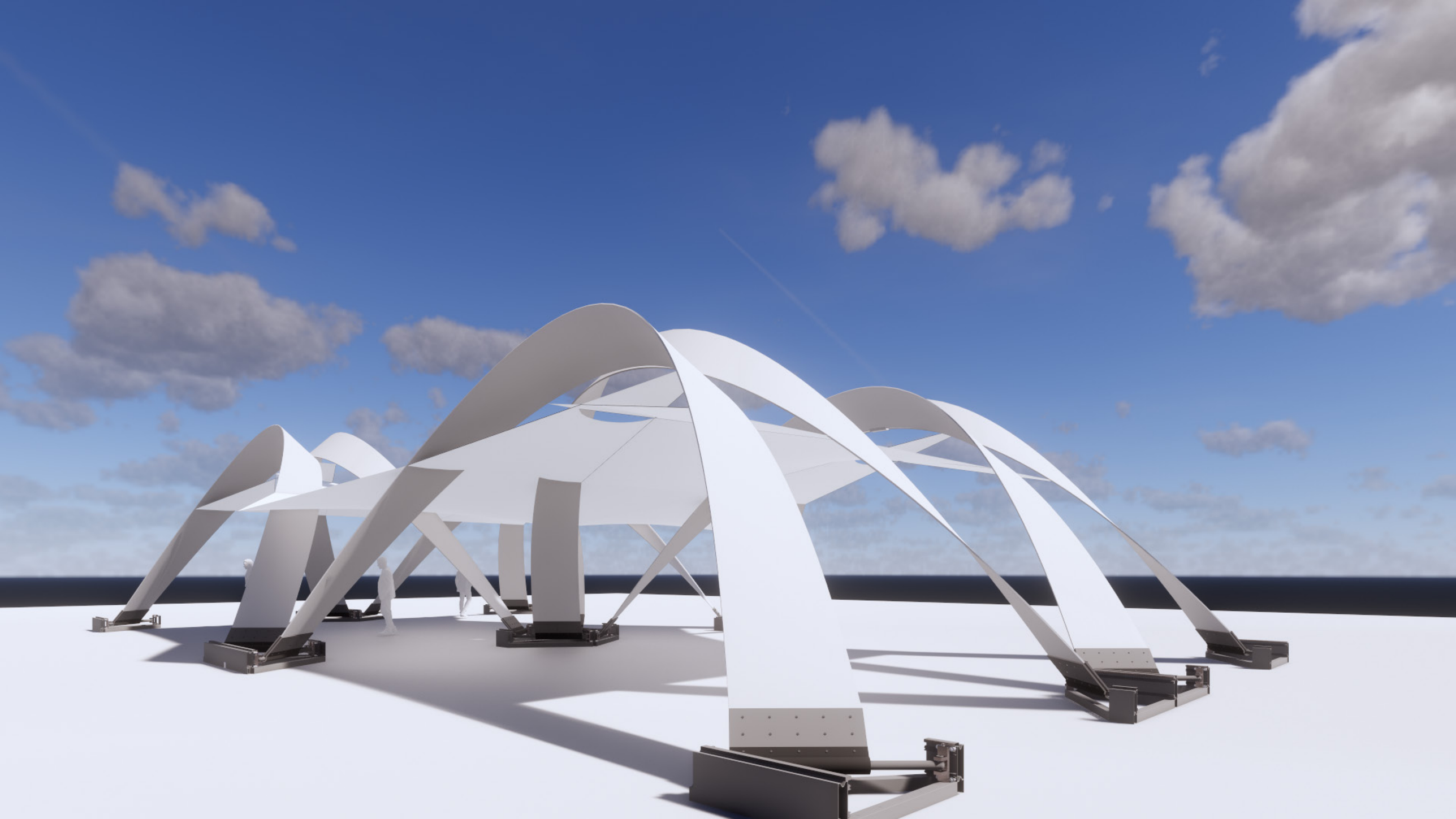


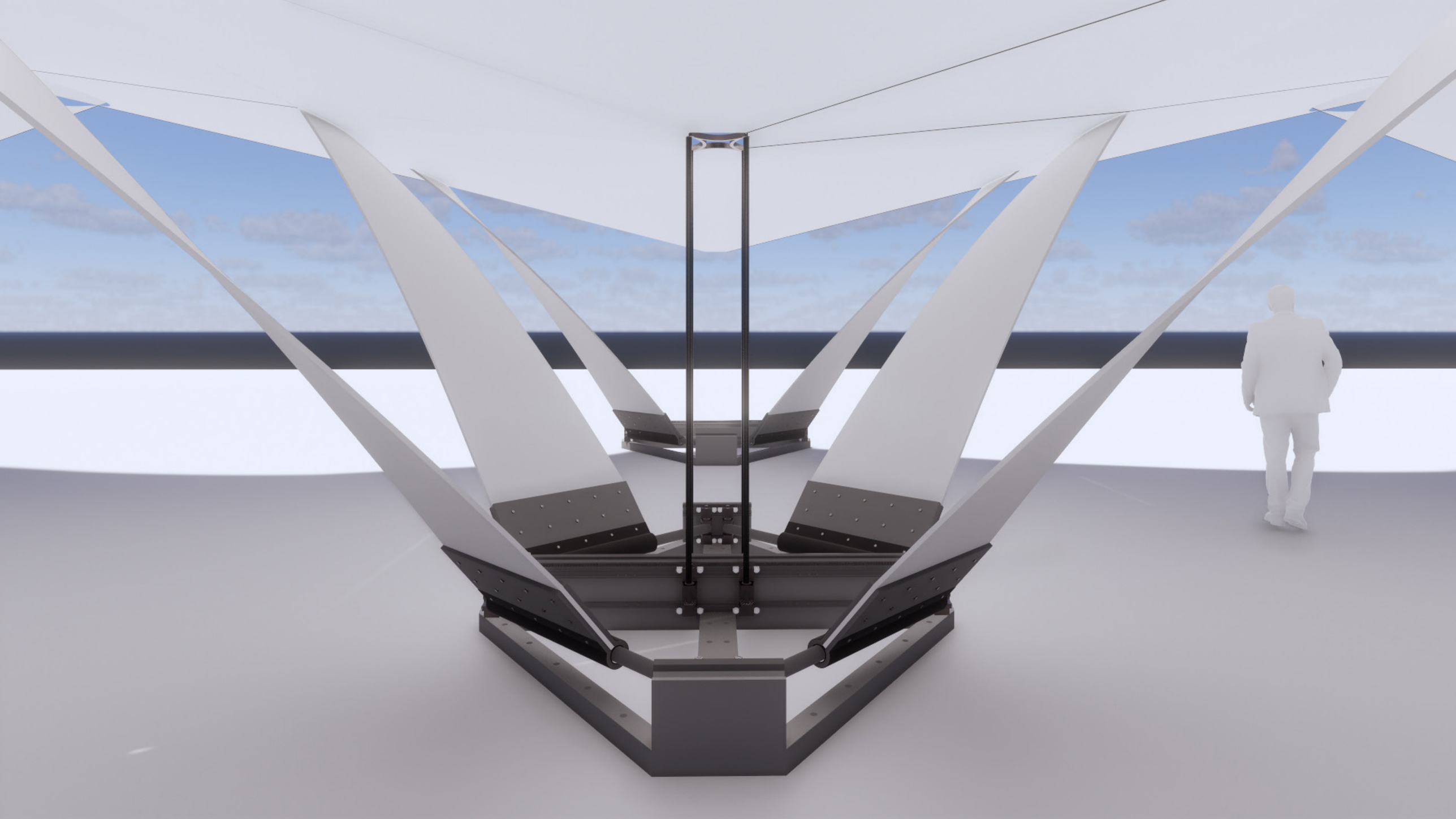












Future trends

Final statement

Final statement

Active-bending as a formation process

Final statement

Active-bending as a formation process

Material properties Gaussian measure

Final statement

Active-bending as a formation process

Material properties Gaussian measure

Active plate bending simplicity in structural engineering

Final statement

Active-bending as a formation process

Material properties Gaussian measure

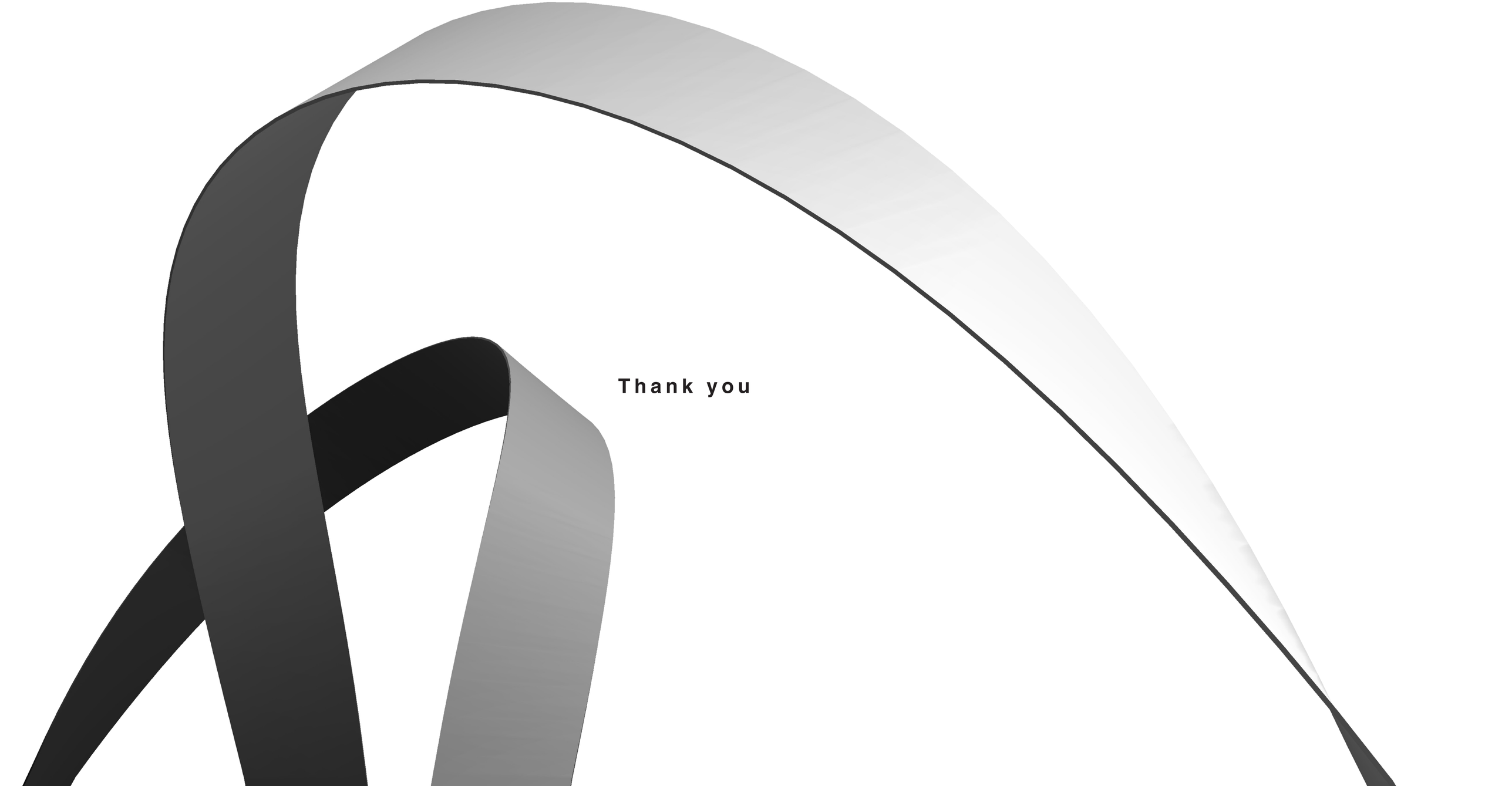
Active plate bending simplicity in structural engineering

