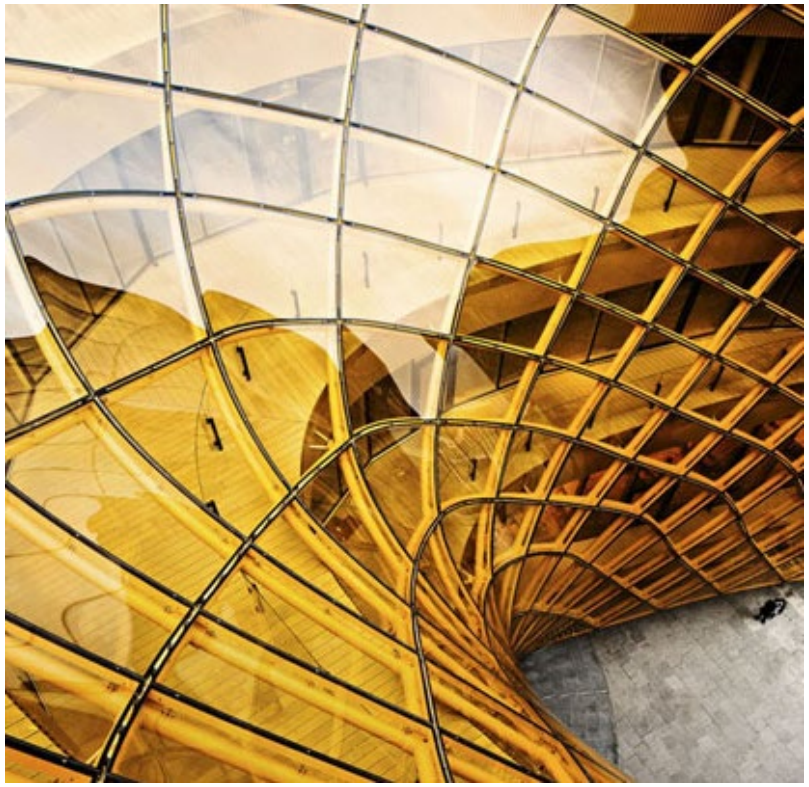
Design and testing of a flexible thin-glass IGU
Increasing the curvatures of cold bent Insulated Glass Units

4884469
03 July 2025
Koen van Deurzen
Mauro Overend, Marcel Bilow

Master Research Thesis P5 presentation

Fish scaling



Hot bending

Cold bending

Three methods for fabricating curved glass façades

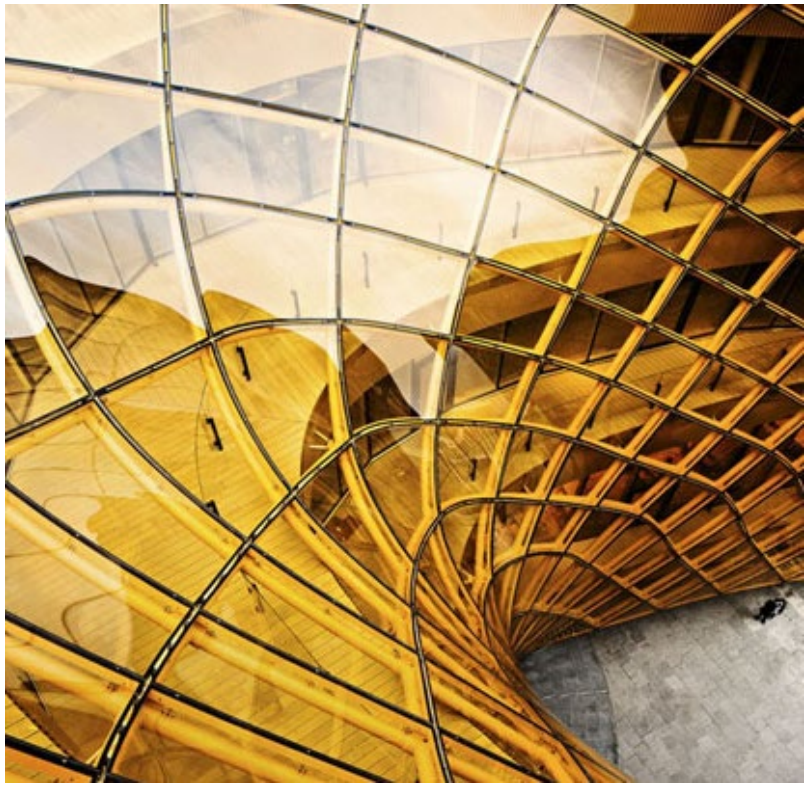
Fish scaling

+ Easy to install
+ Cheap

- No real curved façade

Rua da Saude Glass Roof, Brazil

Fish scaling



Hot bending

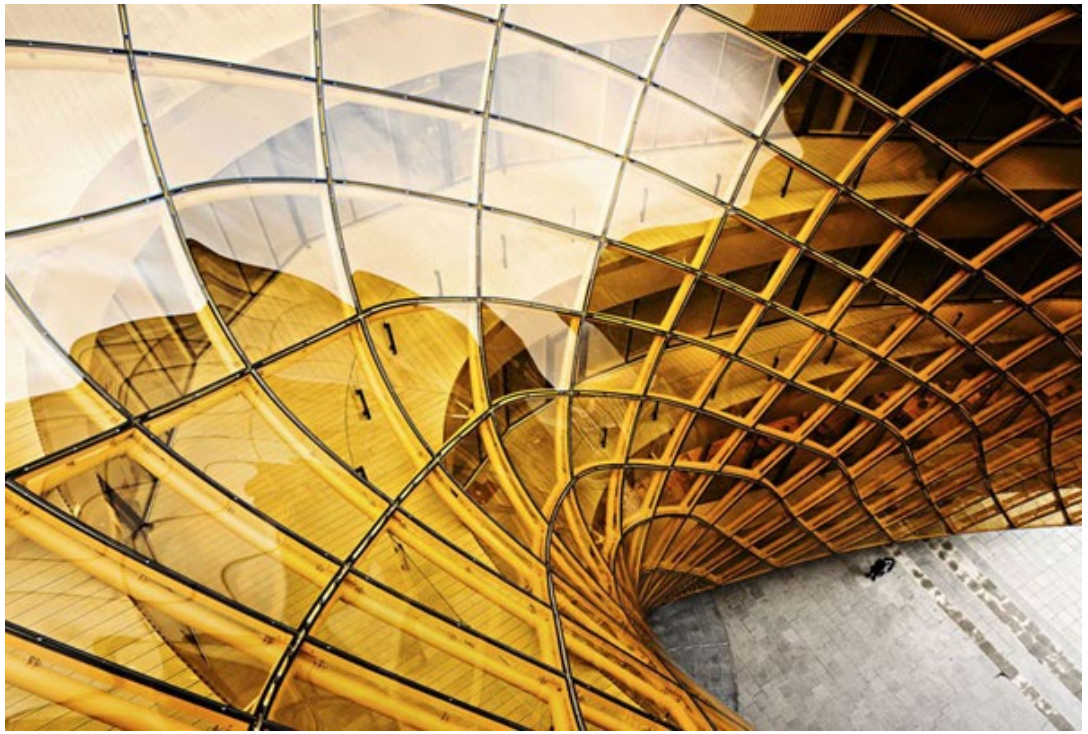
Cold bending

Three methods for fabricating curved glass façades

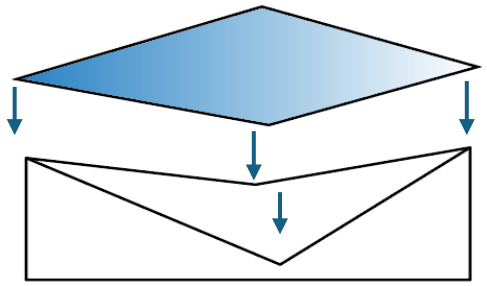
Hot bending

+ Limitless design freedom

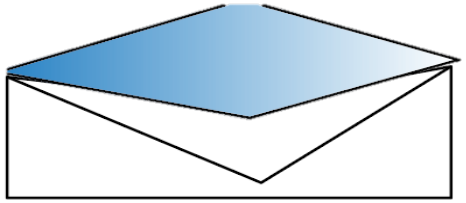
- Hot bending surface distortion
- Time inefficient
- Energy inefficient
- Expensive



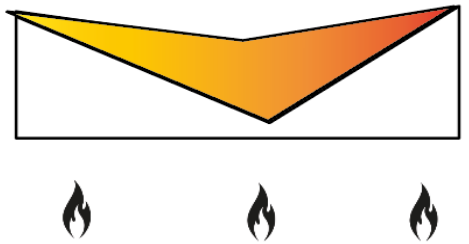
Emporia shopping mall Mälmo, 2023



Float glass pane

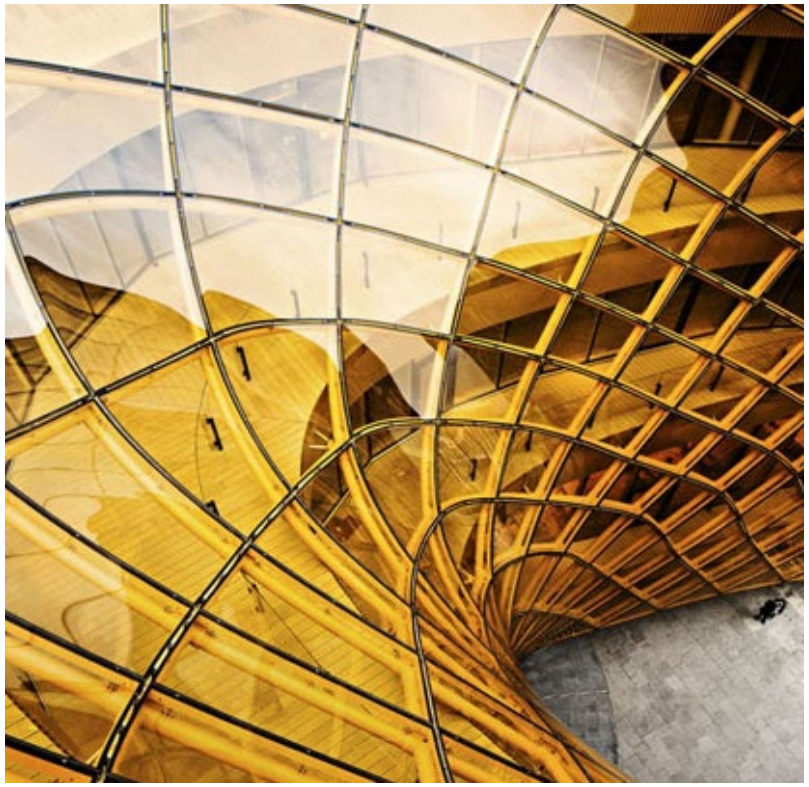


Place on unique mall



Heat to 600 degrees

Fish scaling



Hot bending

Cold bending

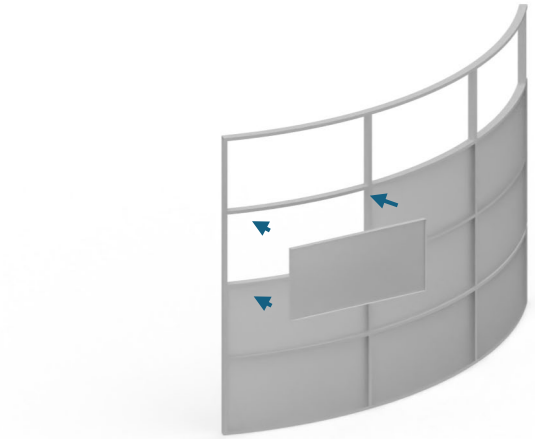
Three methods for fabricating curved glass façades

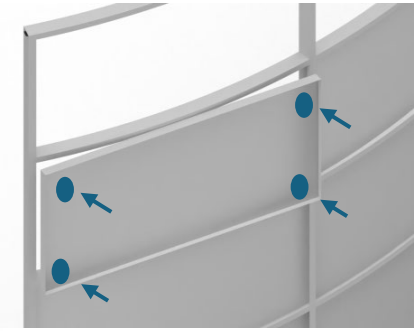
Cold bending

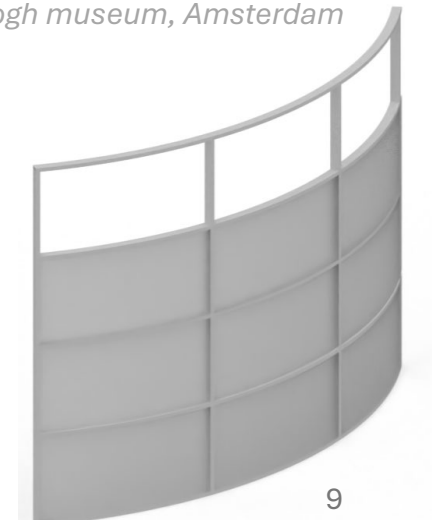
+ Requires less energy
+ Easier manufacturing
+ Cheaper
+ Surface quality

- No complex or extreme curves possible

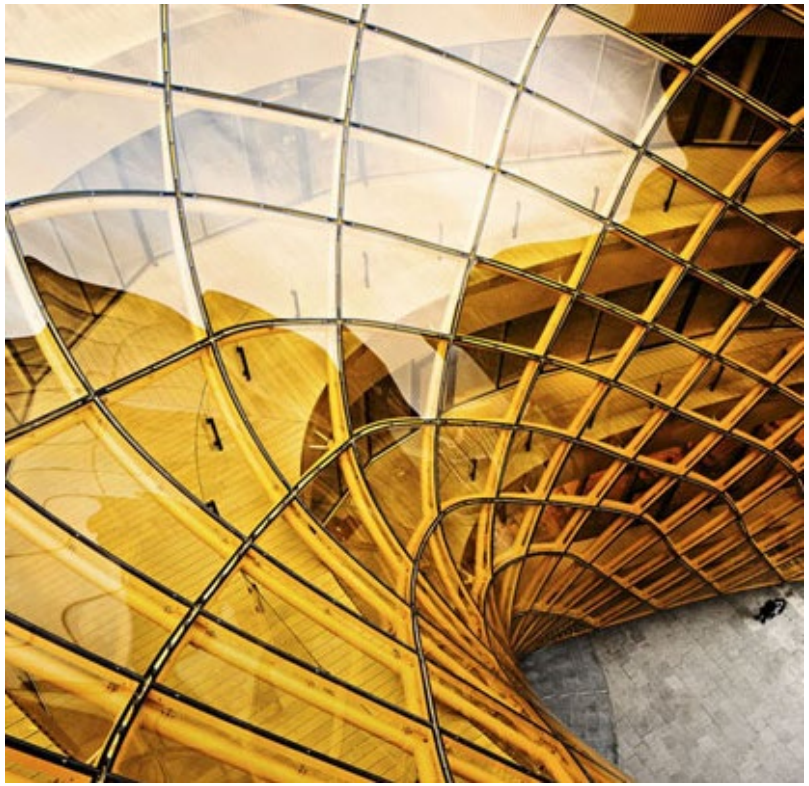
van Gogh museum, Amsterdam







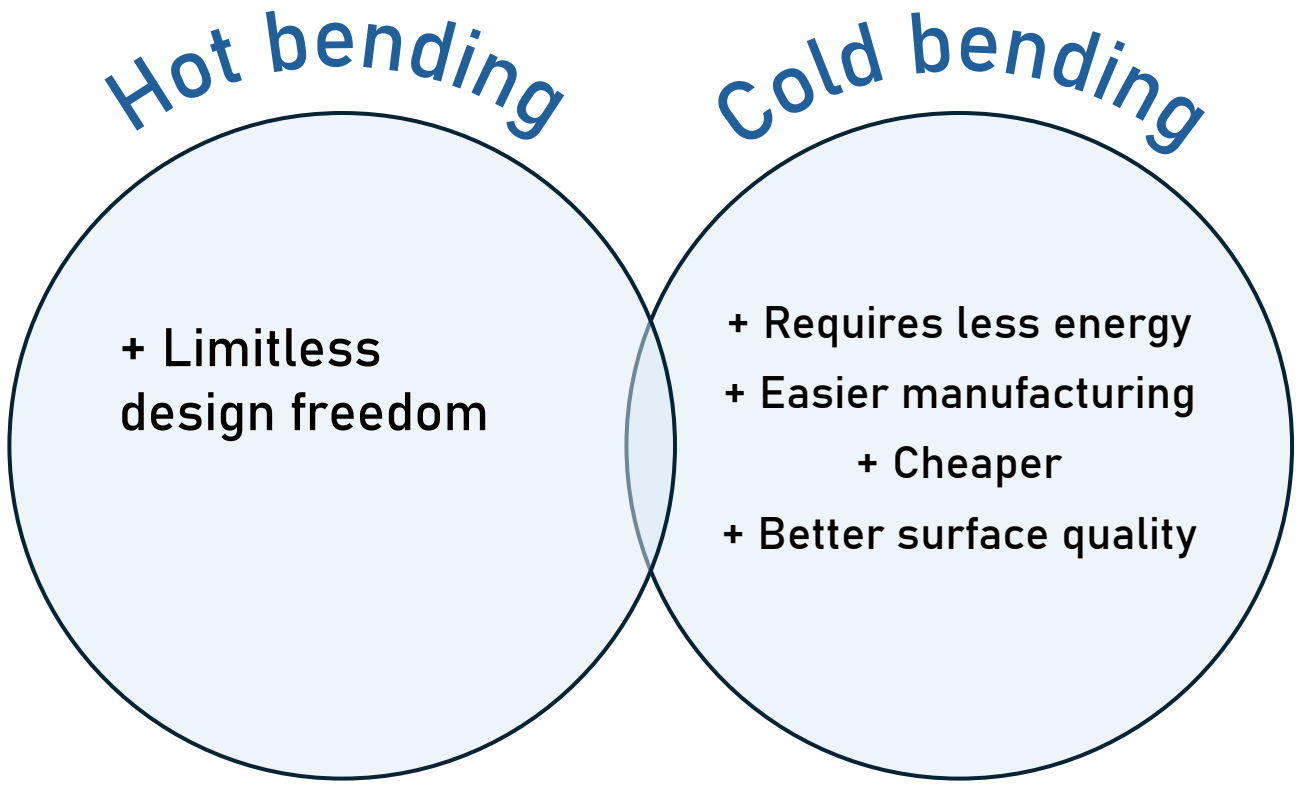
Fish scaling

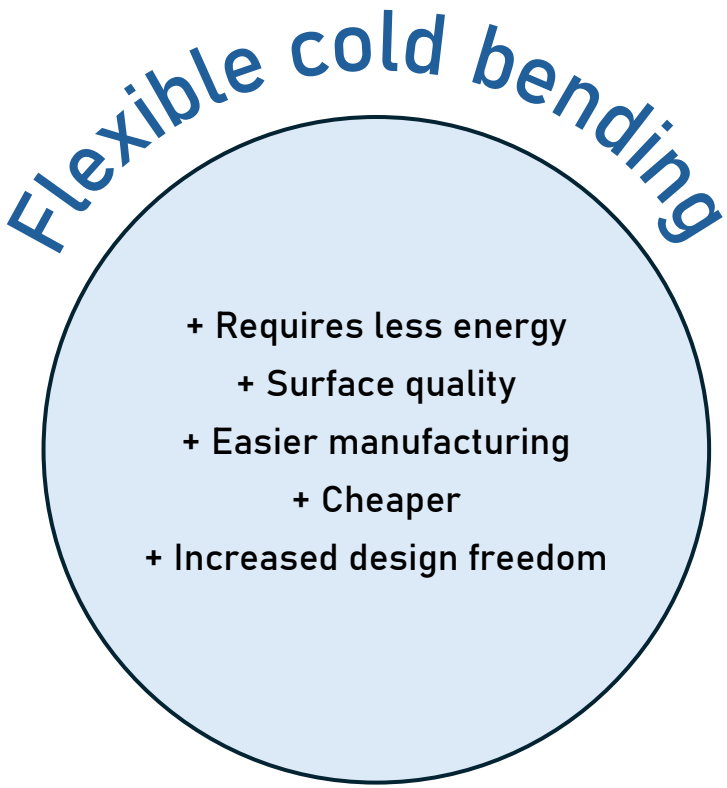


Hot bending

Cold bending

Three methods for fabricating curved glass façades


Hot bending
+ Limitless design freedom
Cold bending
+ Requires less energy
+ Easier manufacturing
+ Cheaper
+ Better surface quality


Flexible cold bending
+ Requires less energy
+ Surface quality
+ Easier manufacturing
+ Cheaper
+ Increased design freedom

Can a higher degree of curvature be achieved in cold bent insulated glass units by applying thin glass?

Can a higher degree of curvature be achieved in cold bent insulated glass units (IGU) by applying thin glass?

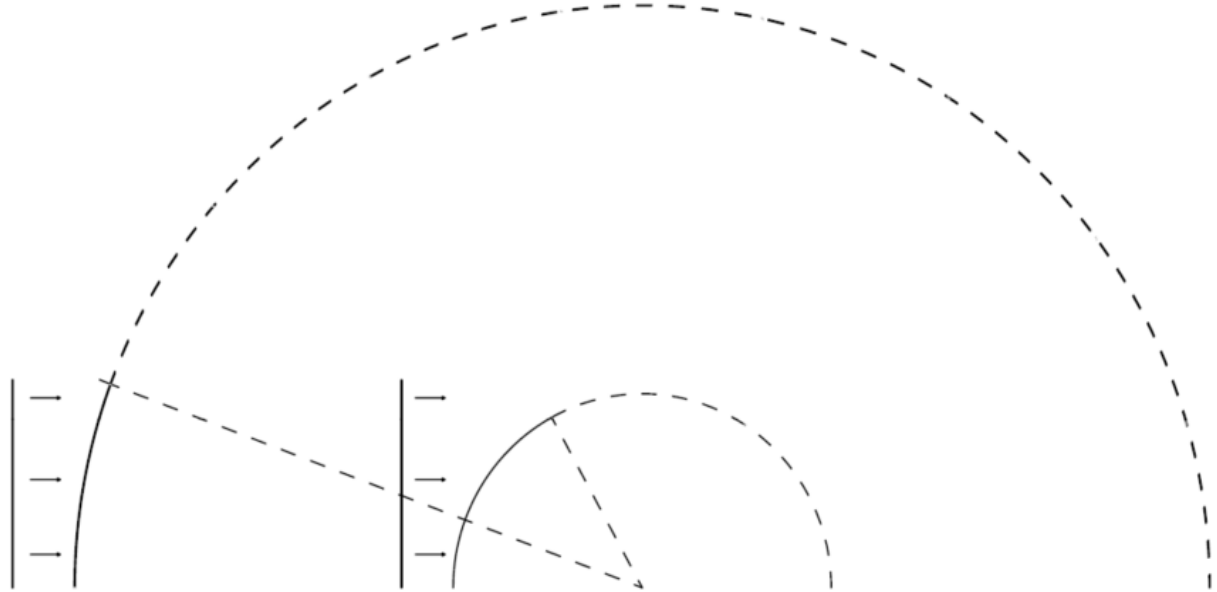
Insulated glass unit

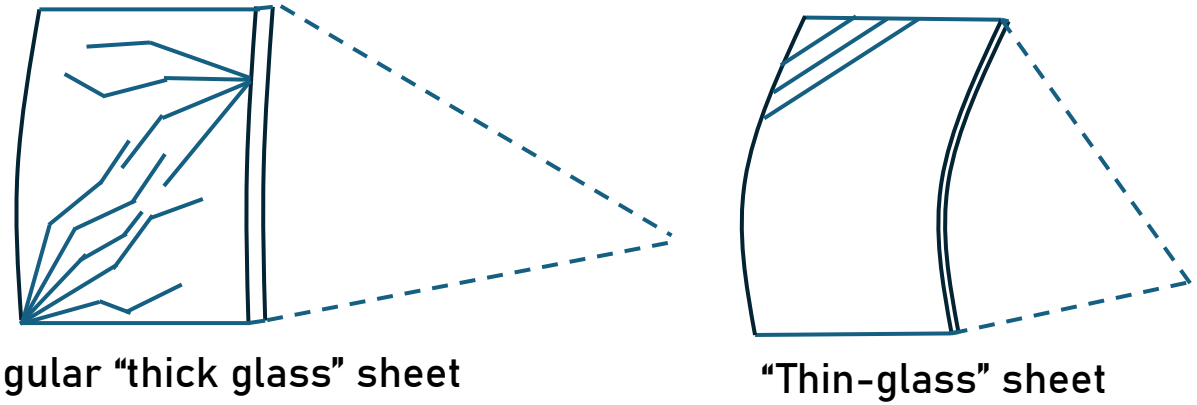
Can a higher degree of curvature be achieved in cold bent insulated glass units by applying thin glass?

Thinner glass panes allow for more flexibility

Cold bending determined by glass thickness

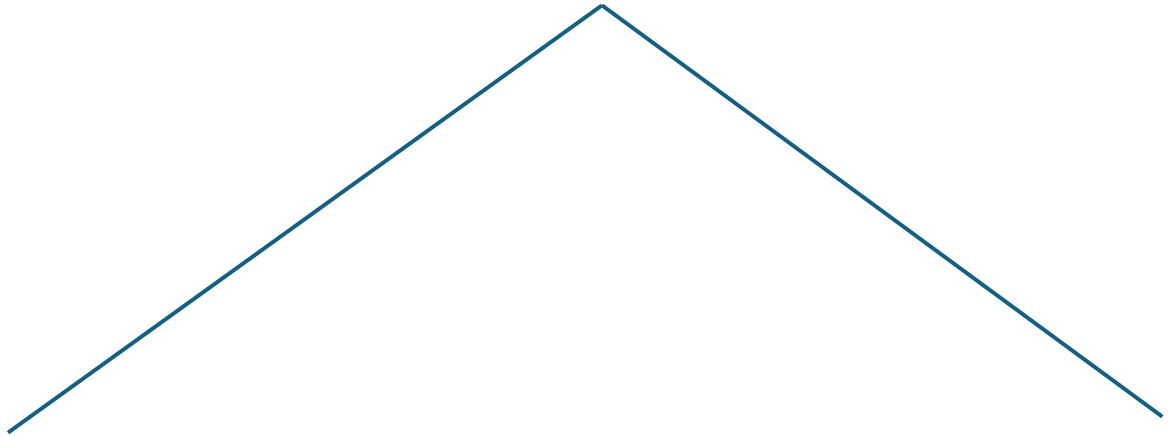
- The **thinner** the glass, the **further** it can bend





Why isn't thinner glass used currently?

Why isn't thinner glass used currently?



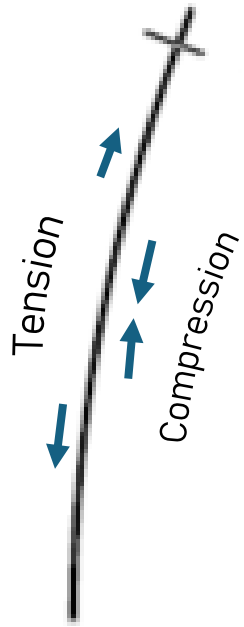
1. It is not strong enough

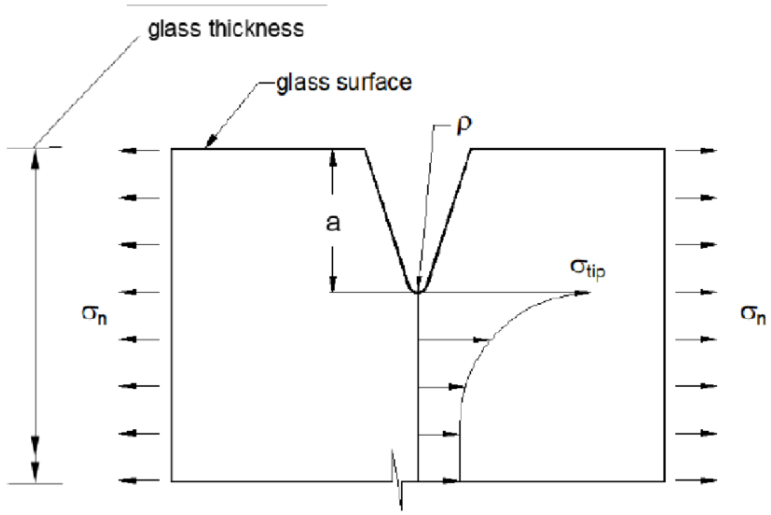
2. It deflects to much under wind load

When and how does glass break?

- Strong in **compression** ~ 1000MPa
- Weak in **tension** ~ 45MPa (deciding factor)

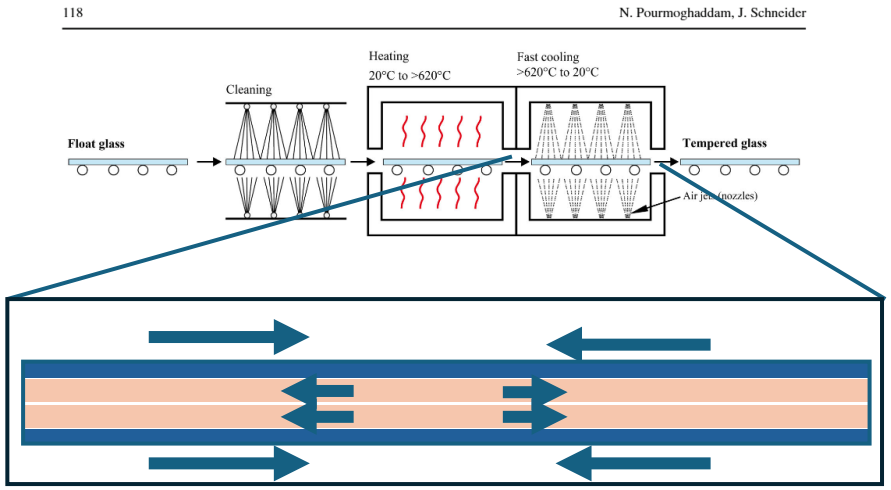
- Glass surface flaws concentrate tensile stress around the tip of the surface flaw – **impact on thinner glass is large**



