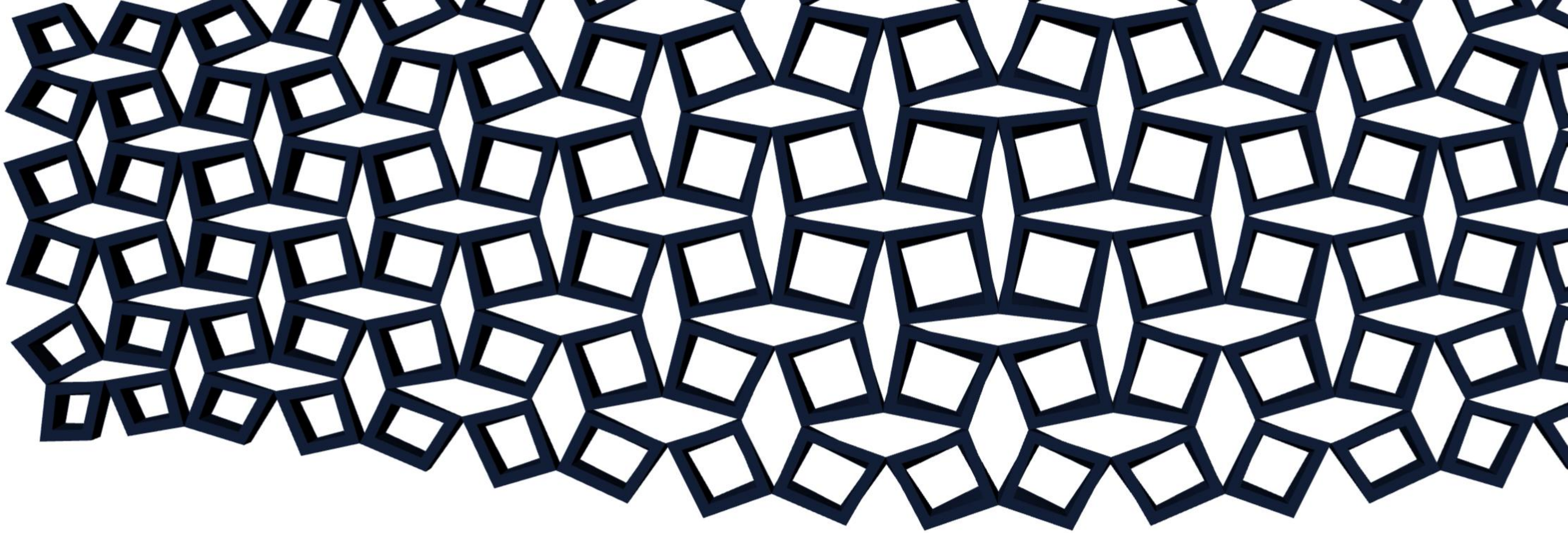


PROGRAMMABLE DEPLOYABLE STRUCTURES

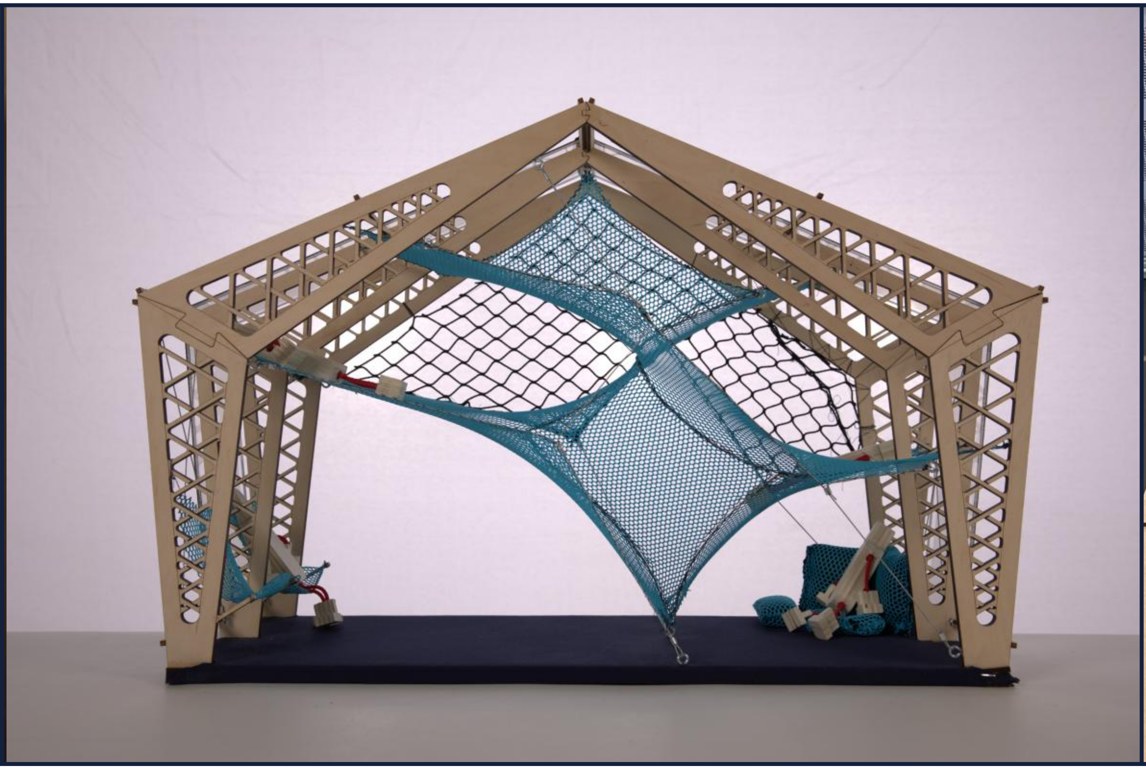
Exploring the Potential of Mechanical Metamaterials and Large-Scale 3D Printing for Fast Production and Assembly of Deployable Structures.

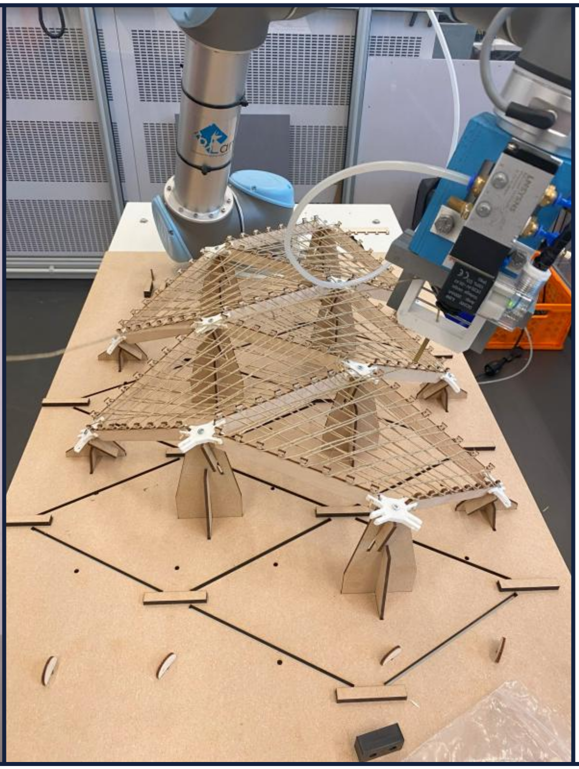
Pepijn Feijen

Thesis Project

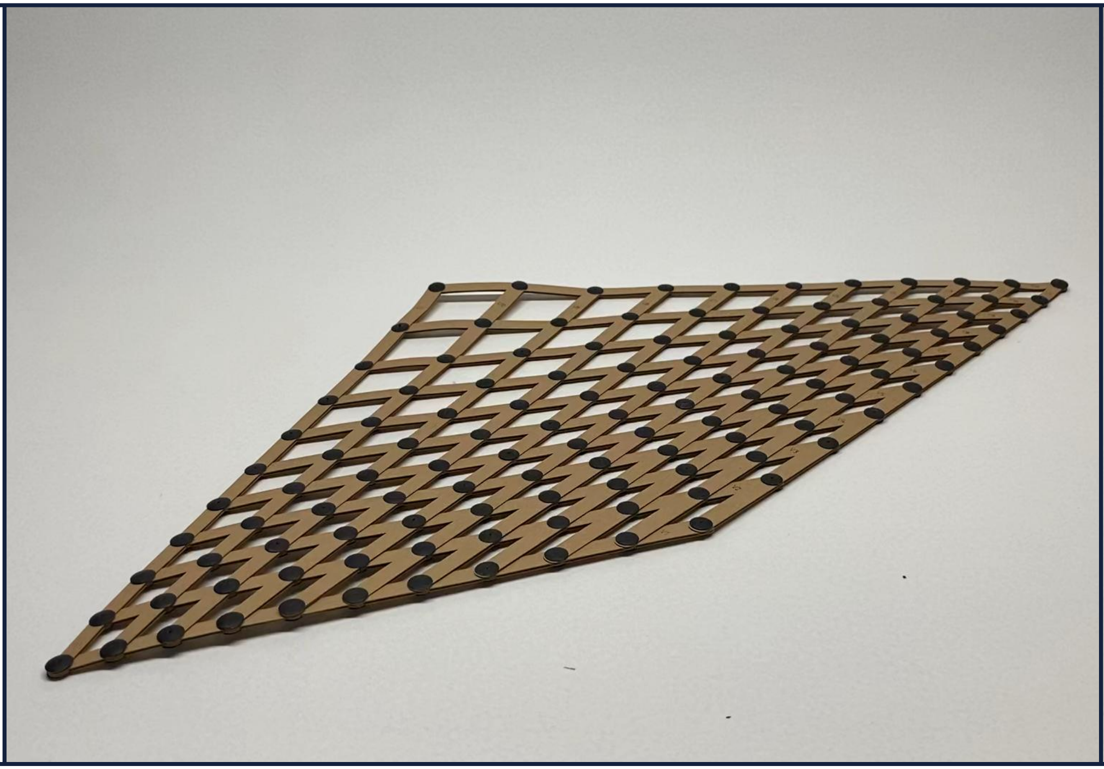
Building Technology

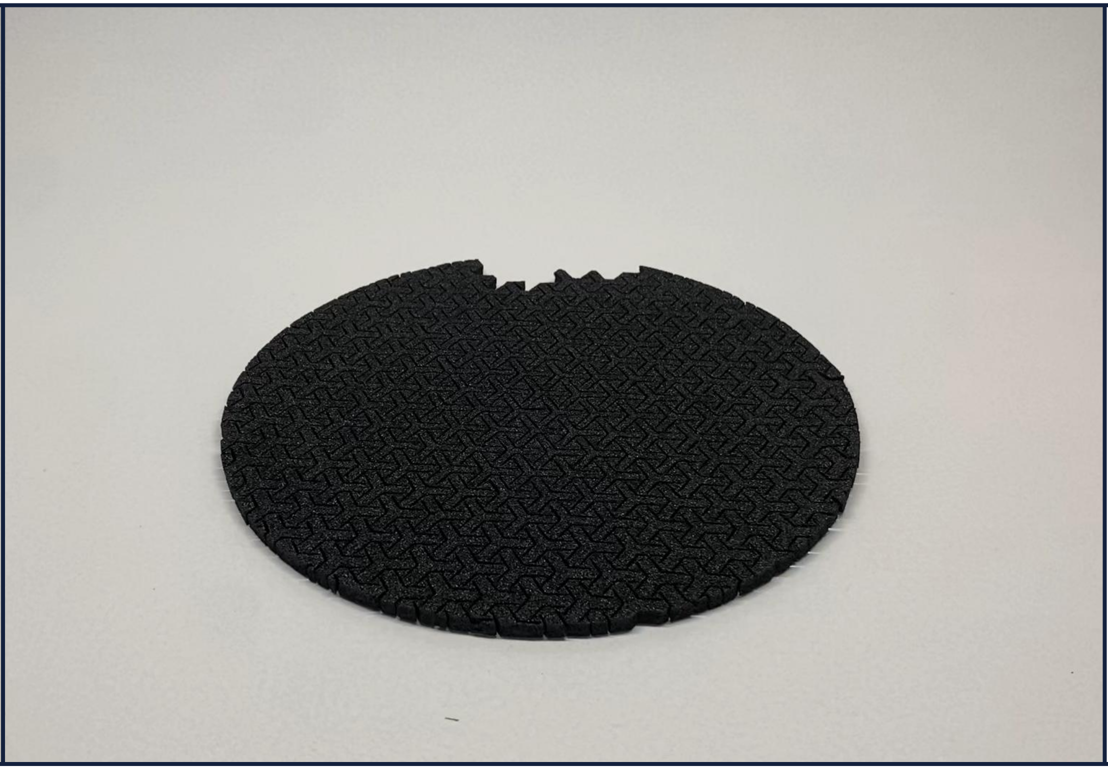
PREVIOUS PROJECTS





PREVIOUS PROJECTS





METAMATERIAL

MECHANICAL METAMATERIAL

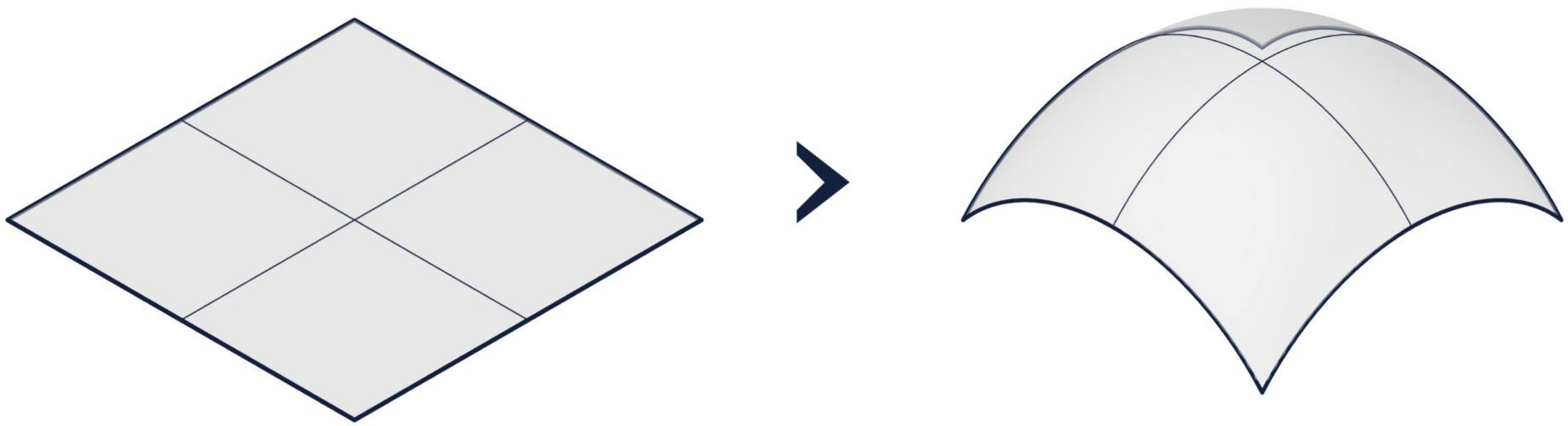
PROGRAMMABLE METAMATERIAL

ADAPTIVE STRUCTURES

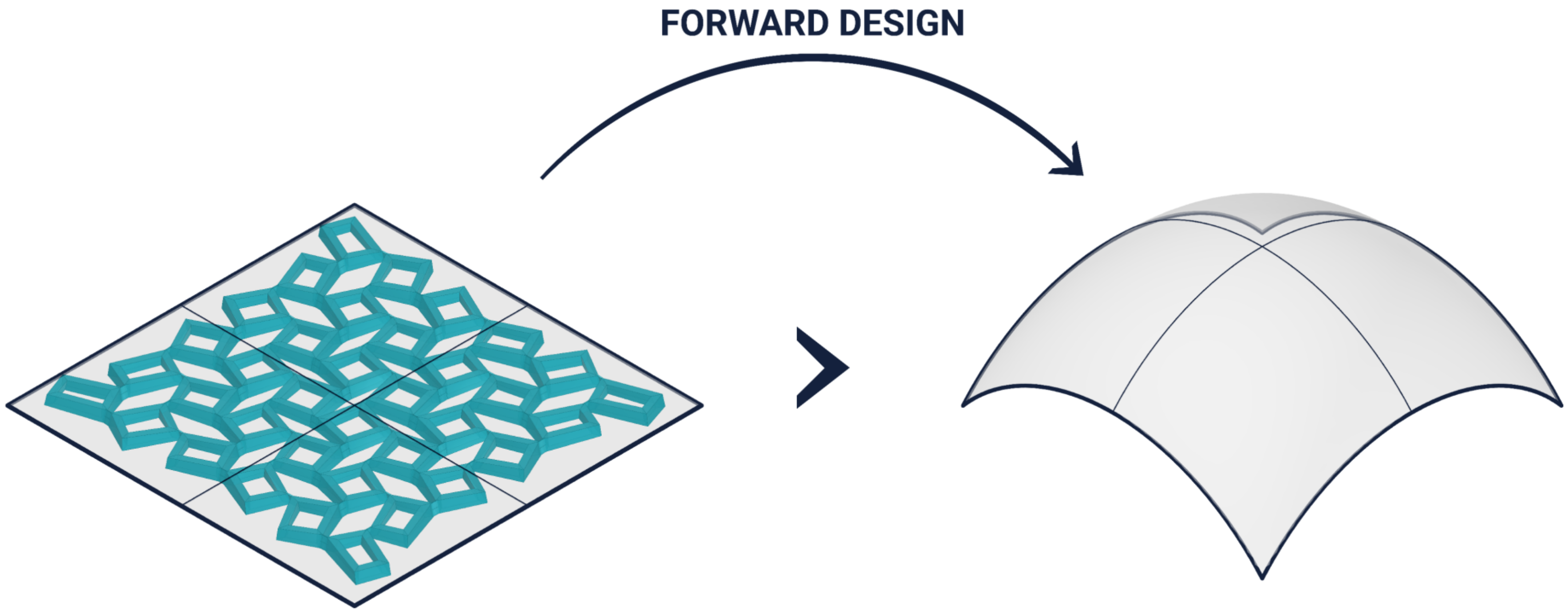
ENGINEERING CHALLENGE

INTERACTIVE

INVERSE DESIGN PROBLEM



INVERSE DESIGN PROBLEM



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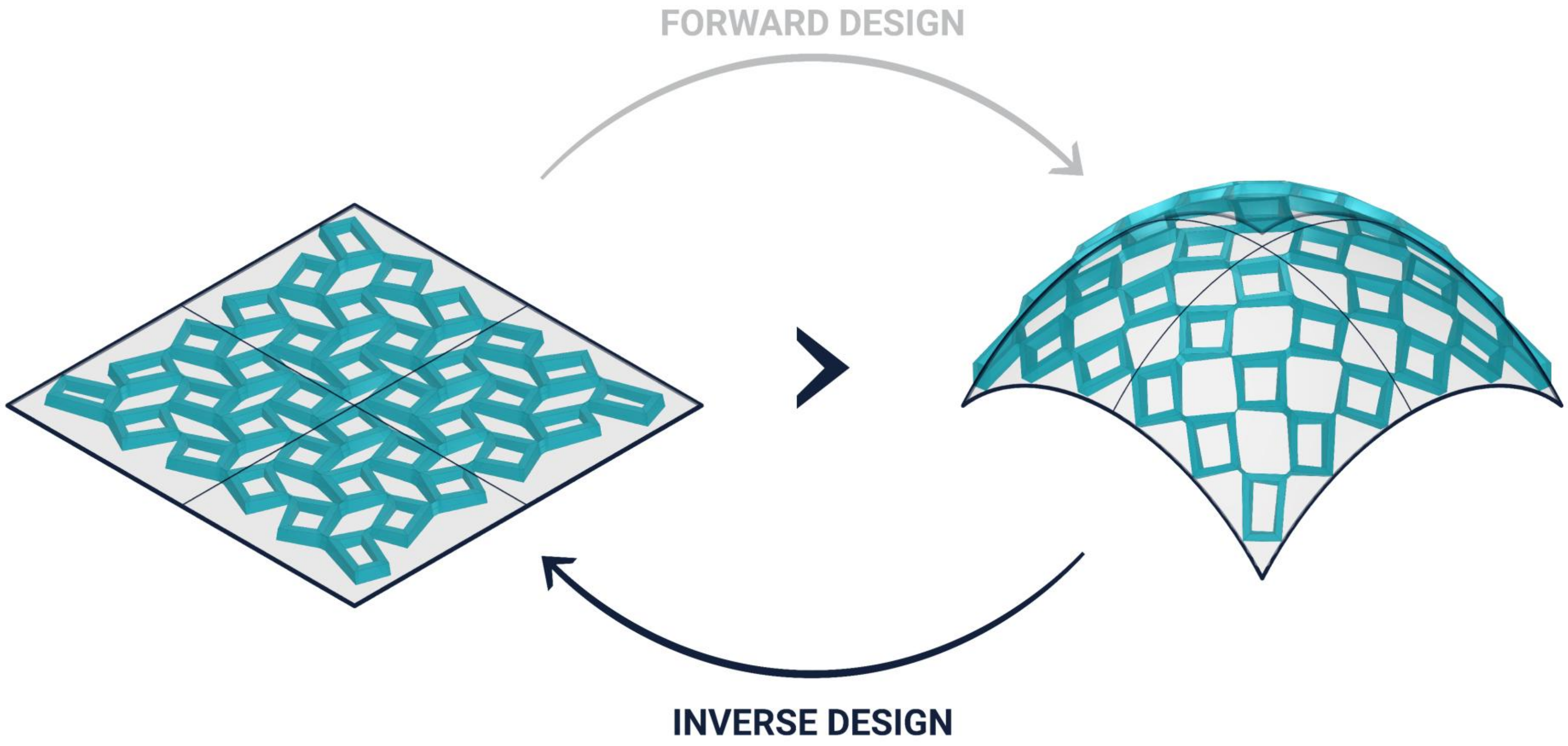
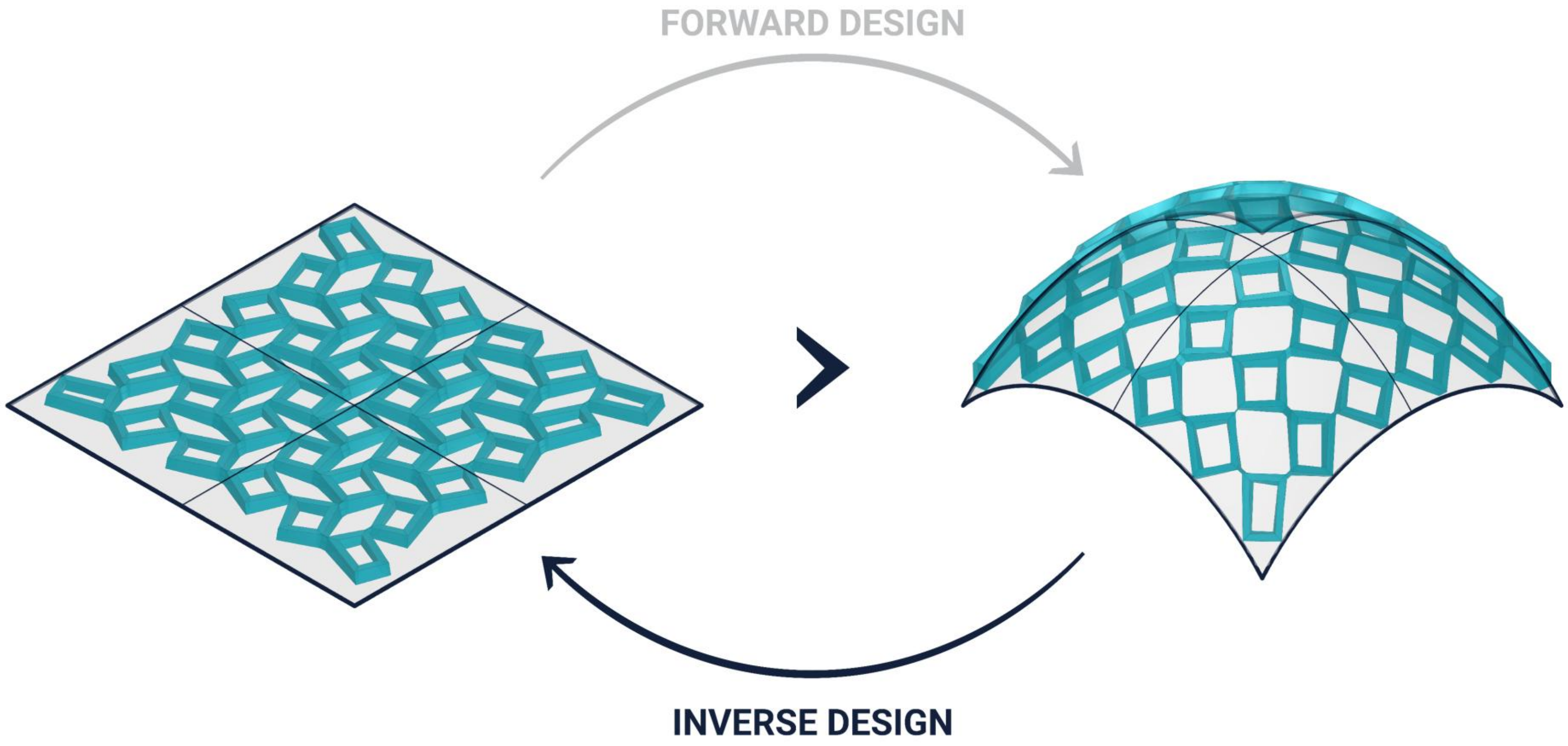
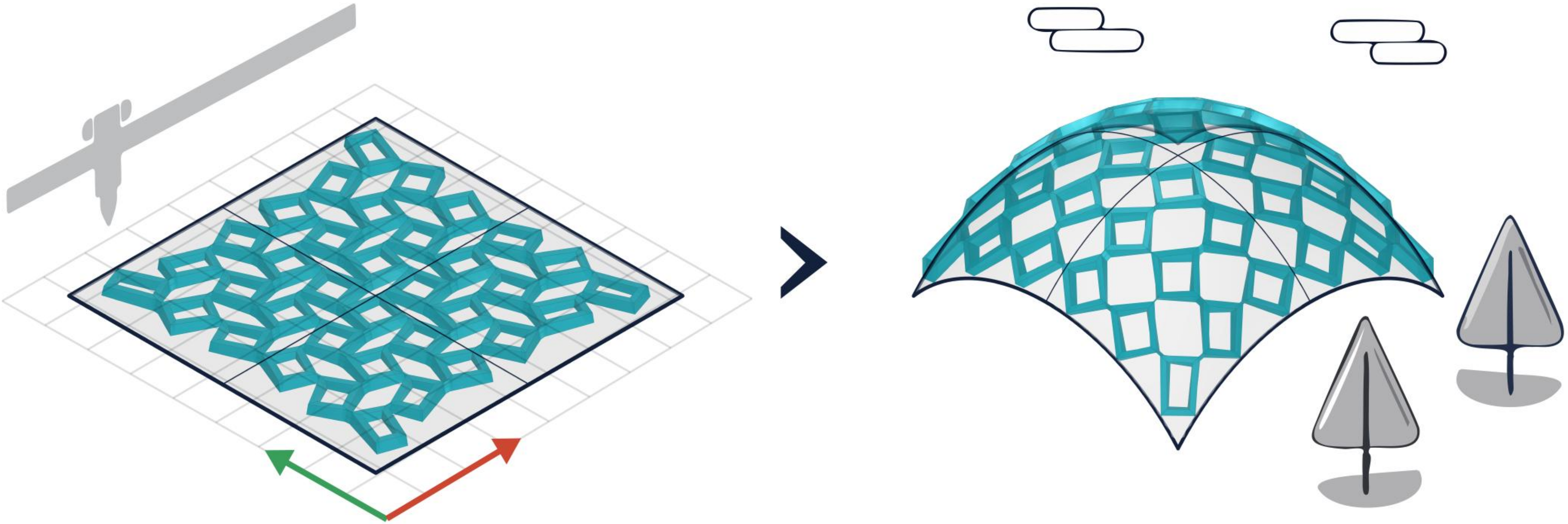


INVERSE DESIGN PROBLEM



PREDICTIVE DESIGN TOOL

INVERSE DESIGN PROBLEM



MAIN RESEARCH QUESTION

- **How can the principles of mechanical-metamaterial be scaled up to design deployable structures?**

SUB-QUESTIONS

- **How can a computational tool be developed to support the design of adaptive deployable structures?**

SUB-QUESTIONS

- How can a computational tool be developed to support the design of adaptive deployable structures?
- **To what extent can programmable mechanical metamaterials be scaled to enable the creation of large, safe, and stable structures?**

SUB-QUESTIONS

- How can a computational tool be developed to support the design of adaptive deployable structures?
- To what extent can programmable mechanical metamaterials be scaled to enable the creation of large, safe, and stable structures?
- **In what ways can the developed computational tool be applied to design a functional, deployable shelter for events?**