Modular and adaptive structural and architectural design

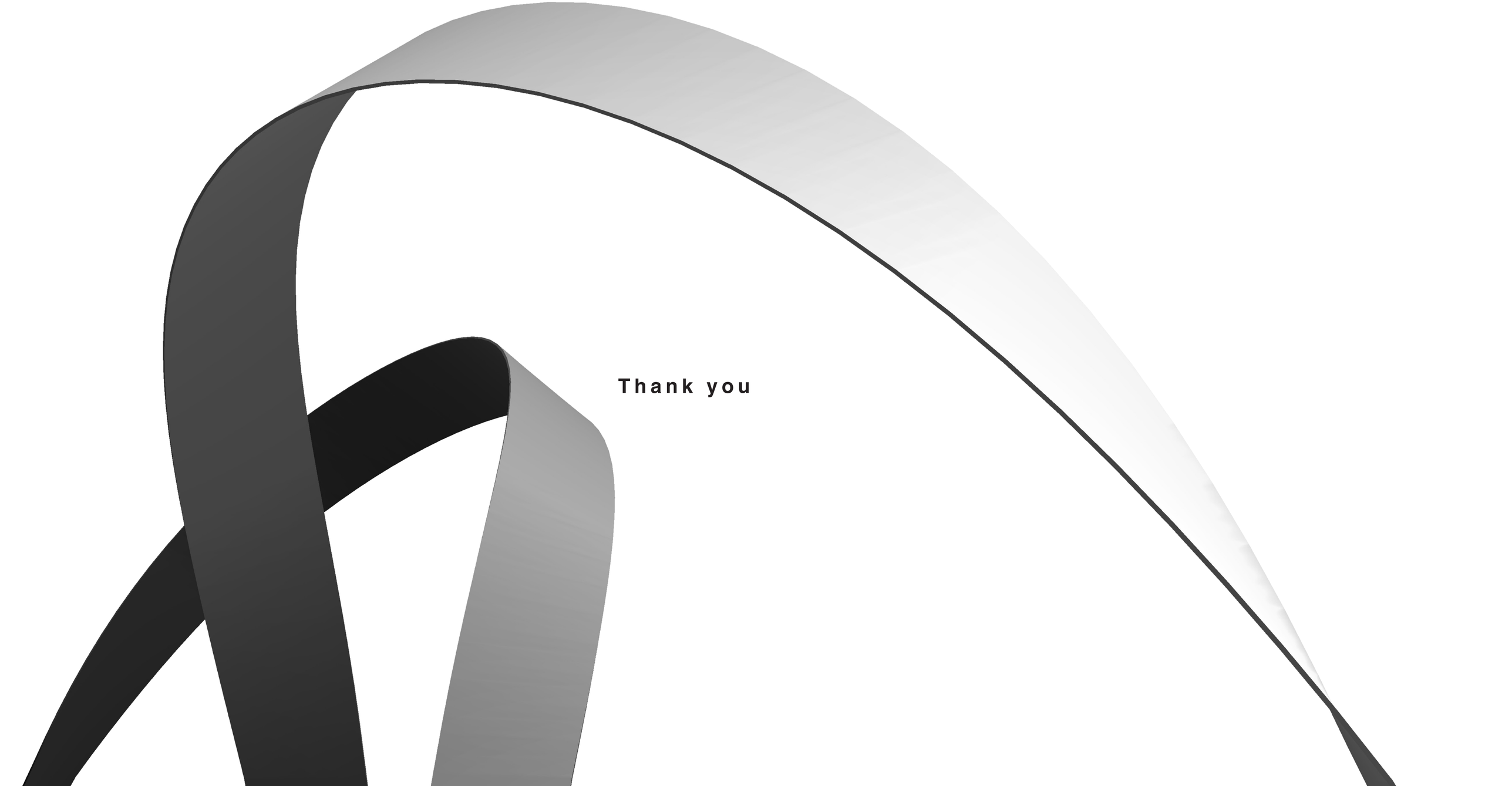
Final statement

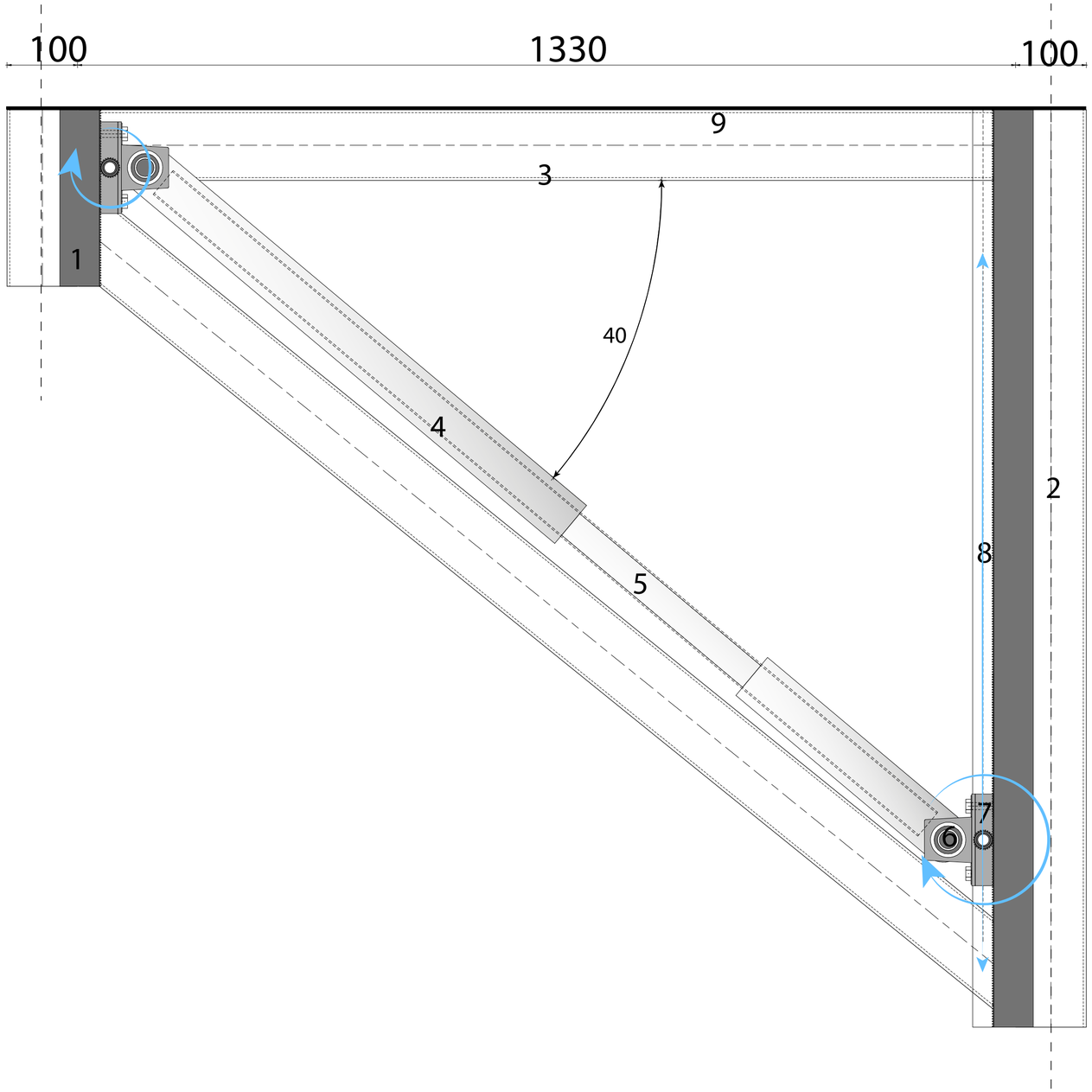
‘Active-bending is the elegance of integrating double curved architecture with minimalistic structural design.’

Thank you



Thank you

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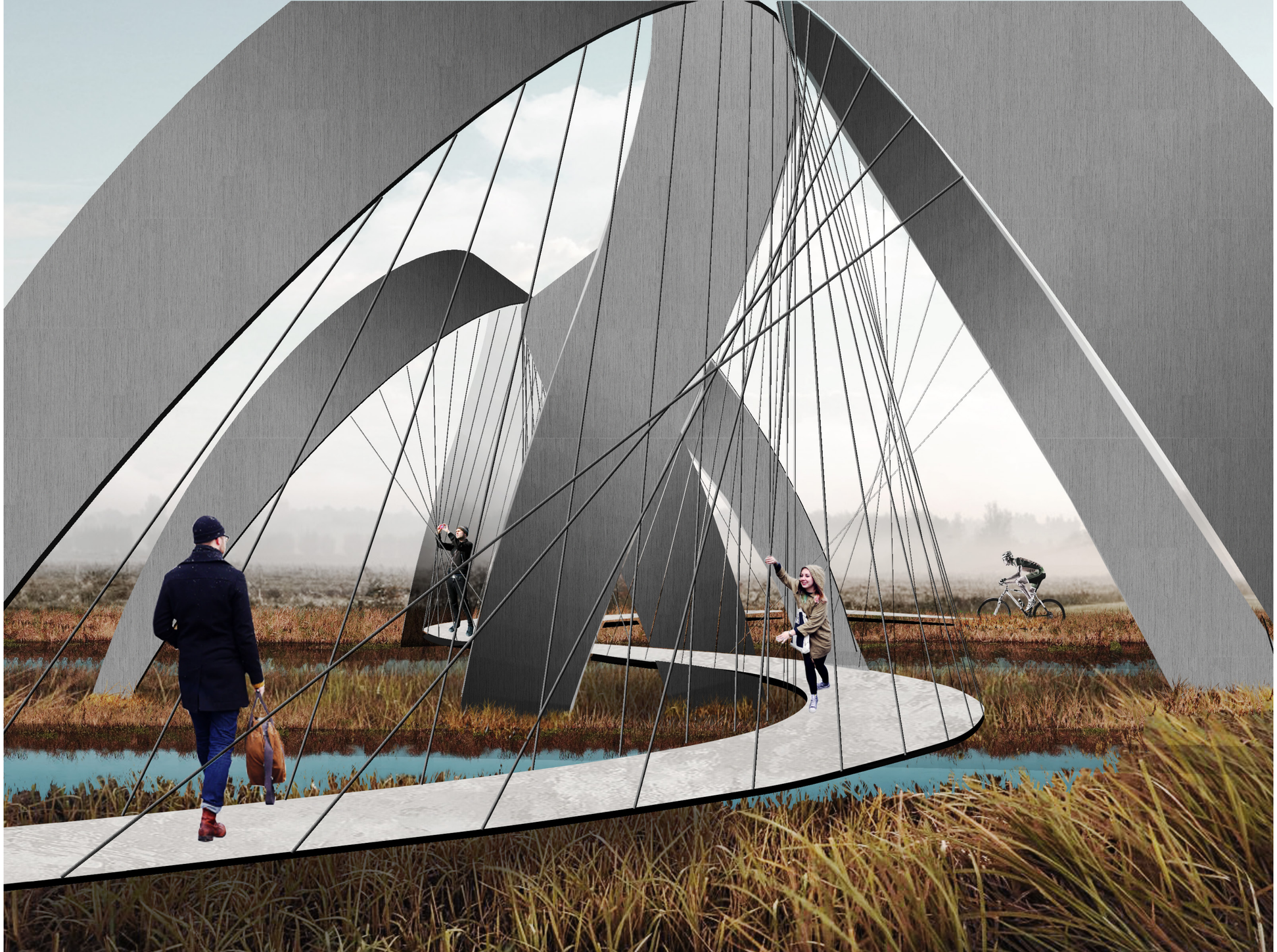