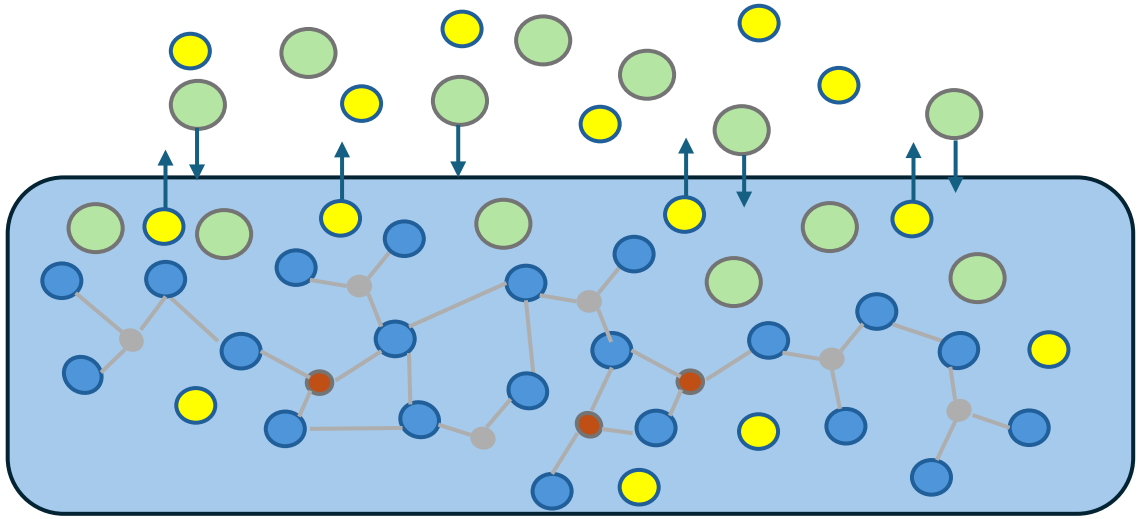


Glass can be strengthened

Strengthening methods

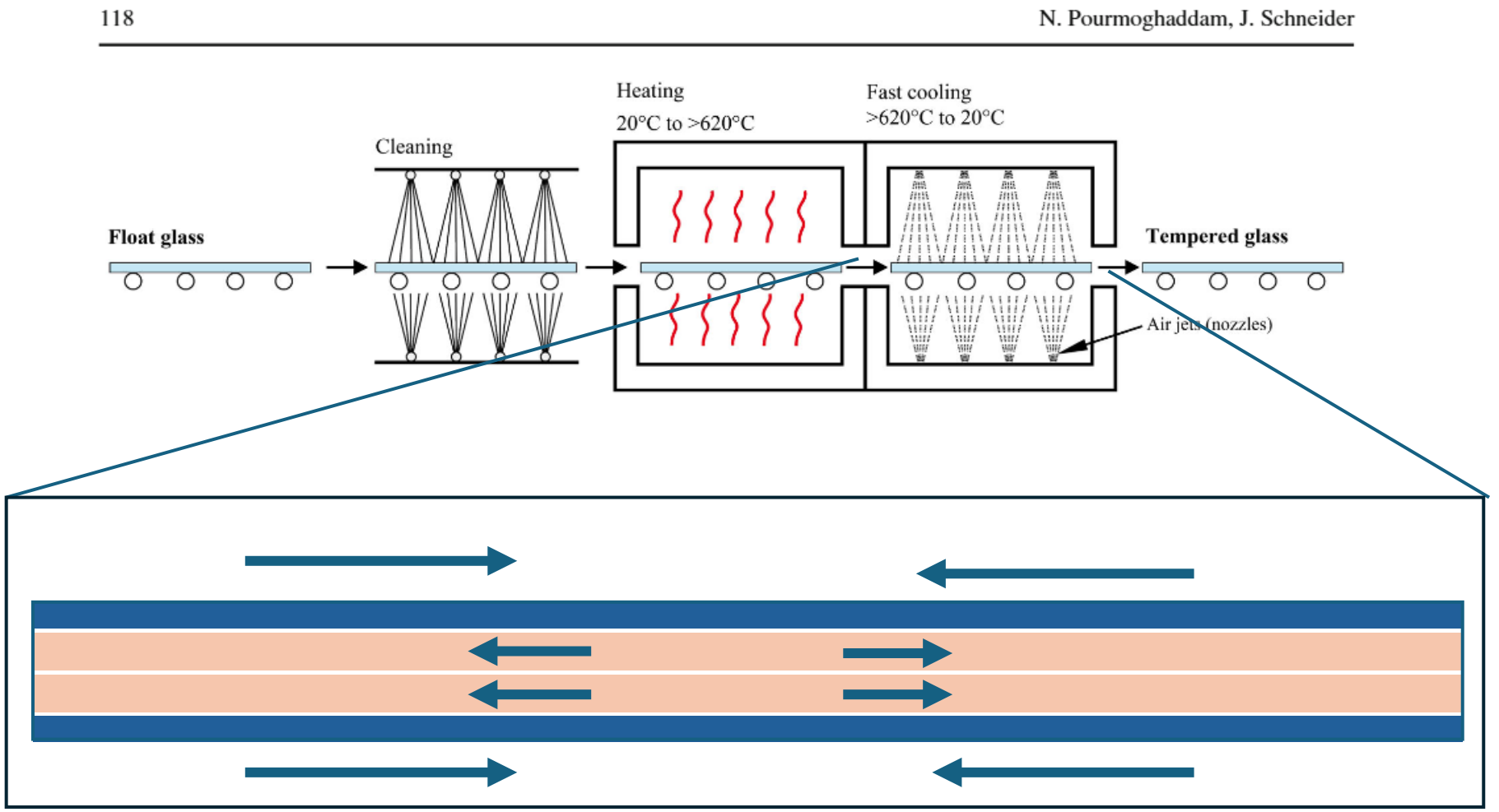


Tempering



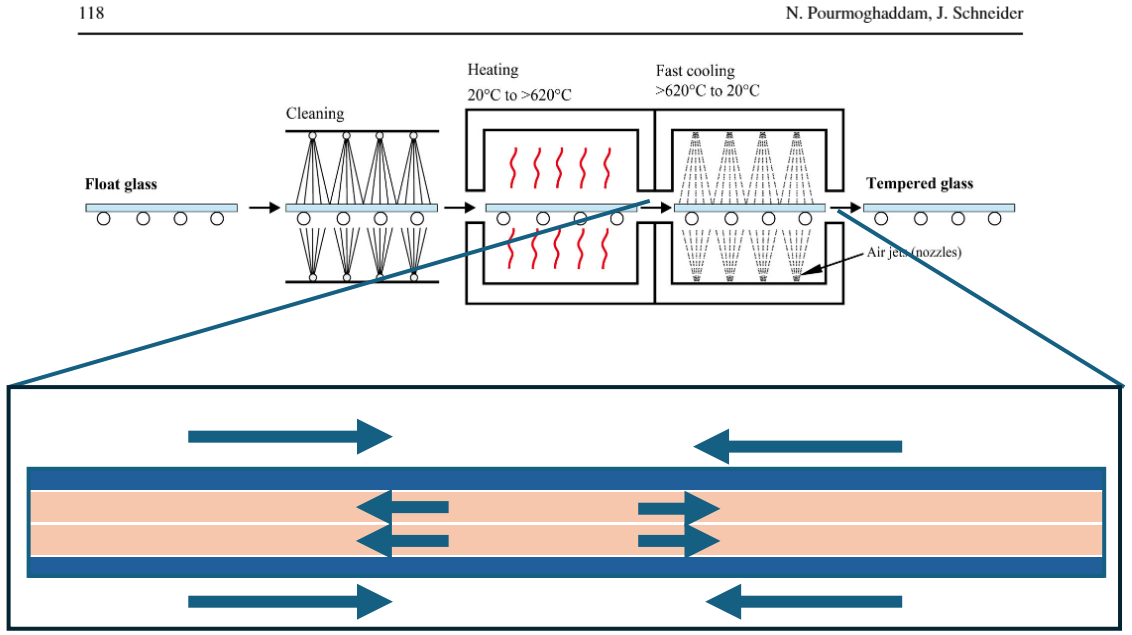
Chemical strengthening

Tempering process

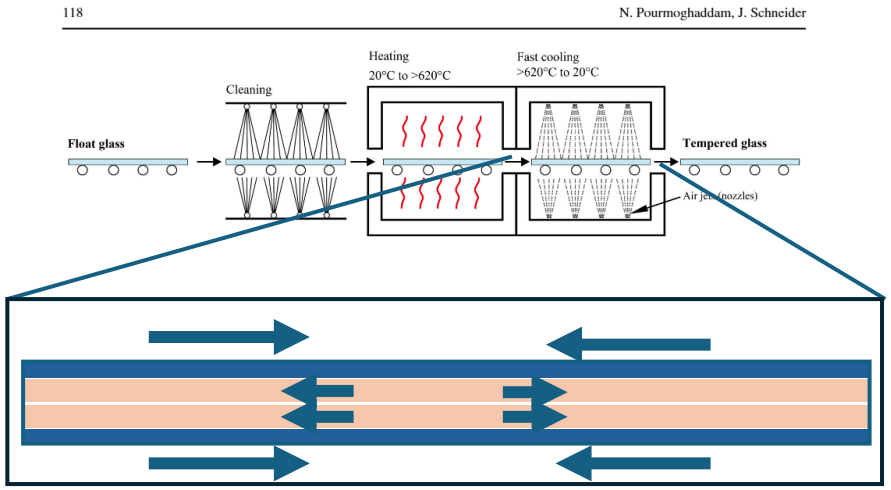


Tempered glass

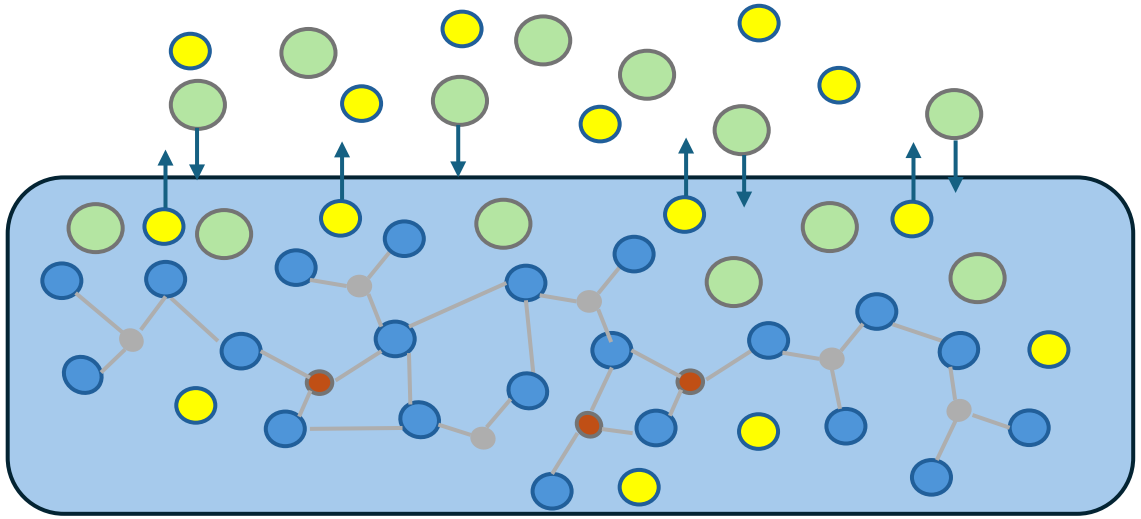
- Found in glass where safety is very important
- Tempering process can only be applied on regular “thick glass sheets”



Strengthening methods

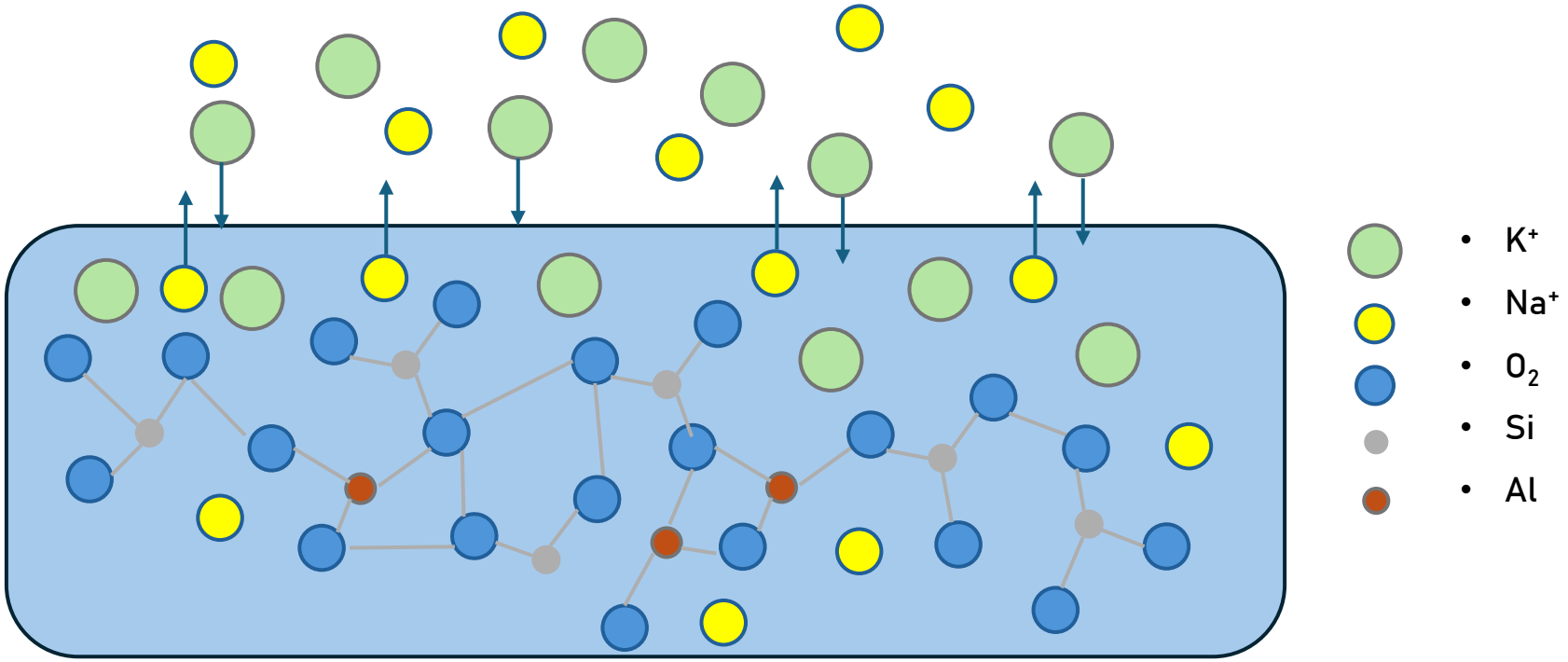


Tempering



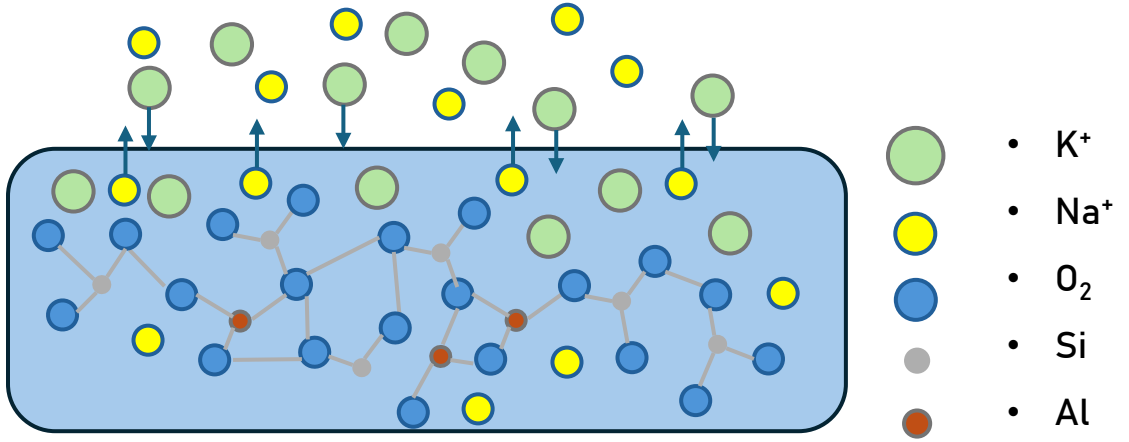
Chemical strengthening

Chemically strengthened glass



Chemically strengthened glass

- Used in electronic devices
- Chemical strengthening process can be applied to extremely thin sheets (0.1-2mm)



Glass types and tensile design strengths

- Annealed (untreated) glass <45MPa CEN/TS 19100
- Fully tempered glass <120MPa CEN/TS 19100
- **Chemically strengthened *<260MPa* (Eckersley O'Callaghan)**

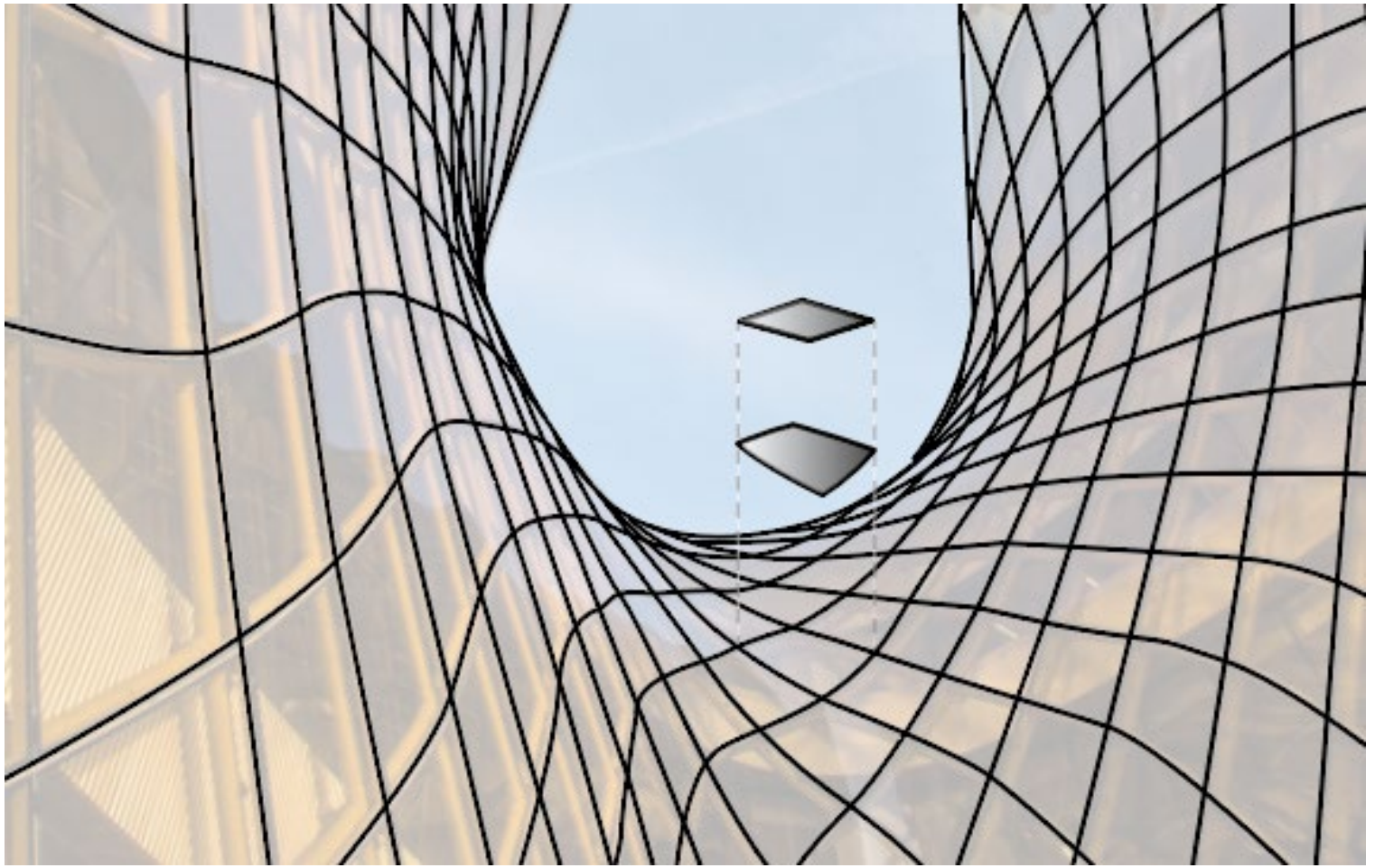
Designing a flexible thin glass IGU…

What are the performance requirements?

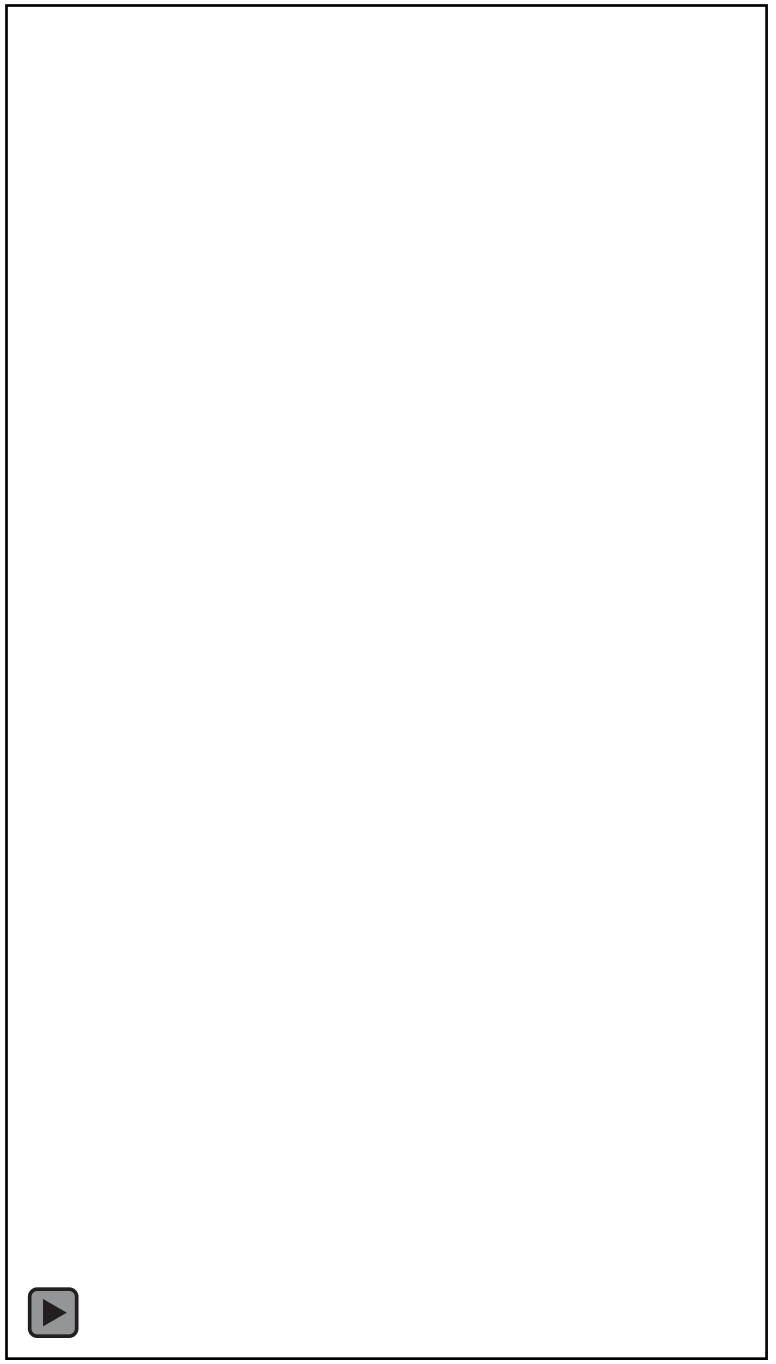
- High flexibility

- Wind load resistance

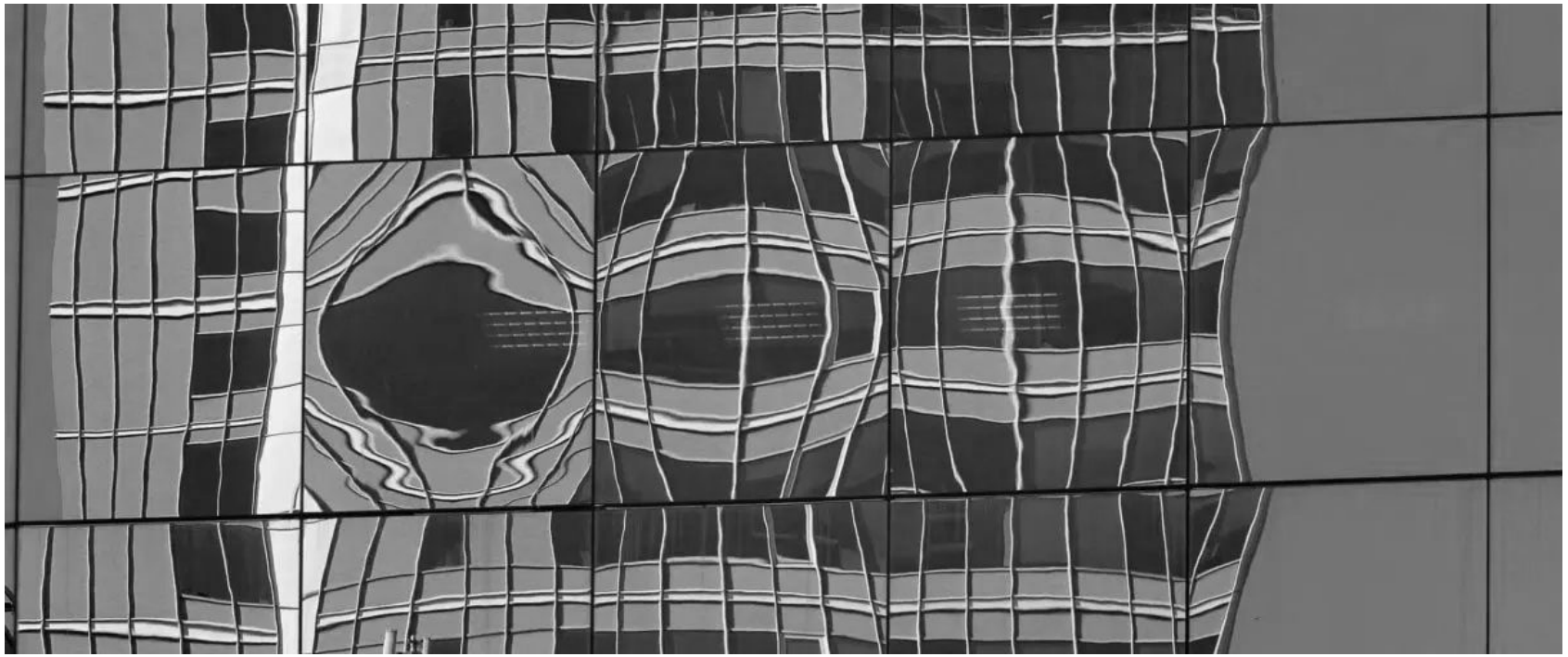
- Optical quality



- High flexibility
- **Wind load resistance**
- Optical quality

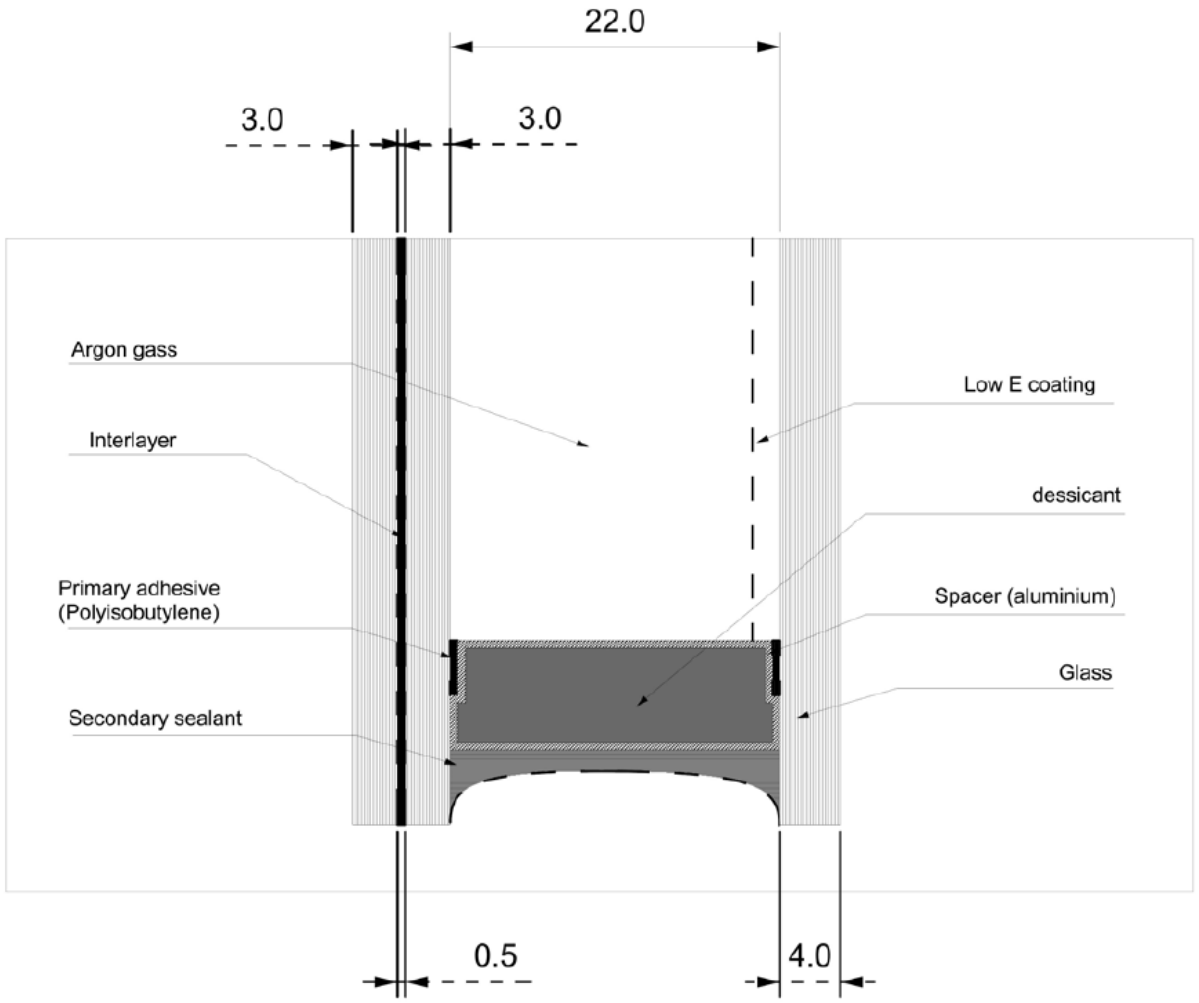


- High flexibility
- Wind load resistance
- **Optical quality**

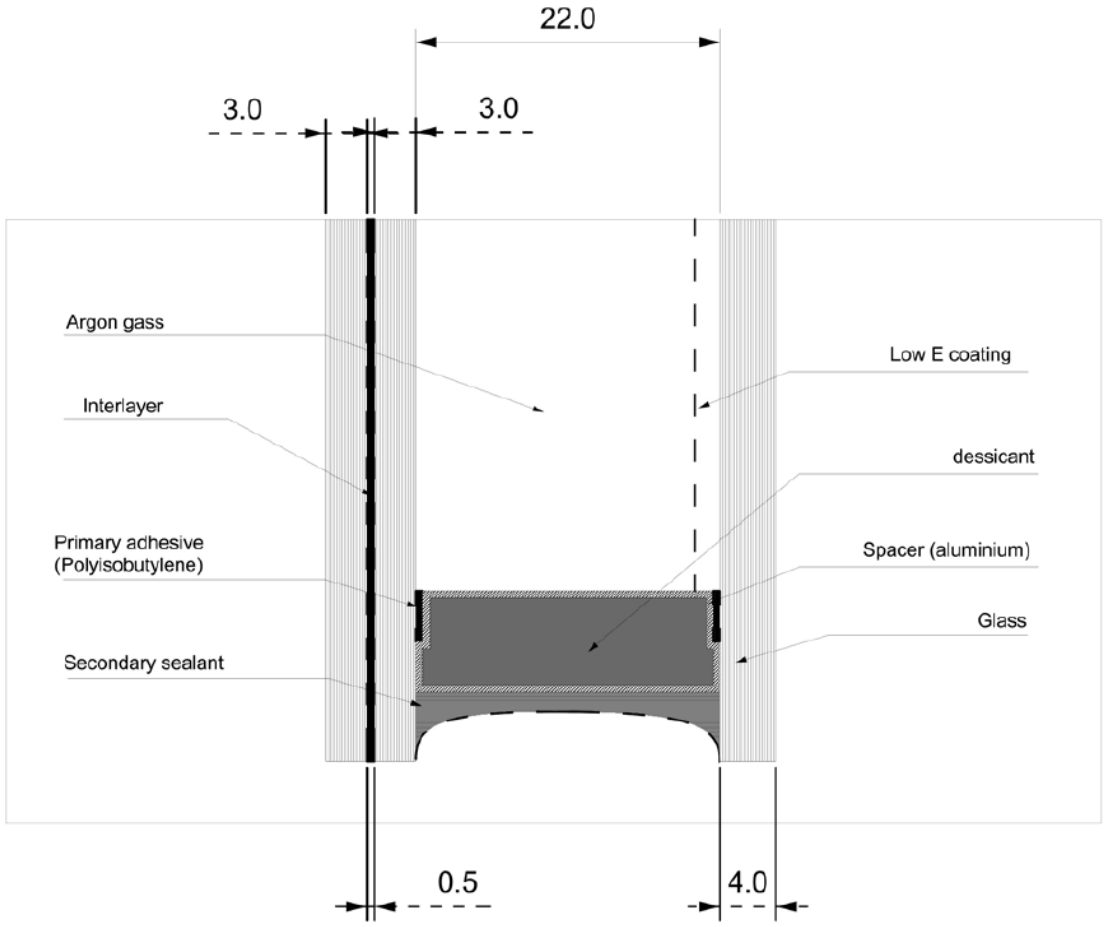


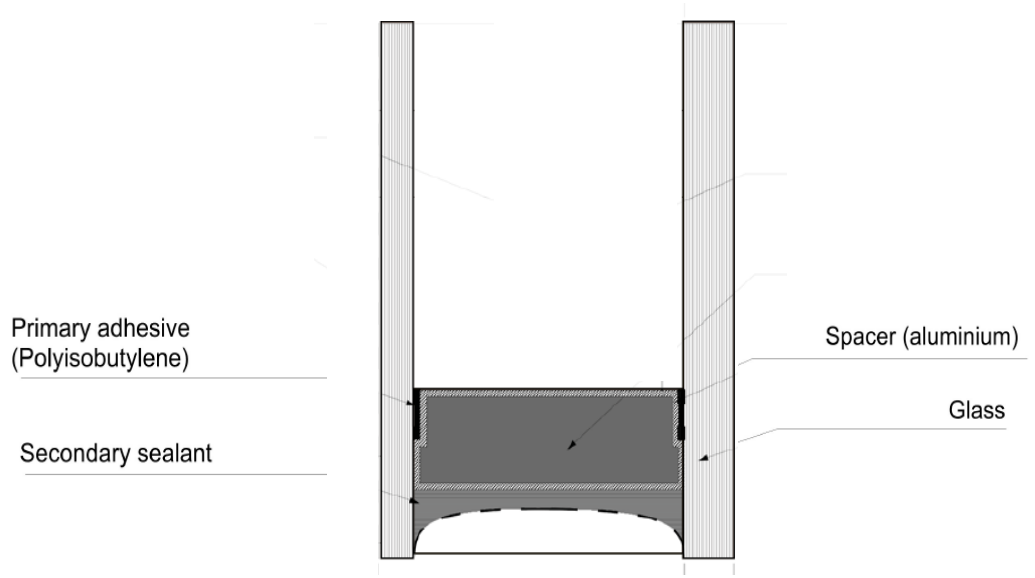
Part I: Flexibility

The Insulated Glazing Unit (IGU)

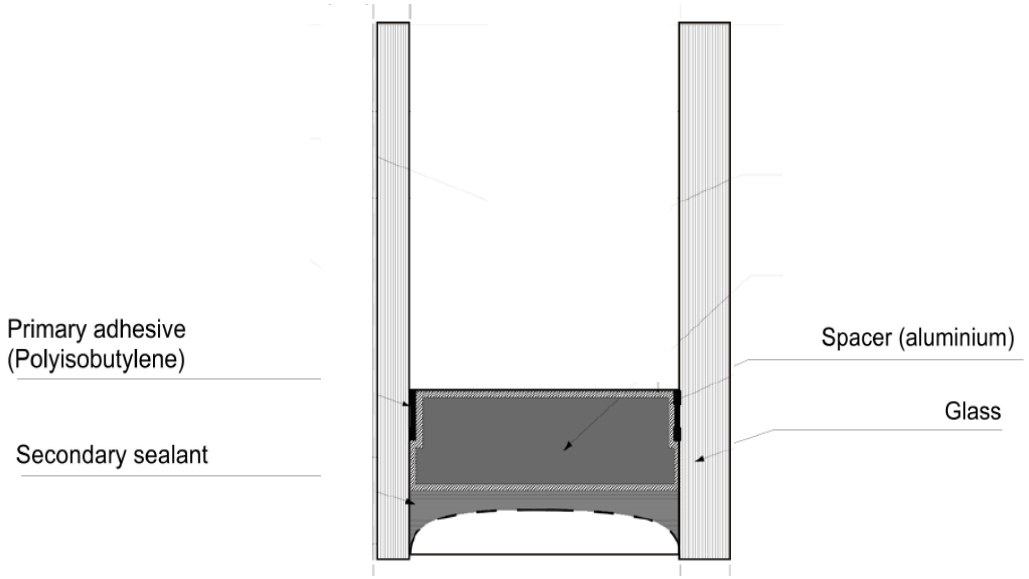


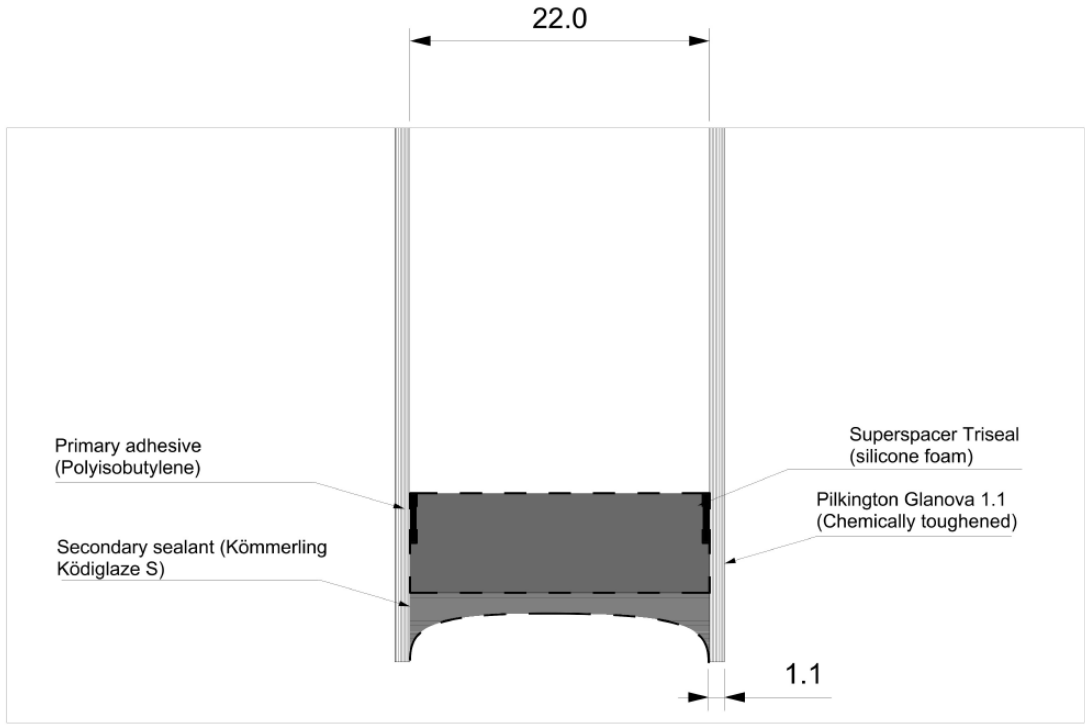
Parts to focus on





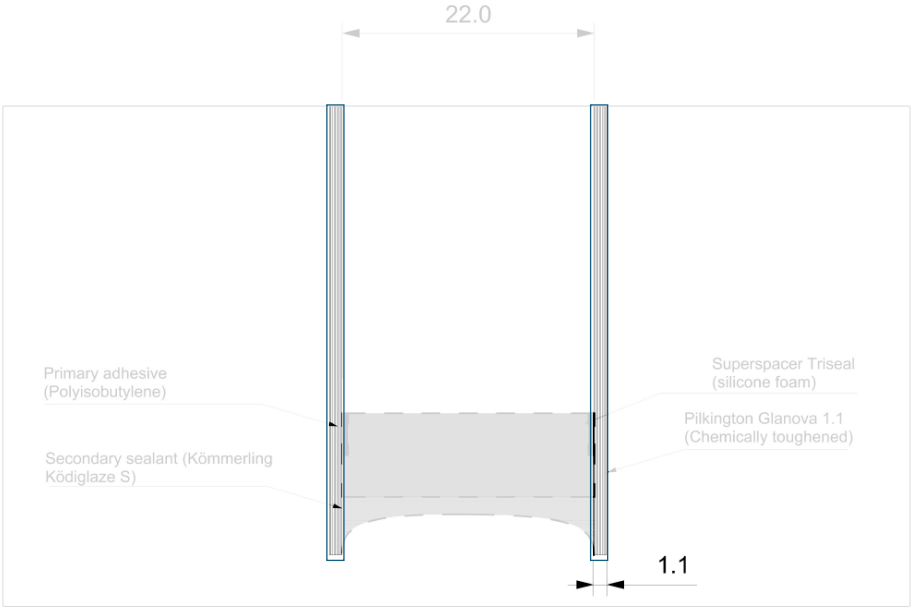
The IGU – Researched parts

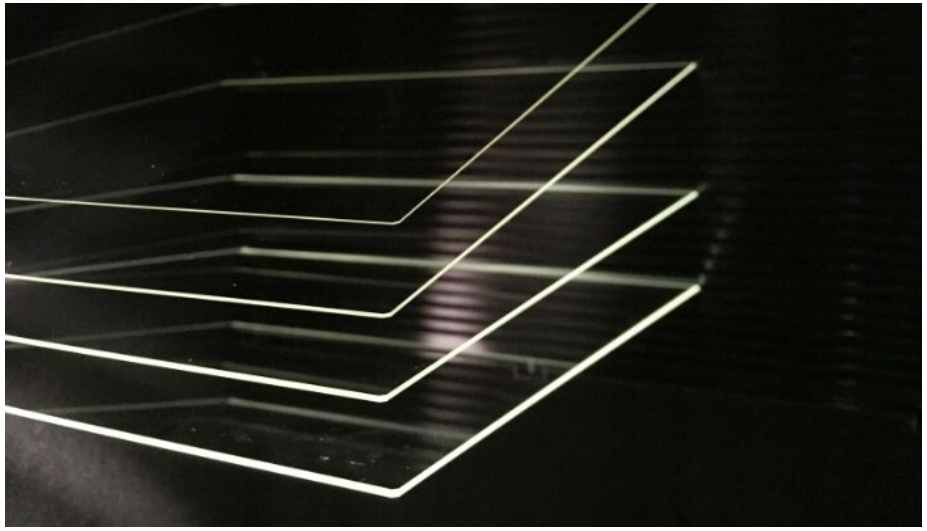




Glass

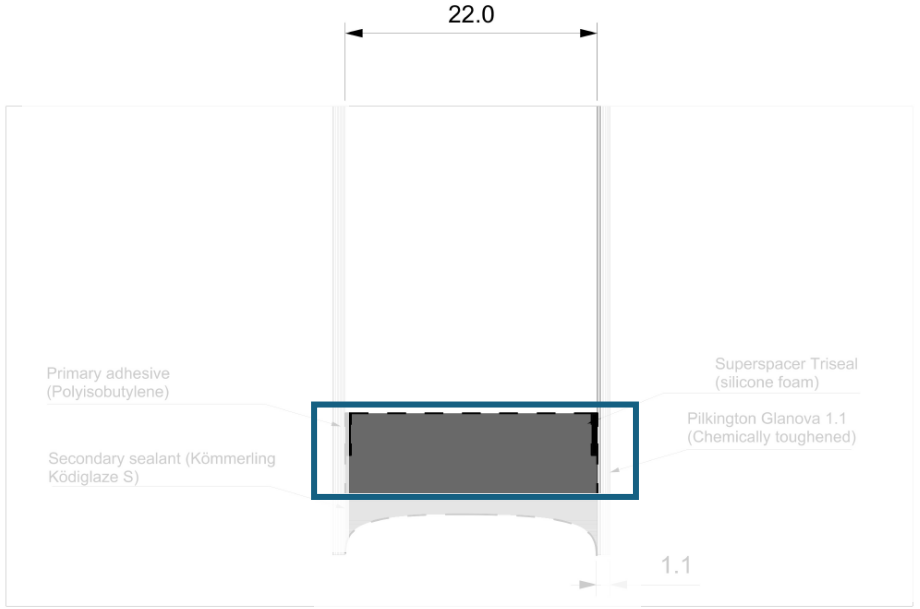
- Consult with Pilkington/NSG
- 80 x 80 cm CS Glanova thin-glass t= 1.1mm

