BUCKLE BENDING COLD LAMINATED THIN GLASS WITH SOLAR CONTROL INTEGRATION

1 July 2025
MSc Building Technology

Sanguk Ryu

Supervisor
Prof. Dr. Mauro Overend
Dr. Eleonora Brembilla
Robert Capel (Octatube)

octatube
PILKINGTON
H.B. Fuller | KÖMMERLING
TTEC

TU Delft



BACKGROUND

Glass



- Broken heat strengthened glass

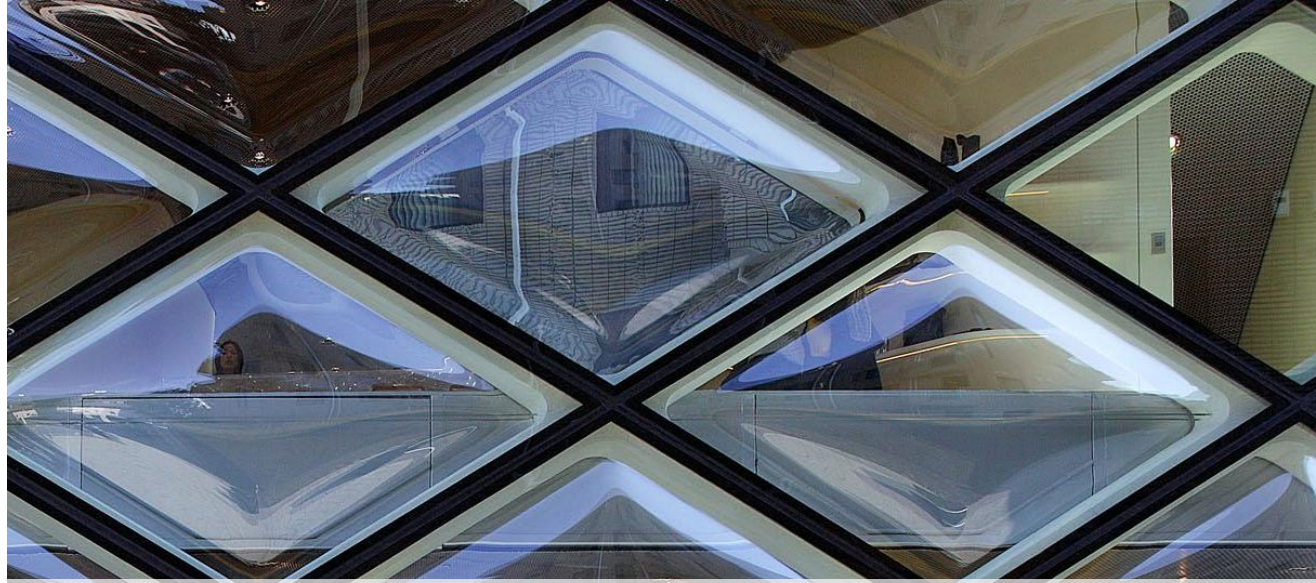


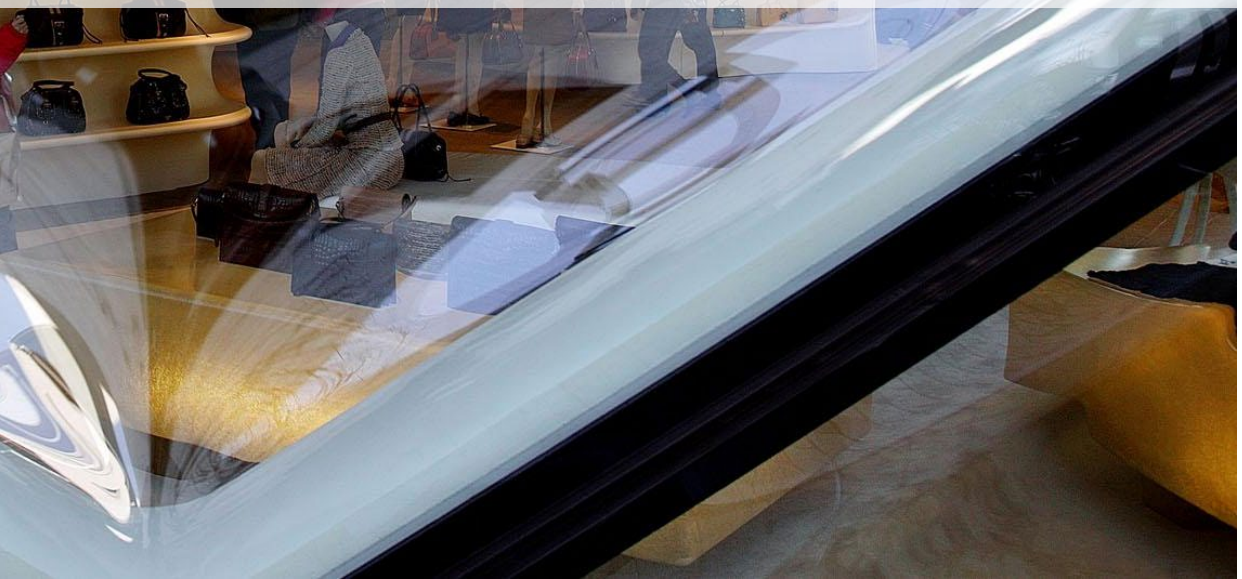
- Galeria de Oficinas Zamora ©Javier Callejas

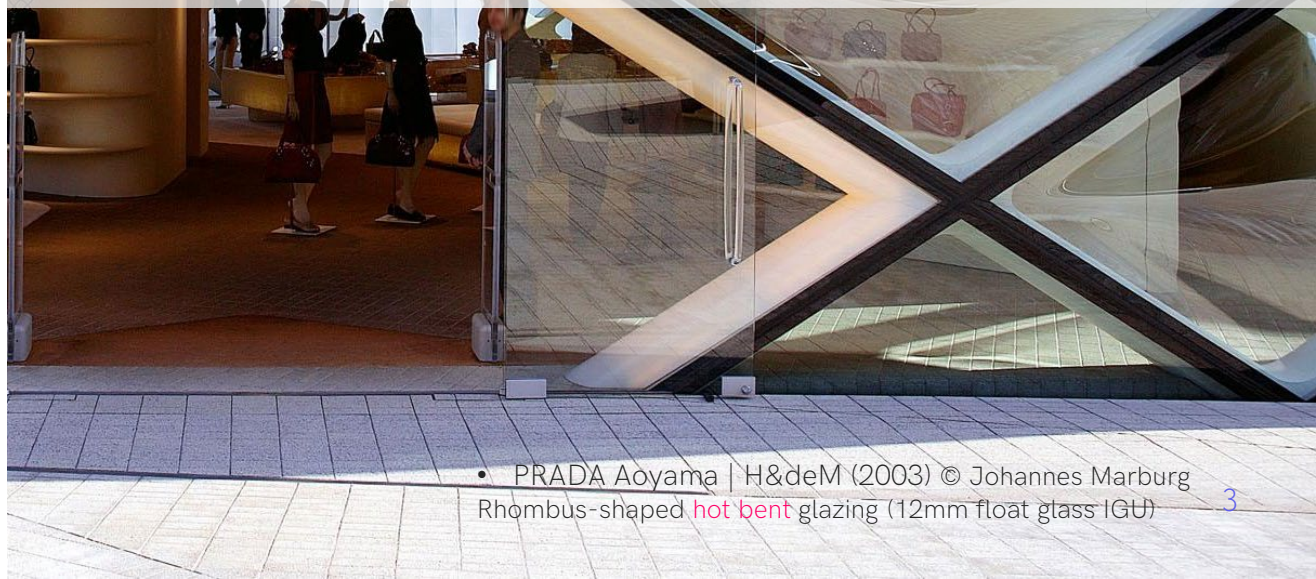
BACKGROUND

Challenging glass designs?
So far, only possible through **hot-bending** technology



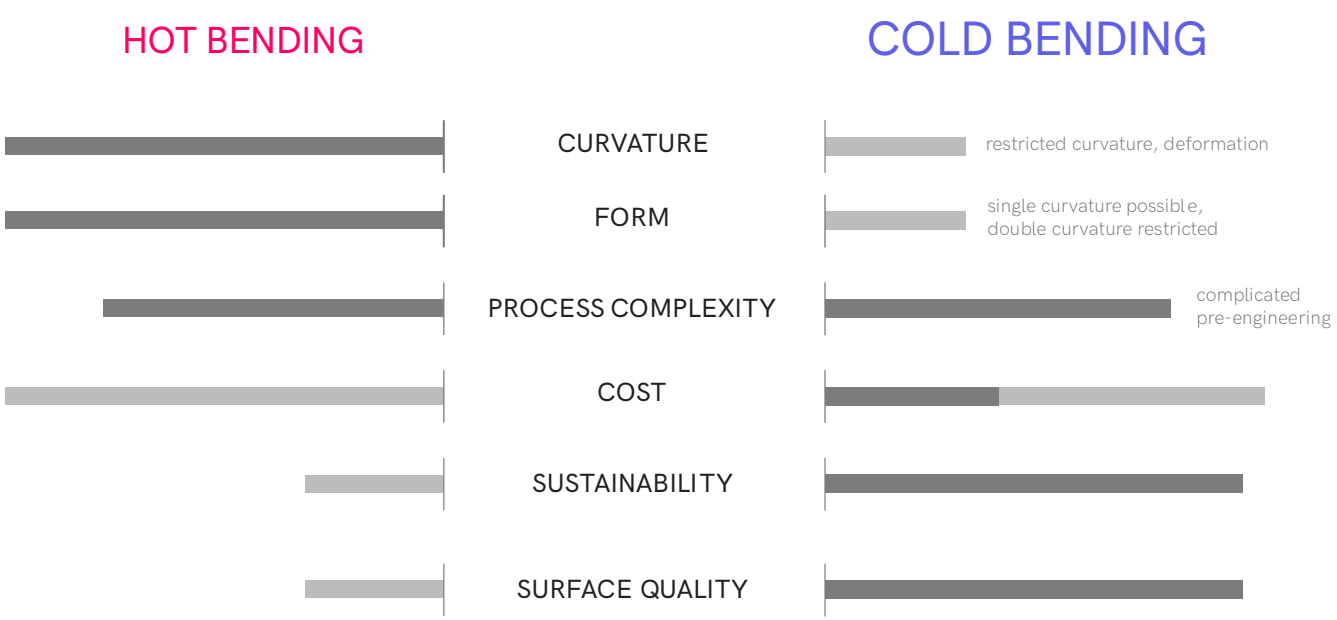


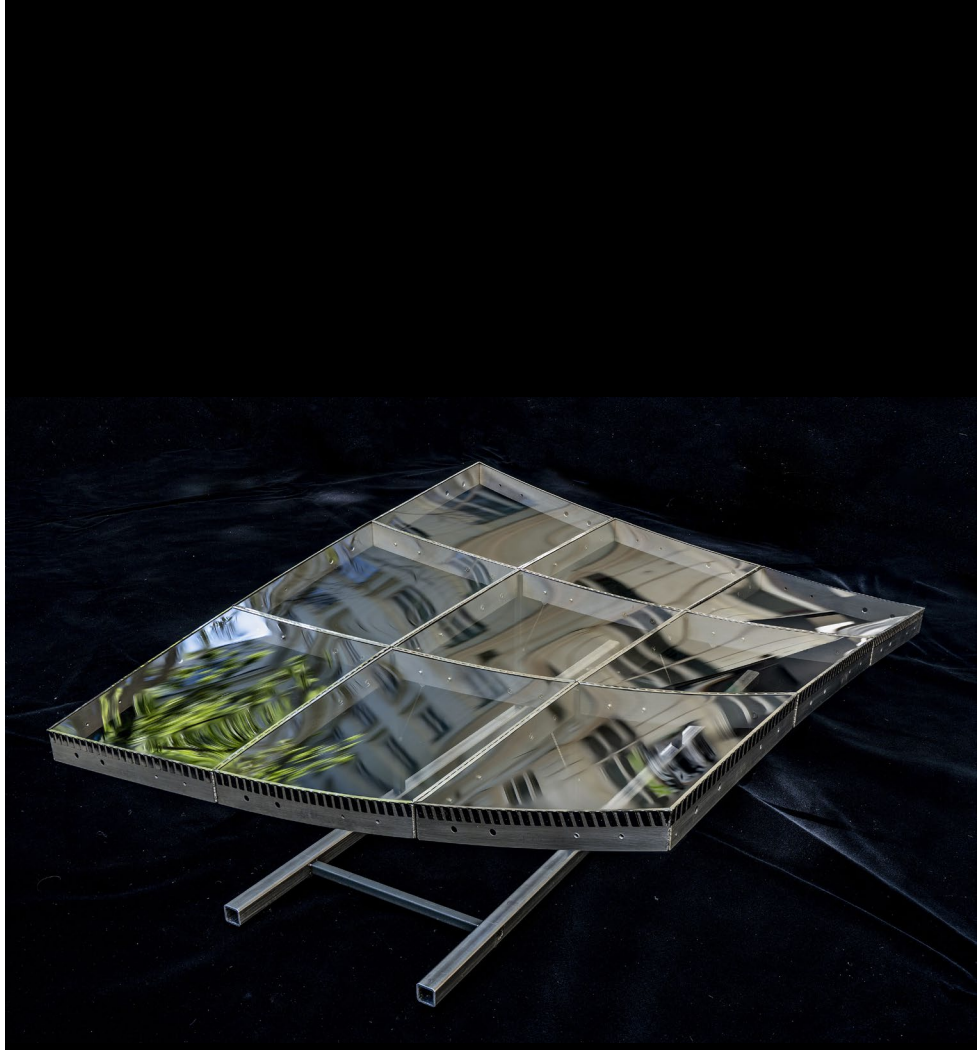




- PRADA Aoyama | H&deM (2003) © Johannes Marburg
  Rhombus-shaped hot bent glazing (12mm float glass IGU)

BACKGROUND



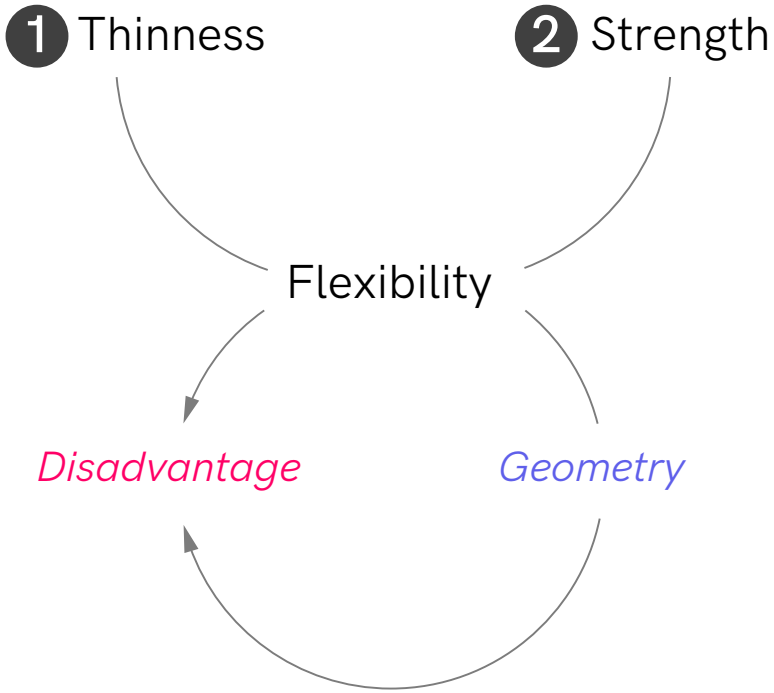


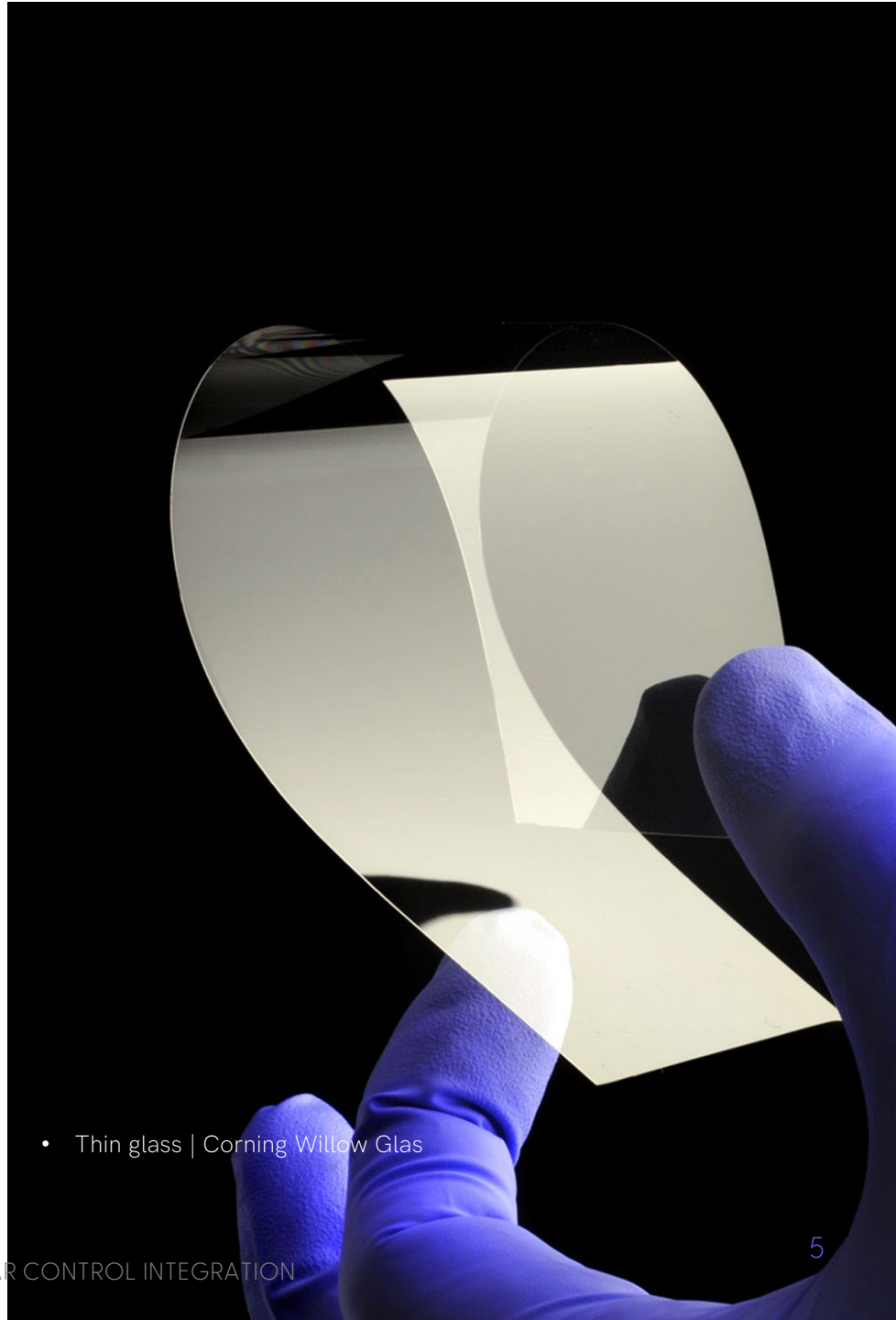
- Double-curved cold bent panel ©Konstantinos Garvriil

BACKGROUND

Thin glass

Chemically toughened thin glass structure,
Ranging from 0.1mm to 2mm





- Thin glass | Corning Willow Glas

BACKGROUND

Thin glass

Chemically toughened thin glass structure,
Ranging from 0.1mm to 2mm

1 Thinness

2 Strength

Flexibility

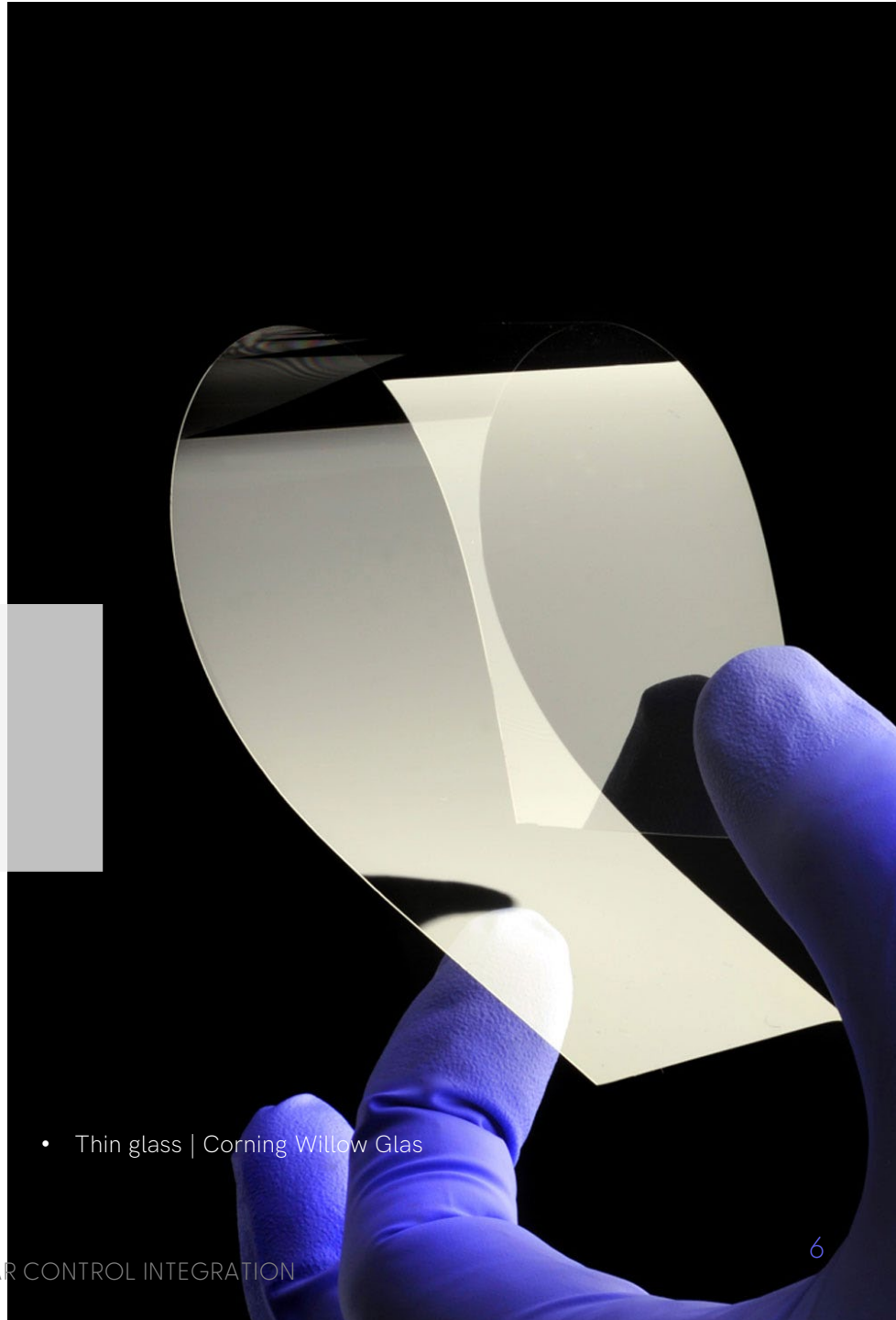
STIFFNESS

Geometry

WHAT GEOMETRY ?

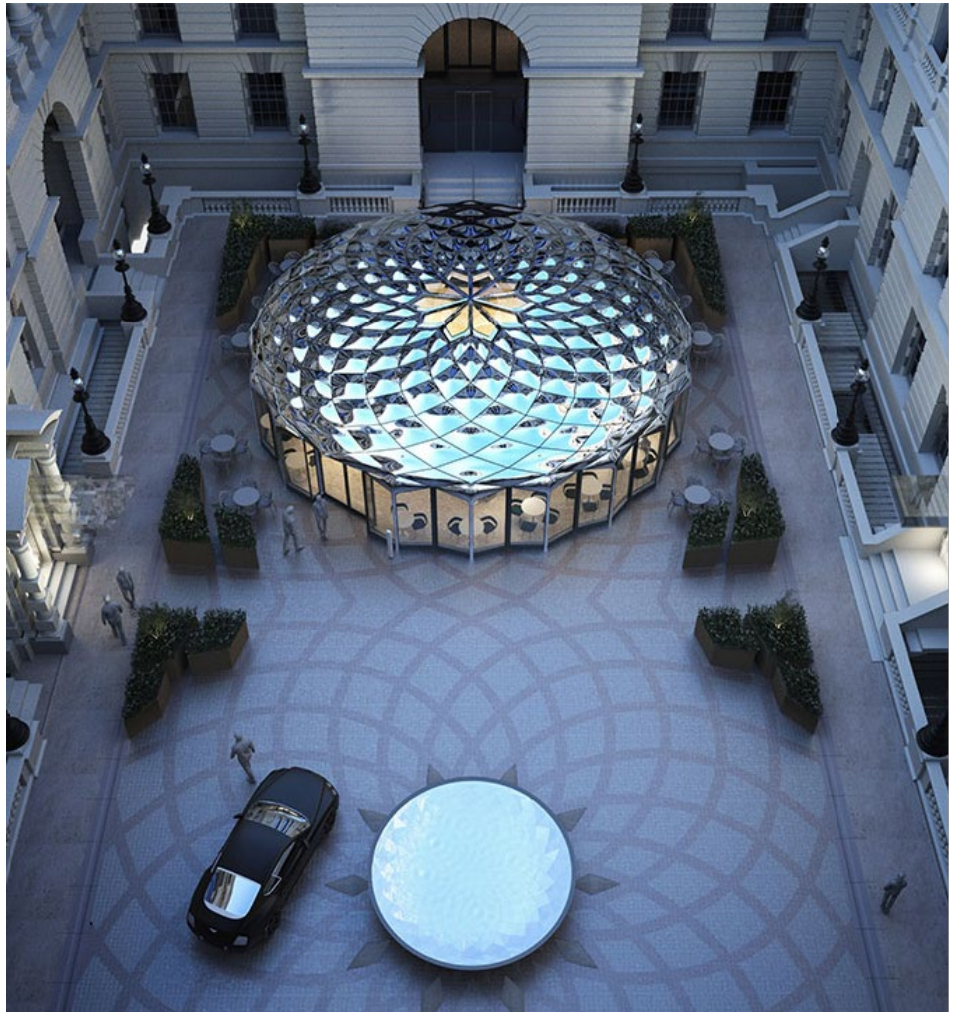
HOW?

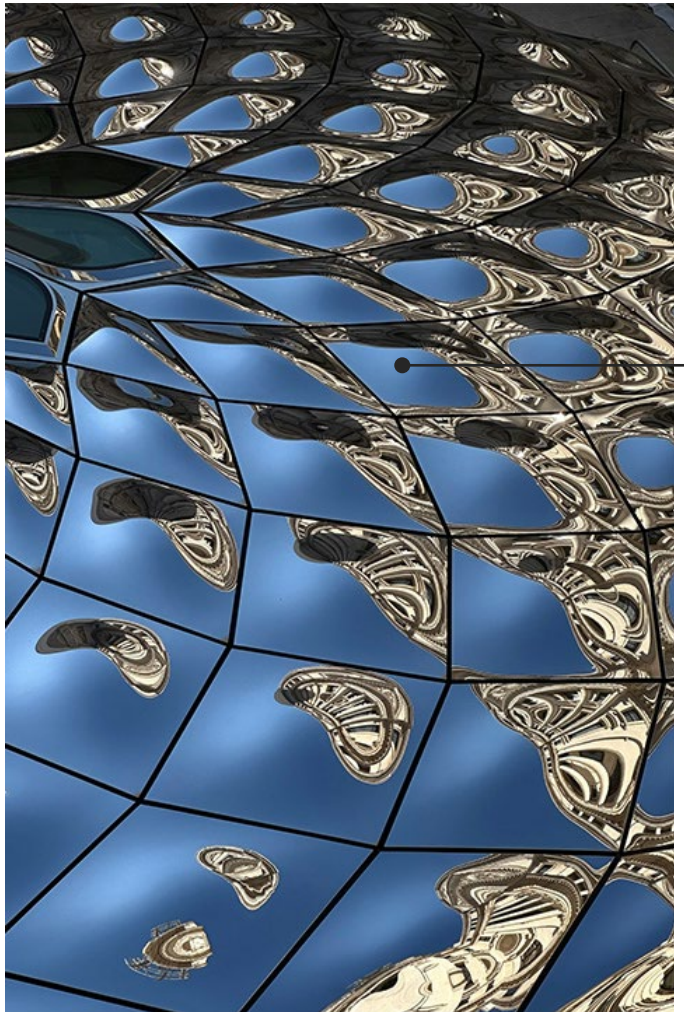
TO WHAT EXTEND?



- Thin glass | Corning Willow Glas

BENCHMARK APPLICATION



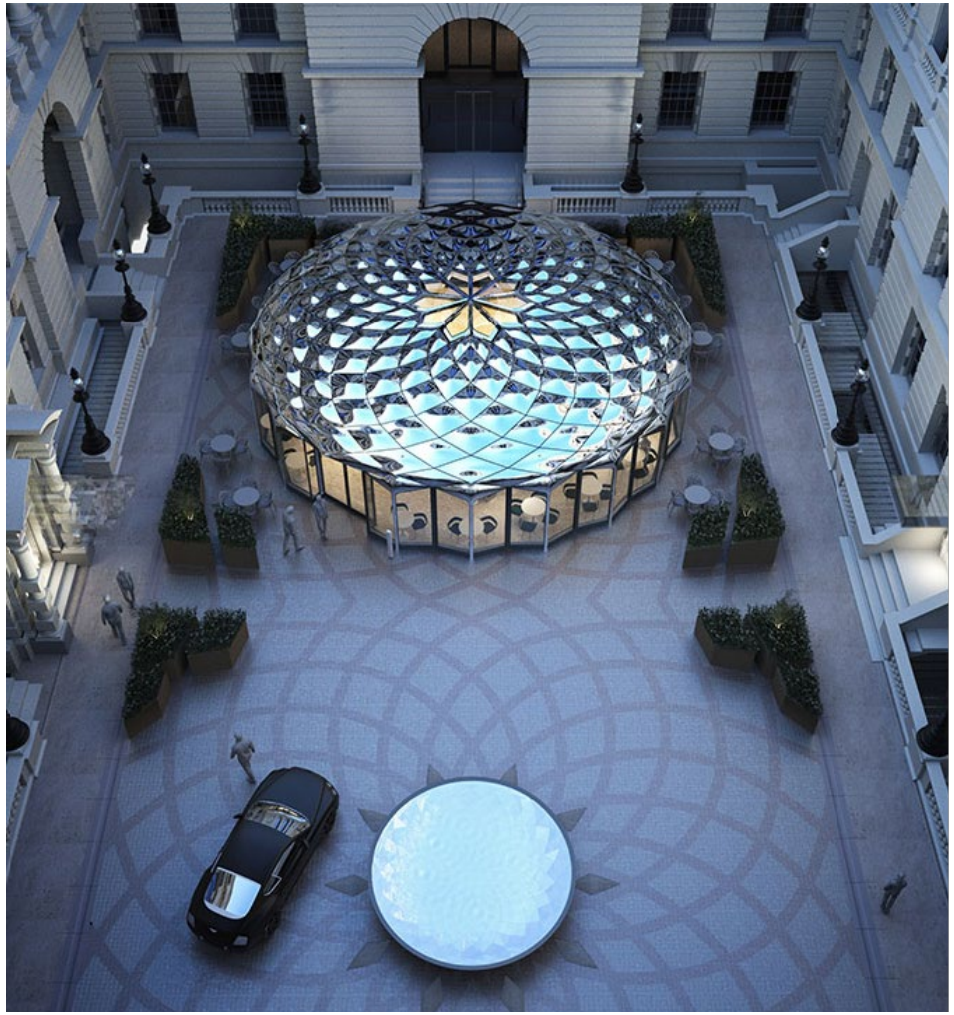


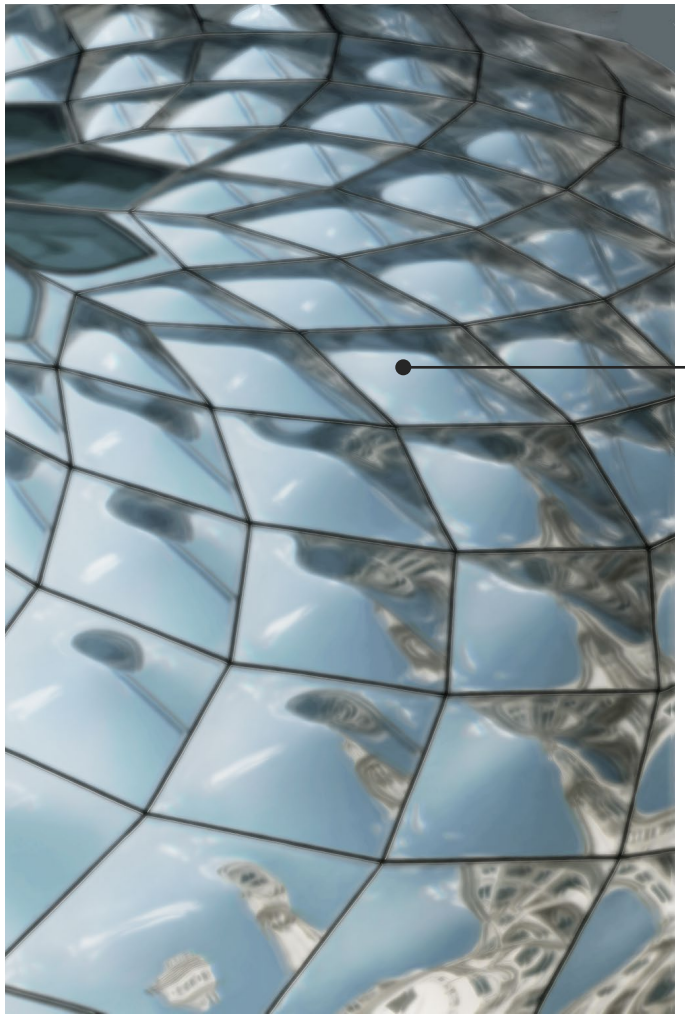
Original Design

SS panel;
Hydraulic
pressure formed;
Mirror polished

- OWO Pavilion, London (2023)
  DAEWHAGANG ARCHITECTURE, OCTATUBE (façade engineering & construction)
  ©Daewha Kang Design

BENCHMARK APPLICATION





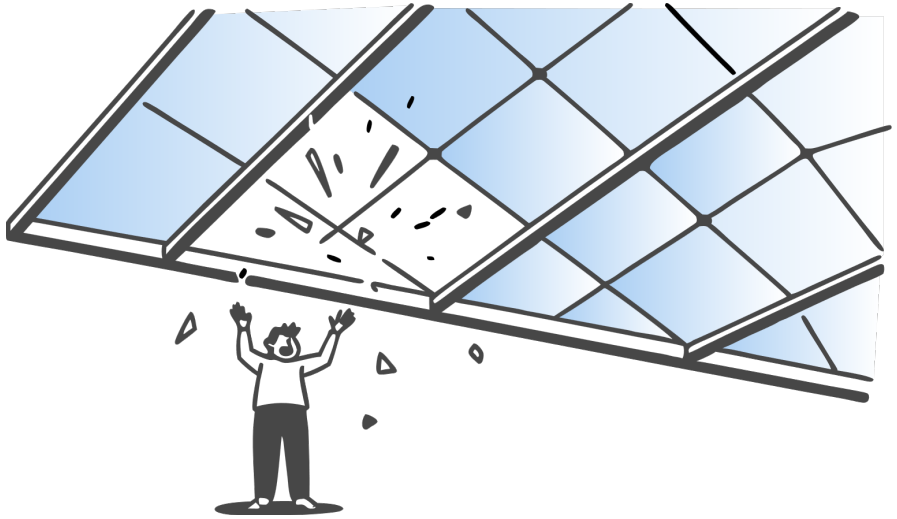
Revised Design

Cold-bent thin glass

- OWO Pavilion, London (2023)
  DAEWHAGANG ARCHITECTURE, OCTATUBE (façade engineering & construction)
  ©Daewha Kang Design

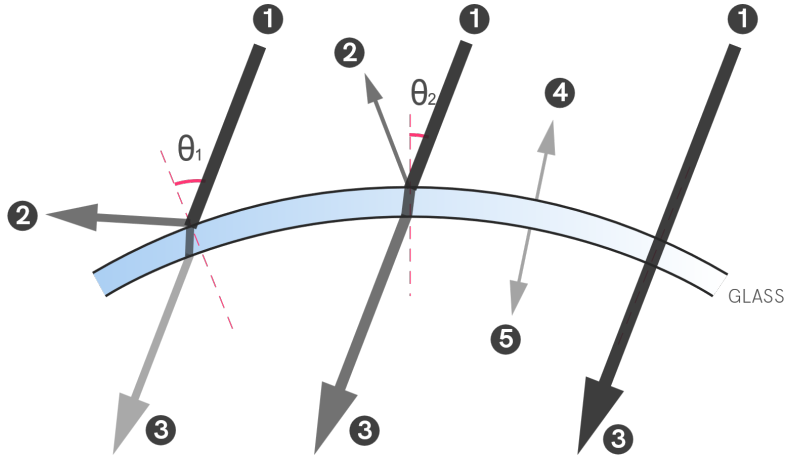
FURTHER CONSIDERATIONS

LAMINATION



- Generated with AI

SOLAR CONTROL



1) Incident radiation 2) Incident reflection 3) Transmitted radiation
4) Secondary emission-outside 5) Secondary emission-inside

RESEARCH QUESTION

How can thin glass be cold bent and laminated into smooth double-curvature forms for architectural applications, while integrating solar control mechanisms?