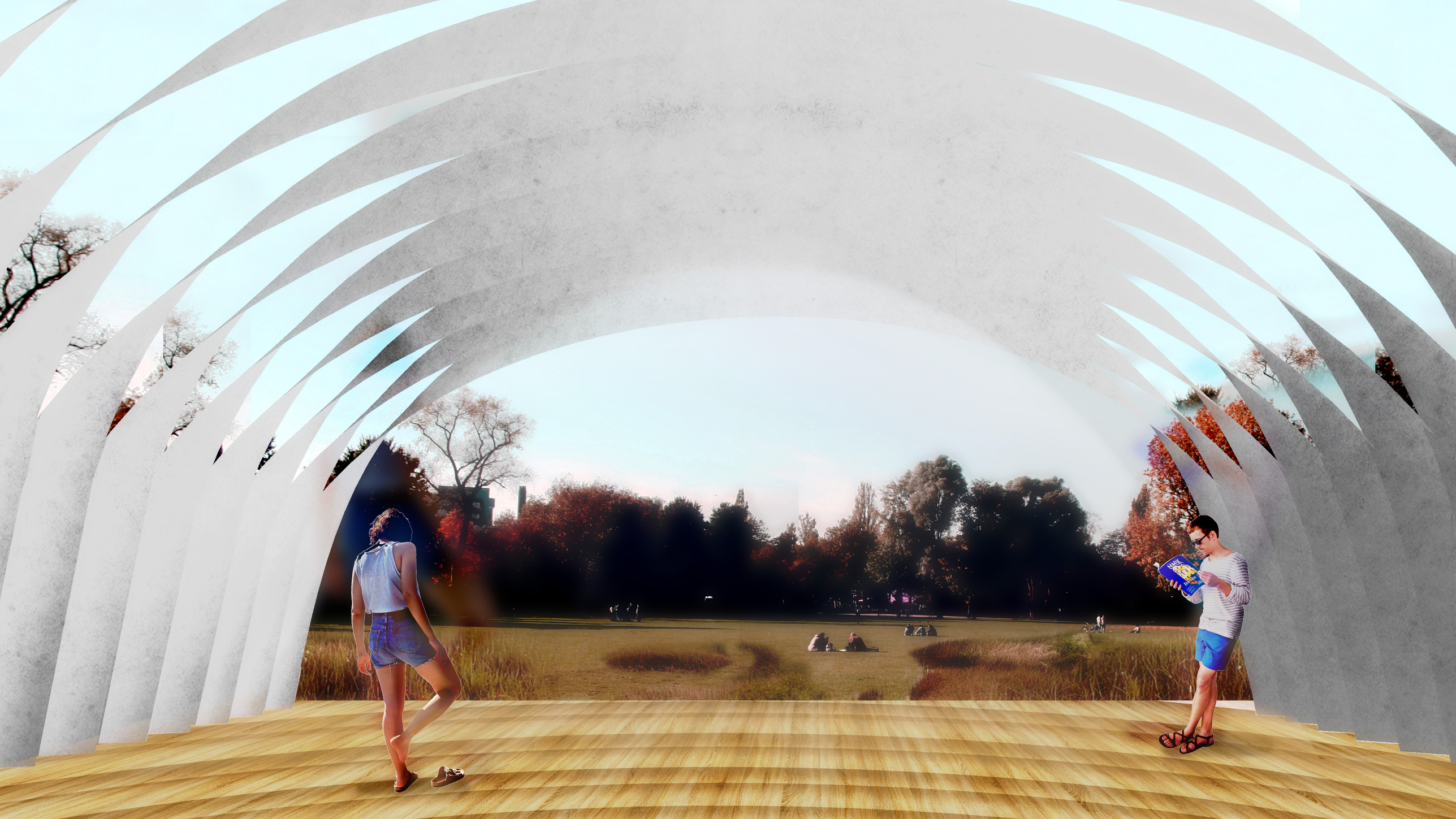

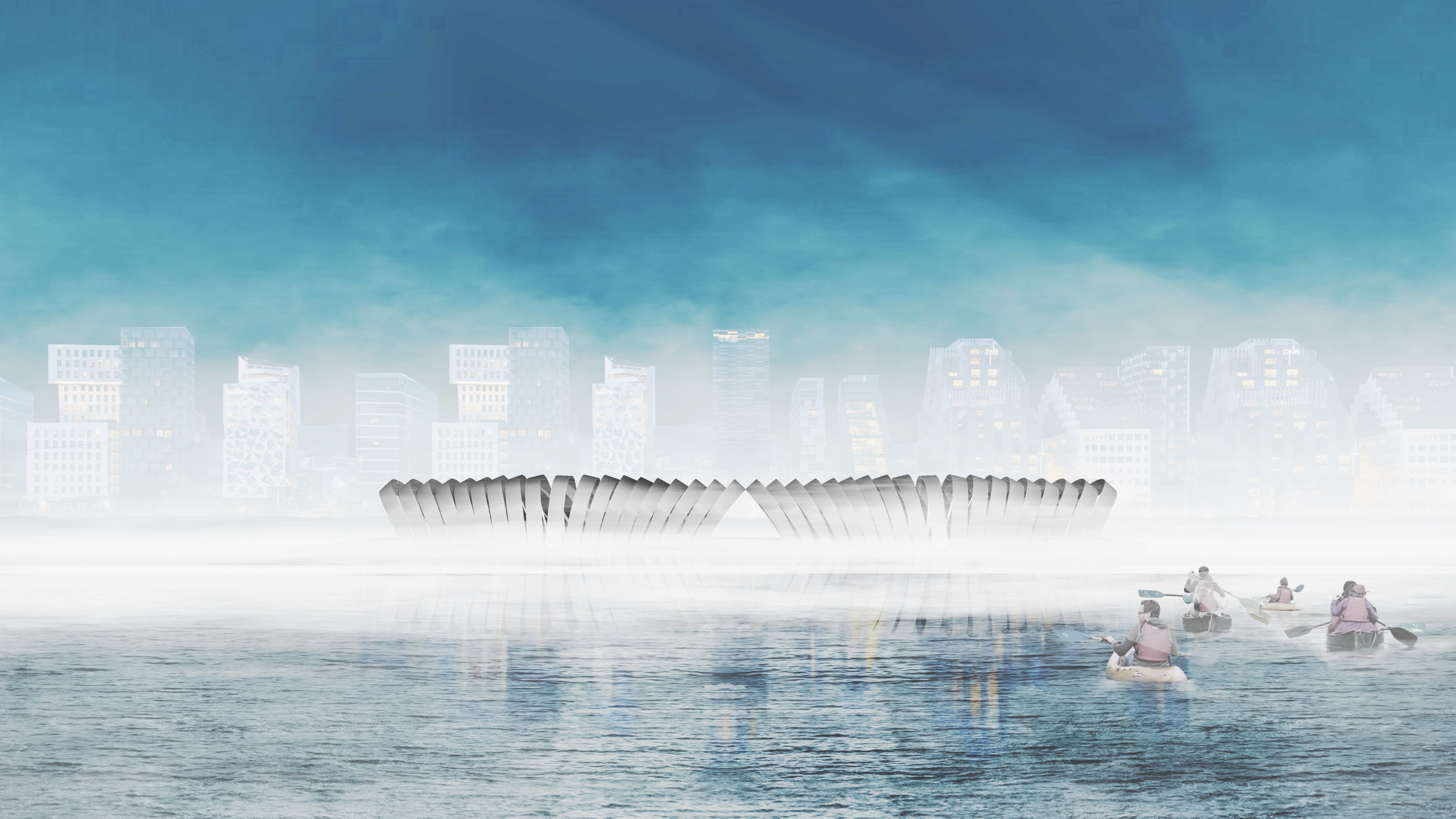
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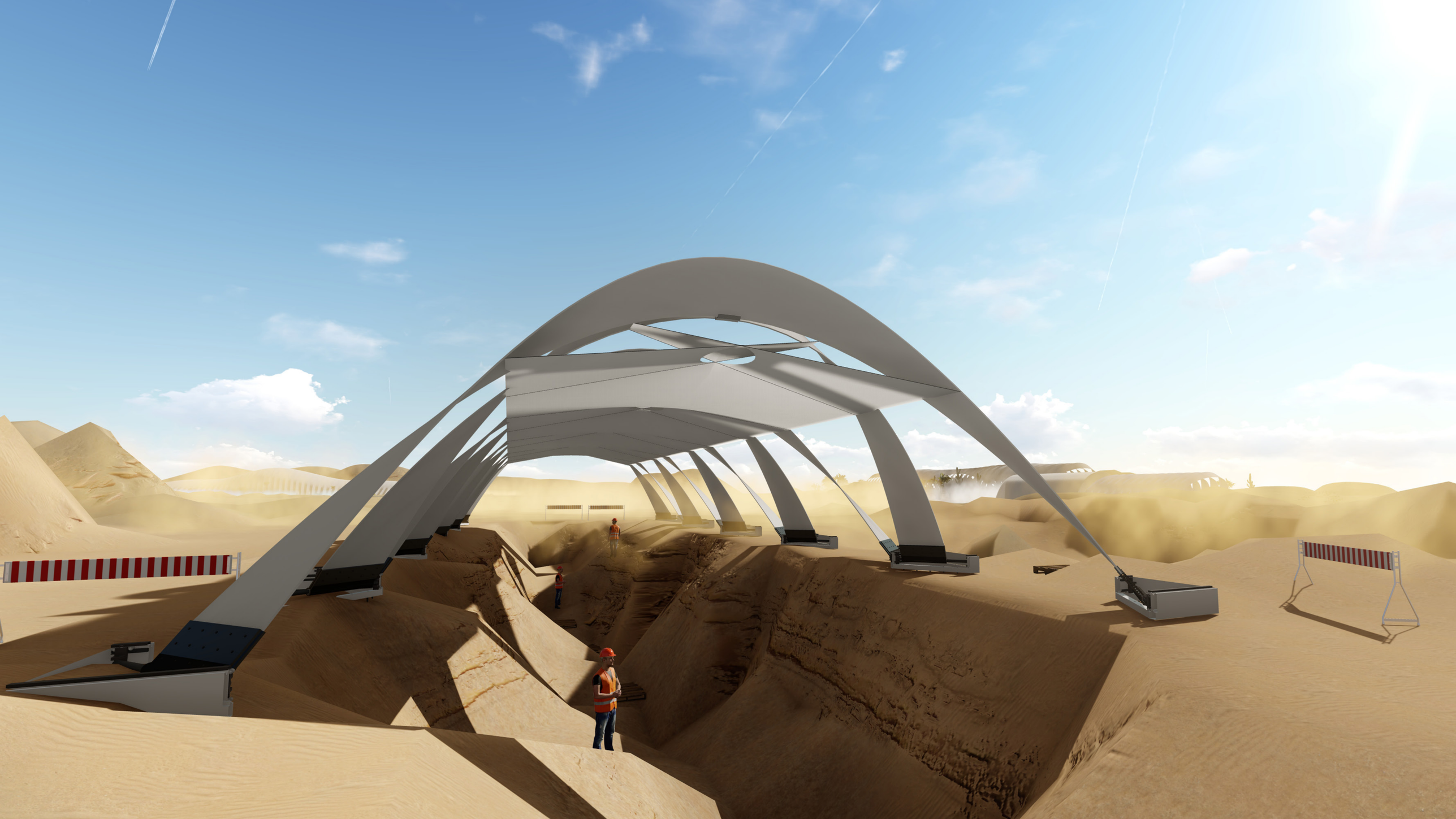