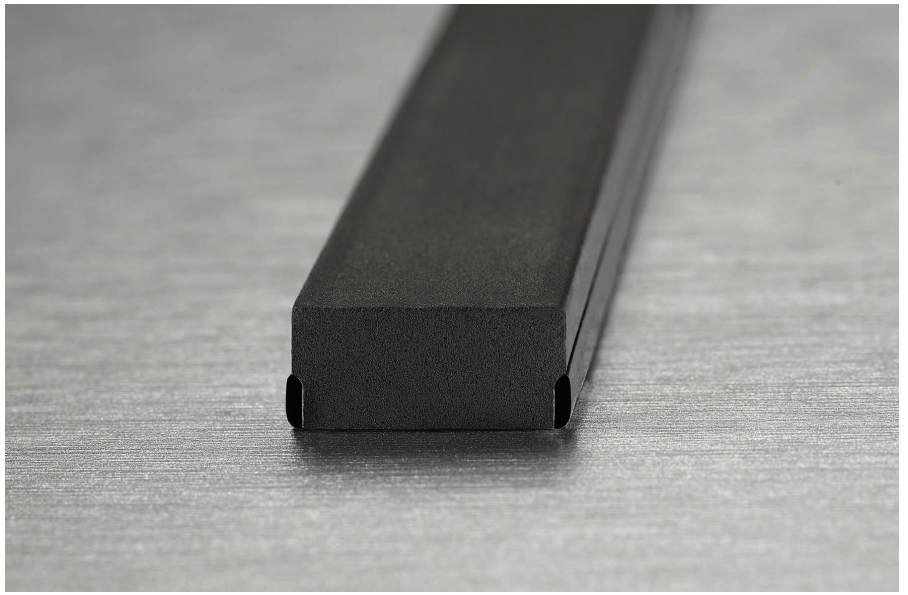




Spacers

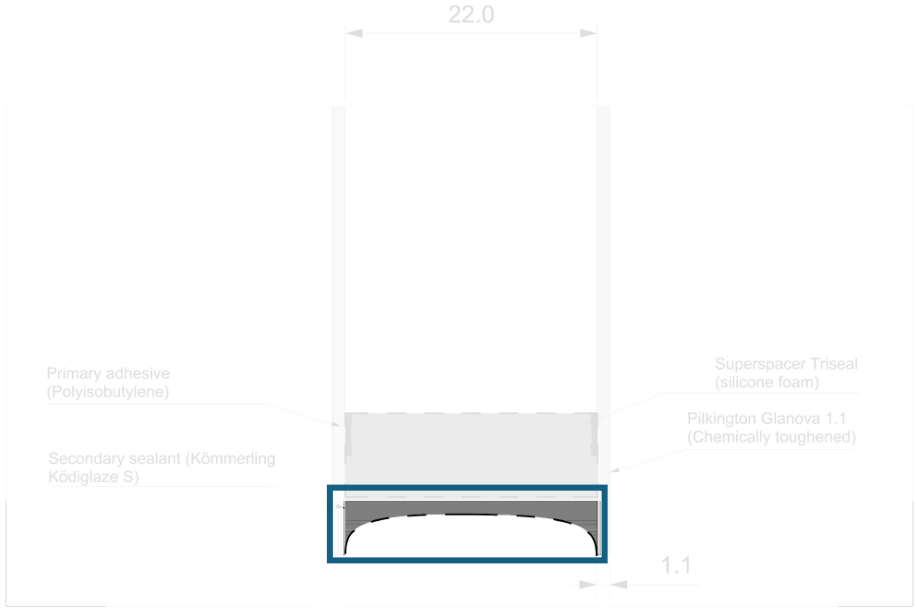
- Metal spacer = too stiff
- TPS/warme edge spacers = flexible





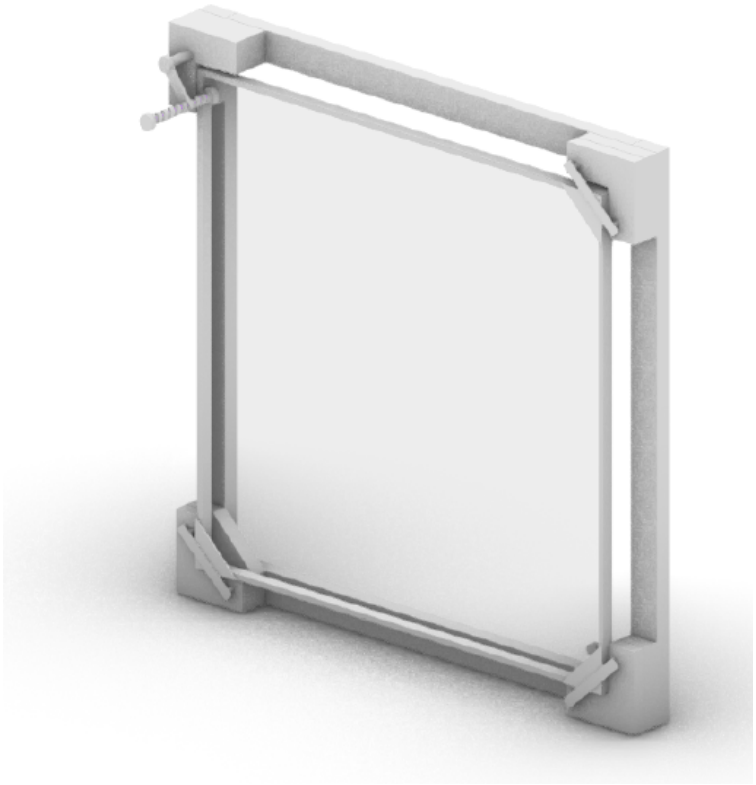
Adhesives & sealants

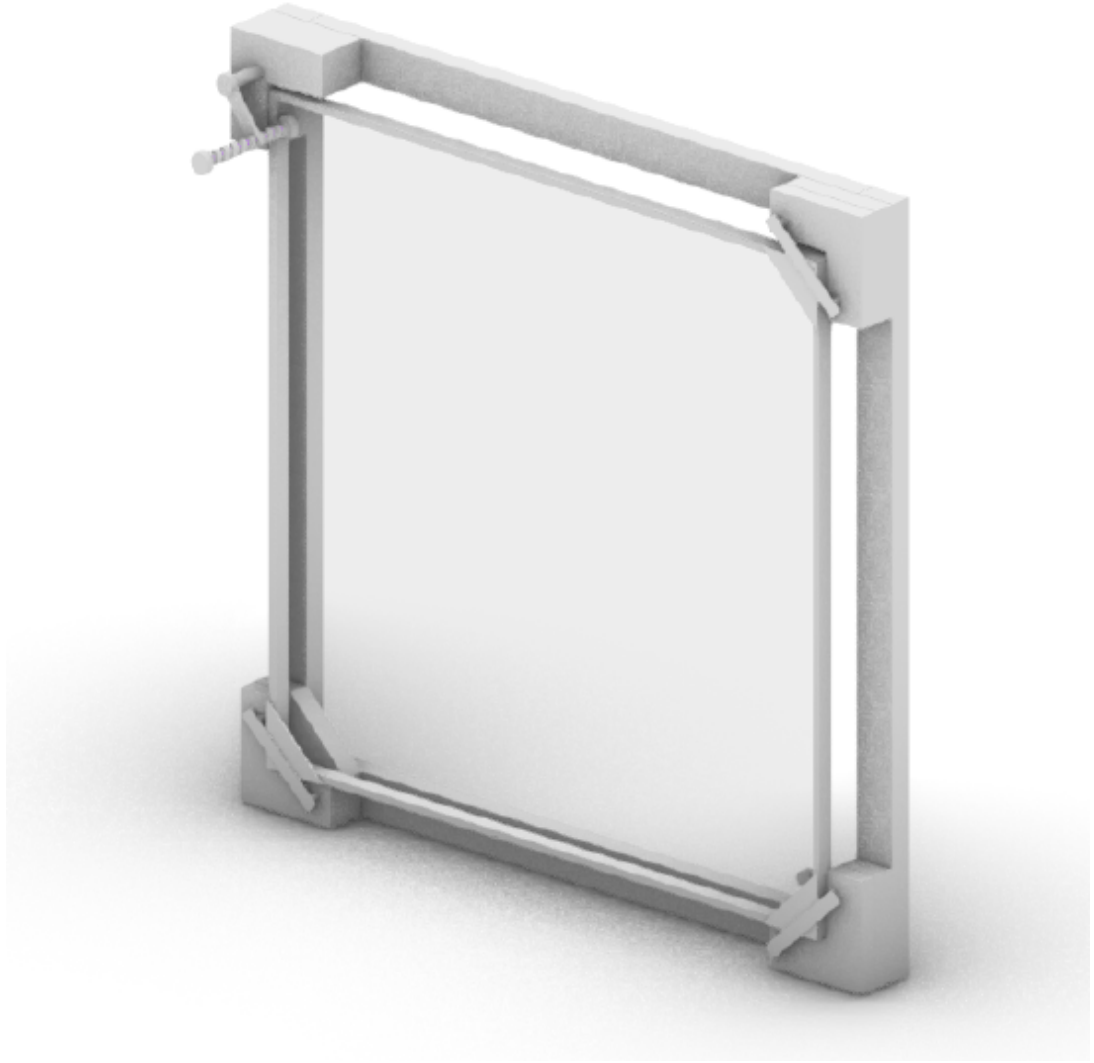
- Not all adhesives are made for cold bending, but influence is limited
- Kömmerling Ködiglaze S



Chosen cold bending method

- Single corner cold bending

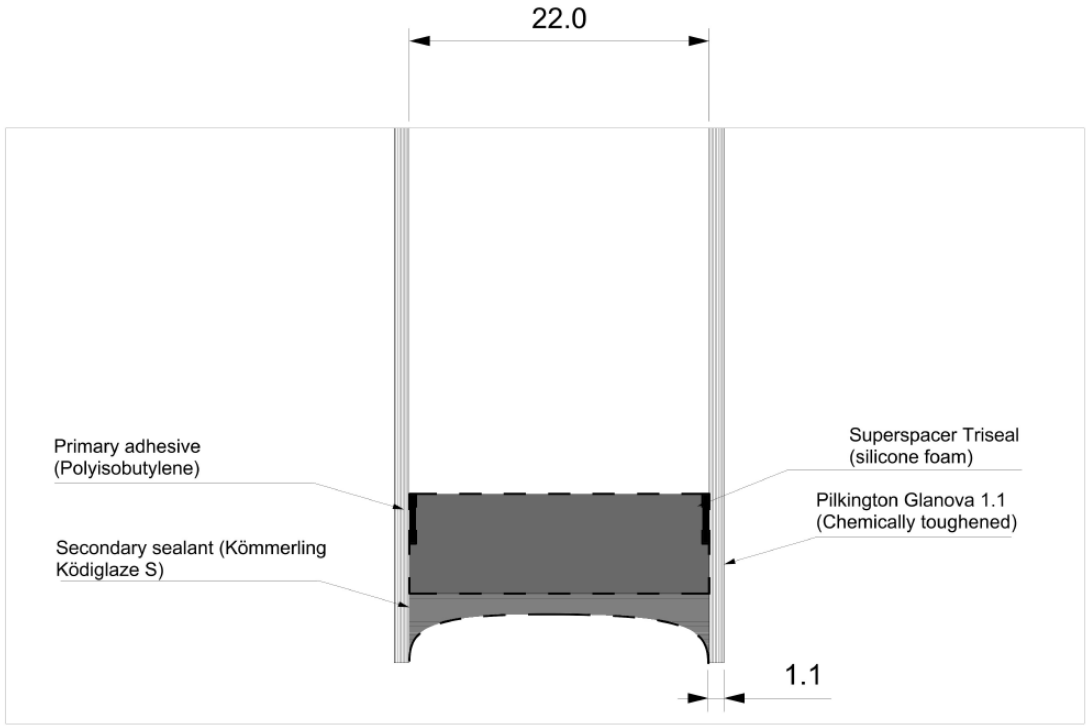




Clamp 3 corners

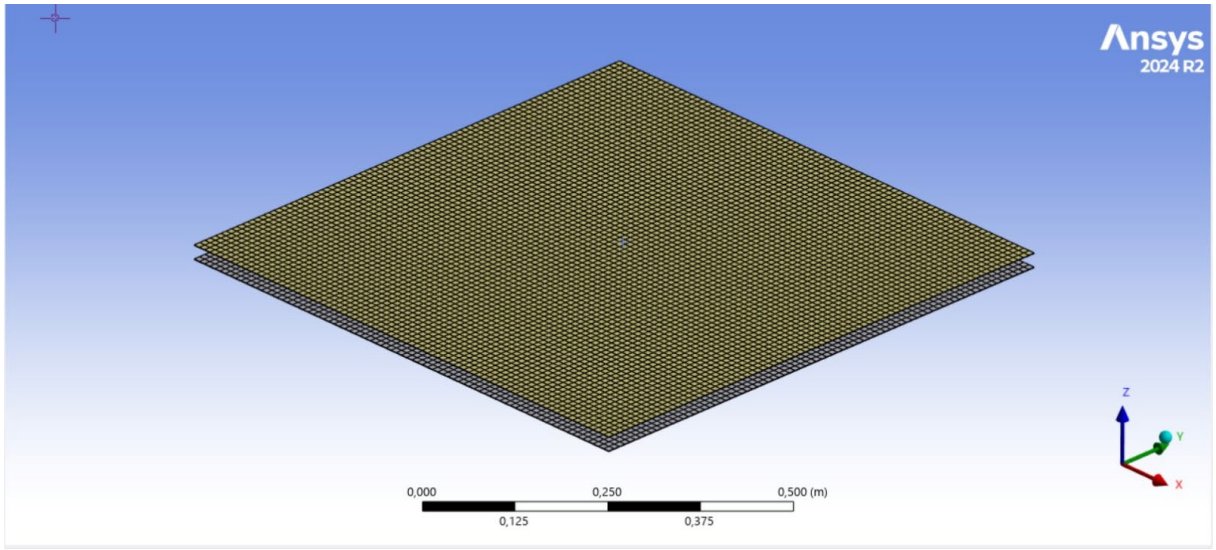
Push one corner “out of plane”

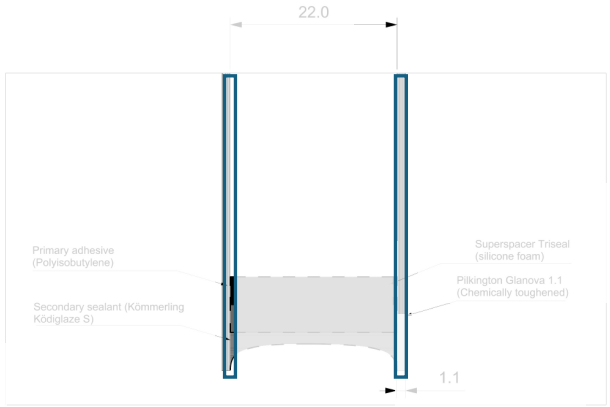
Numerical modelling


22.0
Primary adhesive
(Polyisobutylene)
Secondary sealant (Kömmerling
Ködiglaze S)
Superspacer Triseal
(silicone foam)
Pilkington Glanova 1.1
(Chemically toughened)
1.1

Thin glass panes

- 80x80cm. T=1.1mm
- Glanova Chemically strengthened thin-glass
- Isotropic elasticity

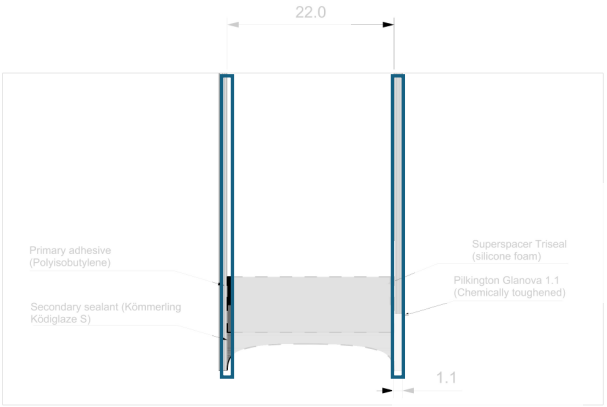




Parameters	Unit	NSG glanova™
Glass properties		
Optical transmittance	%	≥91
Refractive index (λ = 587,6 nm)	—	1,51
Density	g/cm³	2,48
Young's Modulus	GPa	75,4
Poisson's Ratio	—	0,24
Dielectric constant @1GHz	—	6,9
Coefficient of thermal expanssion (50 - 350°C)	x 10^{-7}/°C	91,8
Viscosity		
Softening point	°C	742
Annealing point	°C	552
Strain point	°C	508
Chemical strengthening		
Compressive stress	MPa	600 - 800
DOL	μm	15 - 25
Vickers Hardness (before chemical strengthening)	kgf/mm²	528
Vickers Hardness (after chemical strengthening)	kgf/mm²	583
Dimensions		
Thickness	mm	0,28 - 2

Glanova CS, Mechanical properties (NSG, 2025)

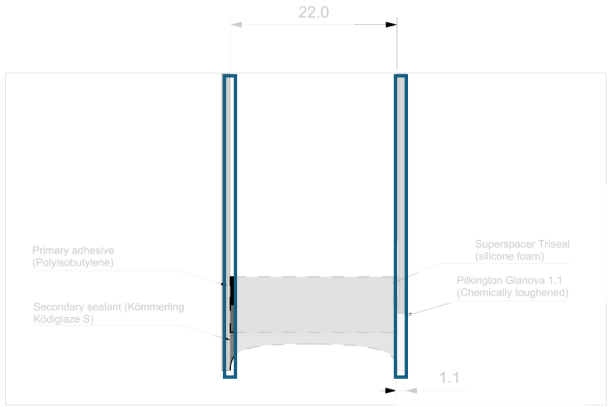
Thin glass panes



- Young's Modulus = 75,4Mpa
- Poisson's Ratio = 0.24
- Tensile strength??

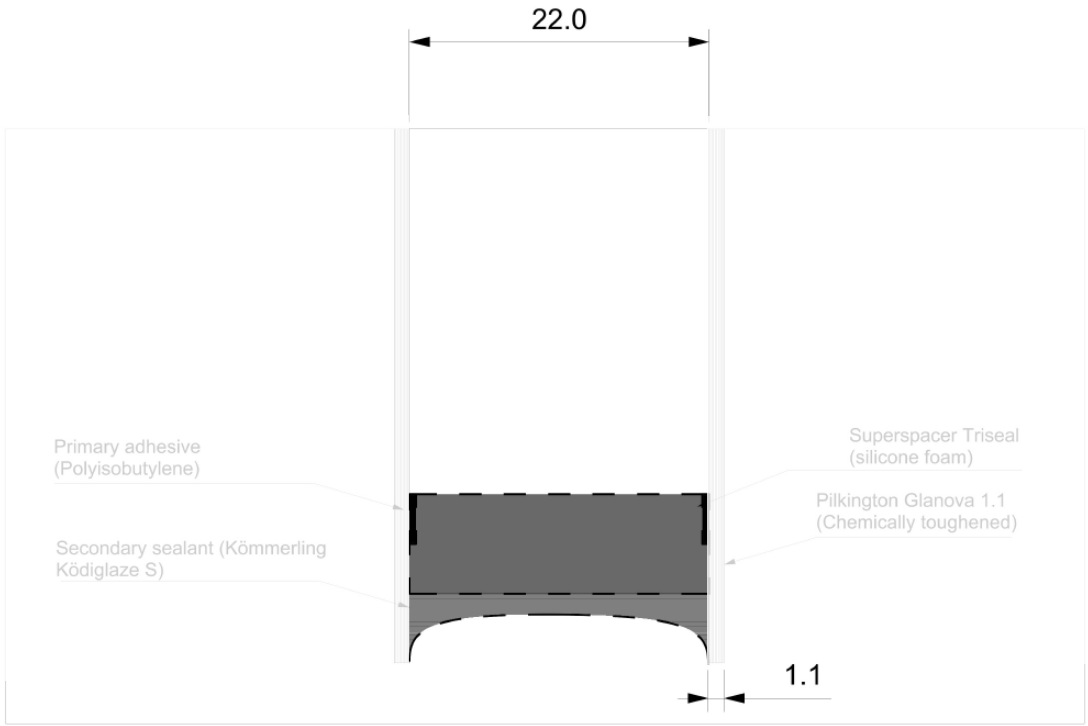
Parameters	Unit	NSG **glanova**™
Glass properties		
Optical transmittance	%	≥91
Refractive index (λ = 587,6 nm)	—	1,51
Density	g/cm³	2,48
Young's Modulus	GPa	75,4
Poisson's Ratio	—	0,24
Dielectric constant @1GHz	—	6,9
Coefficient of thermal expanssion (50 - 350°C)	x 10^{-7}/°C	91,8
Viscosity		
Softening point	°C	742
Annealing point	°C	552
Strain point	°C	508
Chemical strengthening		
Compressive stress	MPa	600 - 800
DOL	μm	15 - 25
Vickers Hardness (before chemical strengthening)	kgf/mm²	528
Vickers Hardness (after chemical strengthening)	kgf/mm²	583
Dimensions		
Thickness	mm	0,28 - 2

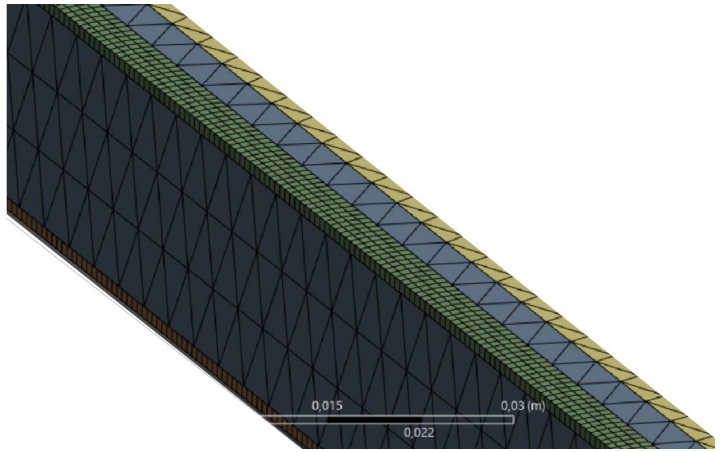
Thin glass panes

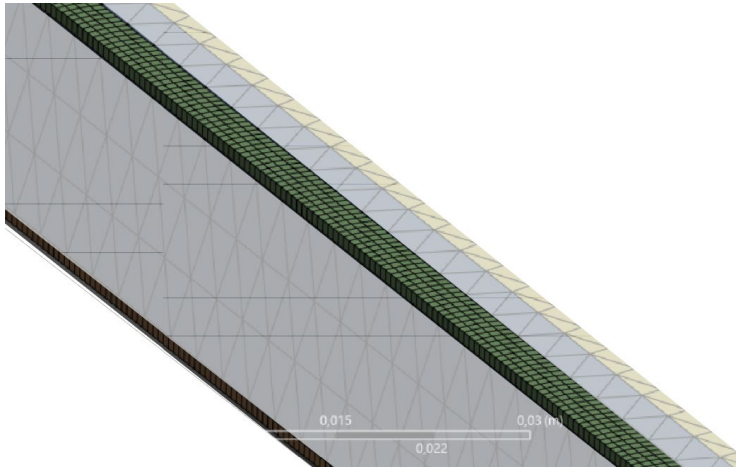


Parameters	Unit	NSG **glanova**™
Glass properties		
Optical transmittance	%	≥91
Refractive index (λ = 587,6 nm)	—	1,51
Density	g/cm³	2,48
Young's Modulus	GPa	75,4
Poisson's Ratio	—	0,24
Dielectric constant @1GHz	—	6,9
Coefficient of thermal expanssion (50 - 350°C)	x 10^{-7}/°C	91,8
Viscosity		
Softening point	°C	742
Annealing point	°C	552
Strain point	°C	508
Chemical strengthening		
Compressive stress	MPa	600 - 800
DOL	μm	15 - 25
Vickers Hardness (before chemical strengthening)	kgf/mm²	528
Vickers Hardness (after chemical strengthening)	kgf/mm²	583
Dimensions		
Thickness	mm	0,28 - 2

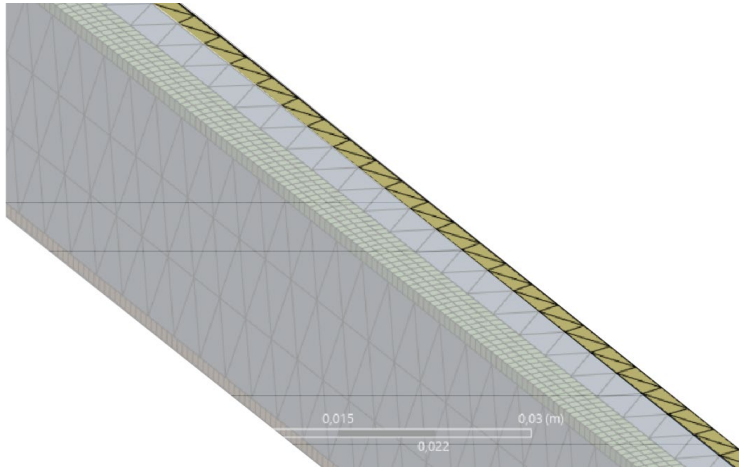
		Leoflex glass (LG)	Saflex DG41 (SAF)	SentryGlas (SG)	
Density	ρ	2480	1080	950	kg/m³
Young's modulus	E	74000	1007	612	MPa
Shear modulus	G	30000	341	211	MPa
Poisson's ratio	v	0.23	0.476	0.449	-
Tensile bending strength	σ_b	260	32.4	34.5	MPa
Maximum size	A	1.5x1.85	2.46x3.2	1.2-200	m
Thickness range	t	0.55-2	0.76	0.89	mm


22.0
Primary adhesive
(Polyisobutylene)
Secondary sealant (Kömmerling
Ködiglaze S)
Superspacer Triseal
(silicone foam)
Pilkington Glanova 1.1
(Chemically toughened)
1.1

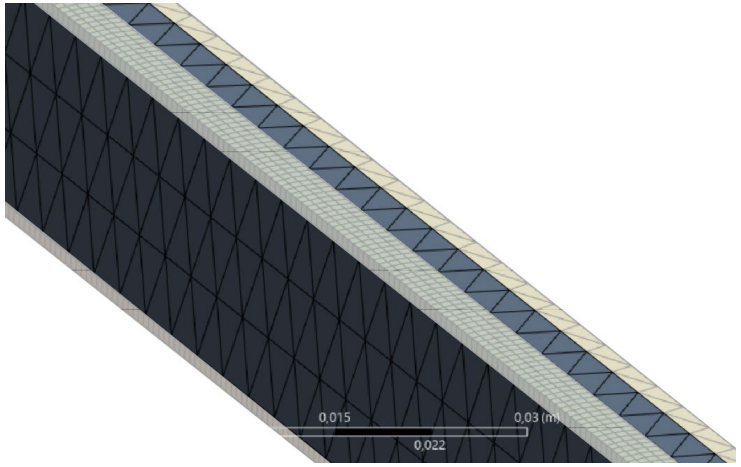




Primary adhesive



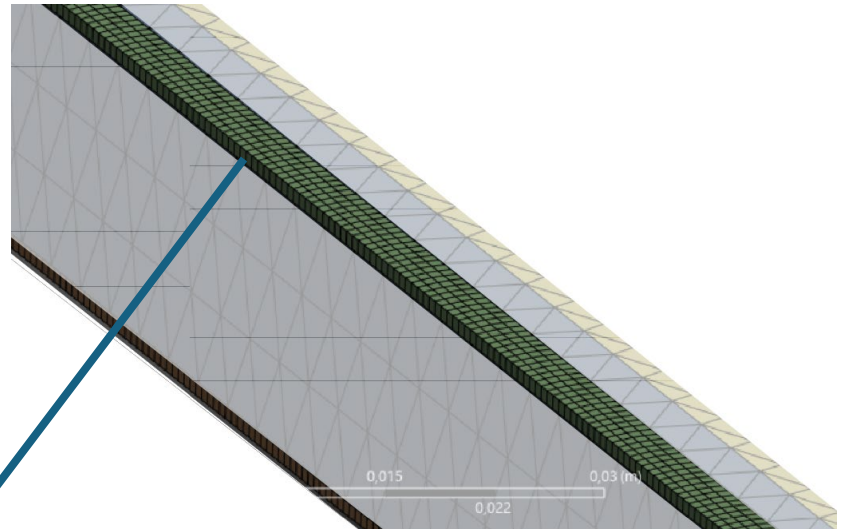
Secondary sealant

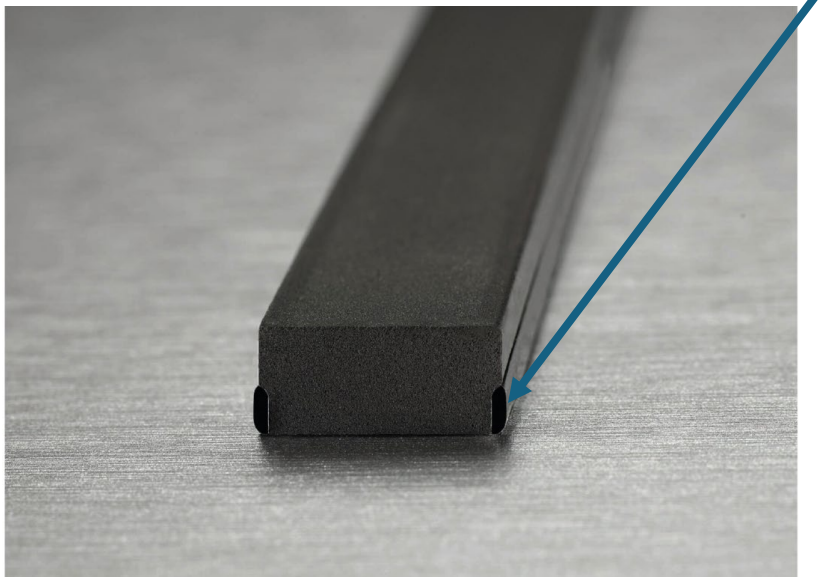


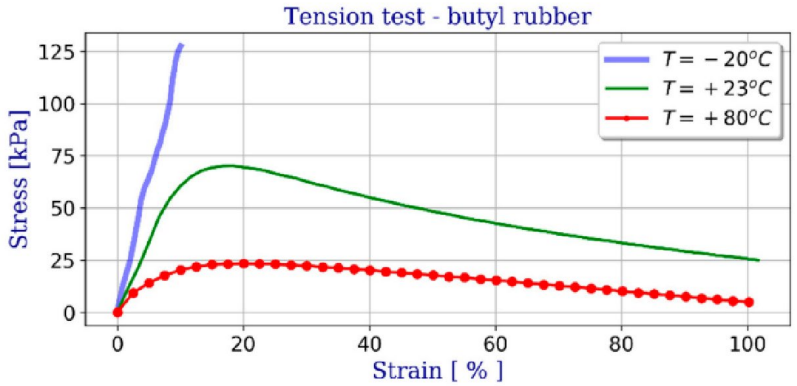
Spacer

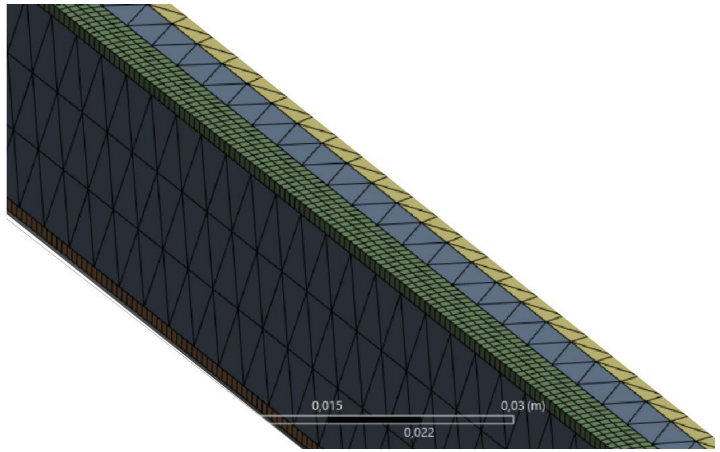
Primary adhesive

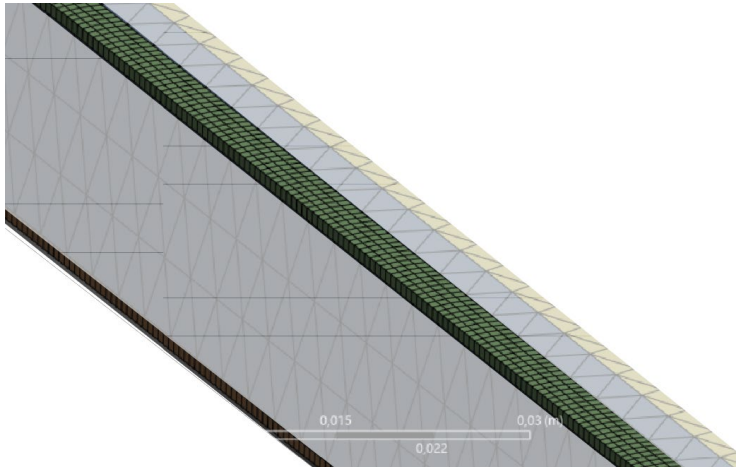
- Polyisobutylene (butyl rubber)
- Neo-Hookean hyper-elastic model