PROCESS

- Approach
- Kinematic system

FORM-FINDING

- Development of the tool
- Computational part

LARGE SCALE PRINTING

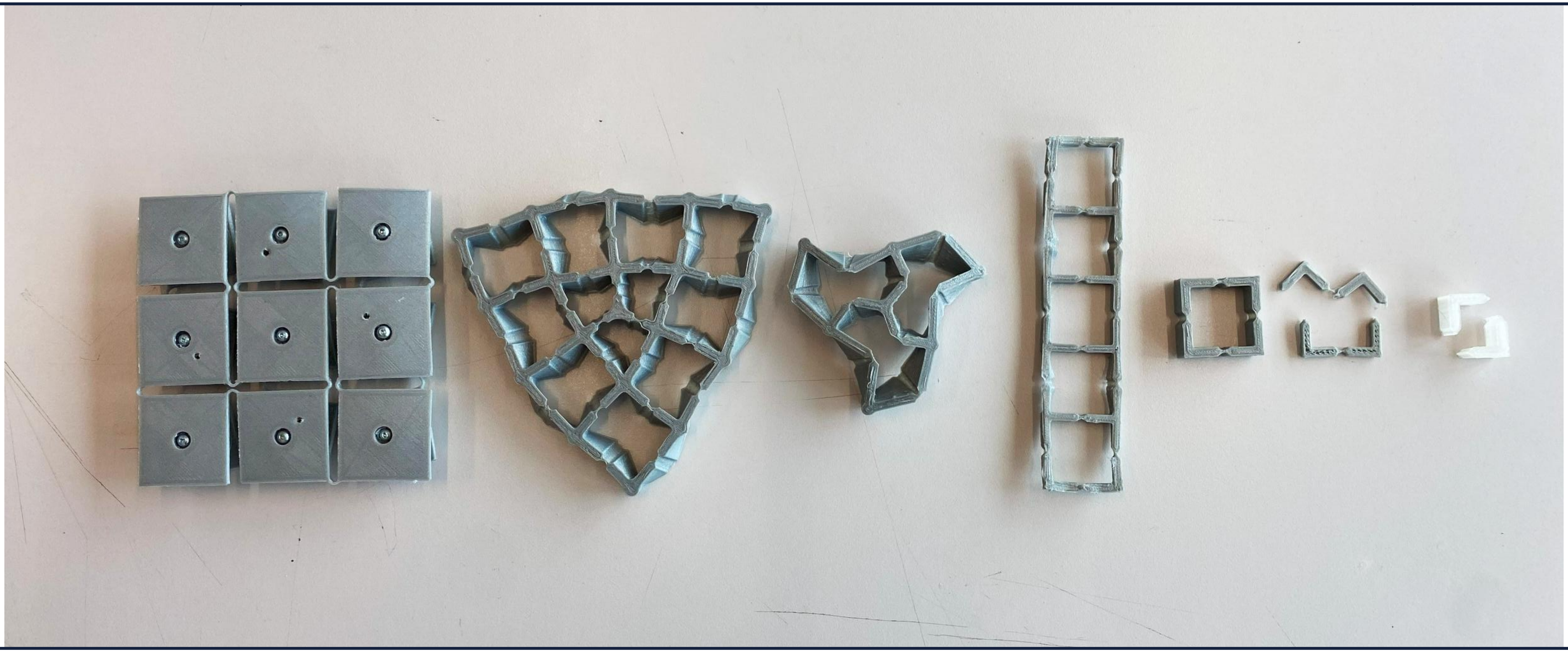
- Challenges manufacturing Scaling up

CASESTUDY

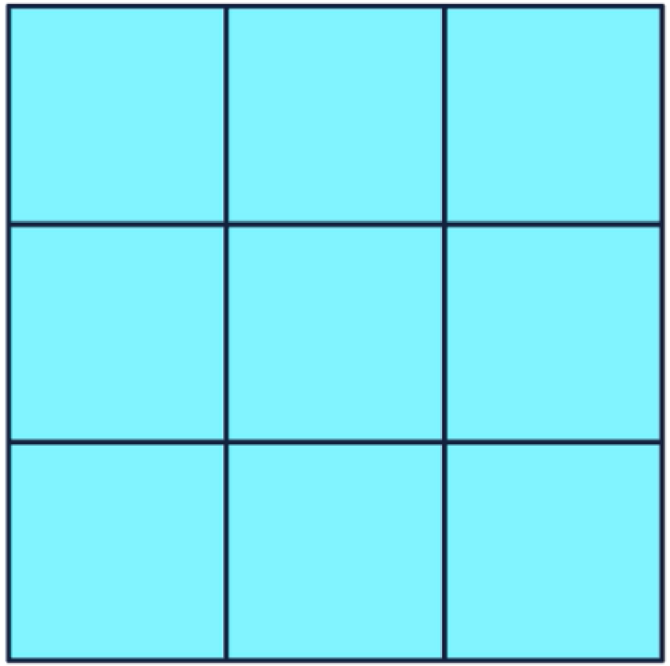
- Application
- Structural analysis

PROCESS

EXPLORATION PHASE

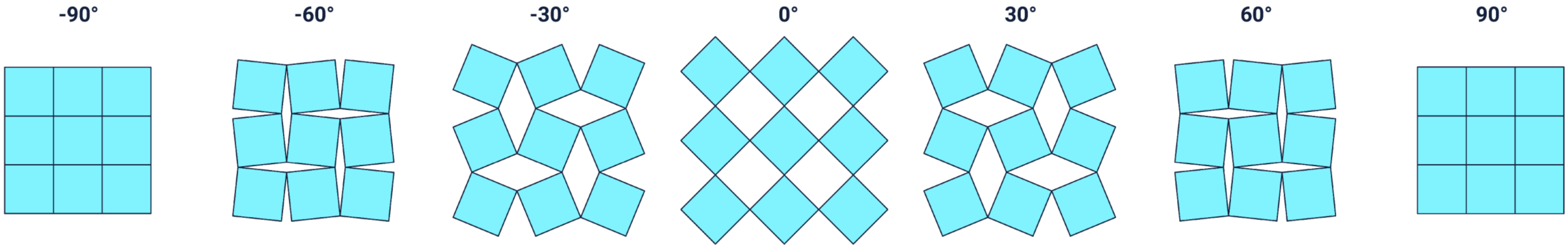


ROTATING POLYGON STRUCTURE

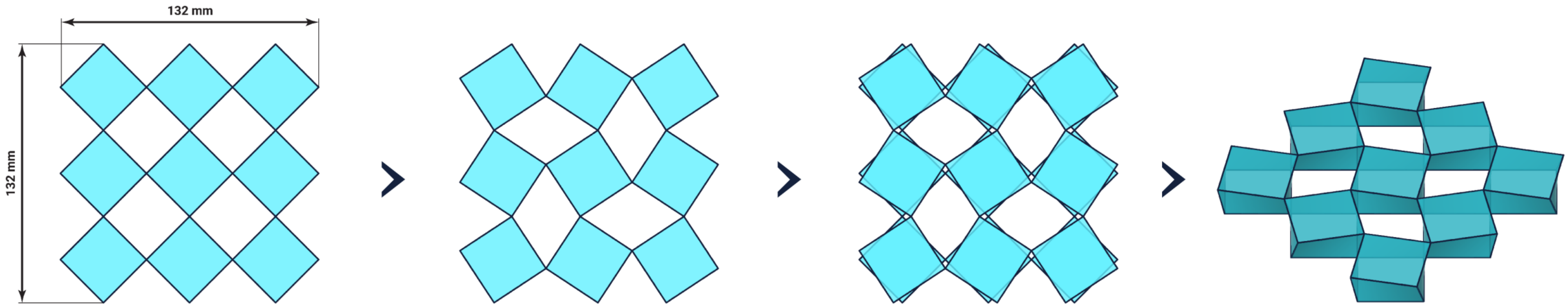


DoD: -90

DEGREE OF DEPLOYMENT:



KINEMATIC SYSTEM



Rotating polygon structure with DoD: 80°

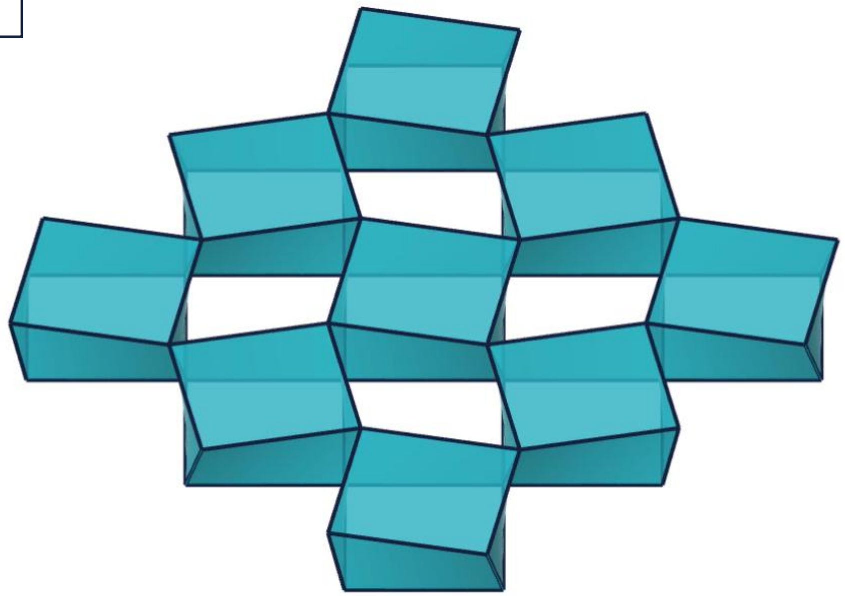
Rotating polygon structure with DoD: 30°

Two structure are stacked on top of each other with distance = 12 mm

Two layers are lofted together, locking them in rotation

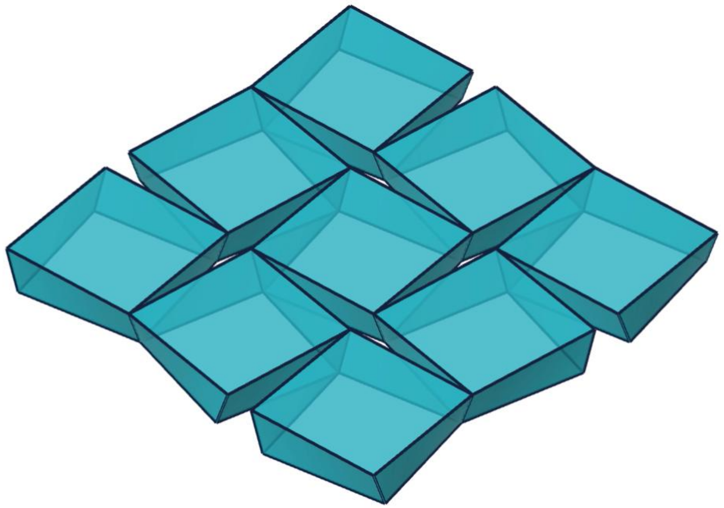
KINEMATIC SYSTEM

DoD top layer:	**15°**
DoD bottom layer:	**0°**
Distance between Layers:	**12 mm**
DoD structure:	**0° - 32 °**



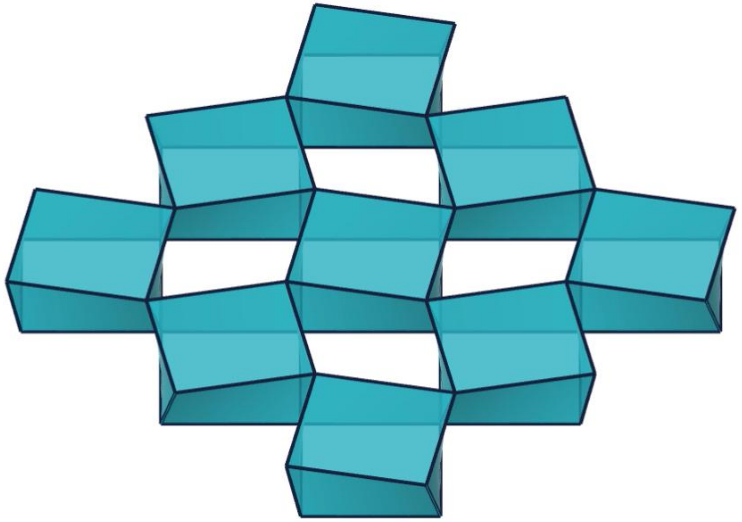
KINEMATIC SYSTEM

DoD top layer:	**60°**
DoD bottom layer:	**45°**
Distance between Layers:	**12 mm**
DoD structure:	**0° - 39 °**



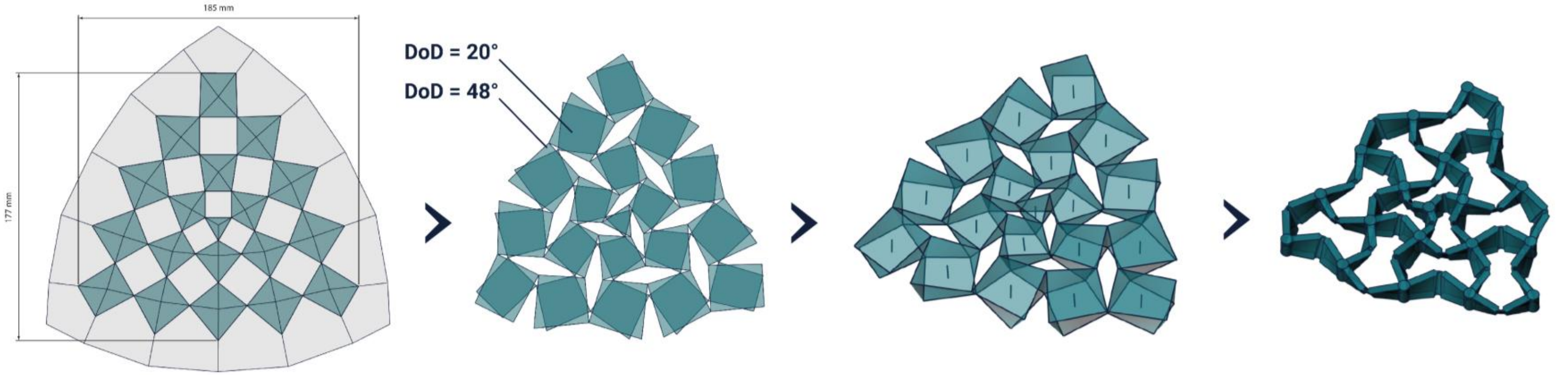
EXPANDING STRUCTURE

DoD top layer:	**15°**
DoD bottom layer:	**0°**
Distance between Layers:	**12 mm**
DoD structure:	**0° - 32 °**



CONTRACTING STRUCTURE

PROCESS MODEL 4



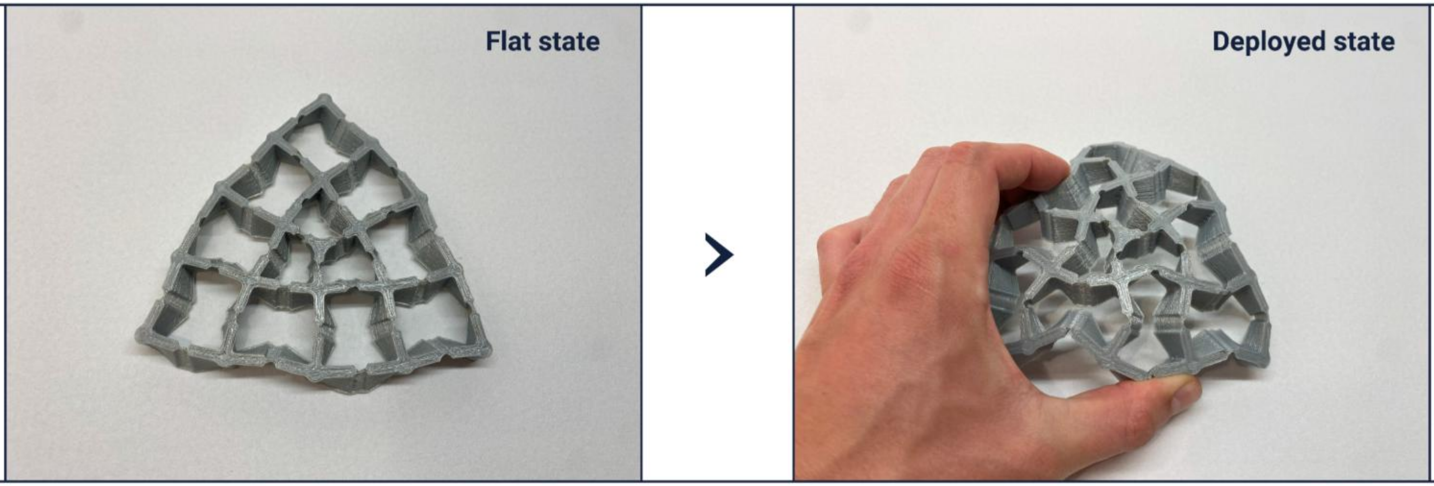
Input mesh with
original configuration
DoD = 0°

Two layered latices
DoD = 20° at bottom
DoD = 48° at top

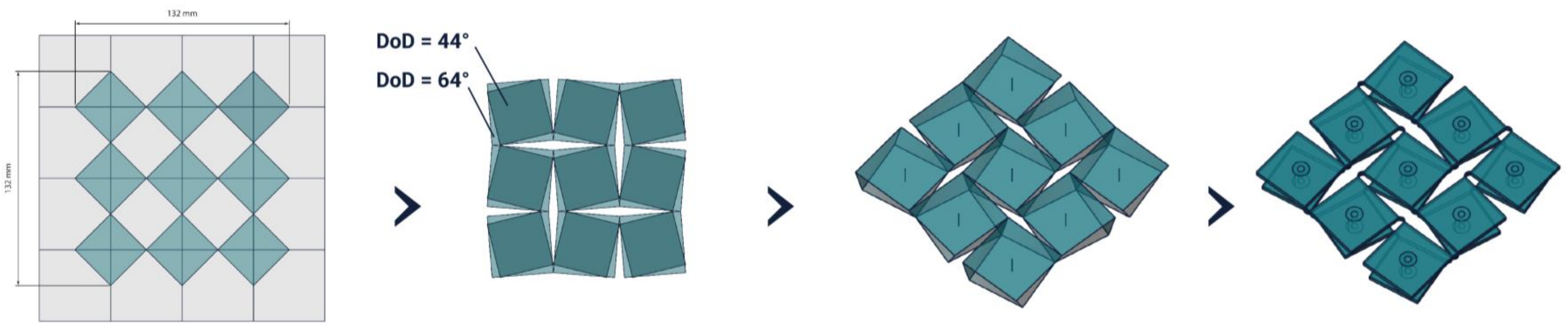
Two layers are lofted
together, locking them
in rotation

materialization
hinge thickness: 0.7 mm
rigid element tickness: 4,2 mm
hight: 13 mm

PHYSCAL MODEL 4



PROCESS MODEL 5



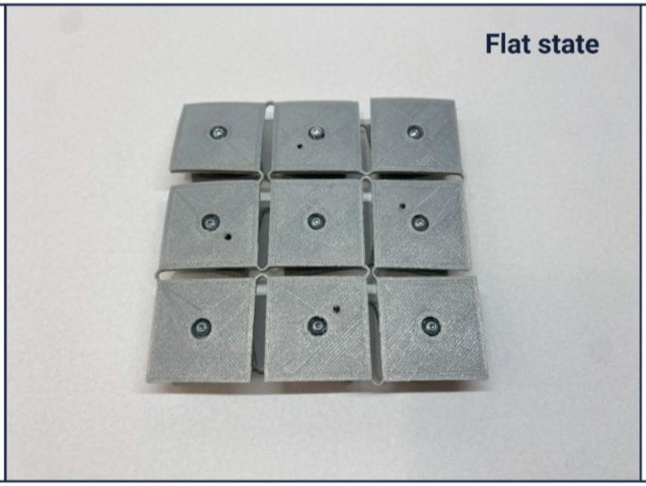
Input mesh with original configuration DoD = 0°

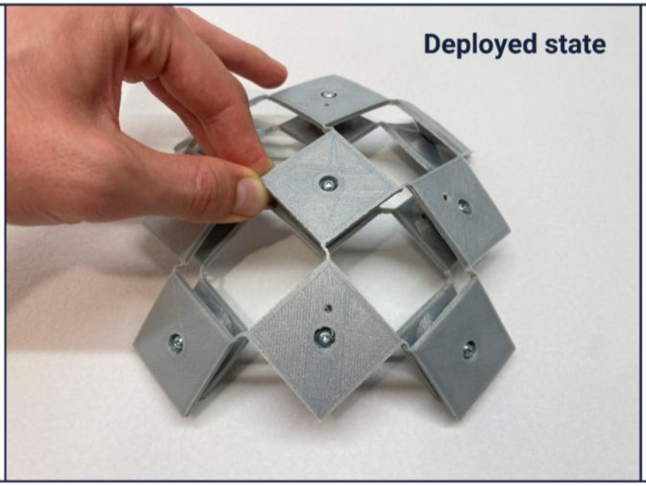
Two layered latices DoD = 44° at bottom DoD = 64° at top