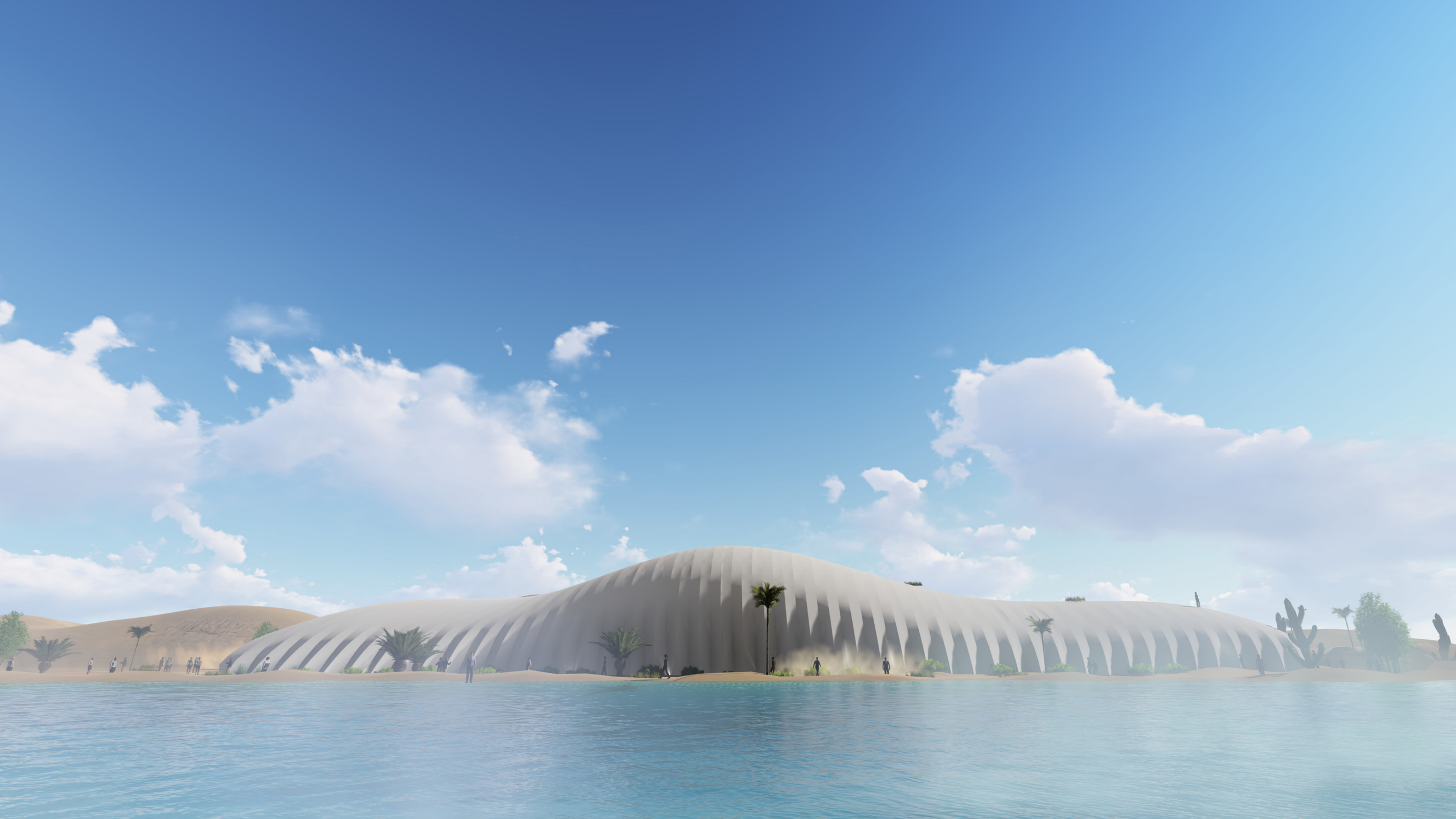

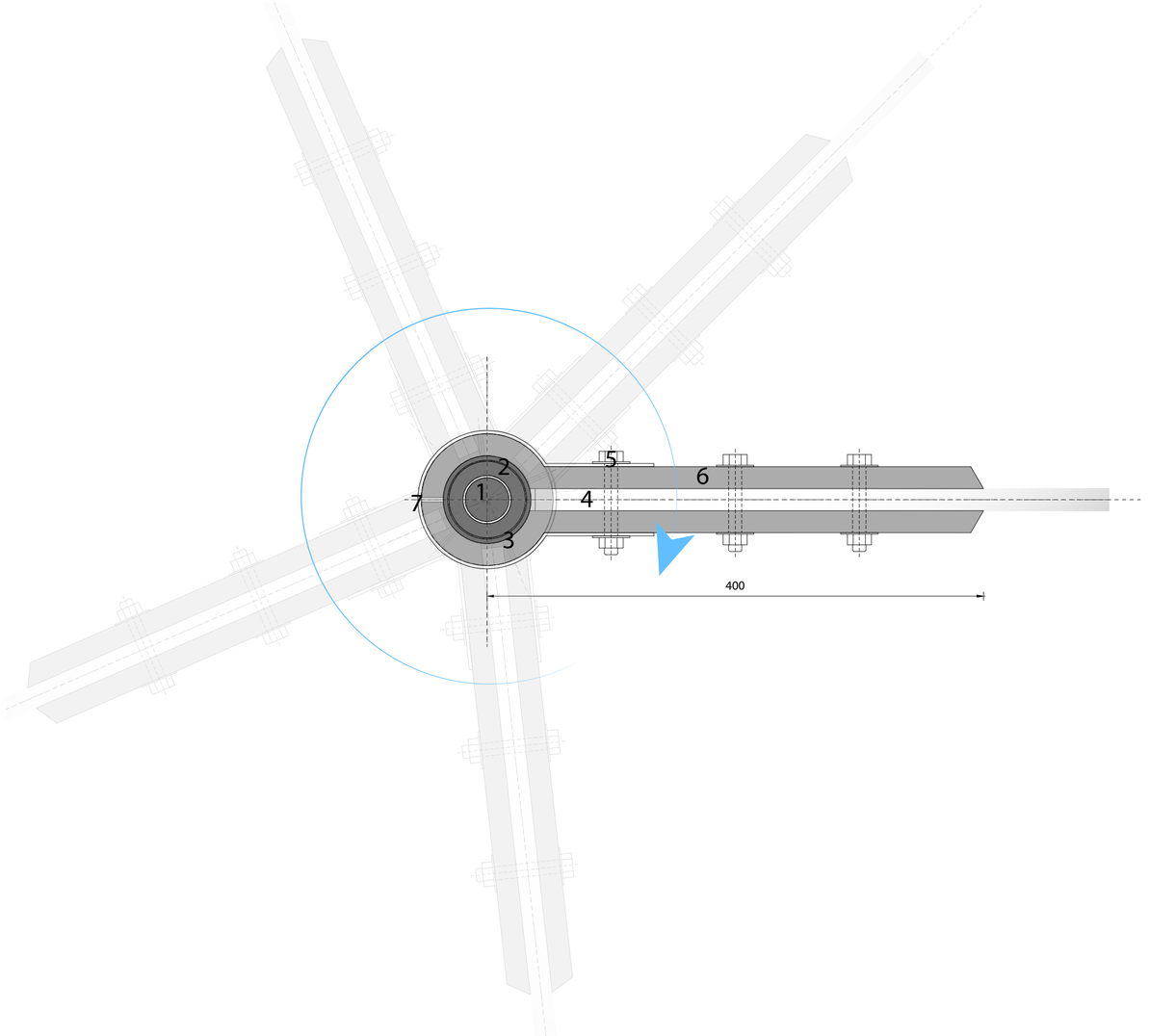
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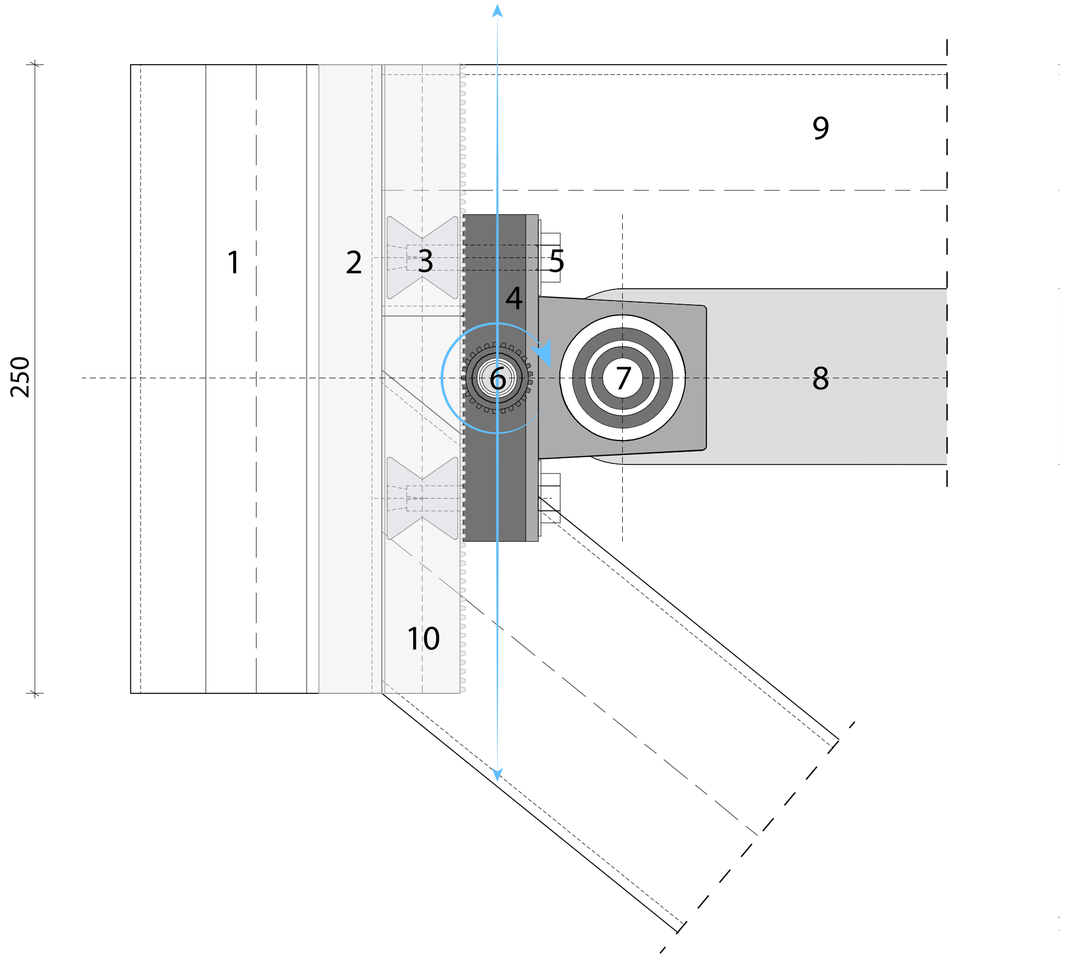
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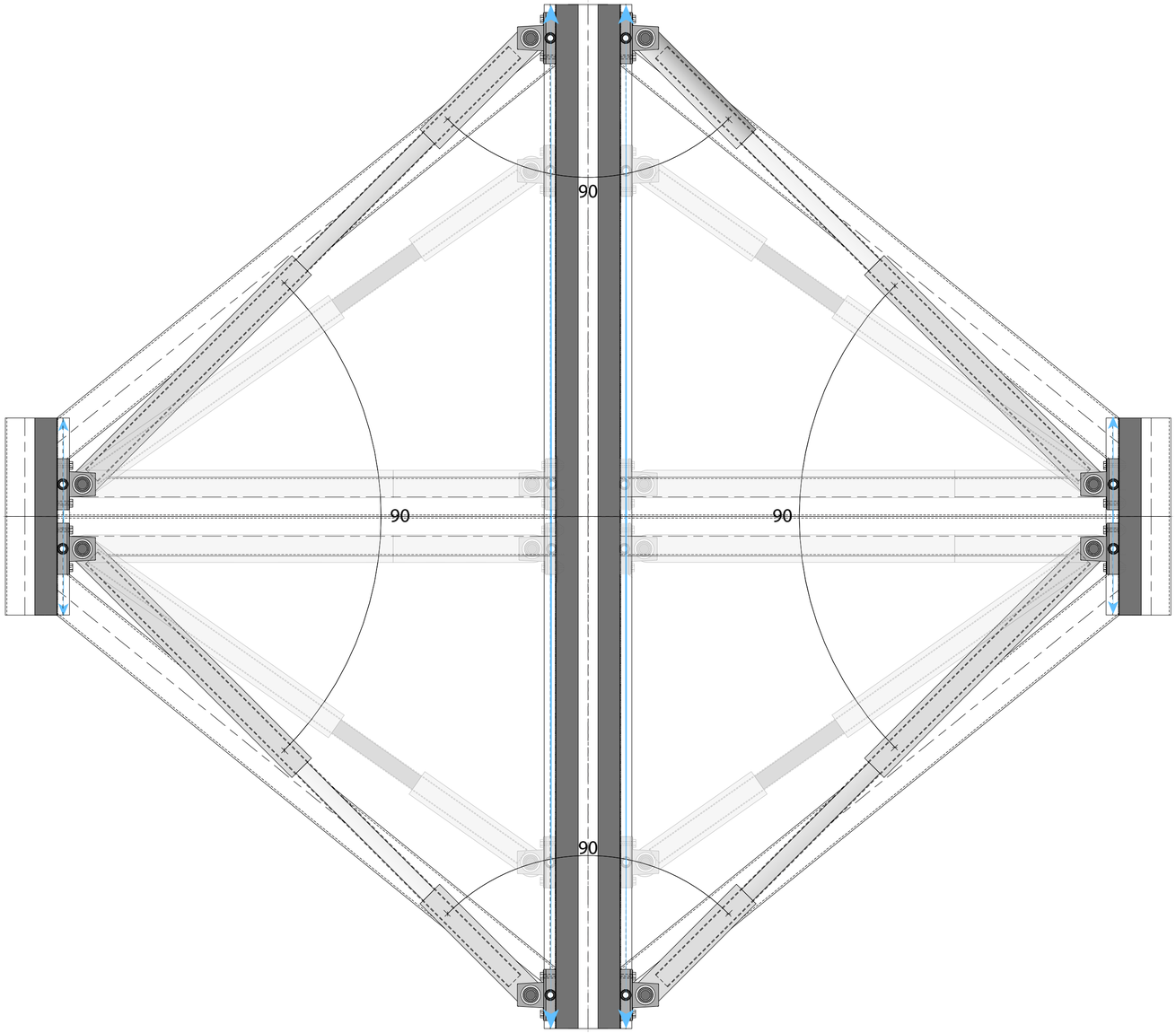
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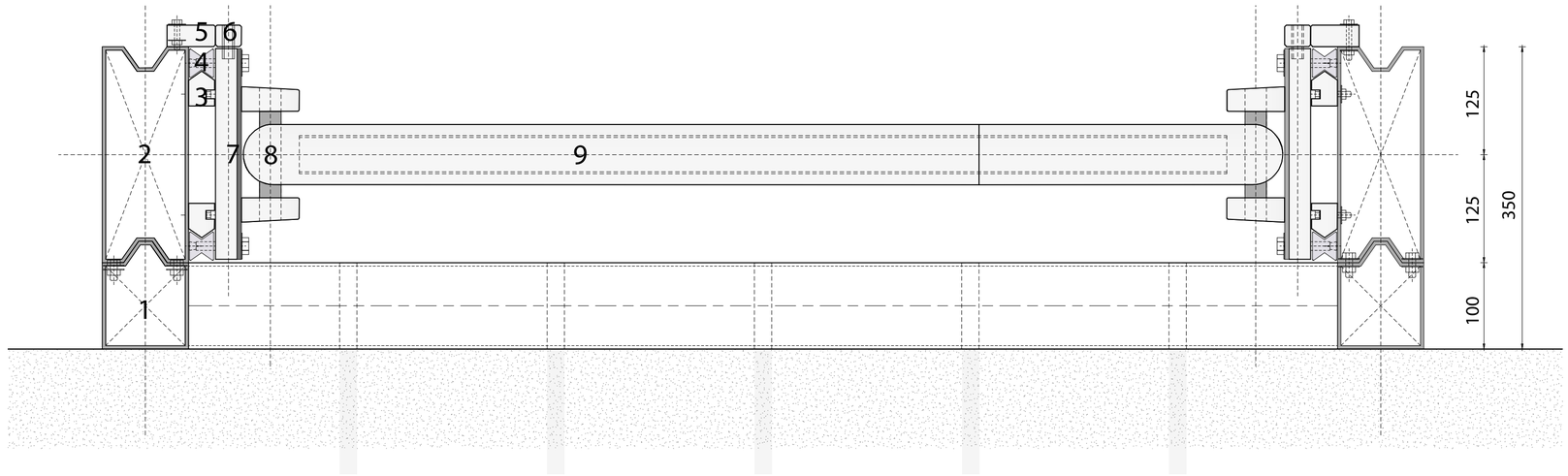