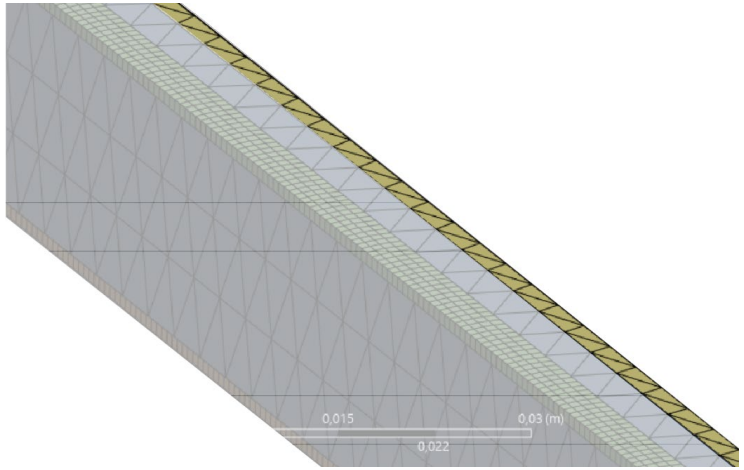




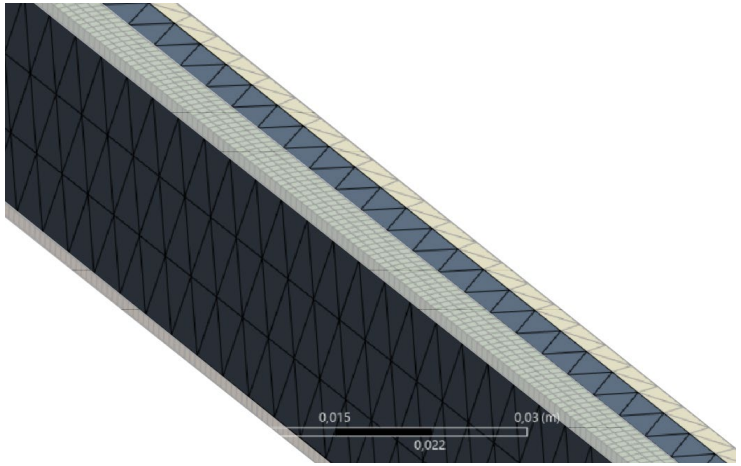




Primary adhesive



Secondary sealant



Spacer

Ködiglaze S

- Arruda-boyce hyper-elastic model

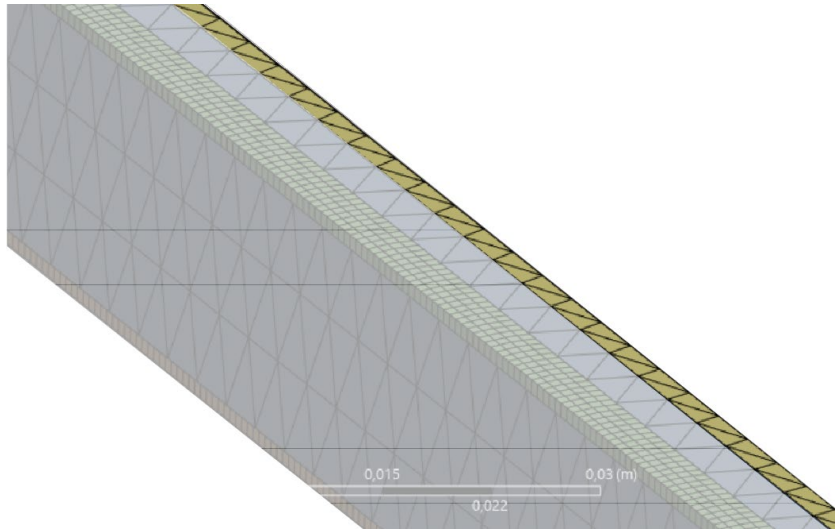
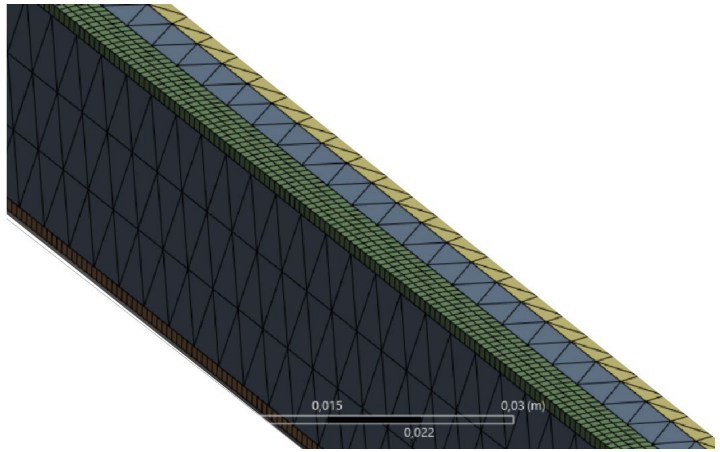
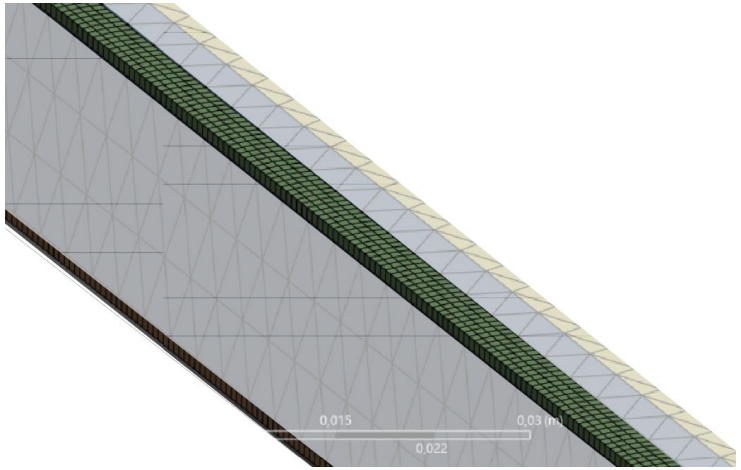


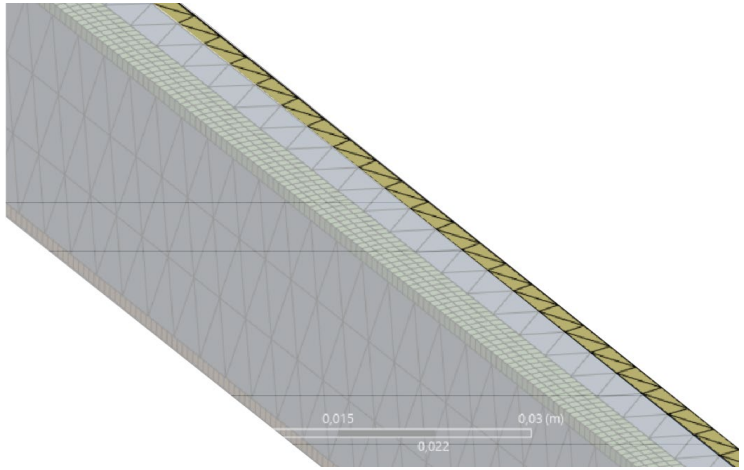
Table 5 Selected material models for each type of adhesive

Adhesive	FE model designation	Material model (Ansys designation)		
		Hyperelastic—Arruda–Boyce (TB HYPER BOYCE)		
Silicone	S3a (M)	Initial shear modulus μ	Limiting network stretch λ_L	Incompressibility parameter d_1
		(MPa)	(–)	(1/MPa)
		0.7066	2.90E+11	0.2143
	S3a (EP)	Elasto-plastic model with isotropic hardening (TB MISO)		
	1B (EP)			
		Hyperelastic—Ogden (TB HYPER OGDEN)		
Polyurethane	S3a (M)	Material constant μ_1	Material constant α_1	Incompressibility parameter d_1
		(MPa)	(–)	(1/MPa)
		0.9126	14,486	0.3
	S3a (EP)	Elasto-plastic model with isotropic hardening (TB MISO)		
	1B (EP)			
Epoxy	S3a (M)	Uniaxial tensile test data (TB EXPE UNIAXIAL)		
	S3a (EP)	Elasto-plastic model with isotropic hardening (TB MISO)		

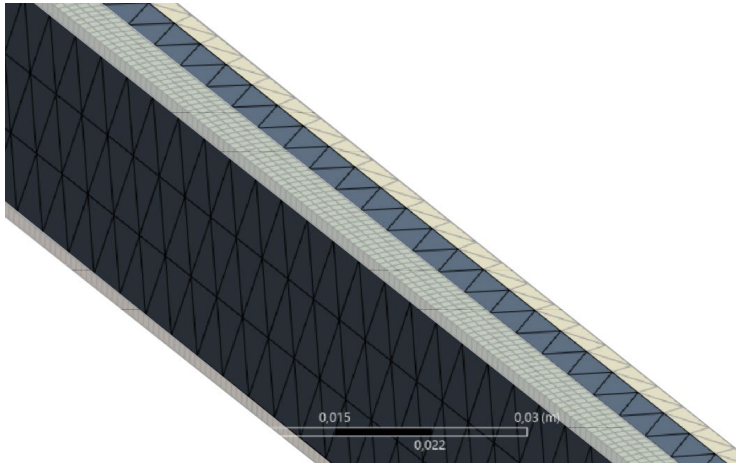




Primary adhesive



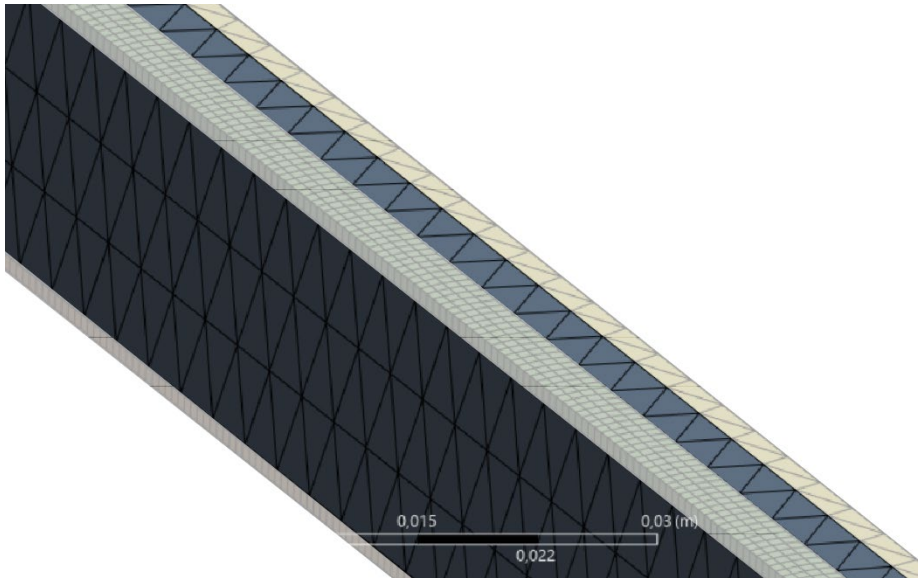
Secondary sealant



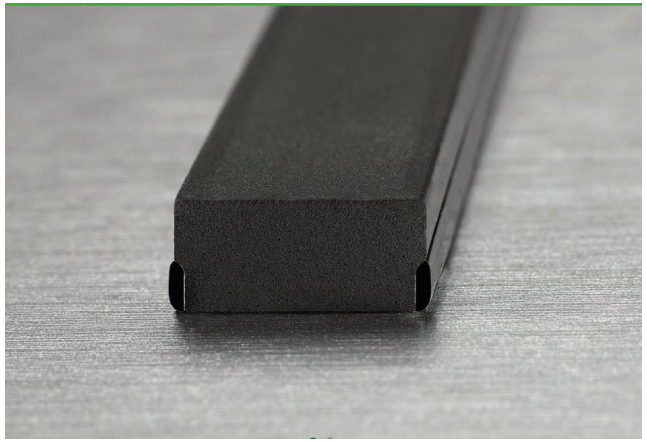
Spacer

Spacer – Edgetech Triseal

- 20.2 x 7.3 mm
- D = 700kg/m3
- “Flexible silicone foam”



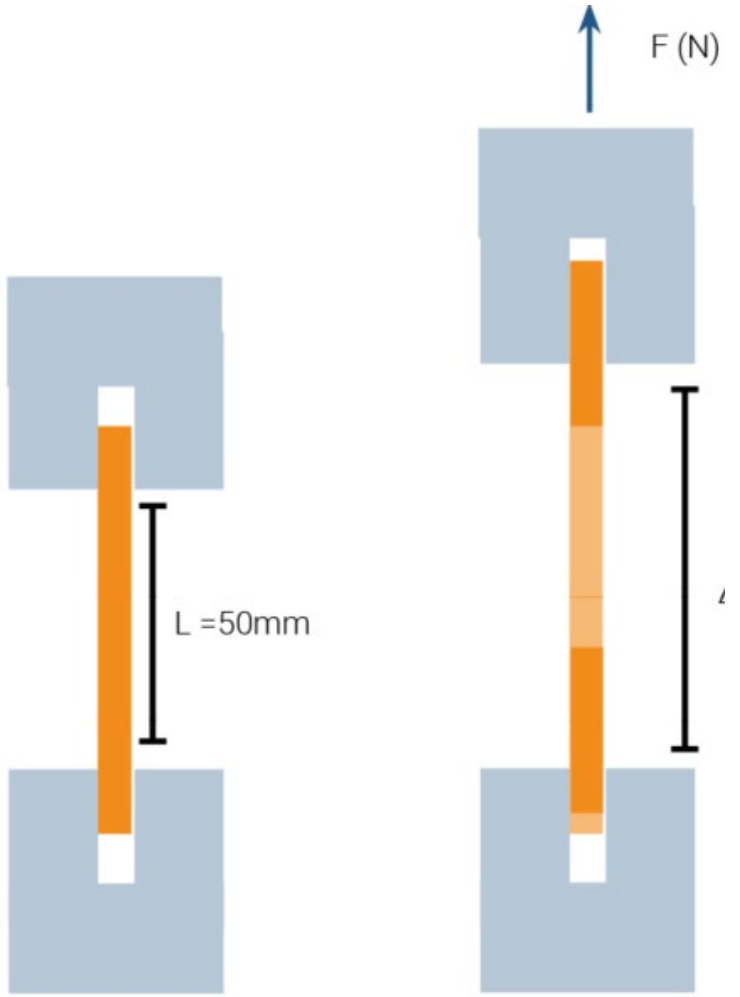
- Young’s modulus = ?
- Poisson’s ratio = ?



Testing material properties

- Uni-axial Tensile test

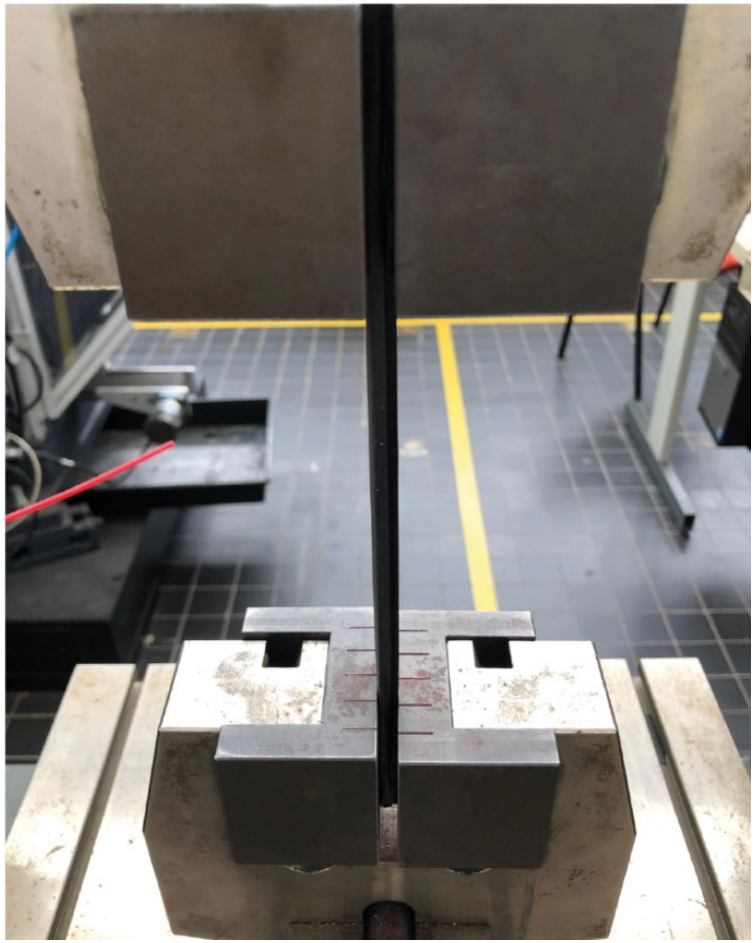
- Gain tensile stress/strain data
- Derive Young's modulus



Schematic of tensile test (Own work)

Uni-axial tensile test

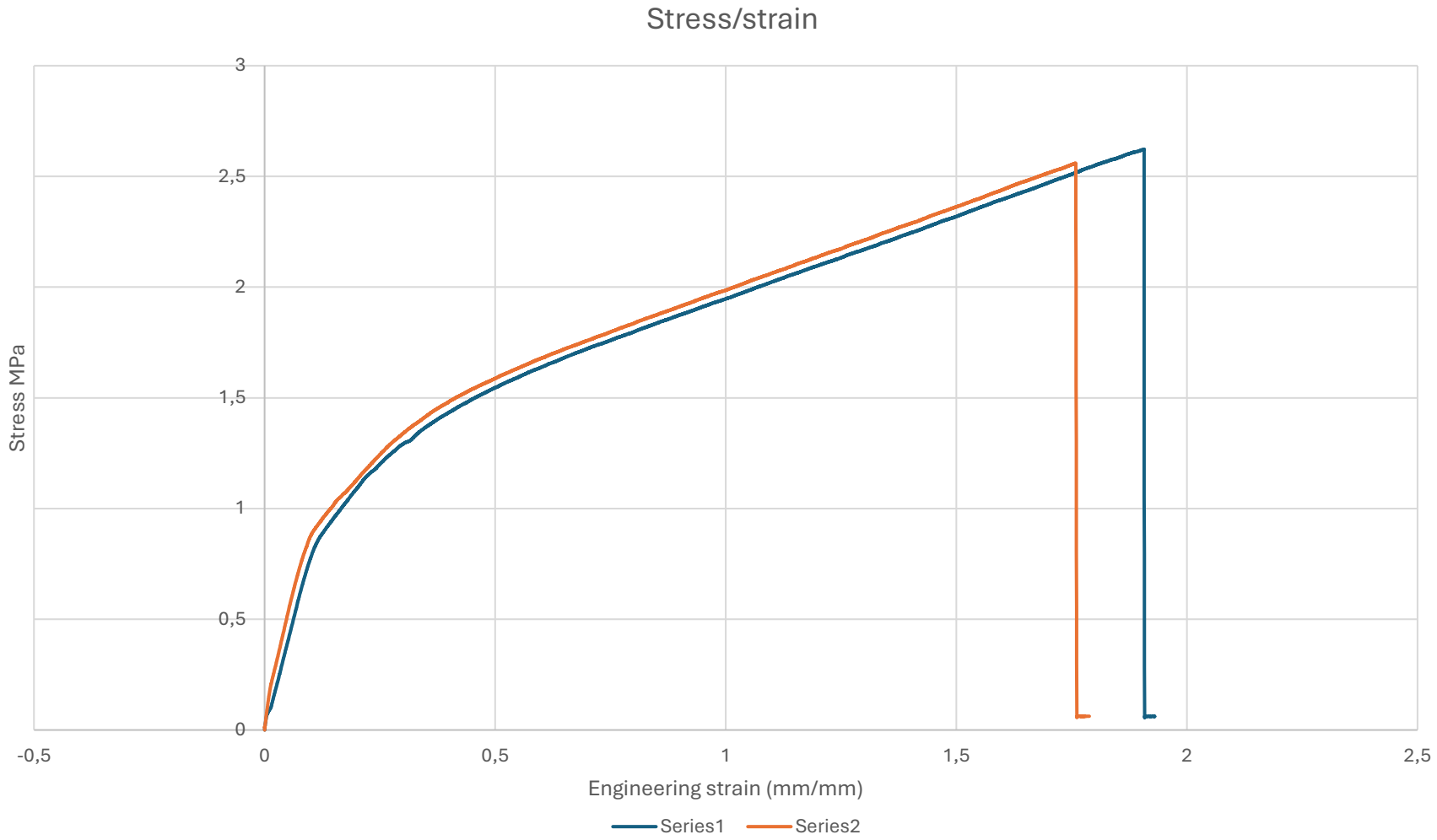
Initial position of a spacer sample in the tensile test (own work)



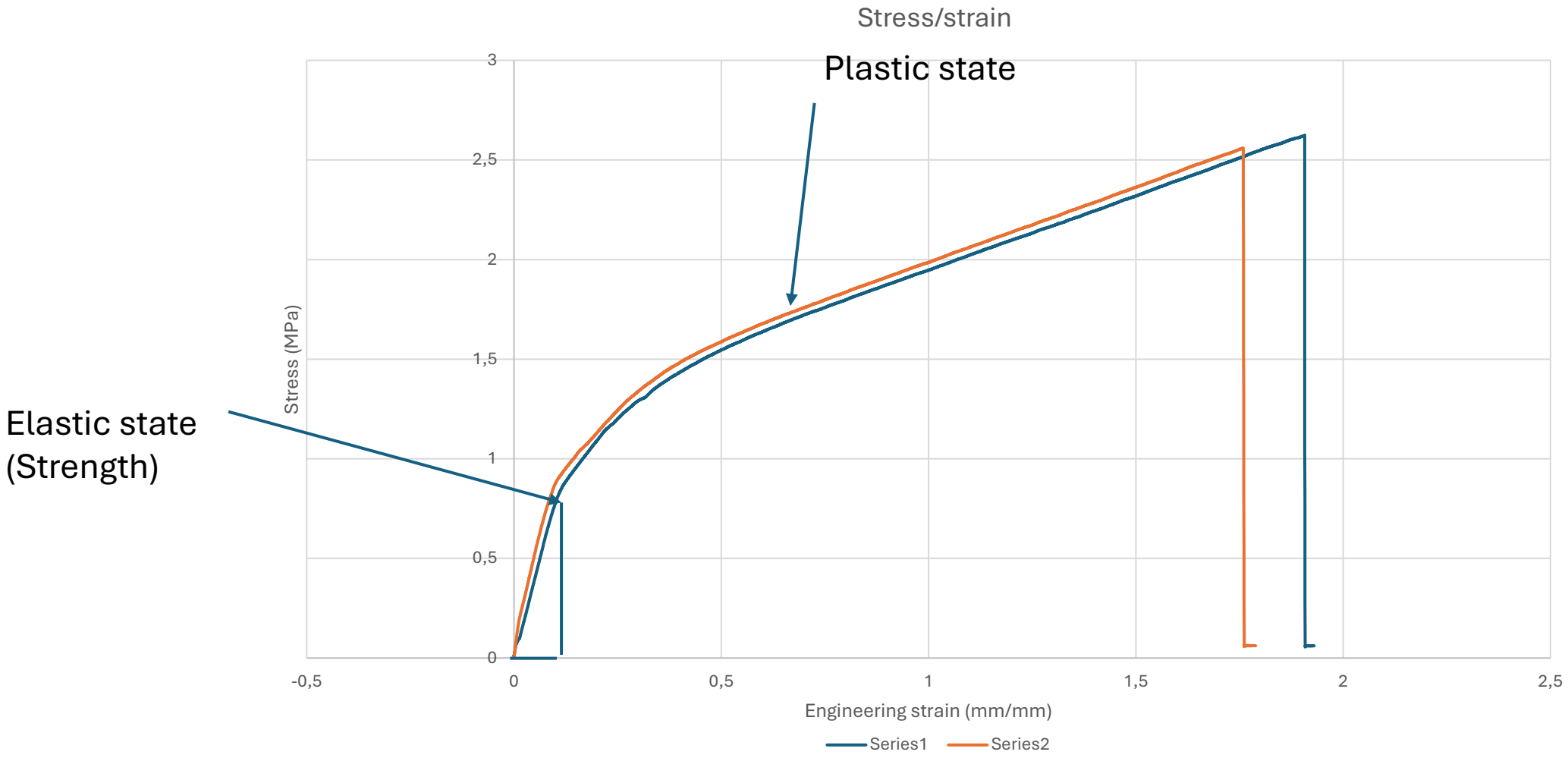
Spacer sample in tensioned state (Own work)

Spacer after reaching ultimate tensile strength (Own work)

Spacer – stress/strain diagram



Spacer - stress/strain diagram



Elastic behavior

$$E = \frac{\sigma}{\varepsilon}$$

$$\sigma = Stress\ (Mpa)$$

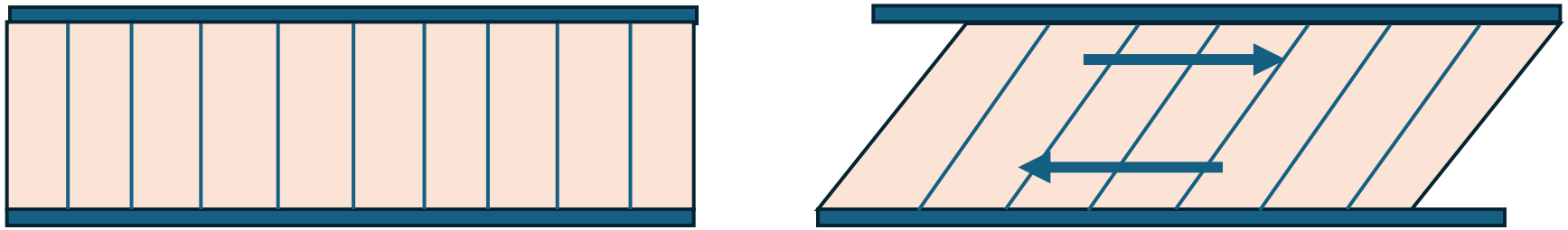
$$E = Young's\ modulus$$

$$\varepsilon = Strain\ (\frac{mm}{mm})$$

E = 0.83/0.1 = 8.17MPa

Isotropic elasticity?

- Spacer material is too complex
- Spacer undergoes too much strain



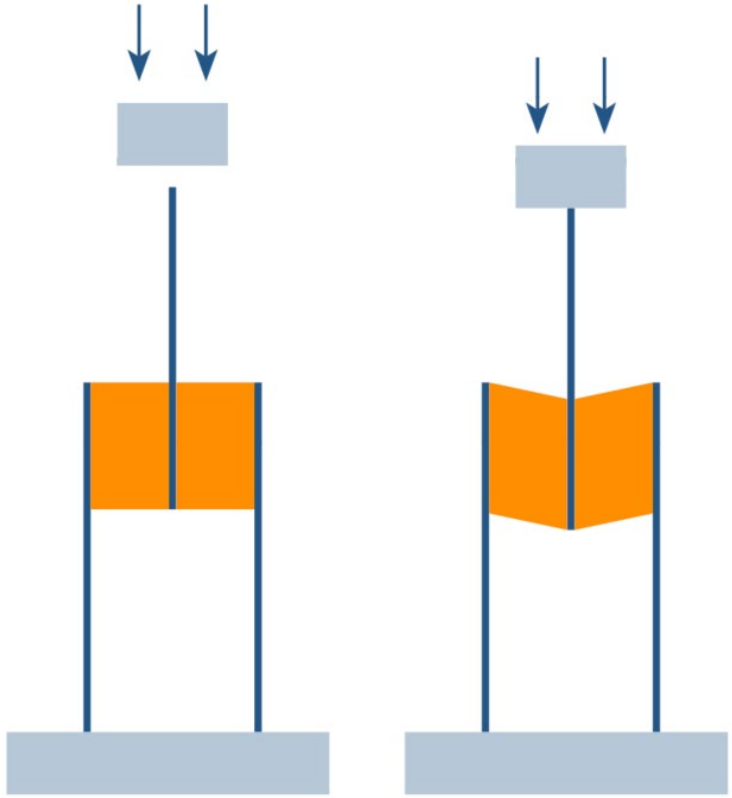
Spacer – hyper-elastic modelling

- Hyper-elastic models
  - ~~Mooney-Rivlin~~
  - **Neo-Hookean**
  - **Yeoh**
  - ~~Ogden~~
  - ~~Gent~~

Not enough data!

Double-lap shear test

- Gain shear stress/strain data
- Determine shear modulus



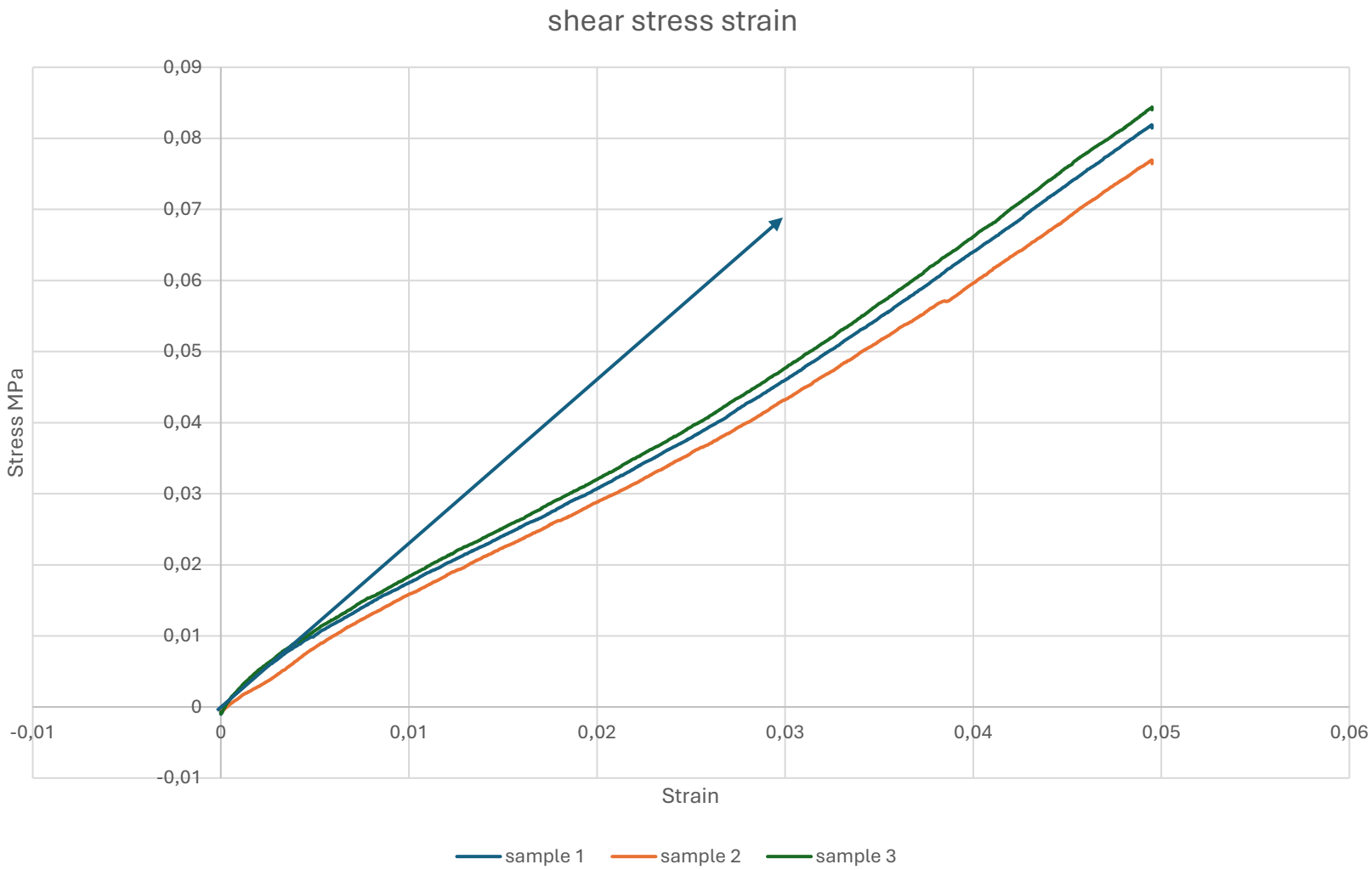
Schematic of tensile test (Own work)