In this model the panels are not locked and free to rotated

materialization
hinge thickness: 0.7 mm
rigid panels tickness: 3 mm
hight: 13 mm

PHYSCAL MODEL 5



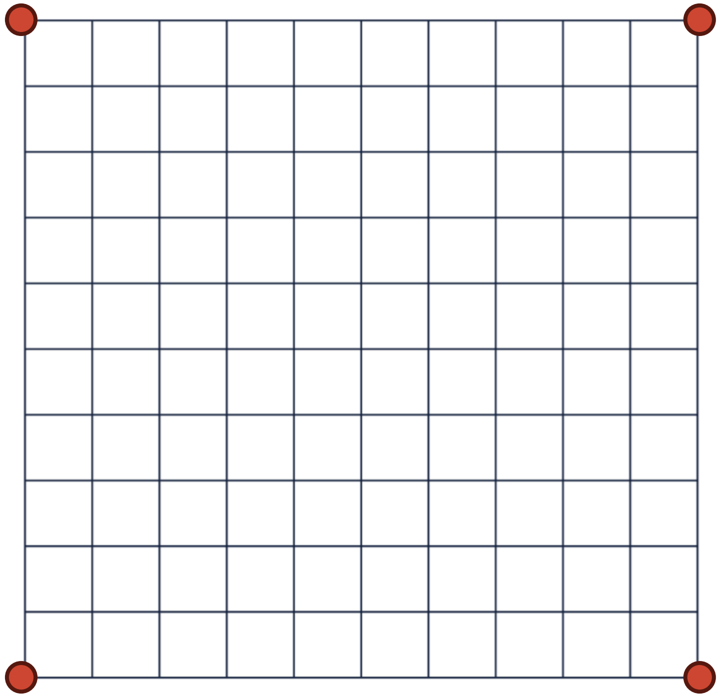


FORM-FINDING

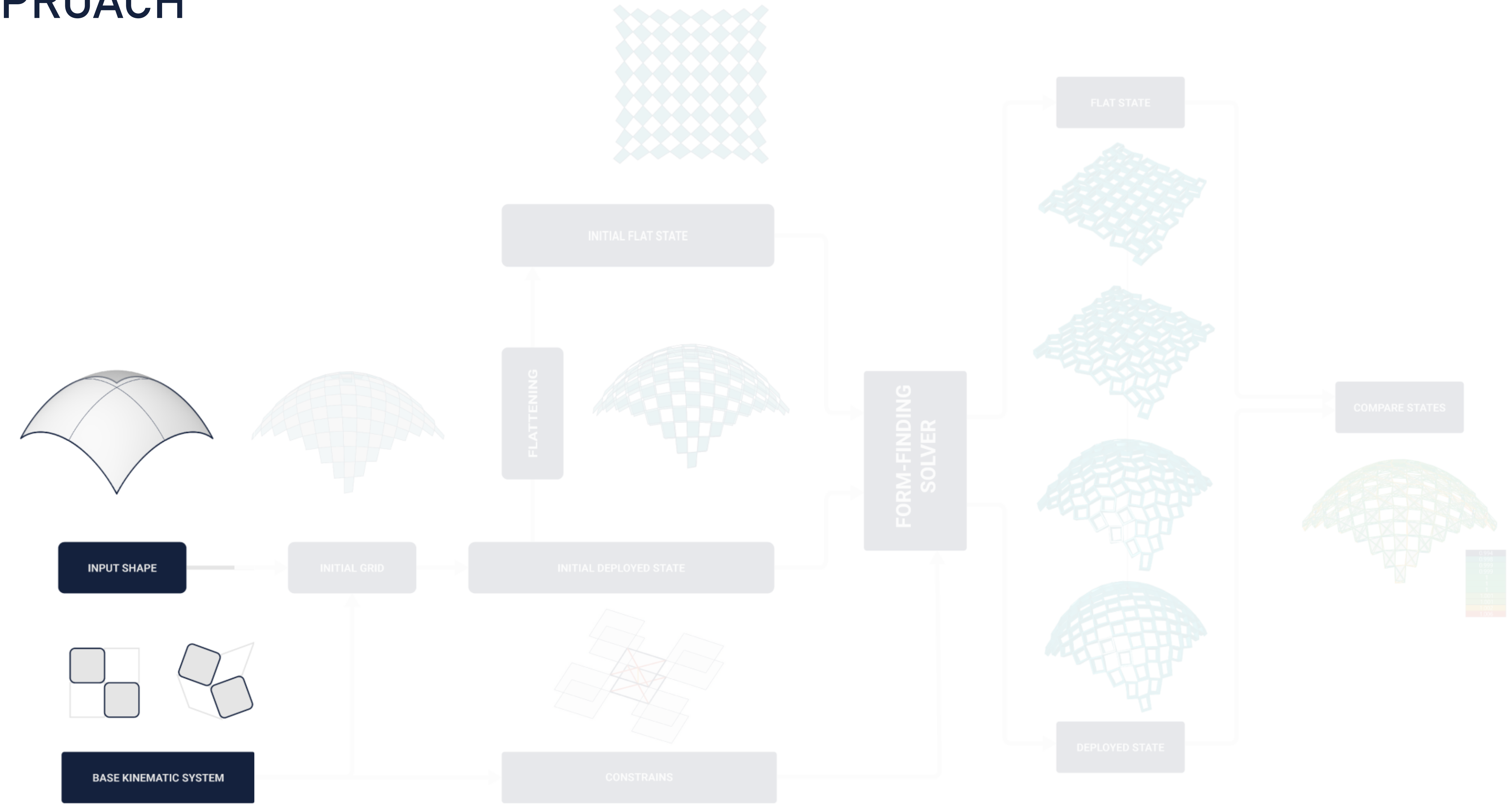
DYNAMIC RELAXATION

FORM-FINDING

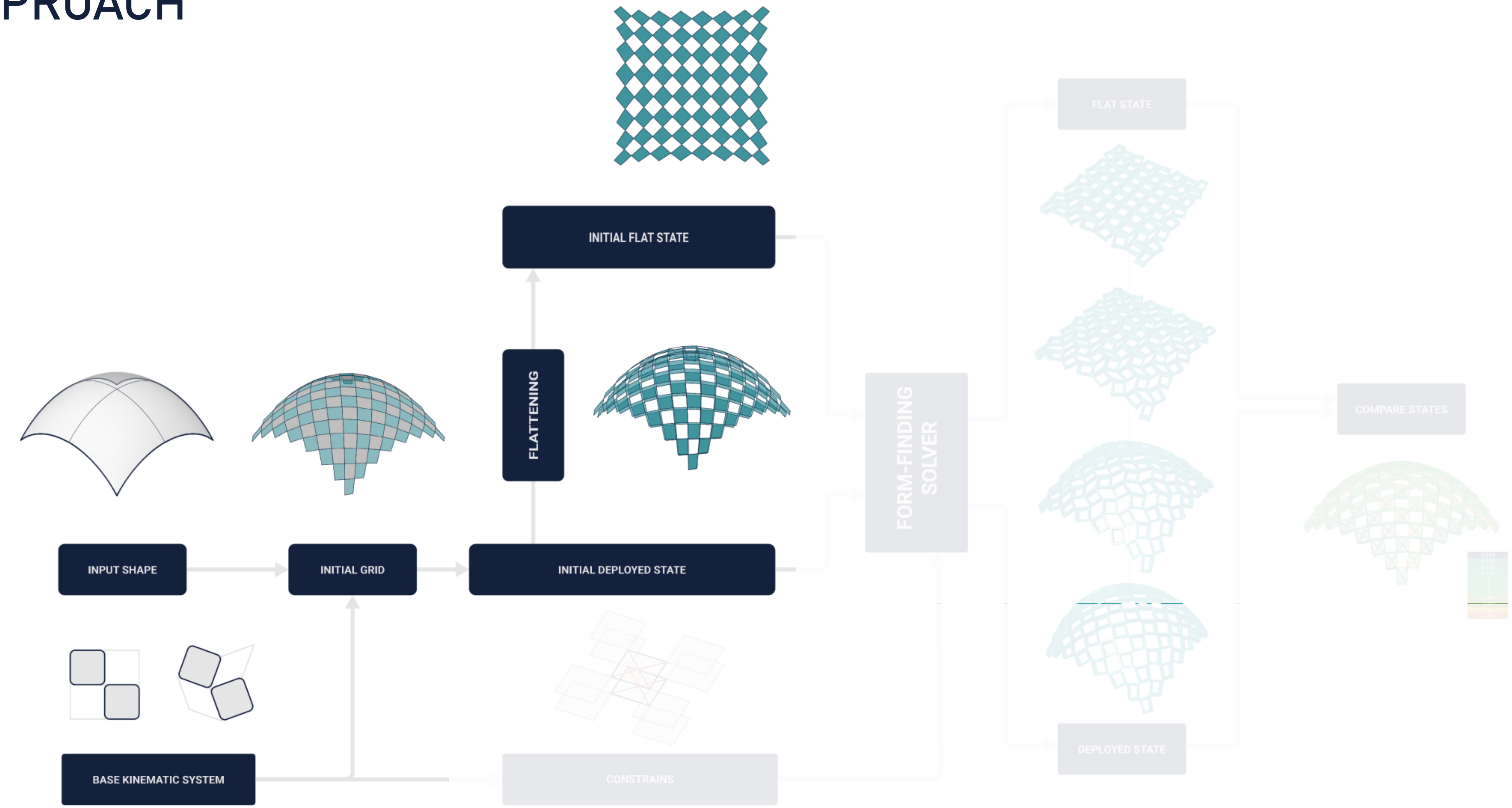
CONSTRAIN BASED SOLVER



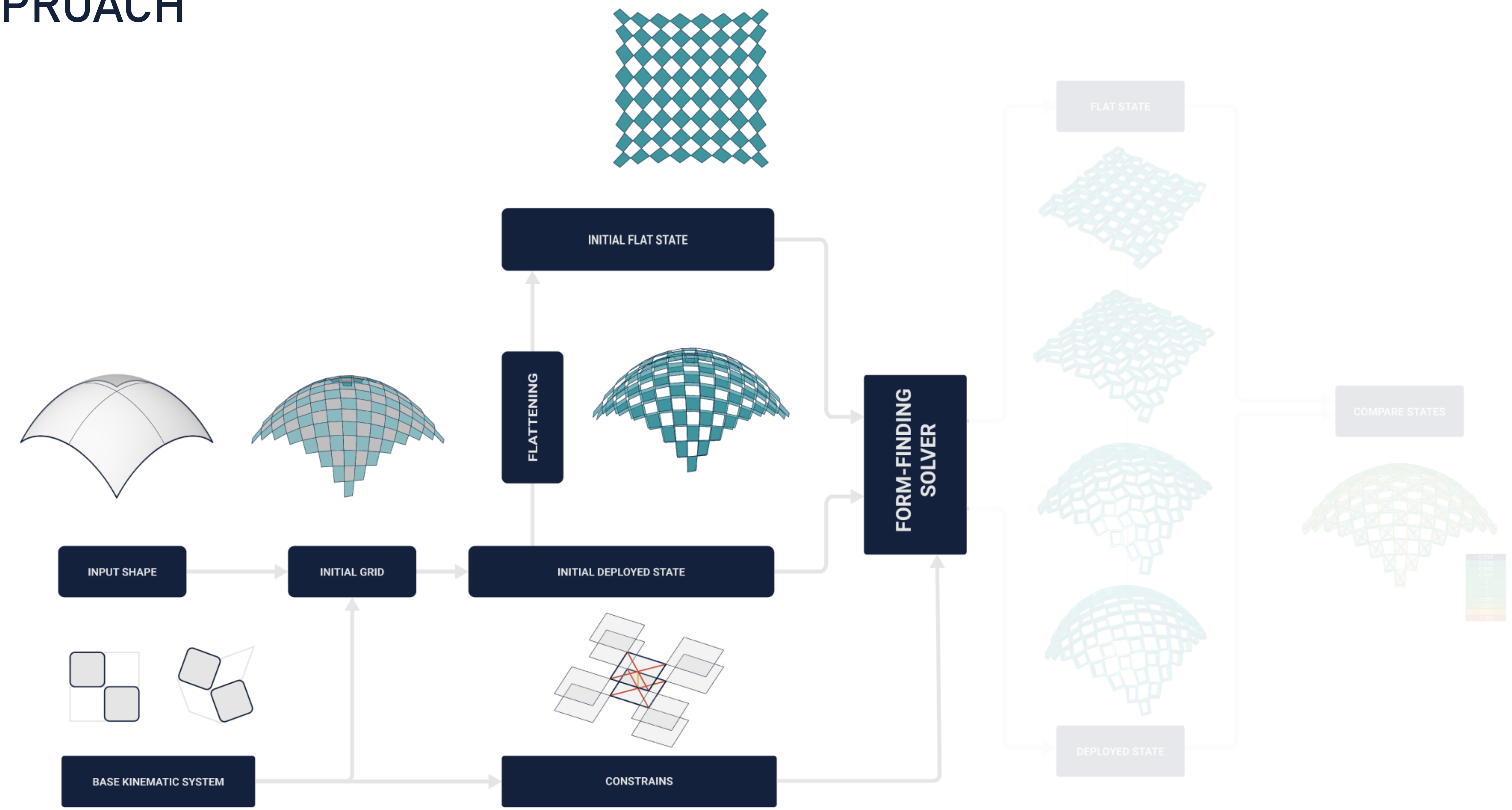
APPROACH


FLAT STATE
INITIAL FLAT STATE
FLATTENING
FORM-FINDING SOLVER
COMPARE STATES
INPUT SHAPE
INITIAL GRID
INITIAL DEPLOYED STATE
BASE KINEMATIC SYSTEM
CONSTRAINS
DEPLOYED STATE

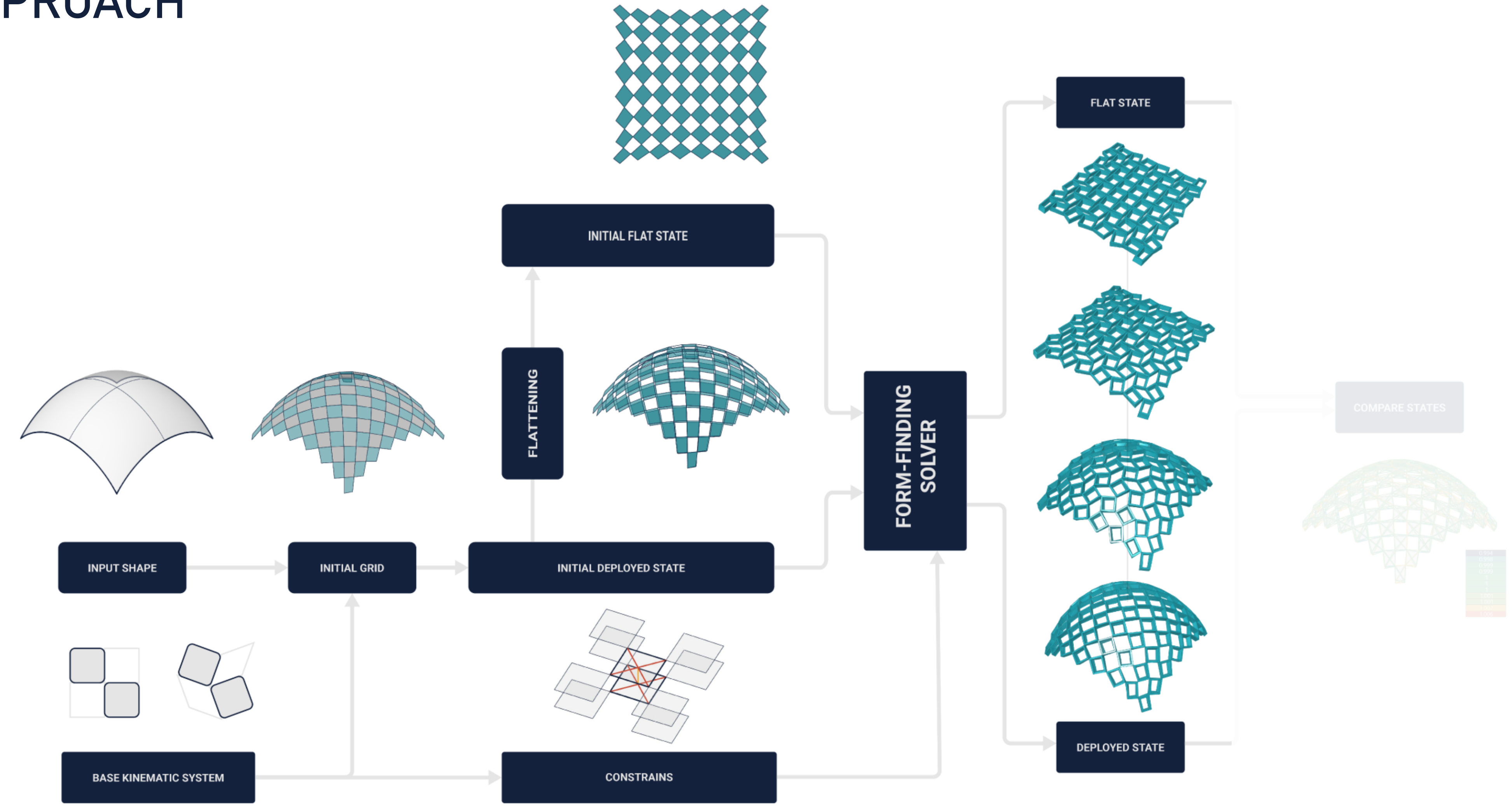
APPROACH


INITIAL FLAT STATE
FLATTENING
INPUT SHAPE
INITIAL GRID
INITIAL DEPLOYED STATE
BASE KINEMATIC SYSTEM
CONSTRAINS
FORM-FINDING SOLVER
FLAT STATE
DEPLOYED STATE
COMPARE STATES

APPROACH


INITIAL FLAT STATE
FLATTENING
INPUT SHAPE
INITIAL GRID
INITIAL DEPLOYED STATE
BASE KINEMATIC SYSTEM
CONSTRAINS
FORM-FINDING SOLVER
FLAT STATE
DEPLOYED STATE
COMPARE STATES

APPROACH


INITIAL FLAT STATE
FLATTENING
INPUT SHAPE
INITIAL GRID
INITIAL DEPLOYED STATE
BASE KINEMATIC SYSTEM
CONSTRAINS
FORM-FINDING SOLVER
FLAT STATE
DEPLOYED STATE
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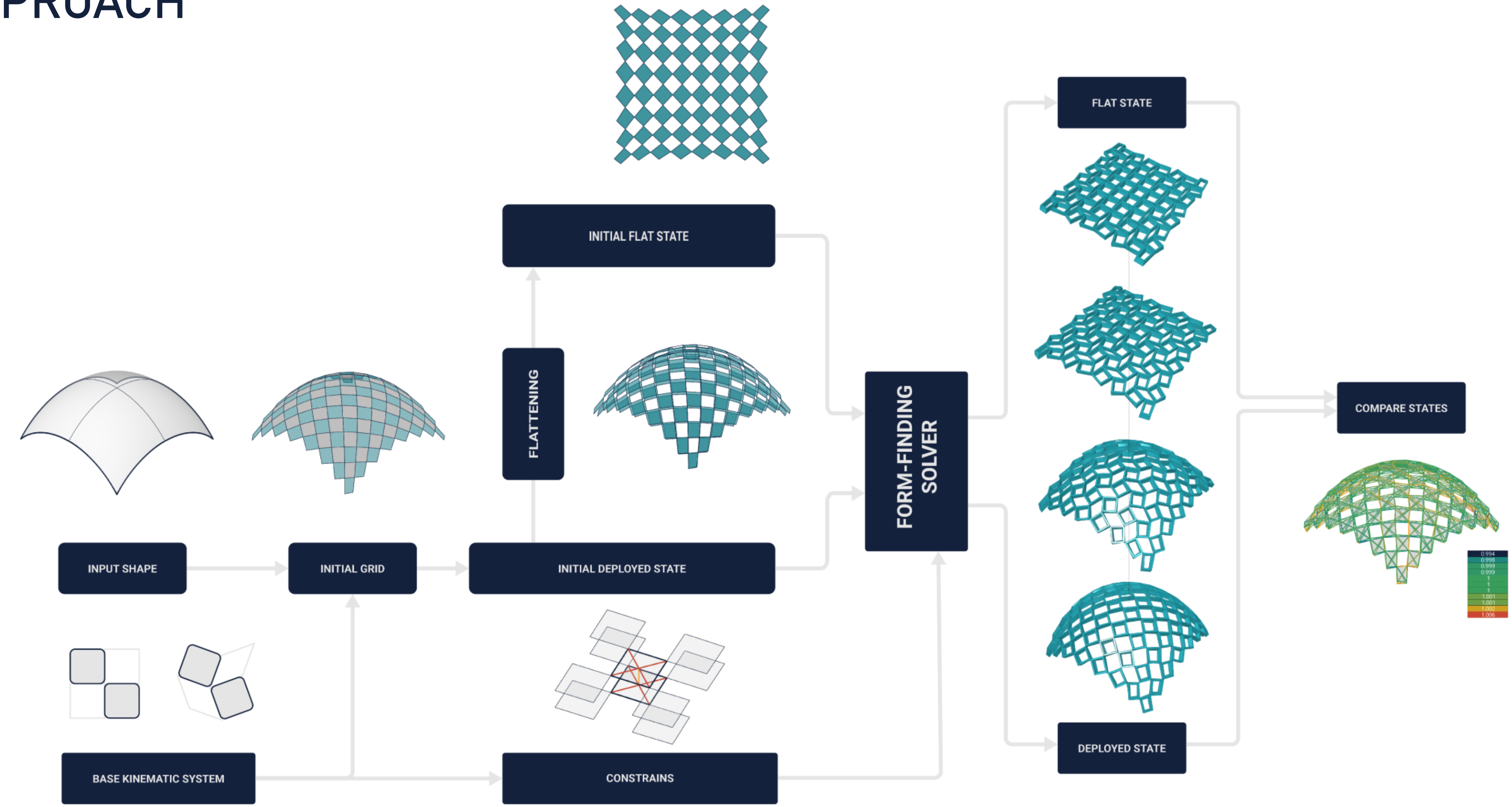
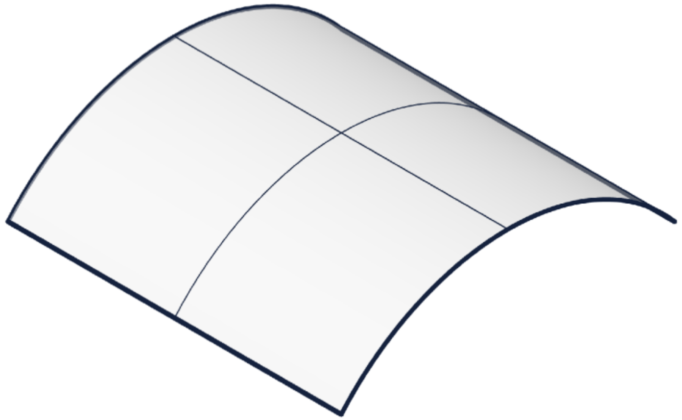
APPROACH


INITIAL FLAT STATE
FLATTENING
FLAT STATE
FORM-FINDING SOLVER
COMPARE STATES
INPUT SHAPE
INITIAL GRID
INITIAL DEPLOYED STATE
DEPLOYED STATE
BASE KINEMATIC SYSTEM
CONSTRAINS

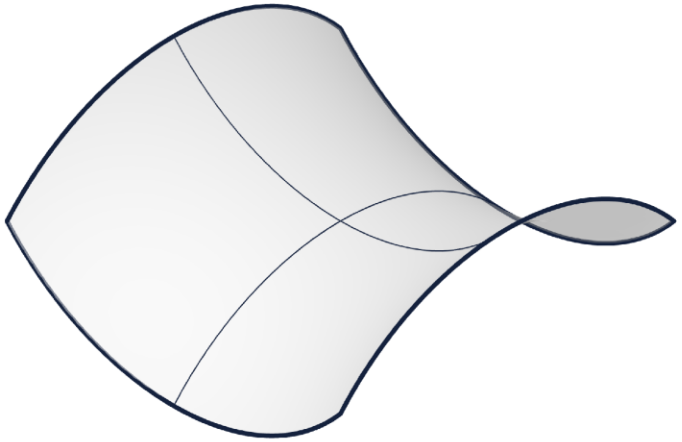
FORM-FINDING

TEST SHAPES



MONOCLASTIC

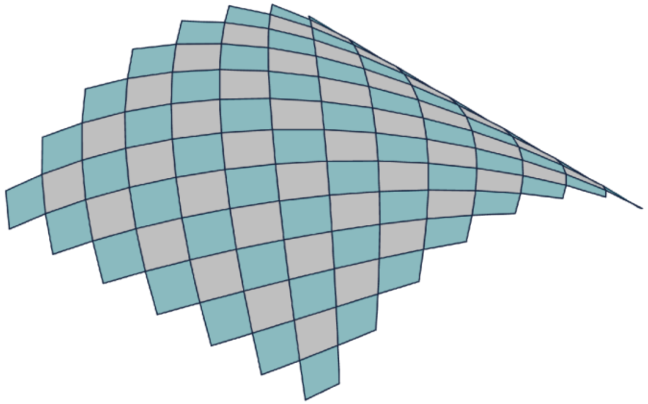
SYNCLASTIC

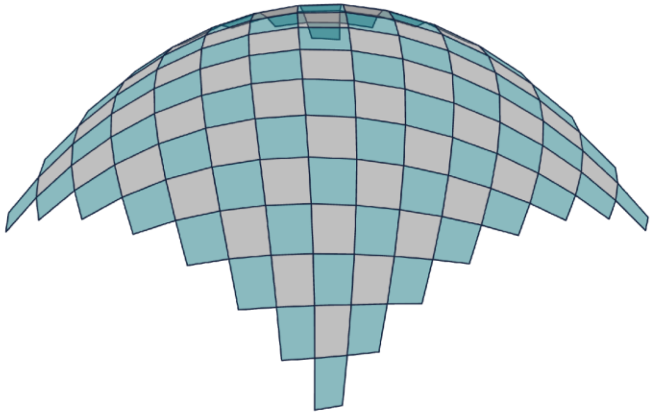


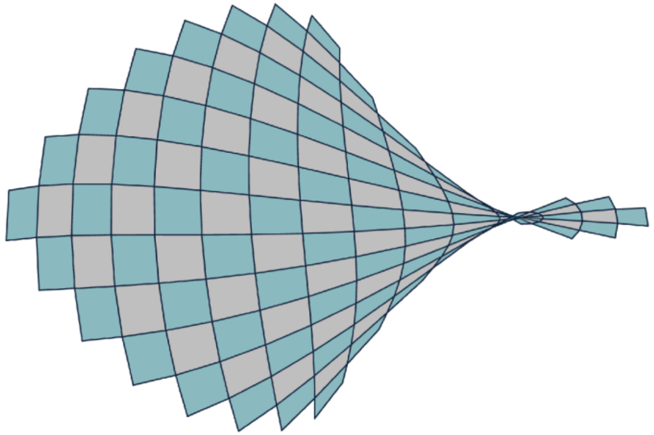
ANTICLASTIC

INITIAL GRID

PANELS NEGATIVE SPACE



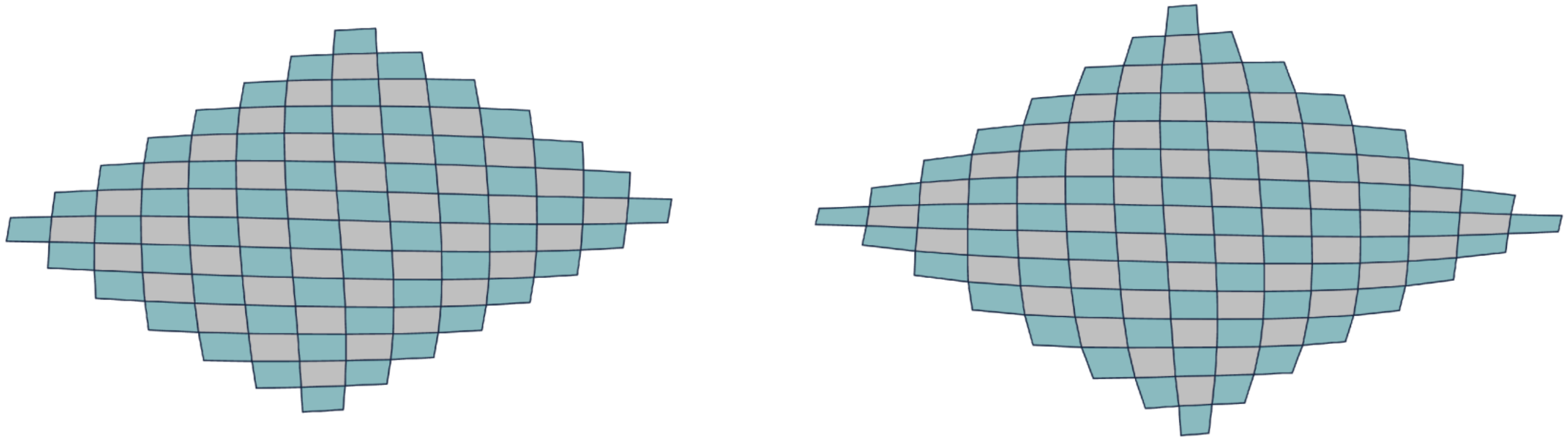




MONOCLASTIC SYNCLASTIC ANTICLASTIC

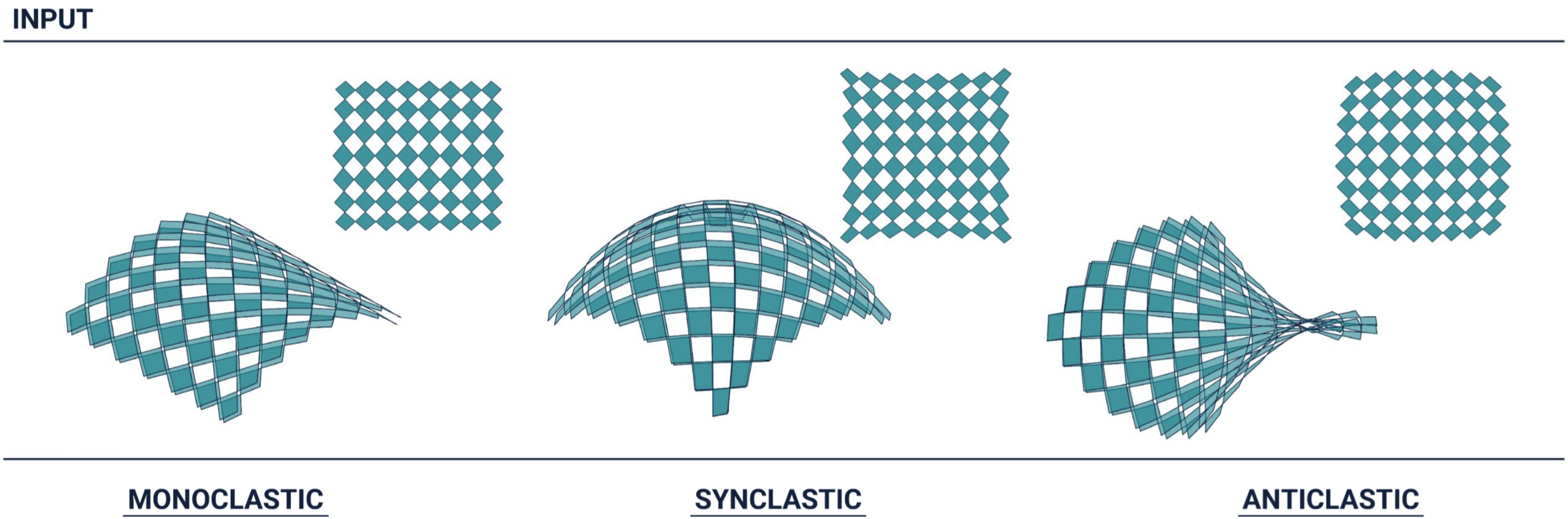
FLATTEN GRID

PANELS NEGATIVE SPACE



MONOCLASTIC **SYNCLASTIC** **ANTICLASTIC**

Form-Finding

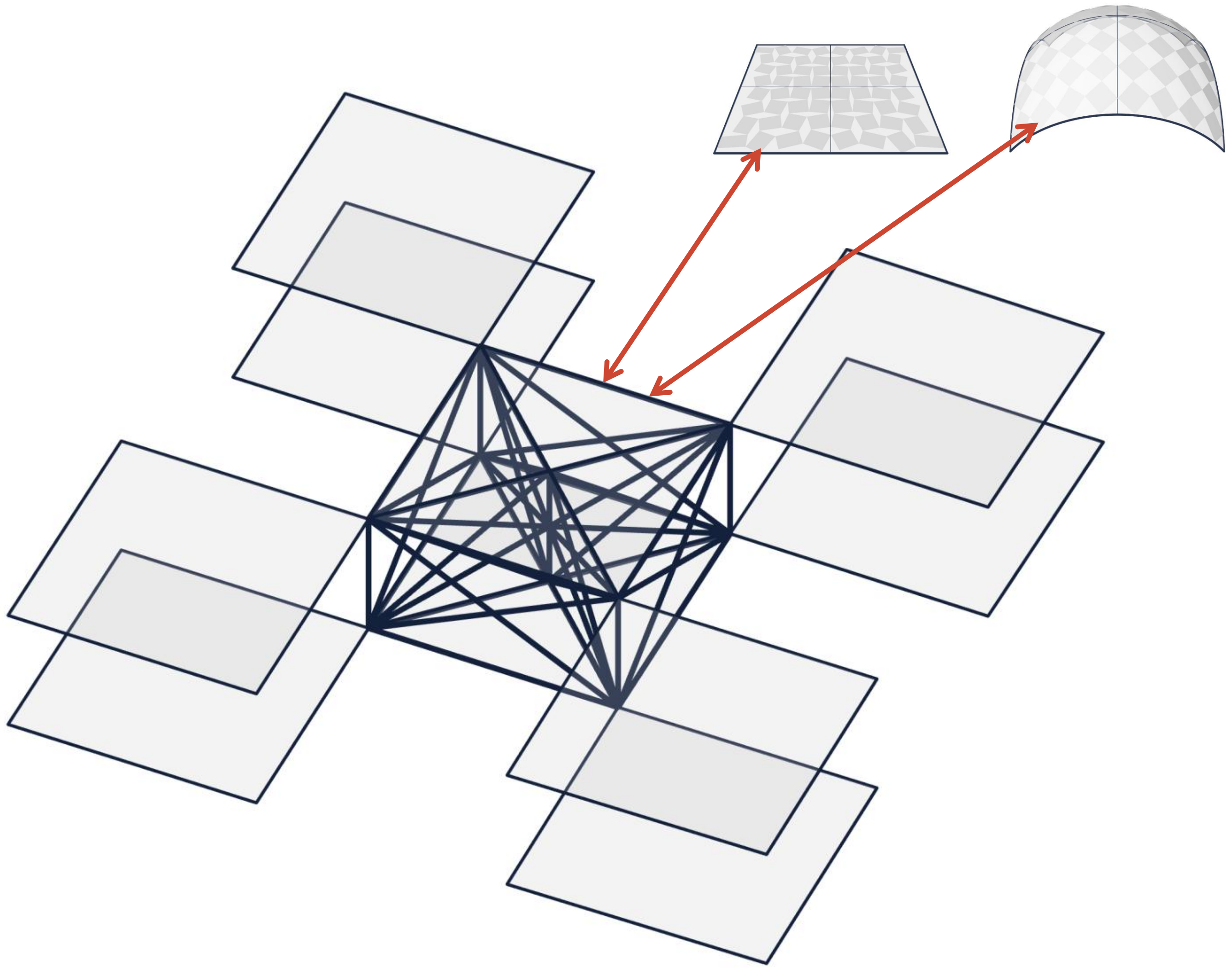


CONSTRAINTS

GLOBAL EQUAL LENGTH CONSTRAIN	INTERNAL CONSTRAINS	KINEMATIC CONSTRAINS	STATE CONSTRAINS

EQUAL LENGTE

- **Global Equal length Constraint**
- every node-to-node link
- Between two states
- Ensure elements to stay similar
- While allowing deformation