SUB-QUESTIONS

1. ***What kind of deformation*** *methods could be used to create a water-droplet like geometry for thin glass?*

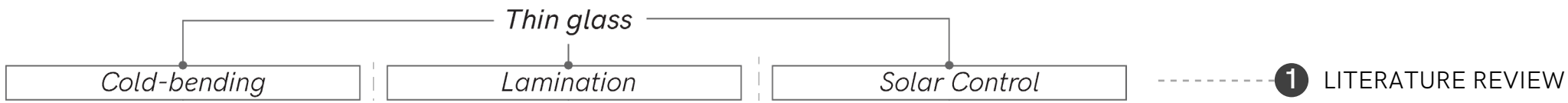
2. *What is the* ***most effective form*** *driven from the cold-bending process to implement the benchmark roof design?*

3. *How does the laminated glass panel* ***behave under*** *general* ***load conditions****, and what are its* ***post-failure characteristics****?*

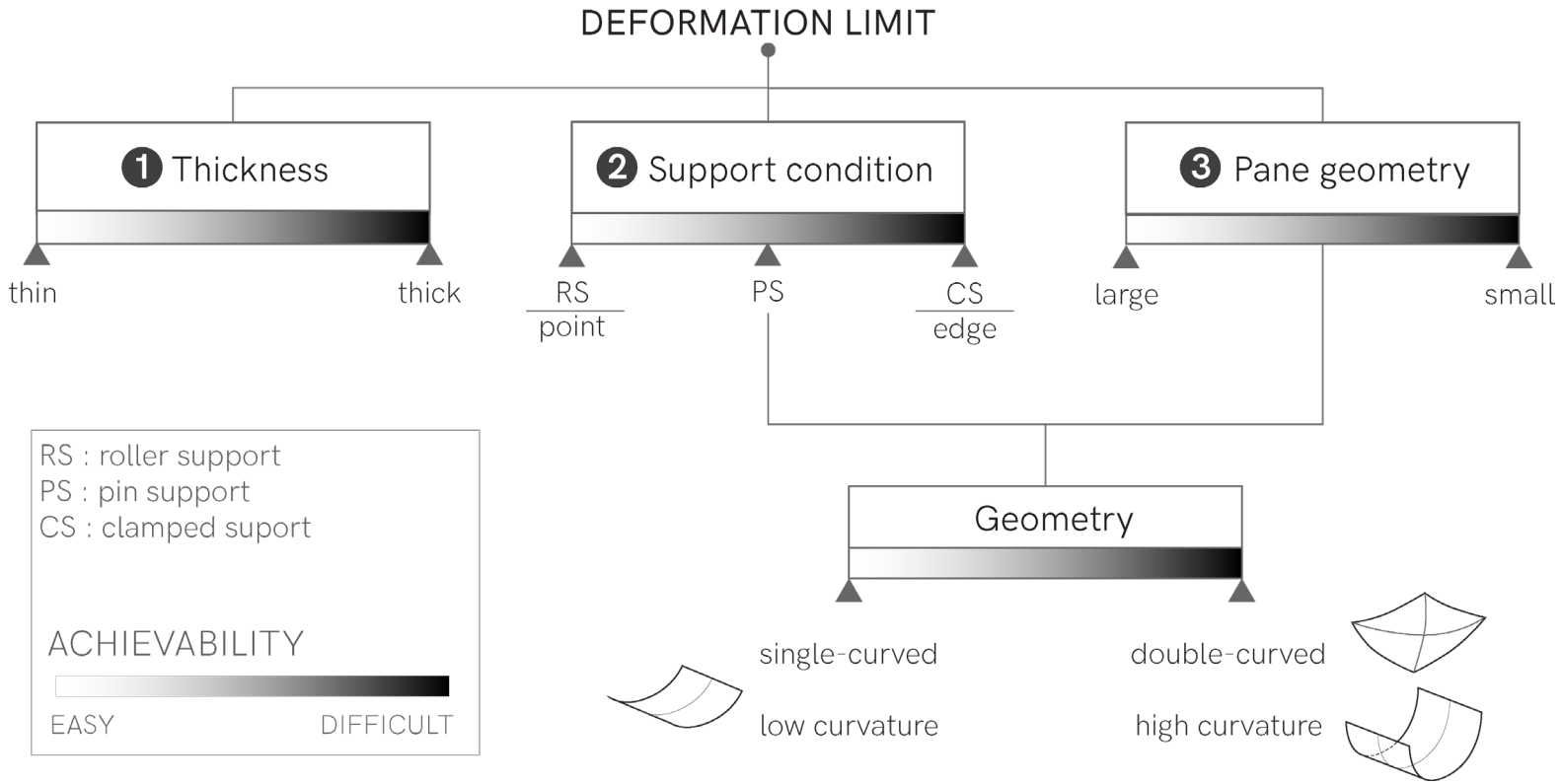
4. *How can solar simulations be utilised to design an* ***effective solar transmittance control*** *mechanism for double-curved thin glass?*

5. *What are the main* ***manufacturing challenges****?*

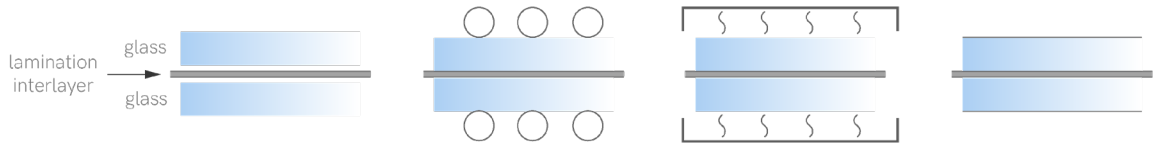
METHODOLOGY



LITERATURE REVIEW Cold Bending

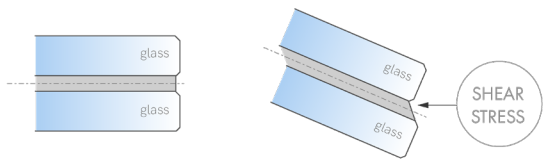


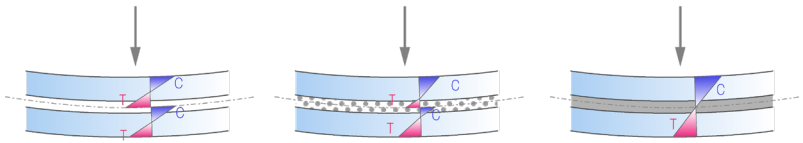
LITERATURE REVIEW Lamination



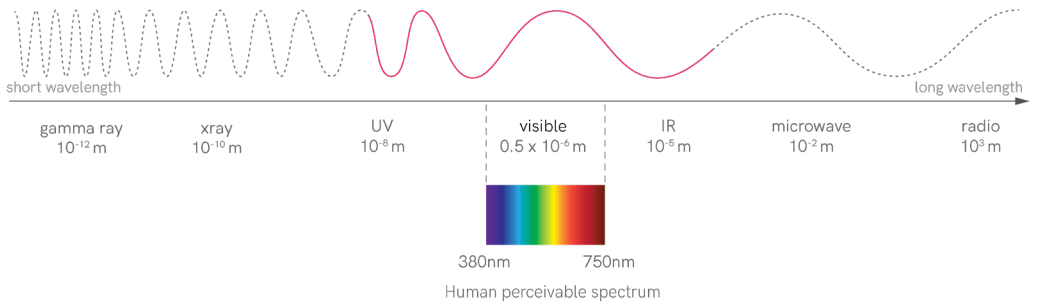
• Typical 2-stage lamination production (PVB & SGP)

	Original state	Process	Structural Character	Cold-bending compatibility
❶ Polyvinylbutyral (PVB)	Film (roll)	Pre-lamination (65°C) -> Autoclave (140 °C, 12-14 bar)	low shear elastic creep	bigger deformation poss. higher degree of spring-back
❷ SentryGlas Plus (SGP)	Film (sheets)		high shear rigid	low curvature poss.
❸ Cast-in-place resin (CIP/ LOCA)	Two-component resin	edge seal & liquid pouring -> curing (UV light)	lower shear than SGP diverse property	compatible to any shape



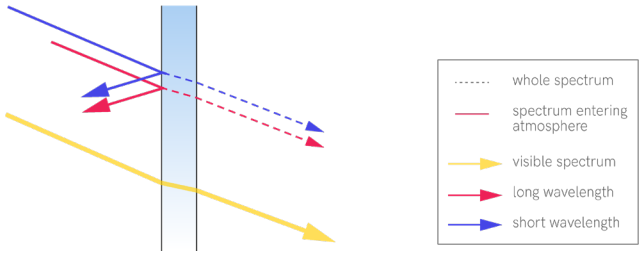


LITERATURE REVIEW Light Transmittance & Control Mechanisms



for other wavelengths,
transmission should be controlled to prevent indoor overheating

transmit visible wavelength as much as possible



1 TINTED GLASS
increasing absorptance

2 SELECTIVE COATING
reflecting or absorbing

absorbed energy could stiff have influence

3 CAVITY ELEMENT
blinds, films (low-E), textile, microlouvres, mirror array prismatic panel
...

4 SWITCHABLE GLAZING
electrochromic glazing

challenges applying to curved panel

5 CHANGING COATING POSITION

6 CHANGING GLASS THICKNESS

N/A

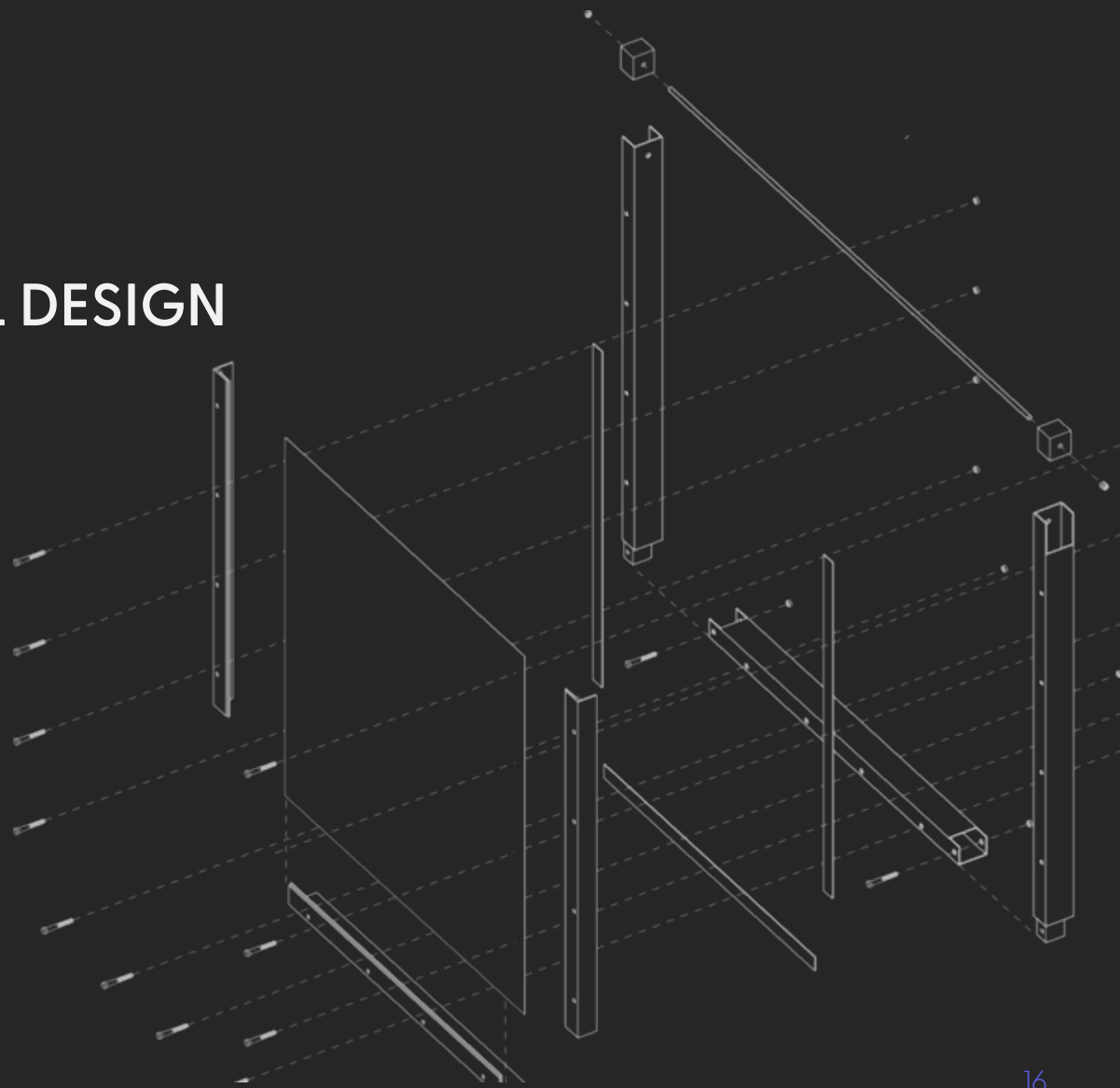
7 TREATMENT OF GLASS
etching, frit pattern

8 SHADING DEVICE
external louvre, indoor blind

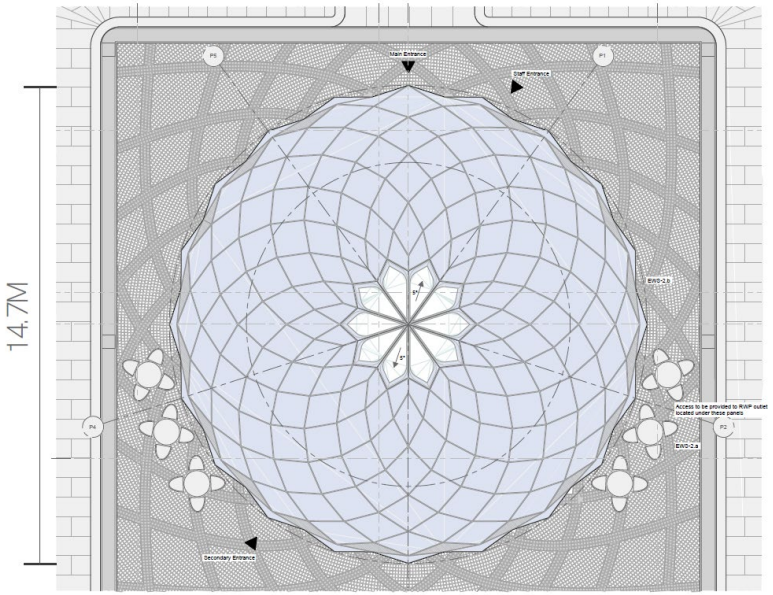
Increased load on structure, aesthetic issues

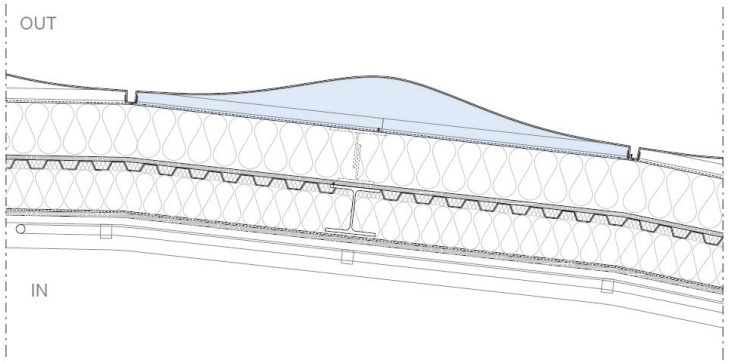
CONCEPTUAL DESIGN

Buckle Bending Machine: 3-edge fixture assembly



DESIGN OBJECTIVE

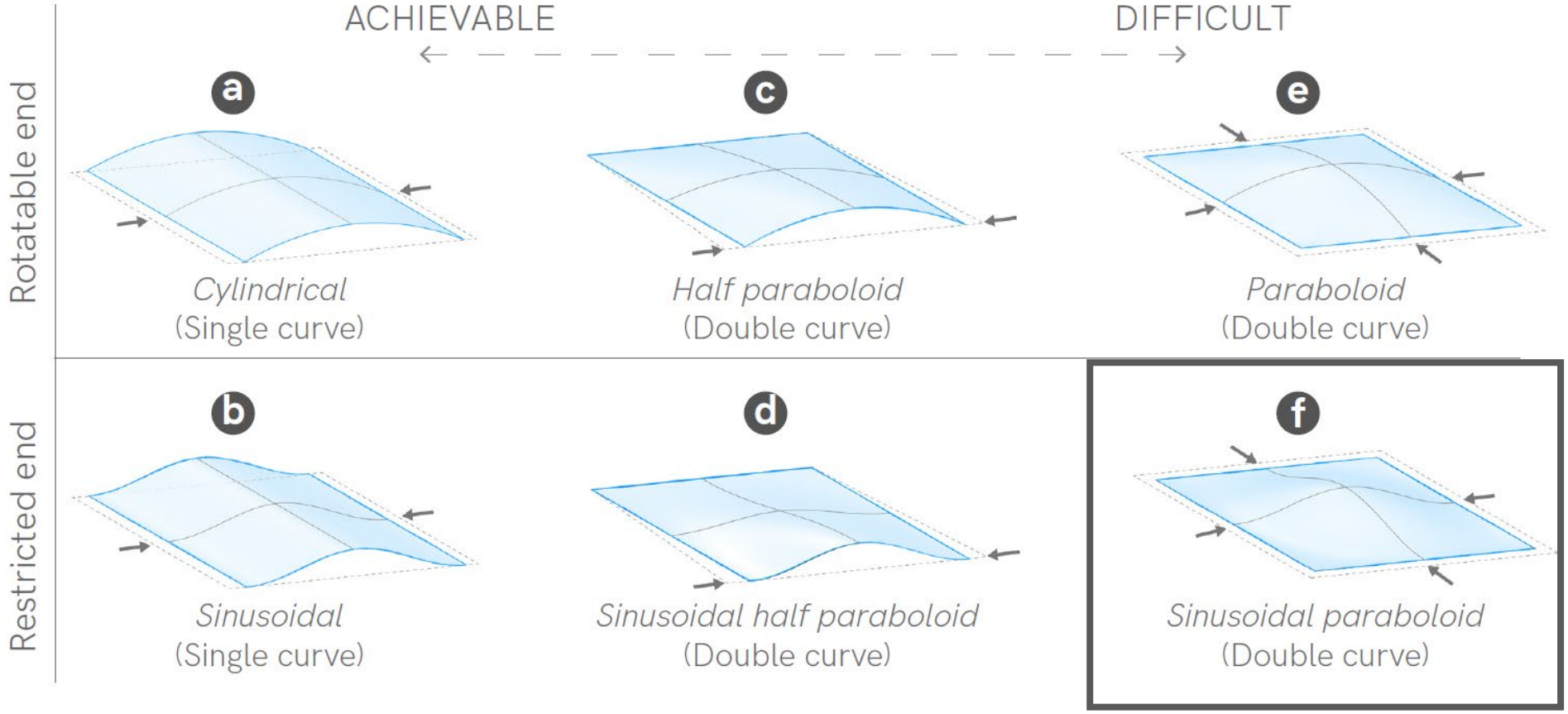




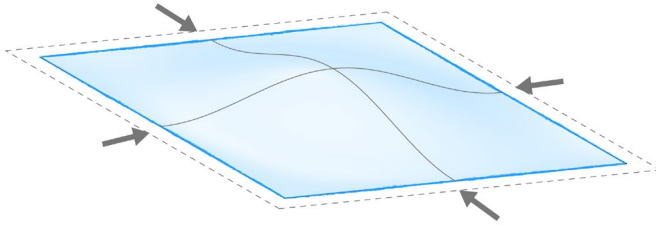
Elements where stainless steel panels are going to be replaced with glass within this research

1. Preserve the **original design**
2. **Avoid** reflection-distorting geometry
3. Meet basic **load requirements**
4. **Optimise** cold-bending **stress**
5. Uniform thickness & smooth surface

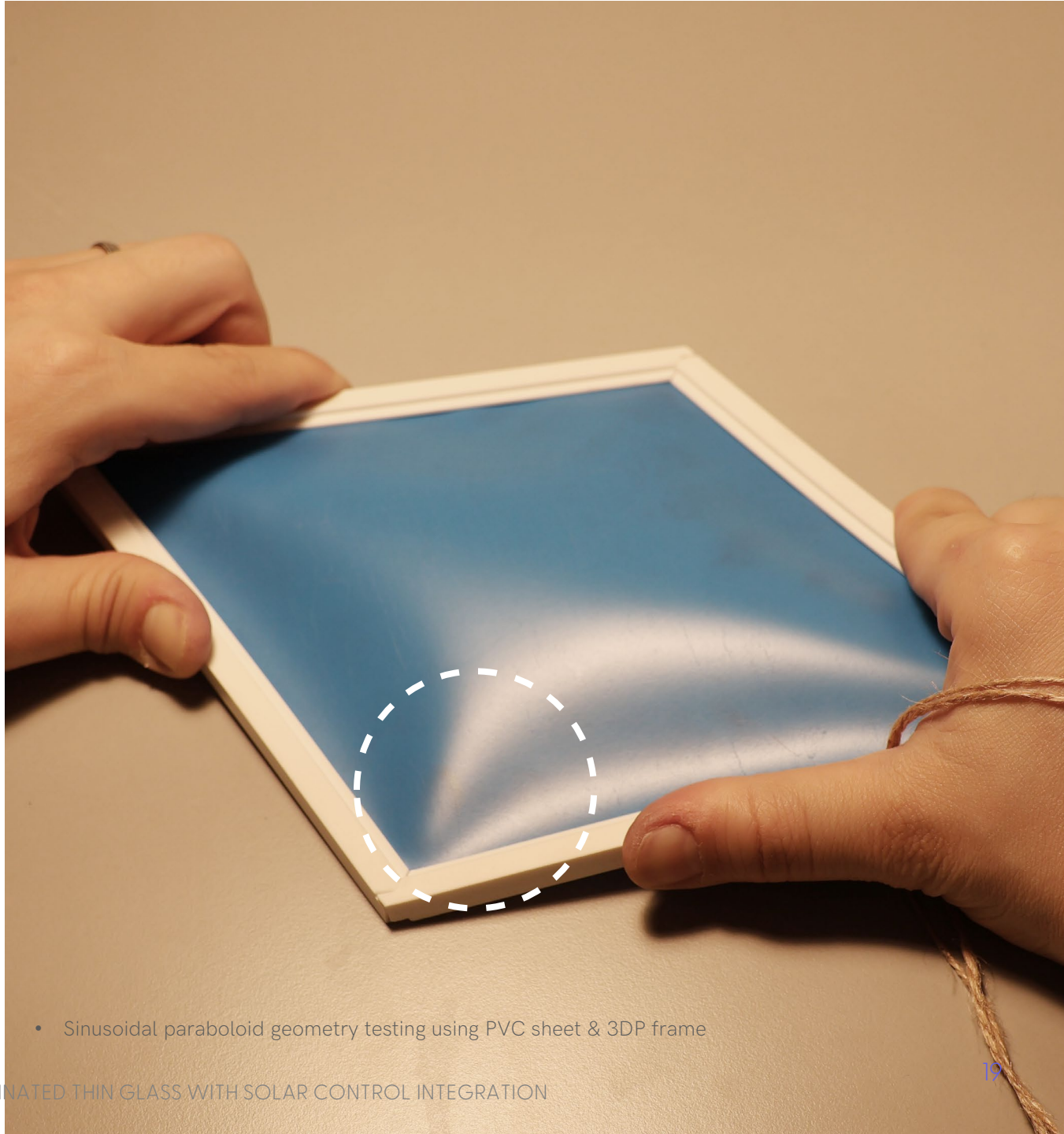
“BUCKLE BENDING”



GEOMETRY TESTING #1

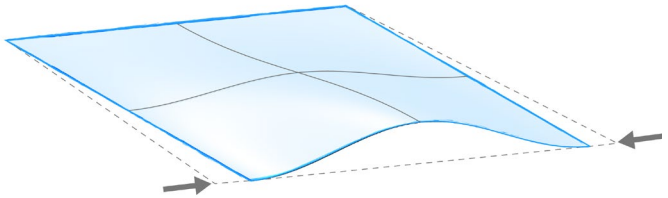


4-edge Rigid Support

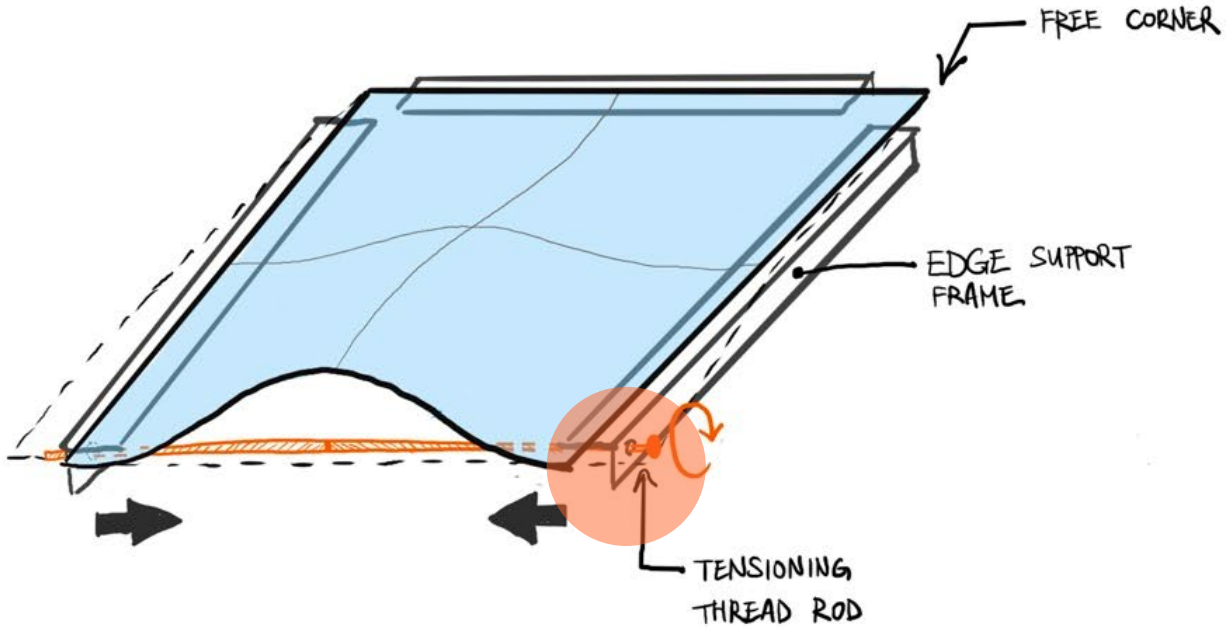


- Sinusoidal paraboloid geometry testing using PVC sheet & 3DP frame

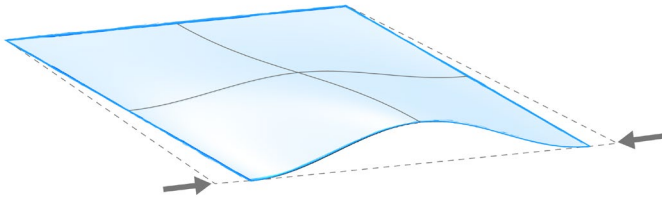
GEOMETRY TESTING #2



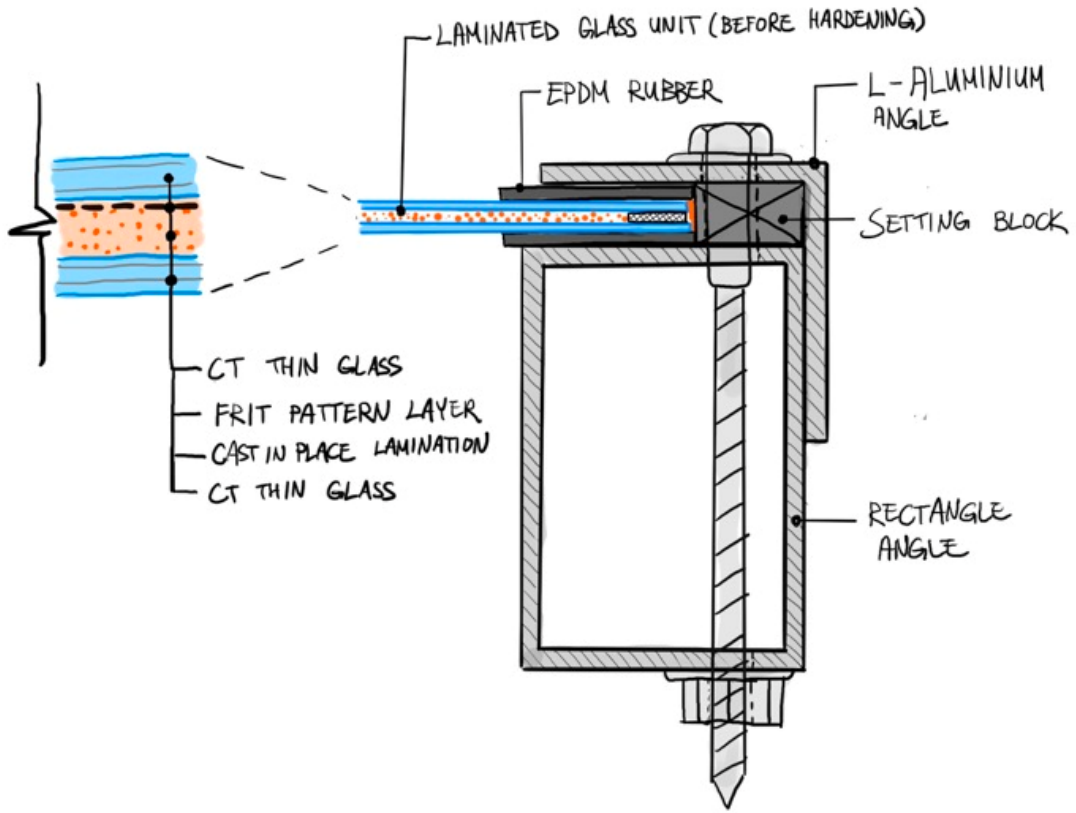
3-edge Rigid Support
(1-free edge)



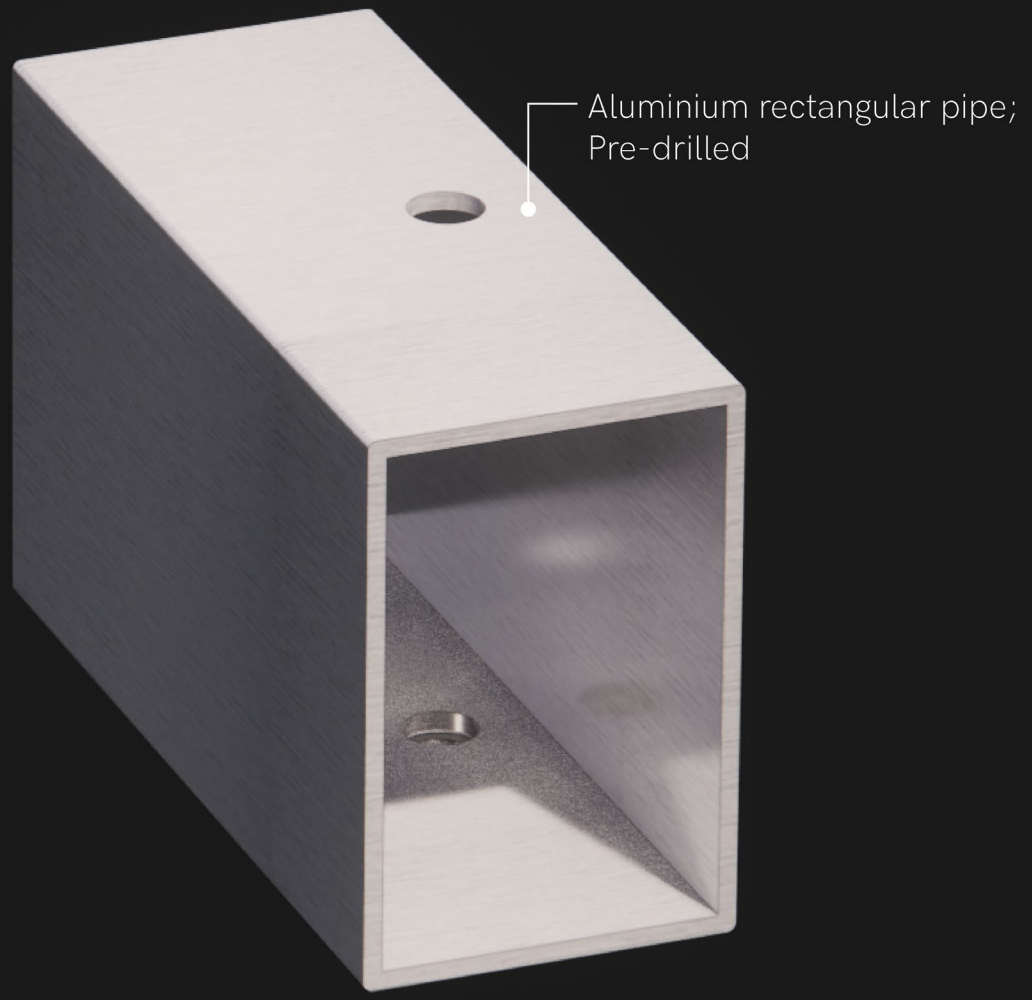
GEOMETRY TESTING #2 Detail



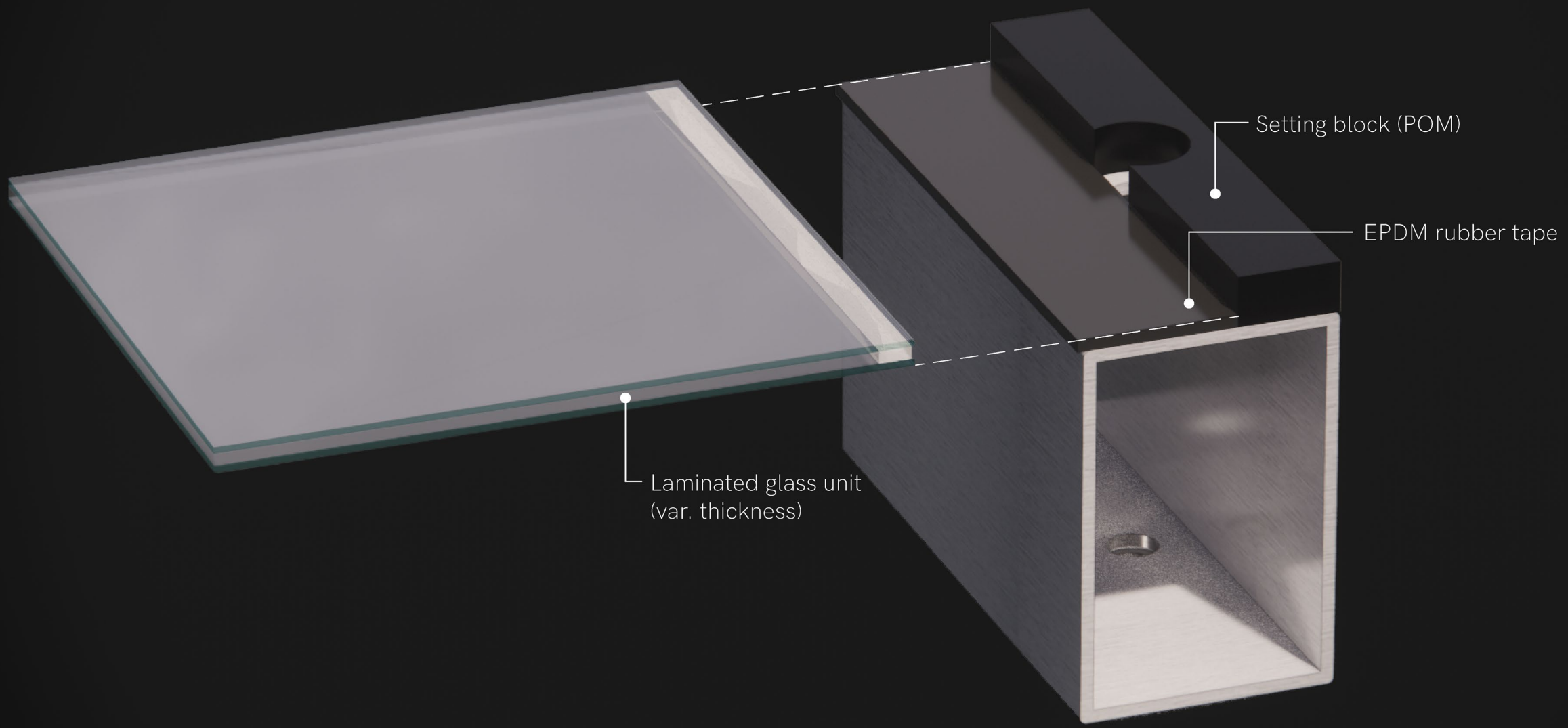
3-edge Rigid Support
(1-free edge)