Double-lap shear test

- 3 samples with a displacement of 2mm

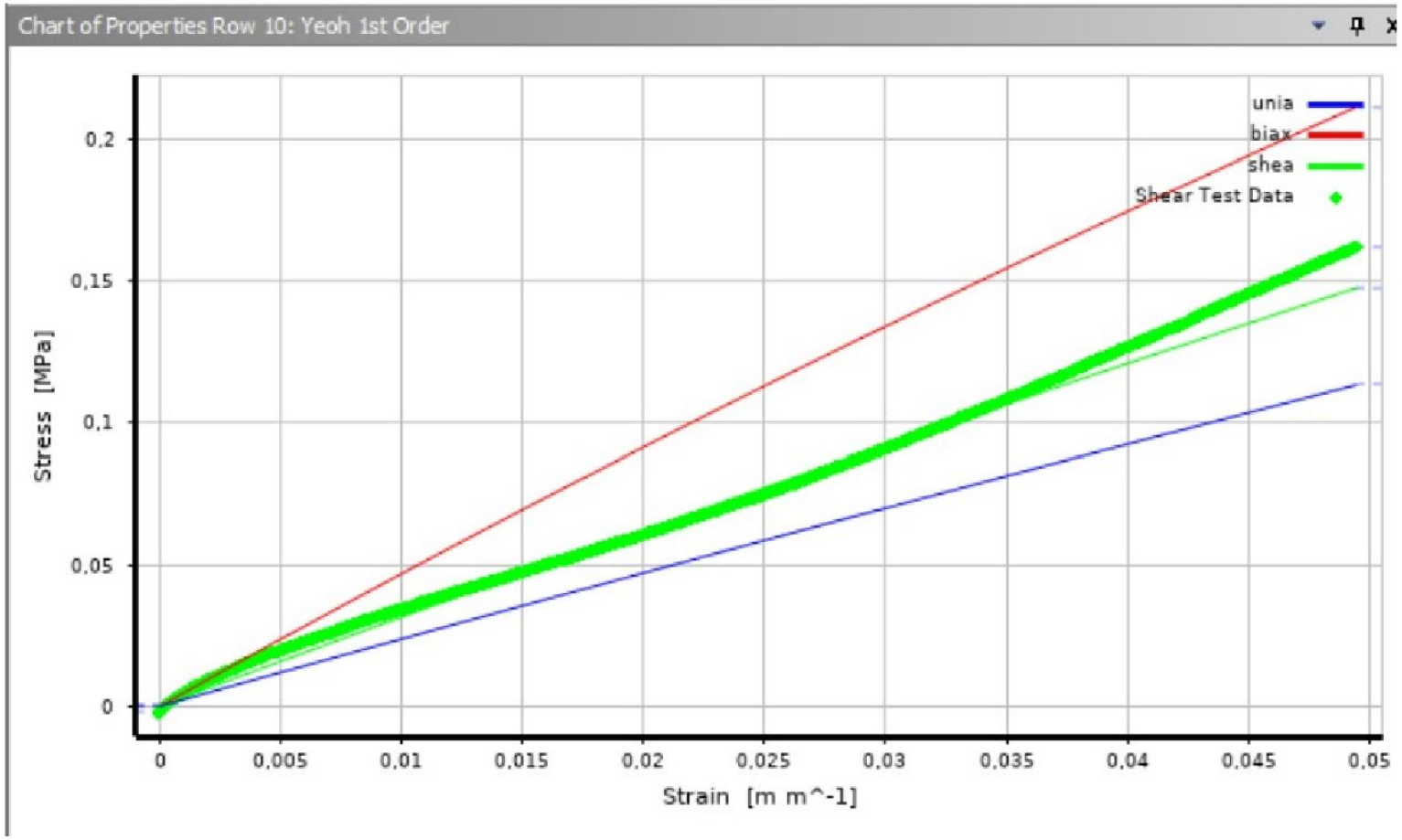
Double-lap shear test

- Initial shear modulus = 0.0011/0.0005 = 2.2MPa

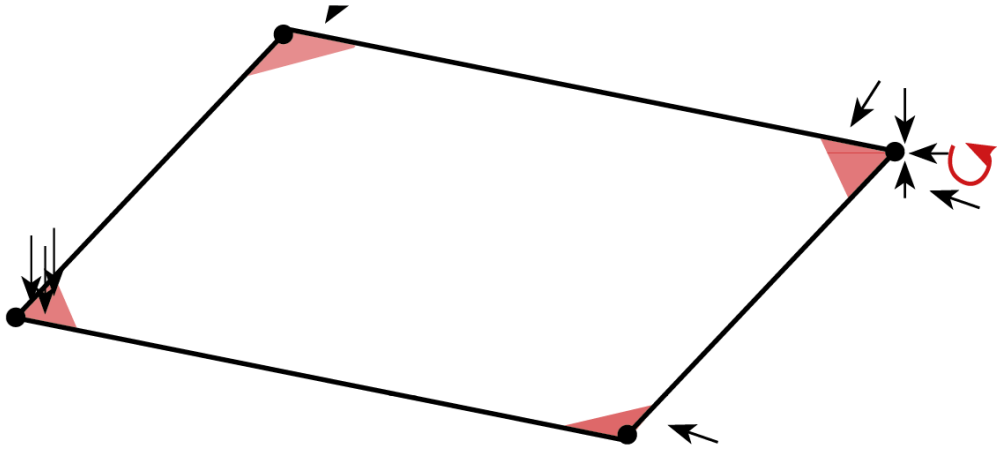


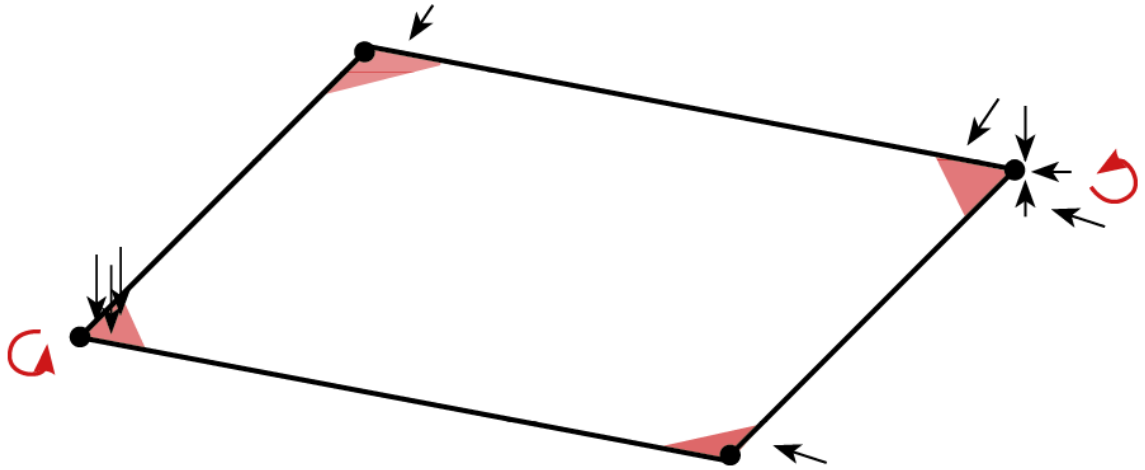
Hyper-elastic model

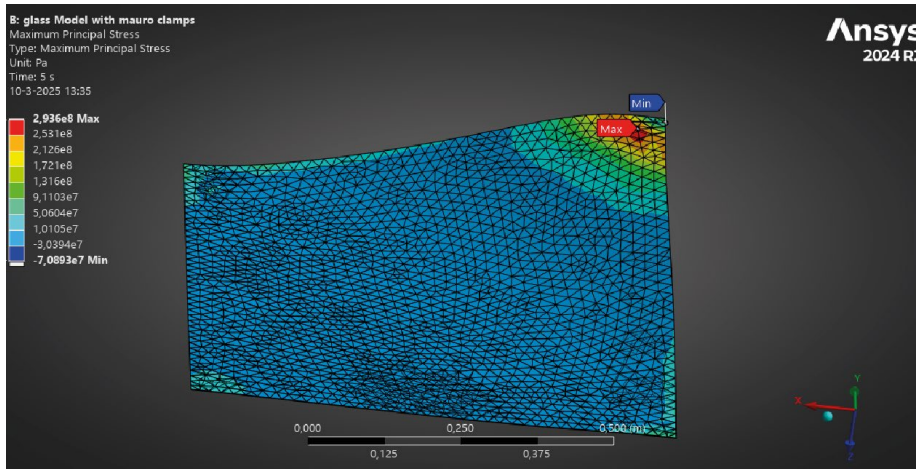
- Yeoh 1st order

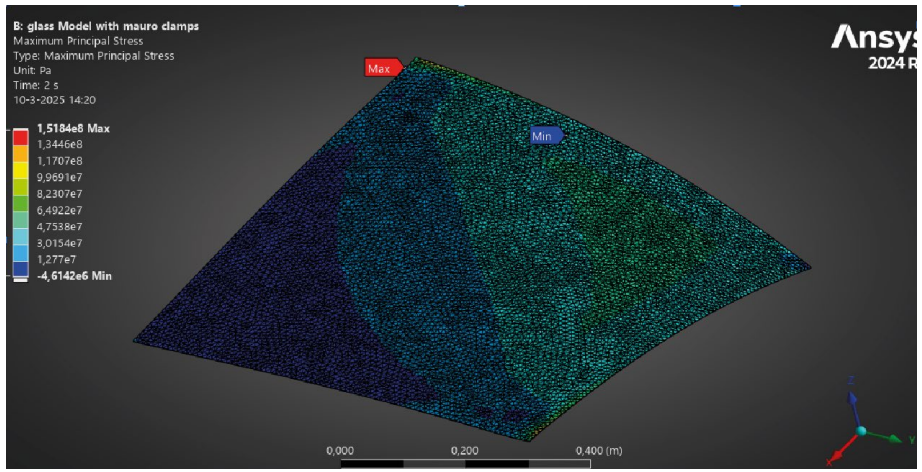


Modeling the boundary conditions



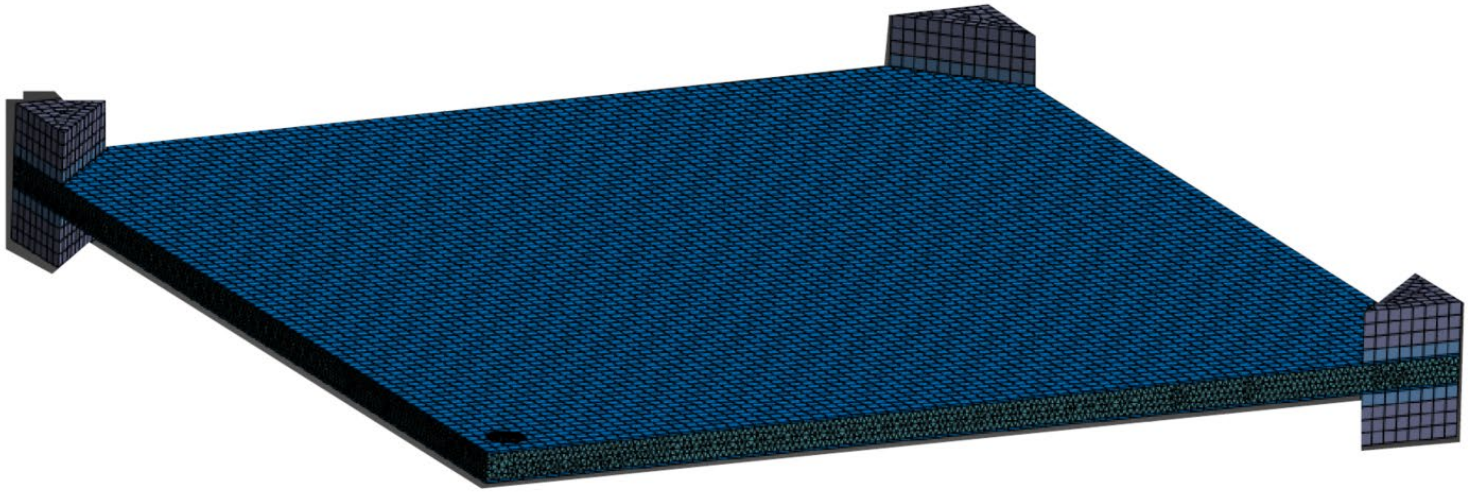




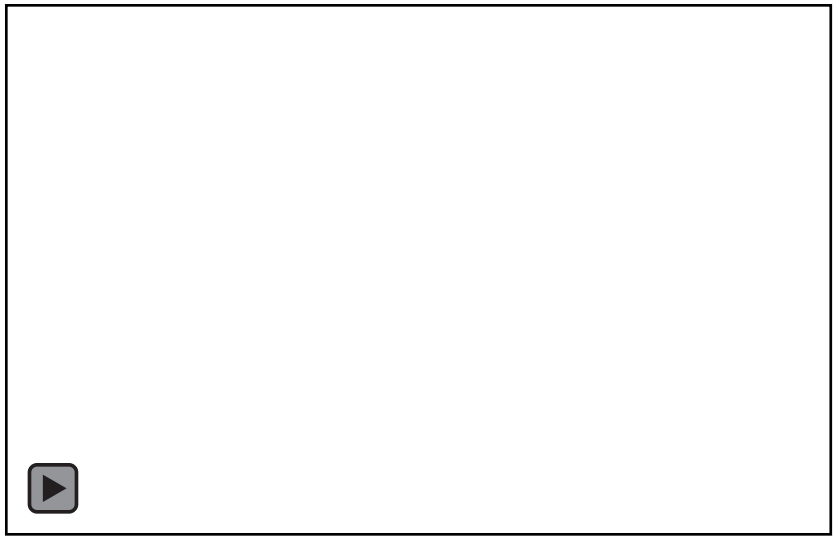


Clamps

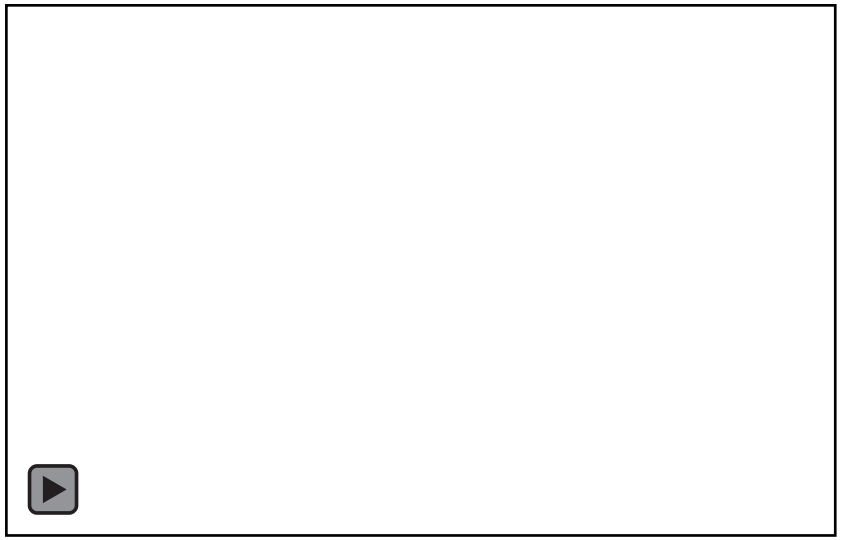
- Steel
- Cushion interlayer
- Friction coefficient



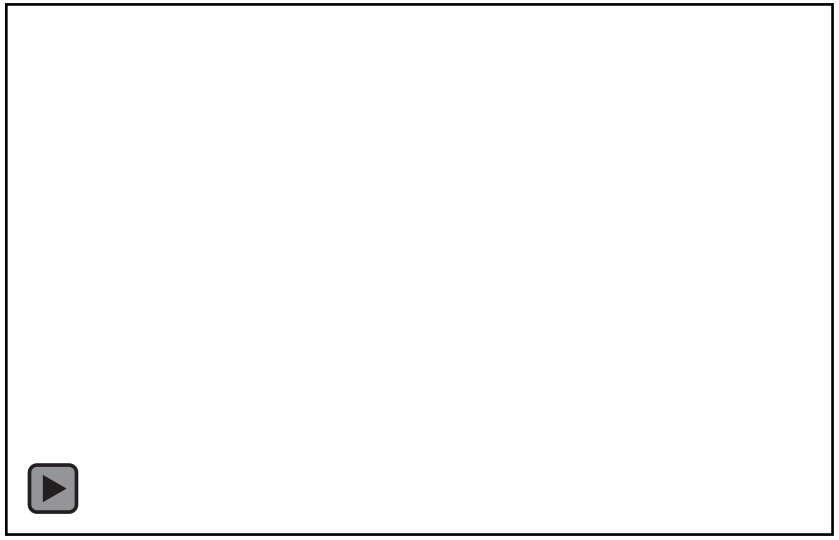
Results – IGU



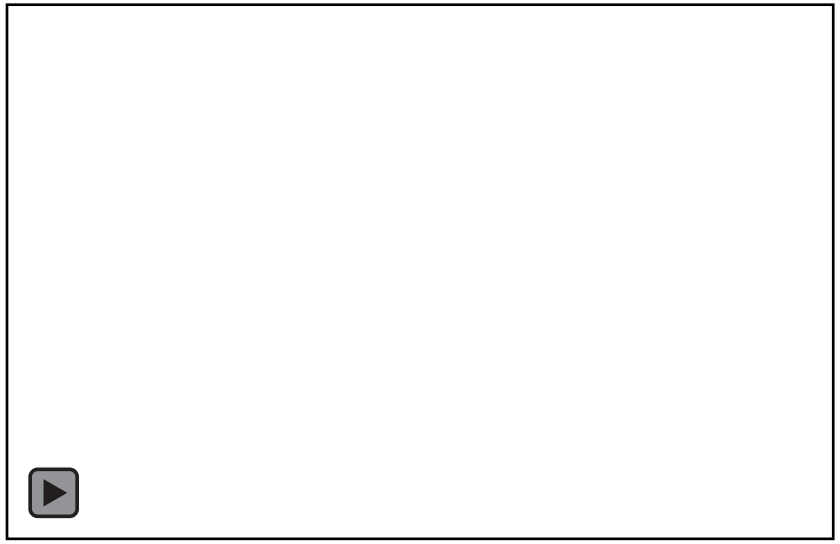
- Deformation



- Maximum principal stress



- Vector principal stress

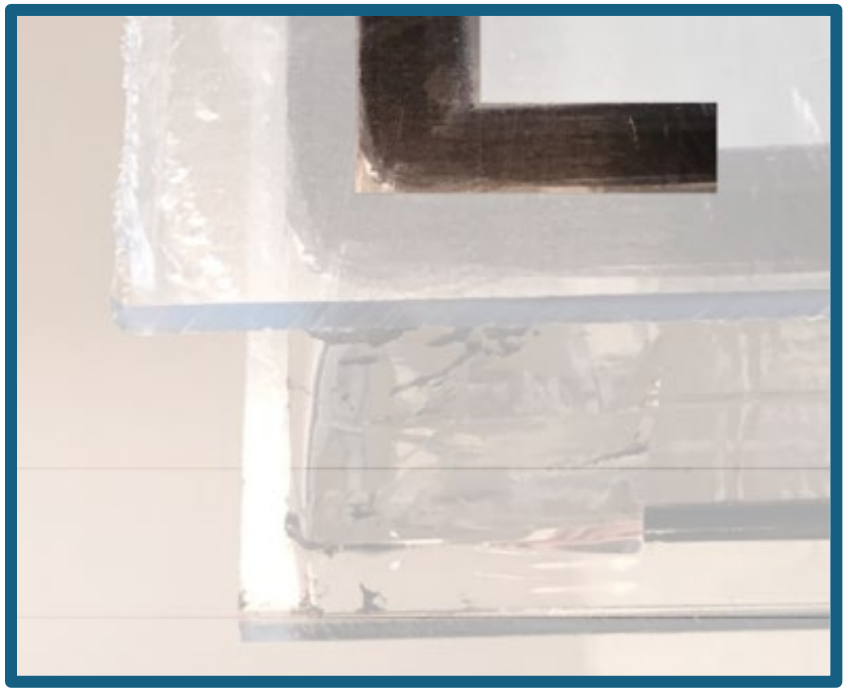


- Maximum principal stress

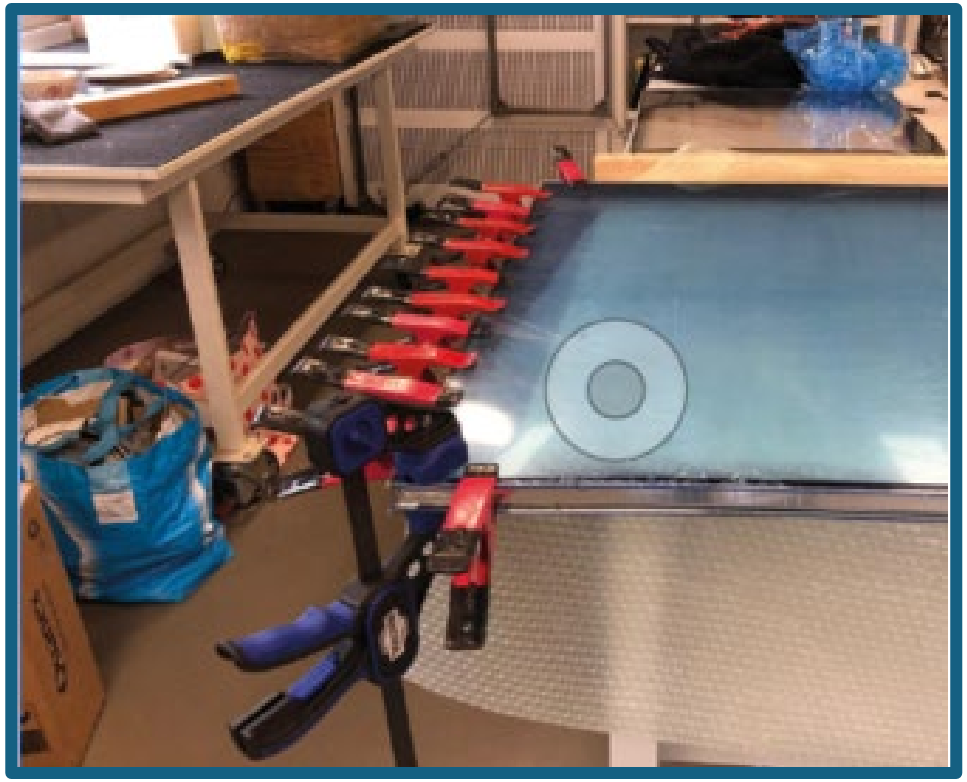
Prototype fabrication

Application of the Triseal

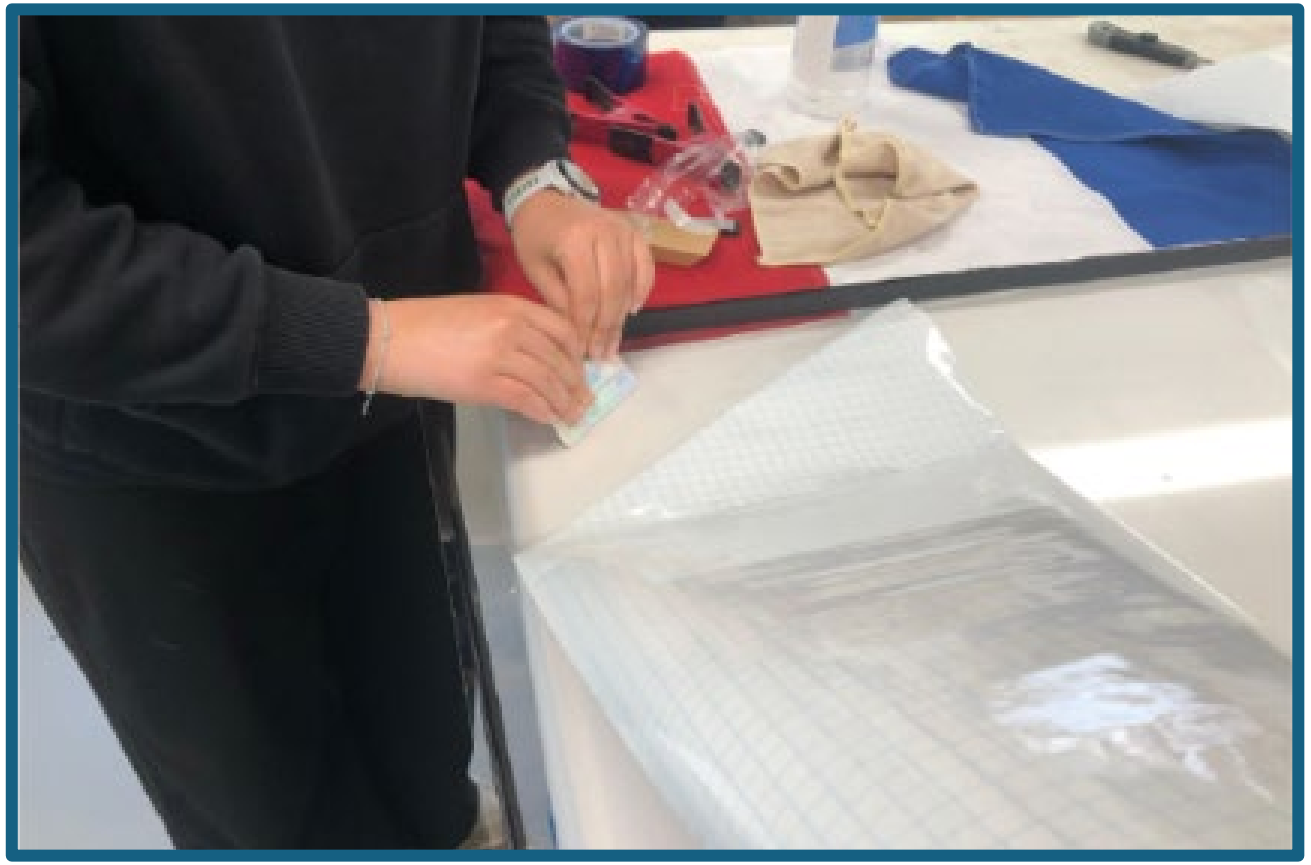
Corners



Sealing with butyl sticker

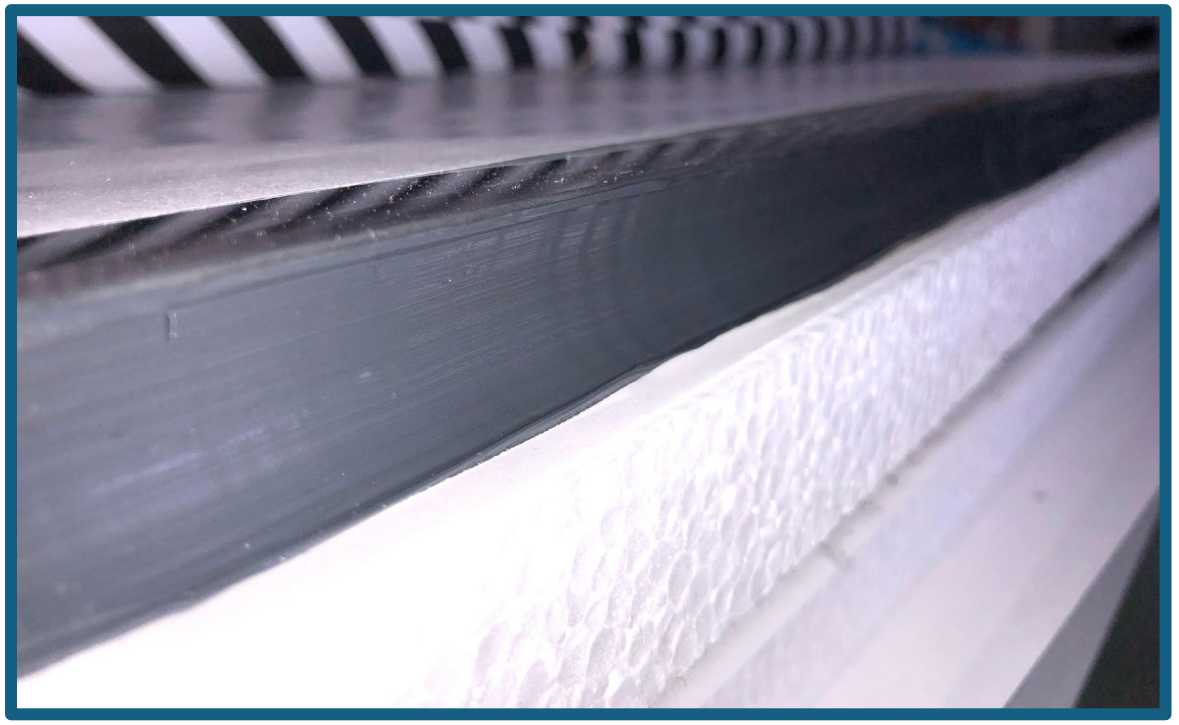


Clamping the edges



Application of “lamination”