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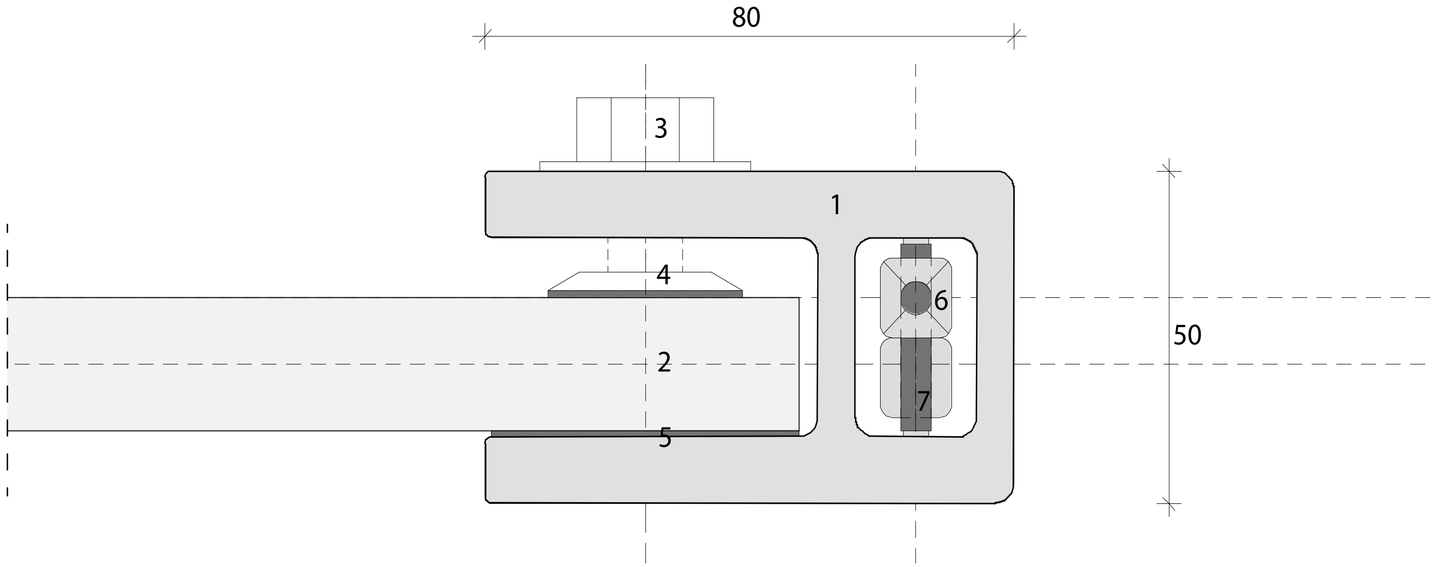
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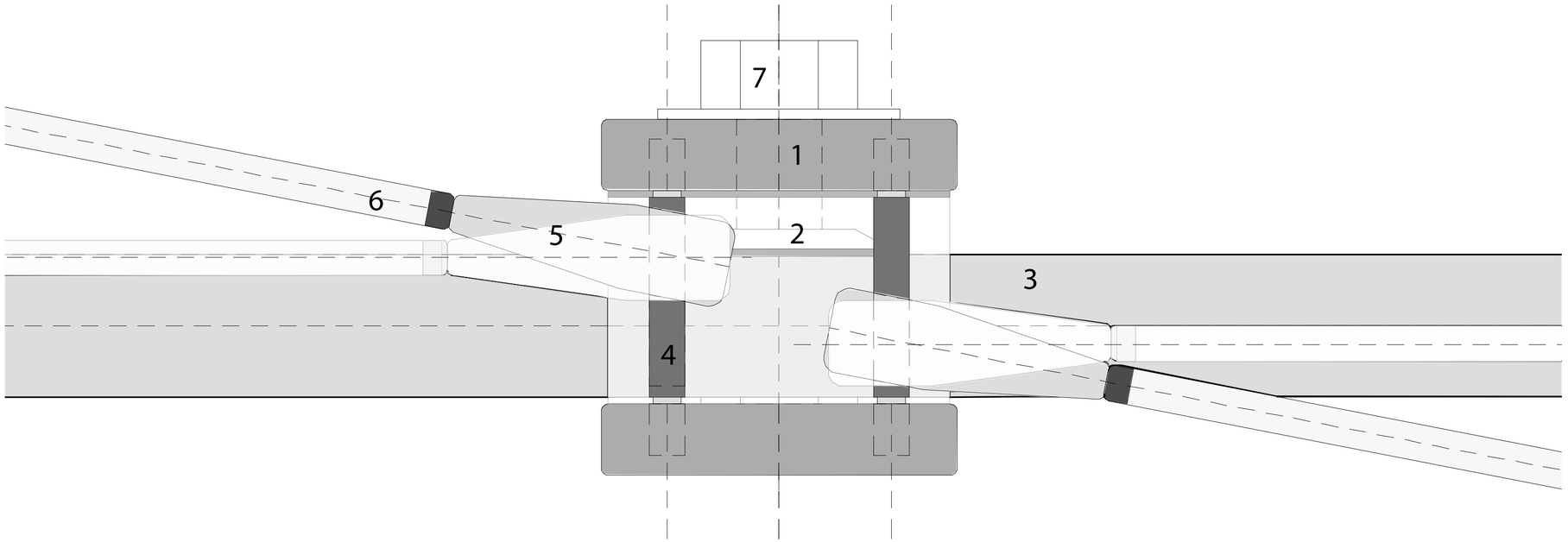
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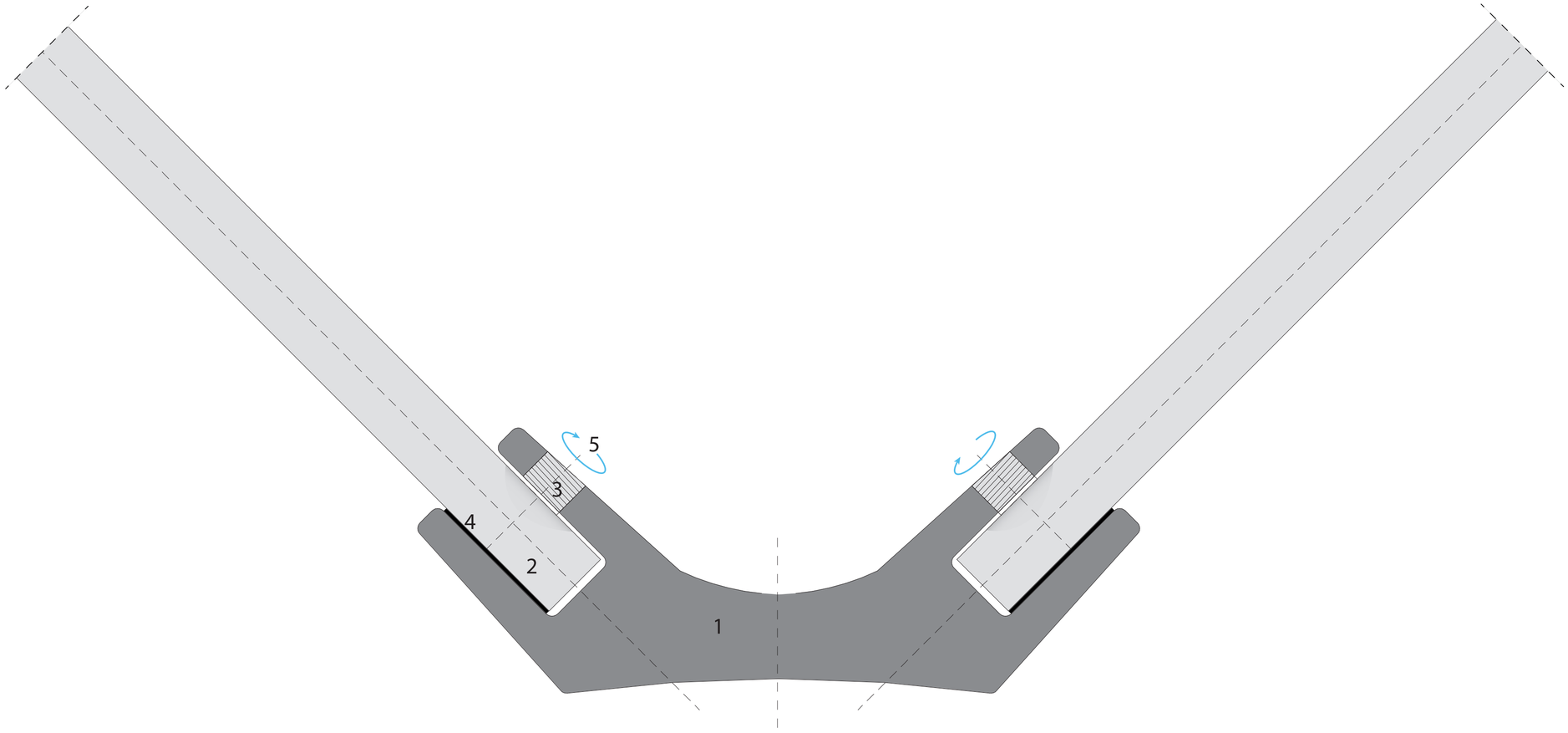