INTERNAL CONSTRAINTS

- **Centre axis**

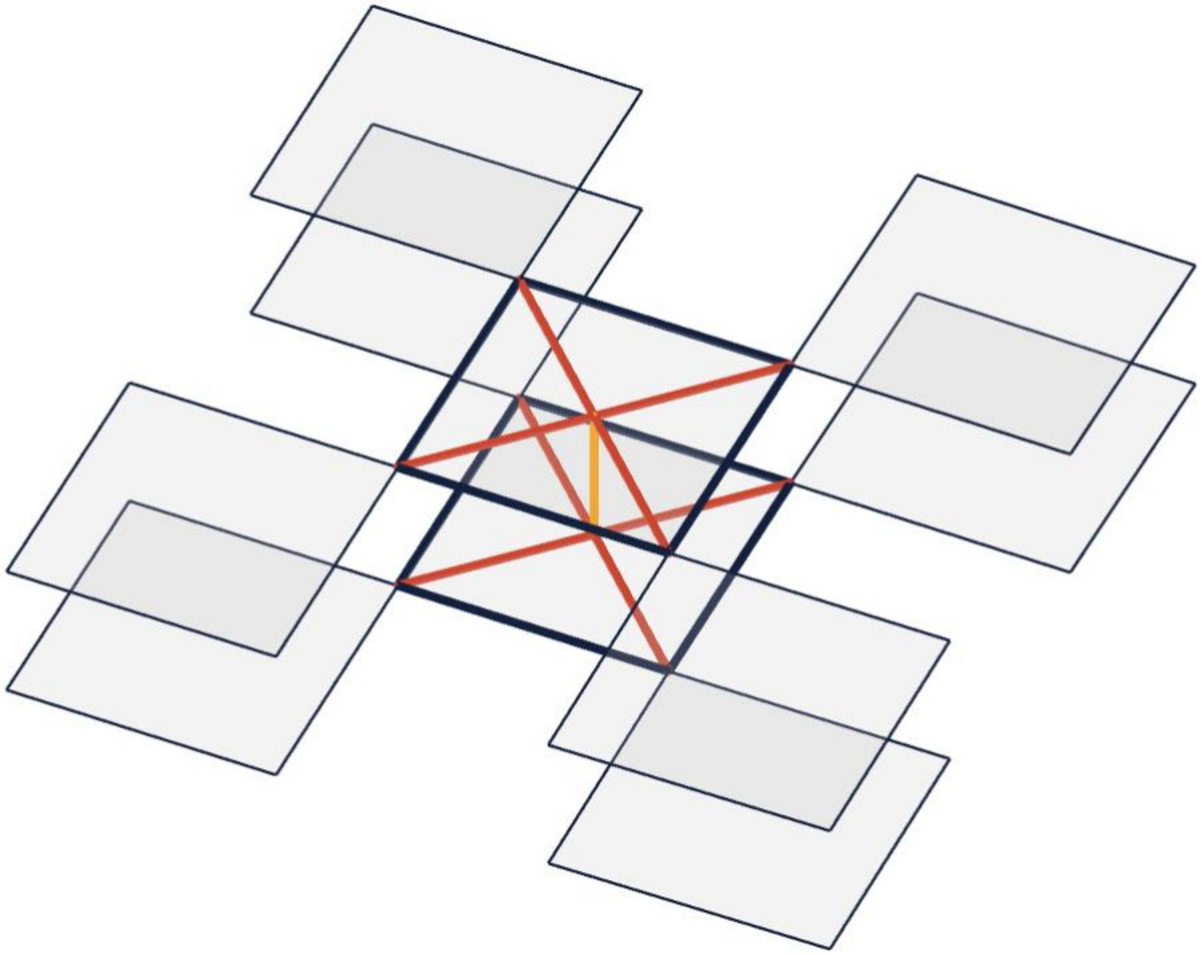
Ensuring rotation between panels

- **Diagonals**

Keep the center in its place, the panels square

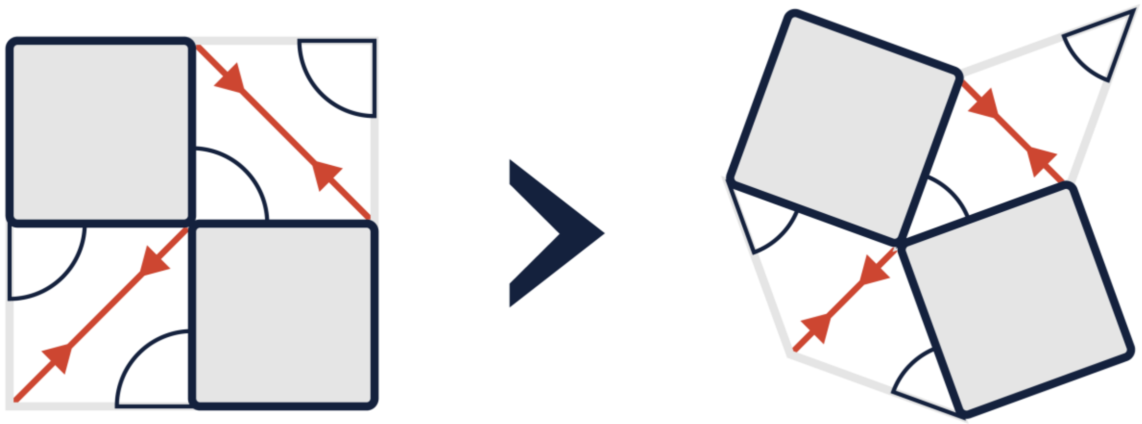
- **Panel edges**

Are allowed limited deformation



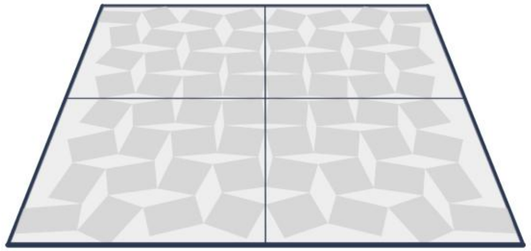
KINEMATIC CONSTRAINTS

- Constrains between the elements
- Applied on negative area
- Encourage the kinematic system from rotating
- Prevent collision

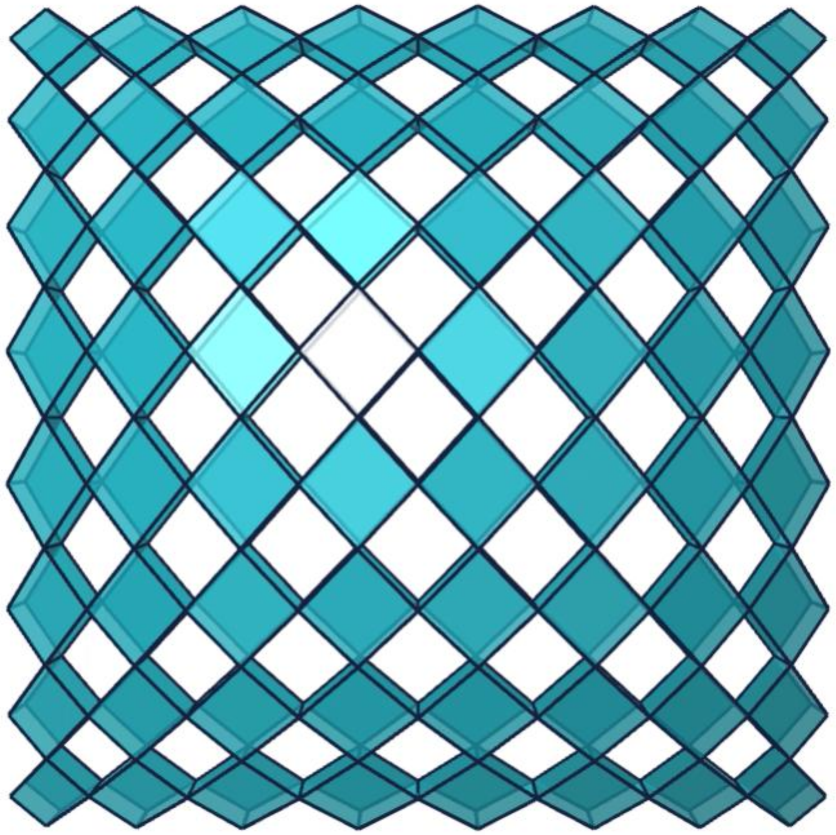


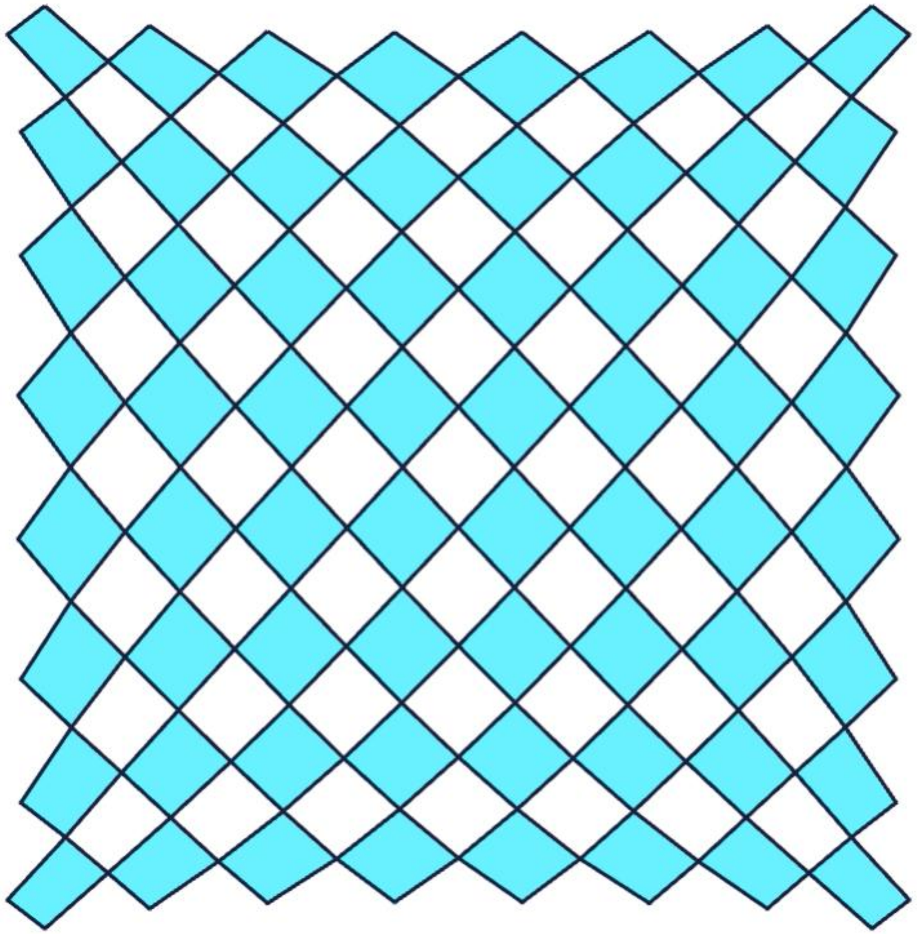
STATE CONSTRAINS

- Constrain that differ per state
- Ensures panels stays flat/ stays on input surface
- Fix boundary points



FORMFINDING PROCESS

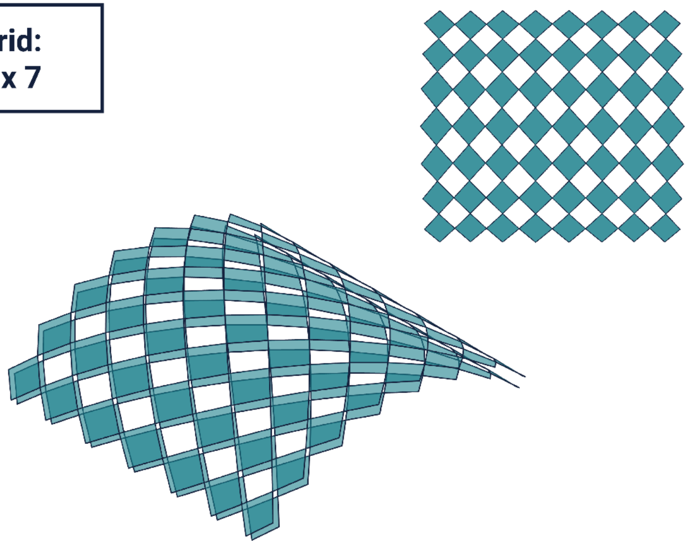




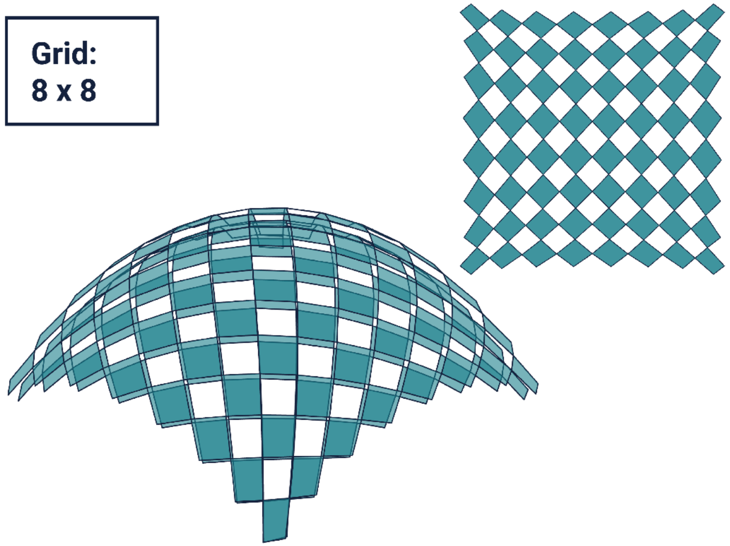
SOLVER

INPUT

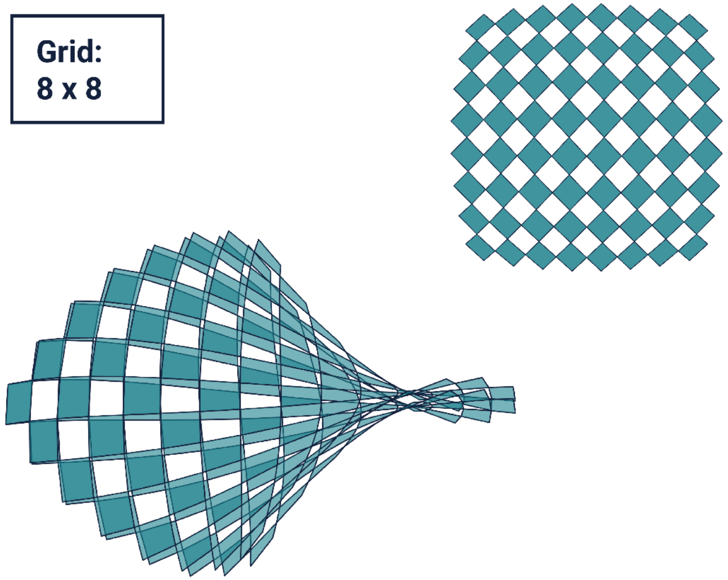
Grid:
8 x 7



Grid:
8 x 8



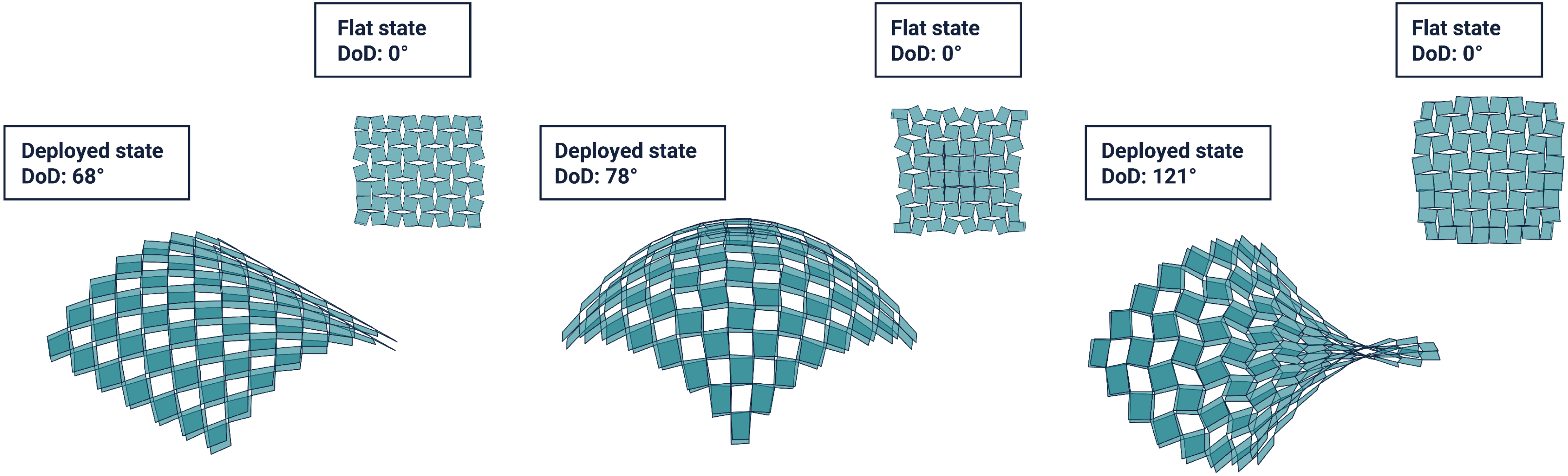
Grid:
8 x 8



MONOCLASTIC **SYNCLASTIC** **ANTICLASTIC**

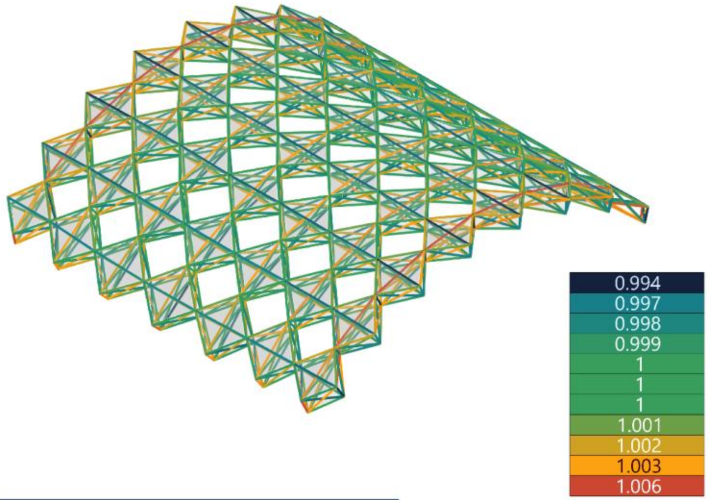
SOLVER

OUTPUT

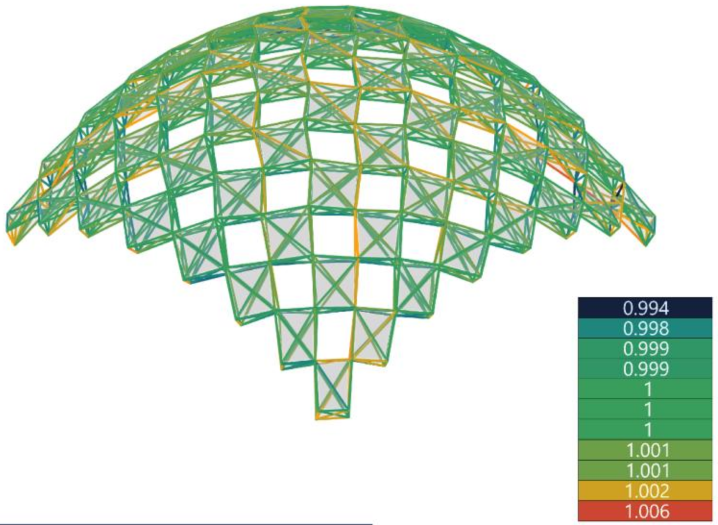


MONOCLASTIC **SYNCLASTIC** **ANTICLASTIC**

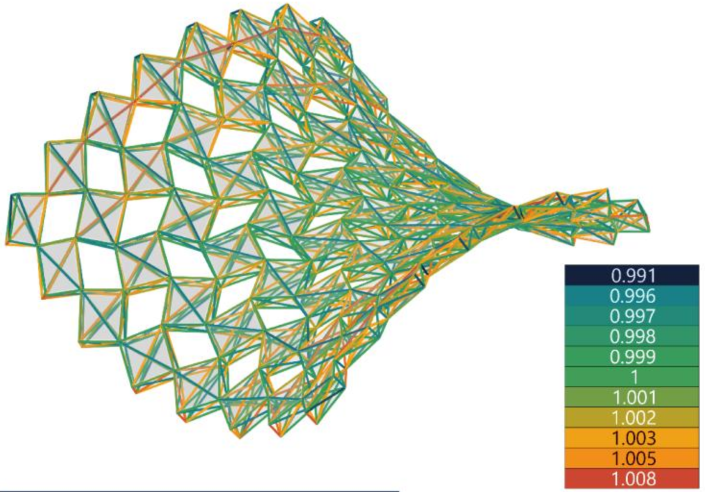
VALIDATION



largest scale differents
0,6%



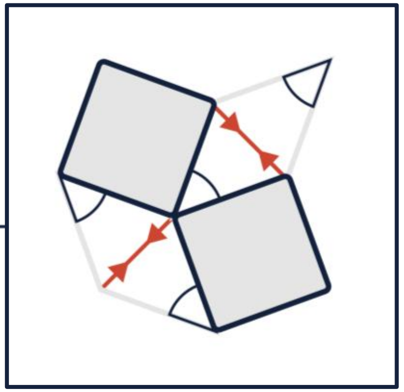
largest scale differents
0,6%

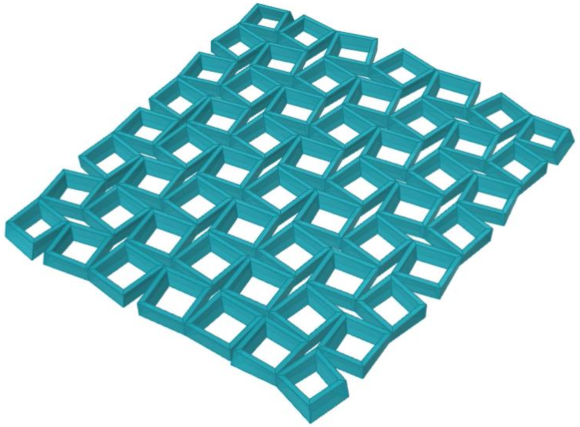


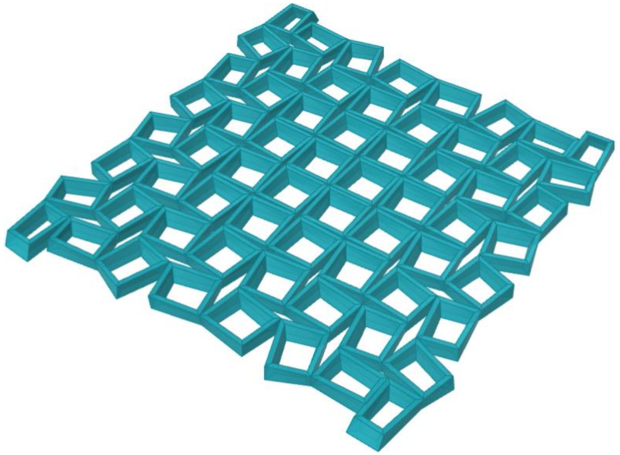
largest scale differents
0,9%

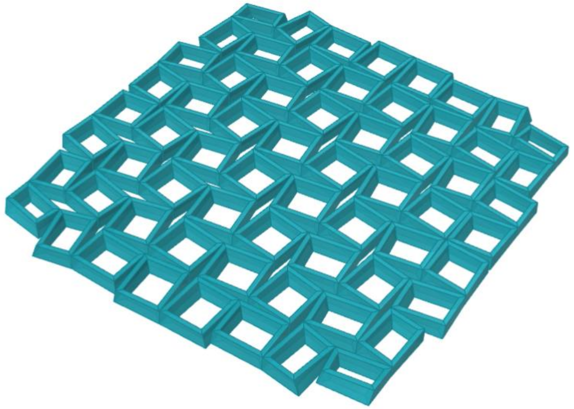
MONOCLASTIC | **SYNCLASTIC** | **ANTICLASTIC**