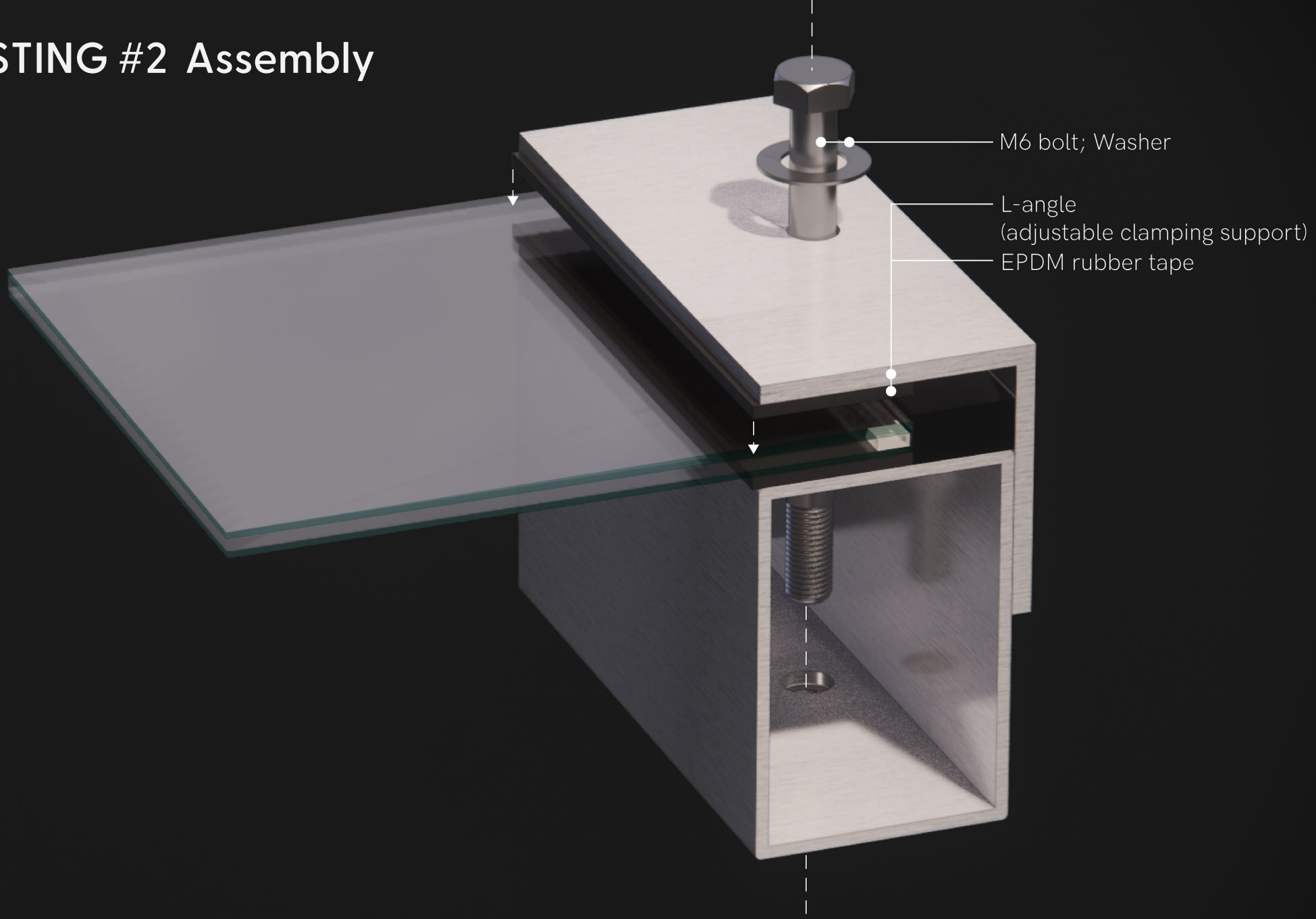
GEOMETRY TESTING #2 Assembly



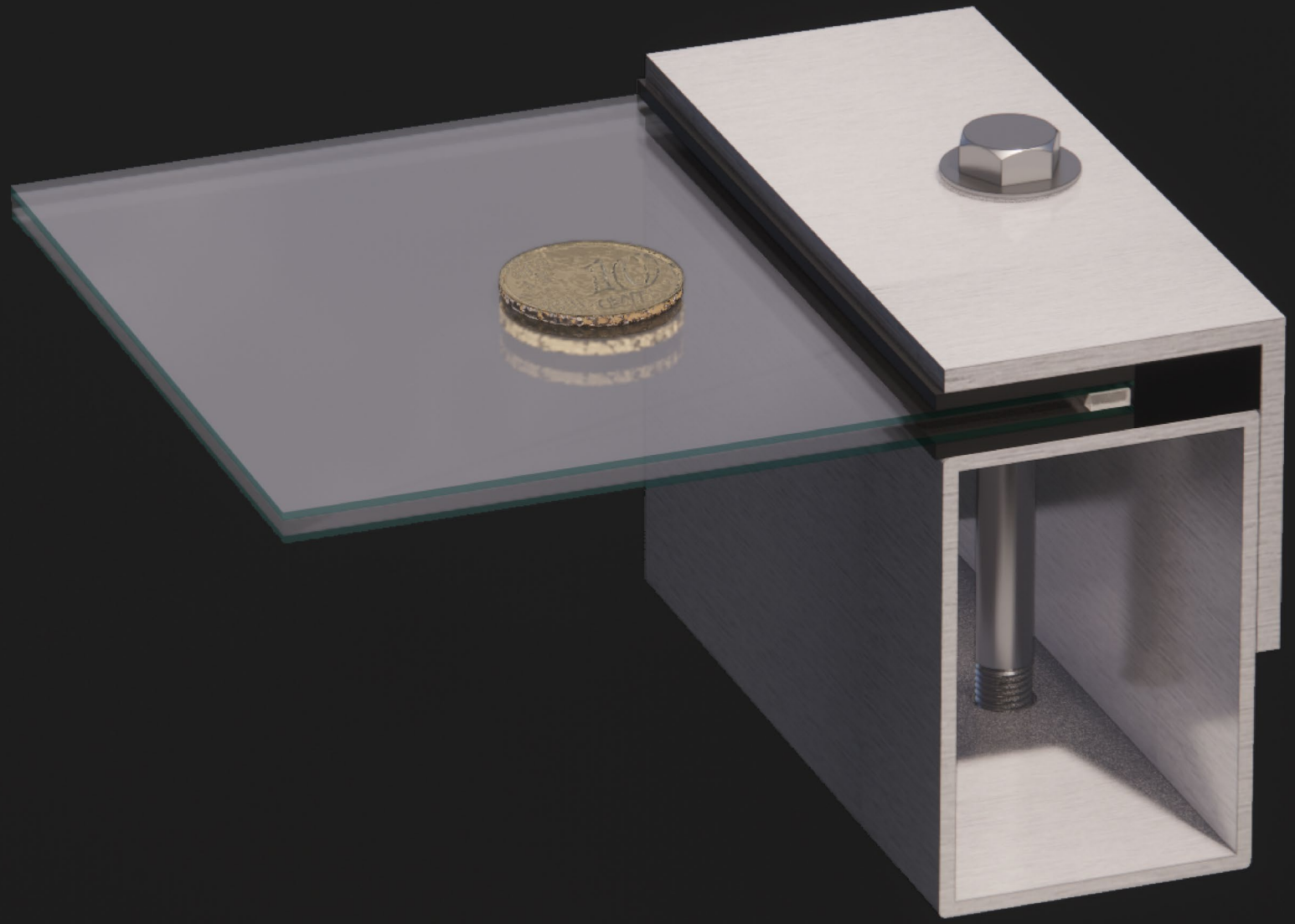
GEOMETRY TESTING #2 Assembly



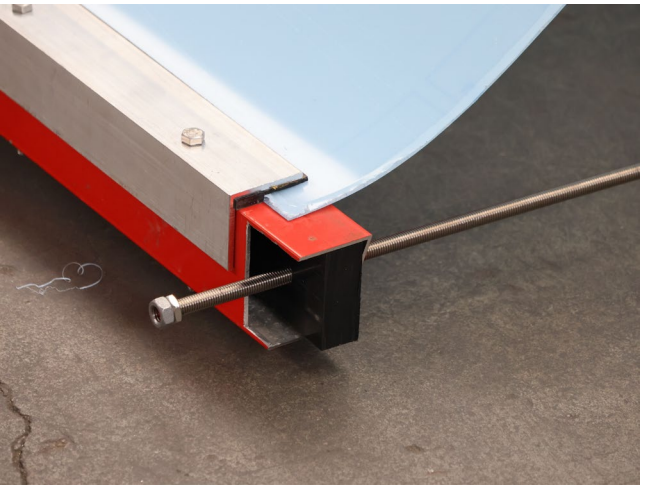
GEOMETRY TESTING #2 Assembly



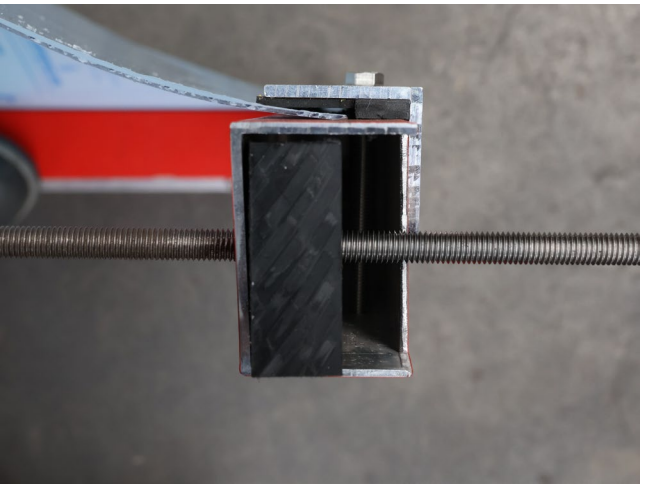
GEOMETRY TESTING #2 Assembly



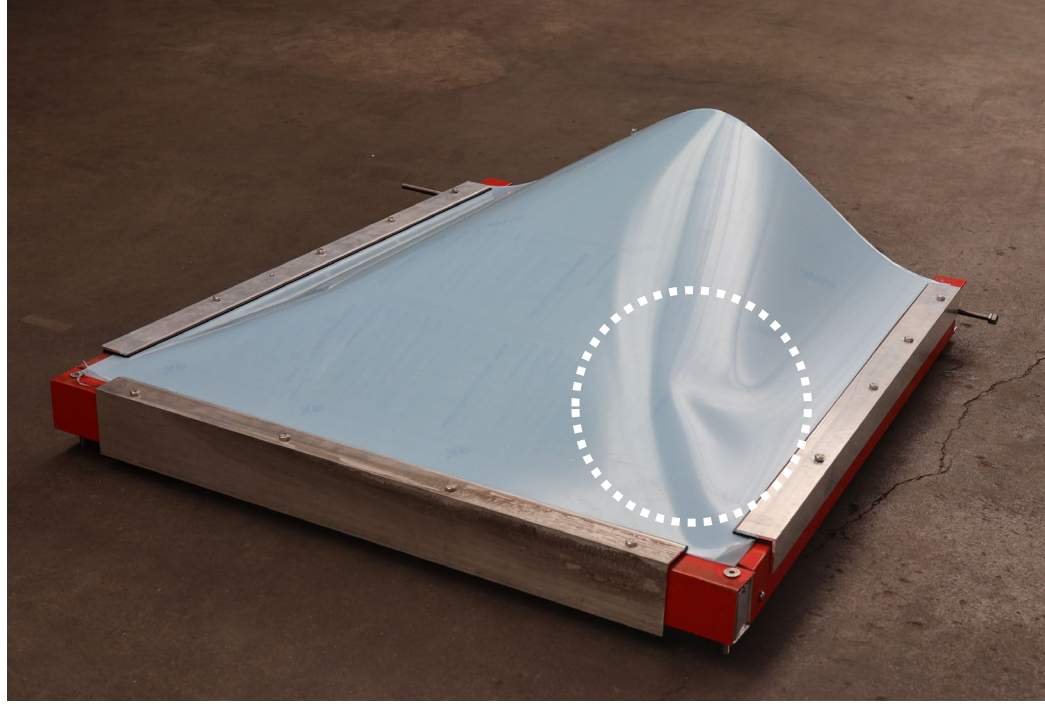
BUCKLE BENDING DEVICE



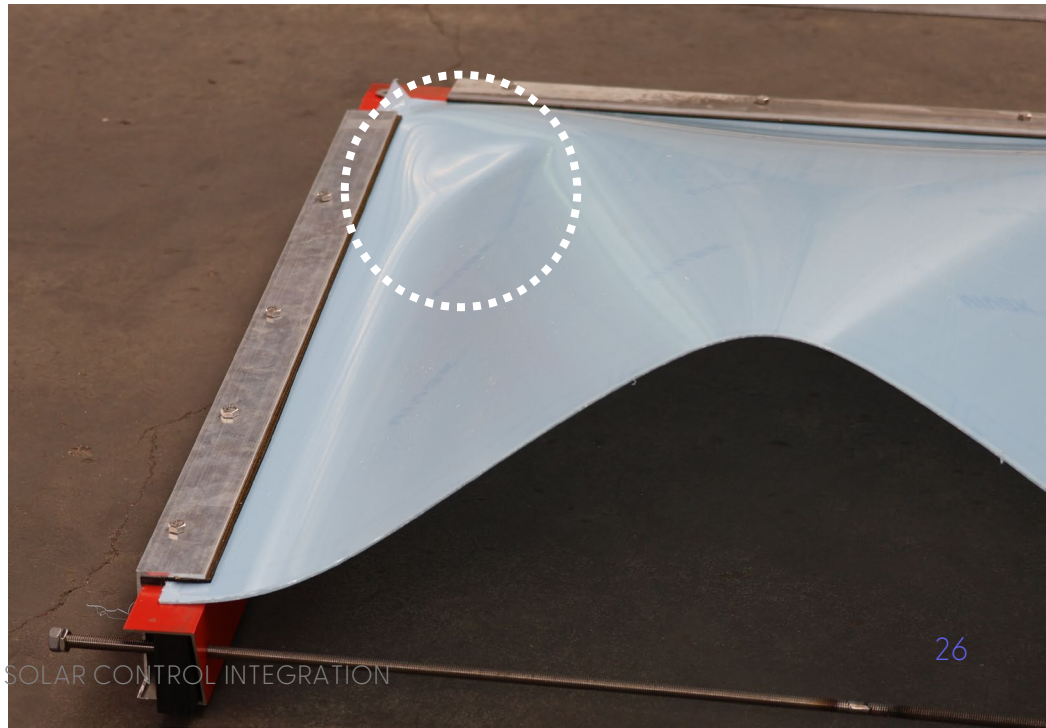
Details



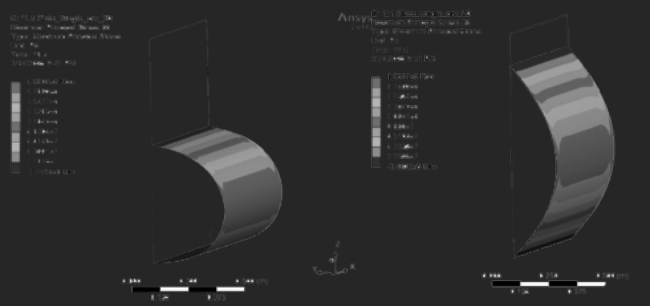




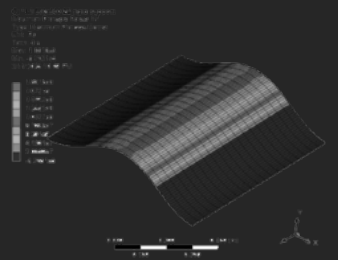
Surface Wrinkles
& Foldings



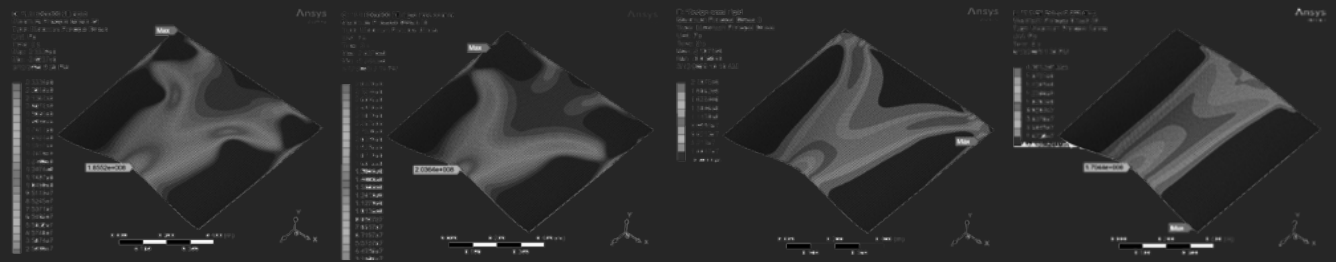
DESIGN DEVELOPMENT



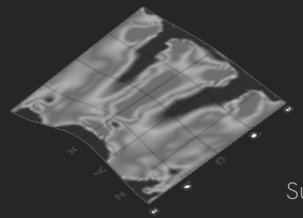
Single curve surface



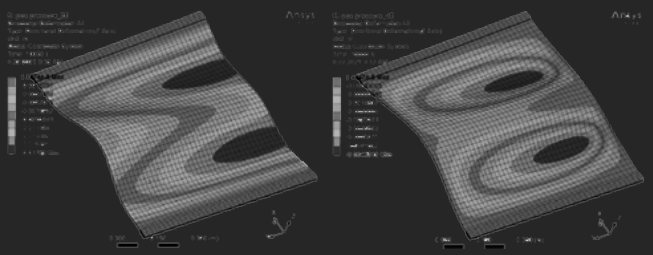
Sinusoidal single curve surface



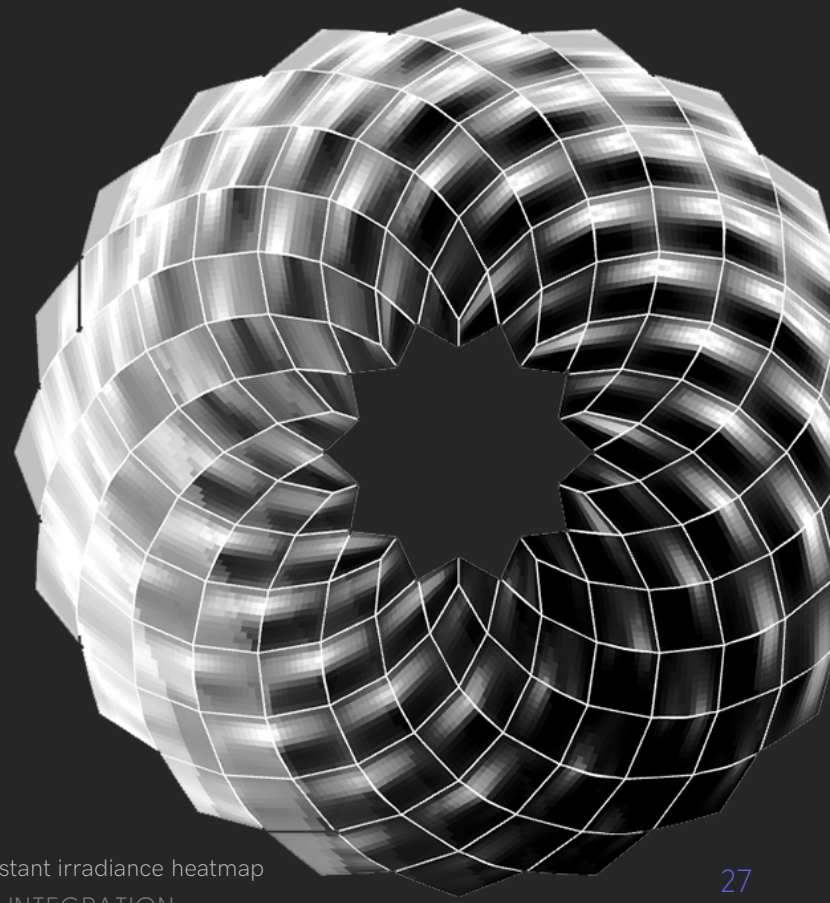
Boundary condition optimisation



Surface curvature validation

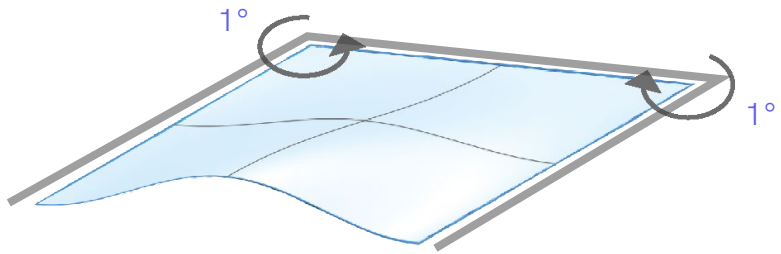


Deflection on different load cases



Instant irradiance heatmap

STRUCTURAL DESIGN Stress Optimisation (single panel)



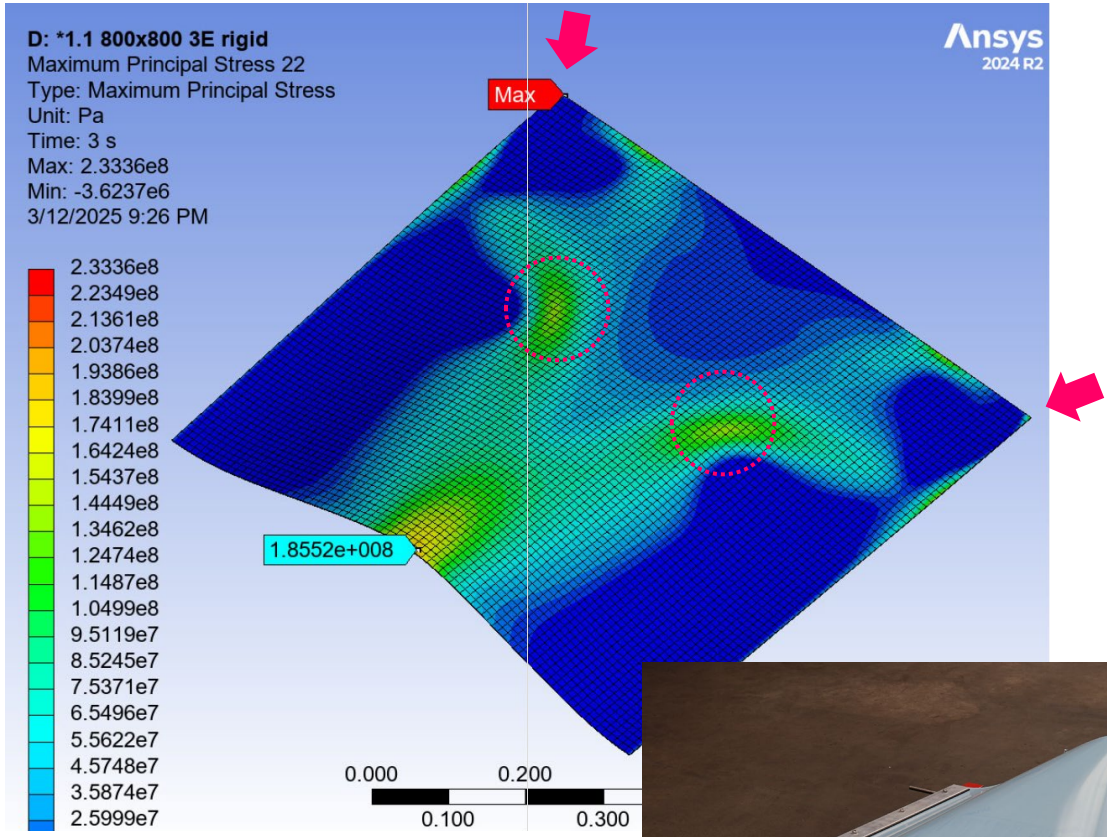
3-edge rigid support

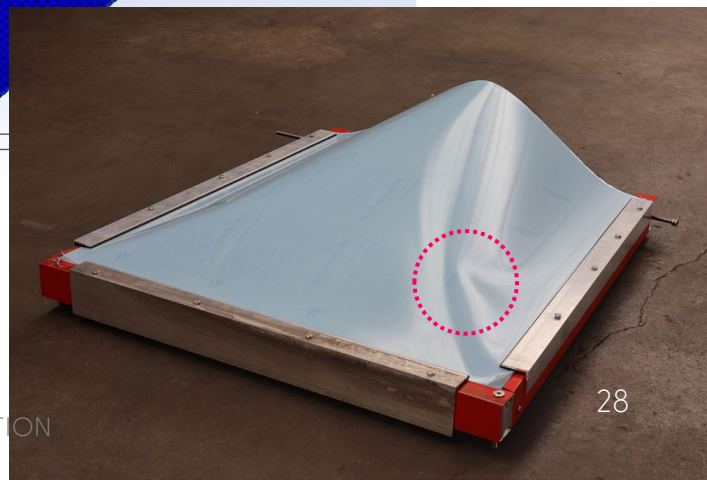
- 1.1mm 800x800mm CT glass
  E = 70 Gpa, ν = 0.22
  Design stress = 200 MPa

rigid support
semi-rigid support
free support

234 MPa

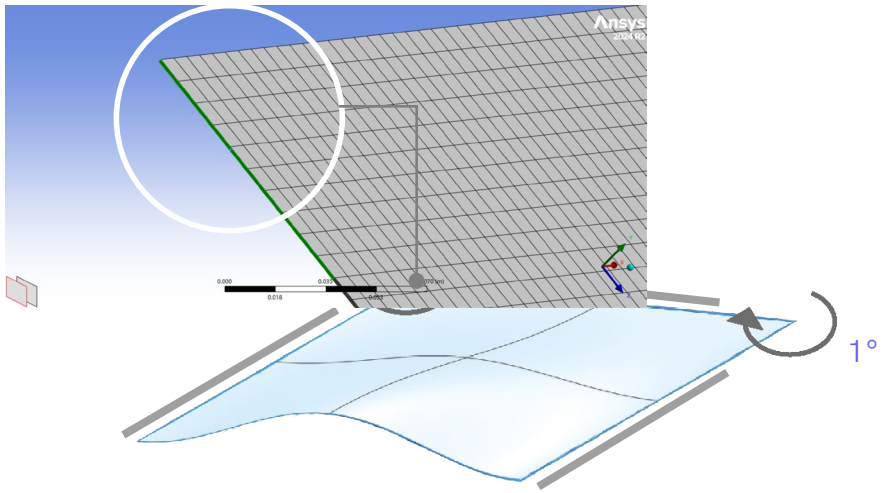
Maximum Principal Stress [Pa]





STRUCTURAL DESIGN Stress Optimisation (single panel)

Support-free corner

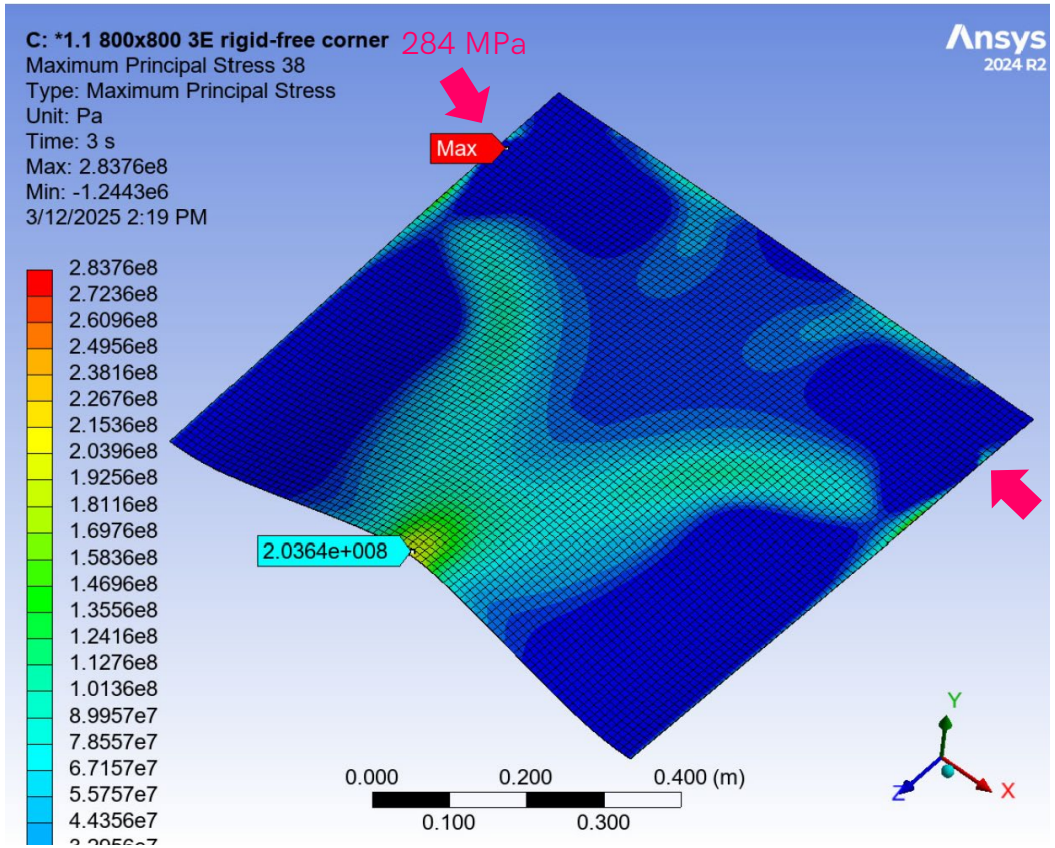


Free corner 3-E rigid support

- 1.1mm 800x800mm CT glass
  E = 70 Gpa, ν = 0.22
  Design stress = 200 MPa

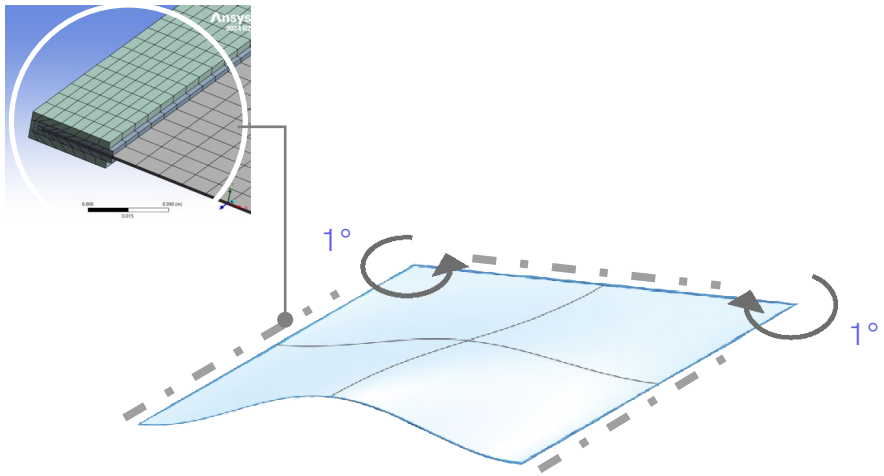
rigid support
semi-rigid support
free support

Maximum Principal Stress [Pa]



STRUCTURAL DESIGN Stress Optimisation (single panel)

Semi-rigid support

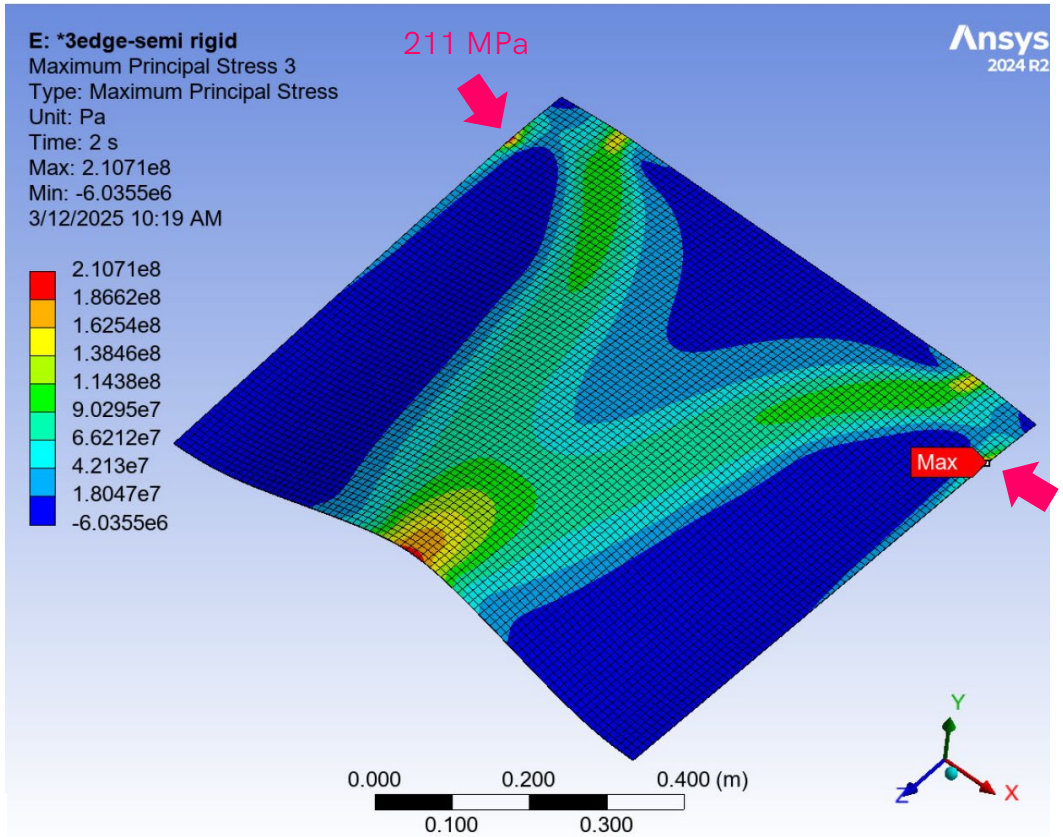


3-E semi-rigid support

- 1.1mm 800x800mm CT glass
  E = 70 Gpa, ν = 0.22
  Design stress = 200 MPa

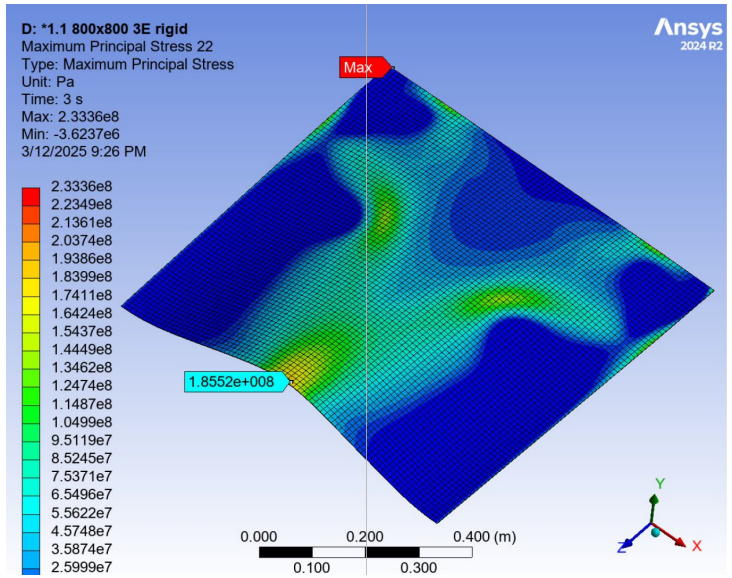
rigid support
semi-rigid support
free support

Maximum Principal Stress [Pa]

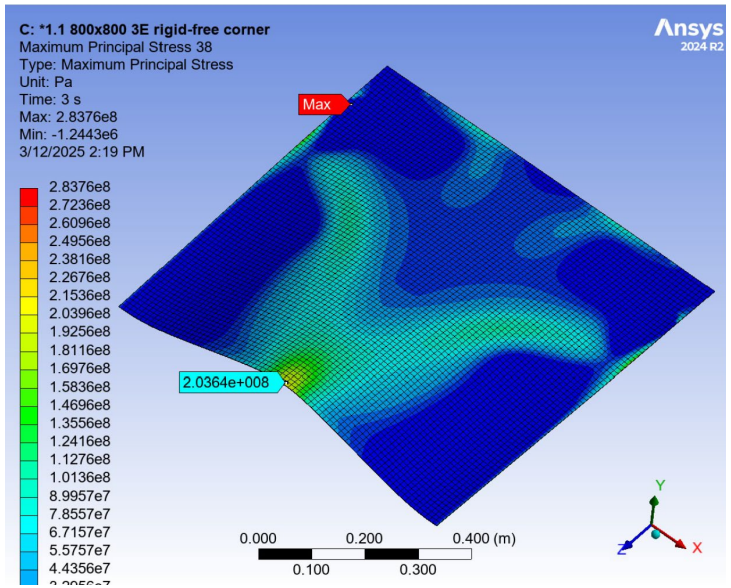


STRUCTURAL DESIGN Stress Optimisation (single panel)

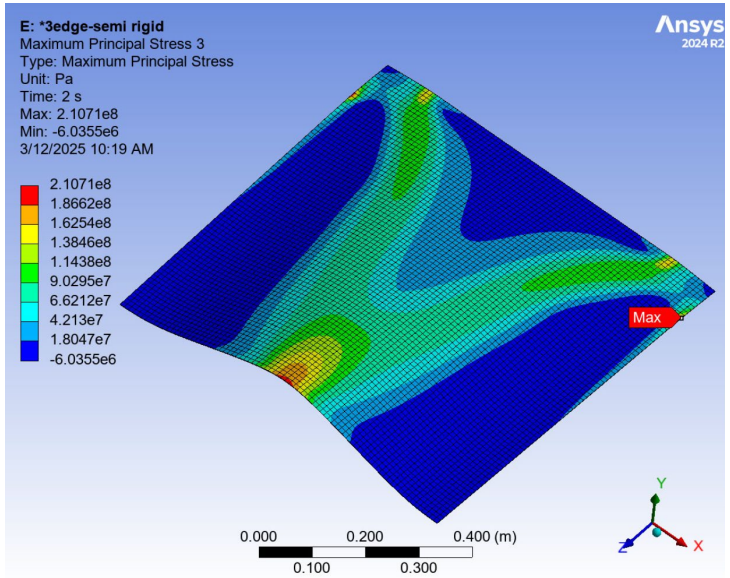
Maximum Principal Stress [Pa]



3-E rigid support

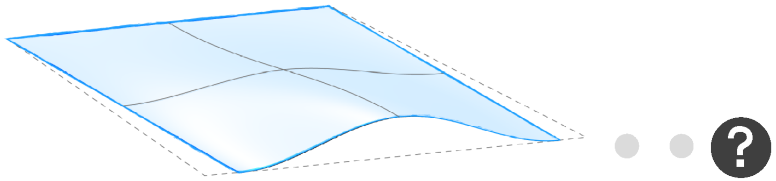


Free corner 3-E rigid support



3-E semi-rigid support

STRUCTURAL DESIGN Stress Mitigation Strategy



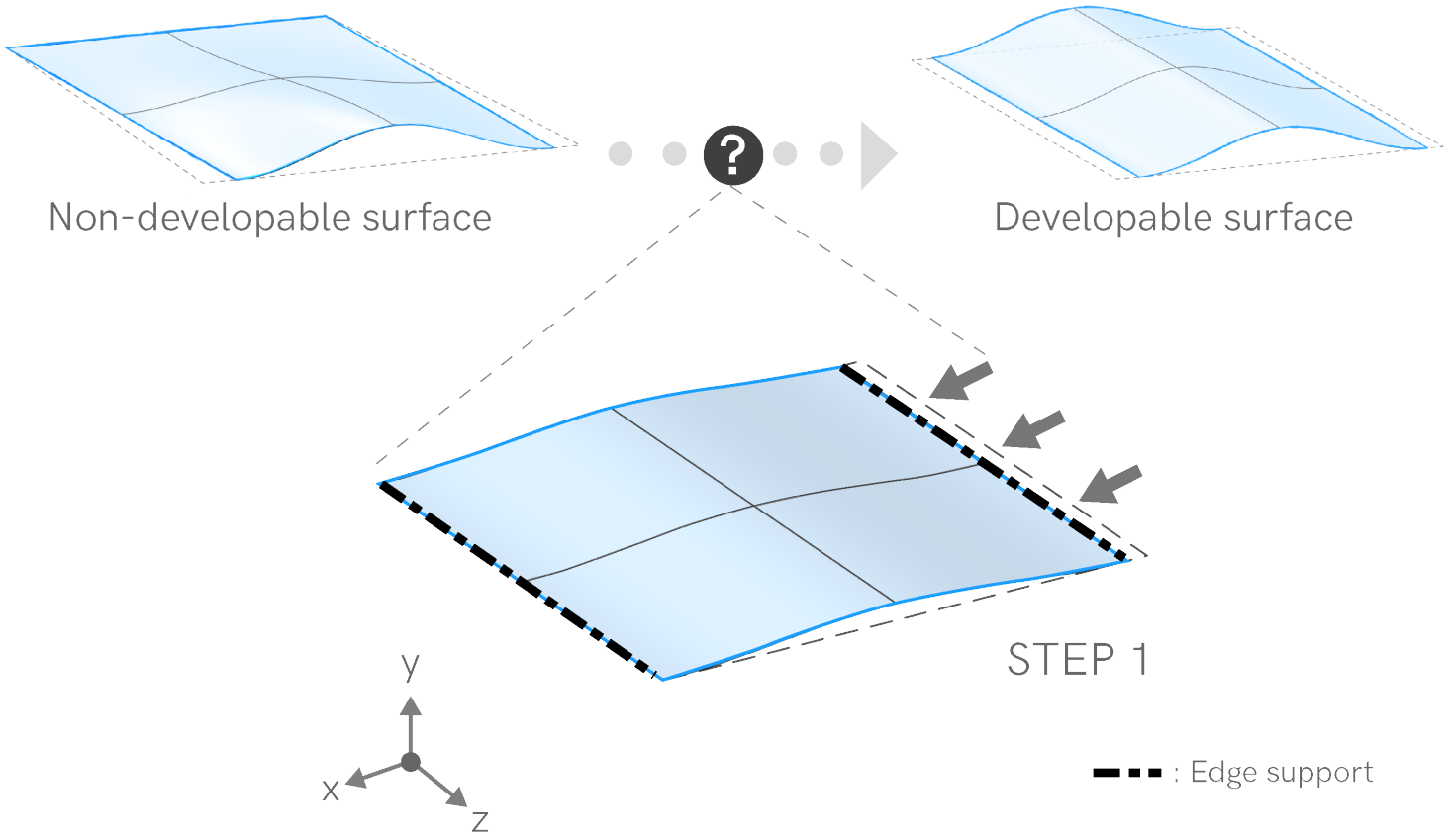
Non-developable surface

Thin plates naturally resist loads via flexural stiffness,

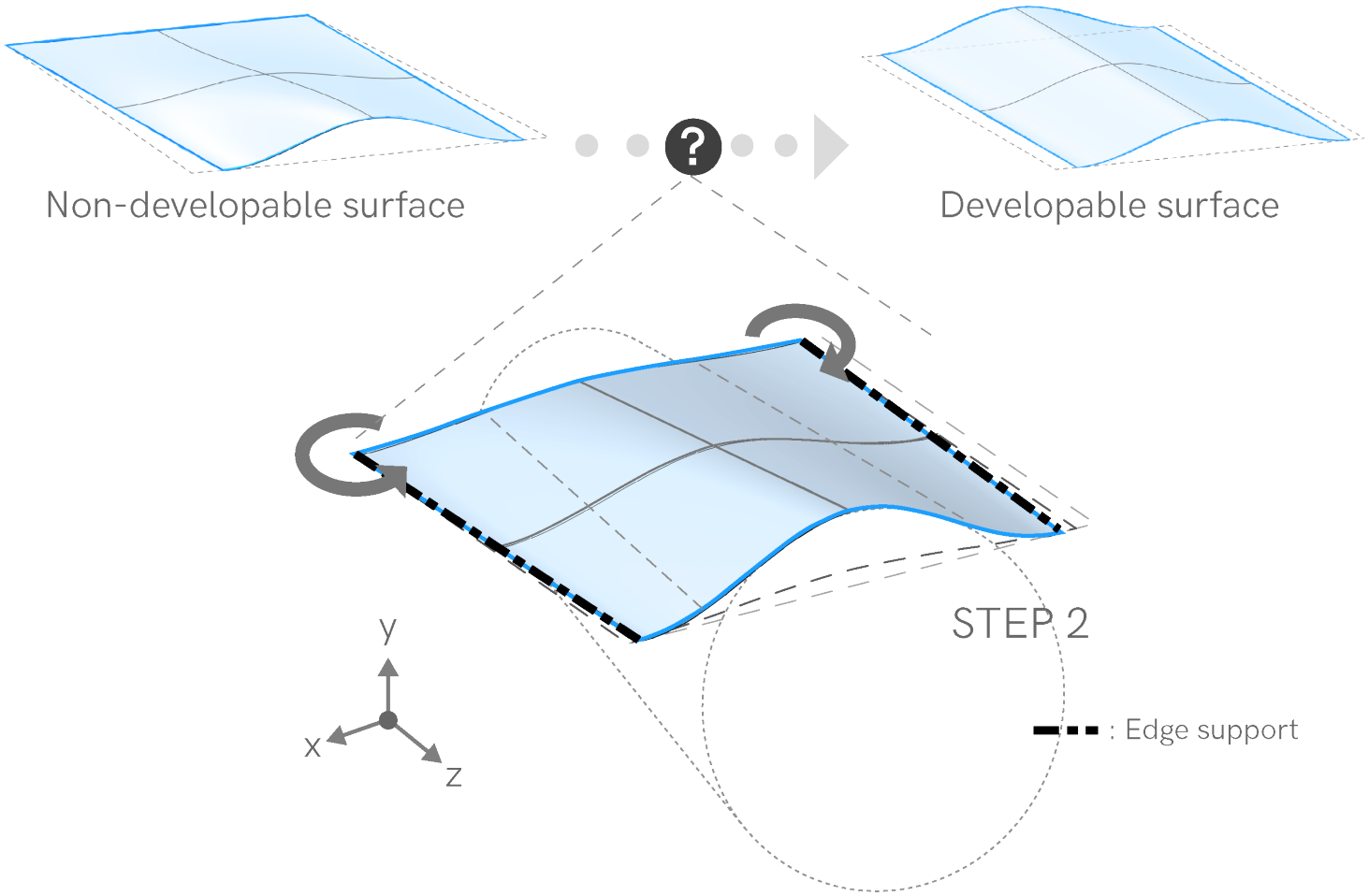
Achieving double curvature contradicts this intrinsic behaviour