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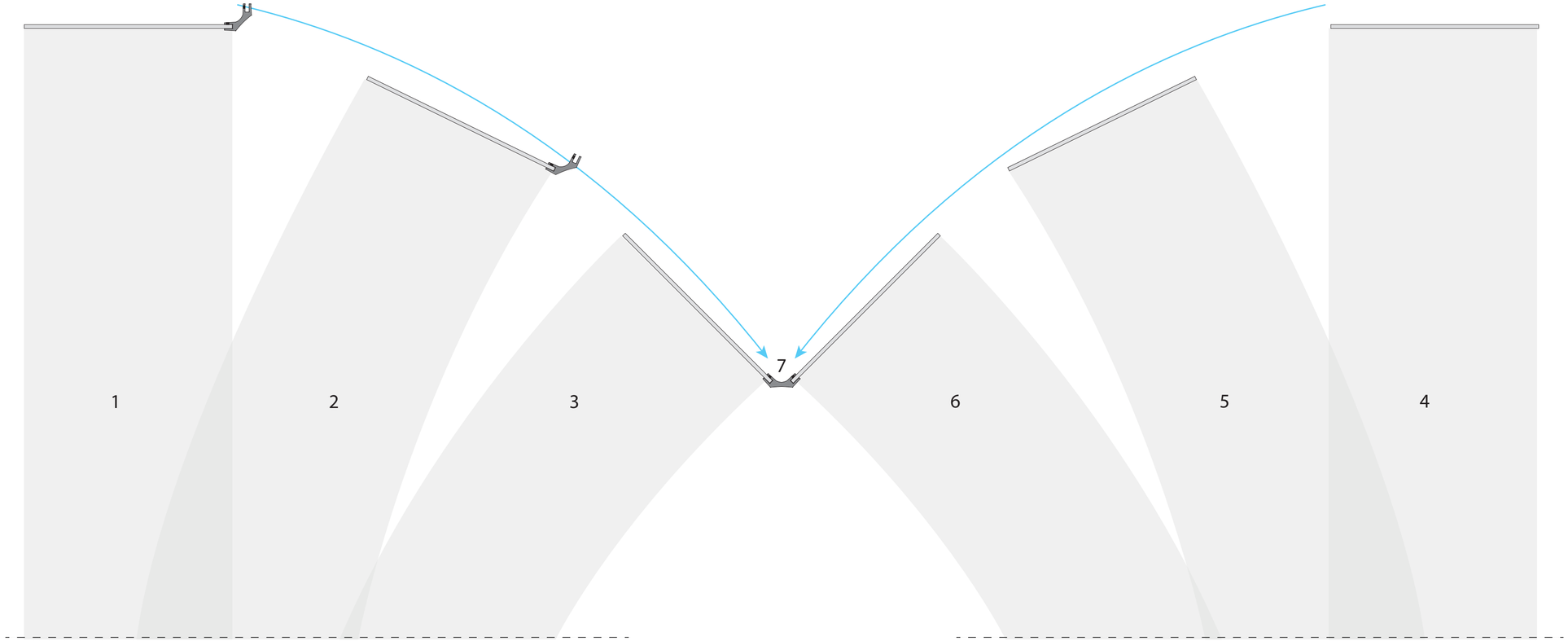
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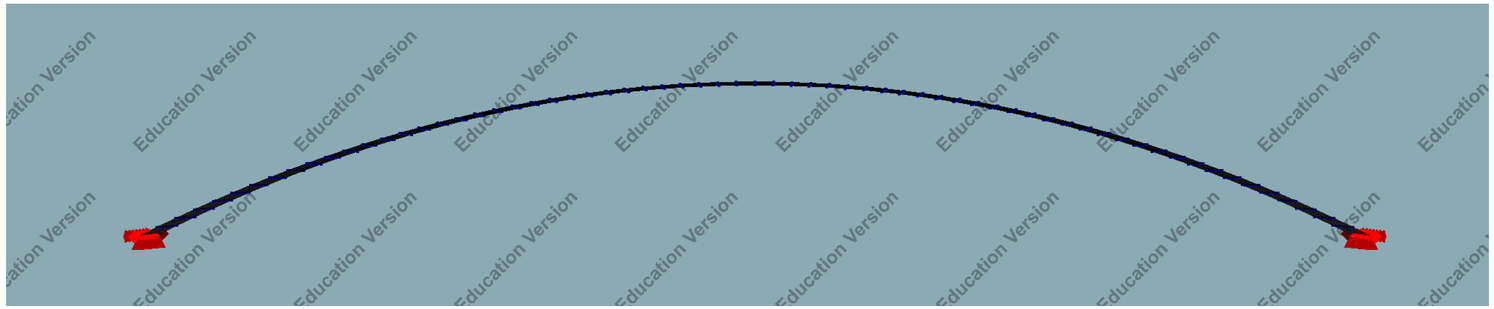
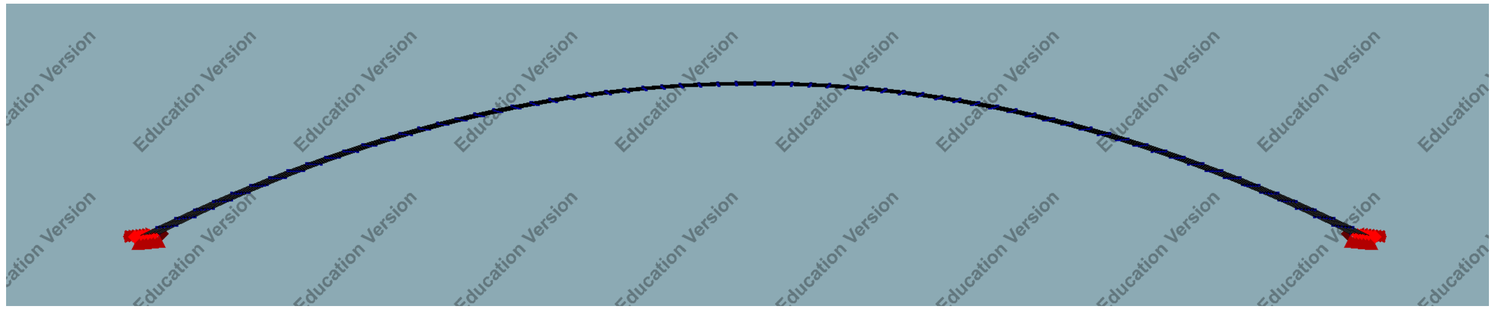
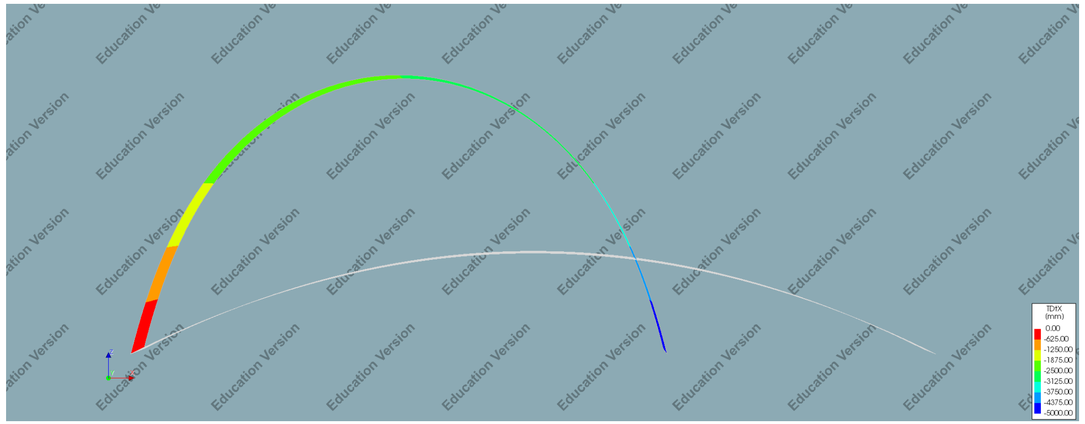
Structural analyses - deformation sequence