Applying the sealant

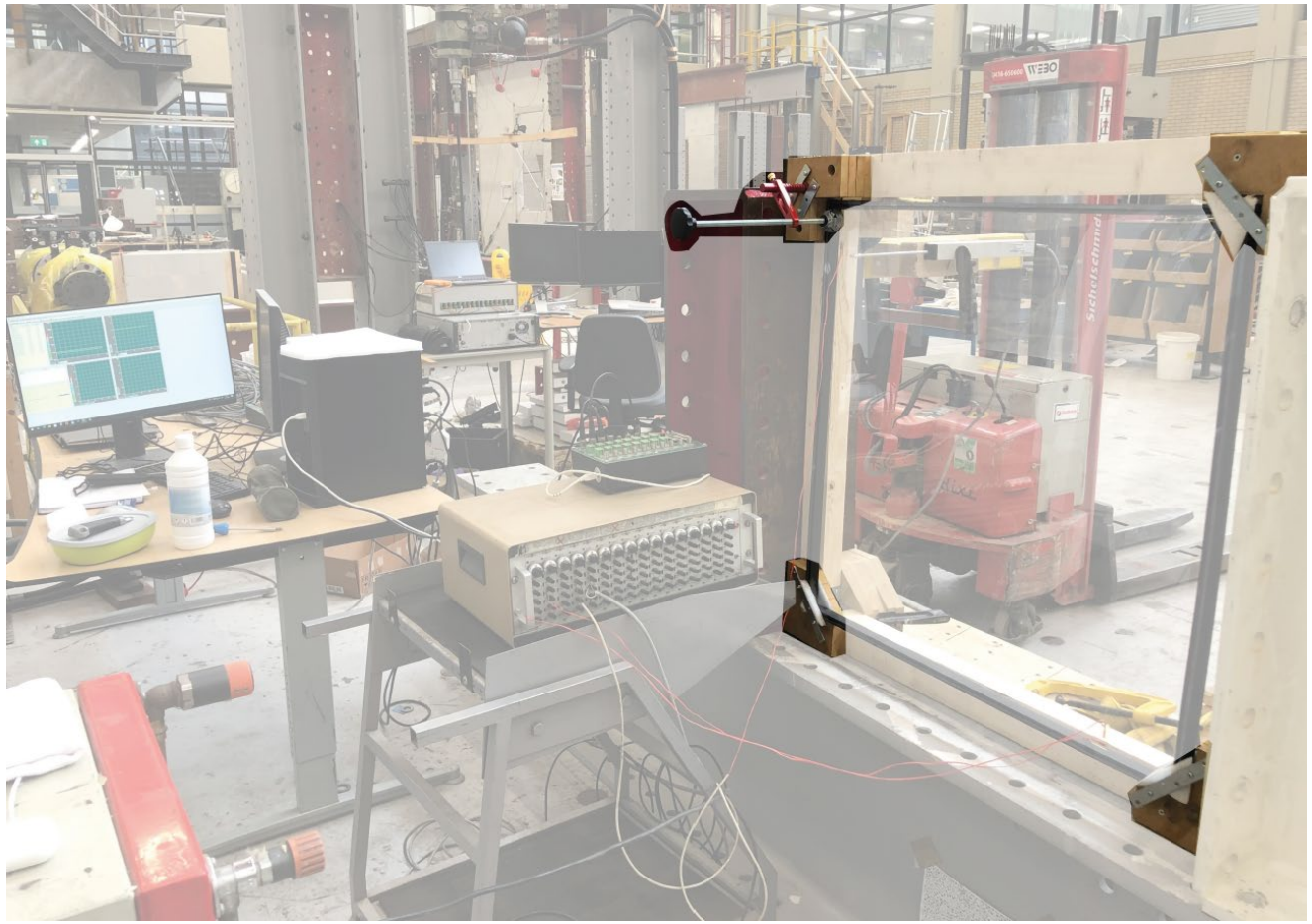


Finishing of the sealant

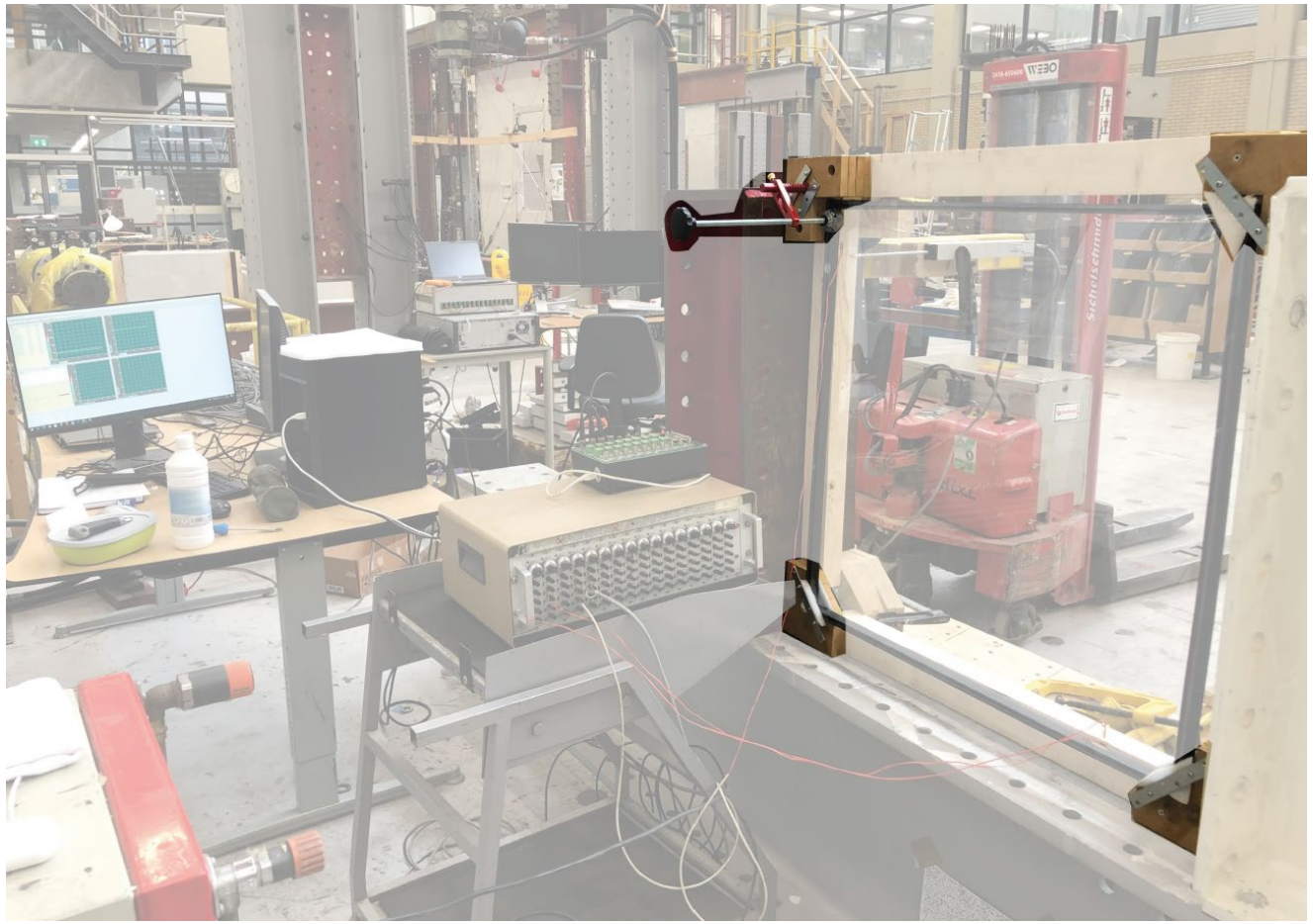
Test setup

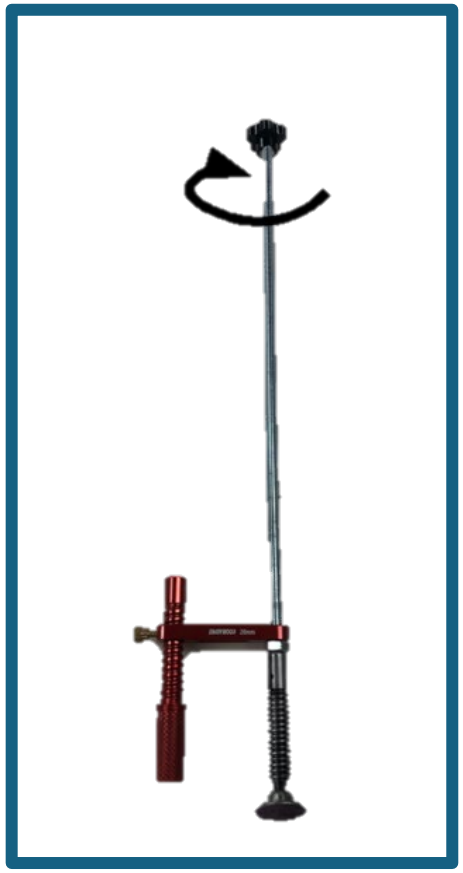
Schelstschmidt

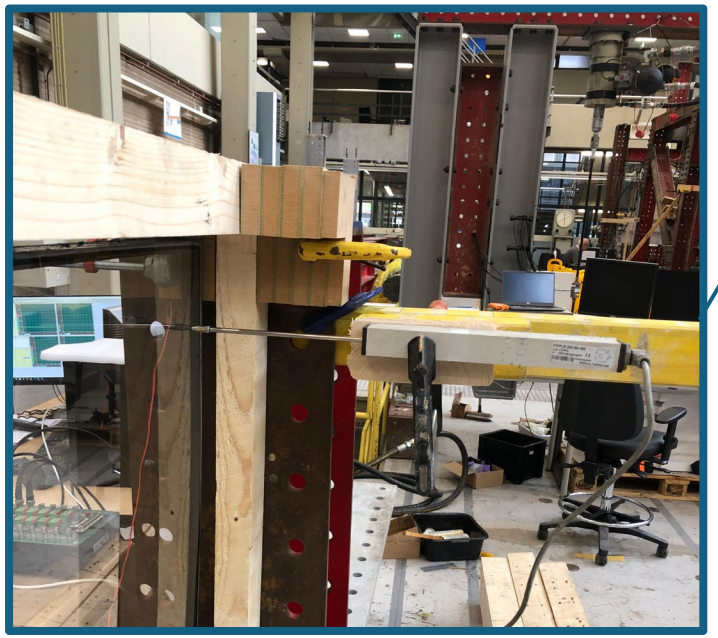
Corner clamps

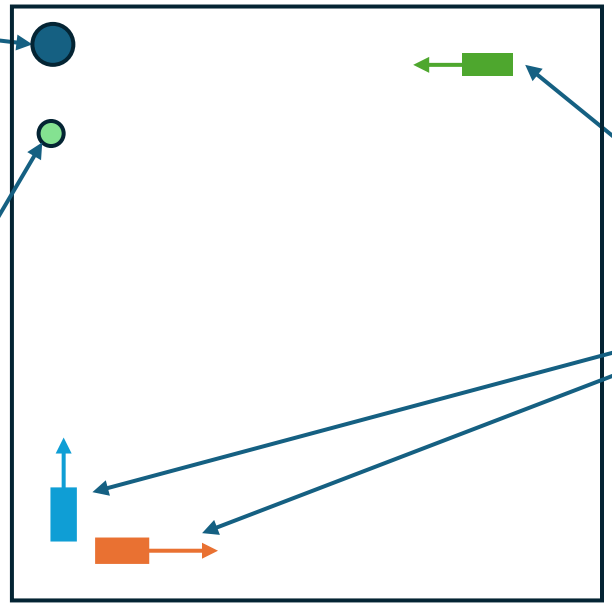


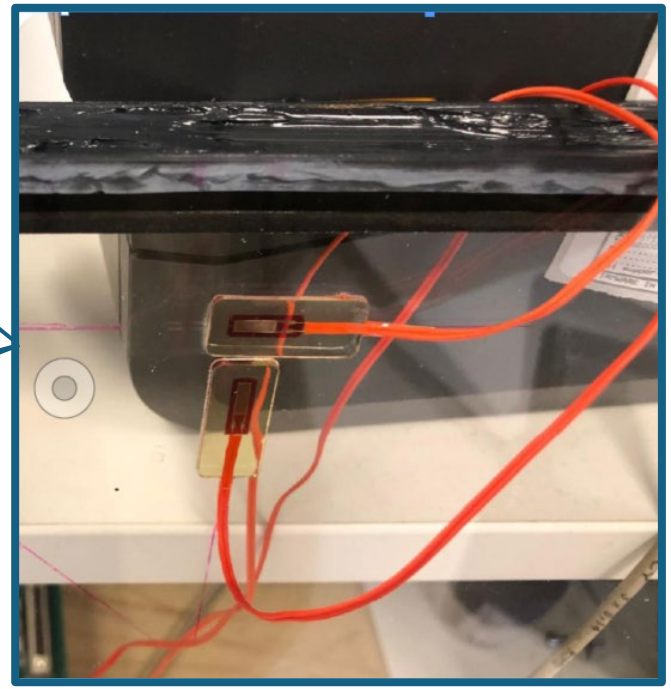
Corner pushing mechanism



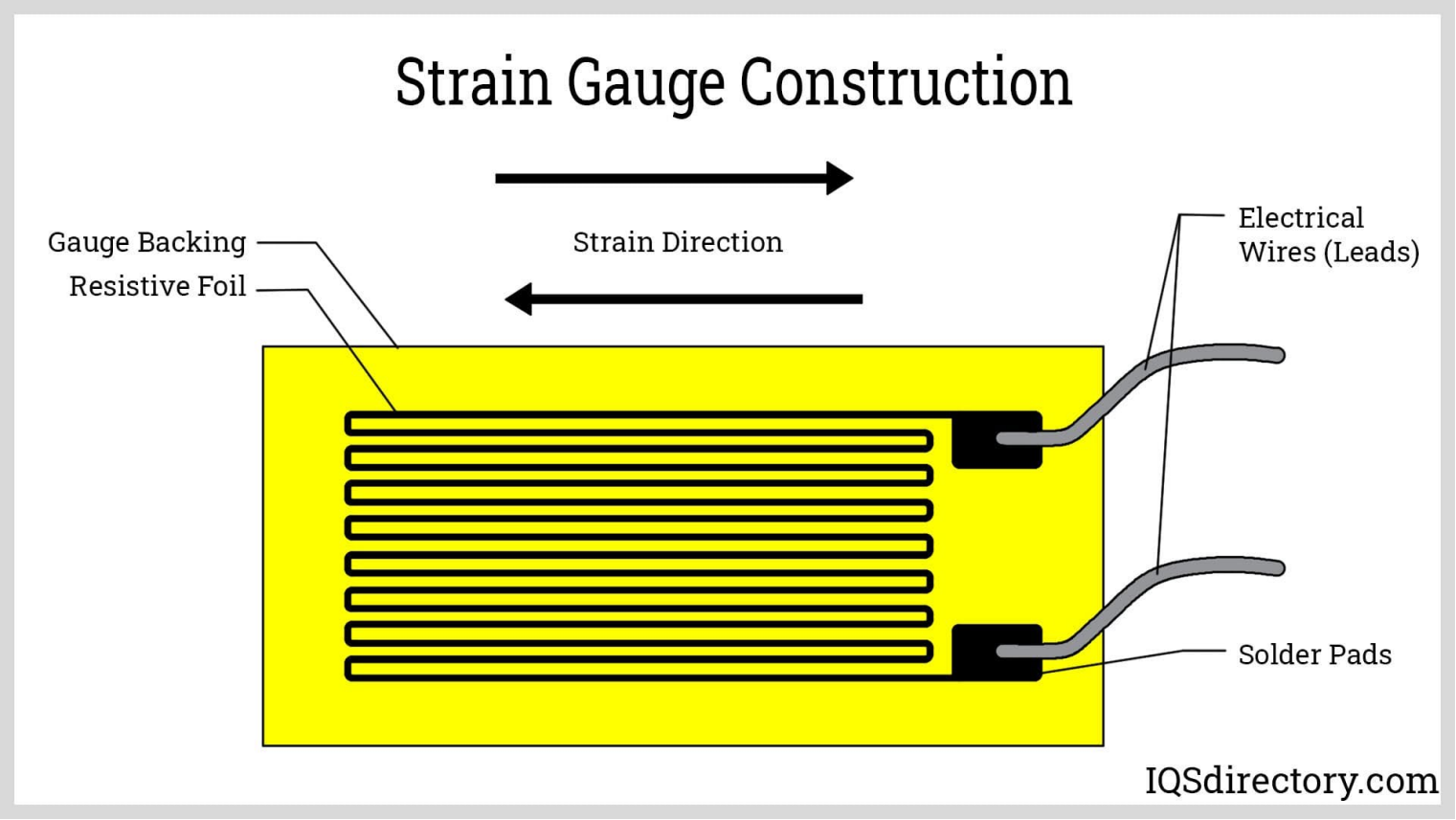








Strain gauges



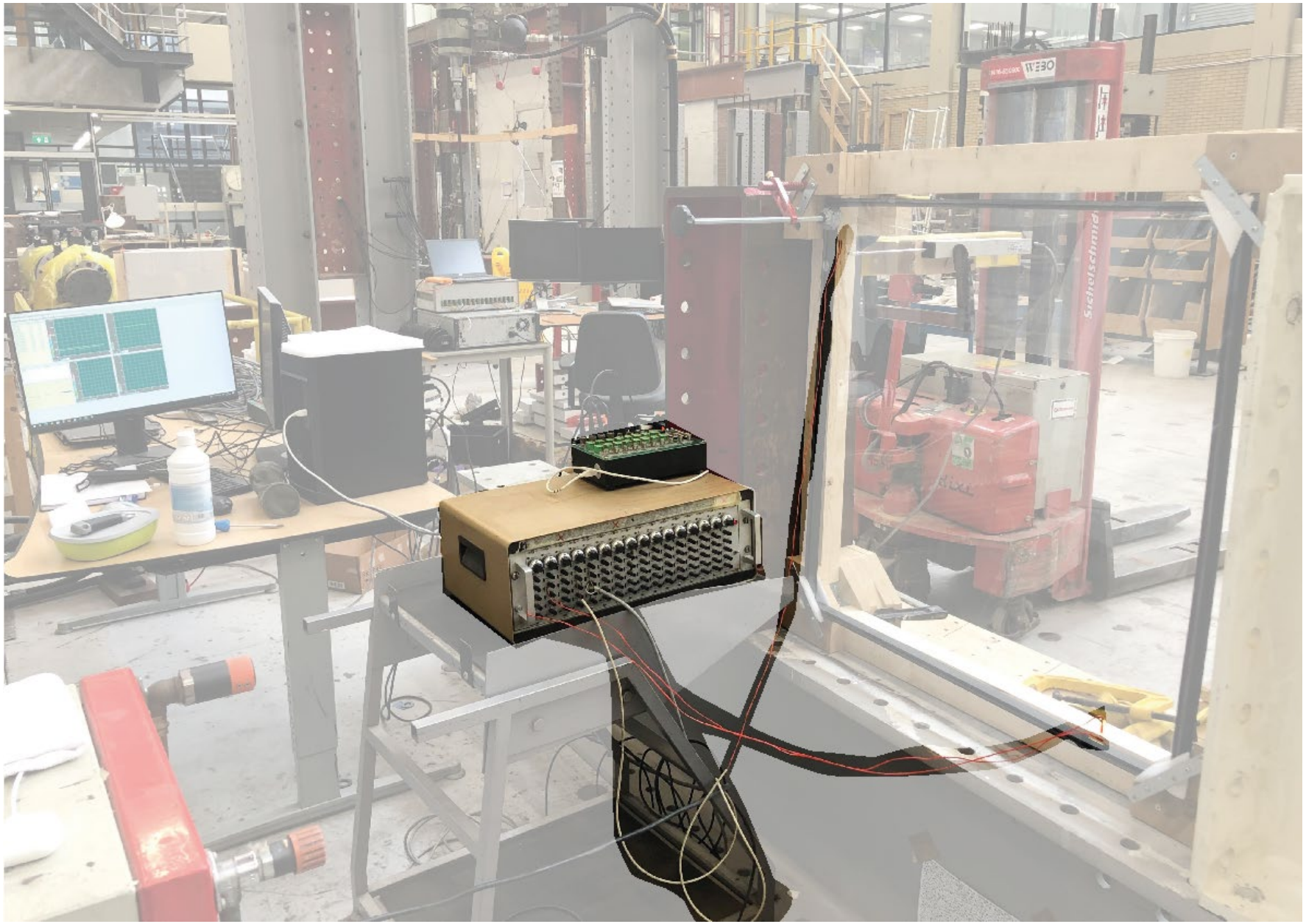
Schematic of strain gauge

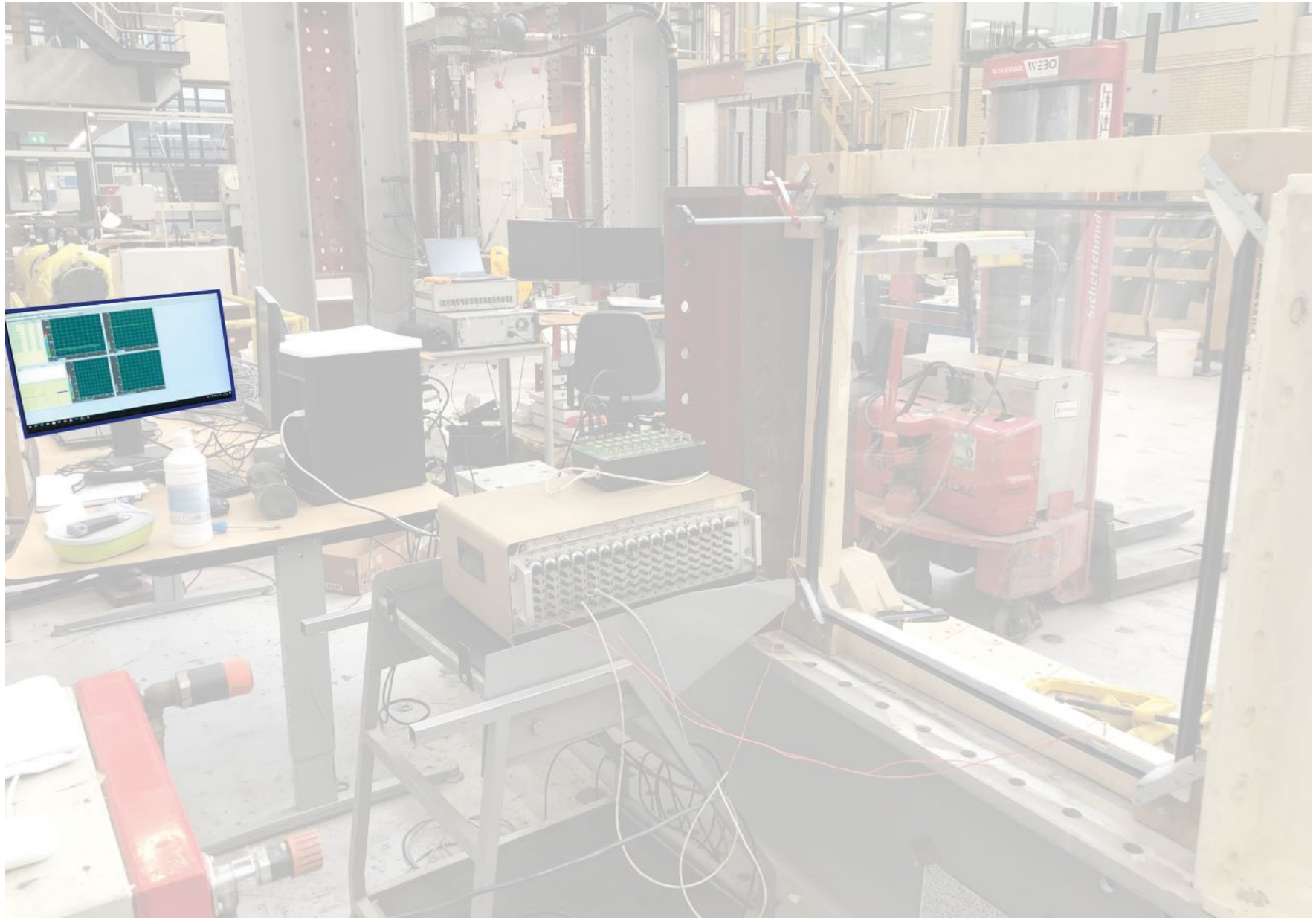
$$E = \frac{\sigma}{\varepsilon}$$

$$\sigma = Stress\ (Mpa)$$

$$E = Young's\ modulus$$

$$\varepsilon = Strain\ (\frac{mm}{mm})$$

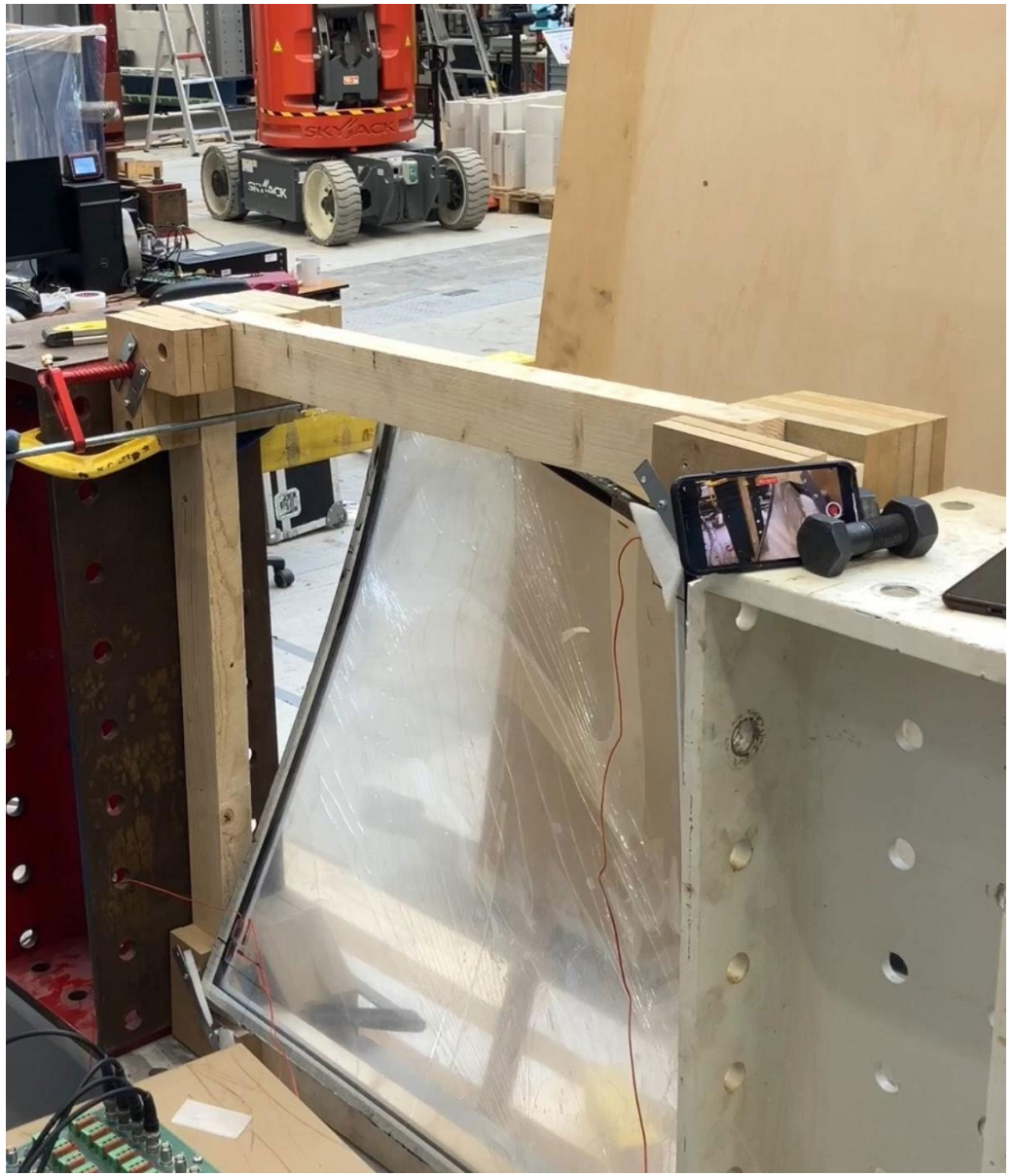




Test results

Results

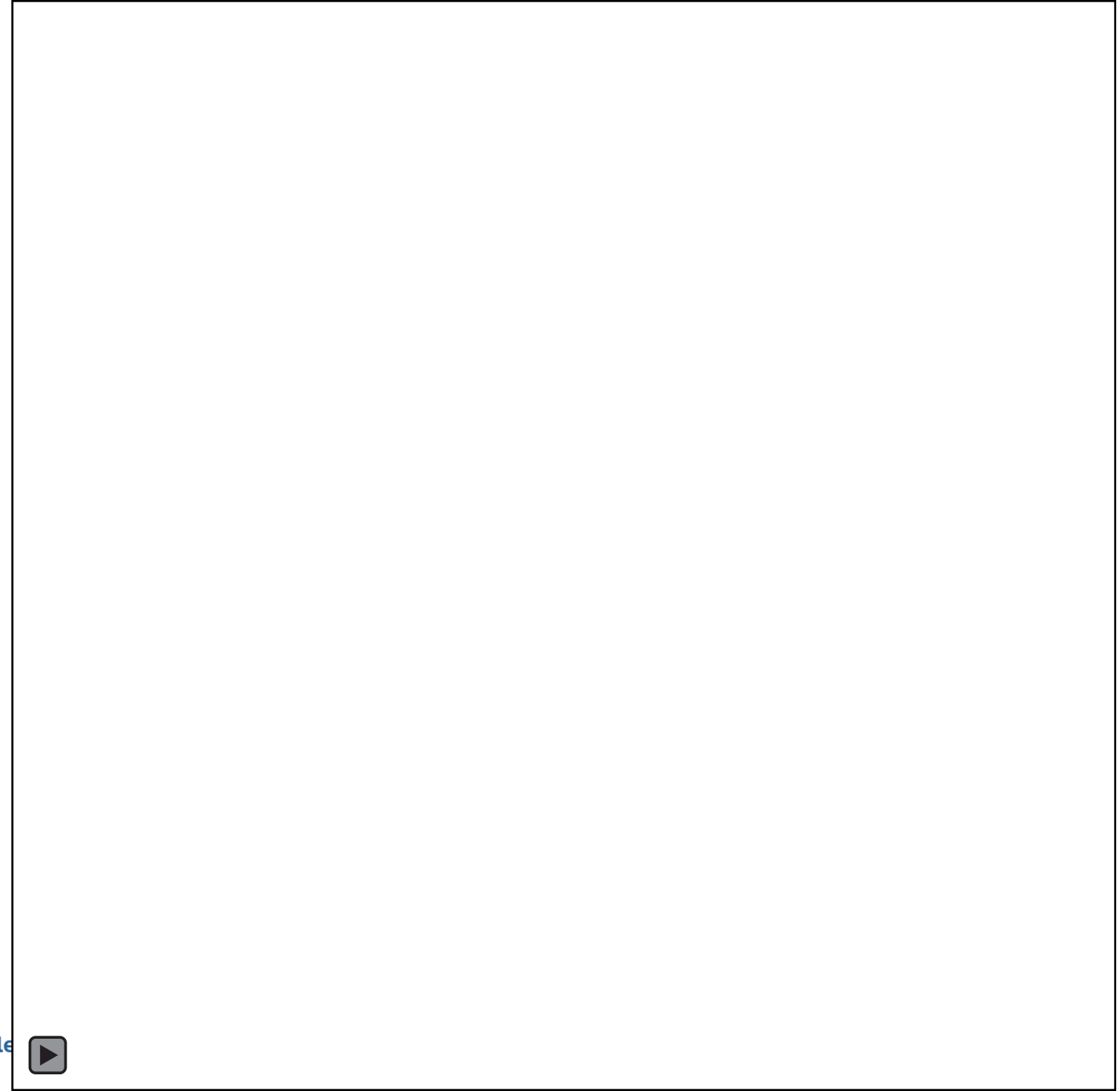
- **First panel → 27.3cm**
- Second panel → 18.5cm
- Third panel → 16.3cm

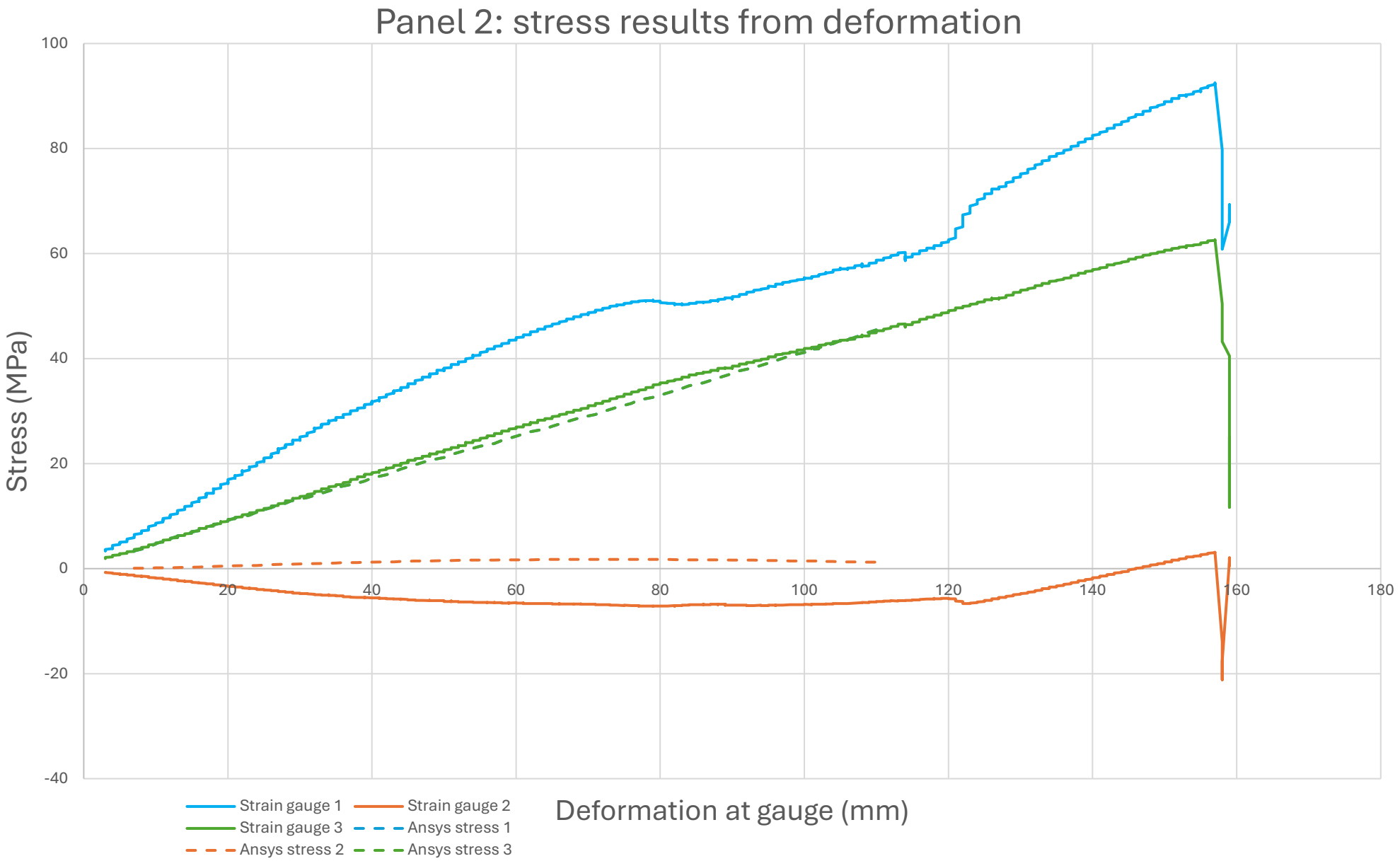


Panel 2

Corner deformation of 18.5cm

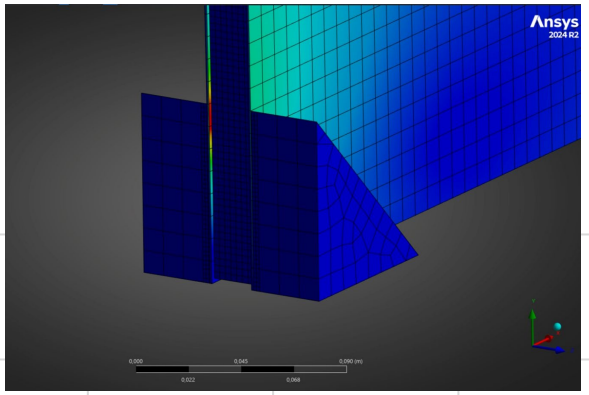
Back panel breaks first

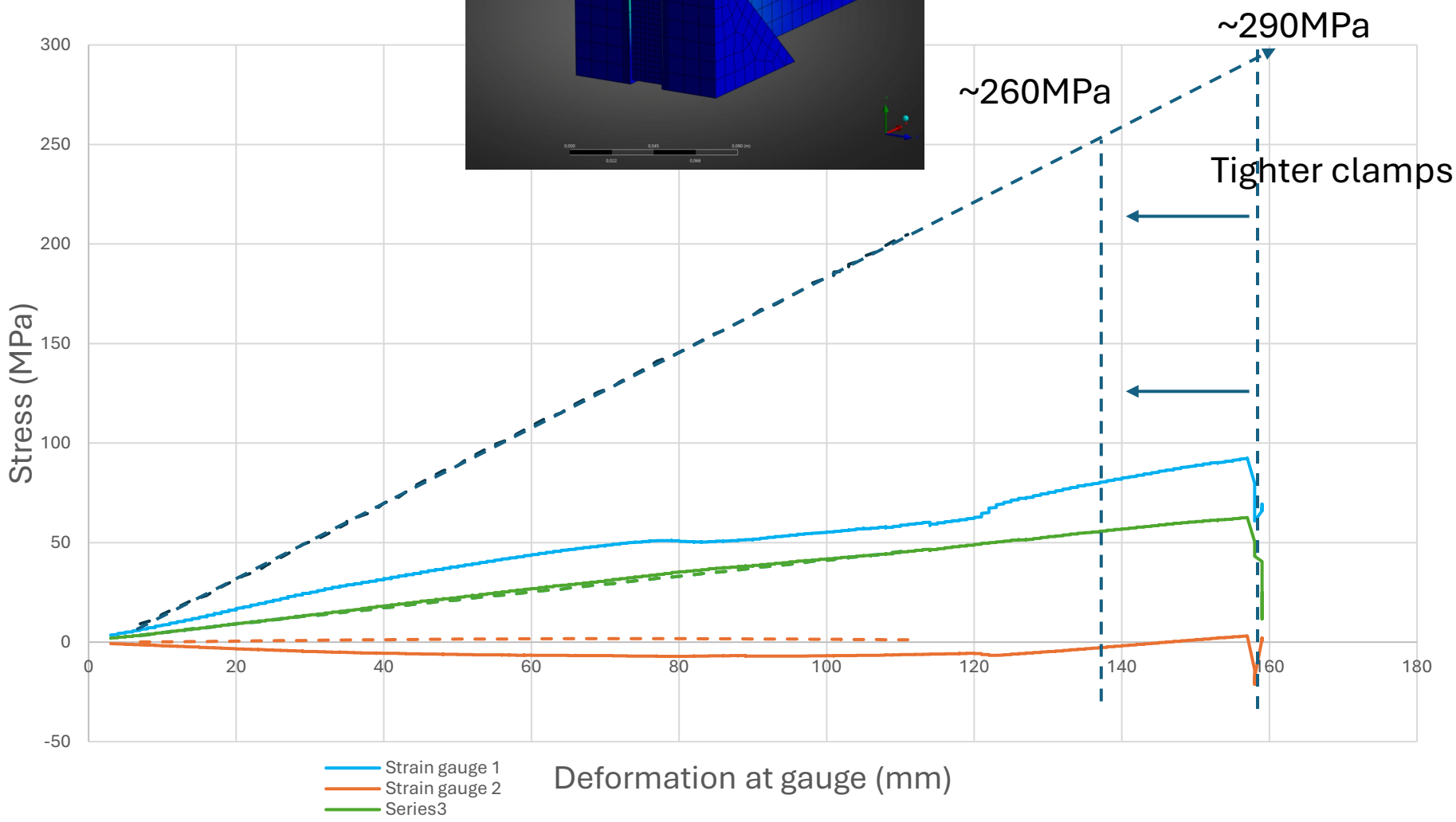



Panel 2: stress results from deformation
Stress (MPa)
100
80
60
40
20
0
-20
-40
0
20
40
60
80
100
120
140
160
180
Deformation at gauge (mm)
Strain gauge 1
Strain gauge 2
Strain gauge 3
Ansys stress 1
Ansys stress 2
Ansys stress 3

Results

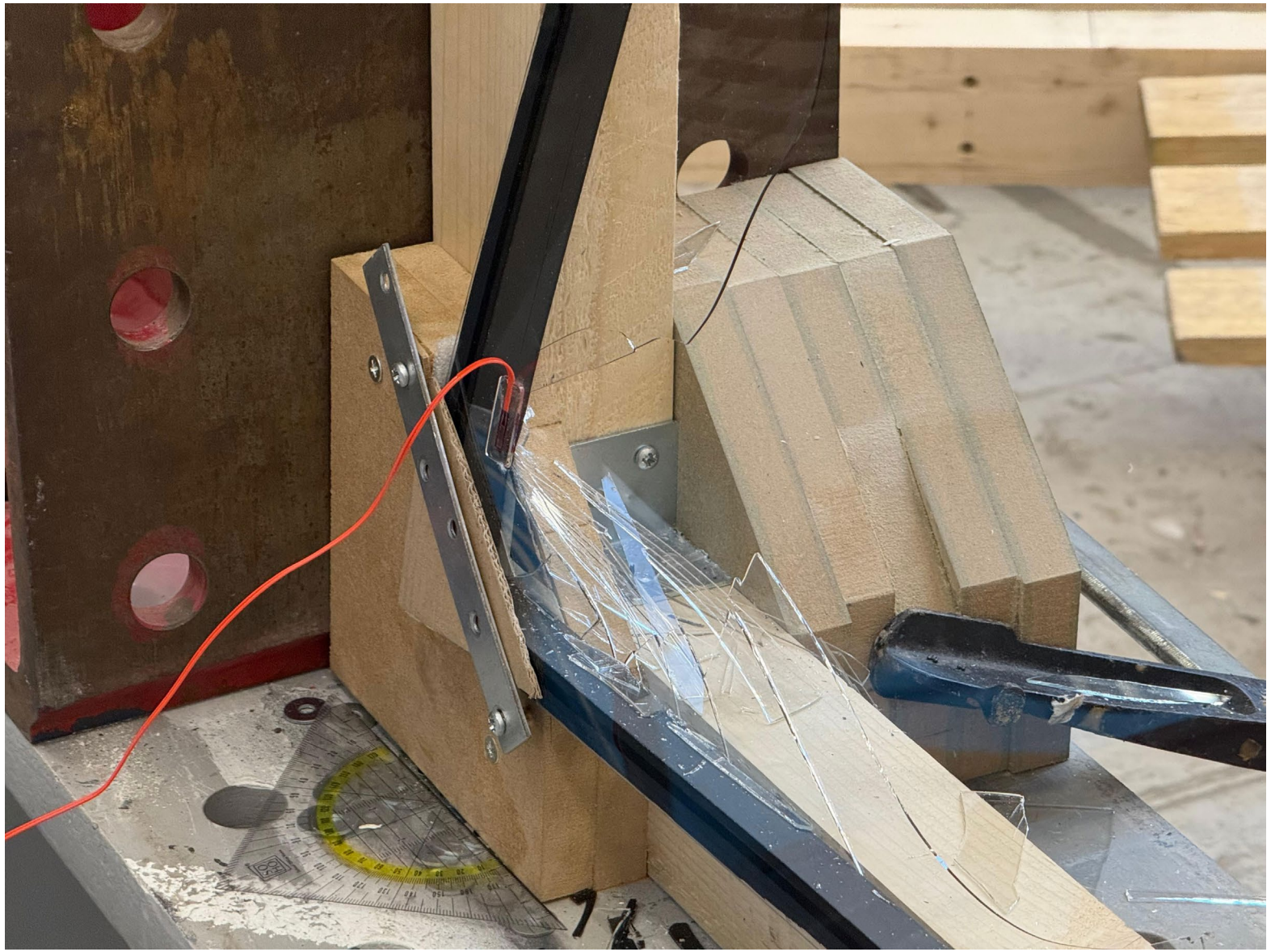
- Likely too high, but maximum design stress of Glanova unknown ATM
- Clamps not tight enough