Mansfield, The inextensional theory for thin flat plates (1955)

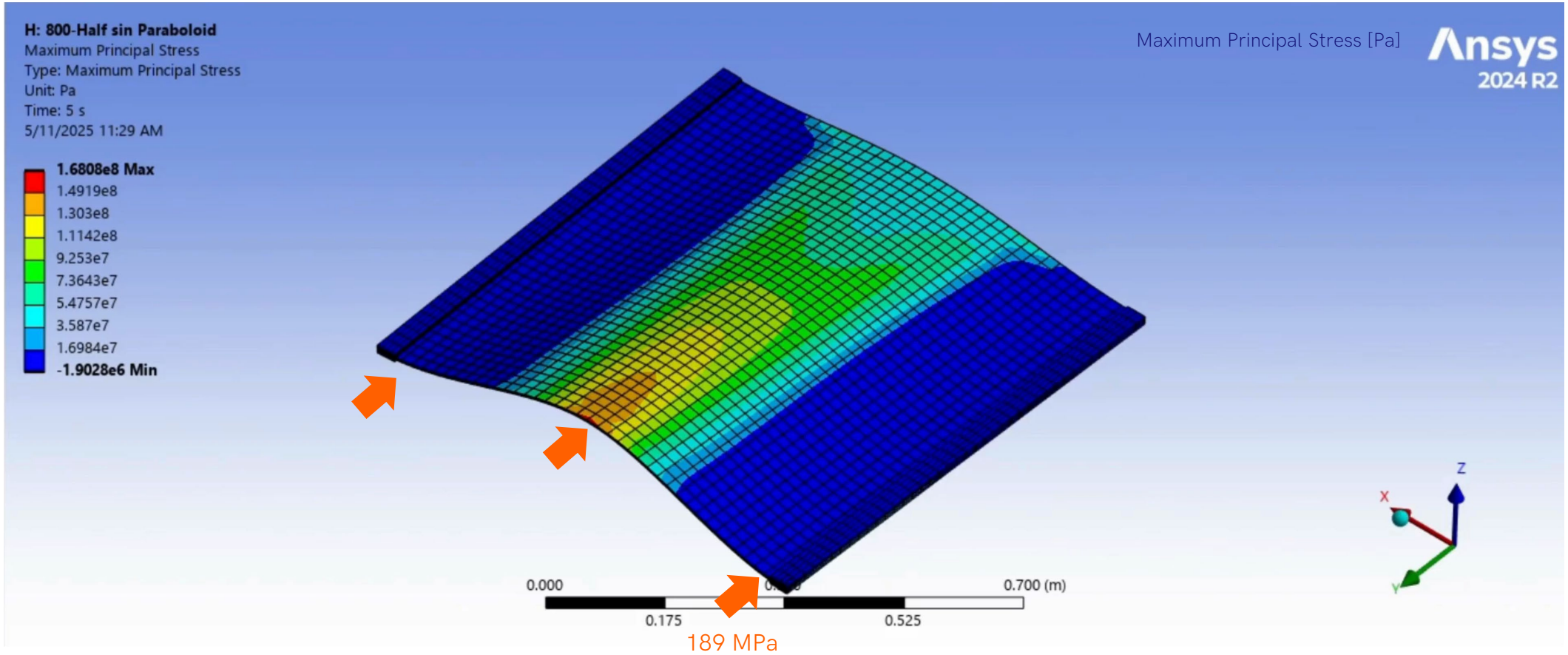
STRUCTURAL DESIGN 2-Step Buckle Bending



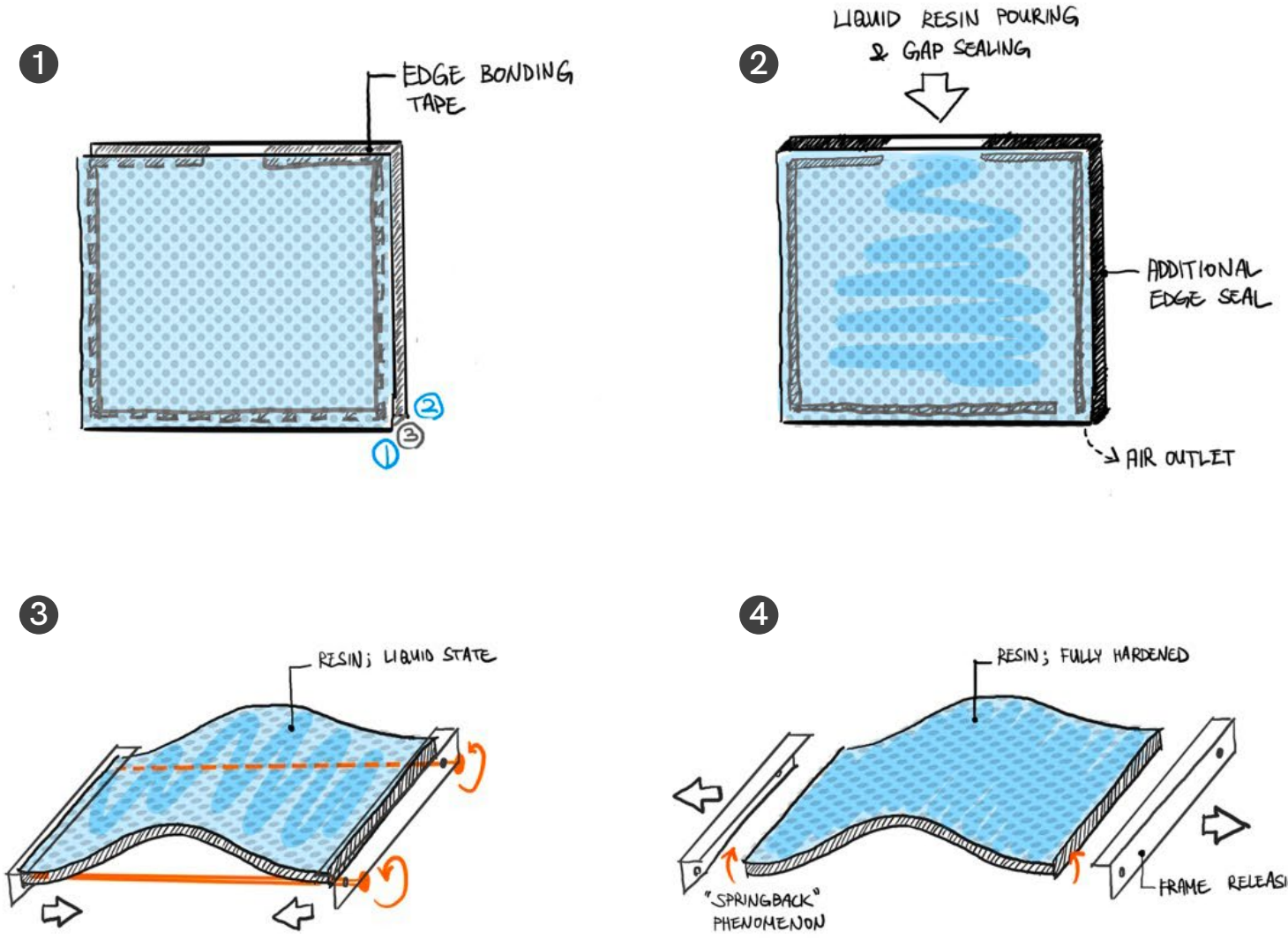
STRUCTURAL DESIGN 2-Step Buckle Bending



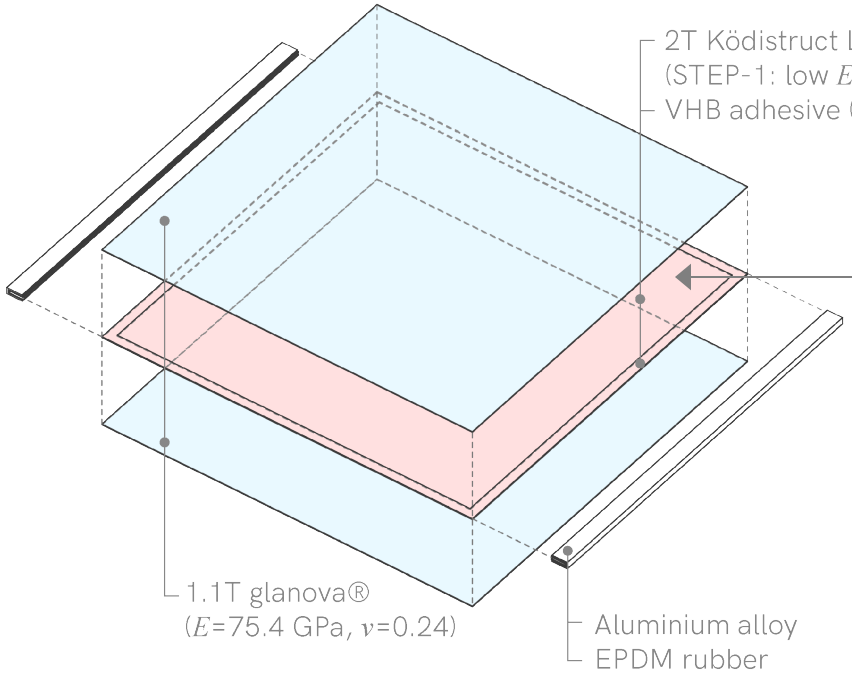
STRUCTURAL DESIGN 2-Step Buckle Bending (single panel)



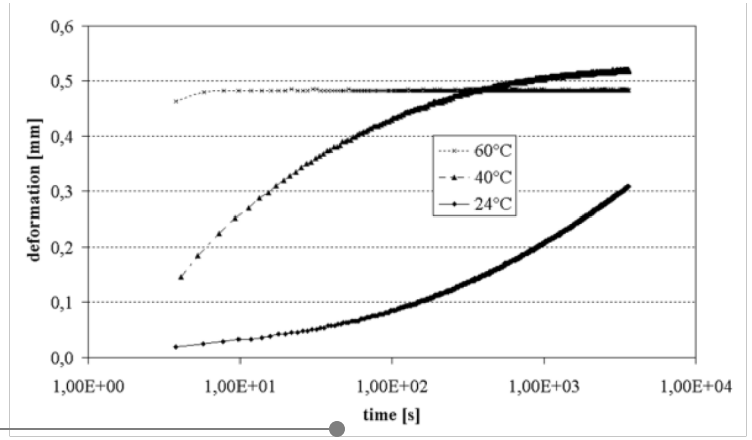
LAMINATION CONCEPT Cold Lamination Buckle Bending



STRUCTURAL DESIGN Laminated Panel Build-Up (sandwich panel)



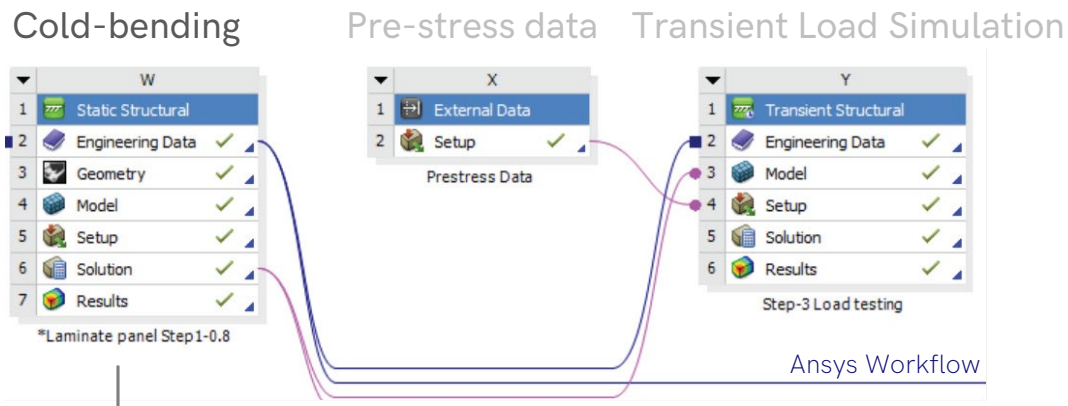
INTERLAYER PROPERTY



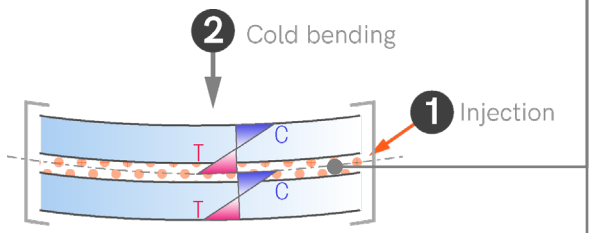
Index [*i*]	G_i / G_0	τ_i [s]
1	2.00E-03	2.77E+05
2	3.10E-03	6.86E+04
3	1.02E-02	2.17E+04
4	3.79E-02	4.13E+03
5	1.26E-01	3.69E+02
6	7.87E-01	1.51E+00

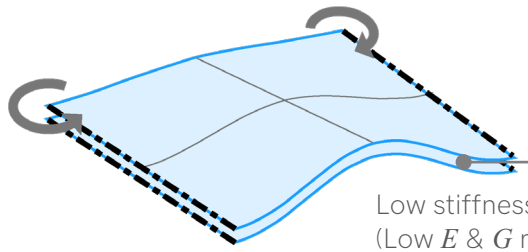
*At temperature 22°C, G0 = 21.8 MPa
(G0 data constructed based on Ansys)

STRUCTURAL DESIGN Laminated Panel Simulation



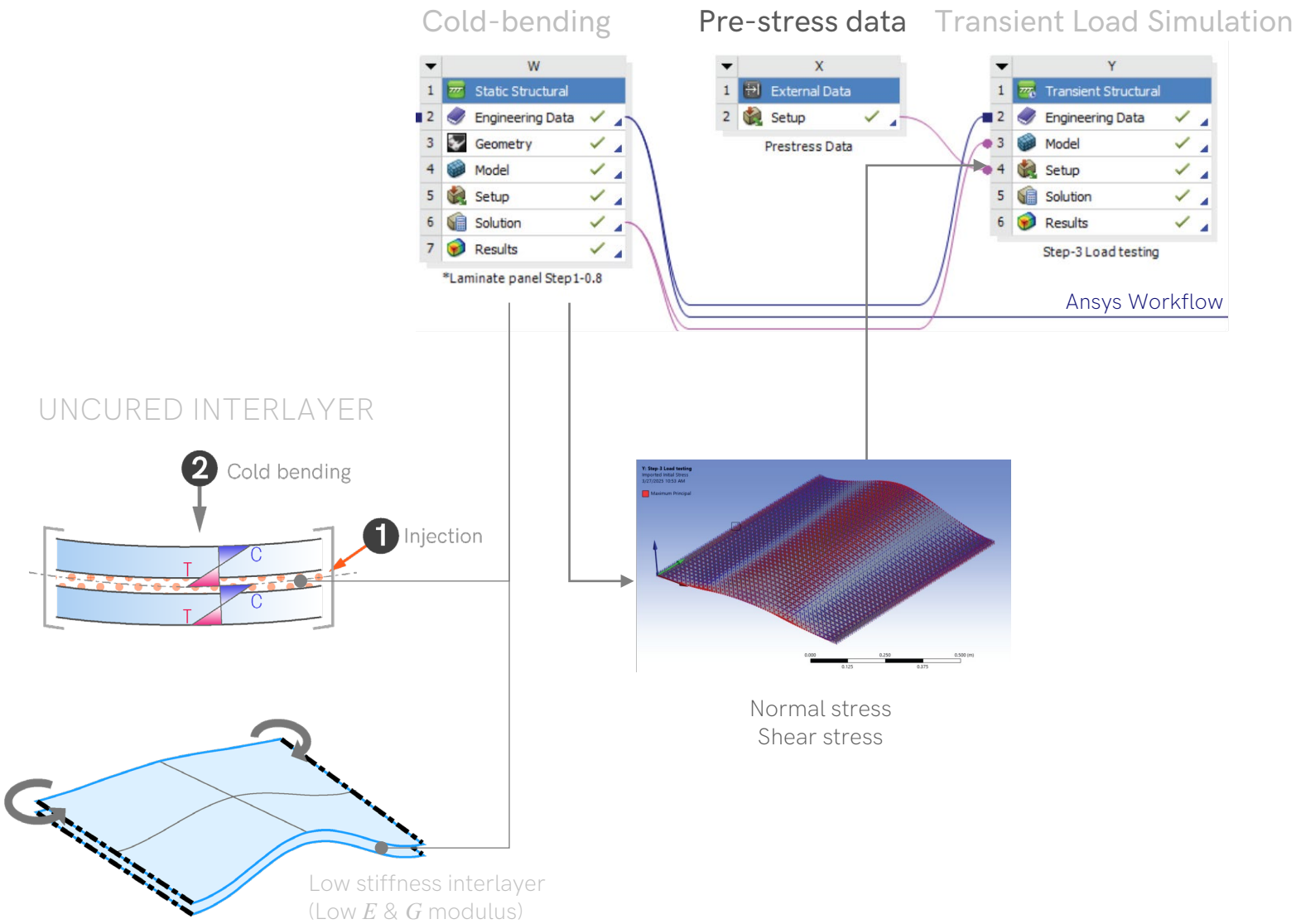
UNCURED INTERLAYER



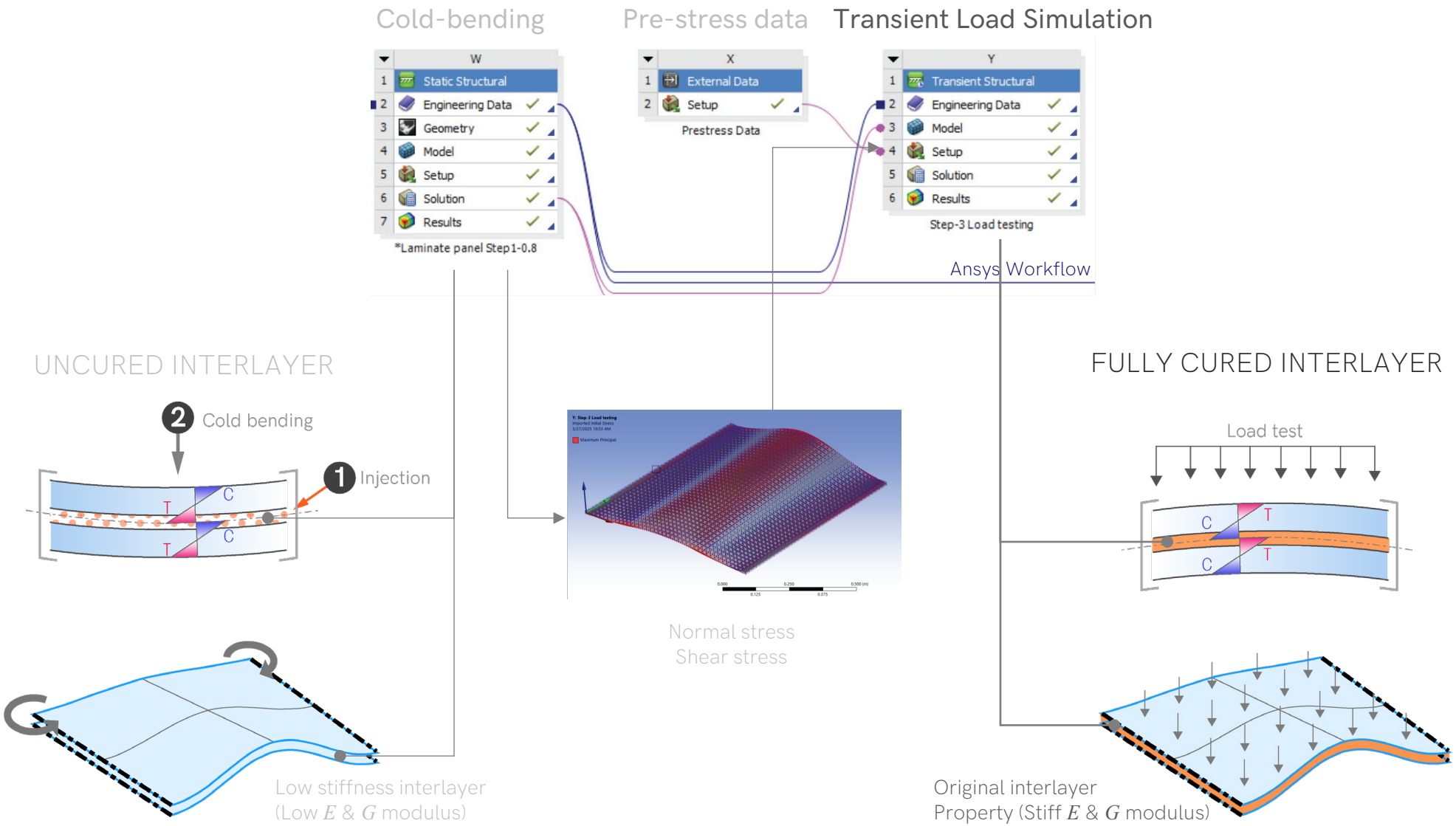


Low stiffness interlayer
(Low E & G modulus)

STRUCTURAL DESIGN Laminated Panel Simulation

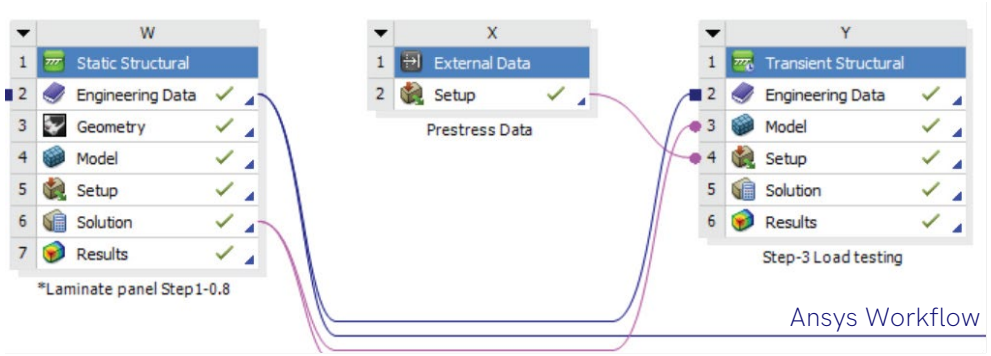


STRUCTURAL DESIGN Laminated Panel Simulation

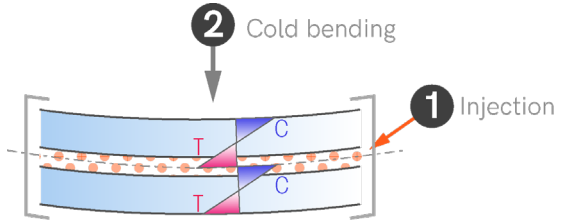


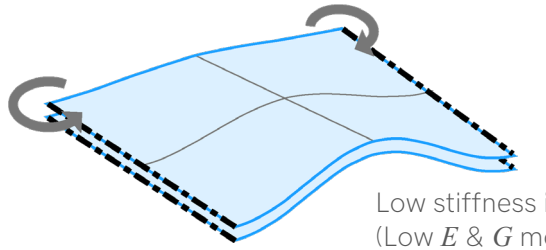
STRUCTURAL DESIGN Laminated Panel Simulation

Cold-bending | Pre-stress data | Transient Load Simulation



UNCURED INTERLAYER

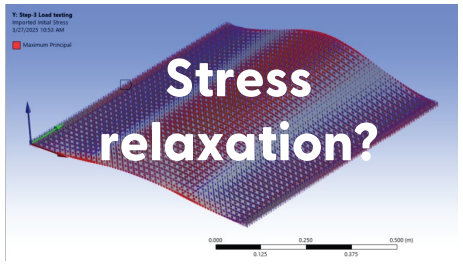




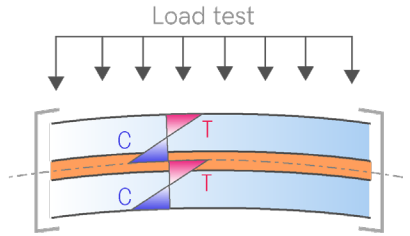
Low stiffness interlayer
(Low E & G modulus)

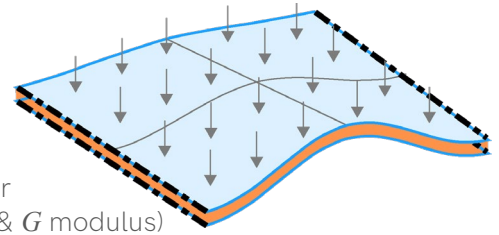
CURING STAGE

Residual stress relaxation



FULLY CURED INTERLAYER

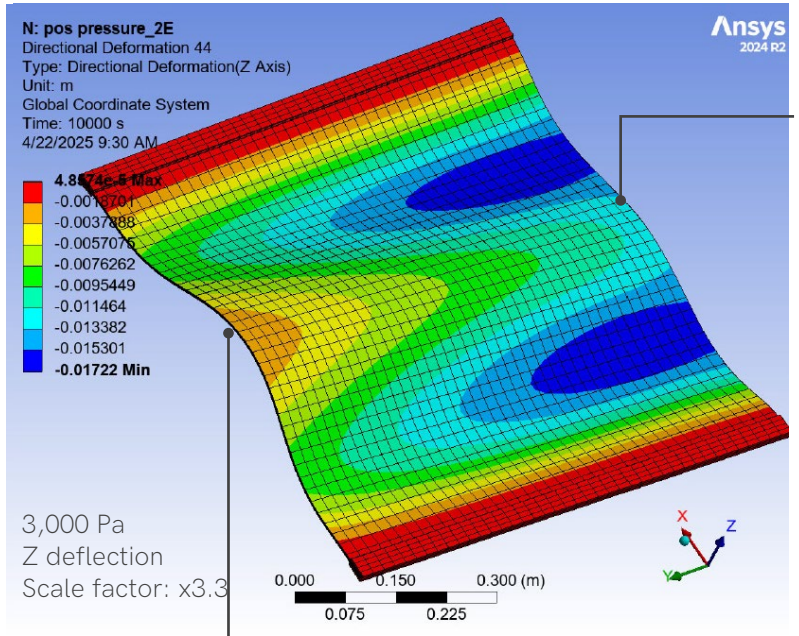




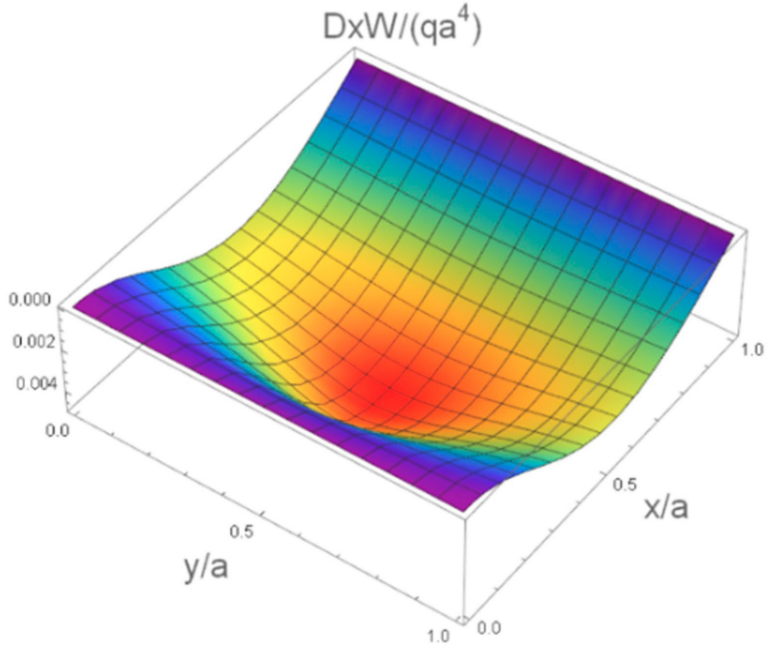
Original interlayer
Property (Stiff E & G modulus)

STRUCTURAL DESIGN Creep Simulation

PRESTRESSED GEO. DEFLECTION

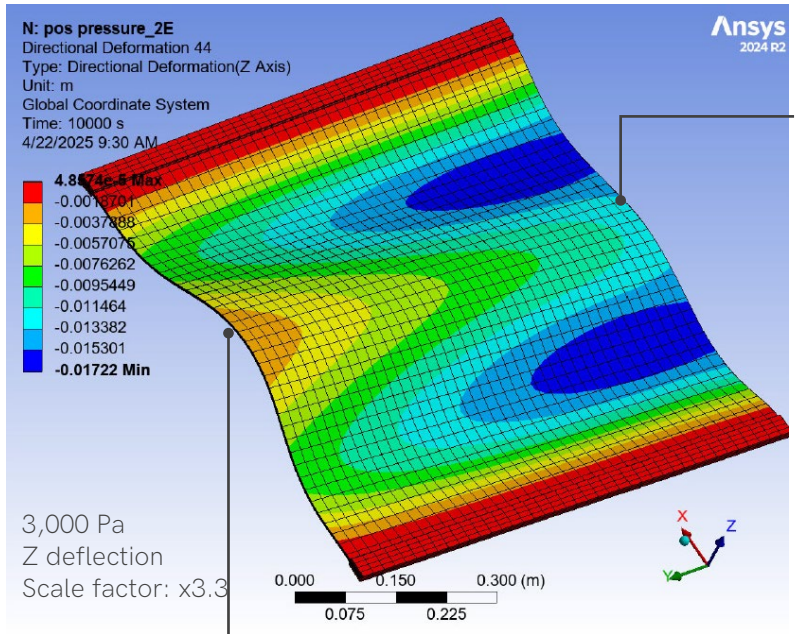


FLAT PLATE DEFLECTION



STRUCTURAL DESIGN Creep Simulation

PRESTRESSED GEO. DEFLECTION



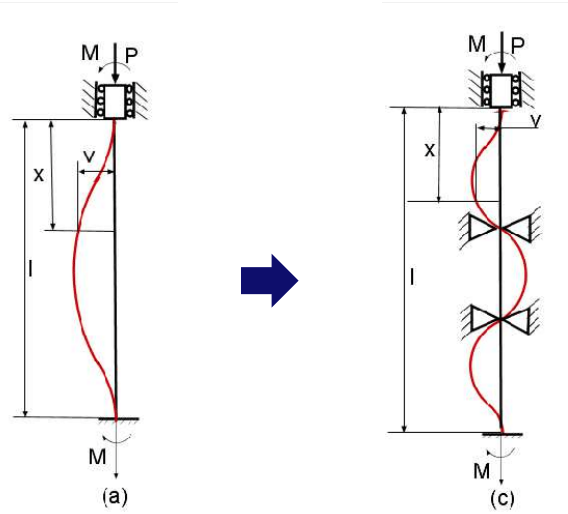
3,000 Pa
Z deflection
Scale factor: x3.3

Less stress
Critical deflection

Deflection prevented
But stress rising

Total Deflection [m]

GEOMETRICAL STIFFNESS

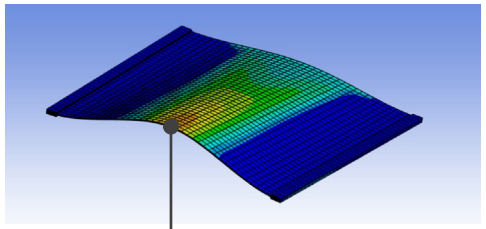


- Critical Buckling Force Variation for Beams with Discontinuities
  Furdui et al. (2016)