DEPLOYMENT







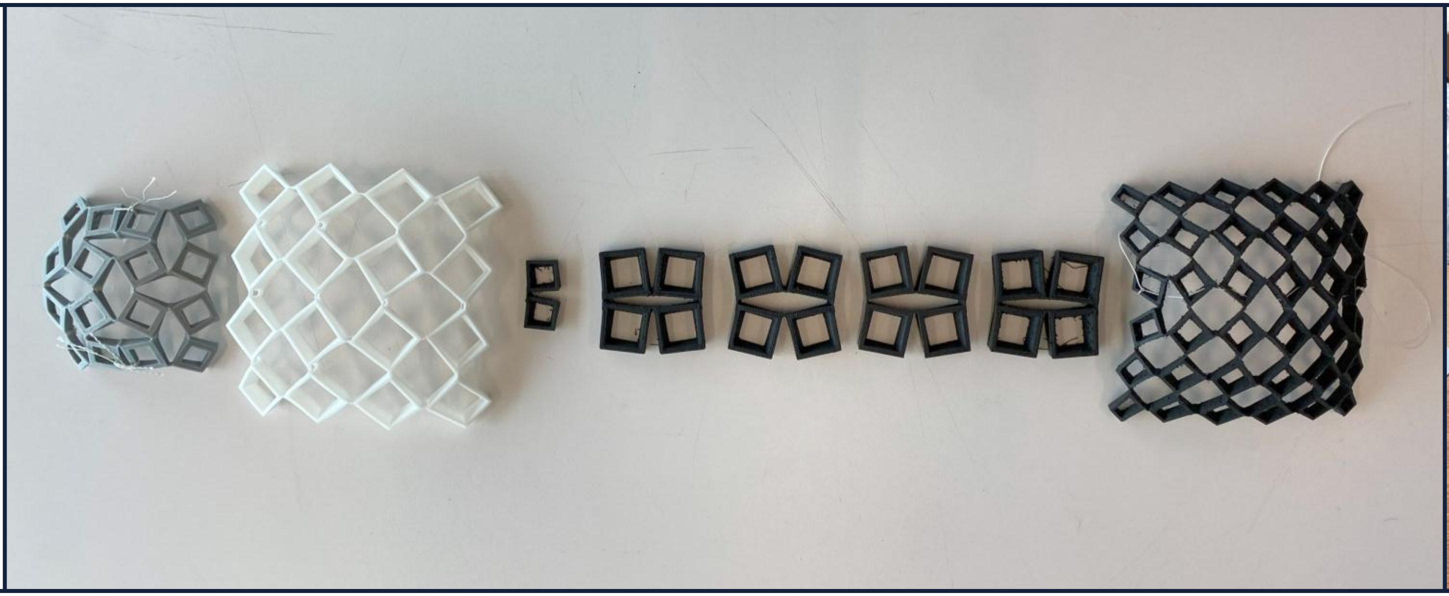


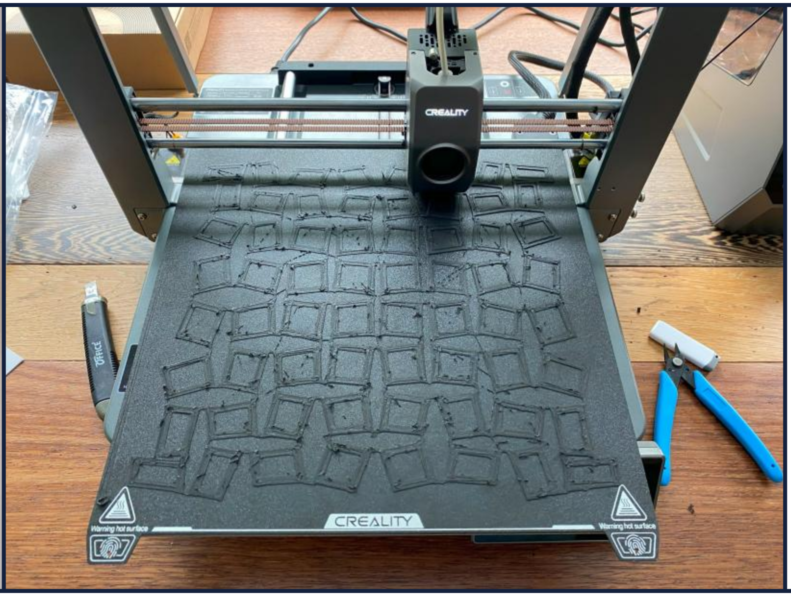
MONOCLASTIC

SYNCLASTIC

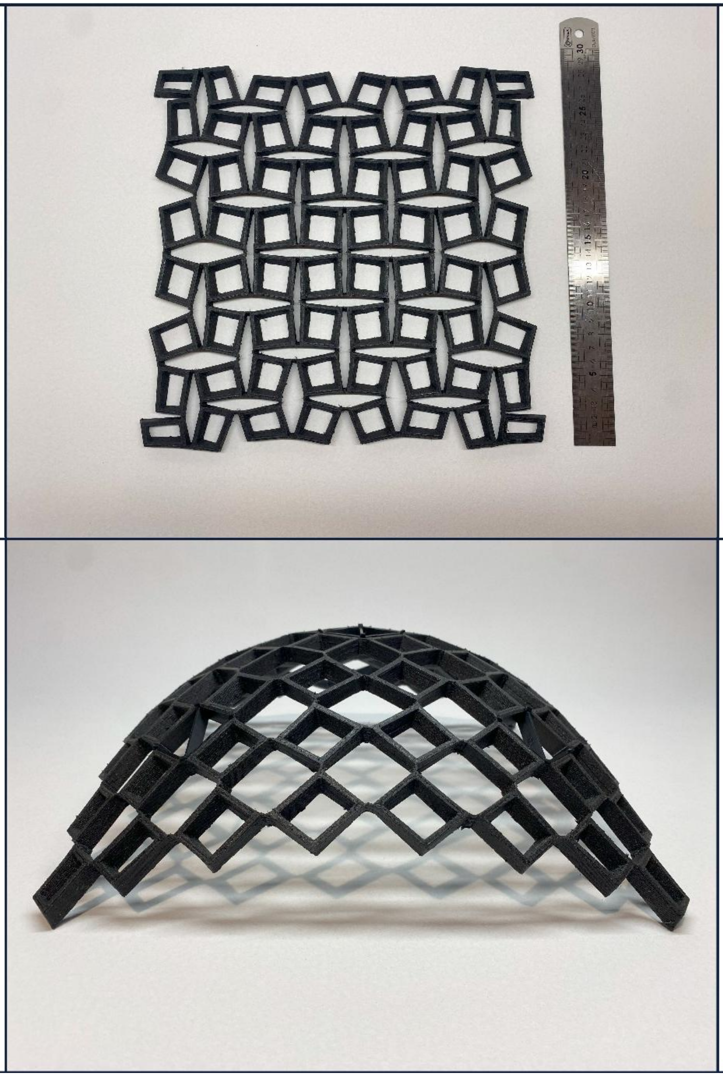
ANTICLASTIC

PRINTING PROCESS

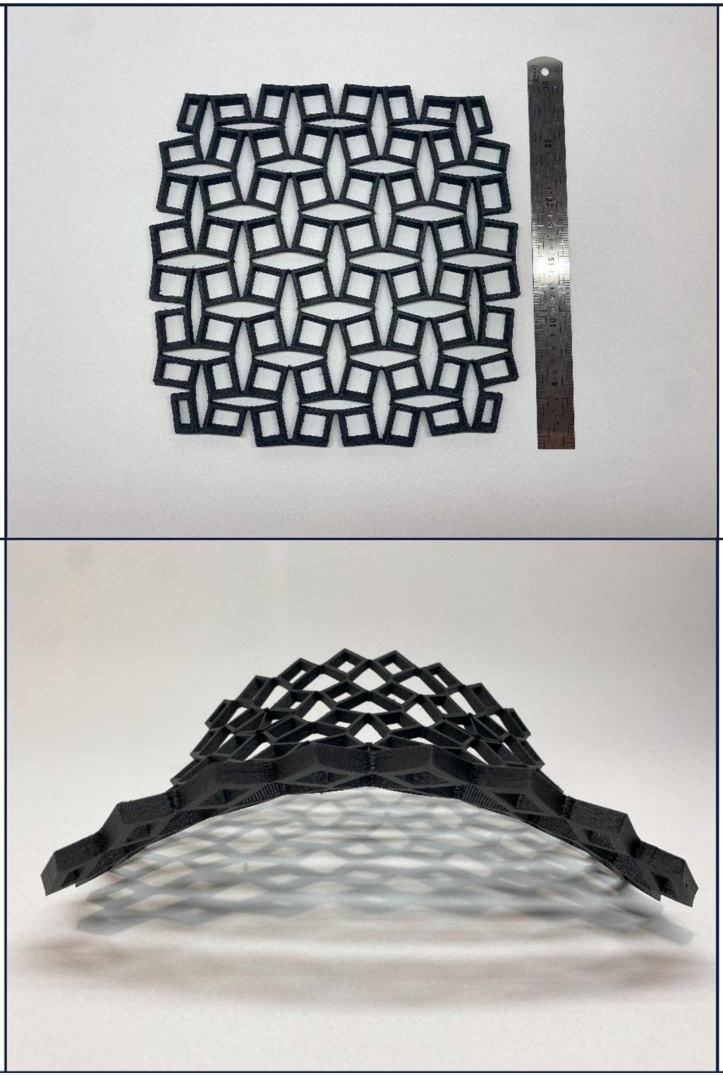




PROTOTYPES TEST SHAPES

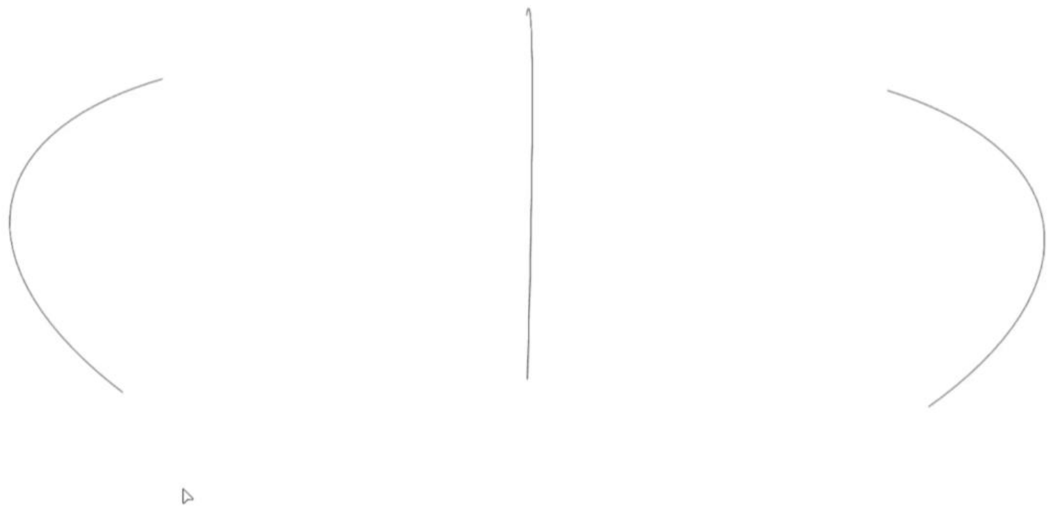


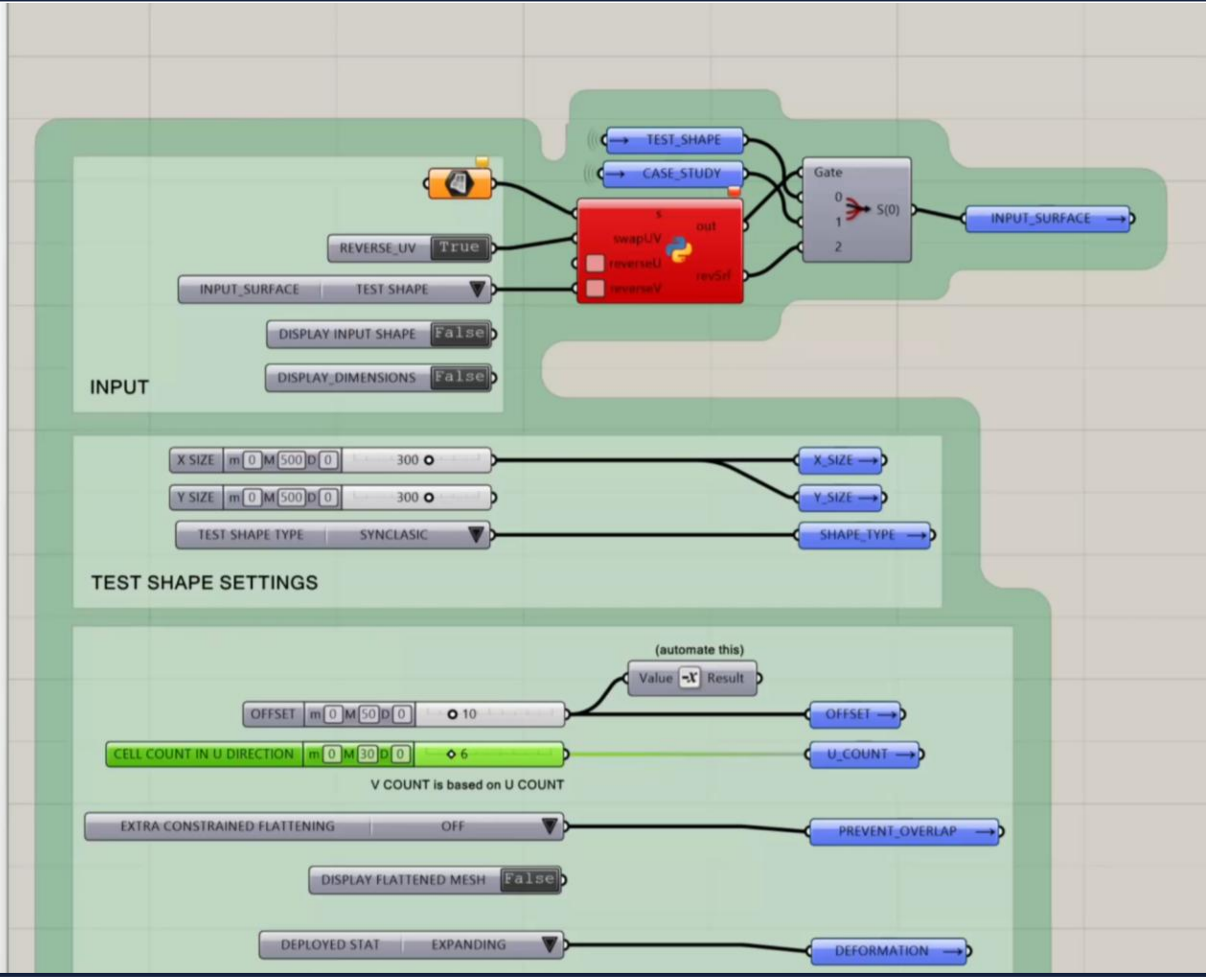
SYNCLASTIC



ANTICLASTIC

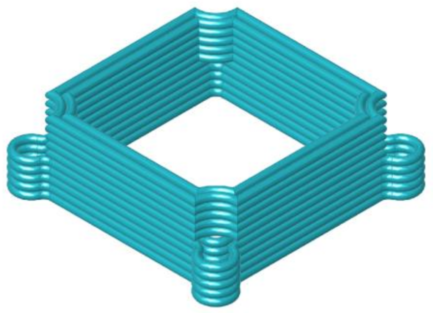
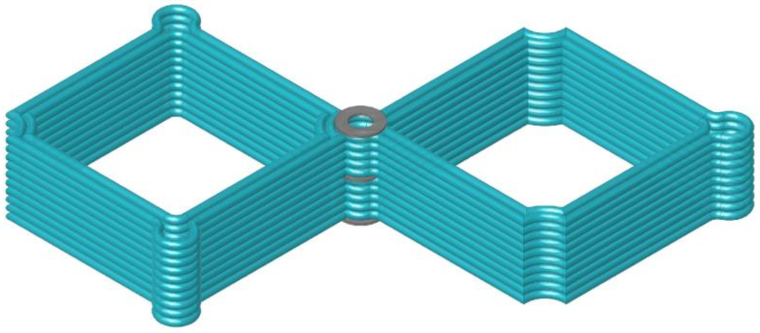
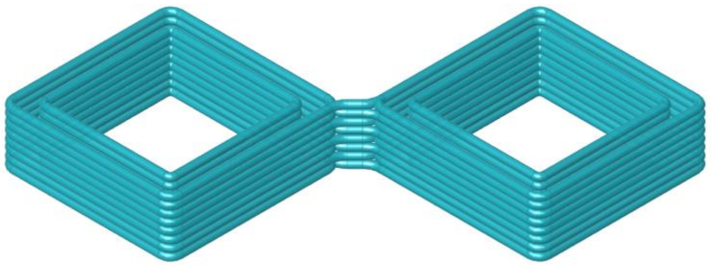
THE TOOL



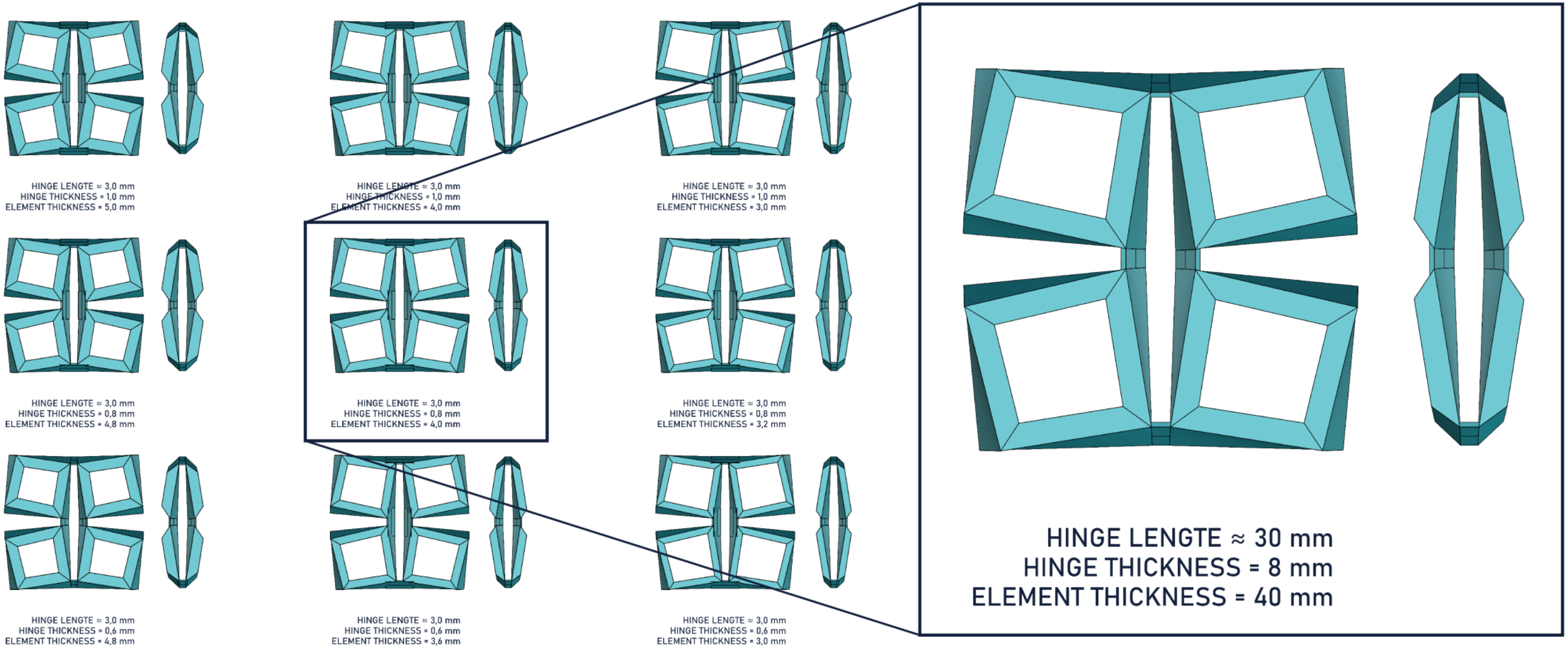

TEST_SHAPE
CASE_STUDY
Gate
INPUT_SURFACE
REVERSE_UV True
INPUT_SURFACE TEST SHAPE
DISPLAY INPUT SHAPE False
DISPLAY_DIMENSIONS False
INPUT
X SIZE 300
Y SIZE 300
X_SIZE
Y_SIZE
TEST SHAPE TYPE SYNCLASIC
SHAPE_TYPE
TEST SHAPE SETTINGS
(automate this)
Value Result
OFFSET 10
OFFSET
CELL COUNT IN U DIRECTION 6
U_COUNT
V COUNT is based on U COUNT
EXTRA CONSTRAINED FLATTENING OFF
PREVENT_OVERLAP
DISPLAY FLATTENED MESH False
DEPLOYED STAT EXPANDING
DEFORMATION

LARGE SCALE PRINTING

HINGES

SEPARATE COMPONENTS	MECHANICAL HINGES INPLACE	SINGLE MATERIAL COMPLIANT HINGES
		

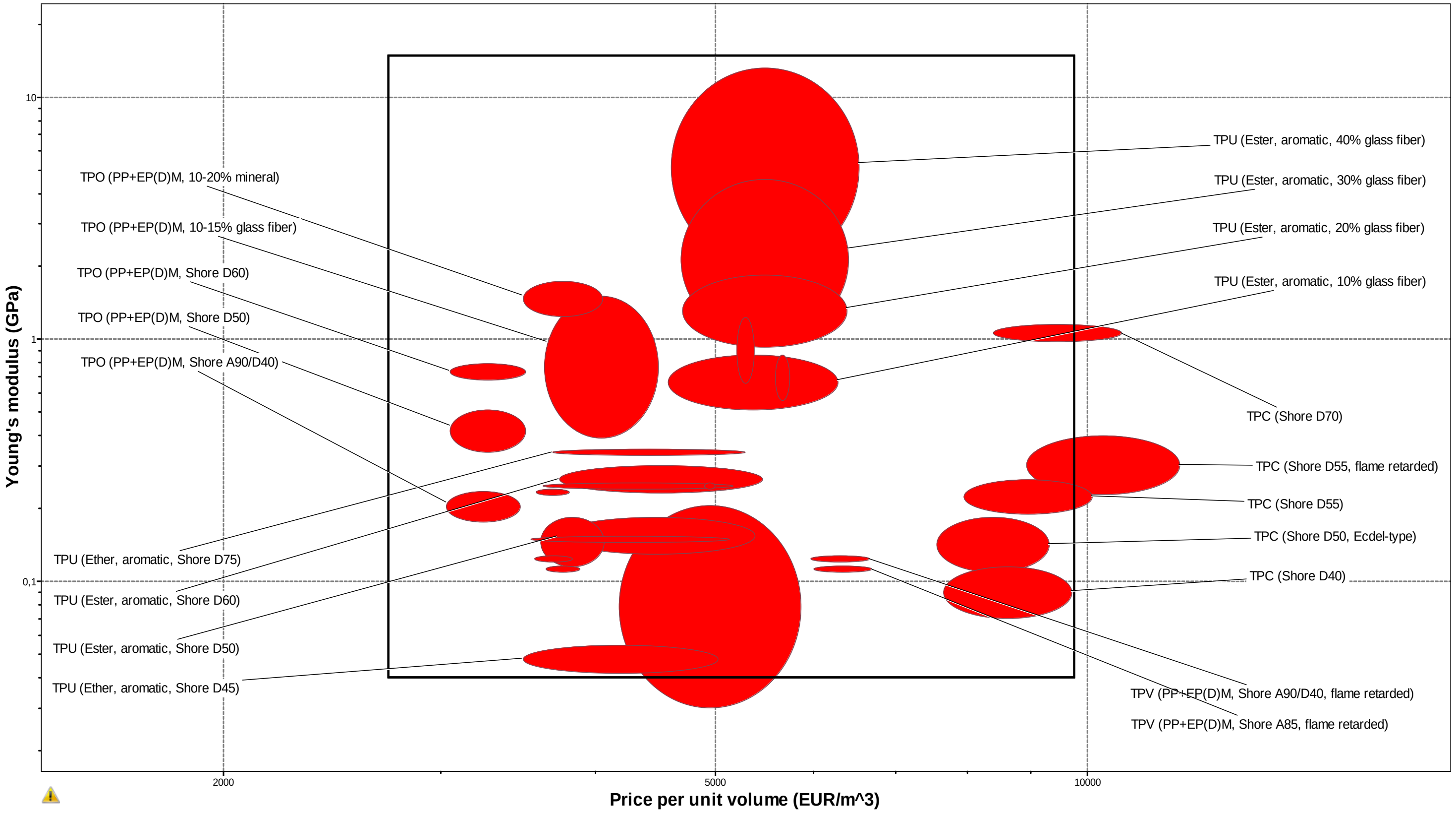
PROTOTYPE CONFIGURATIONS



SELECTED CONFIGURATIONS

MATERIAL

- Thermoplastic elastomers
- Young’s modulus: 0.01 - 5 Gpa
- Adding glass fiber can make TPU stiffer
- Alternative = TPC 70D

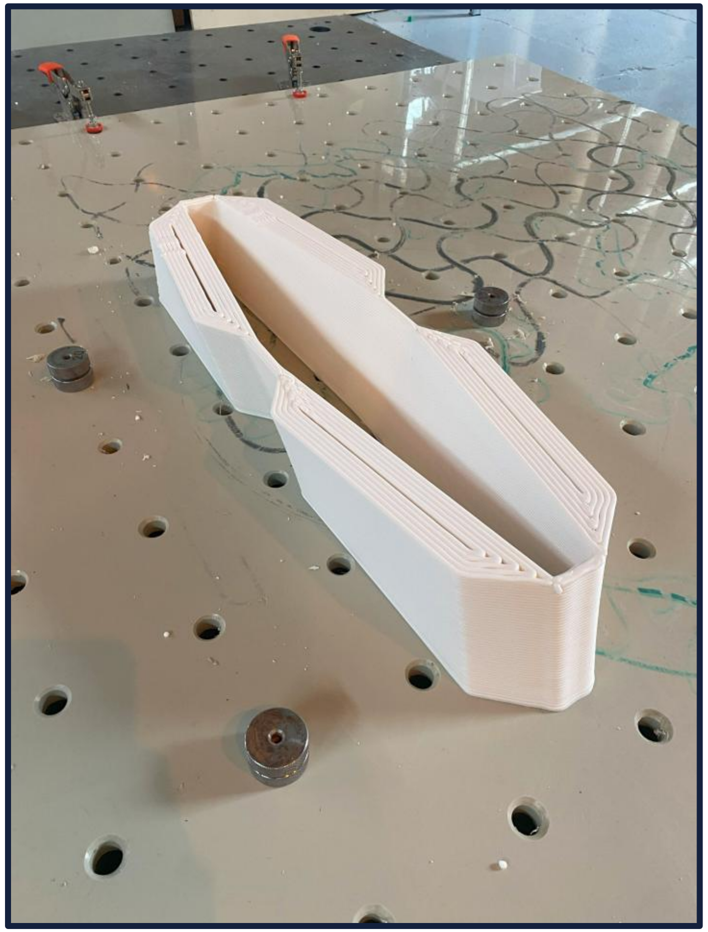


MATERIAL

ESTANE® 3D TPU F98A-030 CR HC PL

Property	Value
Young’s (Elastic) Modulus	35 kN / cm² ≈ 350 MPa
In-plane Shear Modulus	12 kN / cm² ≈ 120 MPa
Transverse Shear Modulus	4.8 kN / cm² ≈ 48 MPa
Specific Weight γ	10.7 kN / m³
Coefficient of Thermal Expansion (linear)	0.9 – 1.1 × 10^{-4} / °C
Tensile Strength (XY build)	2.8 kN / cm² ≈ 28 MPa
Compressive Strength (yield)	1.5 kN / cm² ≈ 15 MPa est.

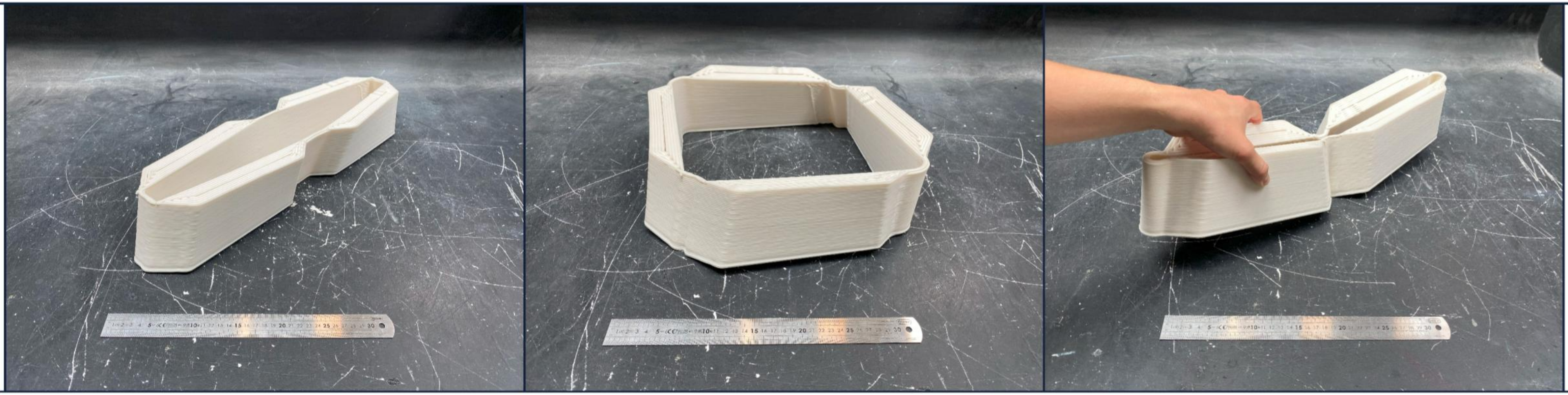
Ensoft SO-161-70A



PRINTING PROCESS

1:1 PROTOTYPES

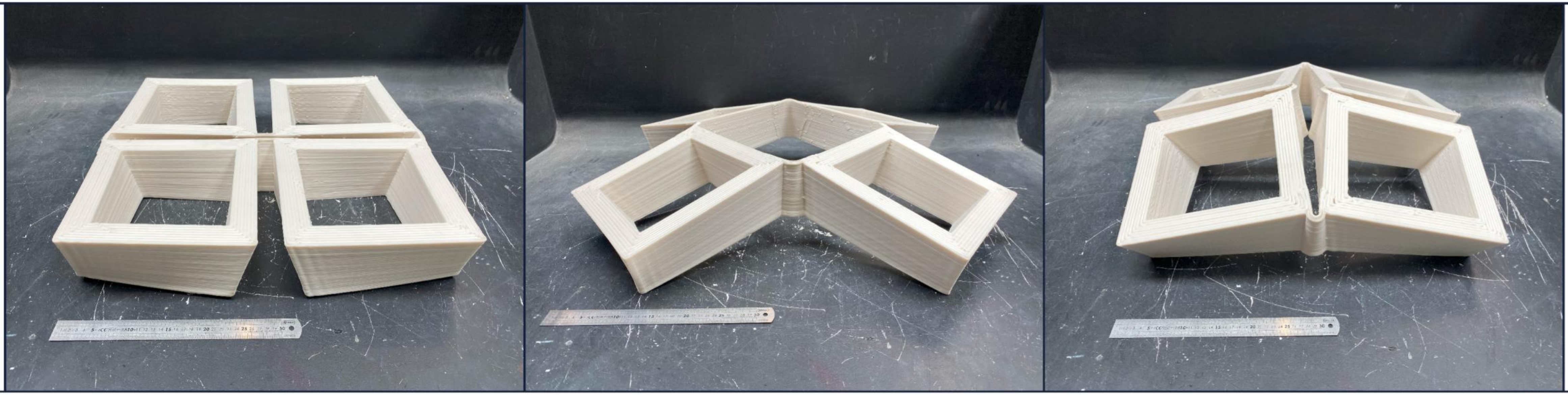
PROTOTYPE 1



FLAT STATE DoD ≈ 0° **DEPLOYED STATE** DoD ≈ 90° **OVER DEPLOYED** DoD ≈ 180°

1:1 PROTOTYPES

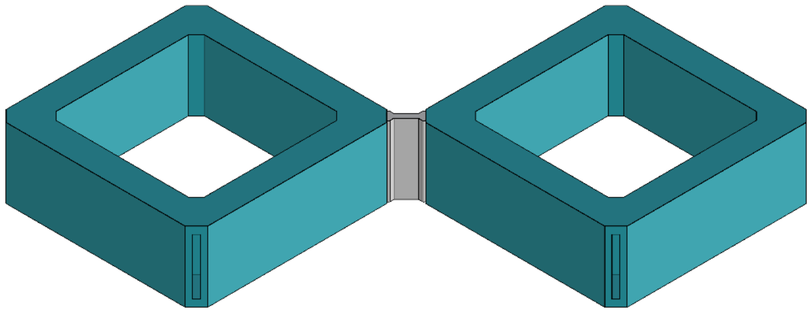
PROTOTYPE 2



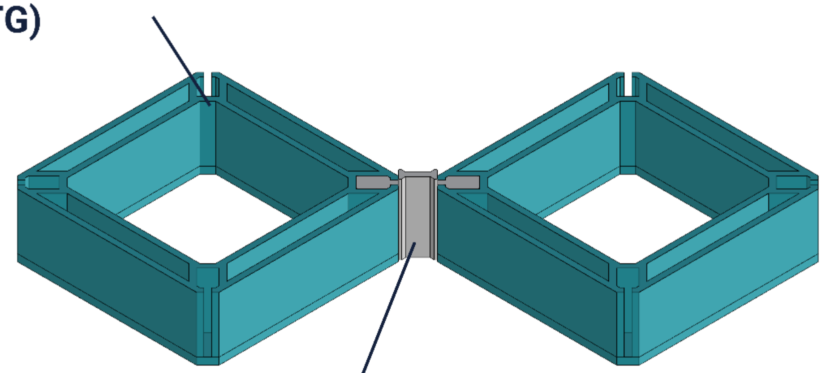
FLAT STATE **DoD ≈ 0°** **DEPLOYED STATE** **DoD ≈ 90°** **OVER DEPLOYED** **DoD ≈ 180°**