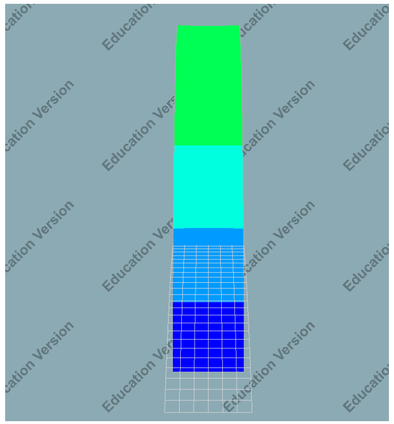


Begin shape slightly curved

Structural analyses - deformation sequence

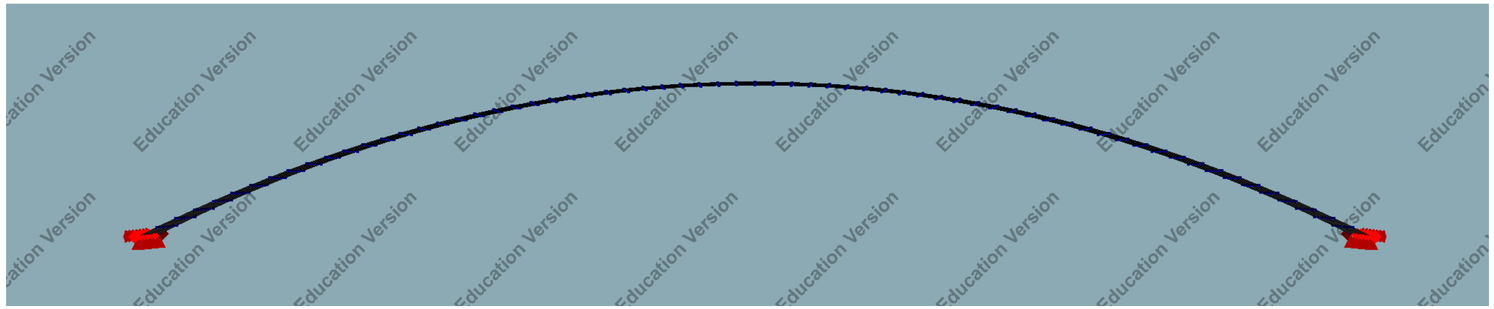


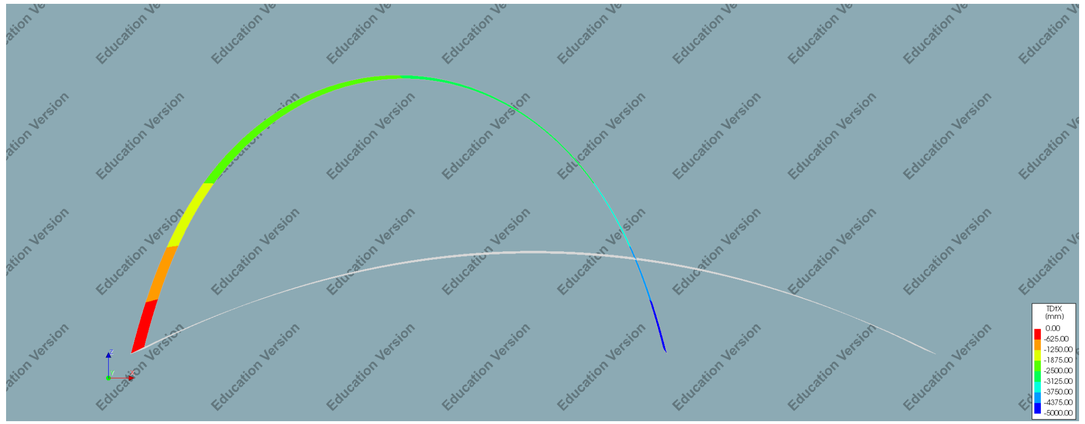


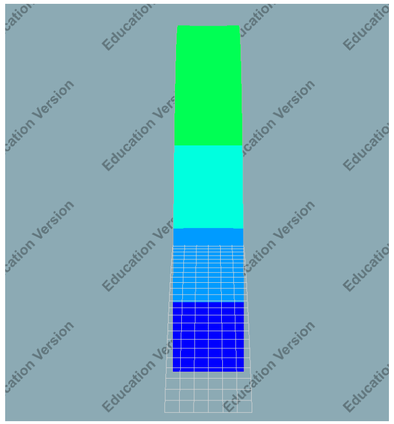


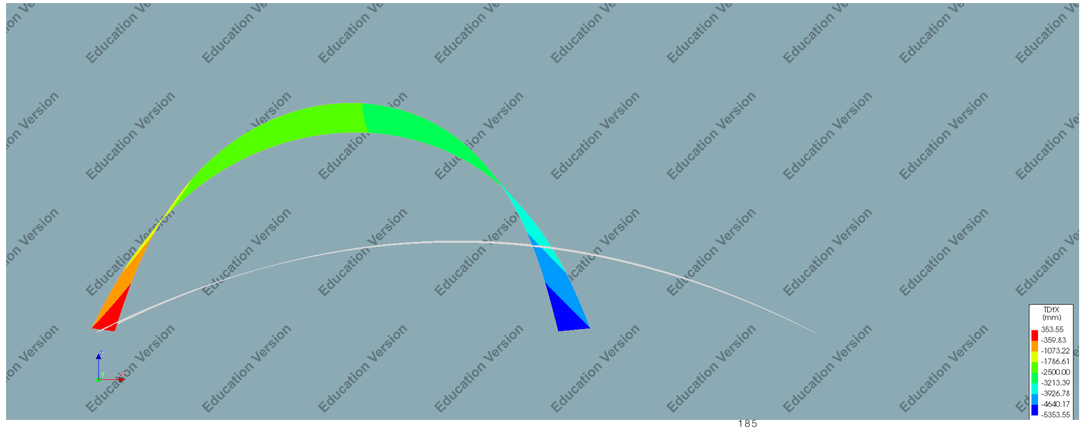
Horizontal displacement support

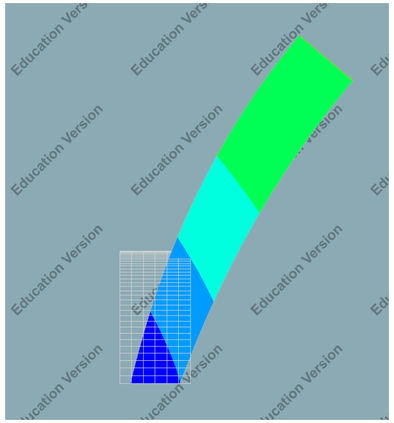
Structural analyses - deformation sequence