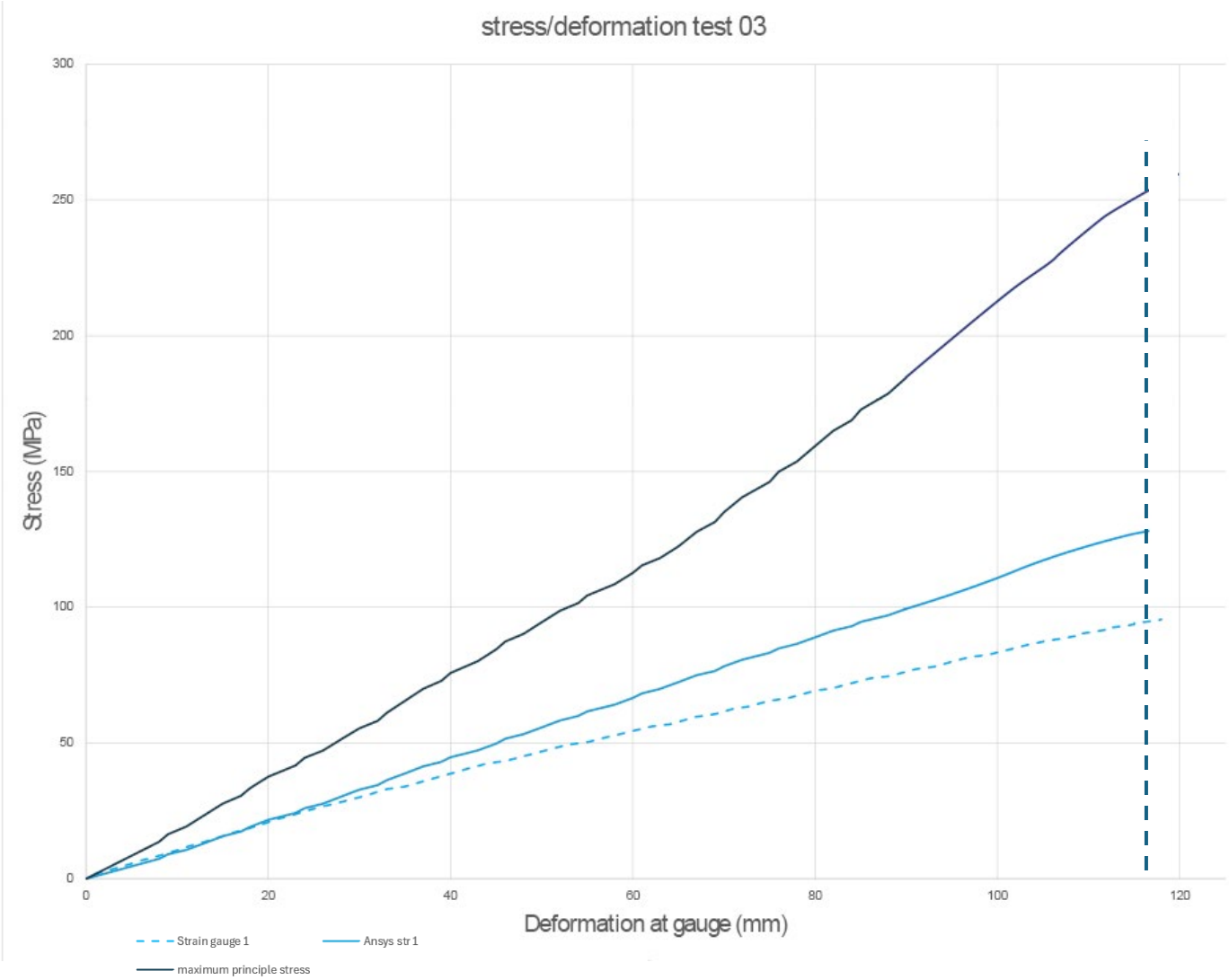


Panel 3

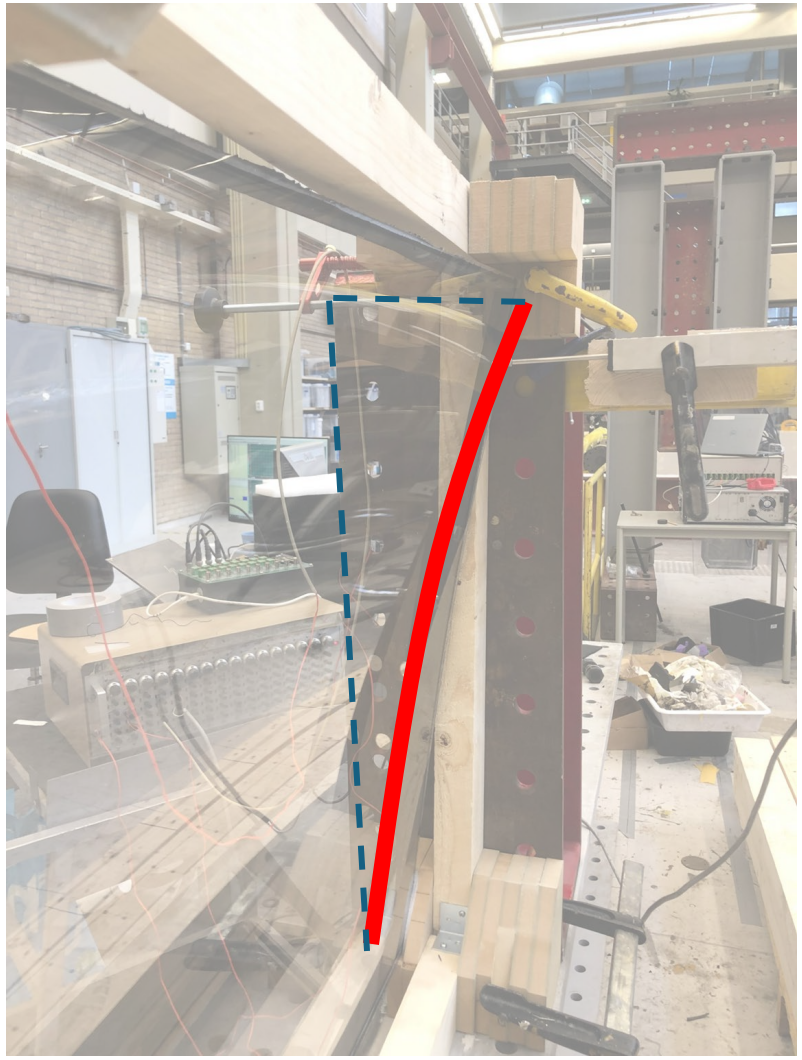
- Back panel broke at a corner deformation of 16.3 centimeters displacement

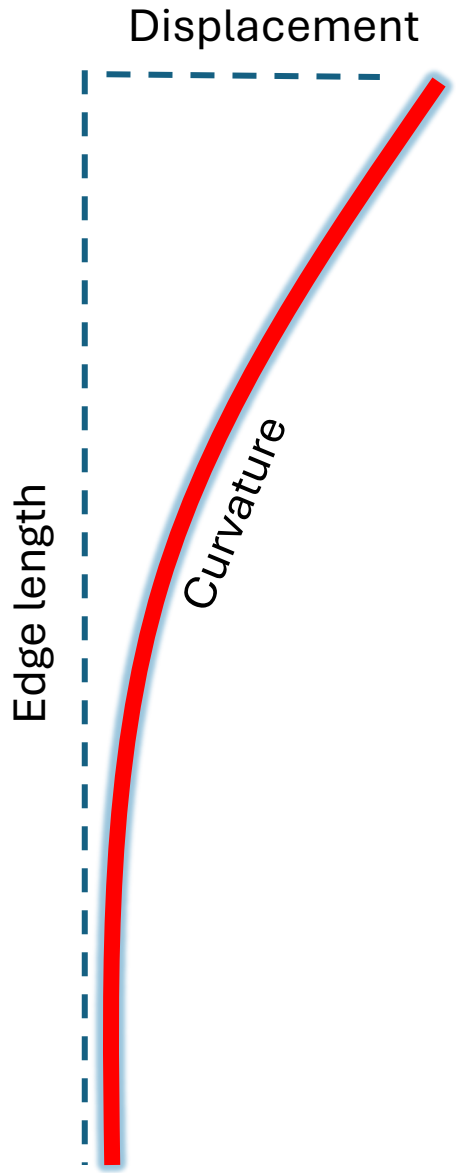


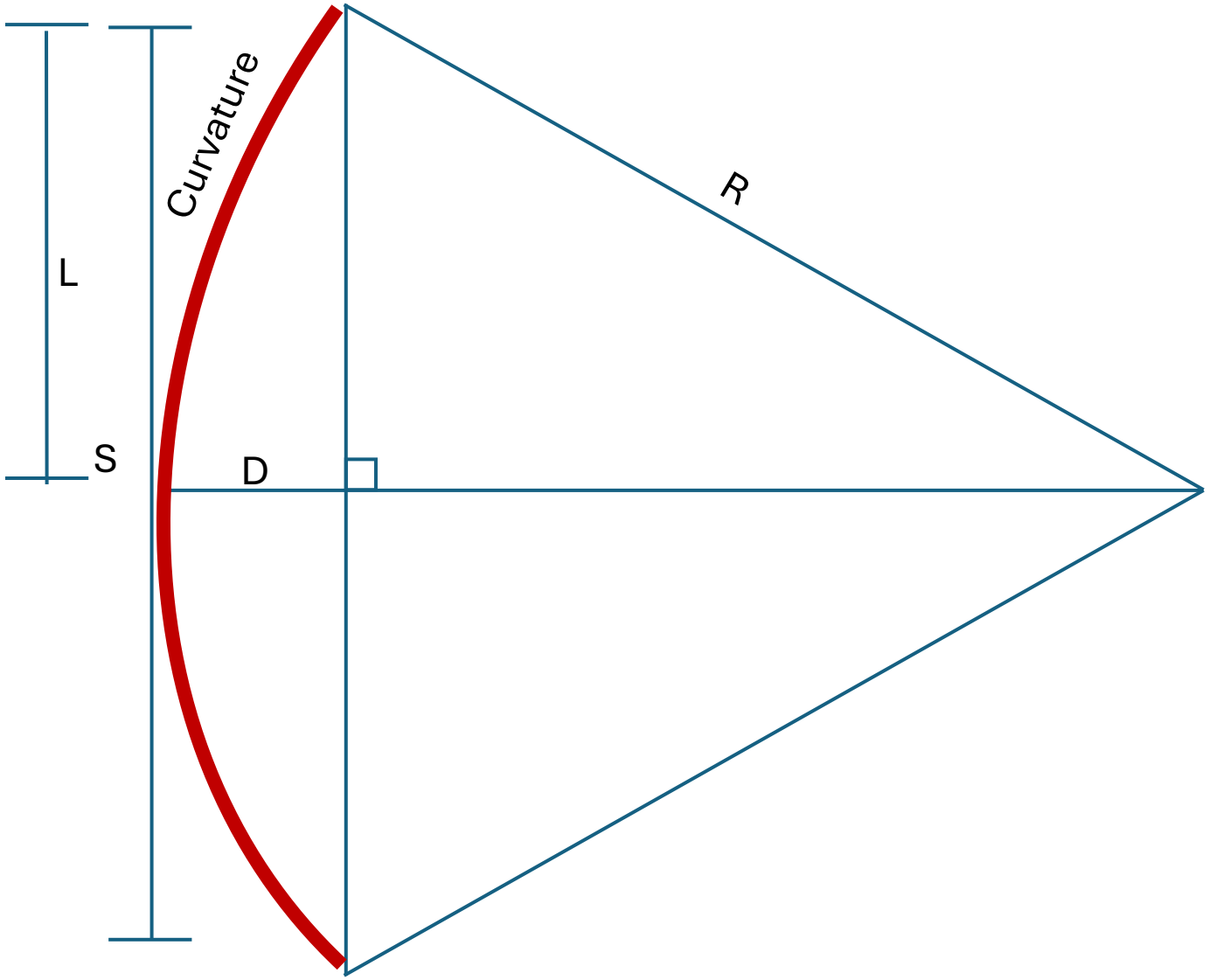
- Strain gauge data not completely accurate
- Maximum principle stress data is accurate



Results







$$L = 80\ cm$$

$$D = 16.3\ cm$$

$$S = 2 * L$$

$$Deformation\ rate\ k = \frac{D}{S}$$

$$Deformation\ rate\ k = \frac{16.3}{2 * 80} = 0.102$$

$$R = \frac{D}{2} + \frac{S^2}{8D}$$

$$R = \frac{16.3}{2} + \frac{160^2}{8*16.3} = 204cm$$

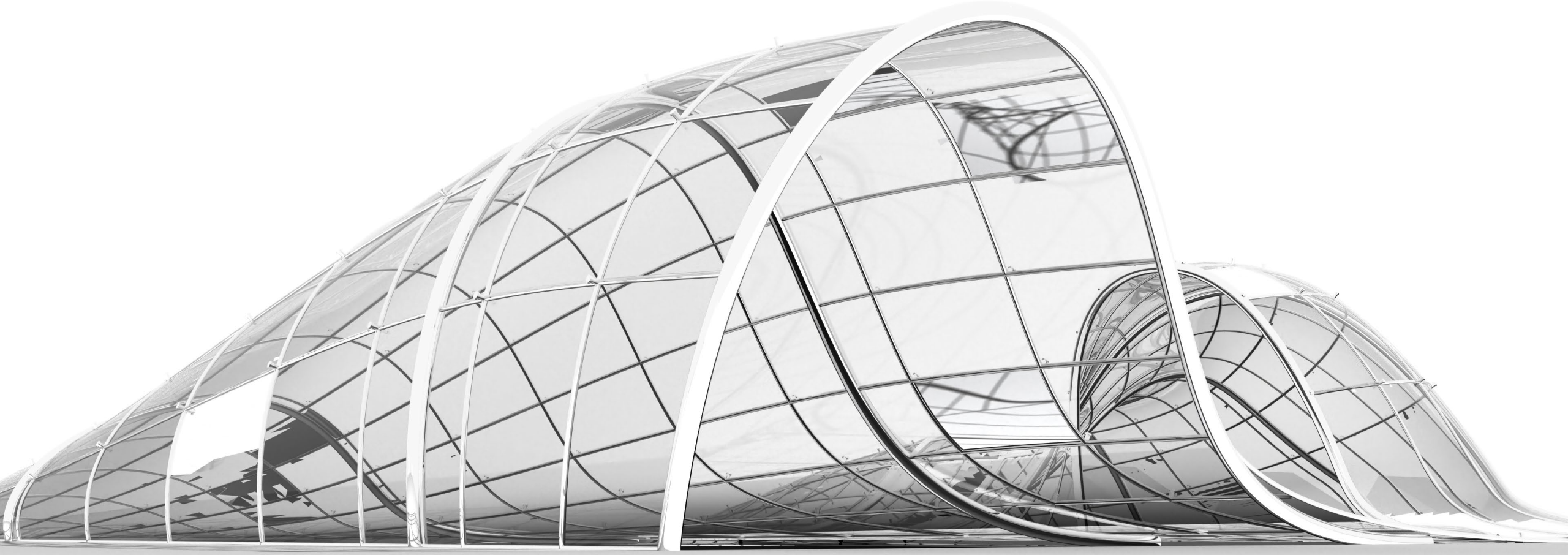
Conclusion 1: Flexibility

Higher **curvature** is **achievable!**

Implementation: Case study

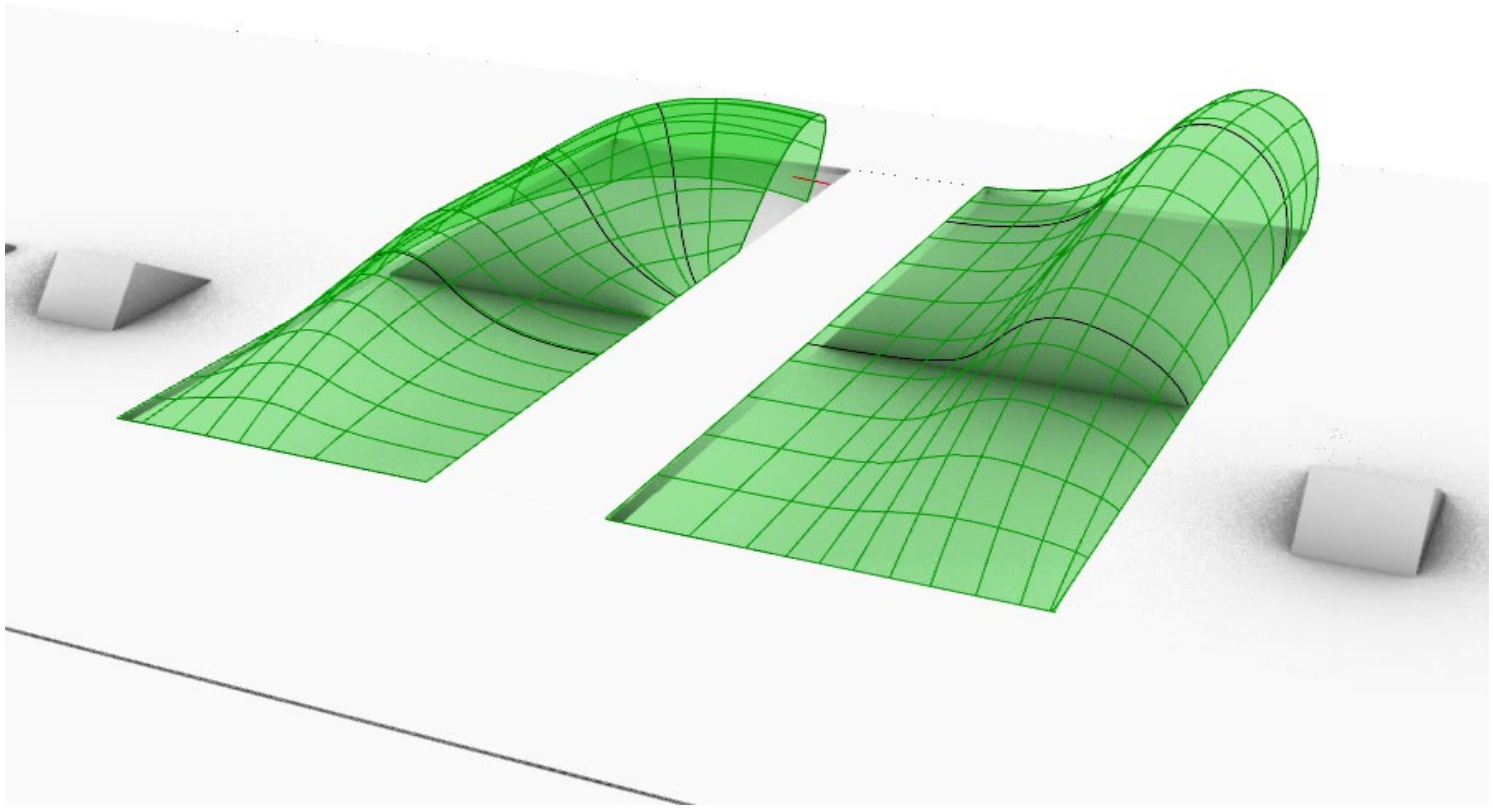
03/07/25

03/07/25

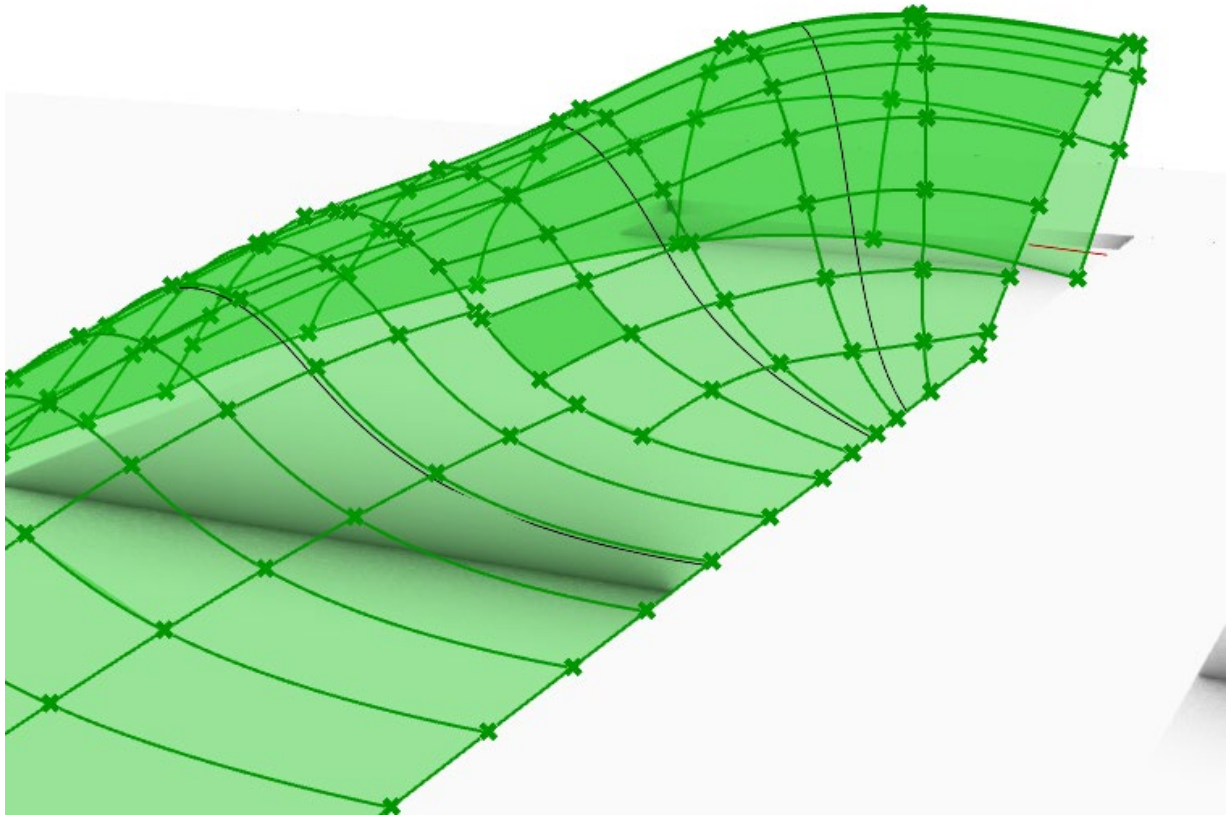


Panel curvature analysis

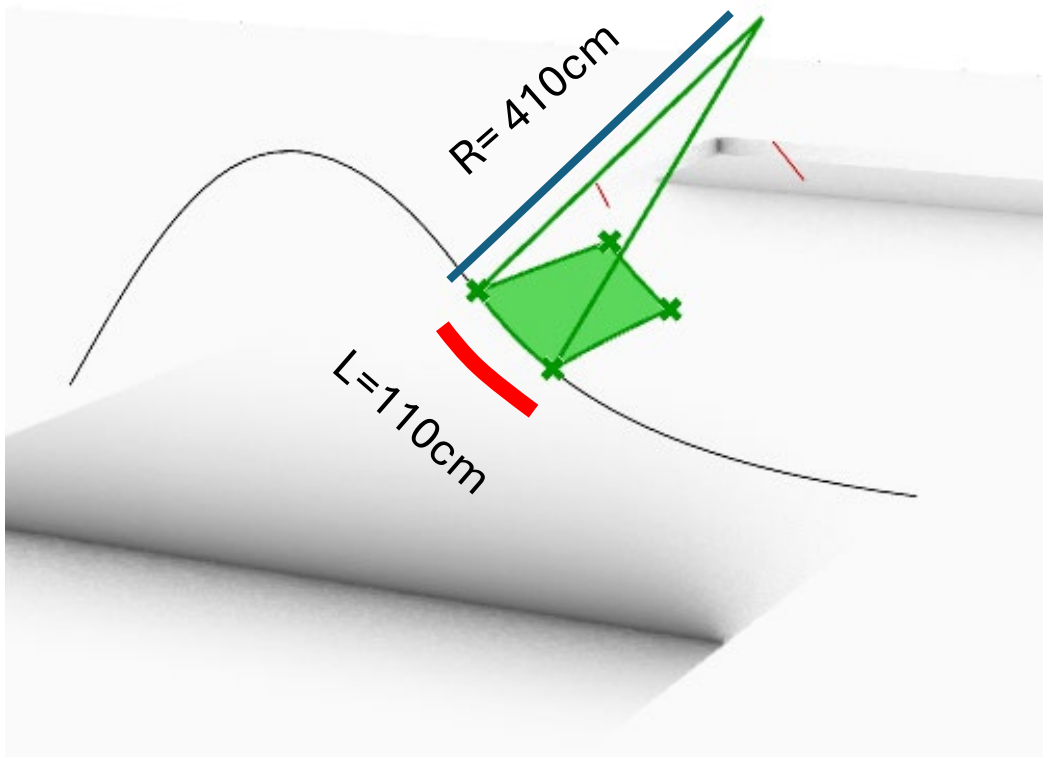
- Divide surface into panels



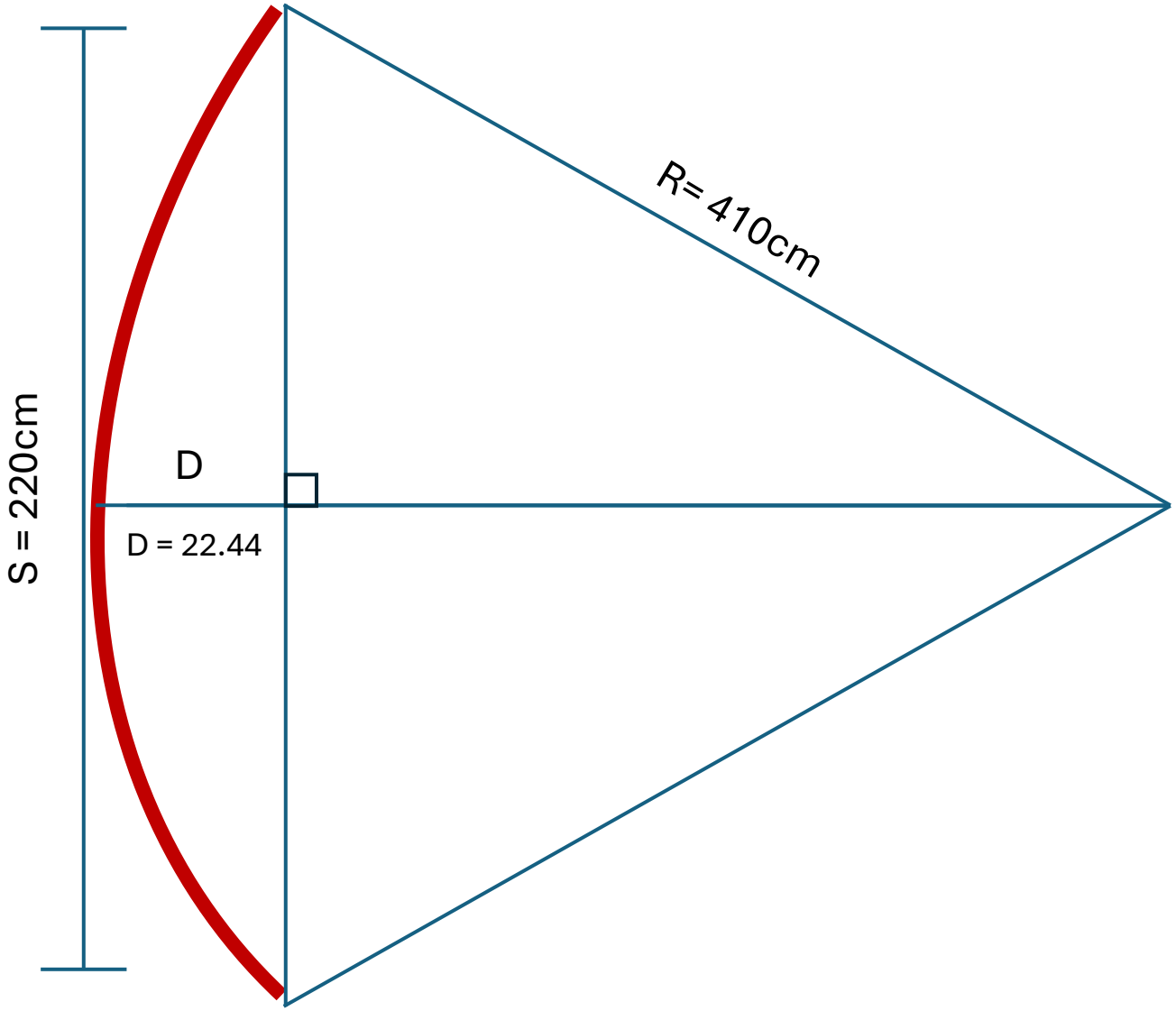
Example panel



Example panel



Calculate edge curve radius



$$L = 80\ cm$$

$$B = 16.3\ cm$$

$$Deformation\ rate\ k = \ 0.102$$

$$Corner\ displacement\ D = 0.102 * 2 * 110 = 22.44$$

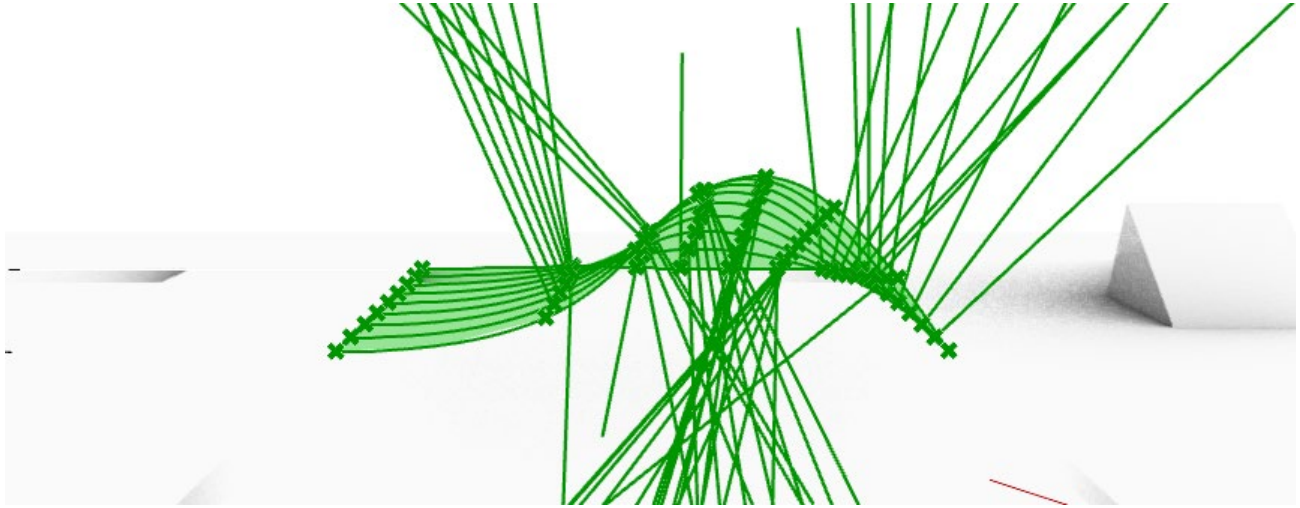
$$R_{max} = \frac{D}{2} + \frac{L^2}{8D}$$

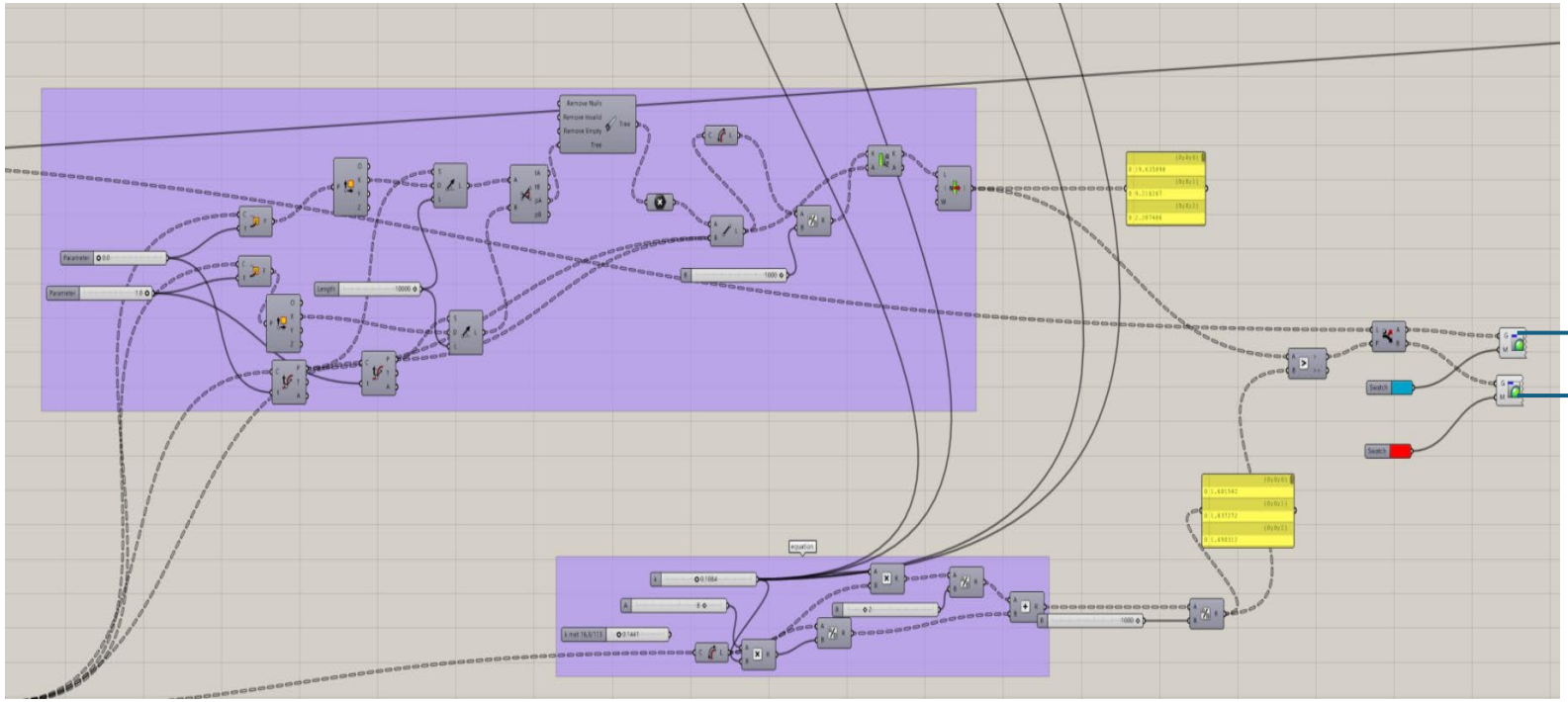
$$R_{max} = \frac{22.44}{2} + \frac{220^2}{8*22.44} = 204cm$$

R_{max}(204) < R (410) = Panel curvature is possible!