IMPROVEMENTS

DUAL MATERIAL 3D PRINTING

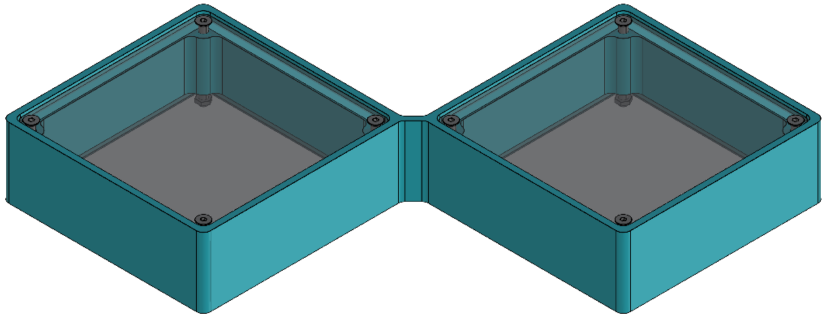


Structure 3D printed in two different materials. Requires dual nozzle

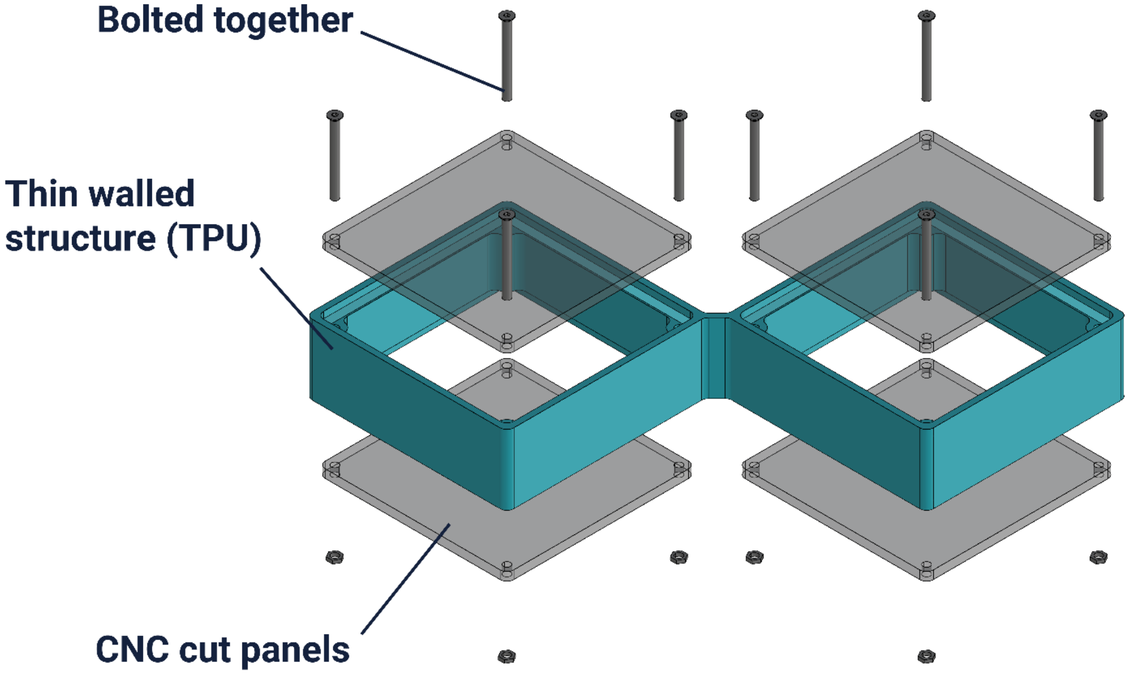


IMPROVEMENTS

STIFFENING BY PANELS



Thin printed elements stiffened by panels of a stiff light weight material

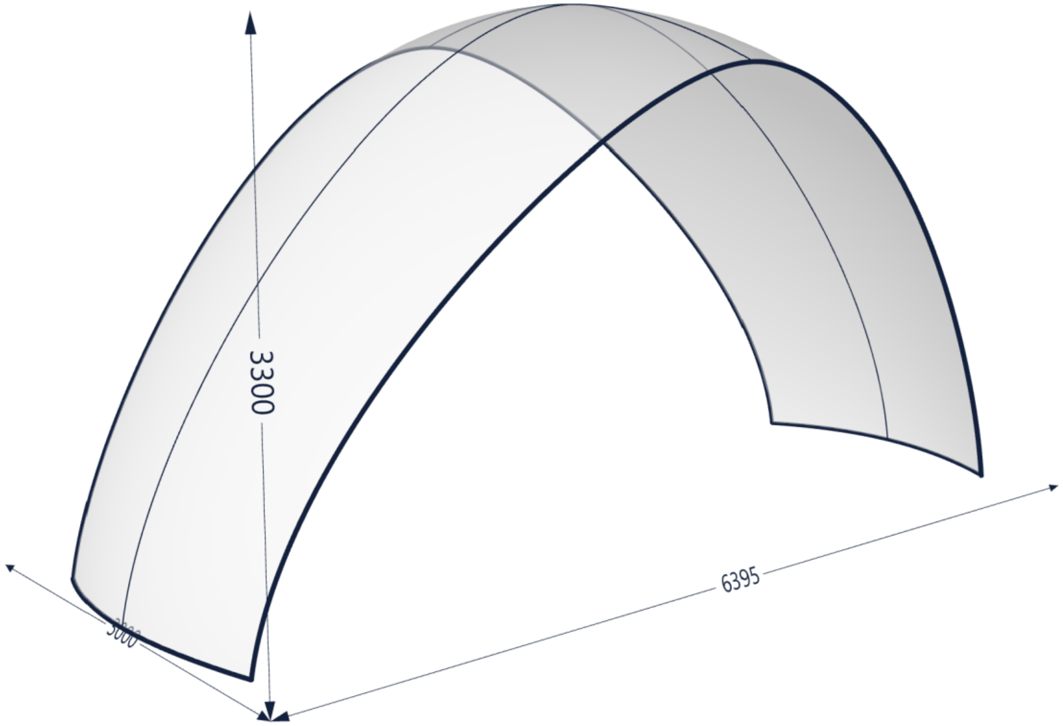


CASE STUDY

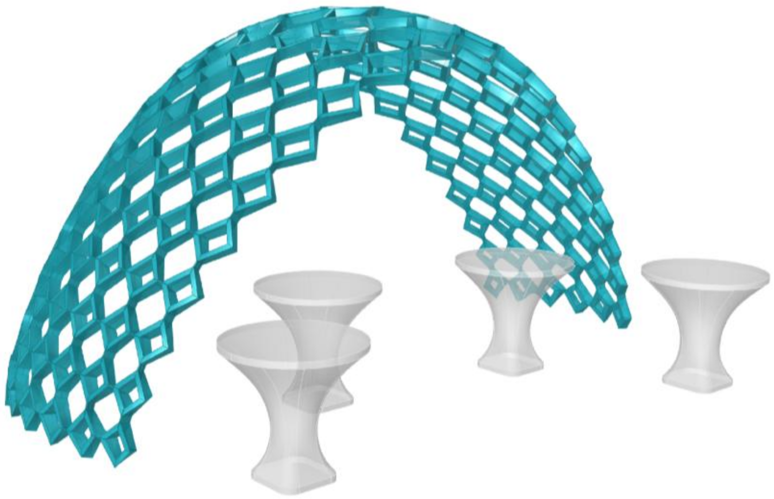
CASE STUDY

Small structure for festival events

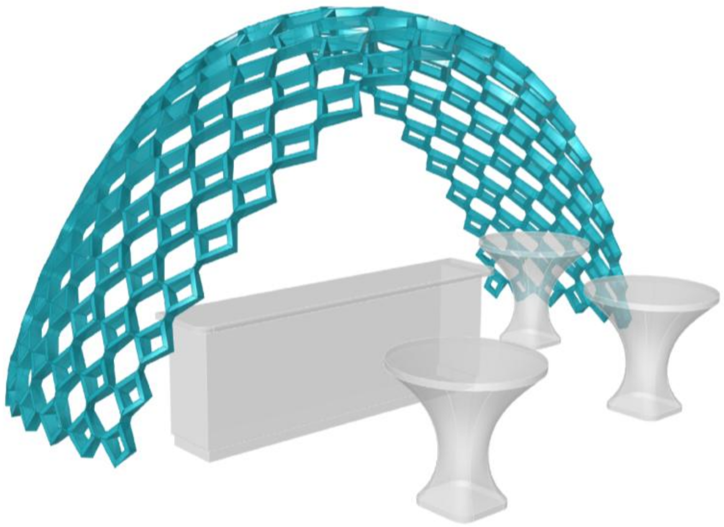
- Build with the knowledge and technology right now
- Demonstrate the ability to span a small distance
- Evaluate whether the system can be deployed quickly and easily



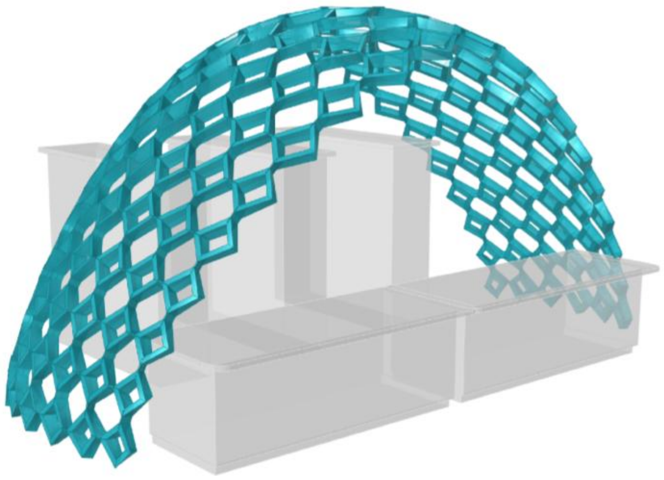
APPLICATION



NETWORKING STAND



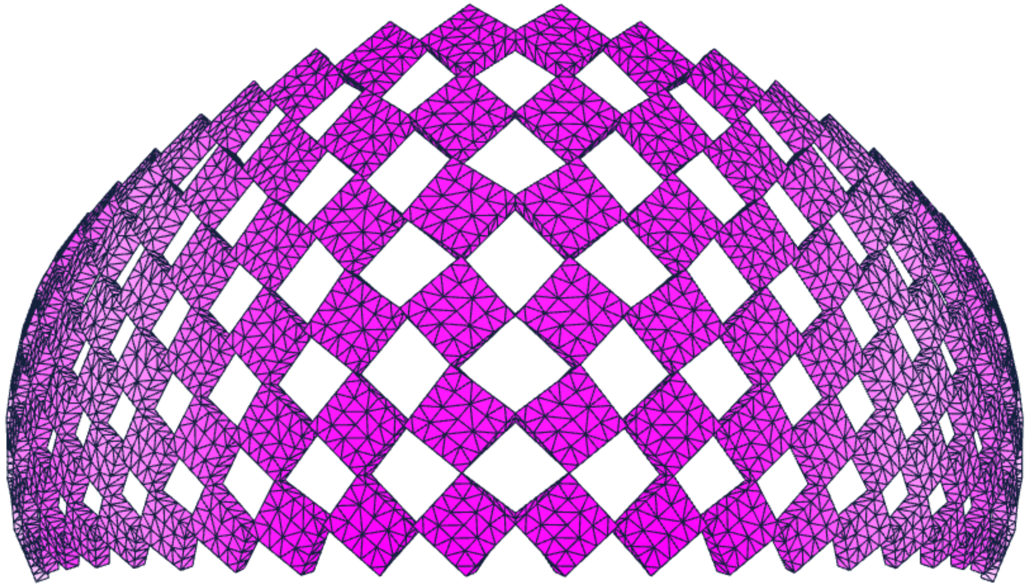
BAR



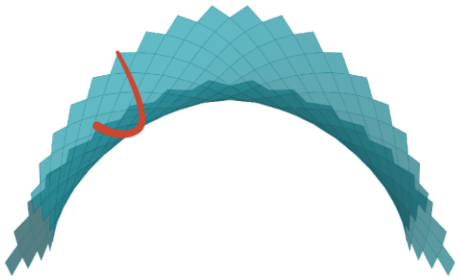
WARDROBE

OPTIMIZATION

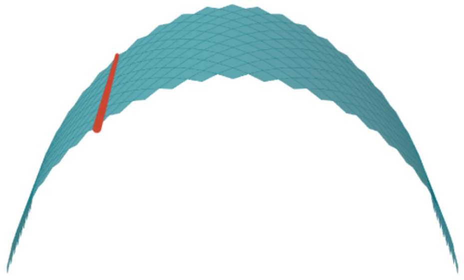
- Optimization Geometry
- Optimization mesh/grid density
- Fitness landscape
  - 2 parameters for x and y
- Deformation as objective
  - Simplified Karamba model
  - Gravity and a vertical load



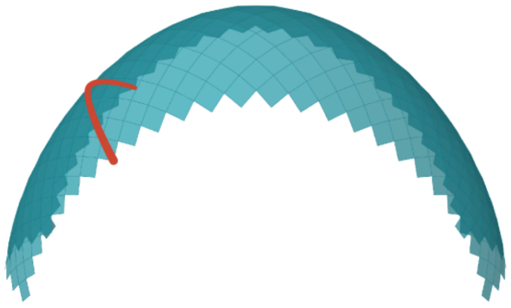
OPTIMISATION PARAMETERS



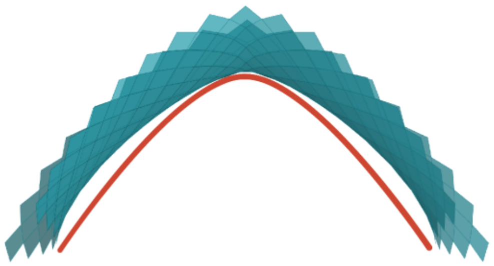
CURVATURE U: 0
CURVATURE V: 0.5



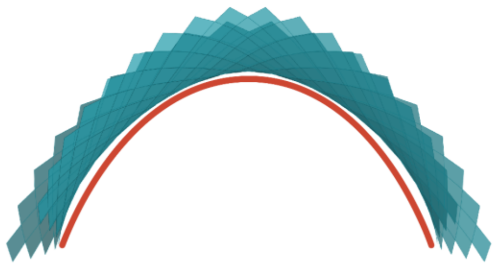
CURVATURE U: 0.5
CURVATURE V: 0.5



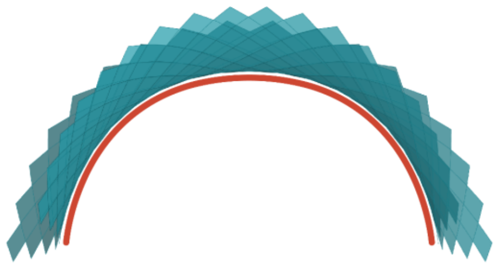
CURVATURE U: 1
CURVATURE V: 0.5



CURVATURE U: 0
CURVATURE V: 0

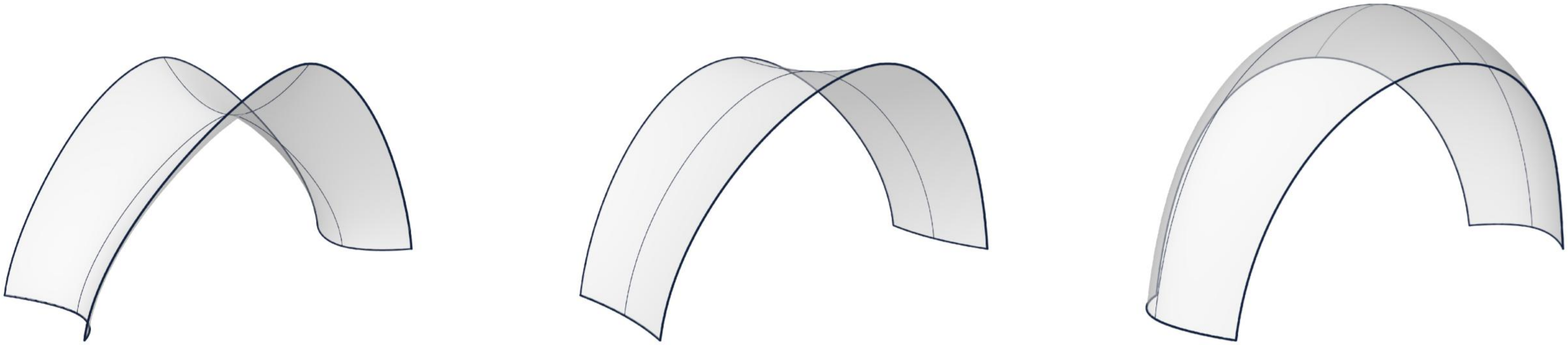


CURVATURE U: 0
CURVATURE V: 0.5

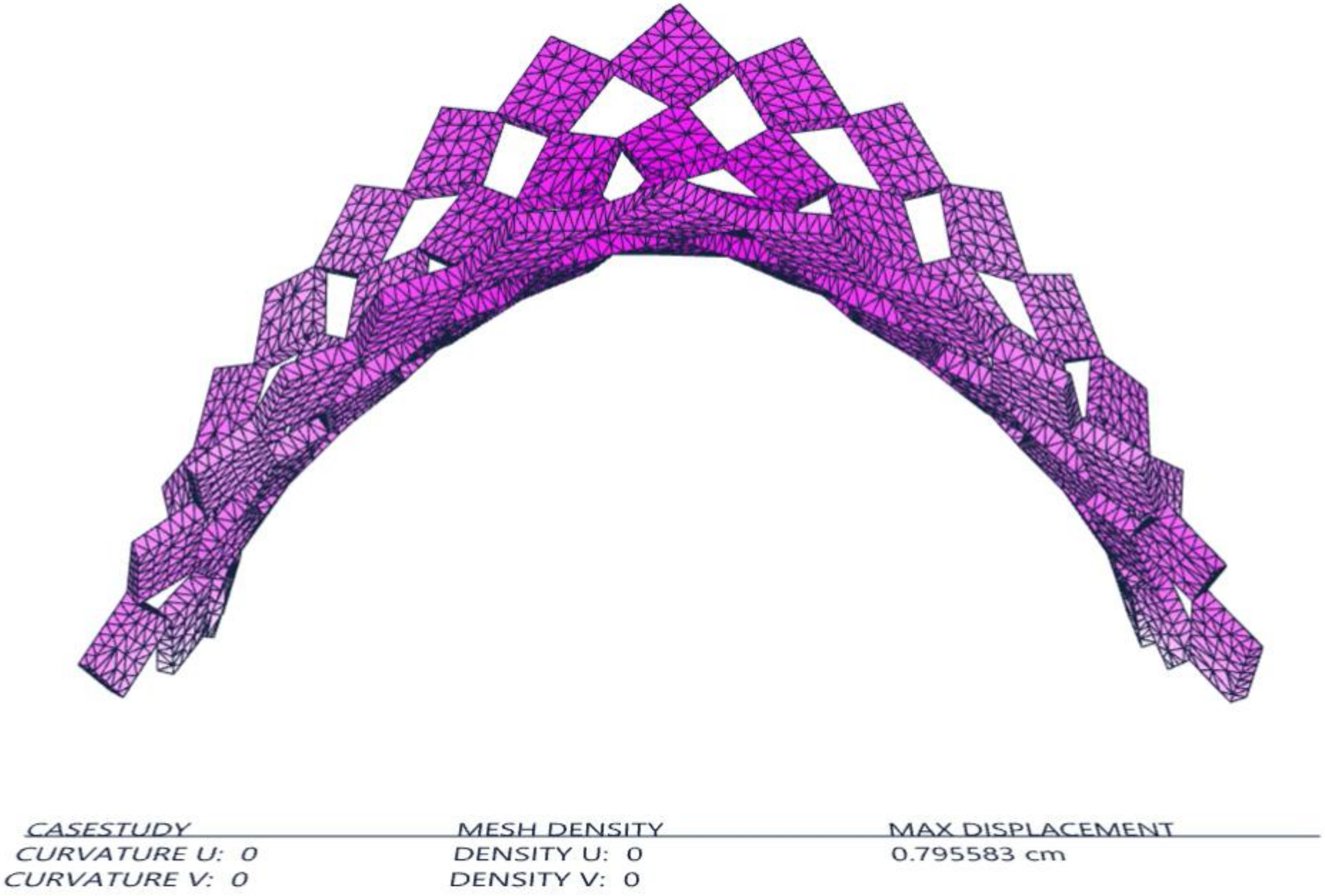


CURVATURE U: 0
CURVATURE V: 1

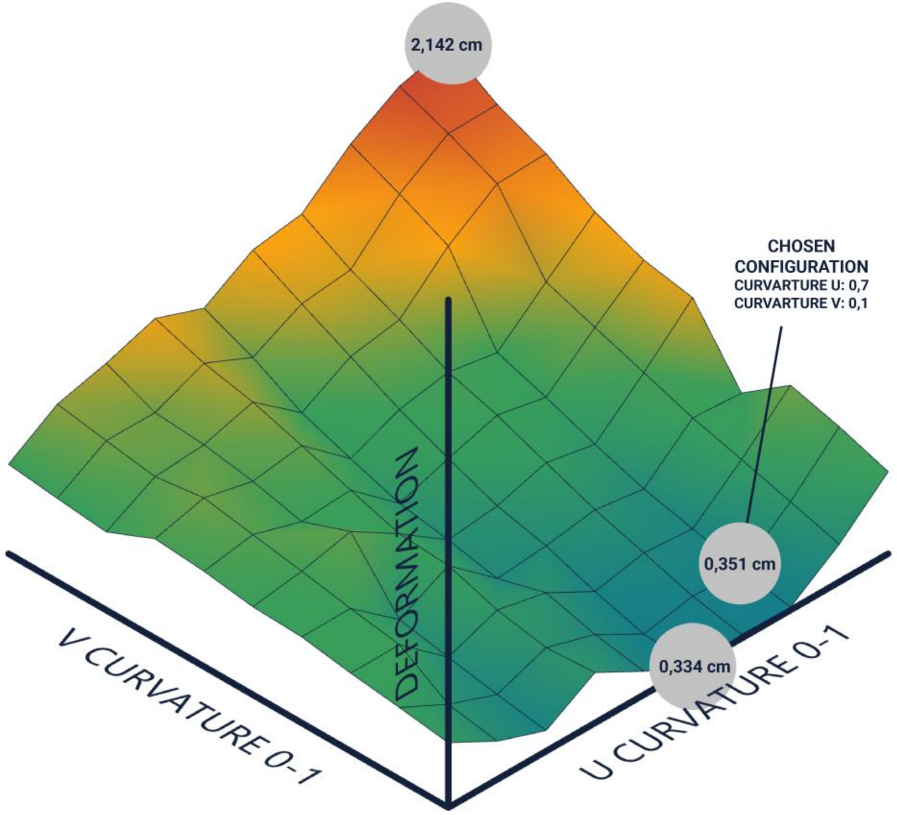
CASE STUDY GEOMETRY



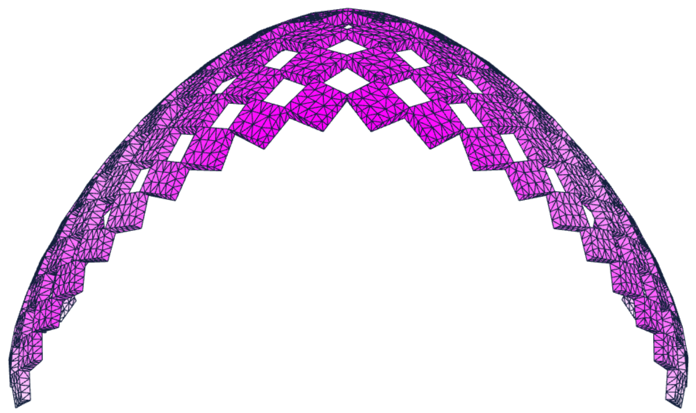
Optimization Geometry



Optimization Geometry



CHOSEN CONFIGURATION

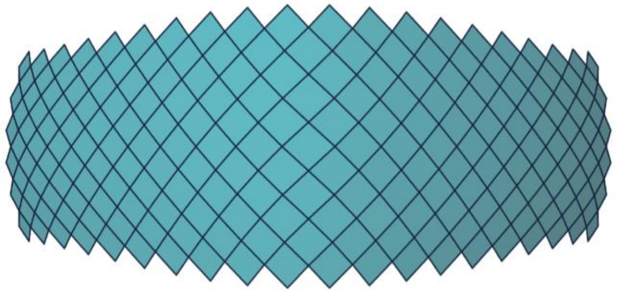


CASESTUDY
CURVATURE U: 0,7
CURVATURE V: 0,1

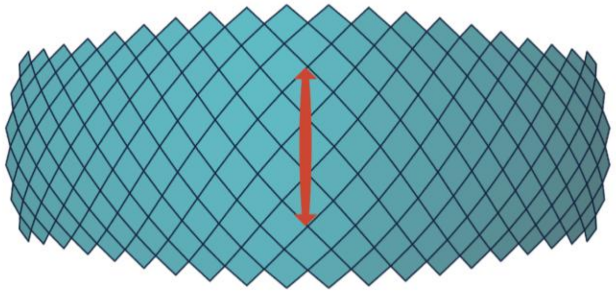
MESH DENSITY
DISTORTION U: 0
DISTORTION V: 0

MAX DISPLACEMENT
0,351 cm

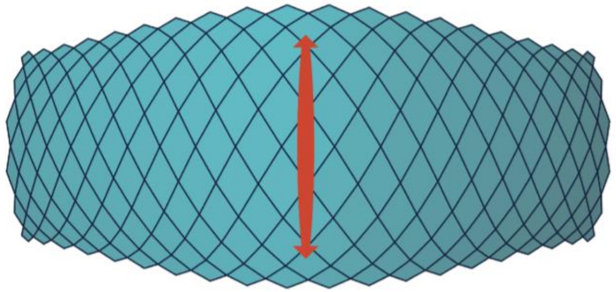
Optimization Mesh Density



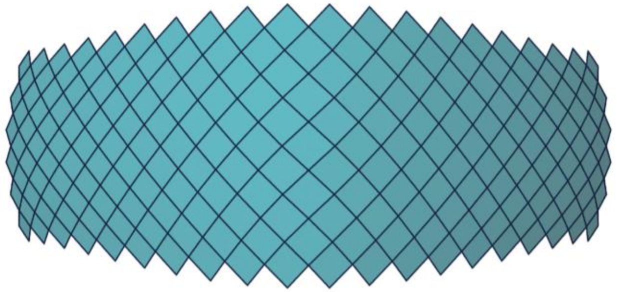
U DISTORTION: 0
V DISTORTION: 0



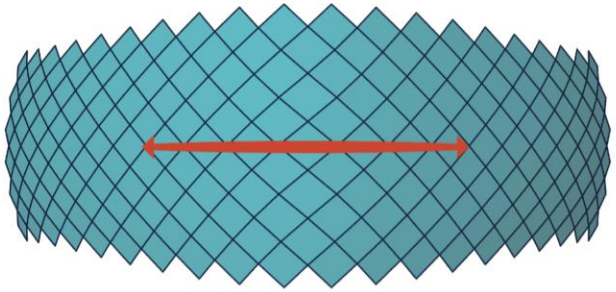
U DISTORTION: 0,5
V DISTORTION: 0



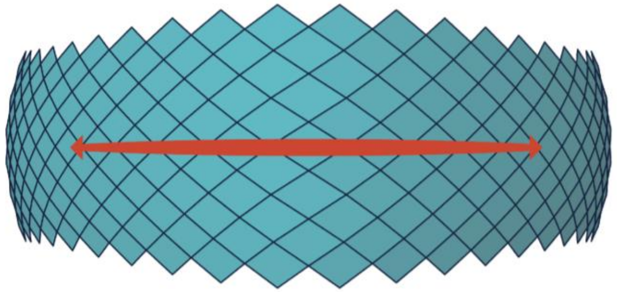
U DISTORTION: 1
V DISTORTION: 0



U DISTORTION: 0
V DISTORTION: 0

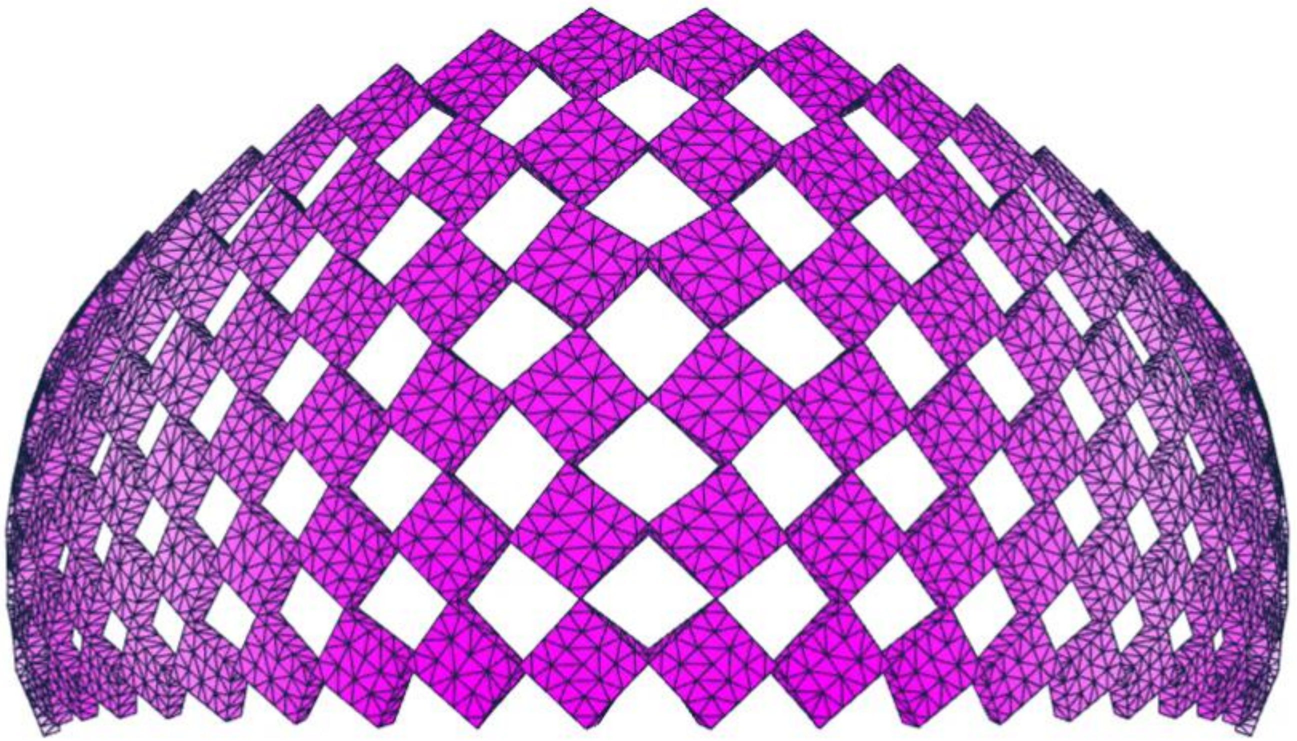


U DISTORTION: 0
V DISTORTION: 0,5



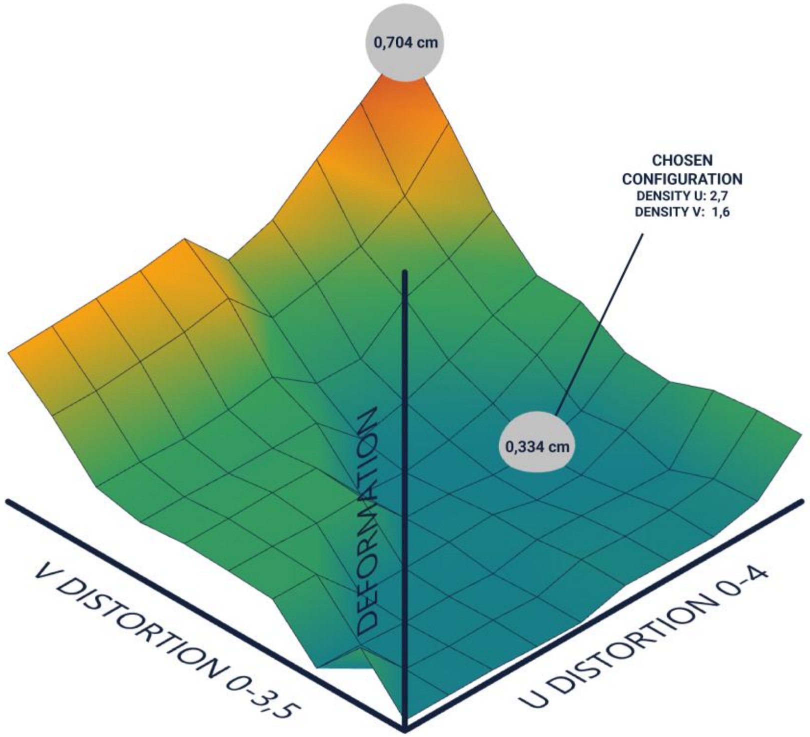
U DISTORTION: 0
V DISTORTION: 1

Optimization Mesh Density

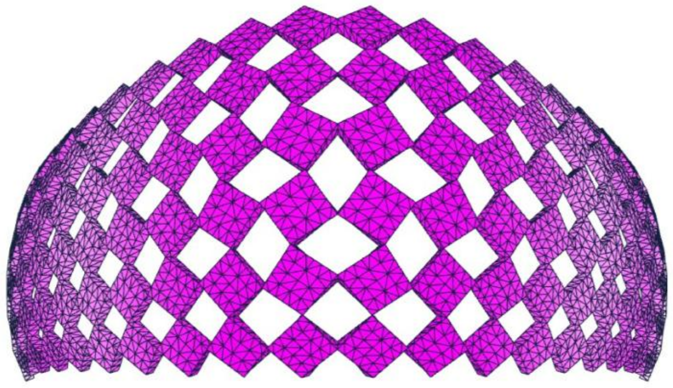


CASESTUDY	MESH DENSITY	MAX DISPLACEMENT
CURVATURE U: 0.7	DENSITY U: 0	0.351222 cm
CURVATURE V: 0.1	DENSITY V: 0	

Optimization Mesh Density



LOWEST MAX DISPLACEMENT



CASESTUDY	MESH DENSITY	MAX DISPLACEMENT
CURVATURE U: 0,7	DENSITY U: 2,722	0,334 cm
CURVATURE V: 0,1	DENSITY V: 1,556	

STRUCTURAL ANALYSIS

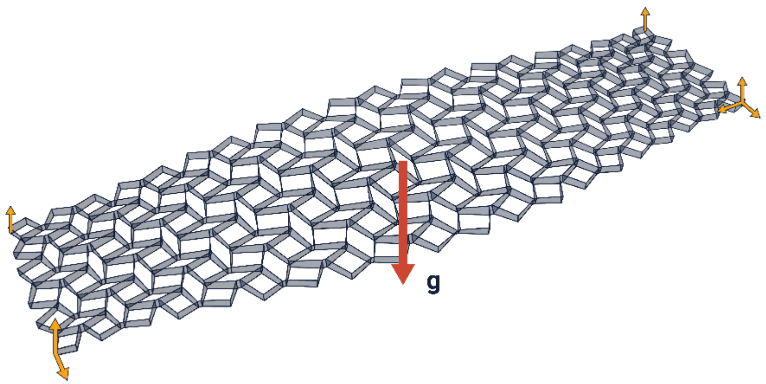
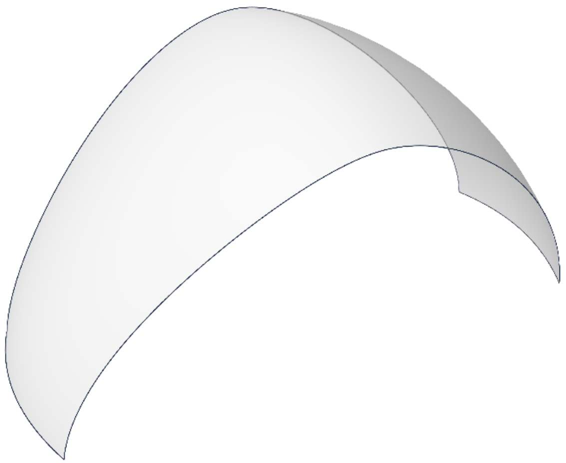
LARGE DISPLACMENT ANALYSIS