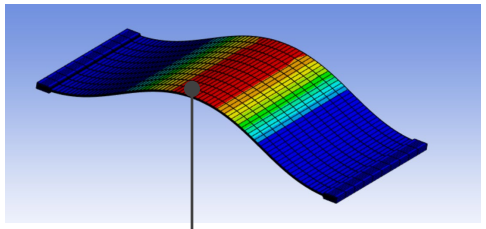
STRUCTURAL DESIGN Spring-back

- Residual stress

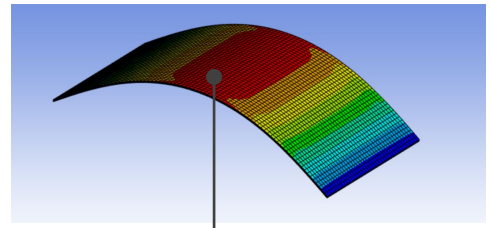
A Sin. Half Paraboloid

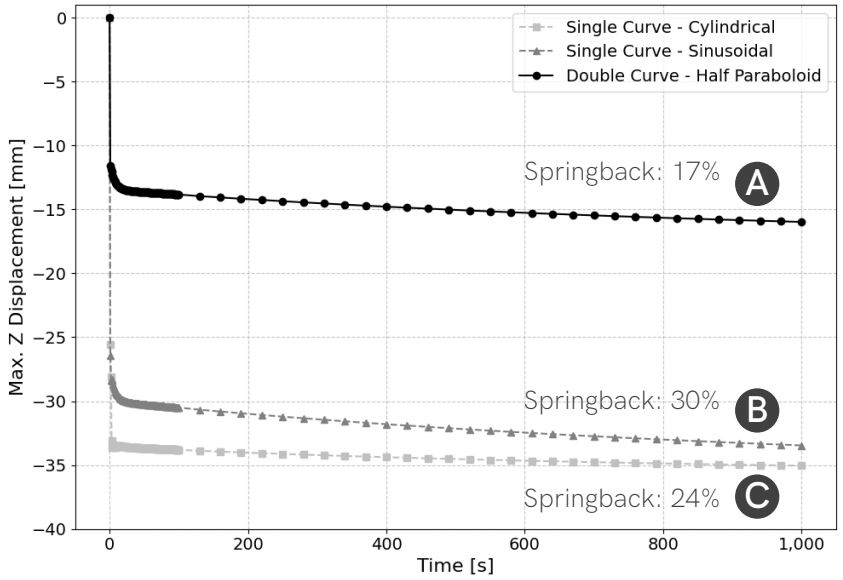


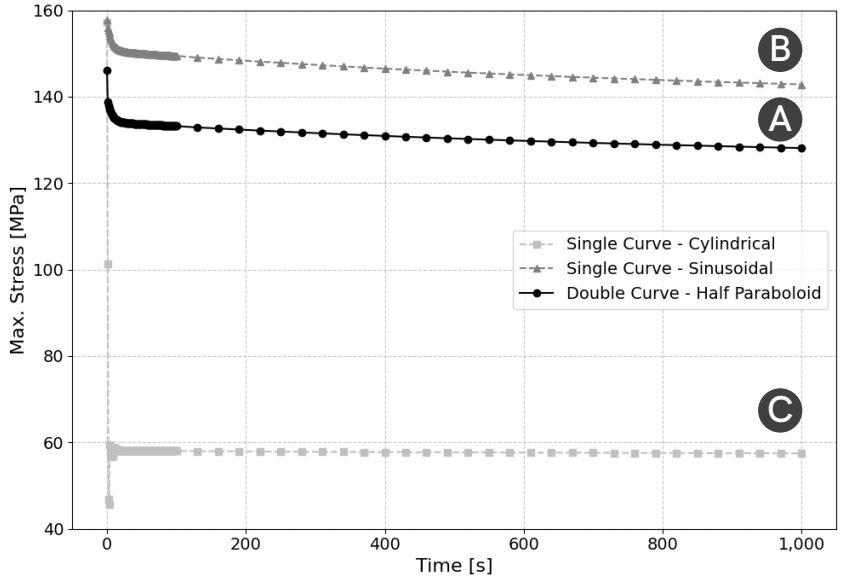
B Sin. Single-Curvature



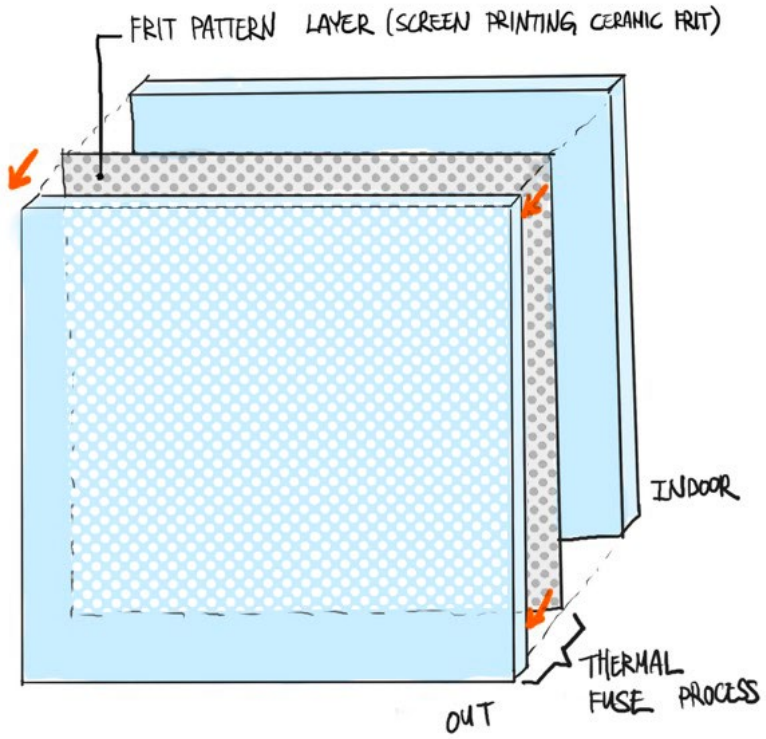
C Cylindrical Single-Curvature



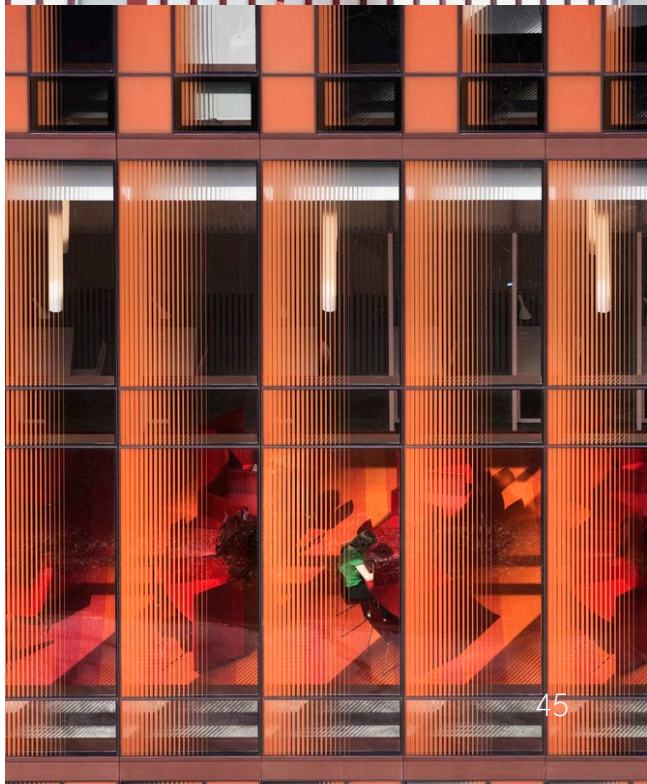




SOLAR CONTROL CONCEPT Ceramic frit

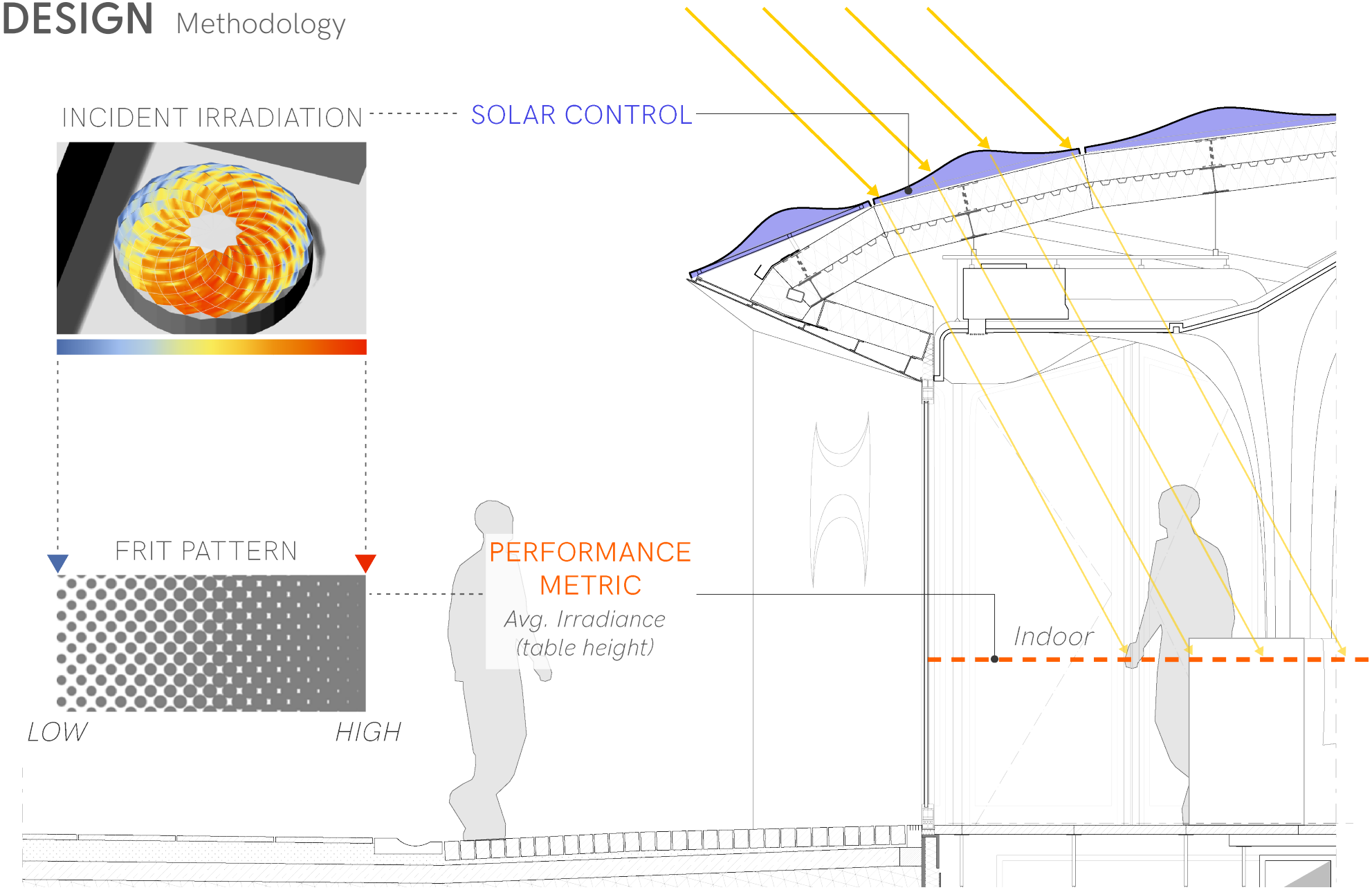






- Diana Center at Barnard College, New York, 2010

SOLAR DESIGN Methodology



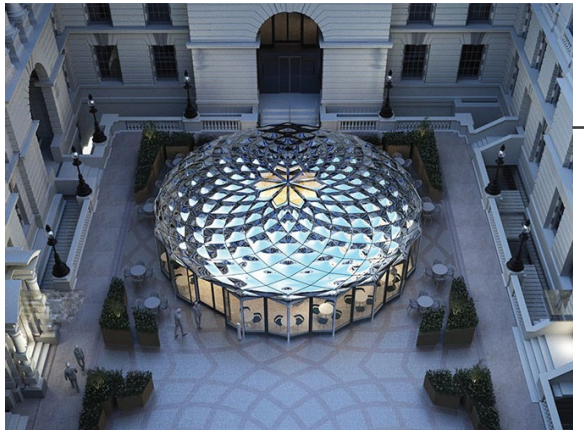
SOLAR DESIGN Simulation Condition

Surrounding Building

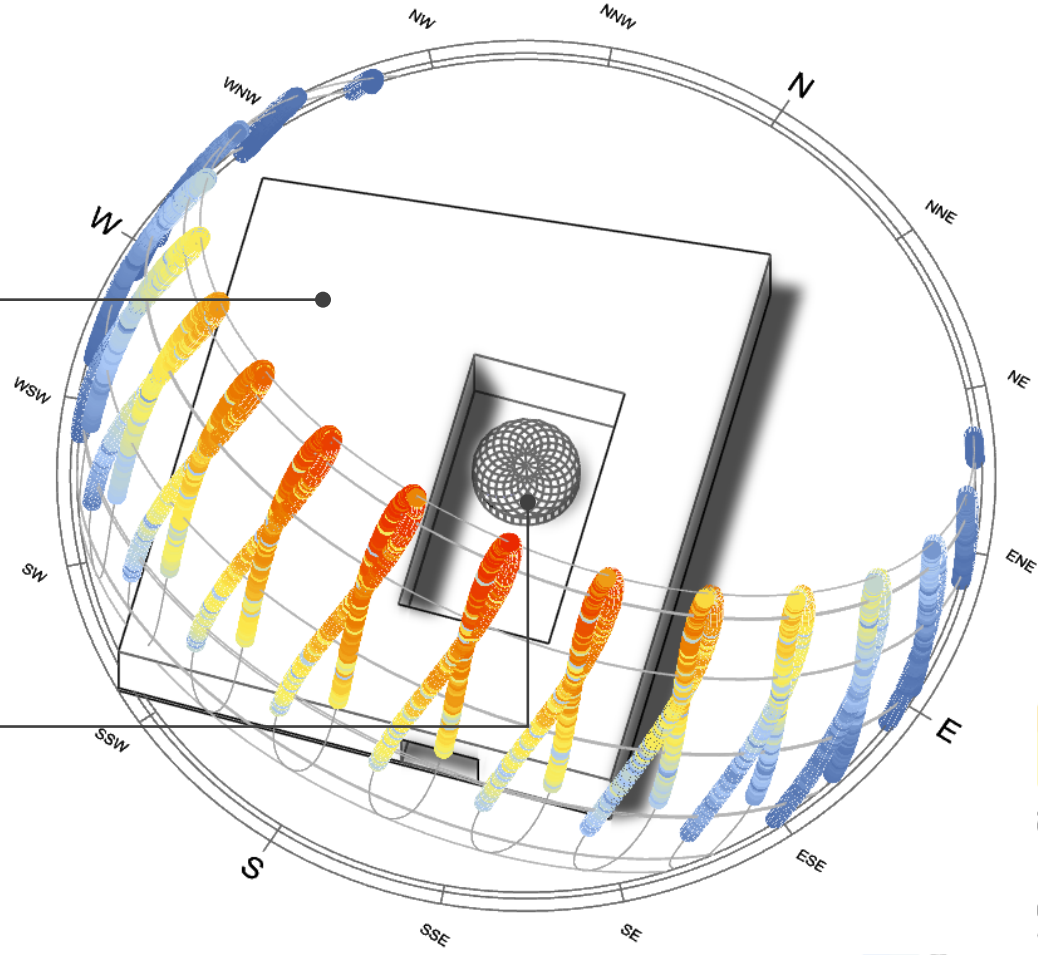


Portland stone - Reflection index: 0.5

Incident Radiation Geometry

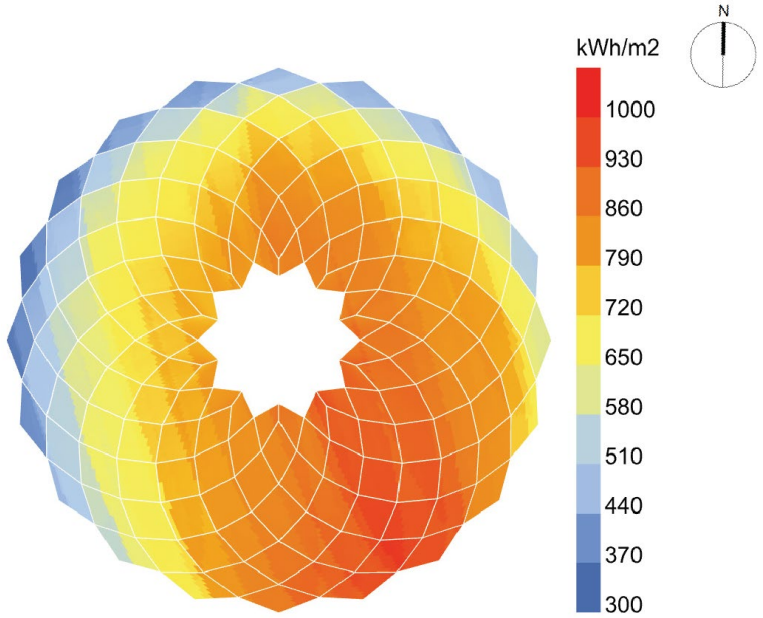


Simulation Location: London, UK
Simulation Period: 9:00 - 18:00, March - October

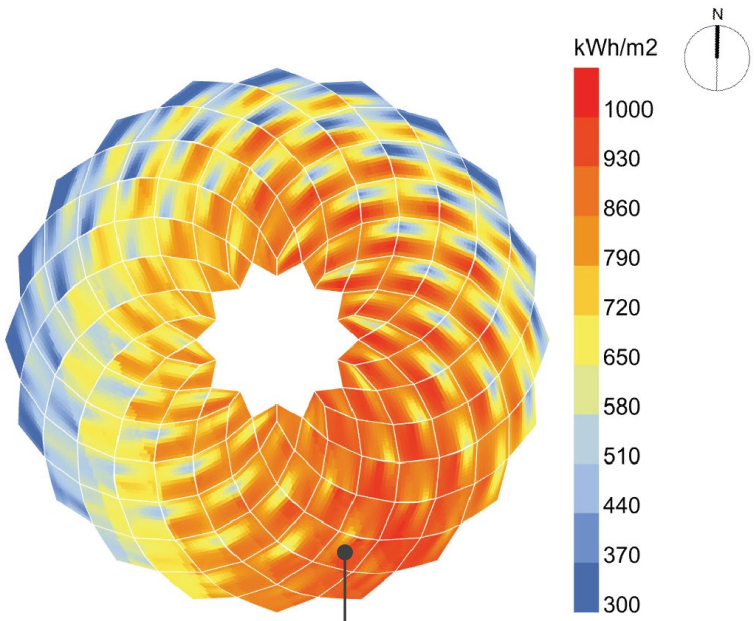


SOLAR DESIGN Incident Irradiation on Roof Geometry

FLAT GLASS PANEL ROOF

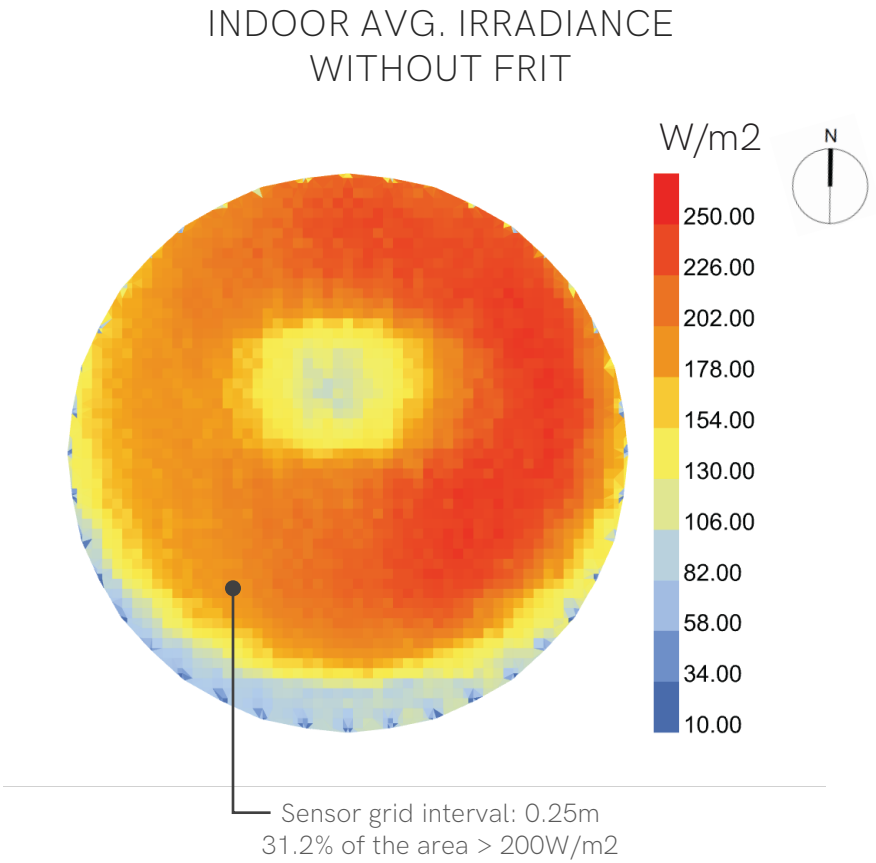


DOUBLE-CURVATURE ROOF



Product	Light transmission [%]	Refractive index
glanova®	91	1.51
Ködistruct LG	89	N/A
Laminated panel	82	1.51

SOLAR DESIGN Optimisation Objectives



Low intensity solar radiation < 100 W/m2

High intensity solar radiation > 100 W/m2

- *Investigation based on physiological parameters of human thermal sensation and comfort zone on indoor solar radiation conditions in summer (Pan et al., 2022)*

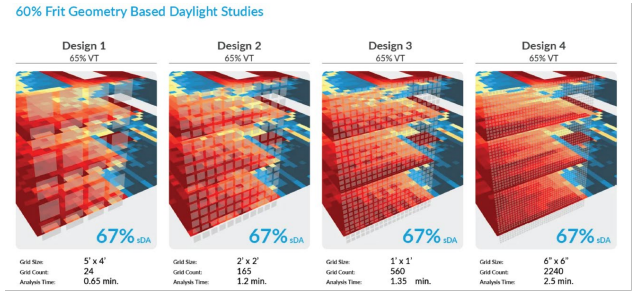
Solar radiation increased by every 200 W/m2,

Skin temperature, thermal comfort increased by 2°C

- *The effects of solar radiation on thermal comfort (Parsons, 2022)*

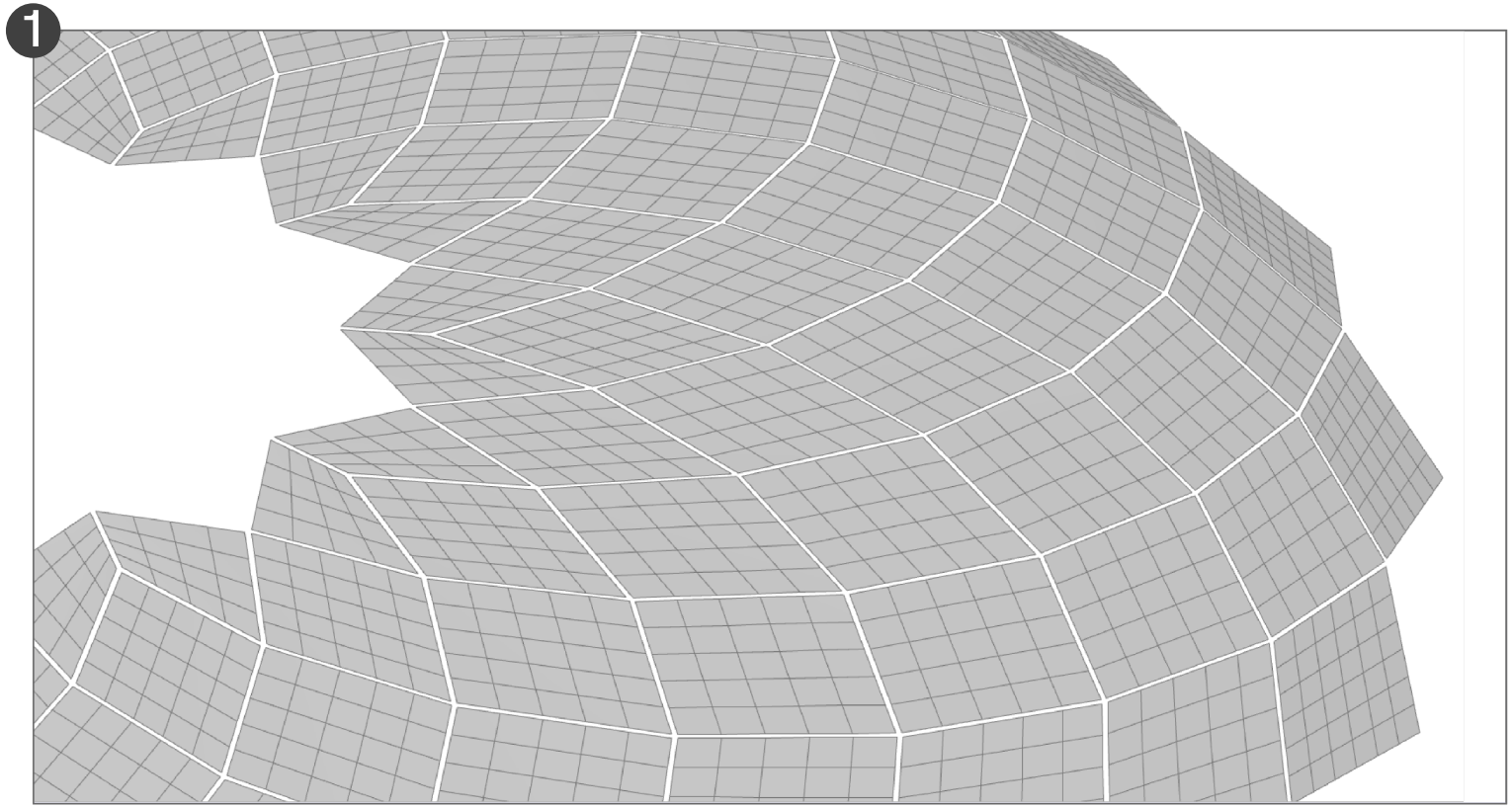
	Performance metric	Condition
Objective 1	Avg. indoor irradiance [W/m2]	90% of sensors ≤ 150 W/m2
Objective 2	Frit covarage [m2]	Minimize

SOLAR DESIGN Optimisation Strategy

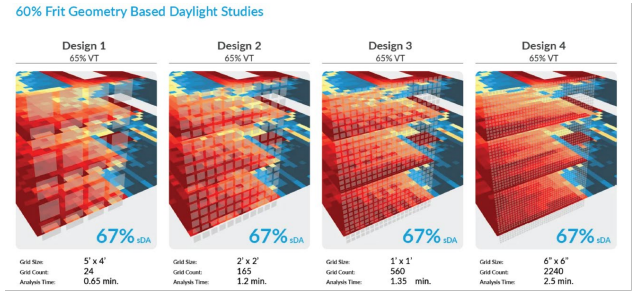


- Simplified approach to model frit patterns for daylight analysis (Essary, 2022)

PANEL DIVISION (Flat roof)



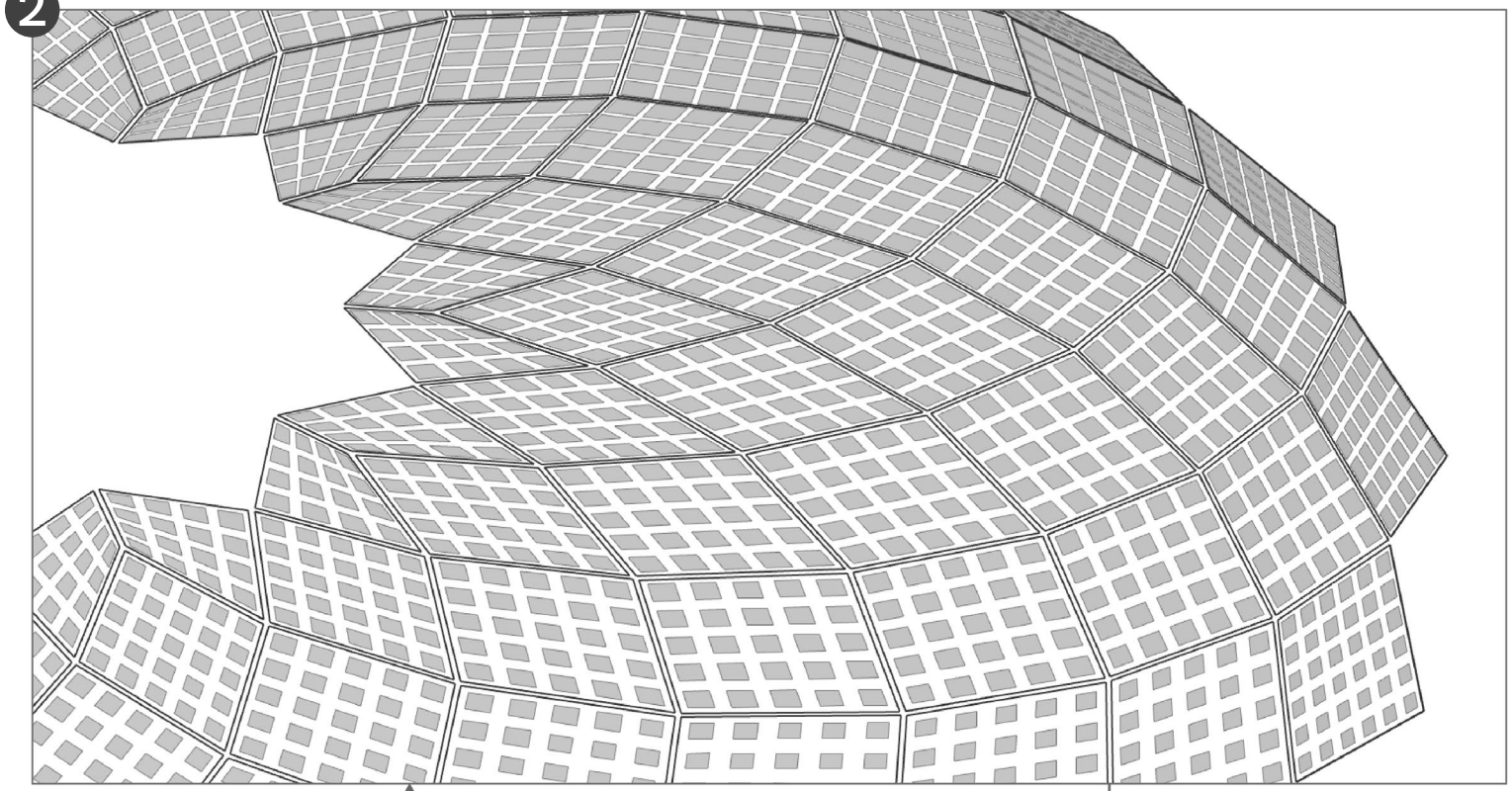
SOLAR DESIGN Optimisation Strategy



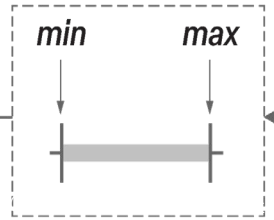
- Simplified approach to model frit patterns for daylight analysis (Essary, 2022)

SCALE BASED ON INCIDENT IRRADIATION (Flat roof)

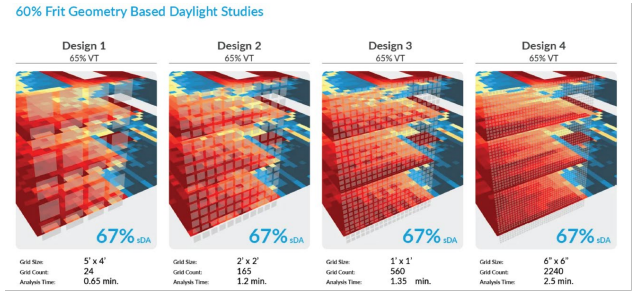
2



SCALE FACTOR OPTIMISATION

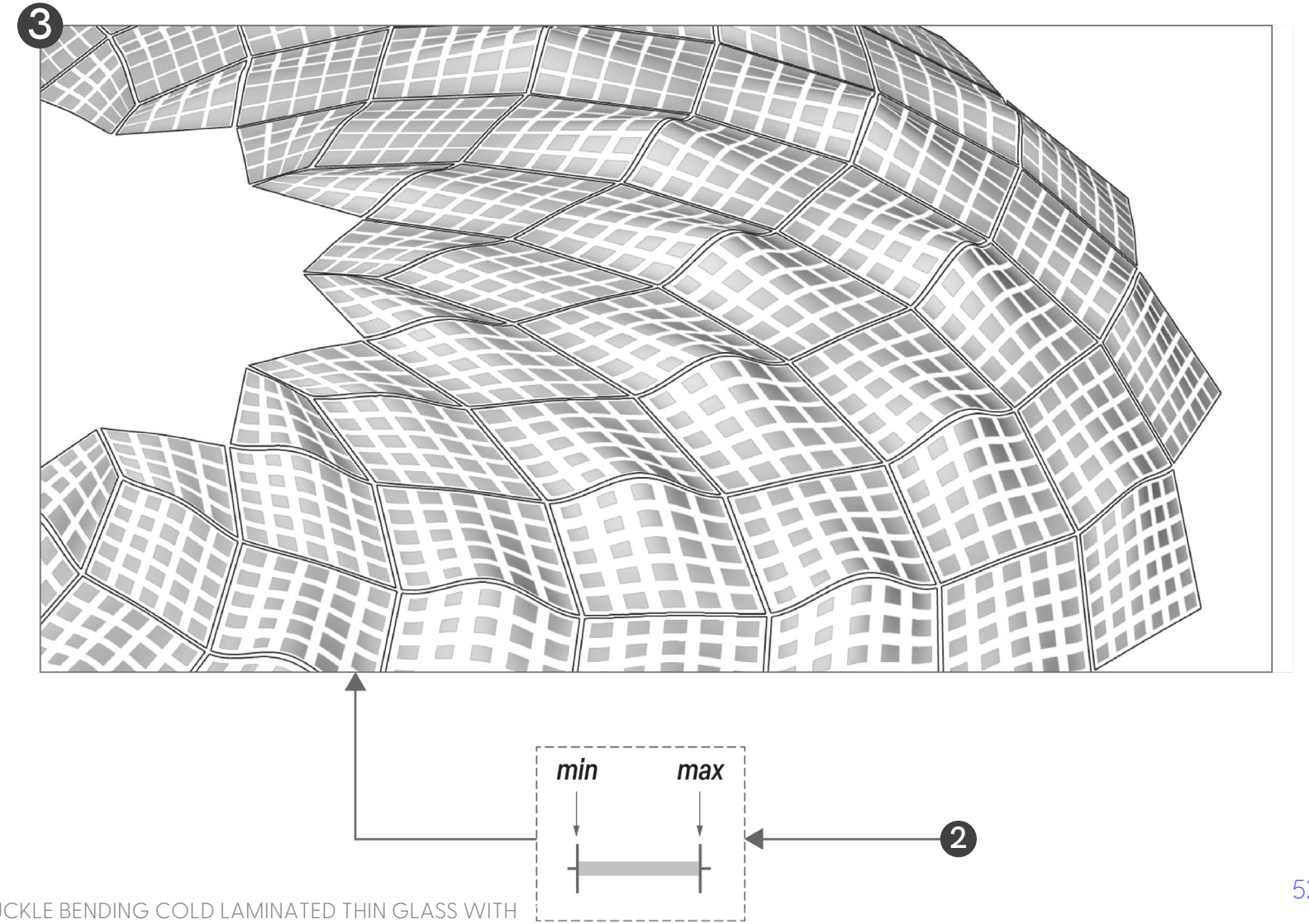


SOLAR DESIGN Optimisation Strategy

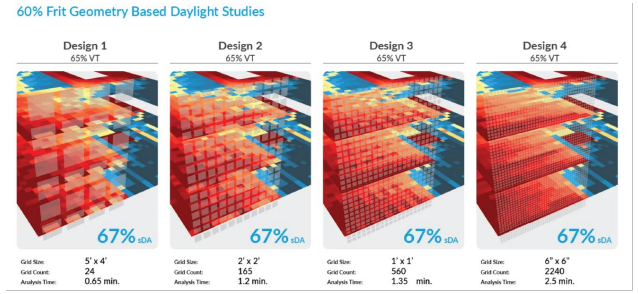


- Simplified approach to model frit patterns for daylight analysis (Essary, 2022)

OPTIMISED SCALE FACTOR APPLIED ON CURVED ROOF



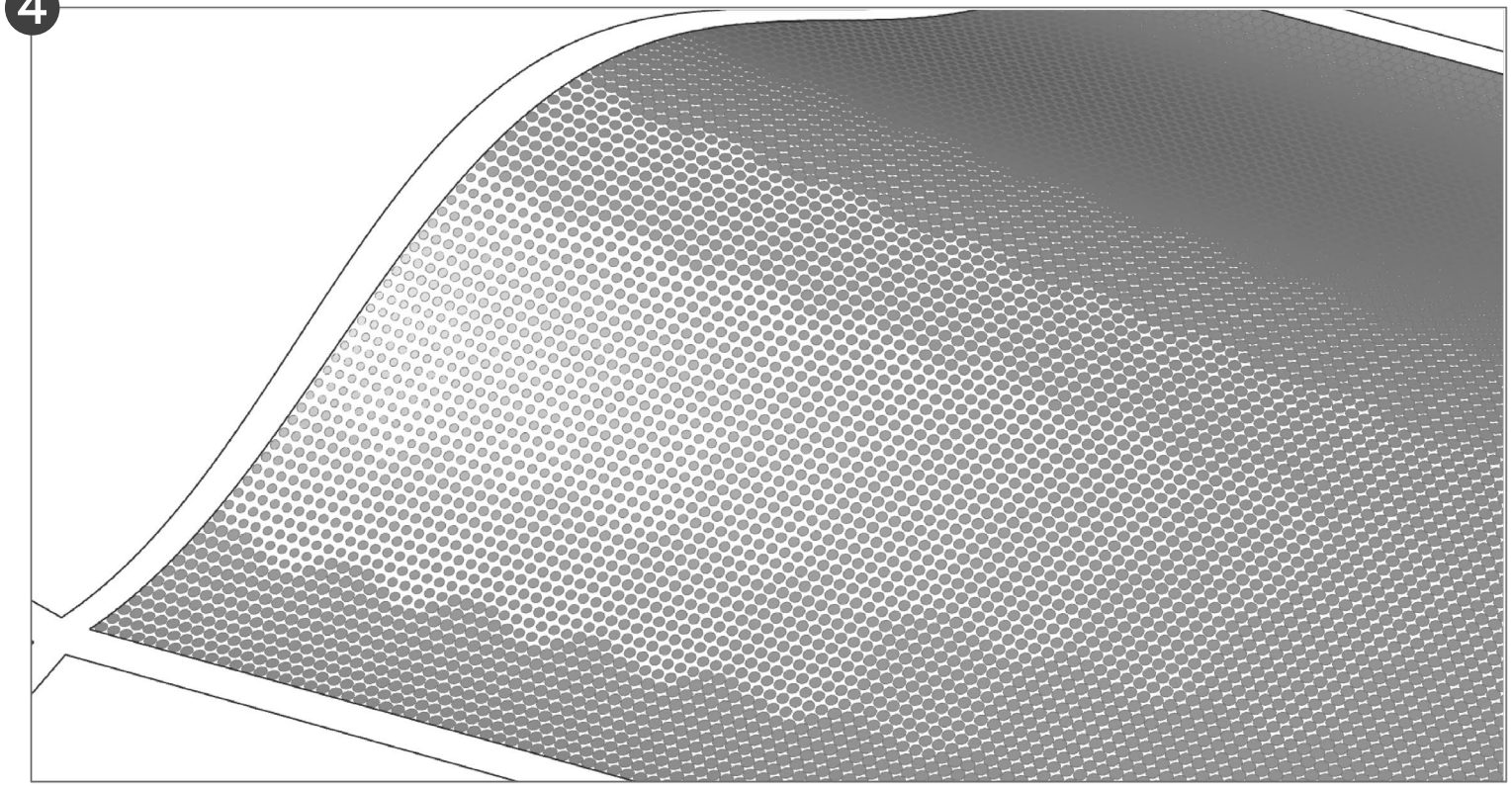
SOLAR DESIGN Optimisation Strategy



- Simplified approach to model frit patterns for daylight analysis (Essary, 2022)

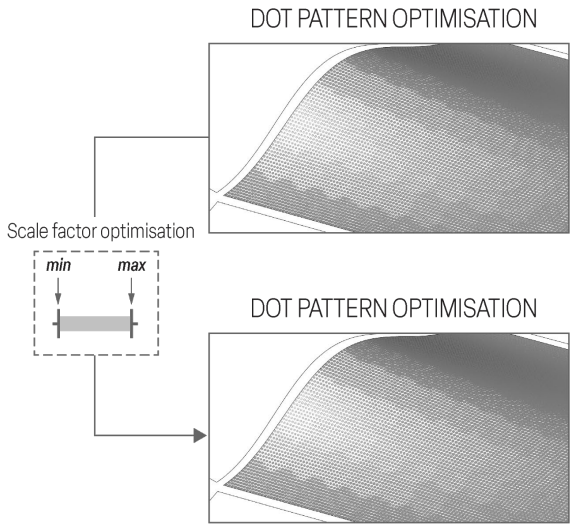
REAL FRIT PATTERN GENERATION

4



SOLAR DESIGN Advantage of Proposed Methodology

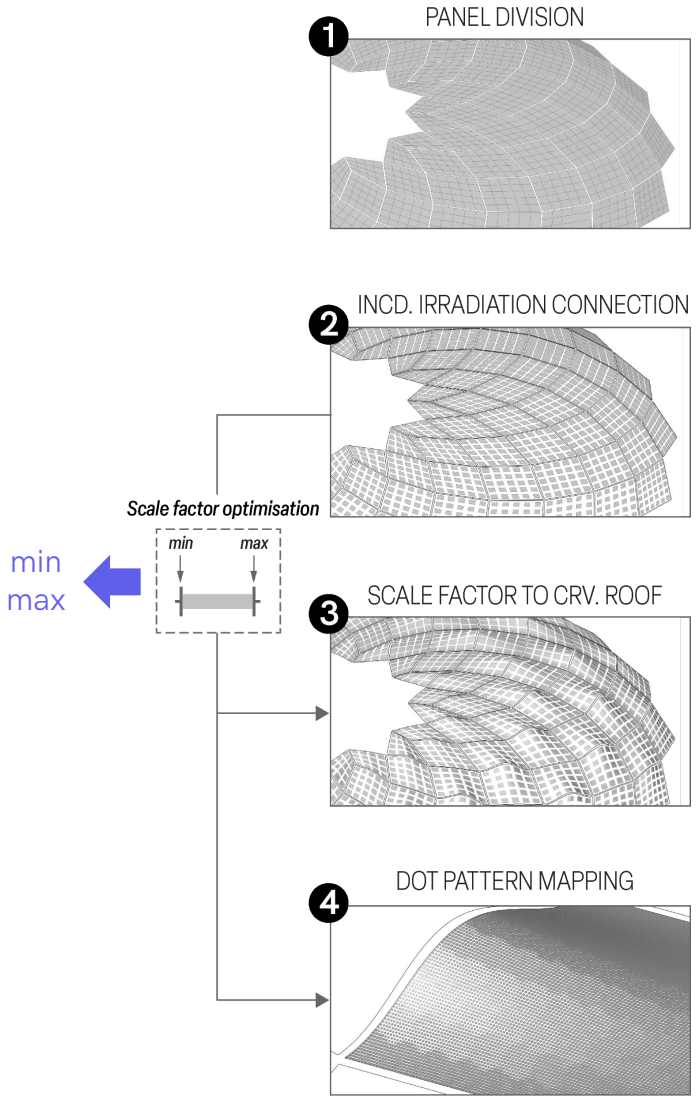
CONVENTIONAL METHOD



4,000
x 160 (panel nr.)
x 90 (dot)

= 57,600,000

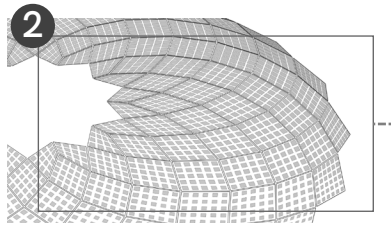
PROPOSED METHOD



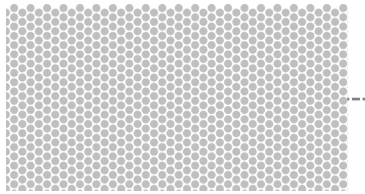
60
x 160 (panel nr.)
x 1 (square)

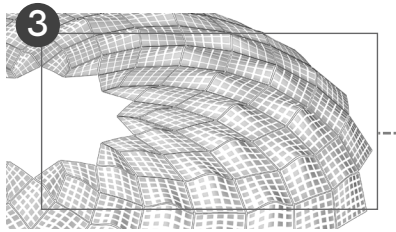
= 9,600
(6000 times faster)