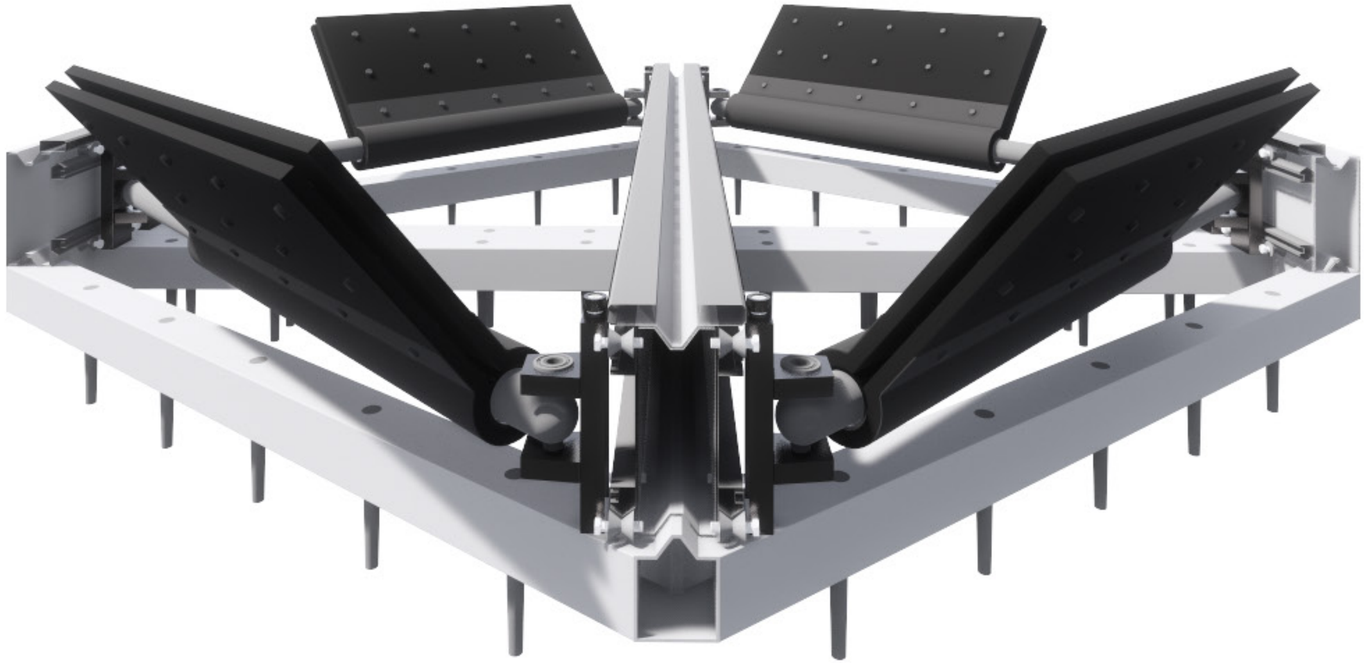






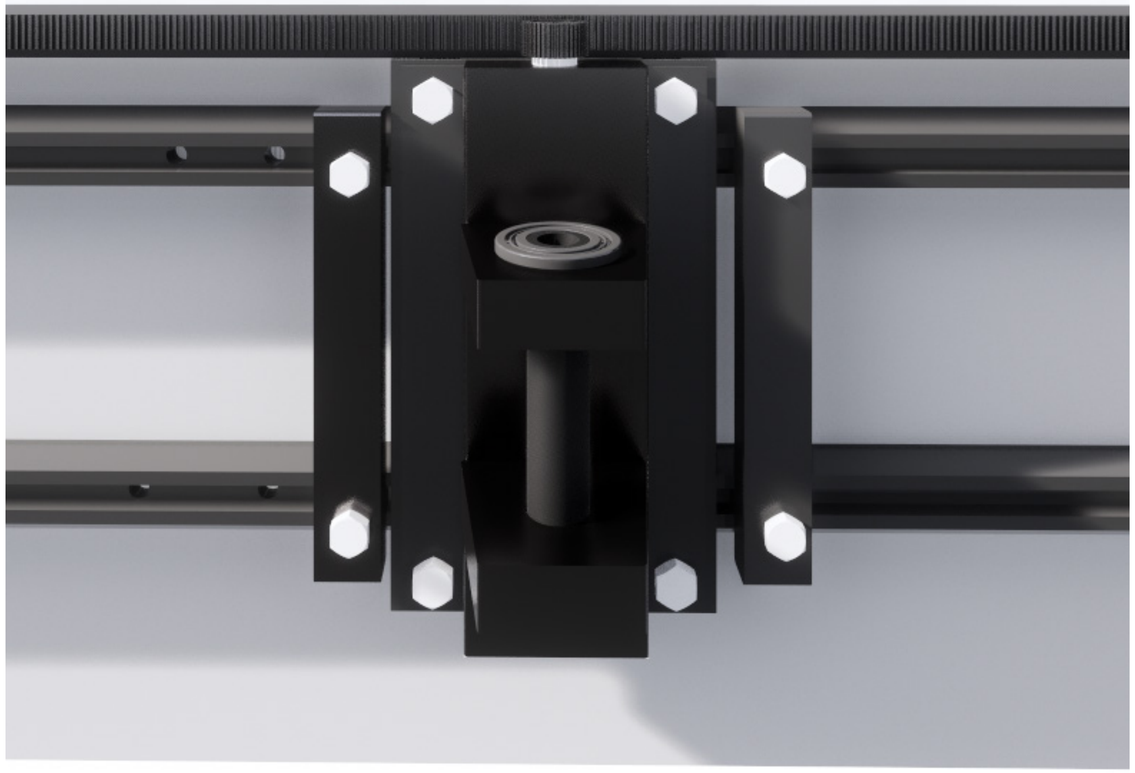
Torsional displacement support

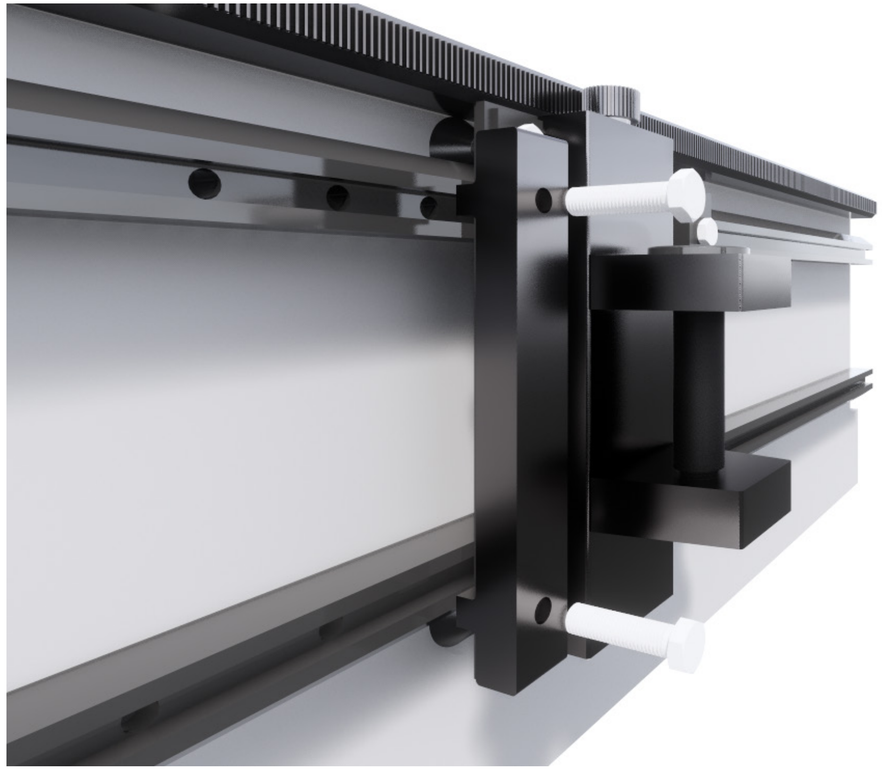
Extension abilities



4 supports, extent middle rails

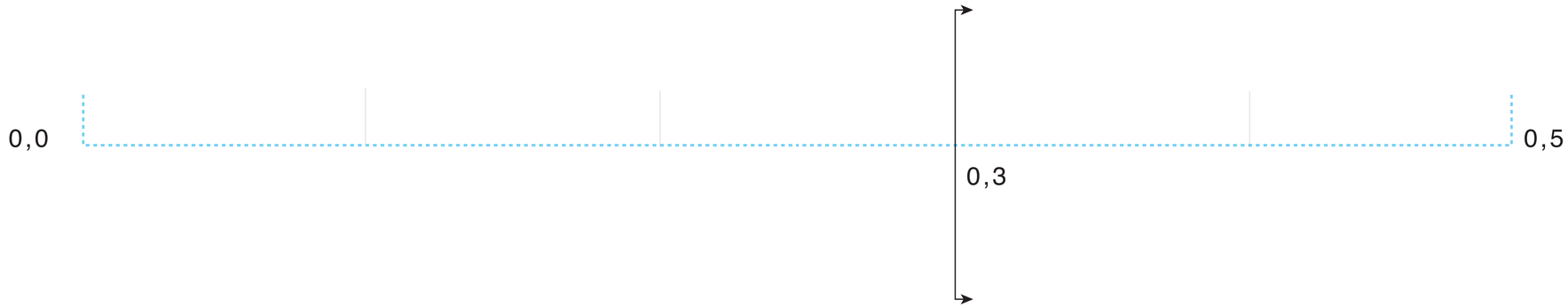
Interlocking gliding mounts





Material parameters

2 Poisson’s ratio > 0.3

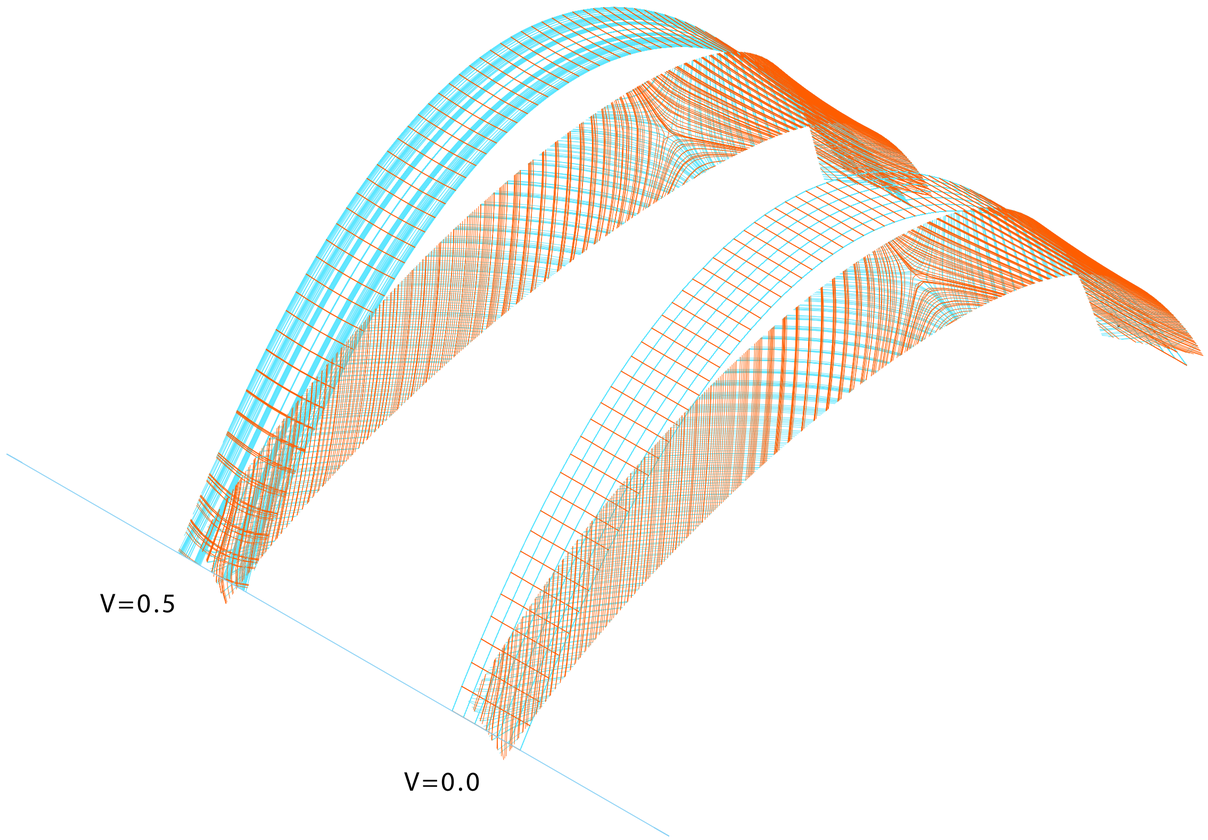


Leading parameter in bending and torsional deformation

$$\nu = -\frac{\epsilon xx}{\epsilon yy}$$

v Poisson's ratio spectrum

Influence Poisson’s ratio torsion geometry



Influence Poisson’s ratio bending geometry