- Simulate deployment
- Effect of compliant hinges and other material deformation during deployment

STATIC ANALYSIS

- On the deformed model
- Load cases
- Stress/Deformation

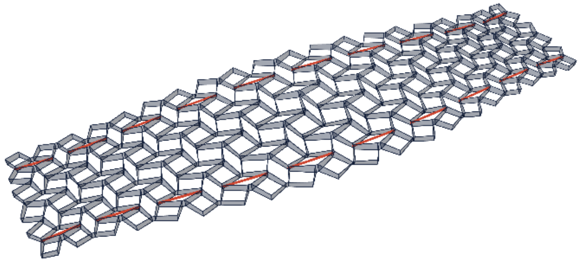
LARGE DISPLACMENT ANALYSIS

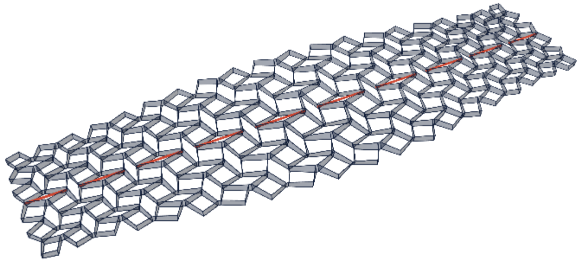
DETAILS	FLAT STATE	TARGET SHAPE
Material: **ESTANE® 3D TPU F98A-030 CR** **THK rigid elements:** 60 mm **THK hinge:** 10 mm **lengte hinge:** 30 mm		

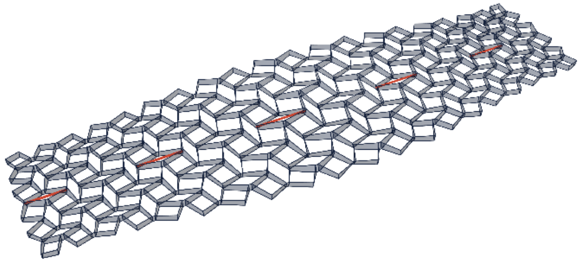
LARGE DISPLACMENT ANALYSIS

20 TENSION POINTS | **10 TENSION POINTS** | **5 TENSION POINTS**

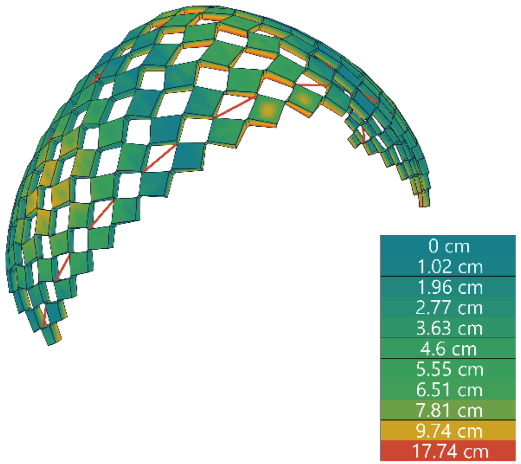
TENSION SYSTEM

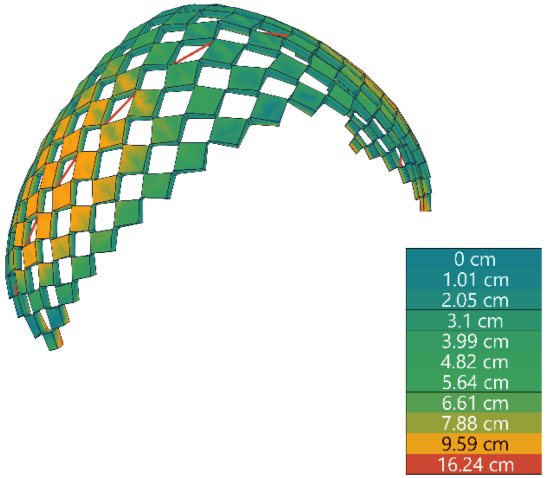


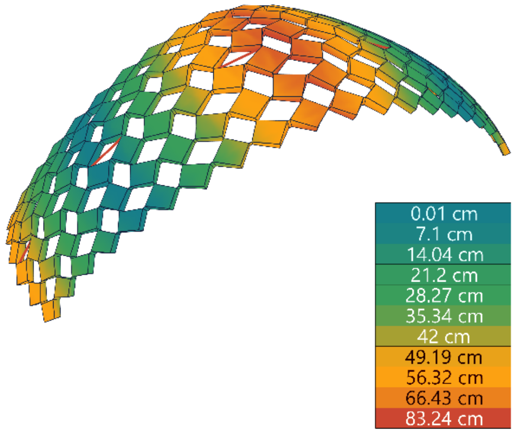




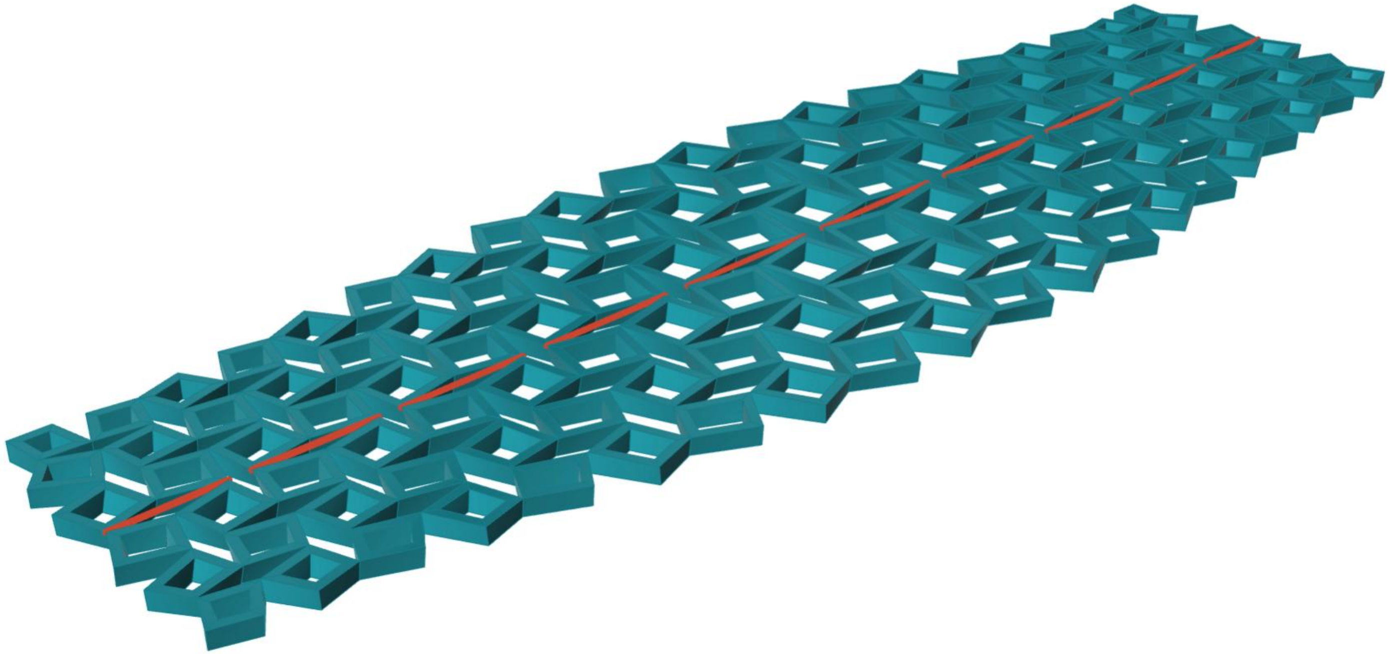
CONTOUR PLOT





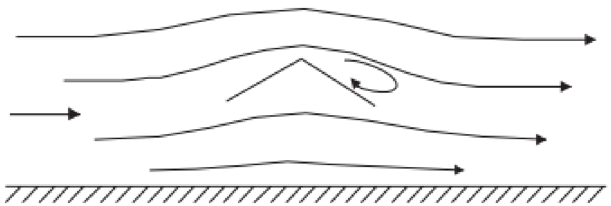


DEPLOYMENT CASE STUDY



STATIC ANALYSIS

- Wind load simplified to a two-sided sloping canopy with free airflow



Lege, vrijstaande, open overkapping (φ= 0)

Ultimate limit state:

ULS 1	1,22	Selfweight			
ULS 2	1,08	Selfweight	+	1,35	Wind 0°
ULS 3	1,08	Selfweight	+	1,35	Wind 90°

Serviceability limit state:

SLS 1	1,0	Selfweight			
SLS 2	1,0	Selfweight	+	1,0	Wind 0°
SLS 3	1,0	Selfweight	+	1,0	Wind 90°

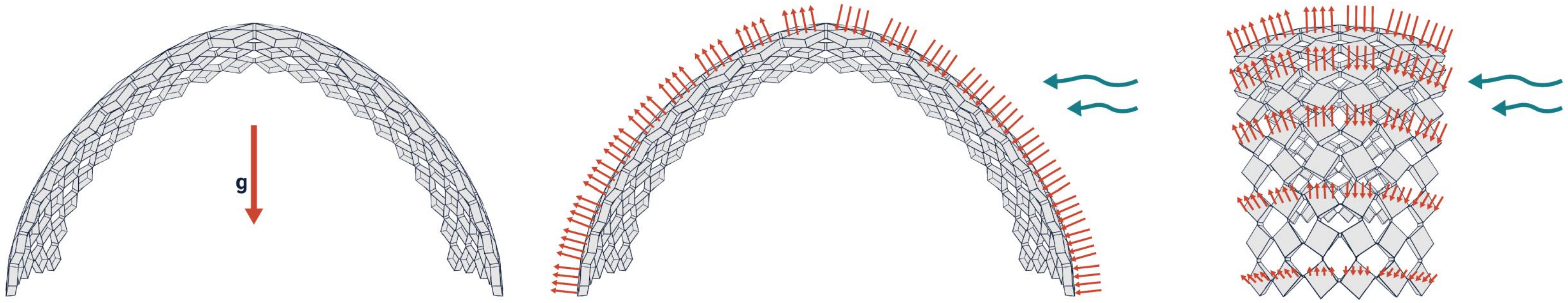
Tabel NB.5 — Extreme stuwdruk in kN/m² als functie van de hoogte

Hoogte	Gebied I			Gebied II			Gebied III	
m	Kust	Onbebouwd	Bebouwd	Kust	Onbebouwd	Bebouwd	Onbebouwd	Bebouwd
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74

STATIC ANALYSIS

LOAD CASE 1 GRAVITY	LOAD CASE 2 WIND 90°	LOAD CASE 3 WIND 0°

LOADS

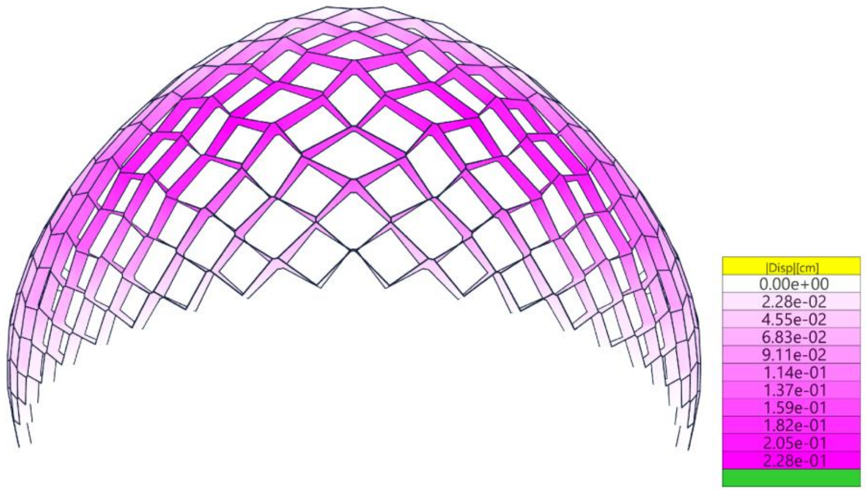


MATERIAL: ESTANE® 3D TPU F98A-030 CR

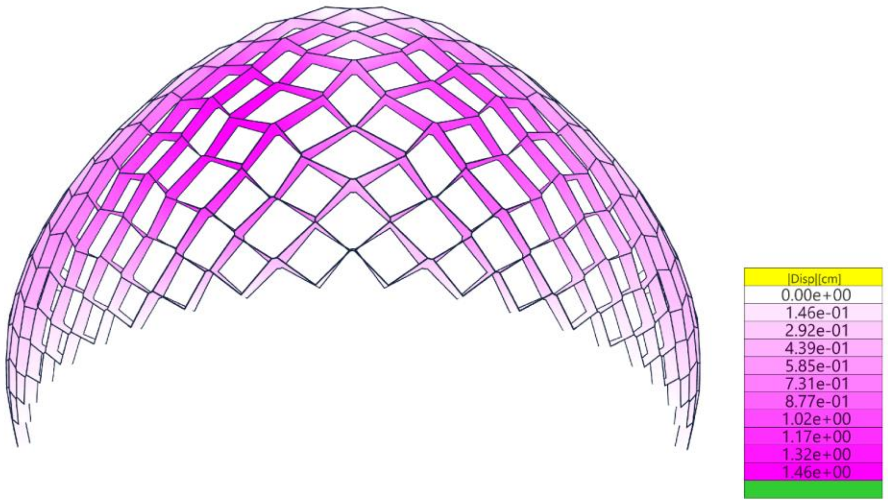
STATIC ANALYSIS

LOAD CASE 1 GRAVITY	LOAD CASE 2 WIND 90°	LOAD CASE 3 WIND 0°

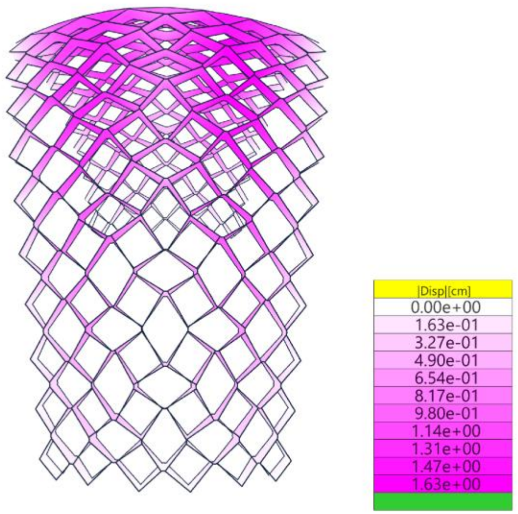
DISPLACEMENT SLS



UNITY DISP. : 2,28 mm



UNITY DISP. : 14,6 mm



UNITY DISP. : 16,3 mm

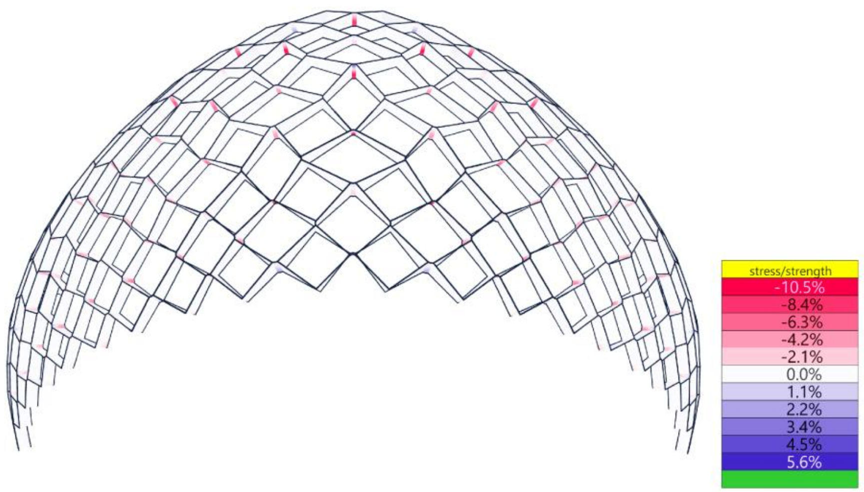
MATERIAL: ESTANE® 3D TPU F98A-030 CR

STATIC ANALYSIS

STRESS/STRENGHT RATIO ULS

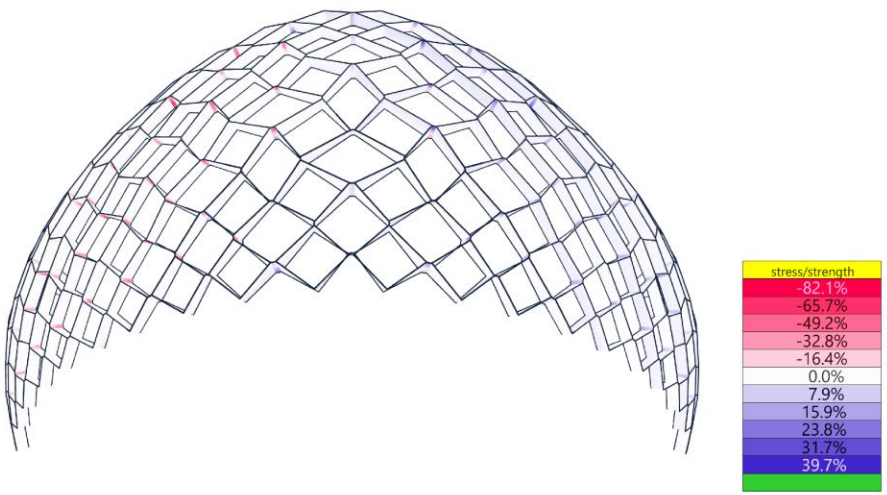
LOAD CASE 1 GRAVITY	LOAD CASE 2 WIND 90°	LOAD CASE 3 WIND 0°

LOAD CASE 1 GRAVITY



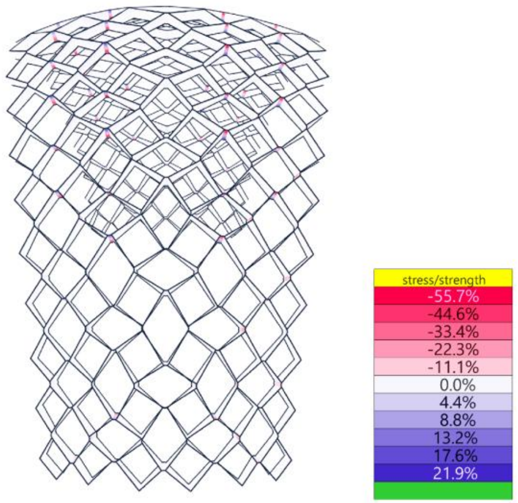
UNITY MAX: 5.6% MIN: -10.5%

LOAD CASE 2 WIND 90°



UNITY MAX: 39.7% MIN: -82.1%

LOAD CASE 3 WIND 0°



UNITY MAX: 21.9% MIN: -55.7%

MATERIAL: ESTANE® 3D TPU F98A-030 CR

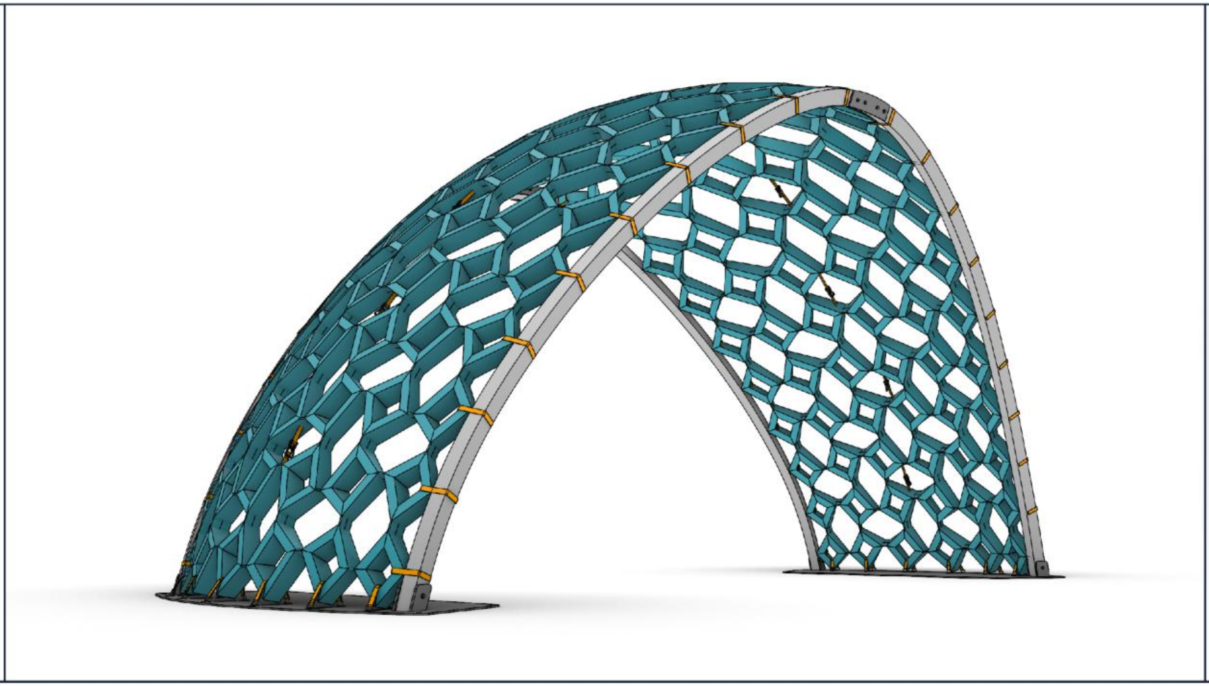
NOTES

Important notes/further research:

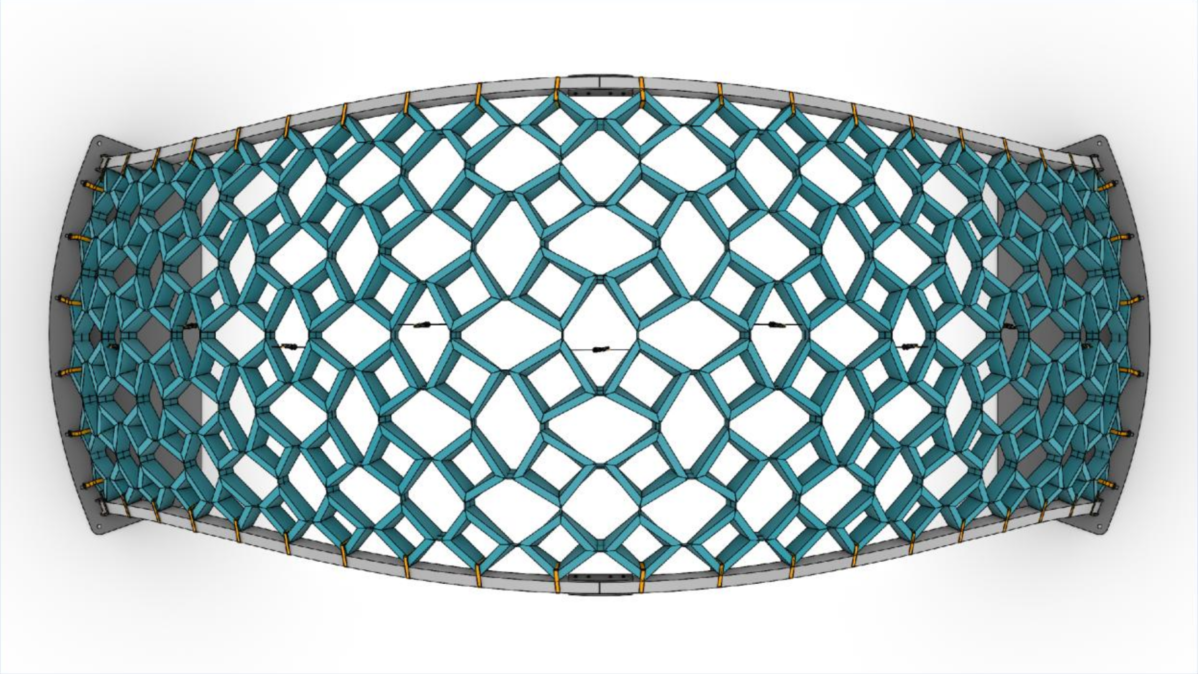
- Stresses from the deployment process (during load cases).
- No material safety factors have been applied (none exist for the selected material).
- Material is assumed isotropic, despite 3D printed parts typically being anisotropic.