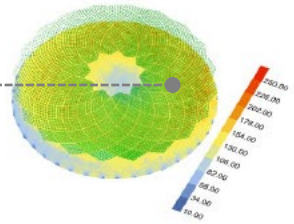
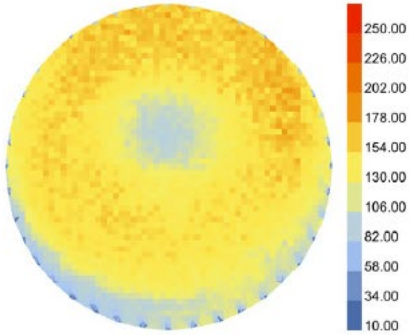
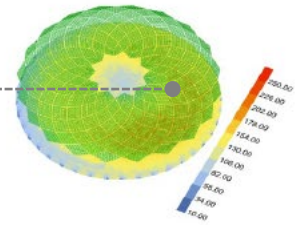
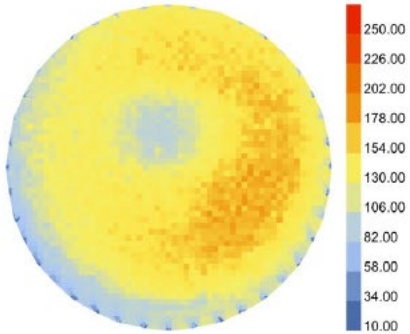
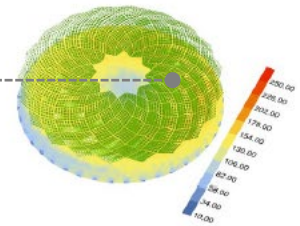
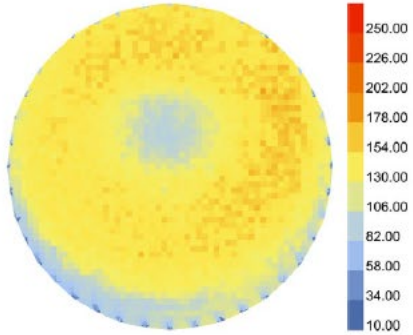
SOLAR DESIGN: Optimisation Result

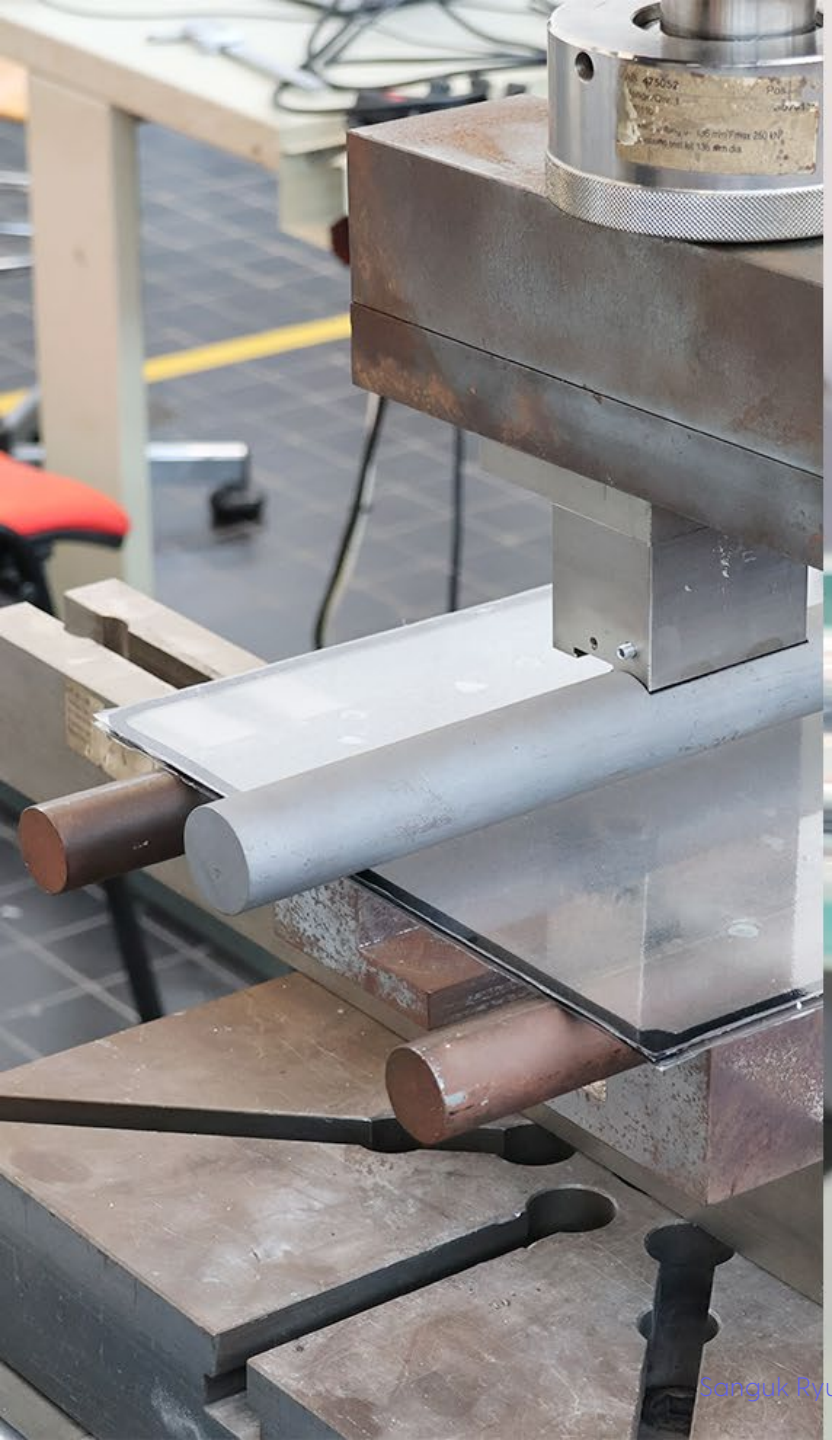


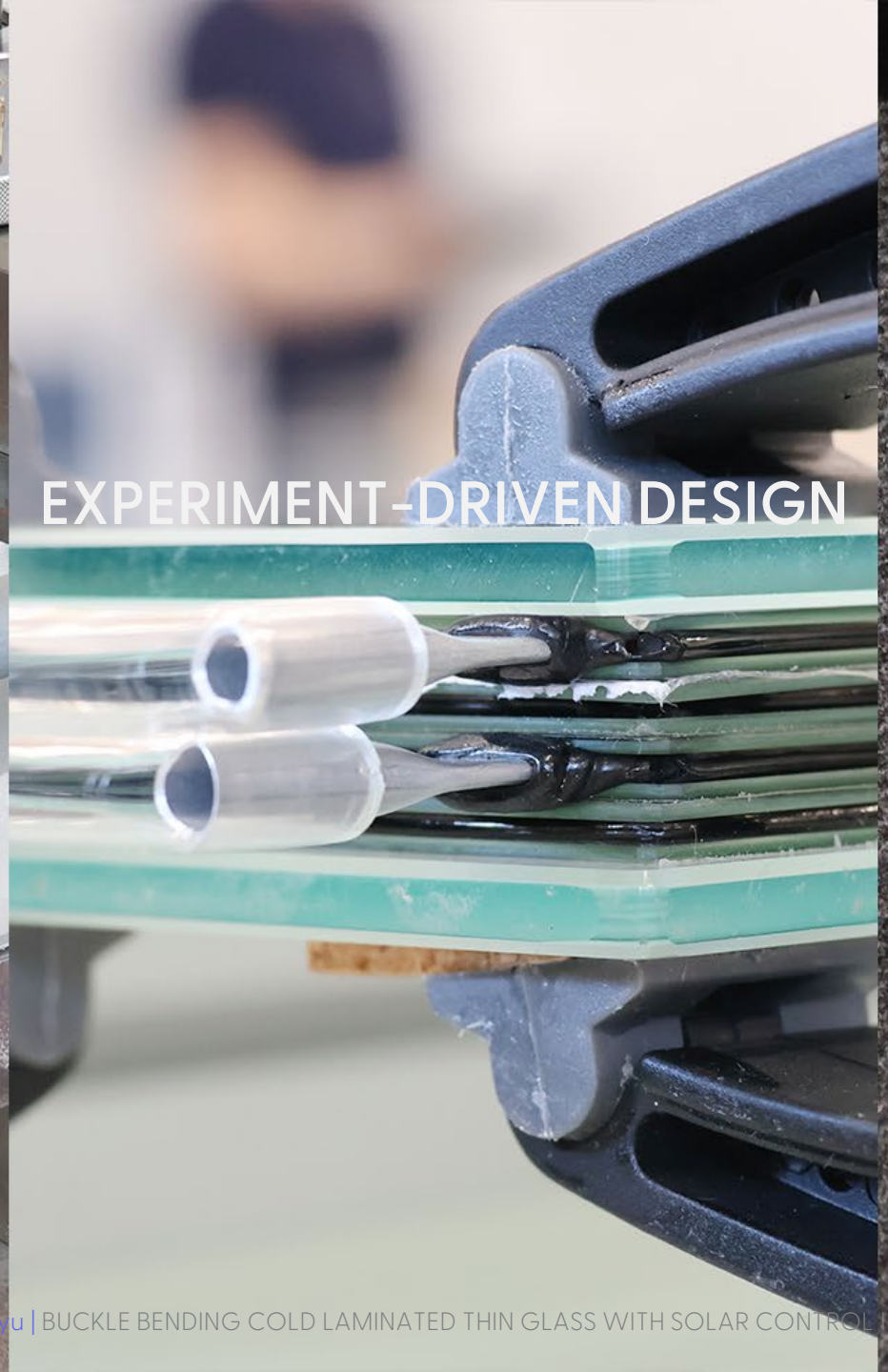
Equal pattern





Condition (Parameter)	Frit Area [m²]	Top 10%th irradiation value [W/m²]	Simulation result [W/m²]
Flat gradient fritting (0.14, 0.9) 	52.858	153.71	
Flat equal fritting (0.72) 	70.64	152.53	
Curved gradient fritting (0.14, 0.9) 	58.77	147.87	





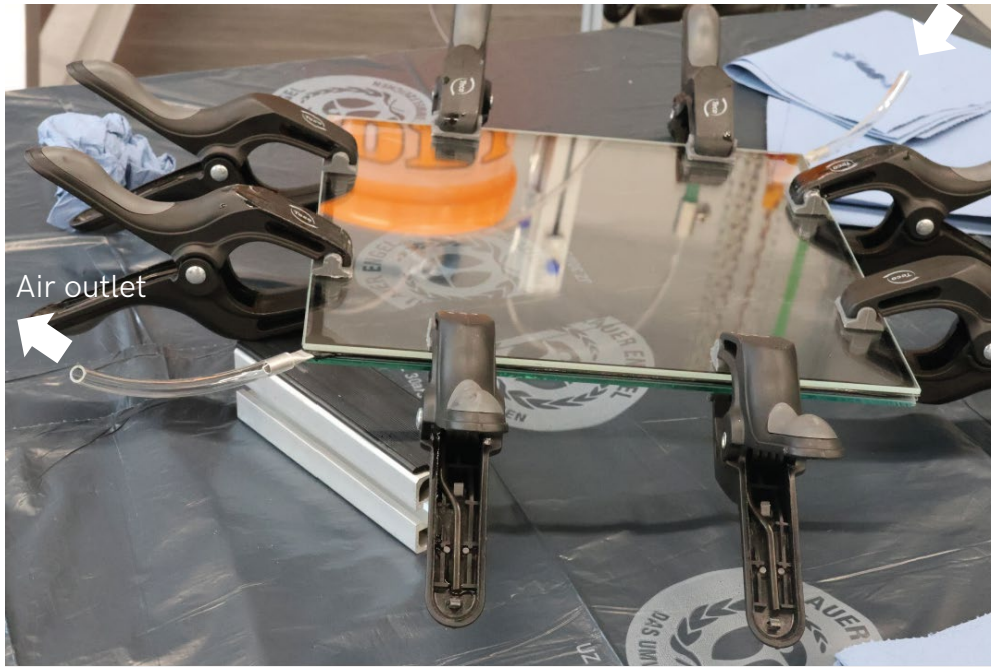
EXPERIMENT-DRIVEN DESIGN



STRUCTURAL TESTING Cold Laminated Thin Glass Preparation

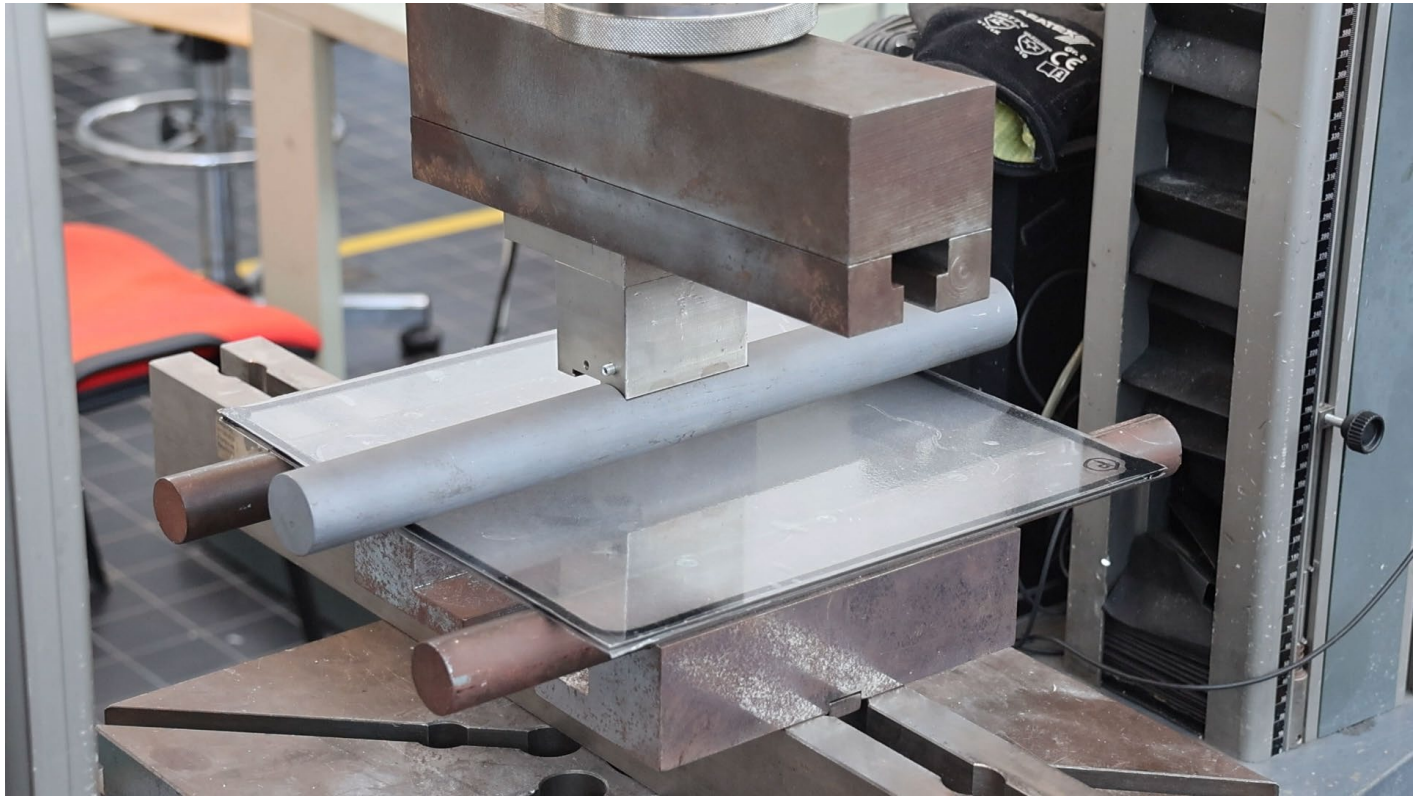


Interlayer inlet

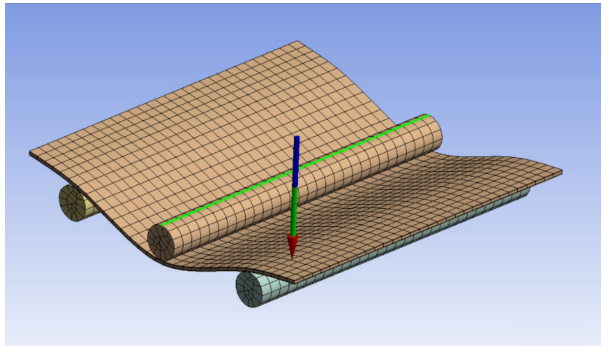


- 0.7-2-0.7 mm sandwich panel build-up with Köraclear XP interlayer

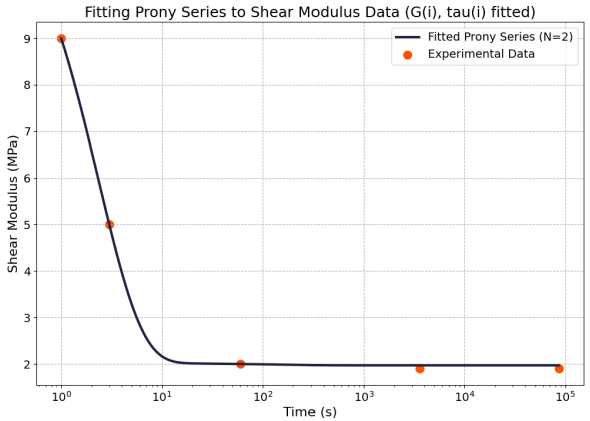
STRUCTURAL TESTING 3-Point Bending Test



DIGITAL TWIN



XP - Prony Series Fitting (22°C)

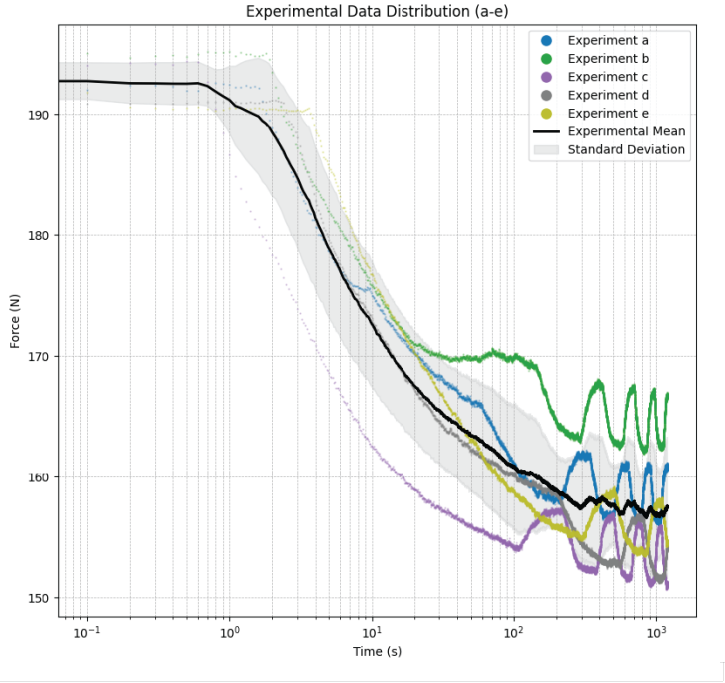


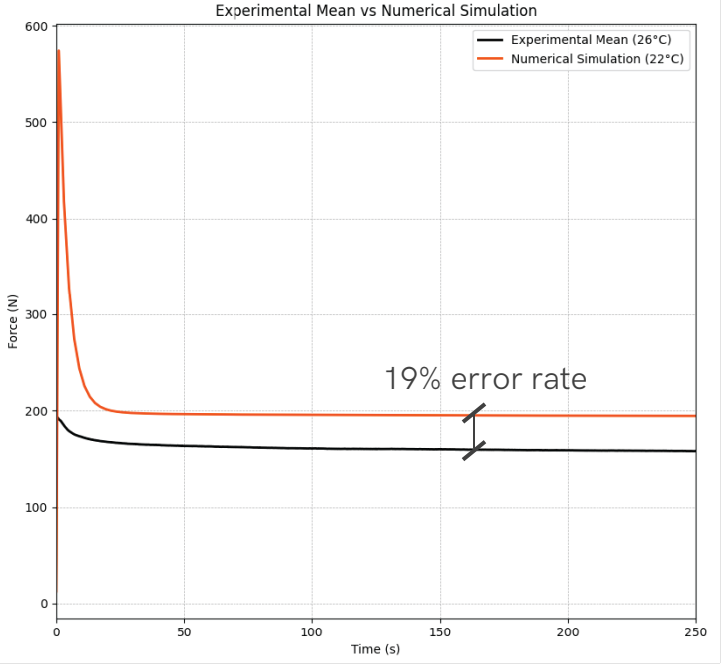
Index [i]	G_i / G_0	τ_i [s]
1	8.4E-01	2.35E+01
2	3.6E-03	1.42E+02

*At temperature 22°C, G0 = 10.4 MPa

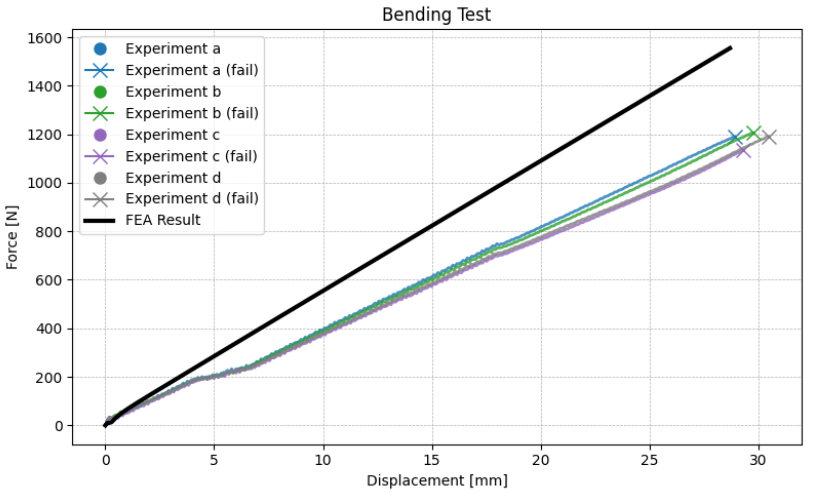
STRUCTURAL TESTING: Holding Test (Stress Relaxation)

HOLDING TEST

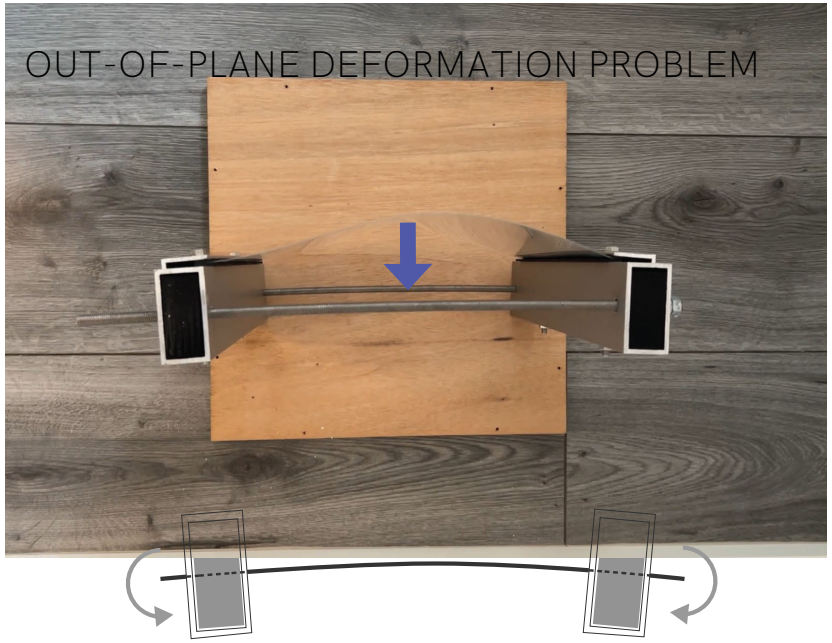


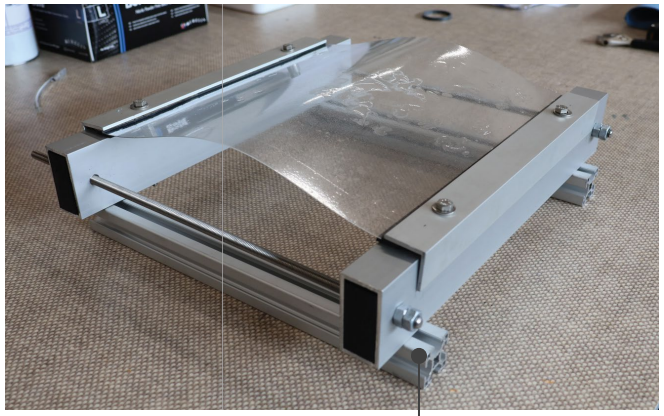


BENDING TEST



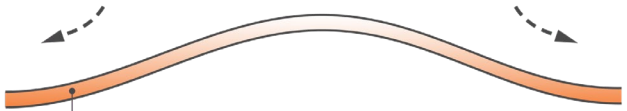
MANUFACTURING Buckle Bending Procedure Development



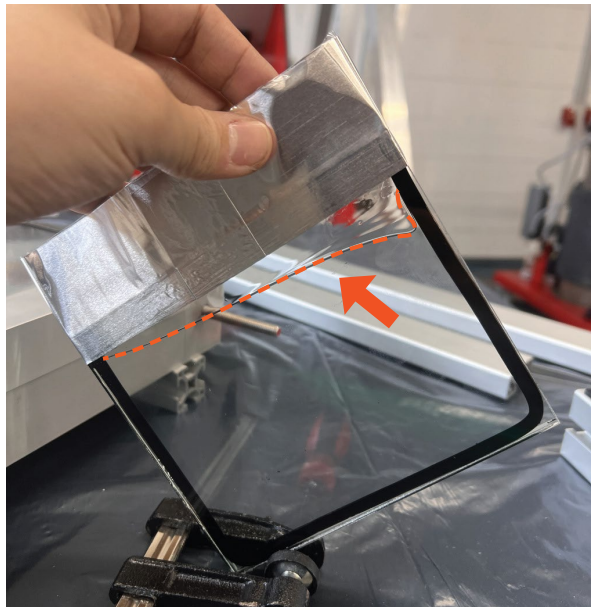


Lateral guiding profile
(prevent out-of-plane rotation)

GRAVITATIONAL FLOW OF LIQUID



Liquid in terlayer tends to
flow from top to bottom,
according to its geometry



MANUFACTURING Buckle Bending Device



800x800 size machine

300x300 size machine

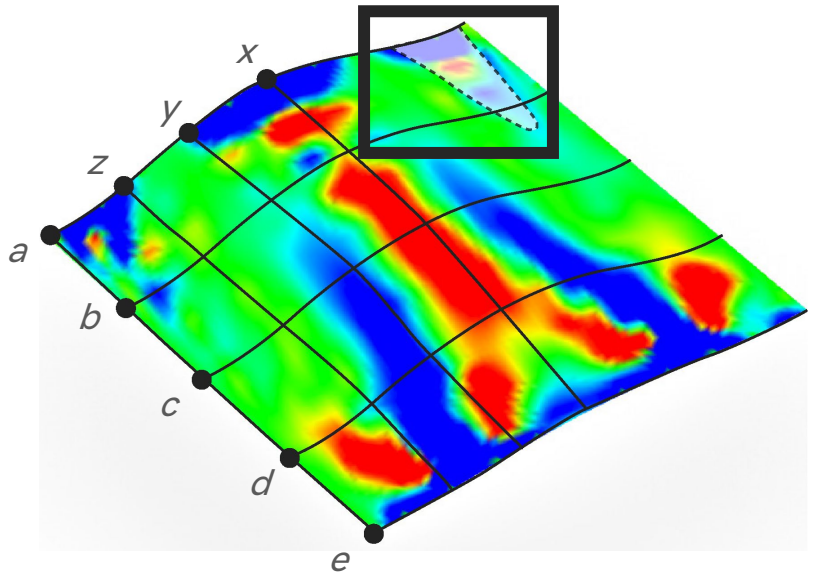
MANUFACTURING 1:1 Scale Cold Buckle Bent Glass Unit





MANUFACTURING Cold Bending Distortions

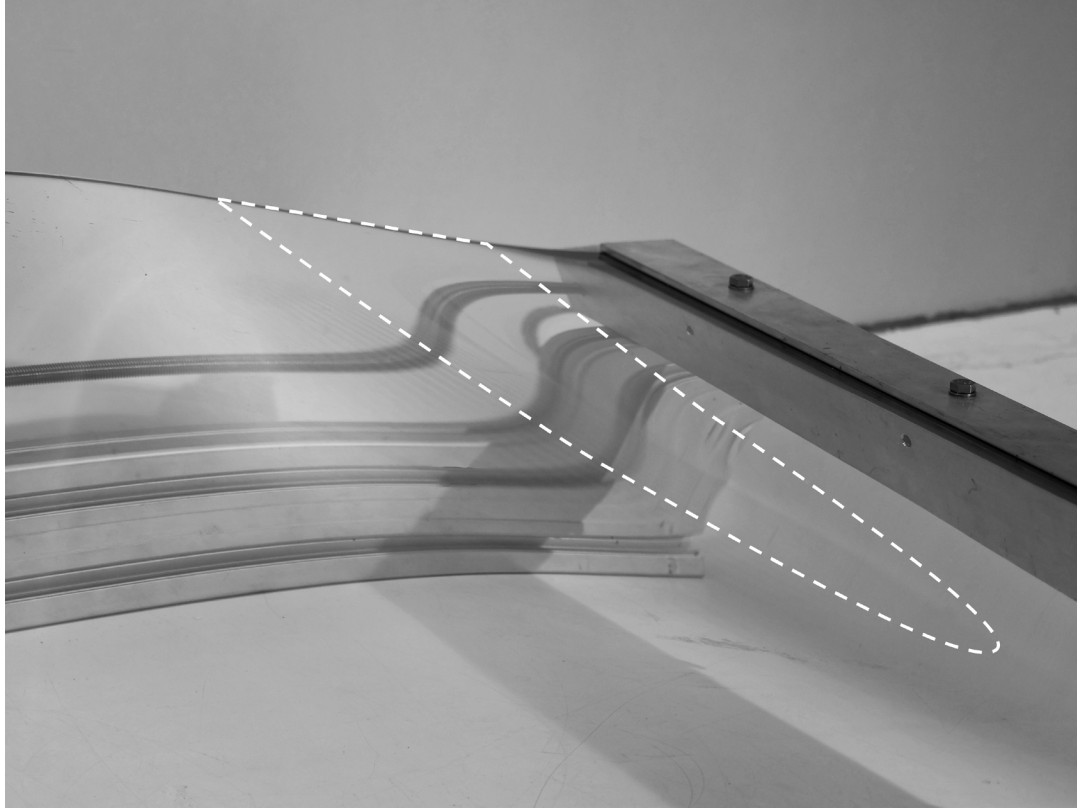
FEA OUTPUT CURVATURE ANALYSIS



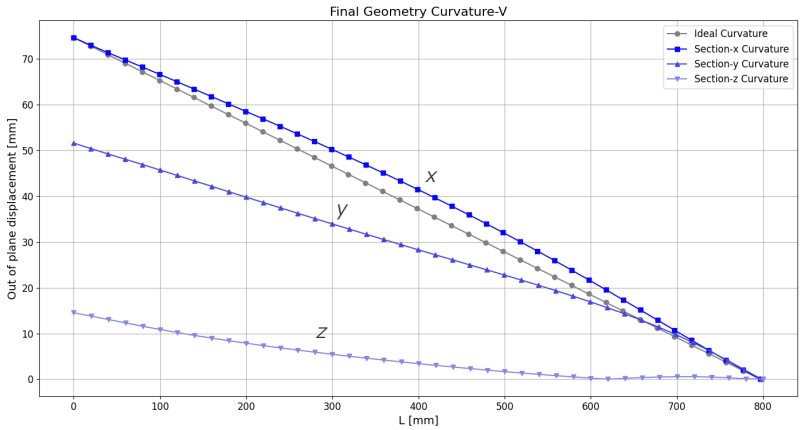
: K > 0 (synclastic surface)

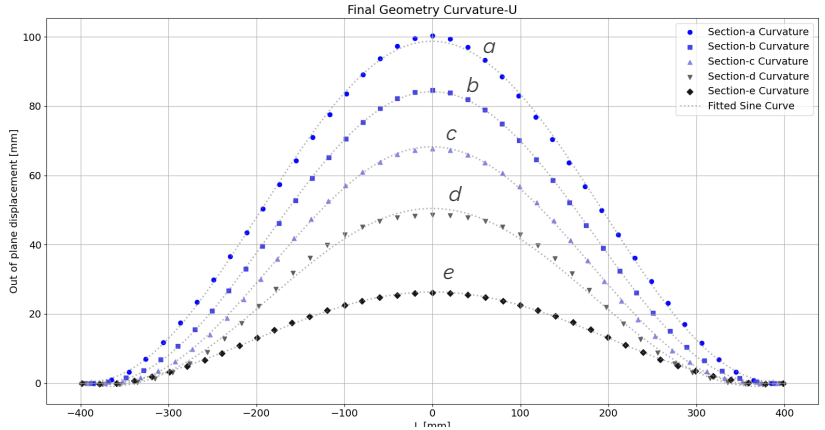
: K = 0 (developable surface)

: K < 0 (anticlastic surface)



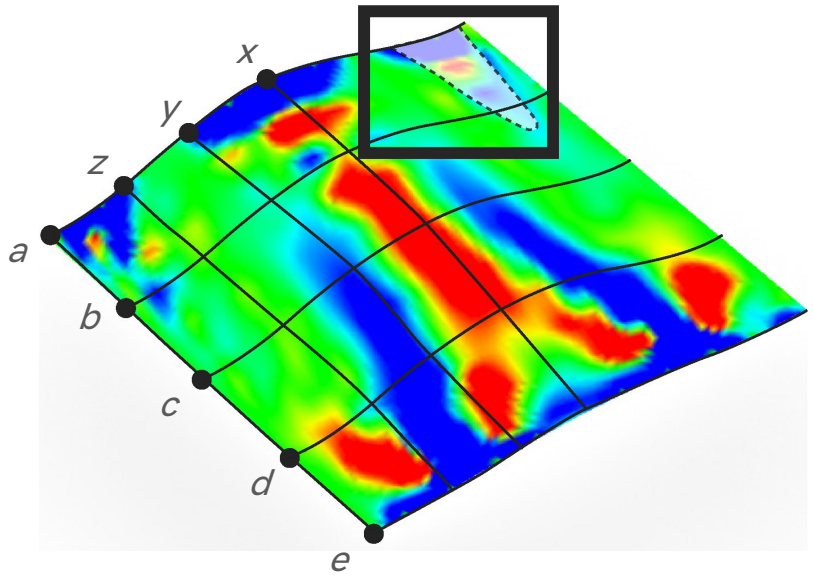
- Cold bending distortion occurring in regions where the transition from syn- to anticlastic curvature is abrupt





MANUFACTURING Cold Bending Distortions

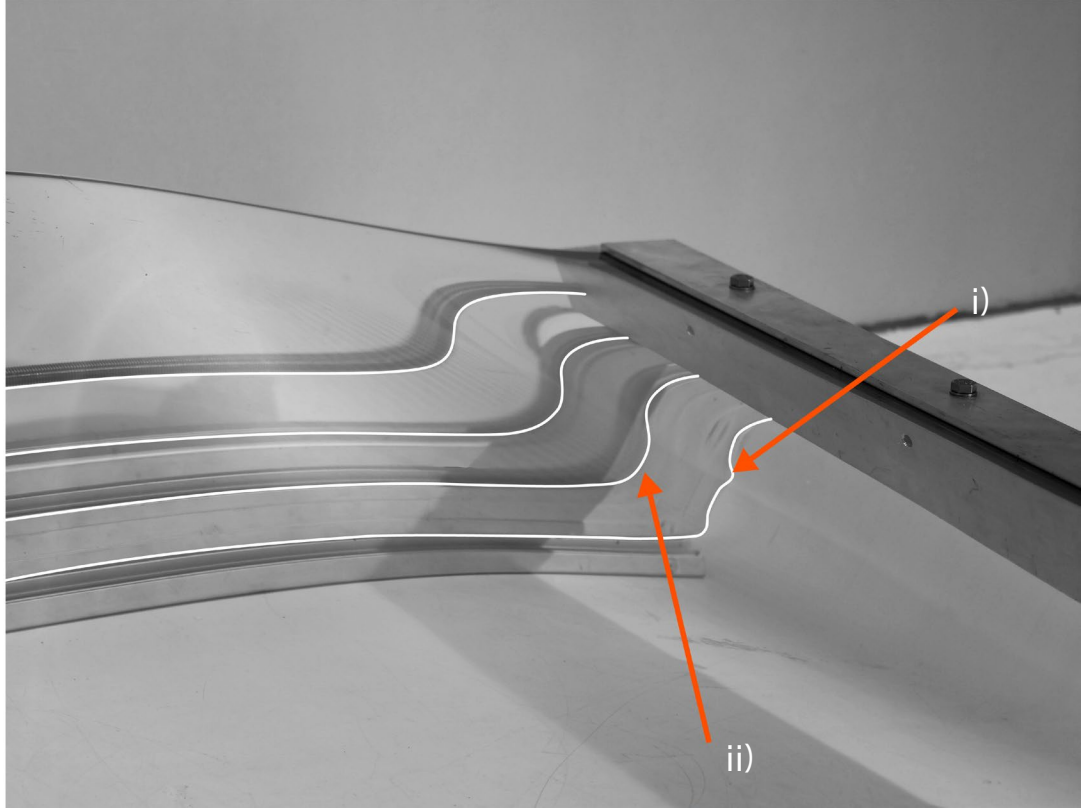
FEA OUTPUT CURVATURE ANALYSIS



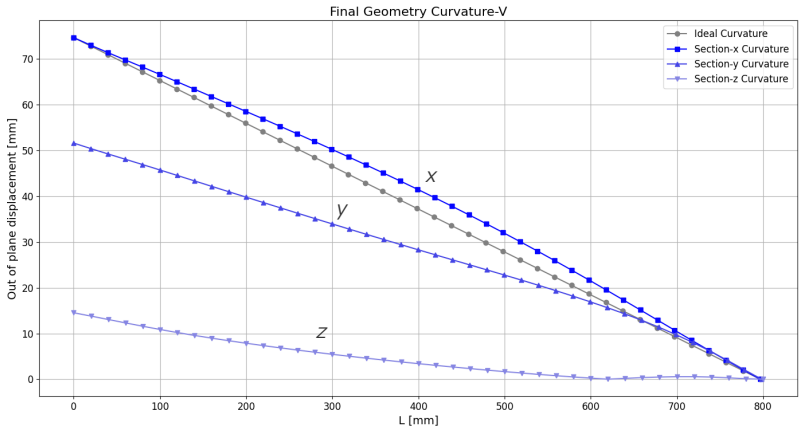
: K > 0 (synclastic surface)

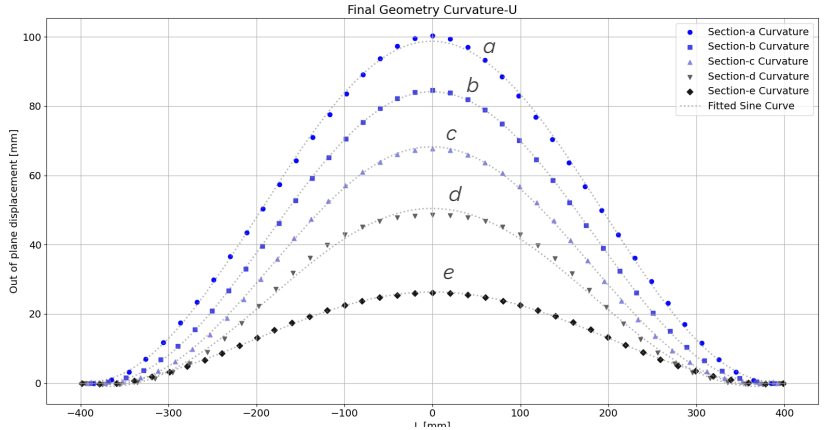
: K = 0 (developable surface)

: K < 0 (anticlastic surface)



- Cold bending distortion occurring in regions where the transition from syn- to anticlastic curvature is abrupt



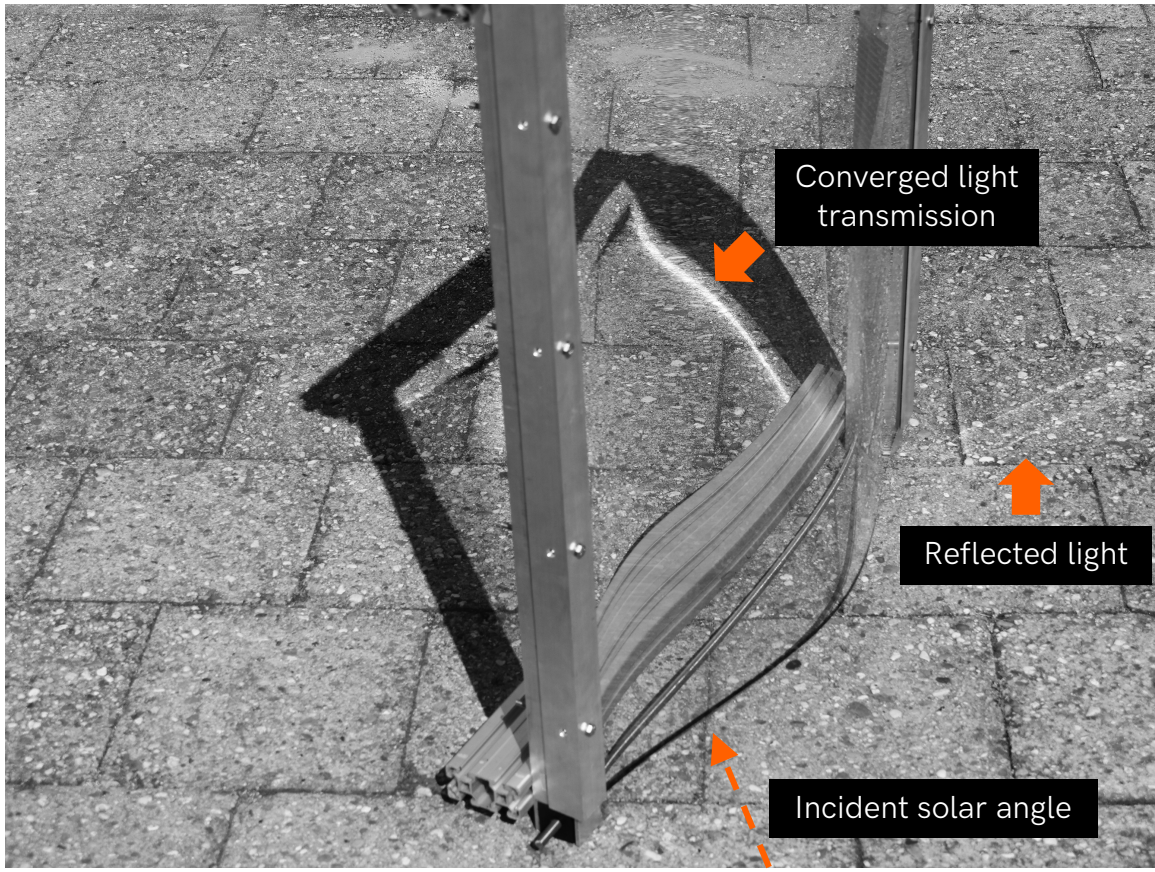


i) Small rippling distortion

ii) Area of rapid change in curvature

MANUFACTURING Optical Behaviour





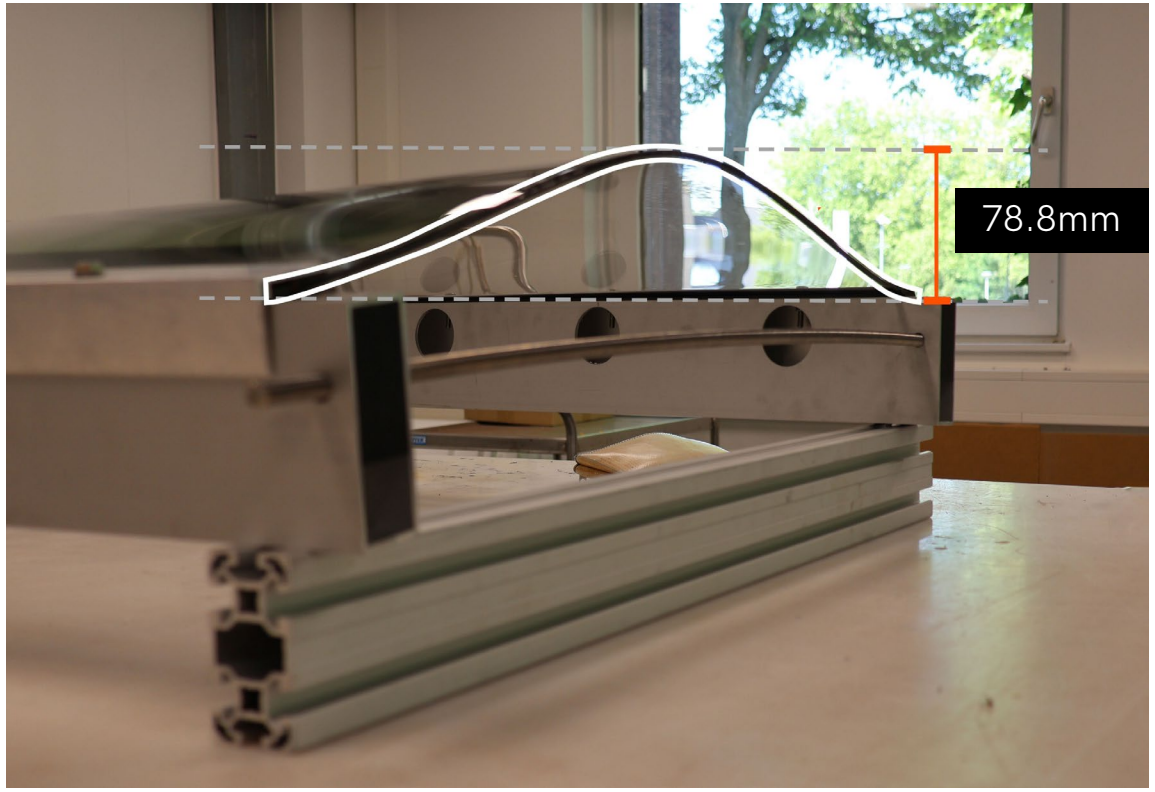
MANUFACTURING Spring-Back Behaviour

Experiment Type	Measurement time after fixture removal [s]	Z disp.$_{max}$ before releasing fixture [mm]	Z disp.$_{max}$ after releasing fixture [mm]	Recovery ratio [%]
Panel B	≈ 300	78.8	71.8	8.9
Digital twin Köraclear XP	290	80.9	60.6	25.1
Digital twin Ködistruct LG	310	80.9	67.3	16.8

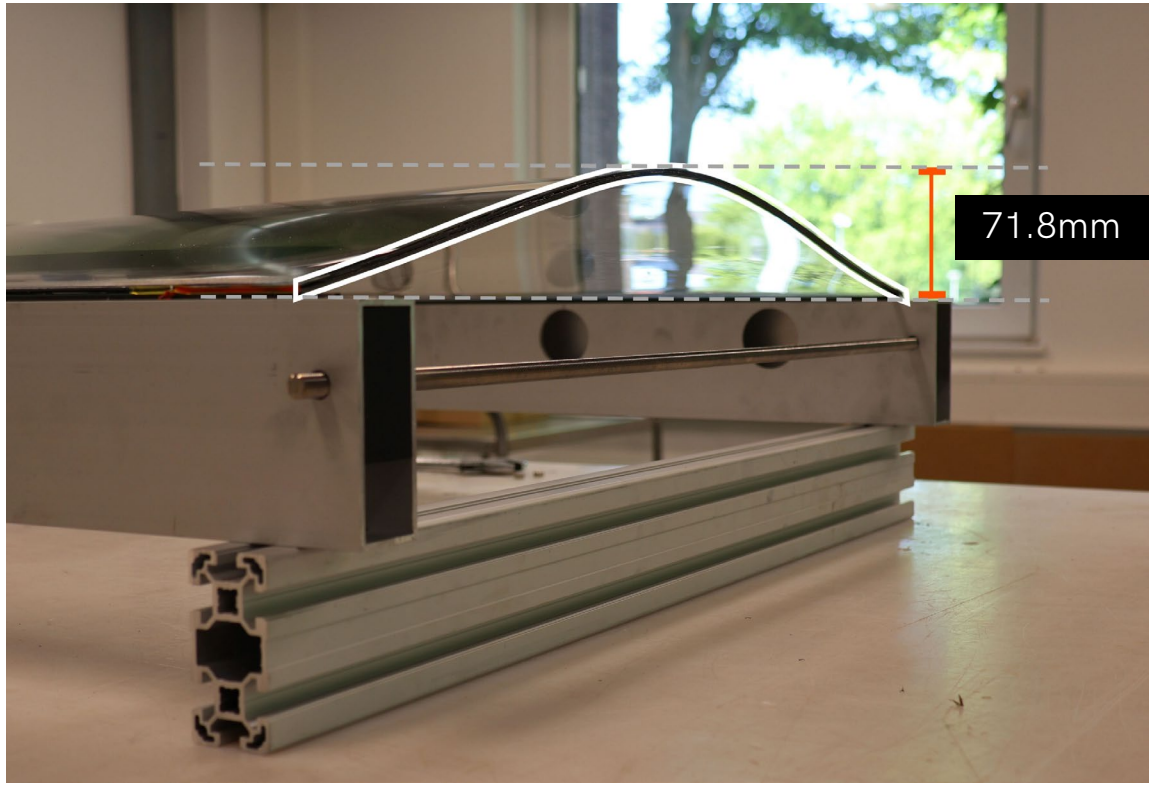
Experiment

Simulation

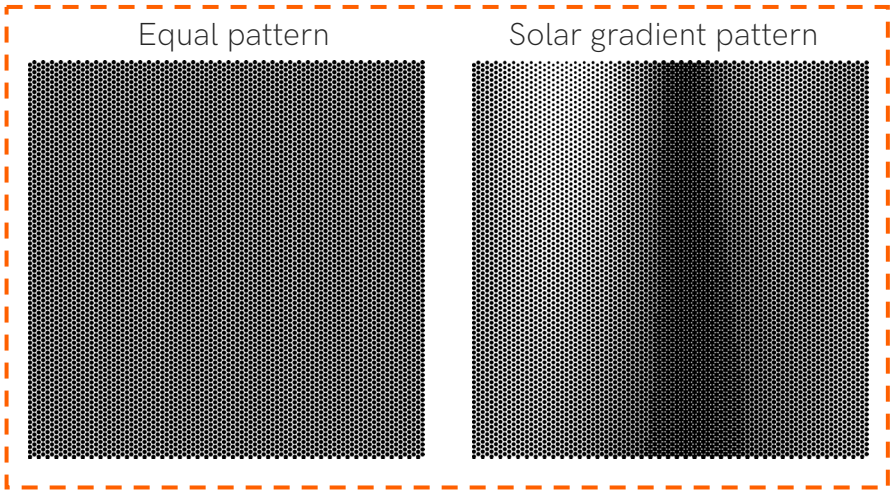
BEFORE FIXTURE REMOVAL



AFTER FIXTURE REMOVAL

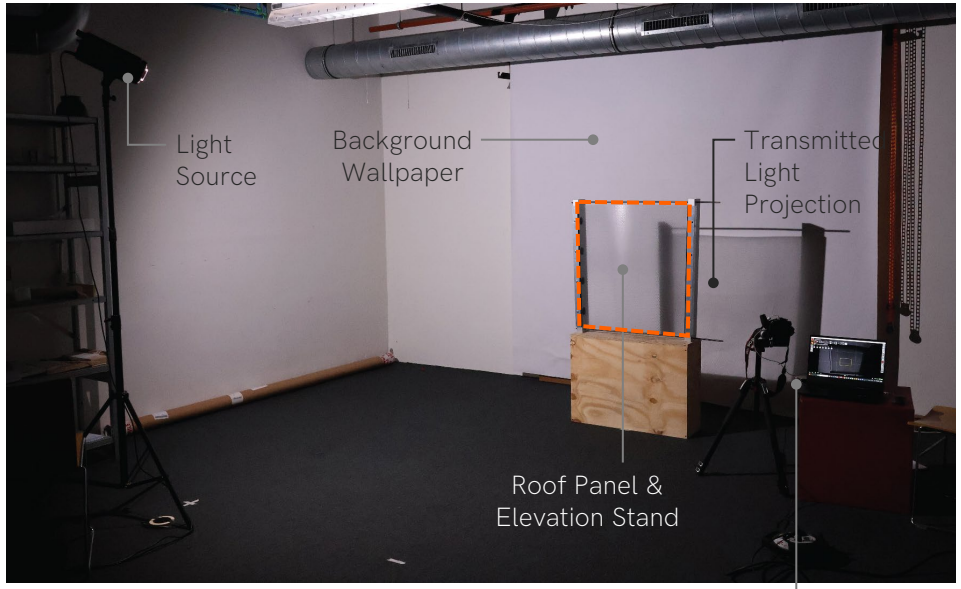


SOLAR TESTING Experiment Setup

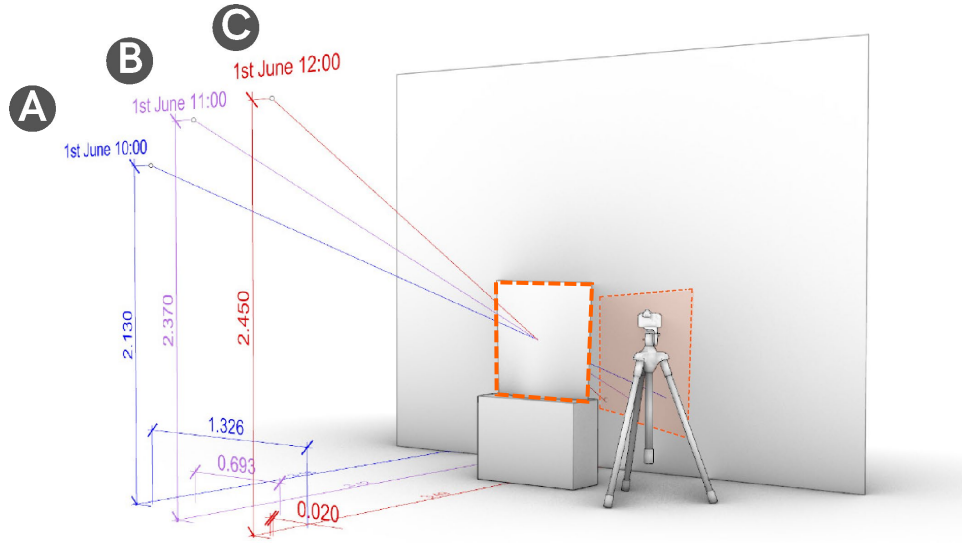


- Same coverage area (64.8%)

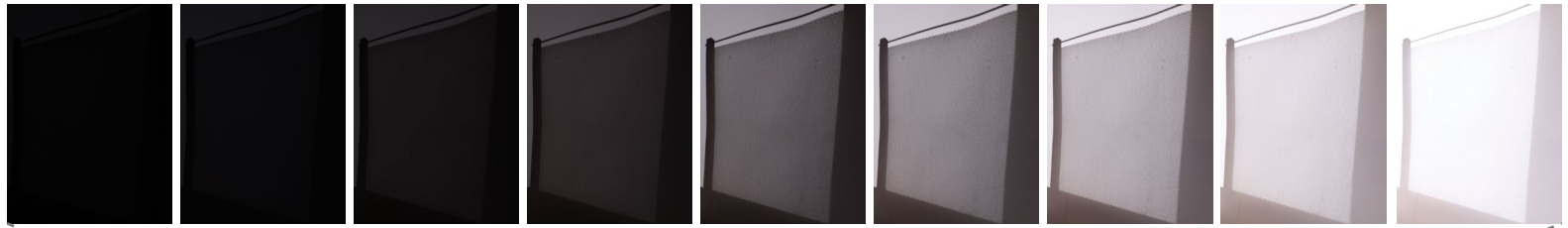
PHYSICAL EXPERIMENT



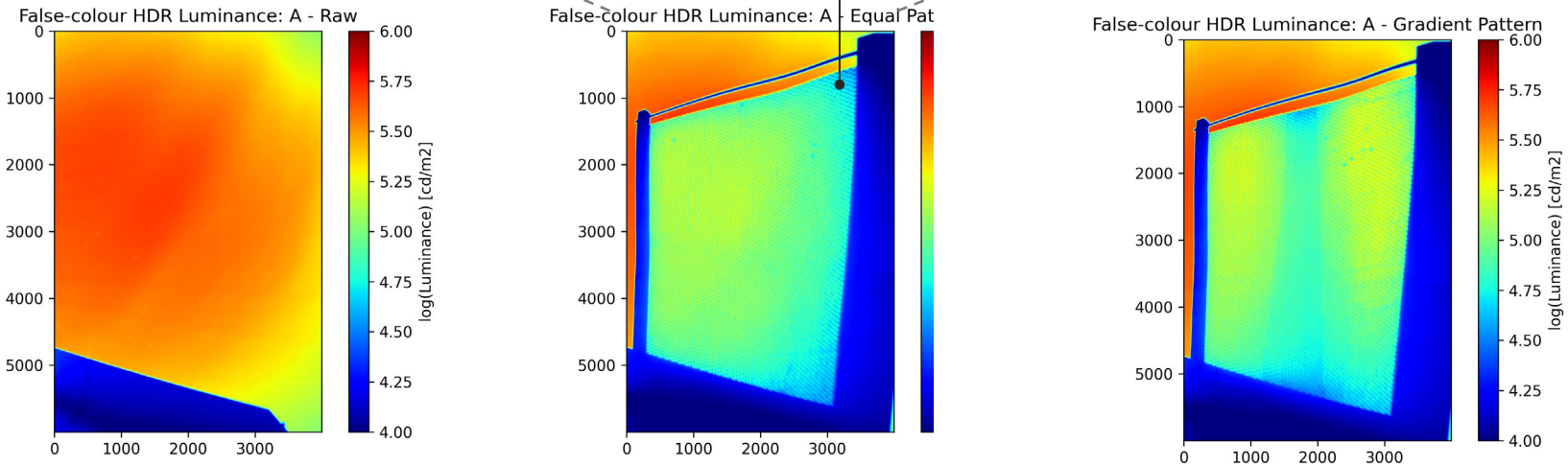
DIGITAL TWIN



SOLAR TESTING HDR Luminance Image Analysis



[cd/m2] value
for each pixel



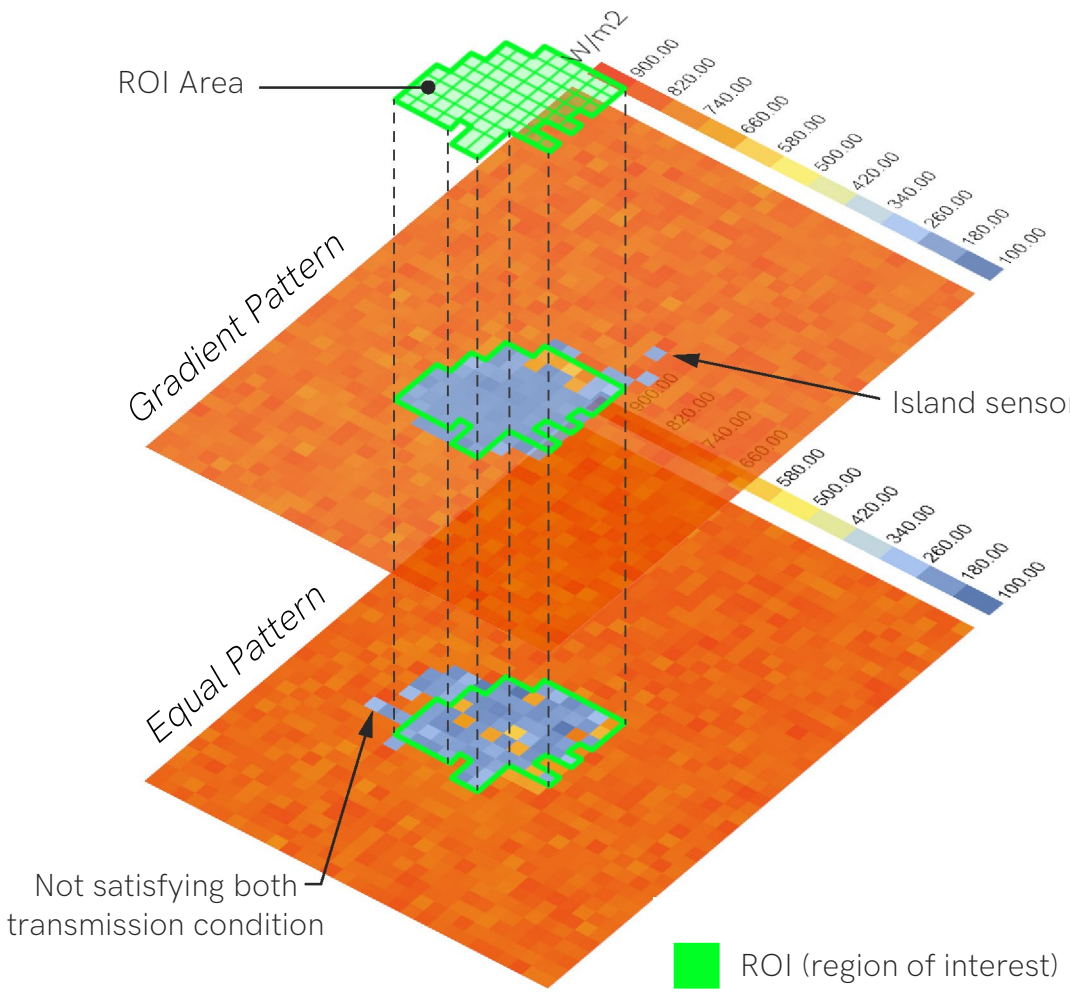
BASELINE EQUAL GRADIENT

T_{equal} (%)

$T_{gradient}$ (%)

SOLAR TESTING Digital Twin Transmittance Comparison

DIGITAL TWIN IRRADIANCE RESULT



NUMERICAL MODEL VALIDATION RESULT

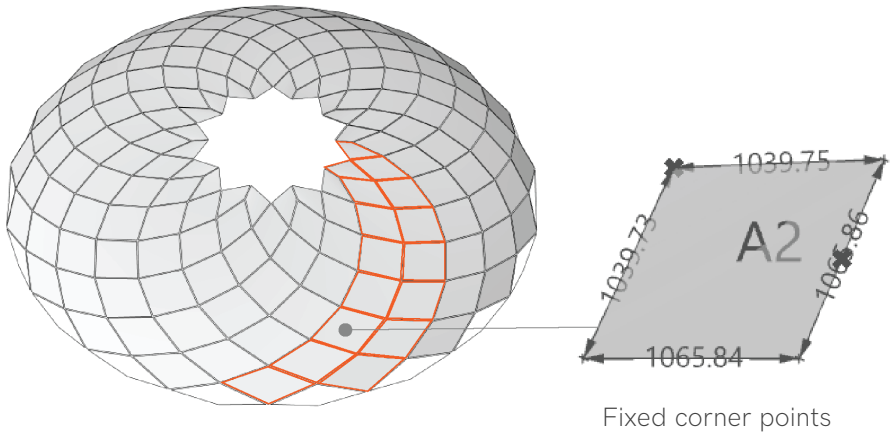
Light location	A		B		C	
Frit type	T_{equal}[%]	$T_{gradient}$[%]	T_{equal}[%]	$T_{gradient}$[%]	T_{equal}[%]	$T_{gradient}$[%]
Physical experiment	54.58	55.82	56.33	60.57	60.20	62.48
Digital twin	31.85	27.89	36.12	30.41	29.69	32.76
$T_{Exp.diff}$[%]	-1.24		-4.24		-2.28	
$T_{Twin.diff}$[%]	3.96		5.71		-3.07	



FINAL DESIGN & CONCLUSION

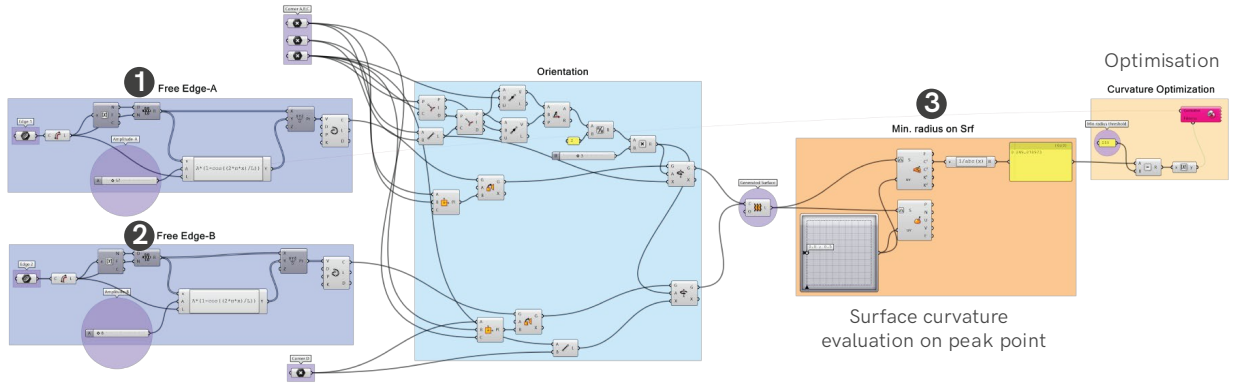
FLATTENED PANEL GENERATION

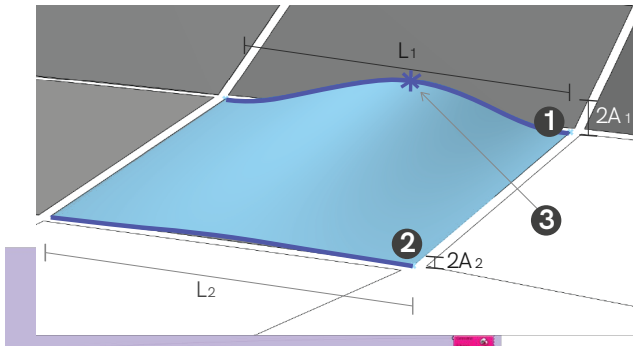
OWO Pavilion

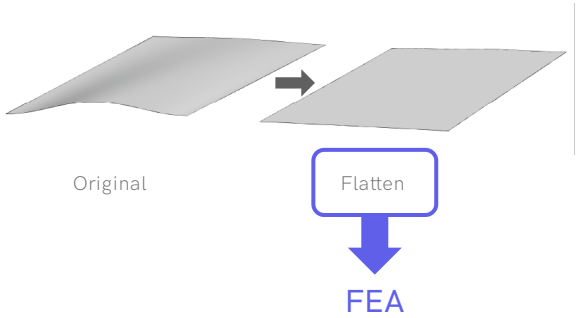


Fixed corner points

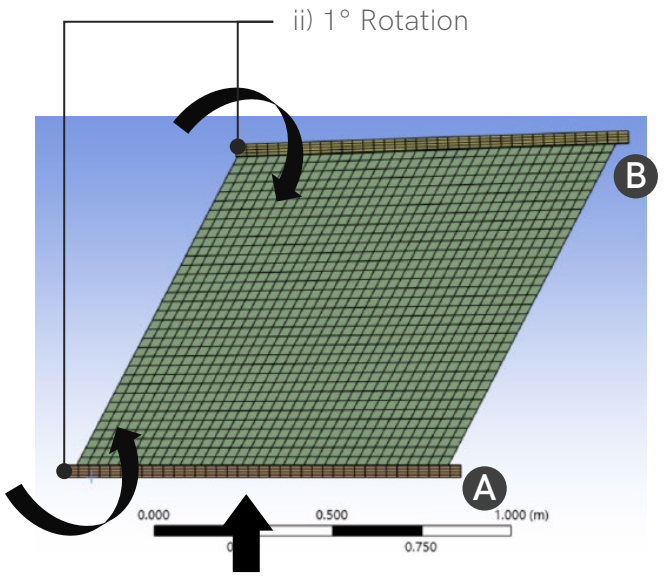
COLD BENDING GEOMETRY GENERATION SCRIPT





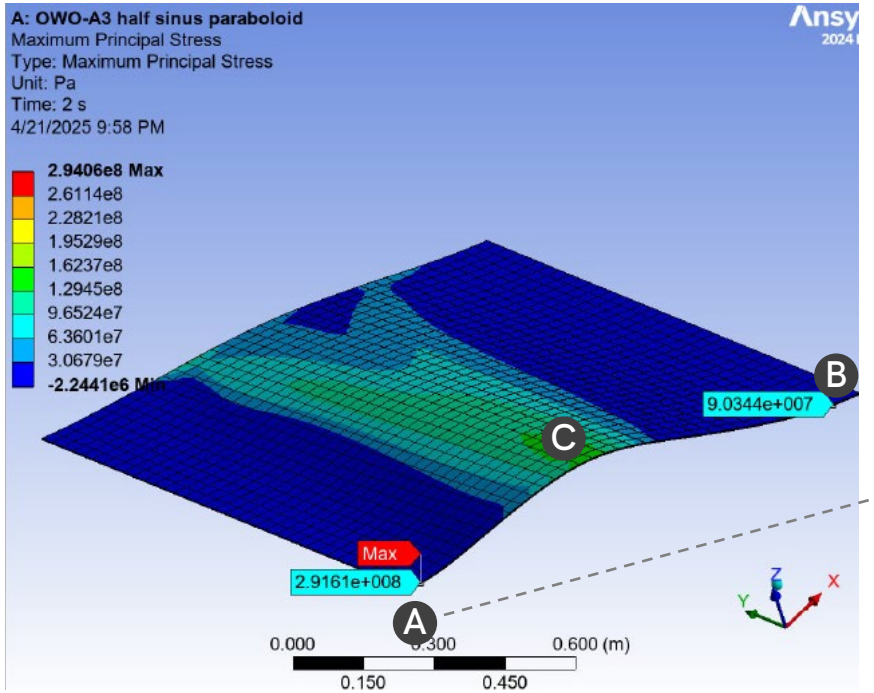


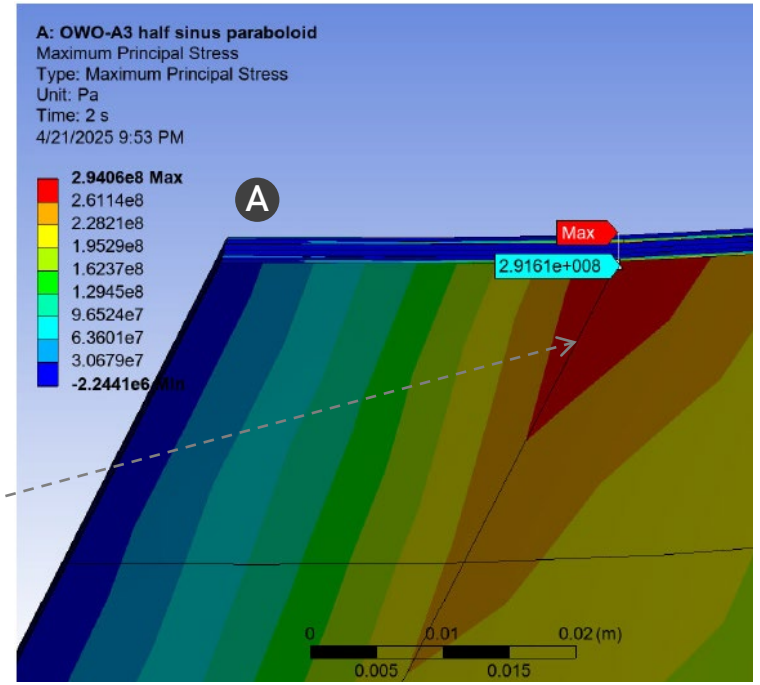
STRUCTURAL DESIGN Sinusoidal Half Paraboloid



i) 3mm Displacement

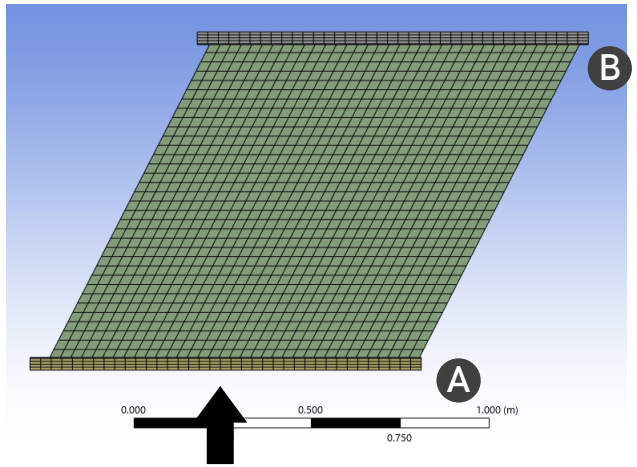
Bending Strength





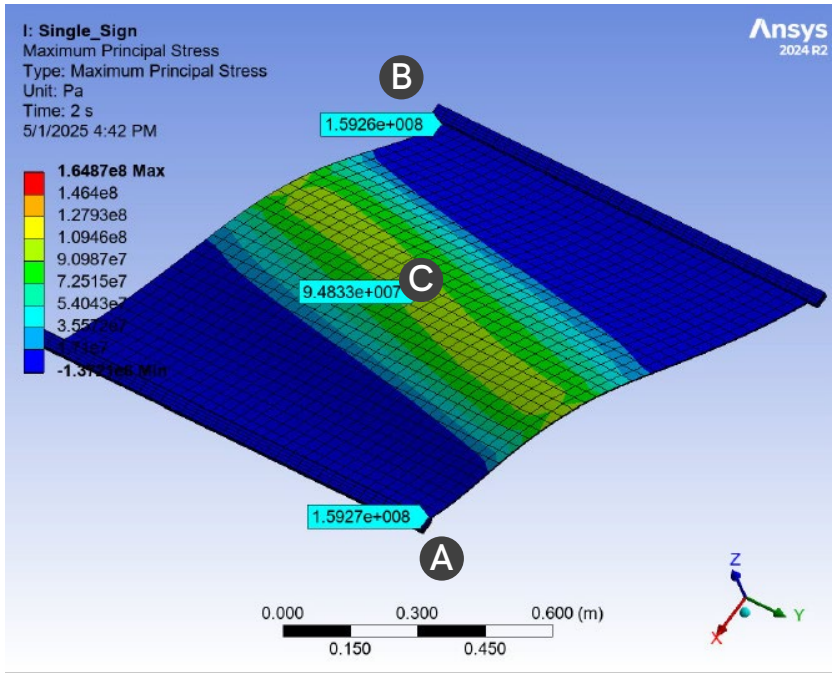
A 291.6 MPa B 90.3 MPa C 150 MPa

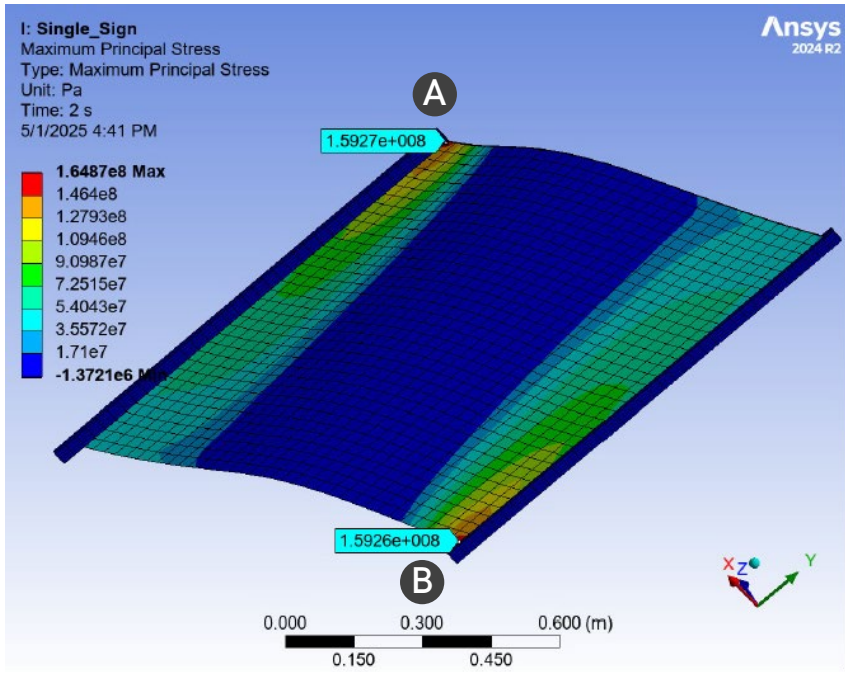
STRUCTURAL DESIGN Sinusoidal Sigle-Curvature



i) Equal Displacement

Bending Strength



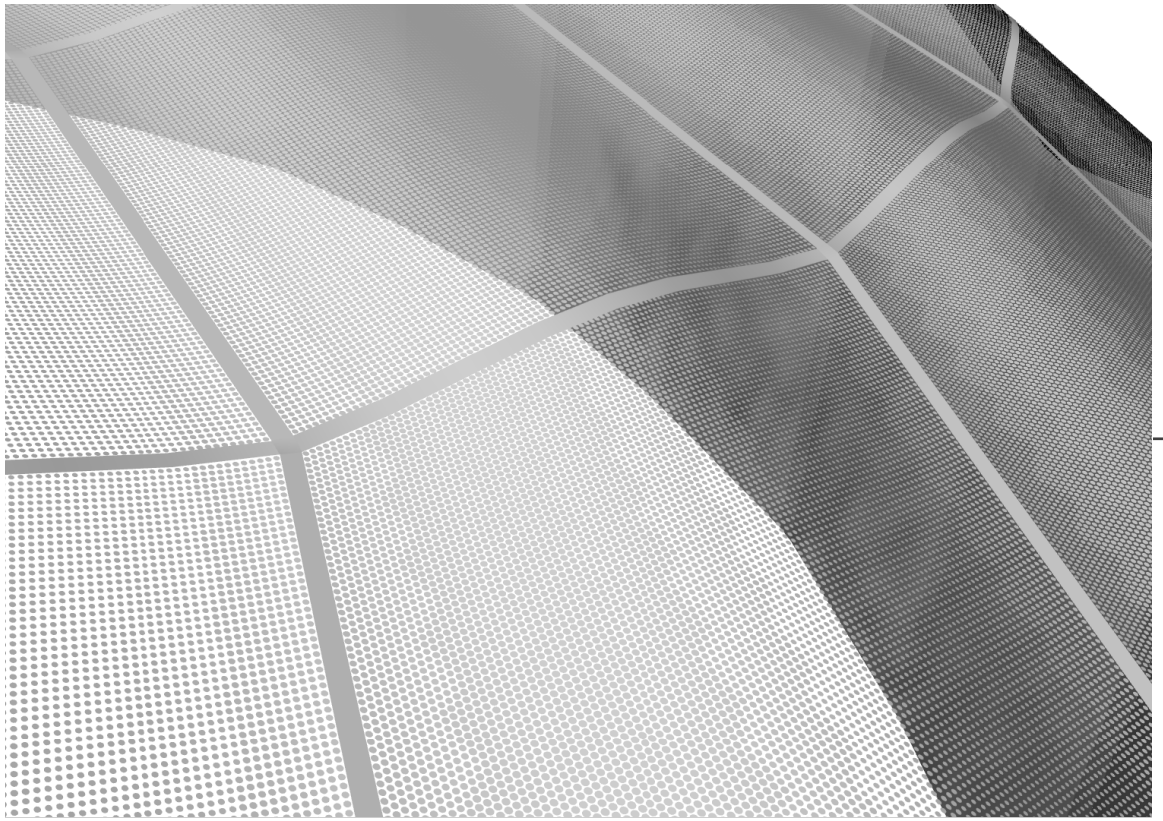


A 159.3 MPa B 159.3 MPa C 94.8 MPa

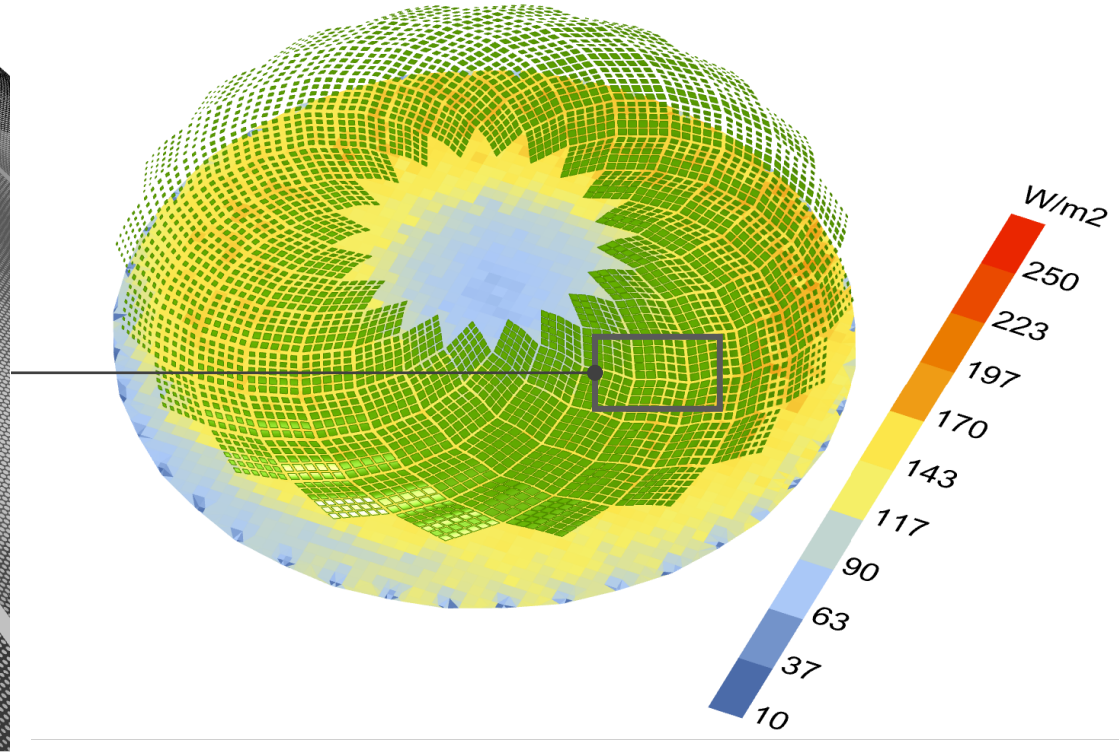
Step	X displacement [mm]	Z displacement [mm]	Max. stress [MPa]
Cold bending	23	90	165