MODEL DETAILS

A. CASE STUDY DESIGN

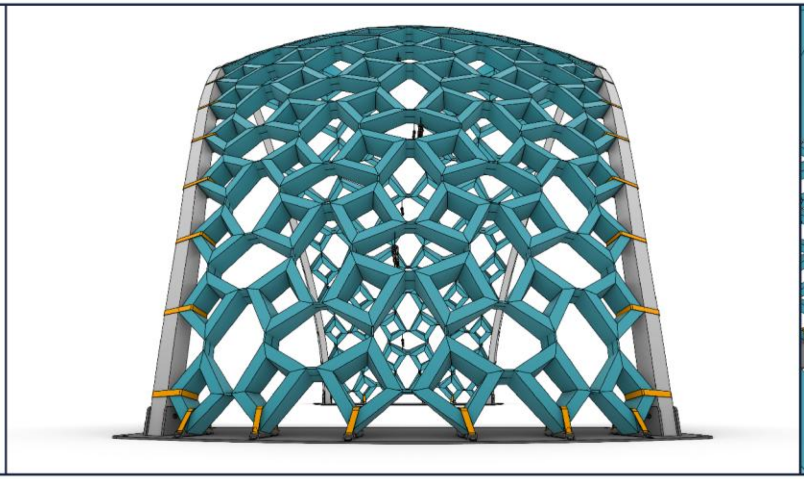


D. TOP VIEW

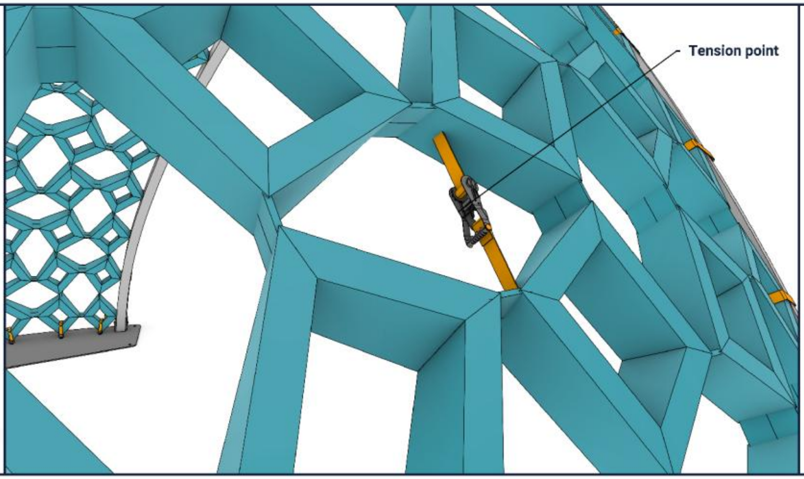


MODEL DETAILS

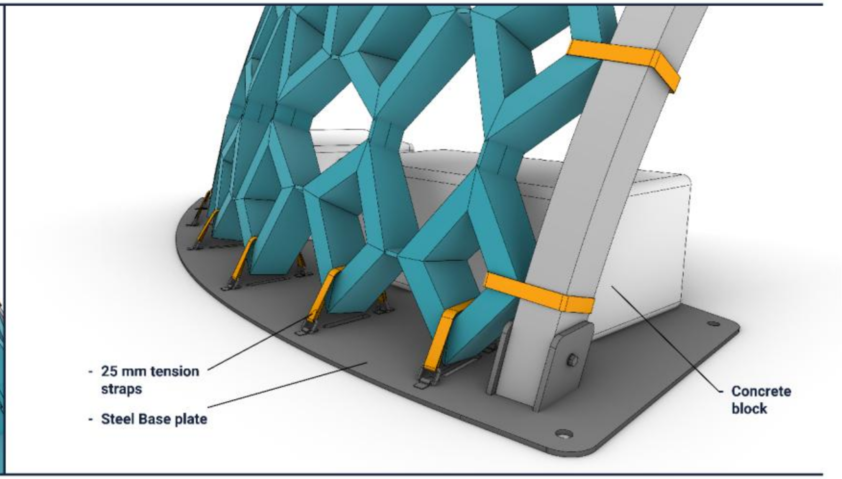
B. SIDE VIEW



E. TENSION POINT

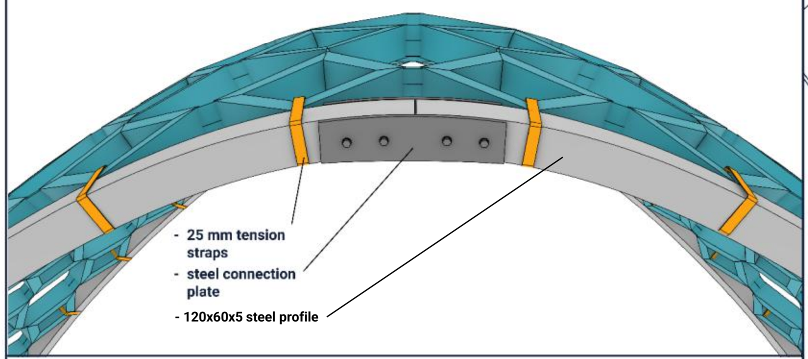


F. BASE PLATE



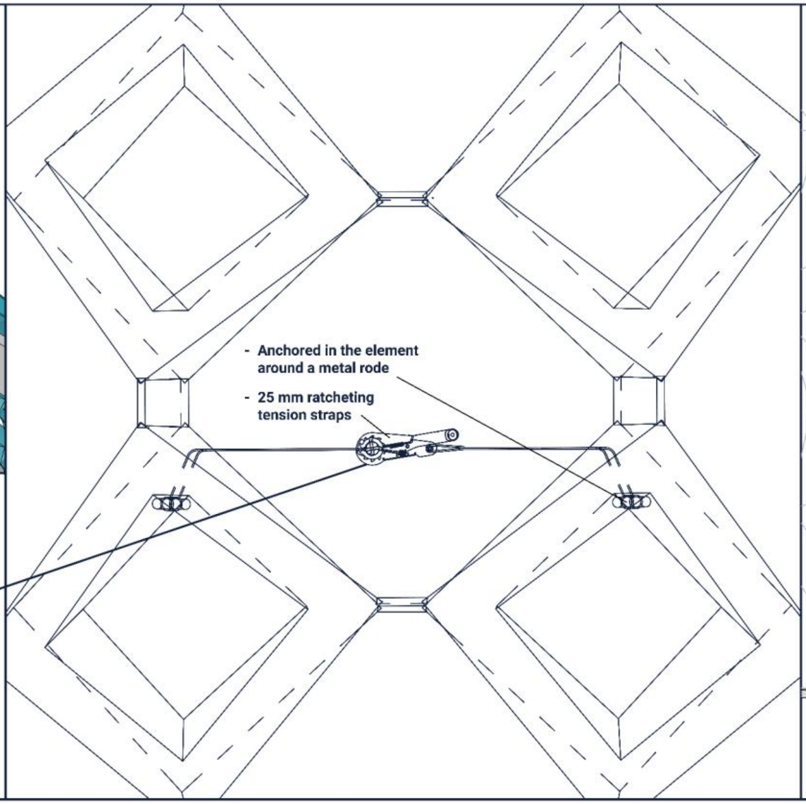
MODEL DETAILS

C. BEAM CONNECTION

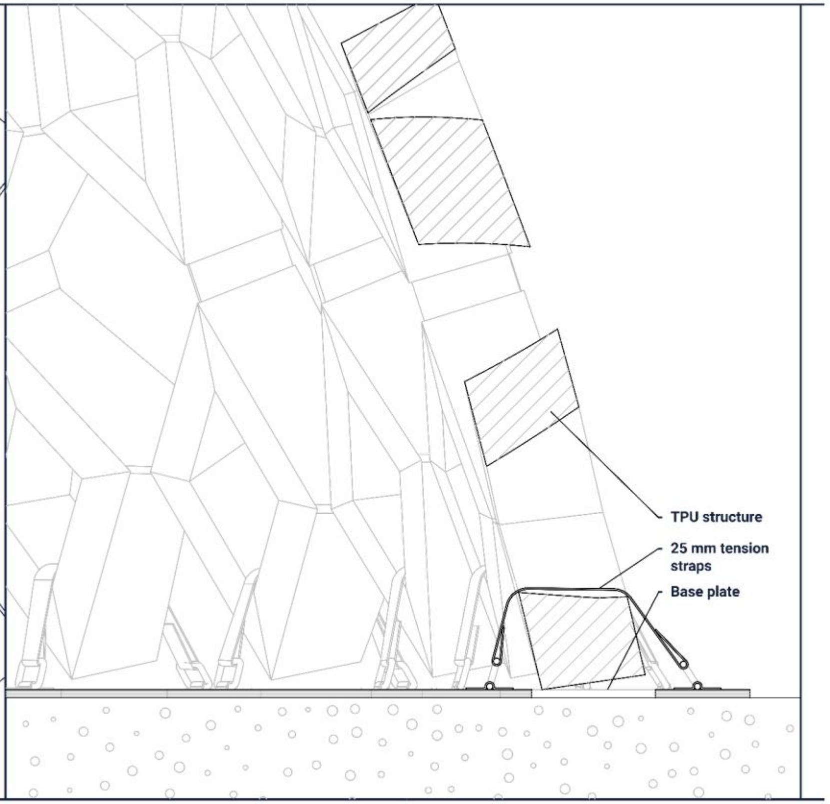


TENSION STRAP

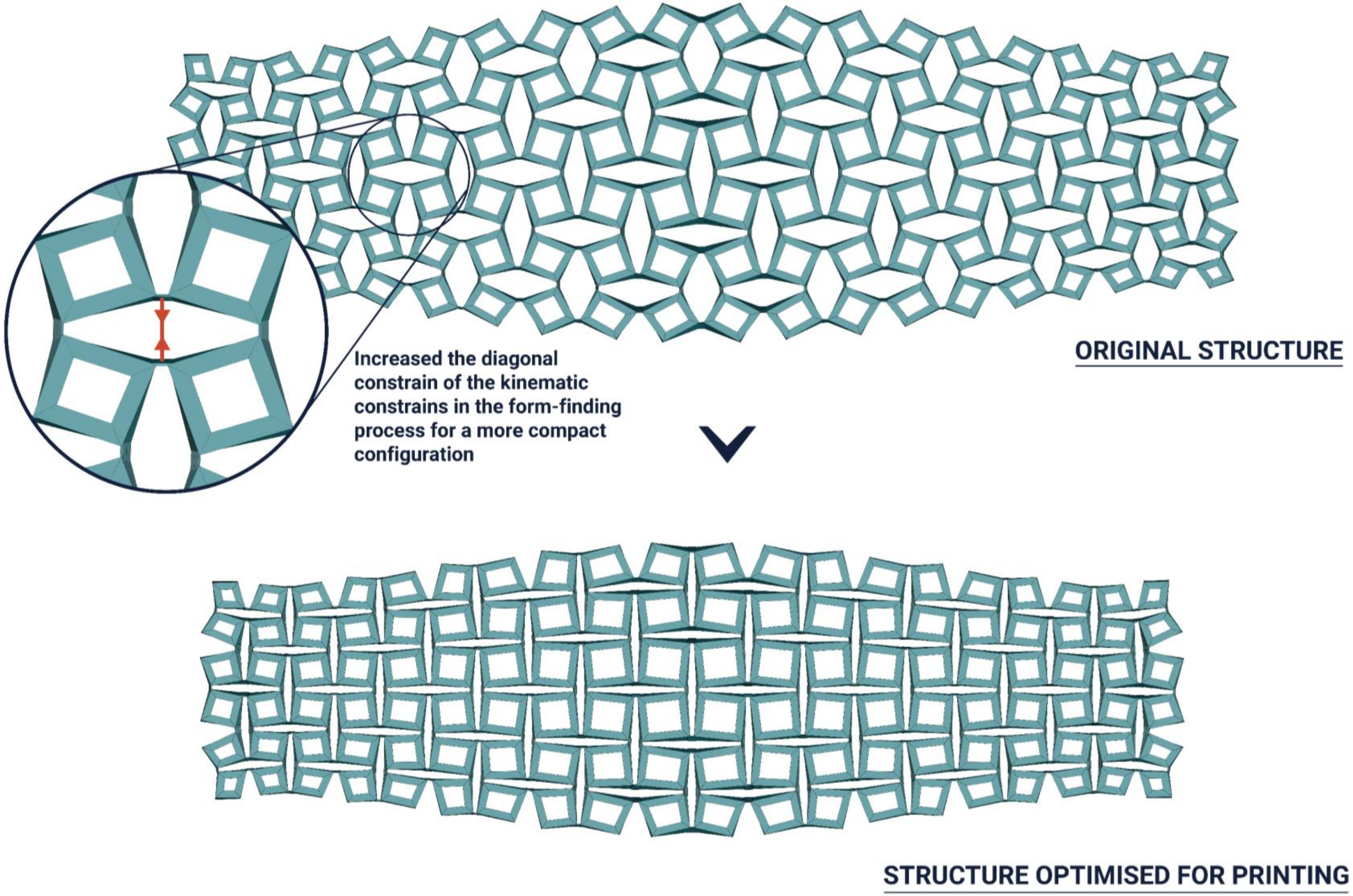
G. 1:2 DETAIL TENSION



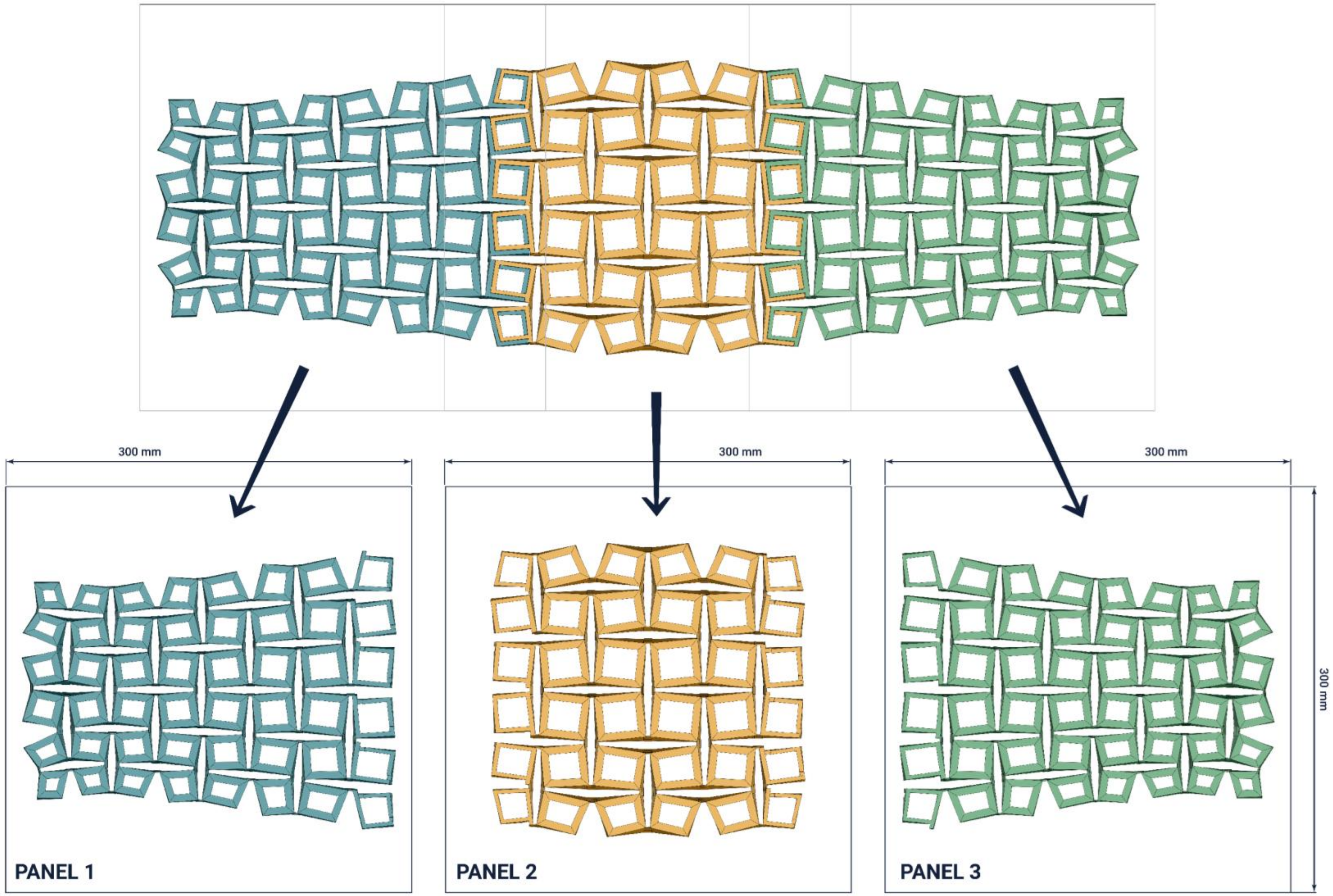
H. 1:2 DETAIL BASE



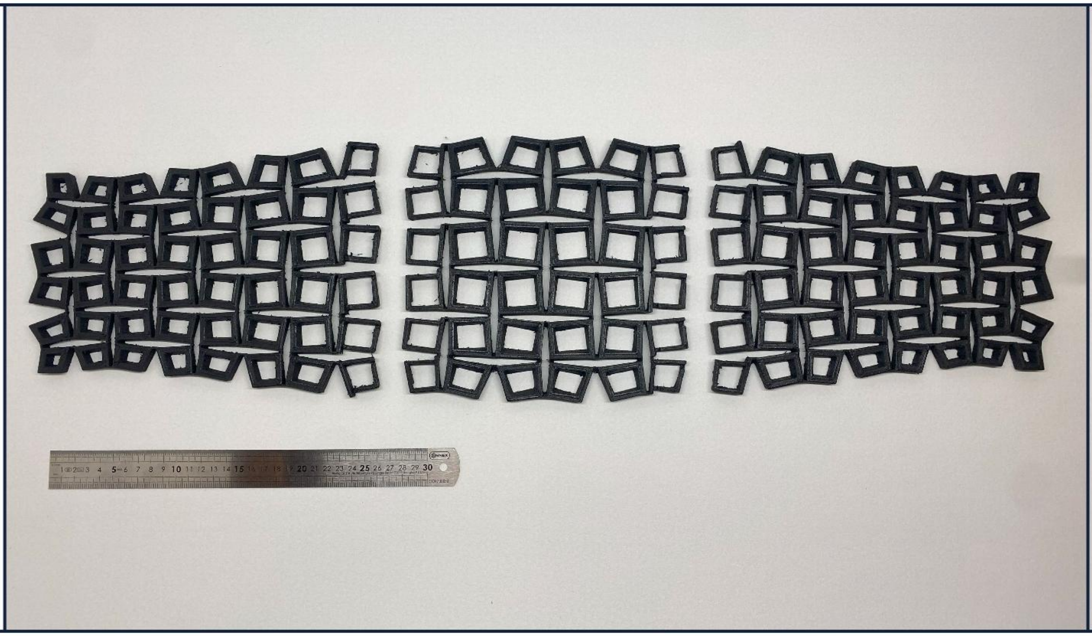
ADJUST FLAT STATE



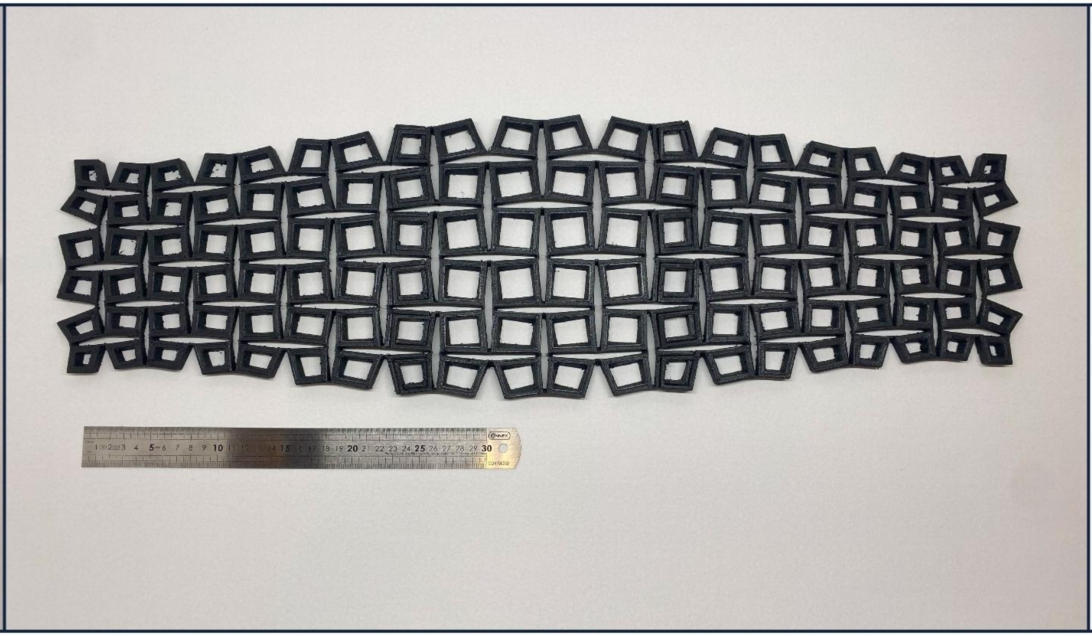
DIVISION IN PANELS



CONNECTION ELEMENTS

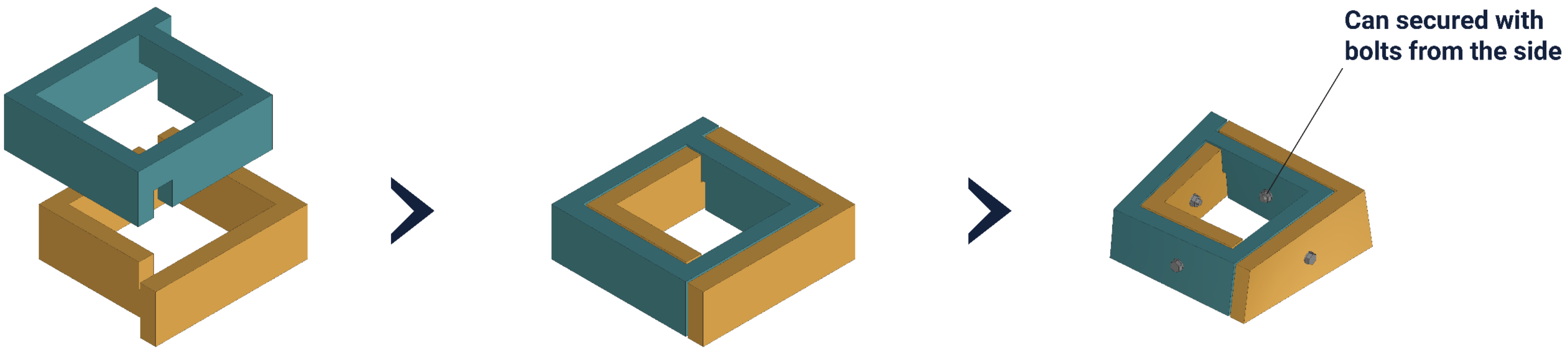


PANELS SEGMENTS



ASSEMBLED STRUCTURE

CONNECTION ELEMENTS

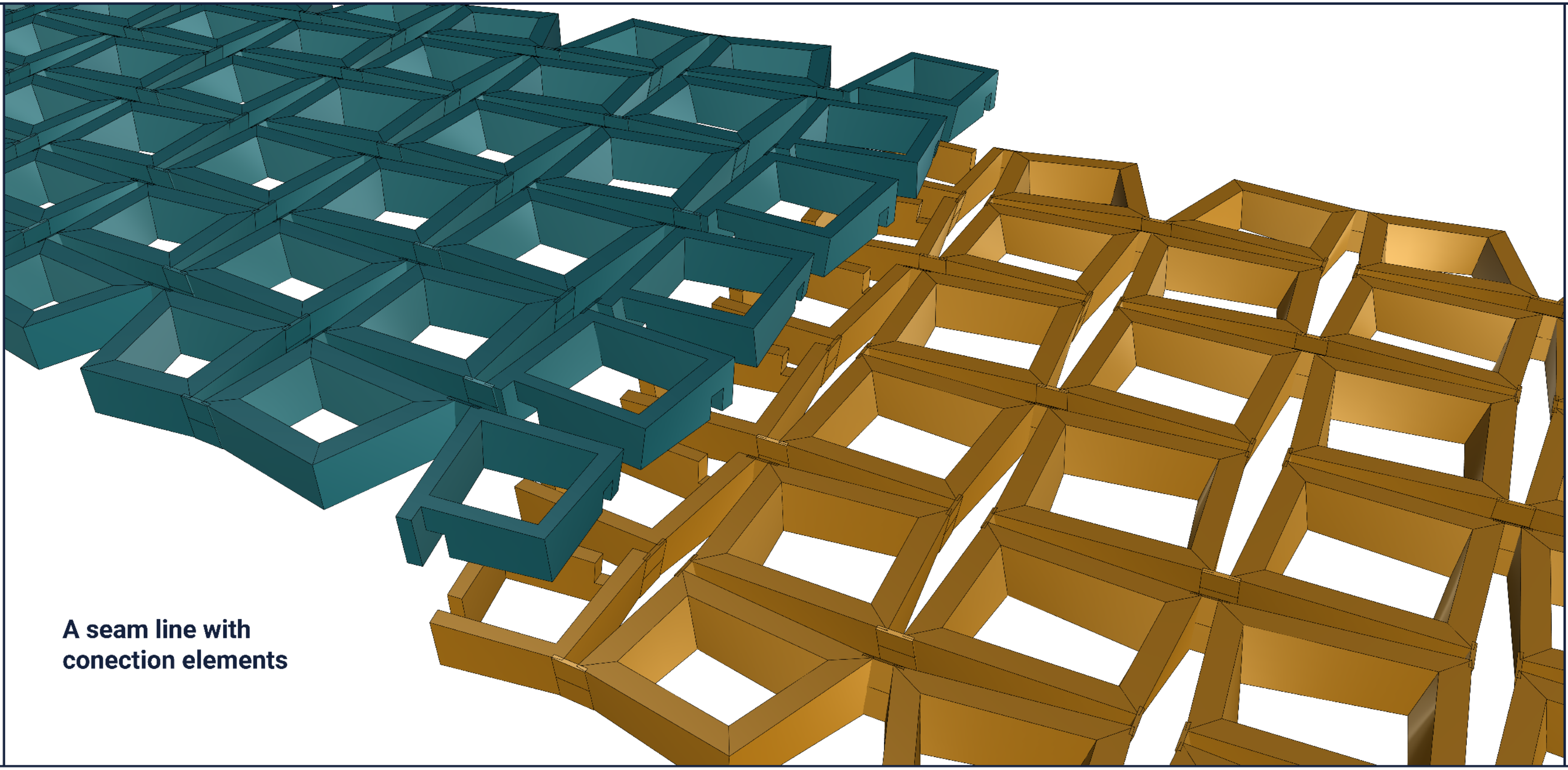


2 Interlocking parts

Join together into one element

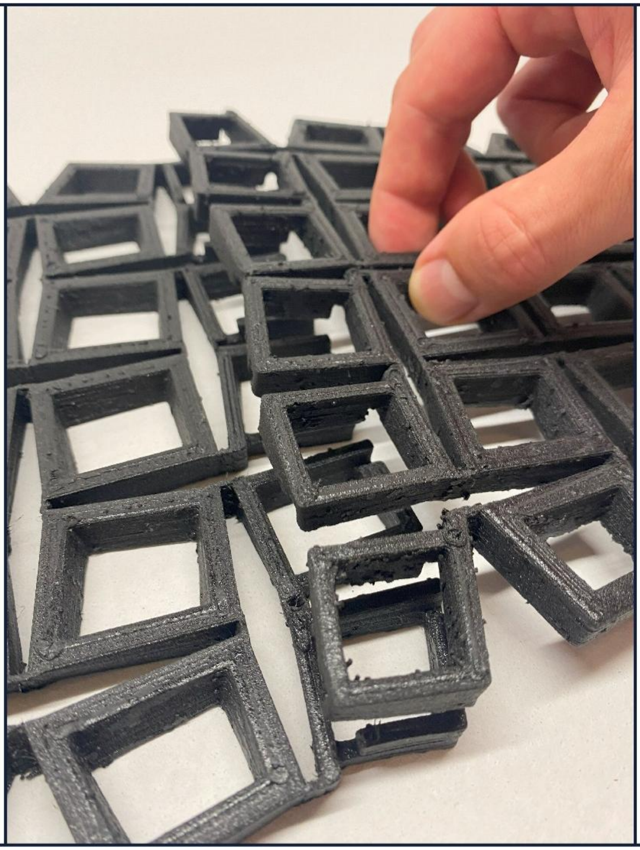
Morphed into the required geometry

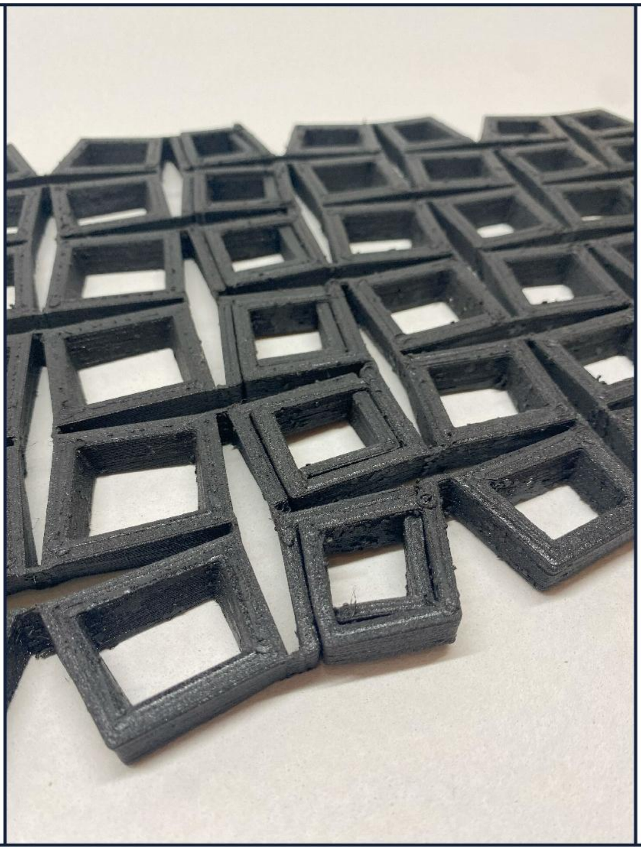
CONNECTION ELEMENTS



A seam line with conection elements

CONNECTION ELEMENTS





CONCLUSION

THE TOOL

- Predictive design tool/ inverse design
- Tested on a variety of surfaces
- Methode shows potential for other kinematic structures/patterns

SCALING UP

- Possible to manufacture on a larger scale
- Weight issue/ alternative designs
- Further research in materials balance structural stiffness and complaint hinges

CASE STUDY

- Design shelter on a architectural scale
- More research on stresses during deployment

END

Questions?