SOLAR DESIGN Solar Design

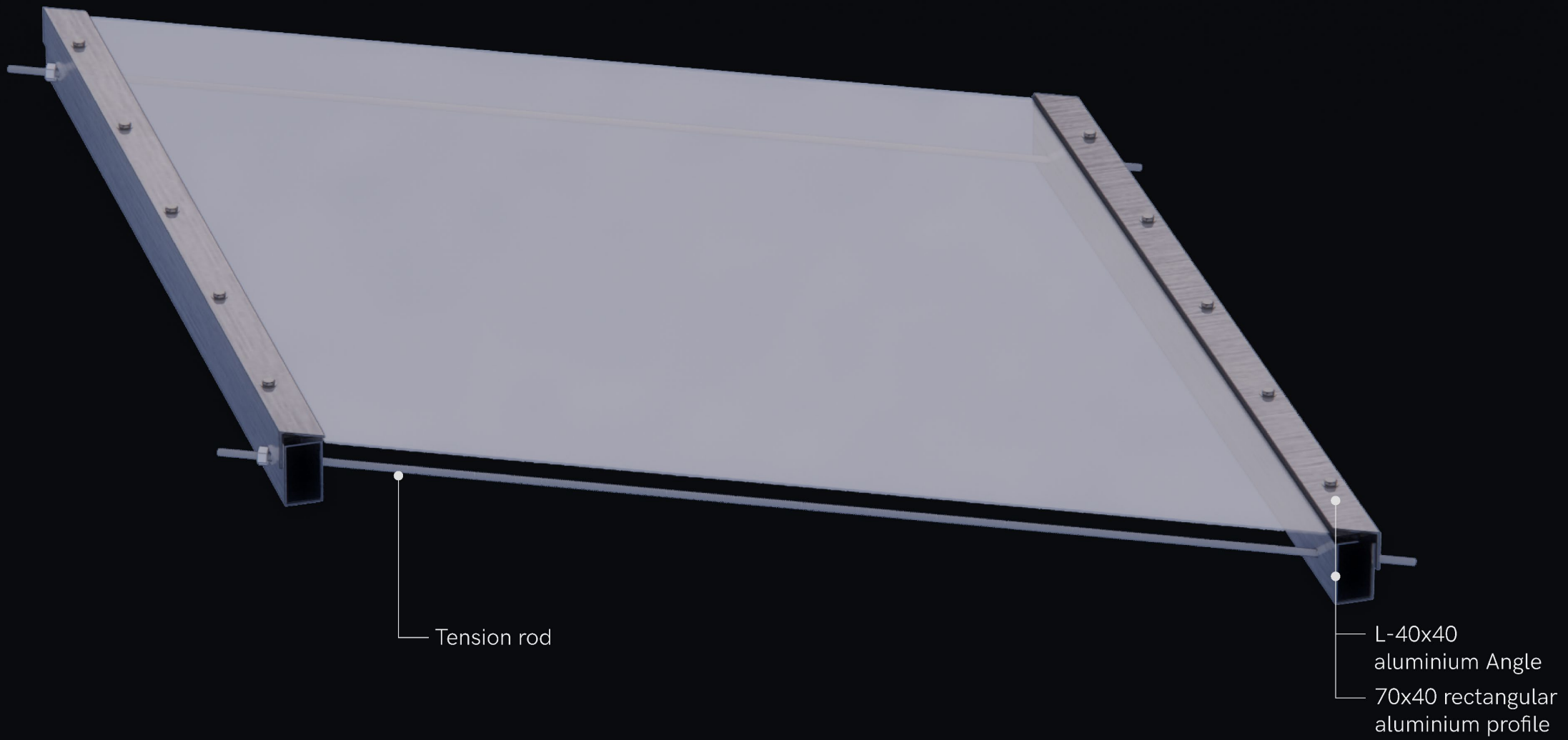
ACTUAL FRIT PATTERN DESIN



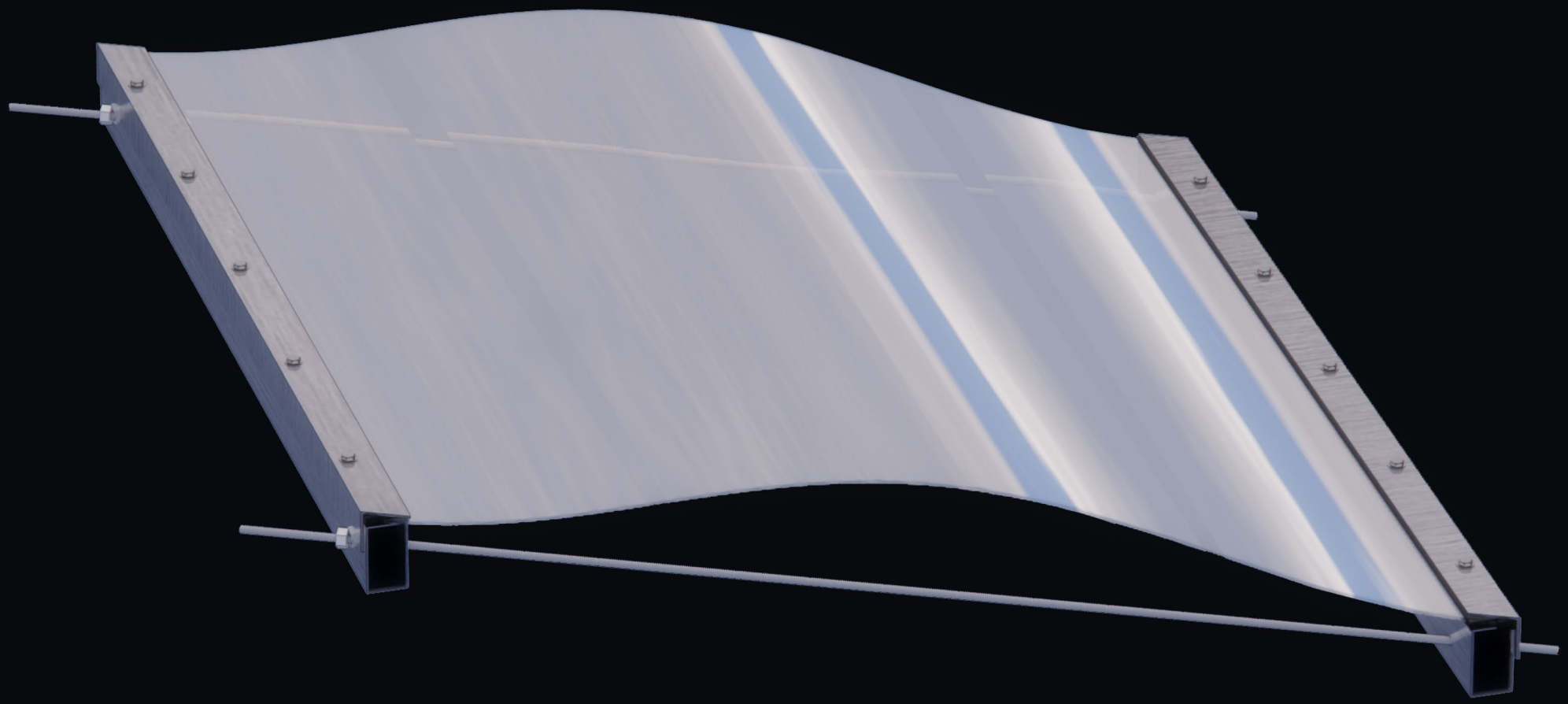
OPTIMISED GRADIENT FRIT



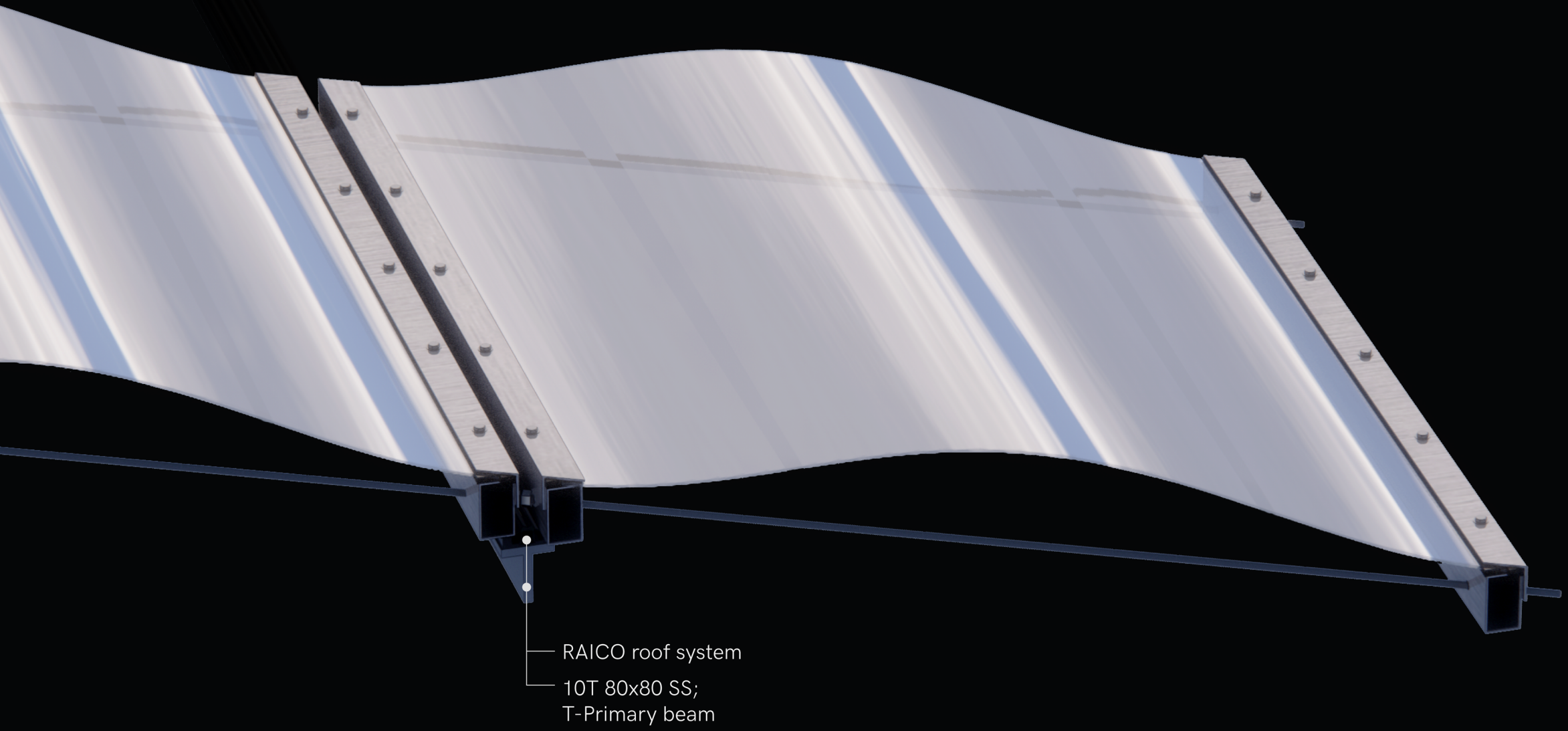
ROOF ASSEMBLY



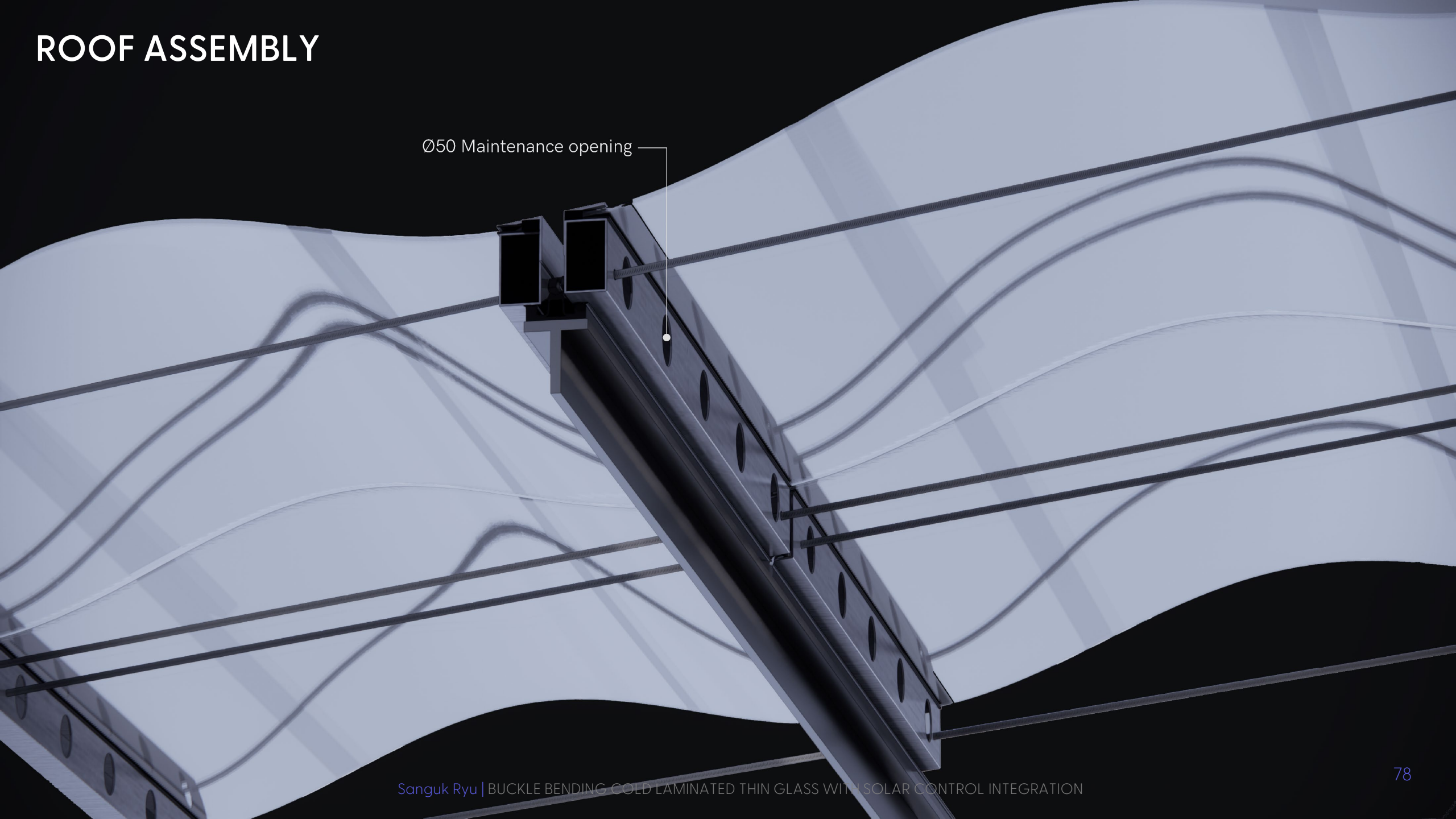
ROOF ASSEMBLY



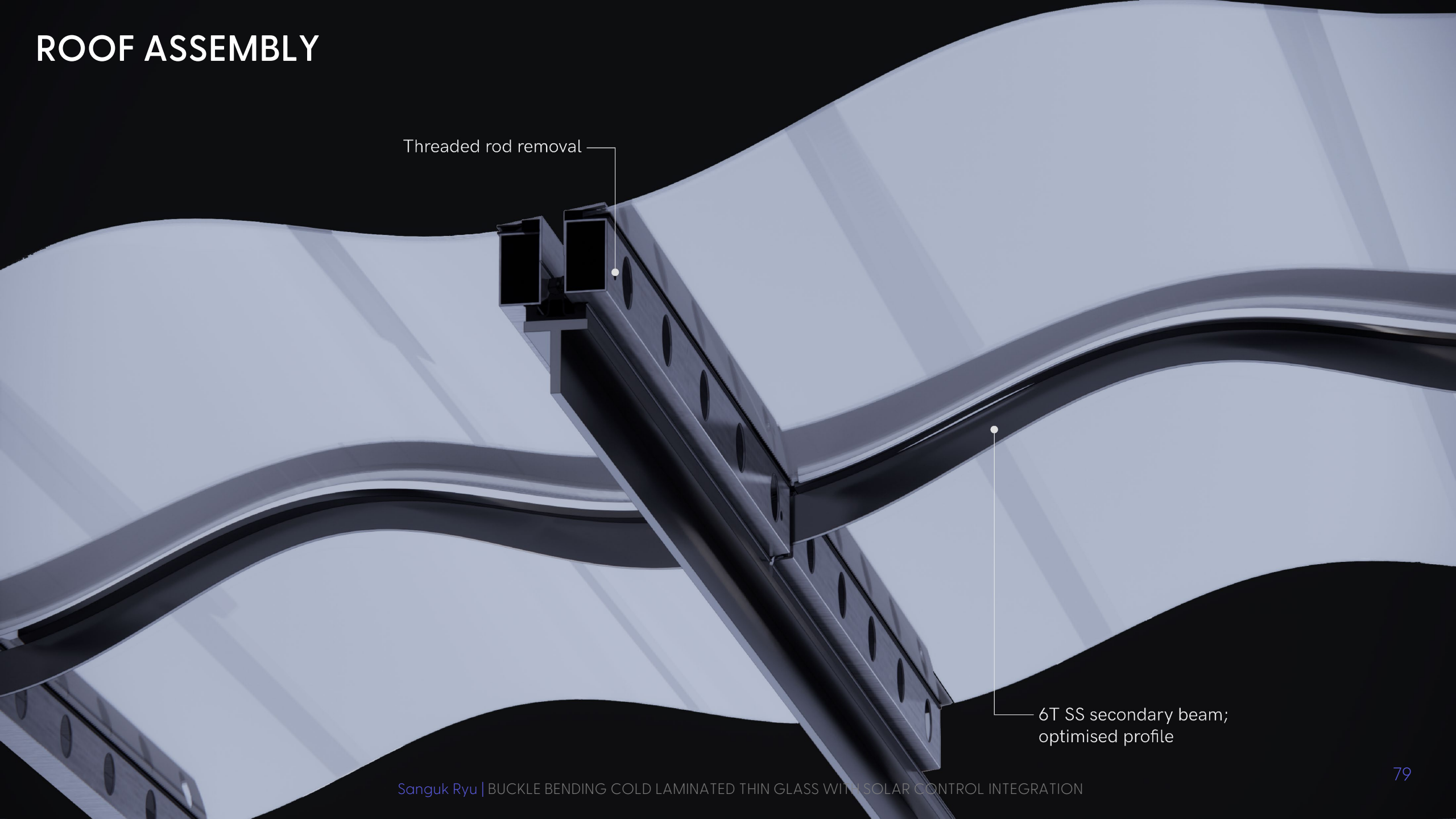
ROOF ASSEMBLY



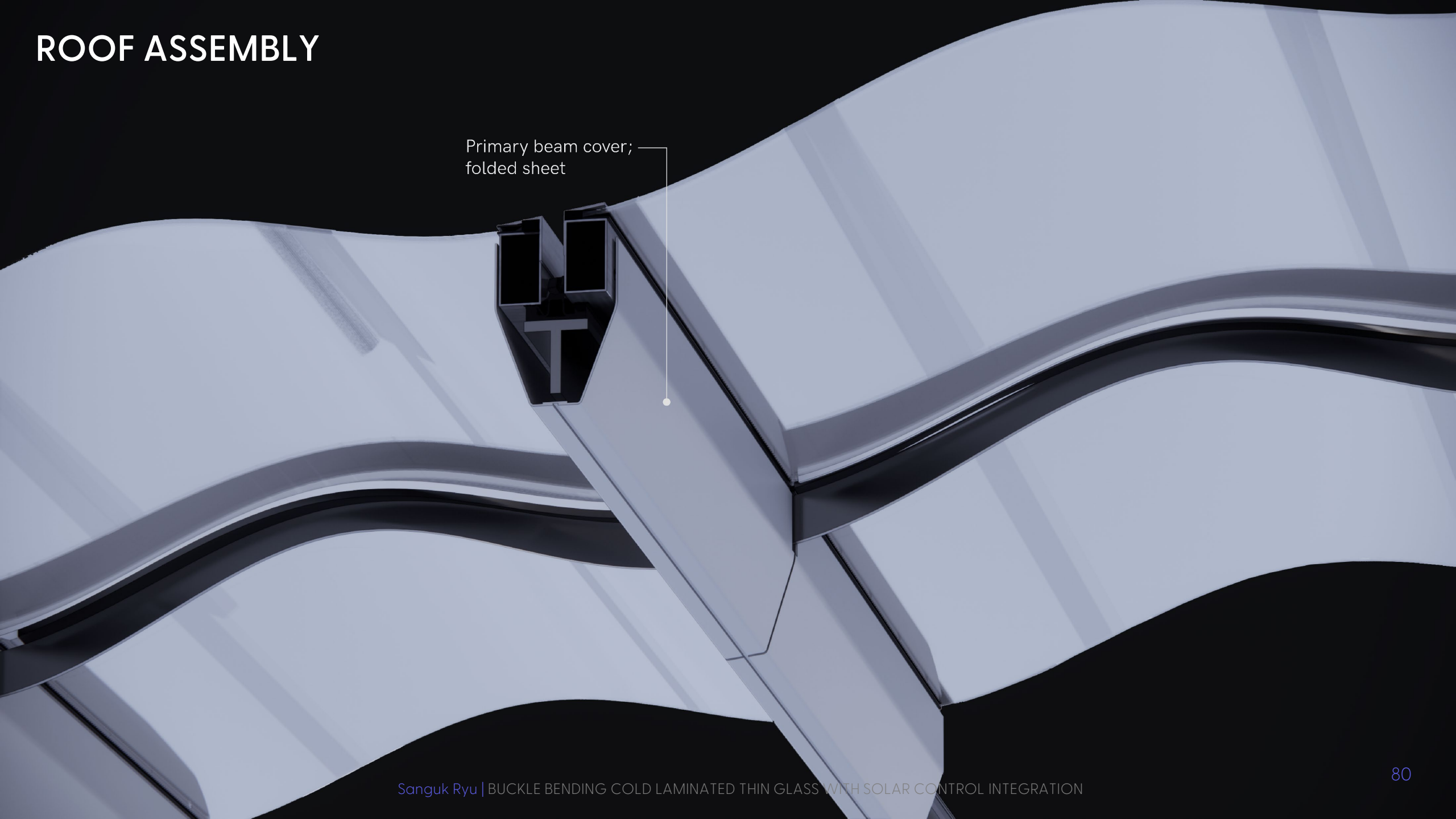
ROOF ASSEMBLY



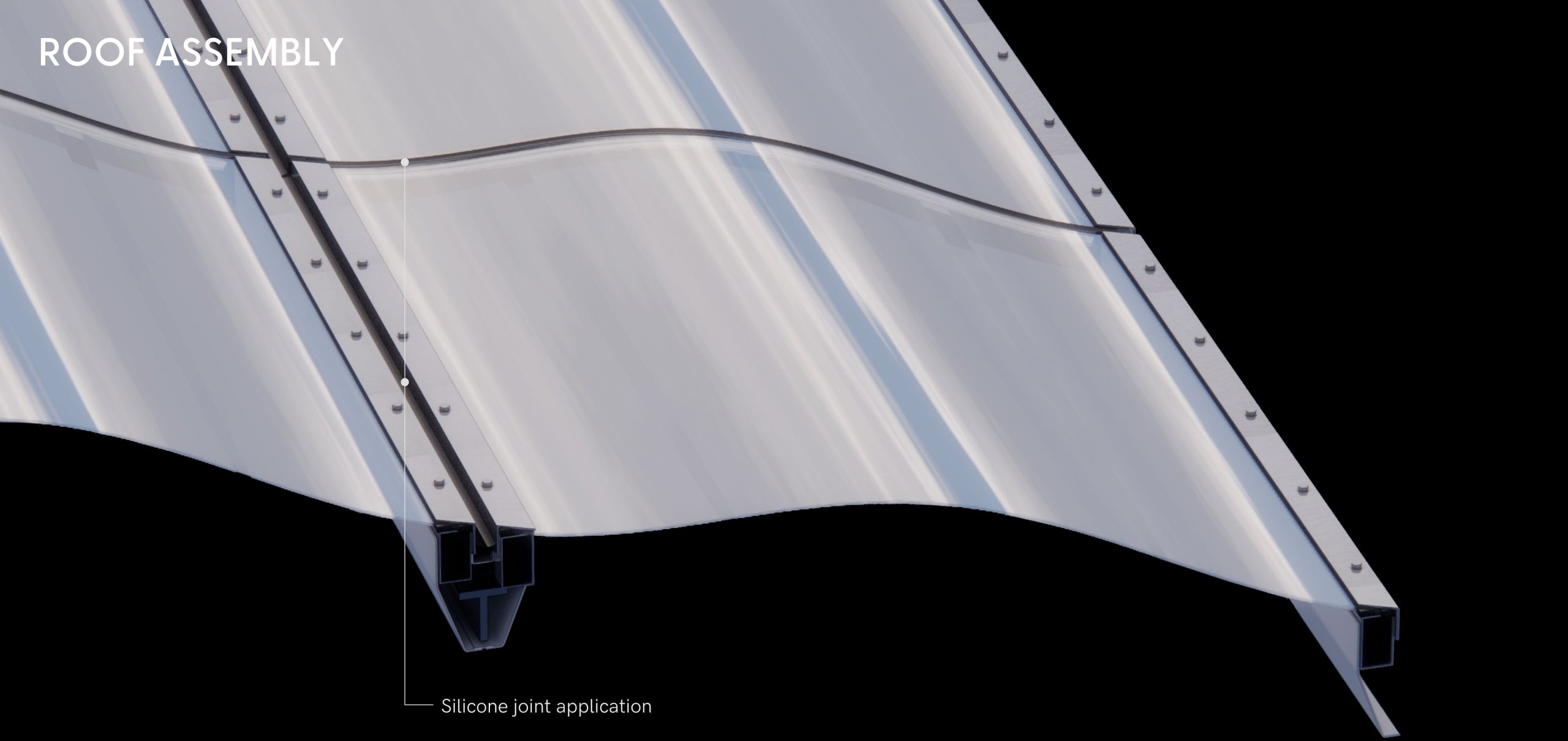
ROOF ASSEMBLY



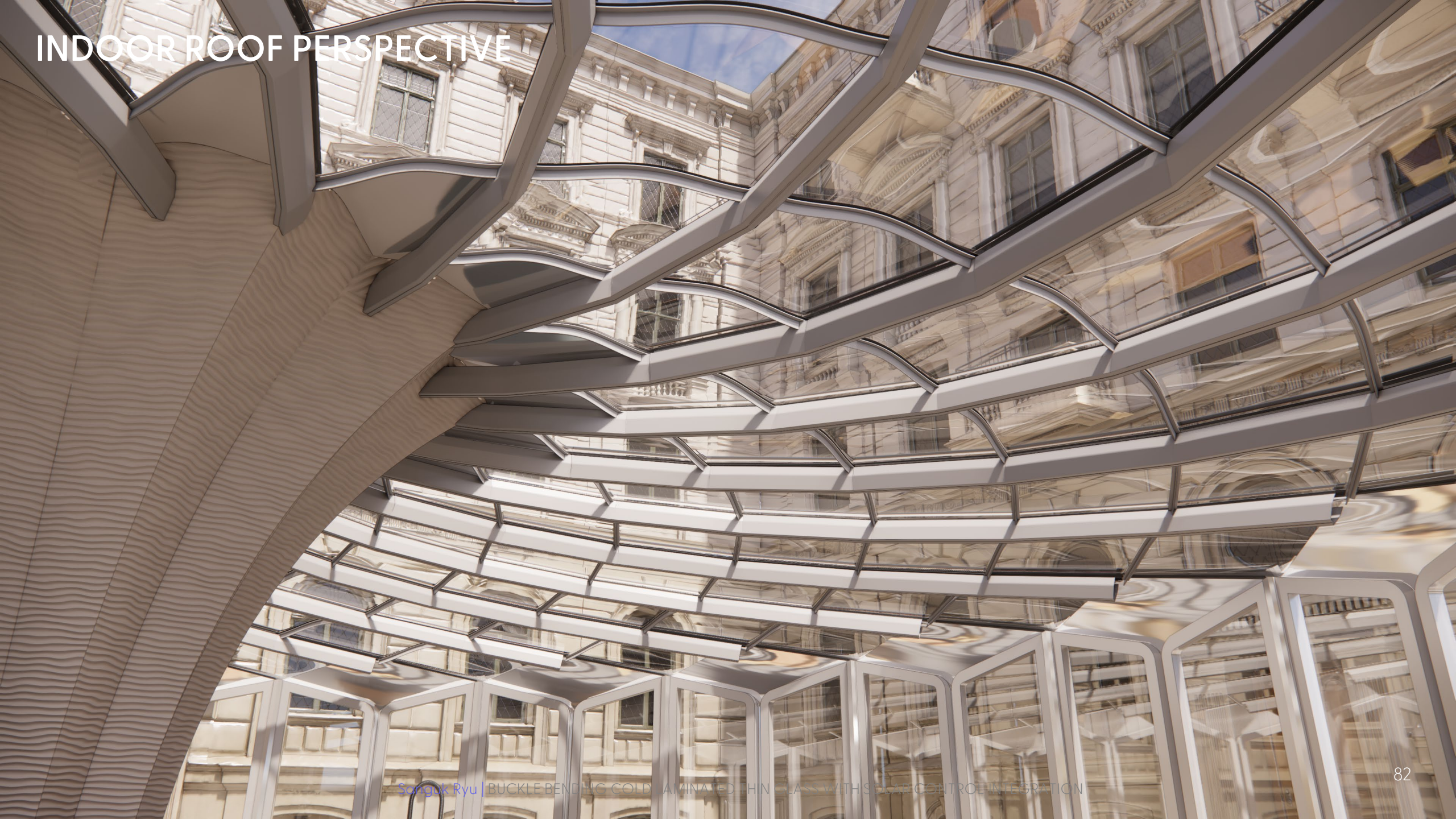
ROOF ASSEMBLY



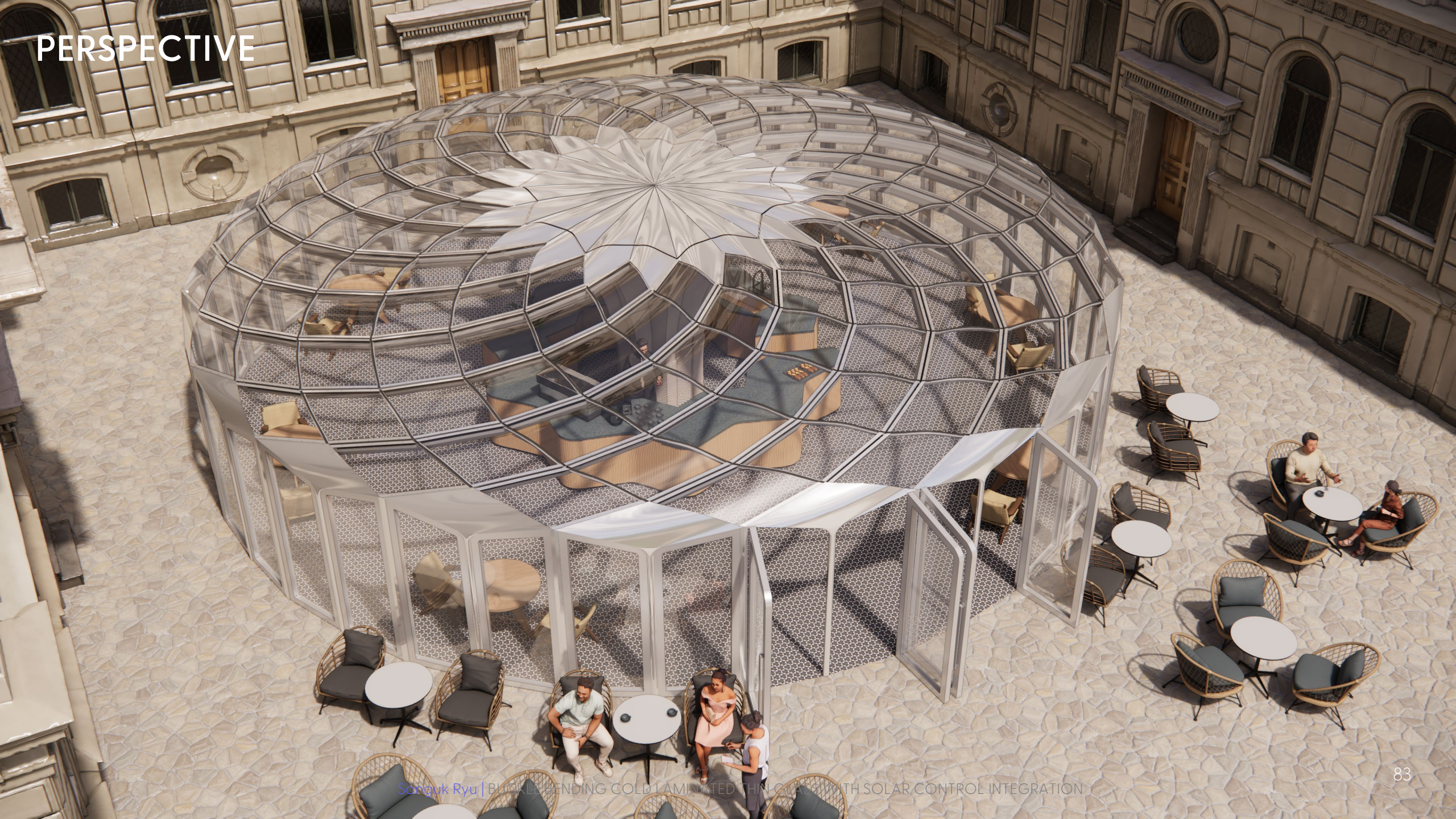
ROOF ASSEMBLY



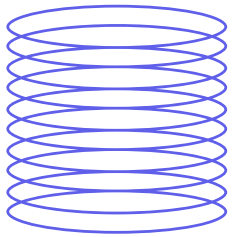
INDOOR ROOF PERSPECTIVE



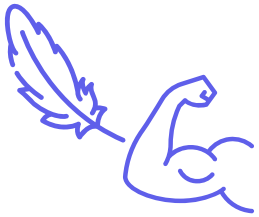
PERSPECTIVE



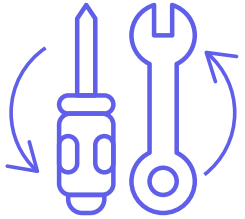
RELEVANCE



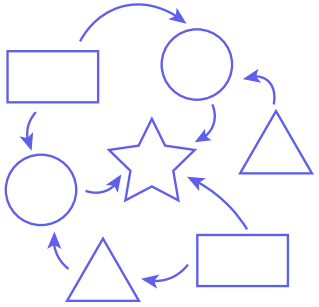
Possibility & potential
undiscovered geometry



Reduced **weight** &
enhanced **stiffness**

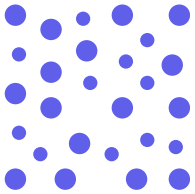


Iterative manufacturing
for real usage

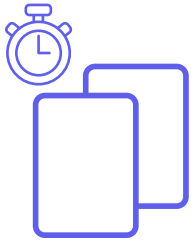


Integrated answer for
interconnected processes

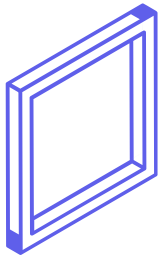
FUTURE RESEARCH



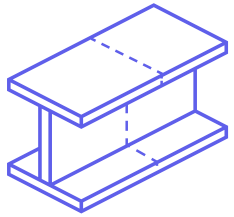
Chemical interactions
between ceramic frit & glass



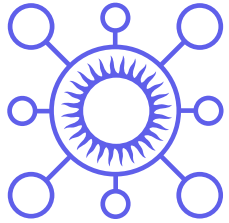
Curing-phase stress
simulation



Extend further
to **IGU**



Integrated substructure
system enabling
cold bending



Advanced multi-criteria
solar simulation