Script

- Determine curve radius for each panel
- Determine max curve radius for each panel

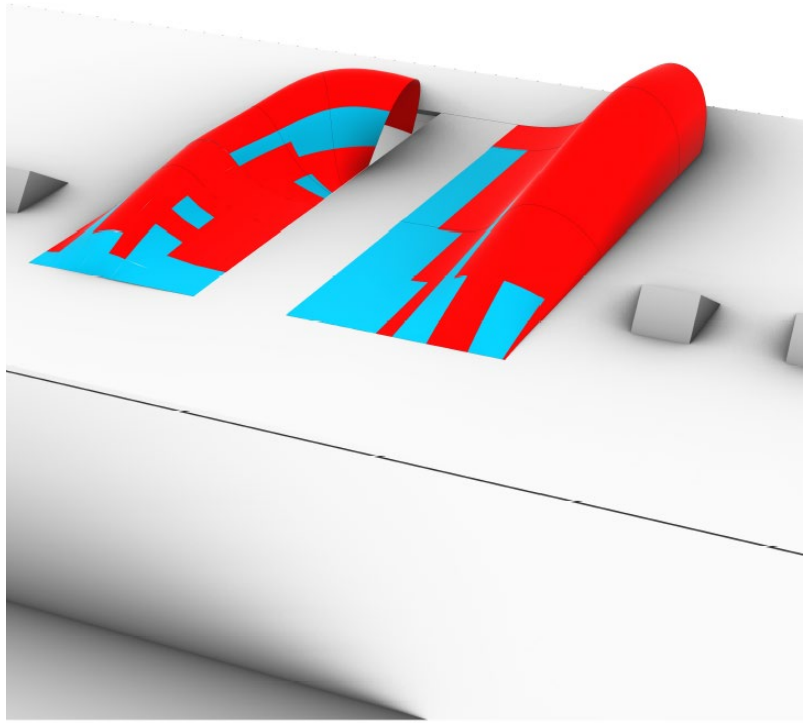




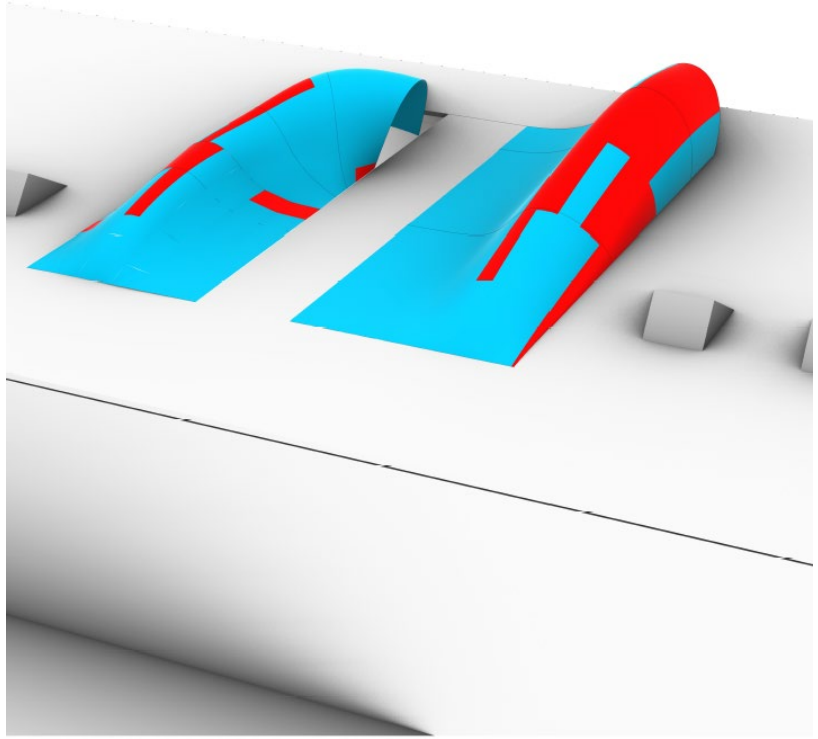
Not possible!

Possible!

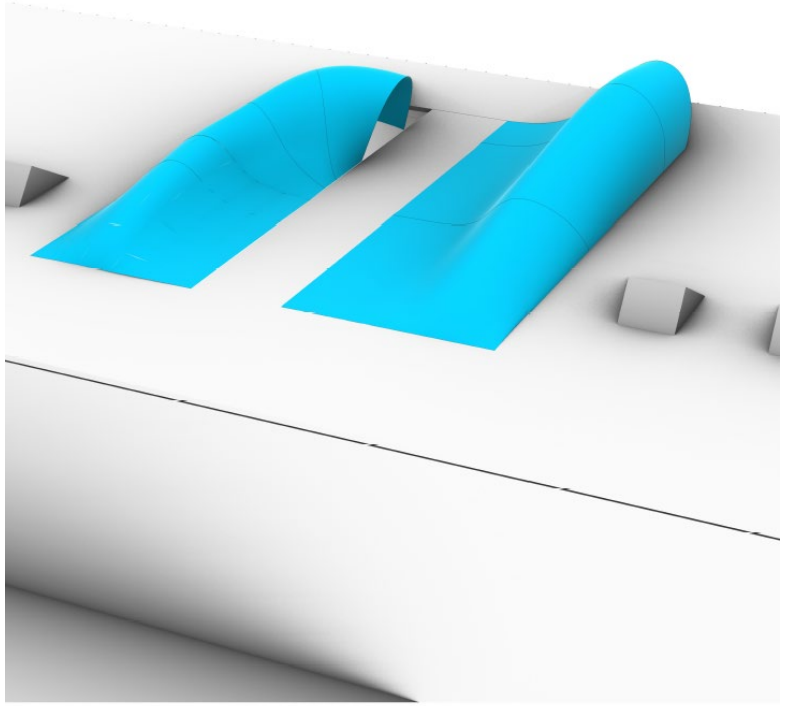
Script output



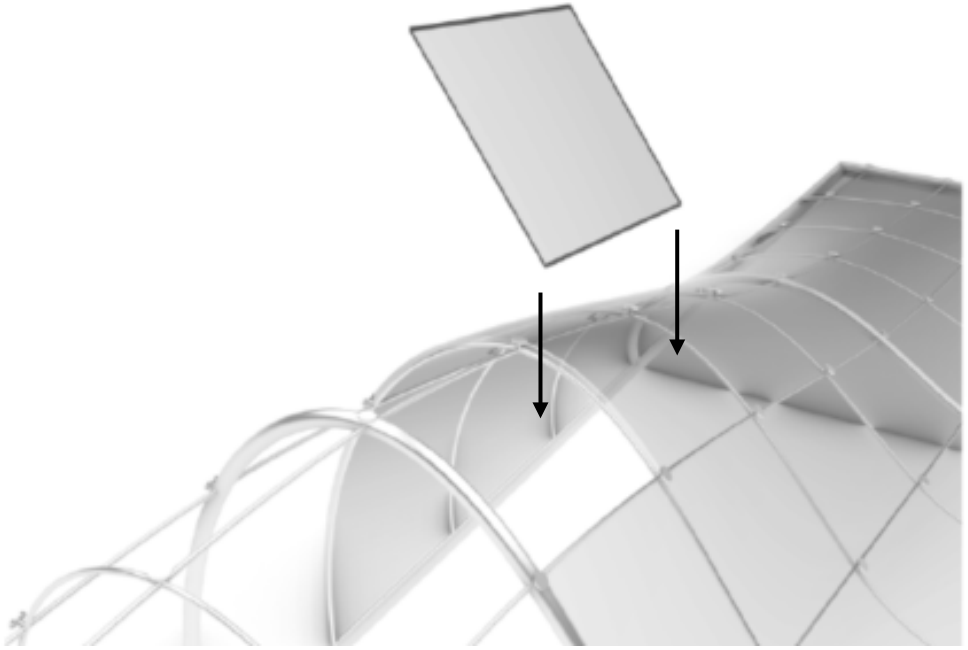
Regular thick glass (estimate)

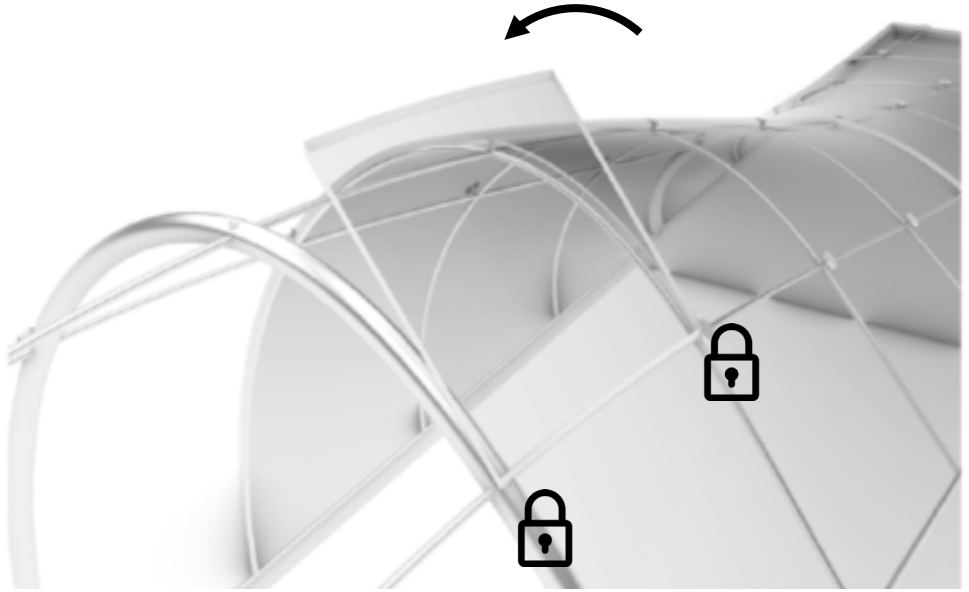


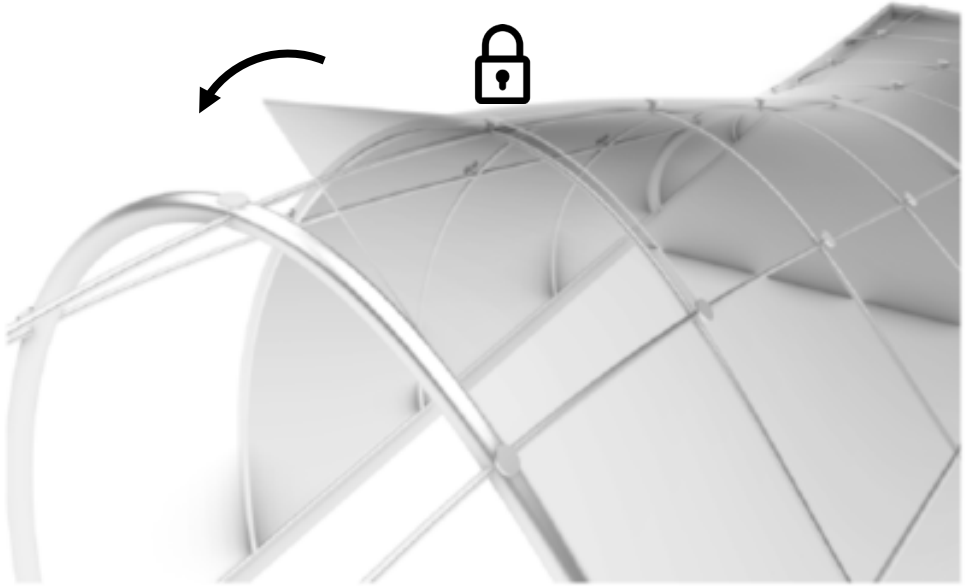
Tempered thin-glass (doesn’t exist)



Chemically strengthened thin glass







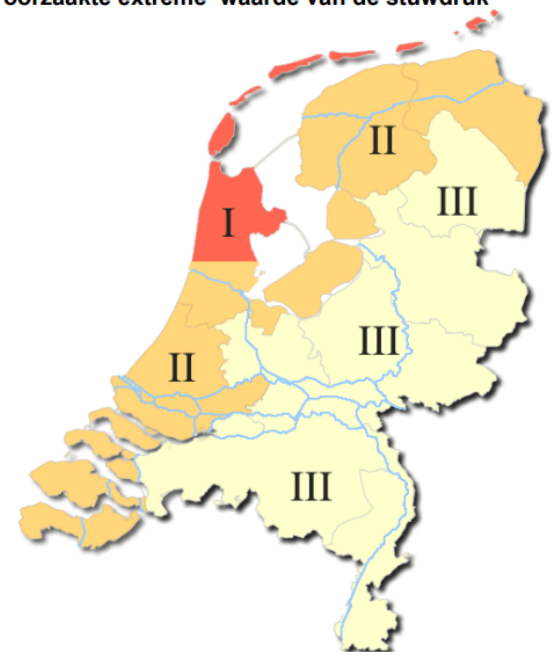
Part II: Wind loads

Wind load

- Maximum wind load in The Netherlands = 2.07KPa

Bijlage: "Tabel 1.A uit NEN 6702 – Door wind veroorzaakte extreme waarde van de stuwdruk"

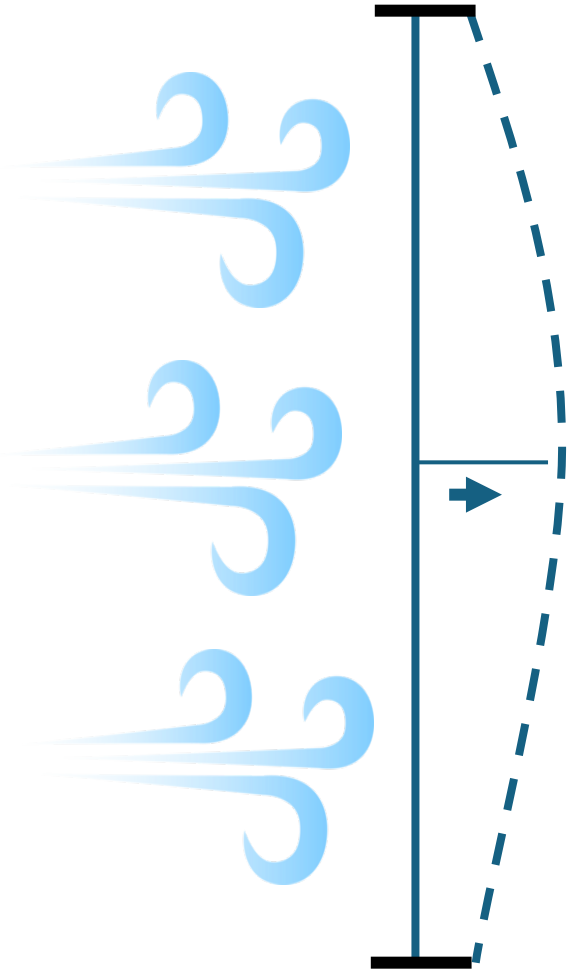
hoogte (m)	Windstuwdruk in kN/m²					
	gebied I		gebied II		gebied III	
	onbebouwd	bebouwd	onbebouwd	bebouwd	onbebouwd	bebouwd
≤ 2	0,64	0,64	0,54	0,54	0,46	0,46
3	0,70	0,64	0,54	0,54	0,46	0,46
4	0,78	0,64	0,62	0,54	0,49	0,46
5	0,84	0,64	0,68	0,54	0,55	0,46
6	0,90	0,64	0,73	0,54	0,59	0,46
7	0,95	0,64	0,78	0,54	0,63	0,46
8	0,99	0,64	0,81	0,54	0,67	0,46
9	1,02	0,64	0,85	0,54	0,70	0,46
10	1,06	0,70	0,88	0,59	0,73	0,50
11	1,09	0,76	0,91	0,64	0,76	0,54
12	1,12	0,81	0,94	0,68	0,78	0,58
13	1,14	0,86	0,96	0,72	0,80	0,61
14	1,17	0,90	0,99	0,76	0,82	0,64
15	1,19	0,94	1,01	0,79	0,84	0,67
16	1,21	0,98	1,03	0,82	0,86	0,70
17	1,23	1,02	1,05	0,85	0,88	0,72
18	1,25	1,05	1,07	0,88	0,90	0,75
19	1,27	1,08	1,09	0,90	0,91	0,77
20	1,29	1,11	1,10	0,93	0,93	0,79
25	1,37	1,23	1,18	1,03	1,00	0,88
30	1,43	1,34	1,24	1,12	1,06	0,95
35	1,49	1,43	1,30	1,20	1,11	1,02
40	1,54	1,50	1,35	1,26	1,15	1,07
45	1,58	1,57	1,39	1,32	1,19	1,12
50	1,62	1,62	1,43	1,37	1,23	1,16
55	1,66	1,66	1,46	1,42	1,26	1,20
60	1,69	1,69	1,50	1,46	1,29	1,24
65	1,73	1,73	1,53	1,50	1,32	1,27
70	1,76	1,76	1,56	1,54	1,34	1,31
75	1,78	1,78	1,58	1,57	1,37	1,33
80	1,81	1,81	1,61	1,60	1,39	1,36
85	1,83	1,83	1,63	1,63	1,41	1,39
90	1,86	1,86	1,65	1,65	1,43	1,41
95	1,88	1,88	1,68	1,68	1,45	1,44
100	1,90	1,90	1,70	1,70	1,47	1,46
110	1,94	1,94	1,74	1,74	1,51	1,50
120	1,98	1,98	1,77	1,77	1,54	1,54
130	2,01	2,01	1,80	1,80	1,57	1,57
140	2,04	2,04	1,83	1,83	1,60	1,60
150	2,07	2,07	1,86	1,86	1,62	1,62

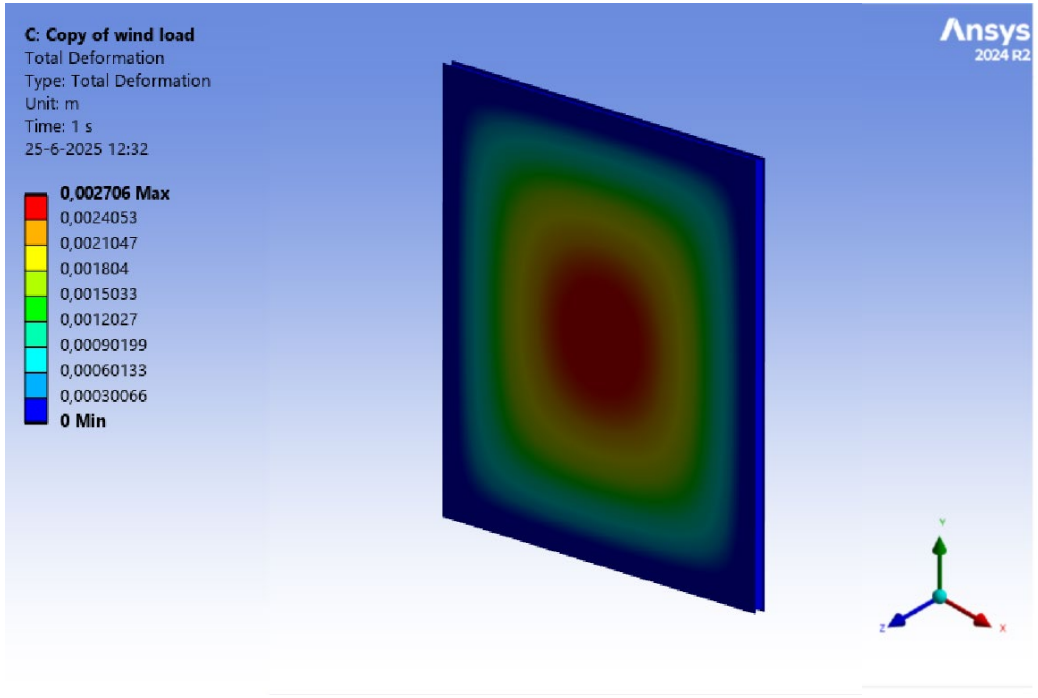


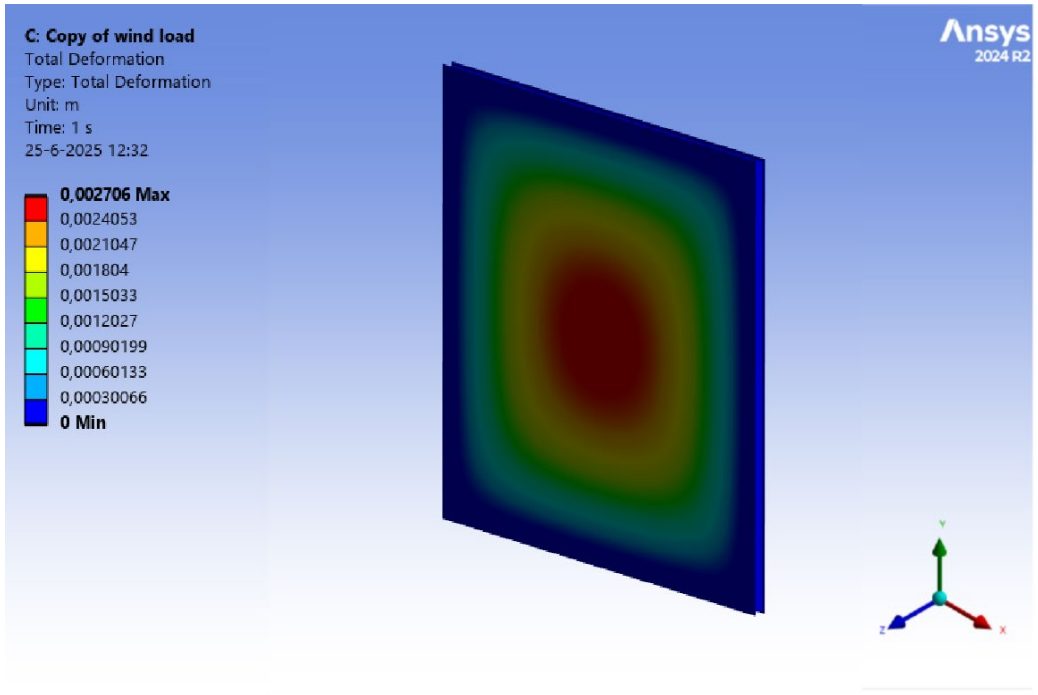
Gebied I	Markermeer, Waddeneilanden en de provincie Noord-Holland ten noorden van de gemeenten Heemskerk, Uitgeest, Wormerland, Purmerend en Edam-Volendam.
Gebied II	Het resterende deel van de provincie Noord-Holland, de provincies Groningen, Friesland, Flevoland, Zuid-Holland en Zeeland.
Gebied III	Het resterende deel van Nederland.

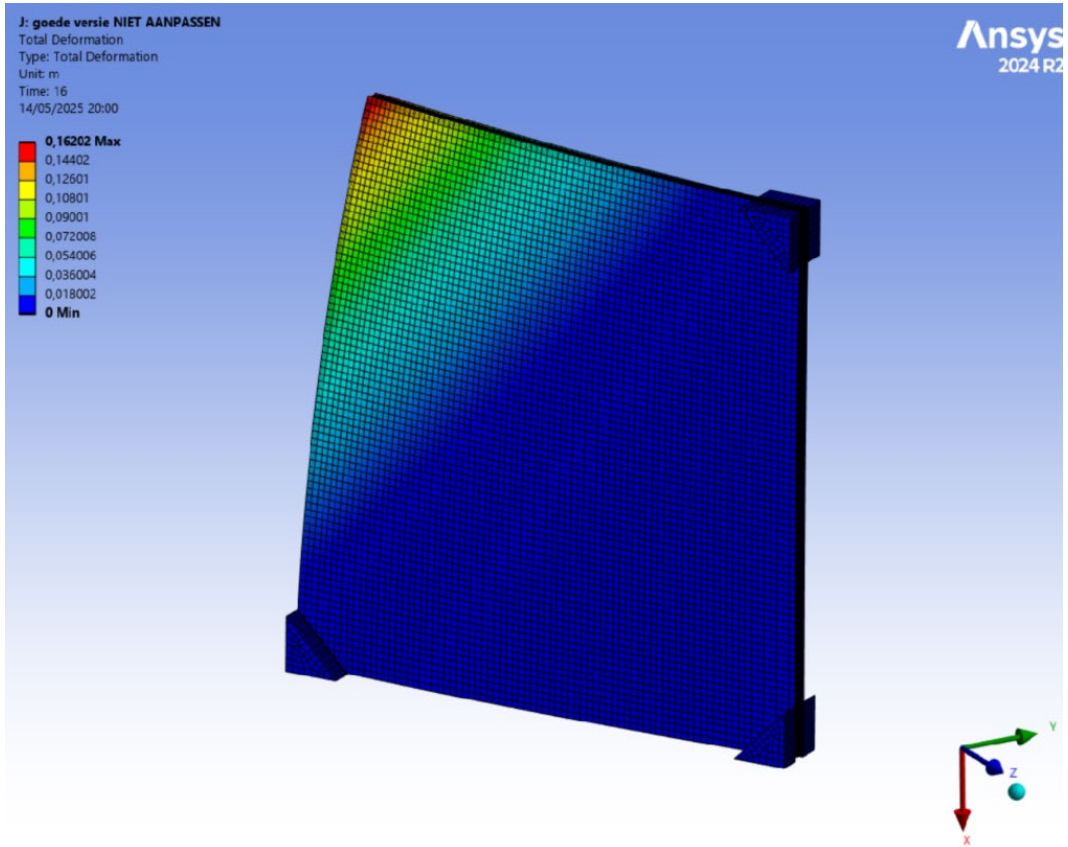
Wind loads – flat panel

- Deformation at panel centre is 2.7cm
- Eurocodes: max is L/50 = 80/50 = 1.6cm
- 2.7cm > 1.6cm **not upto standards!**



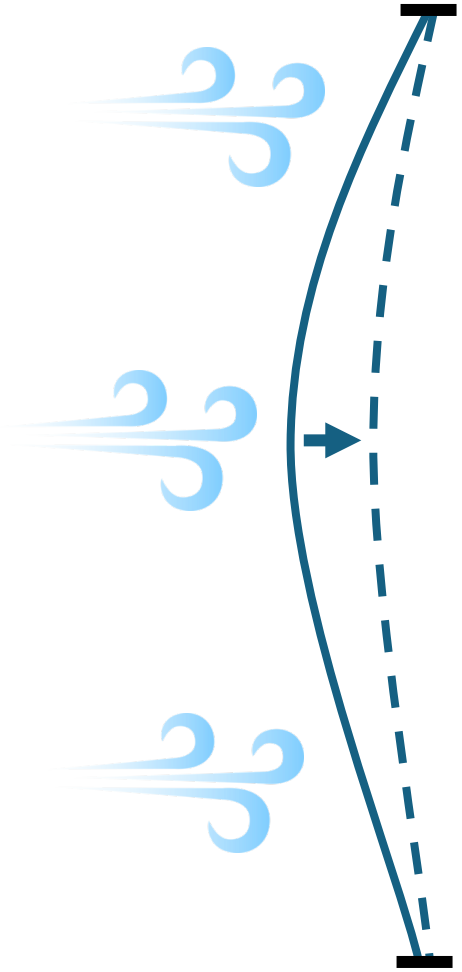


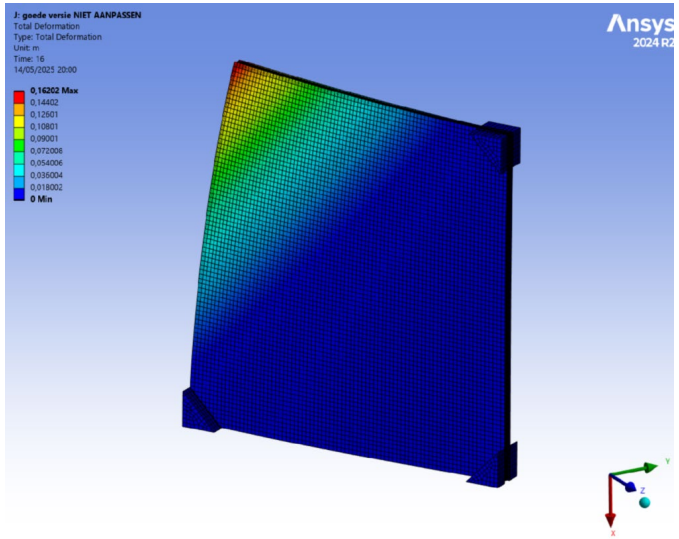

C: Copy of wind load
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
25-6-2025 12:32
0,002706 Max
0,0024053
0,0021047
0,001804
0,0015033
0,0012027
0,00090199
0,00060133
0,00030066
0 Min
Ansys
2024 R2

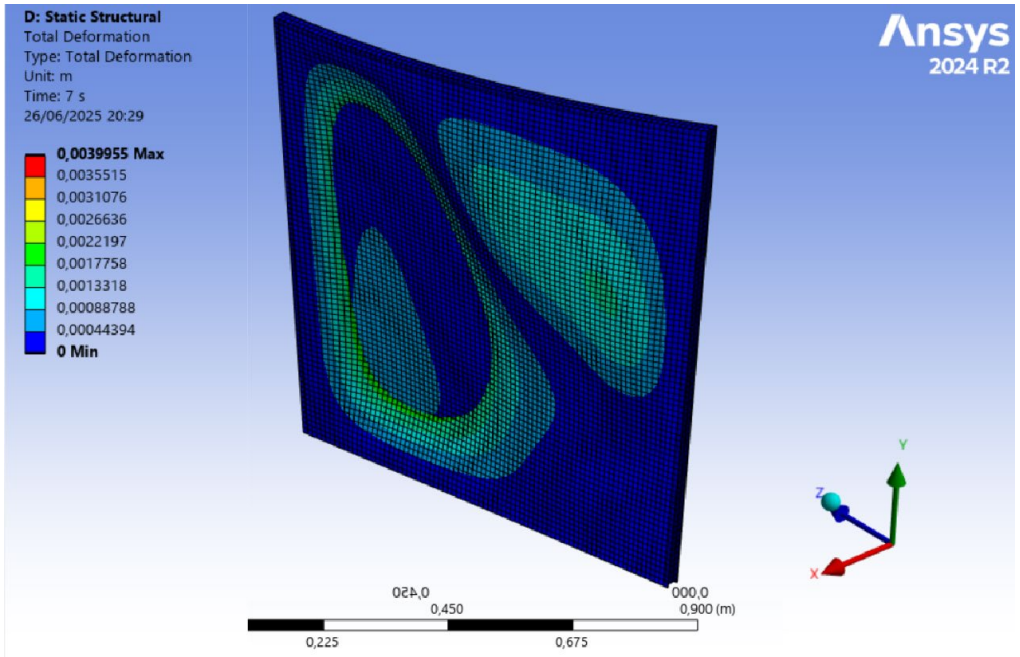

J: goede versie NIET AANPASSEN
Total Deformation
Type: Total Deformation
Unit: m
Time: 16
14/05/2025 20:00
0,16202 Max
0,14402
0,12601
0,10801
0,09001
0,072008
0,054006
0,036004
0,018002
0 Min
Ansys
2024 R2

Wind loads – deformed panel

- Deformed panel
- Curved geometry provides improved stiffness
- Deformation of outer plane=0.4cm



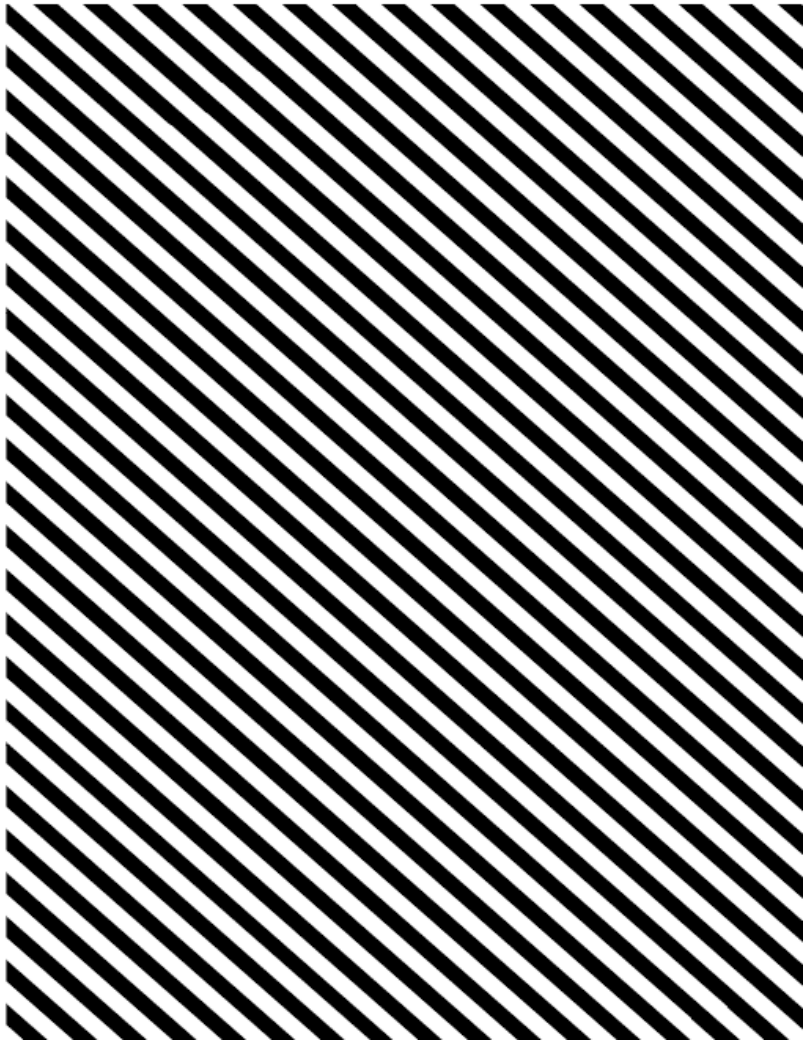


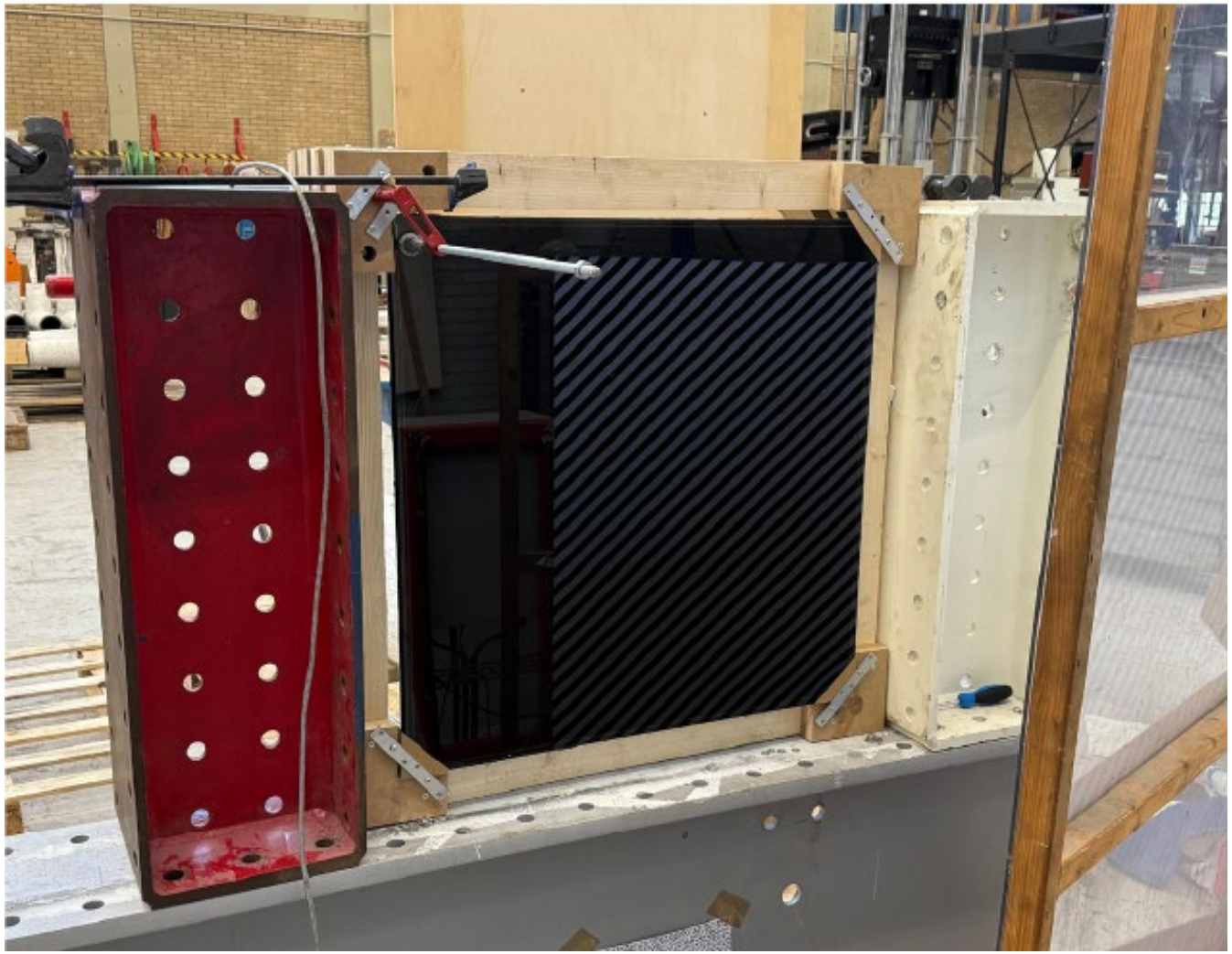


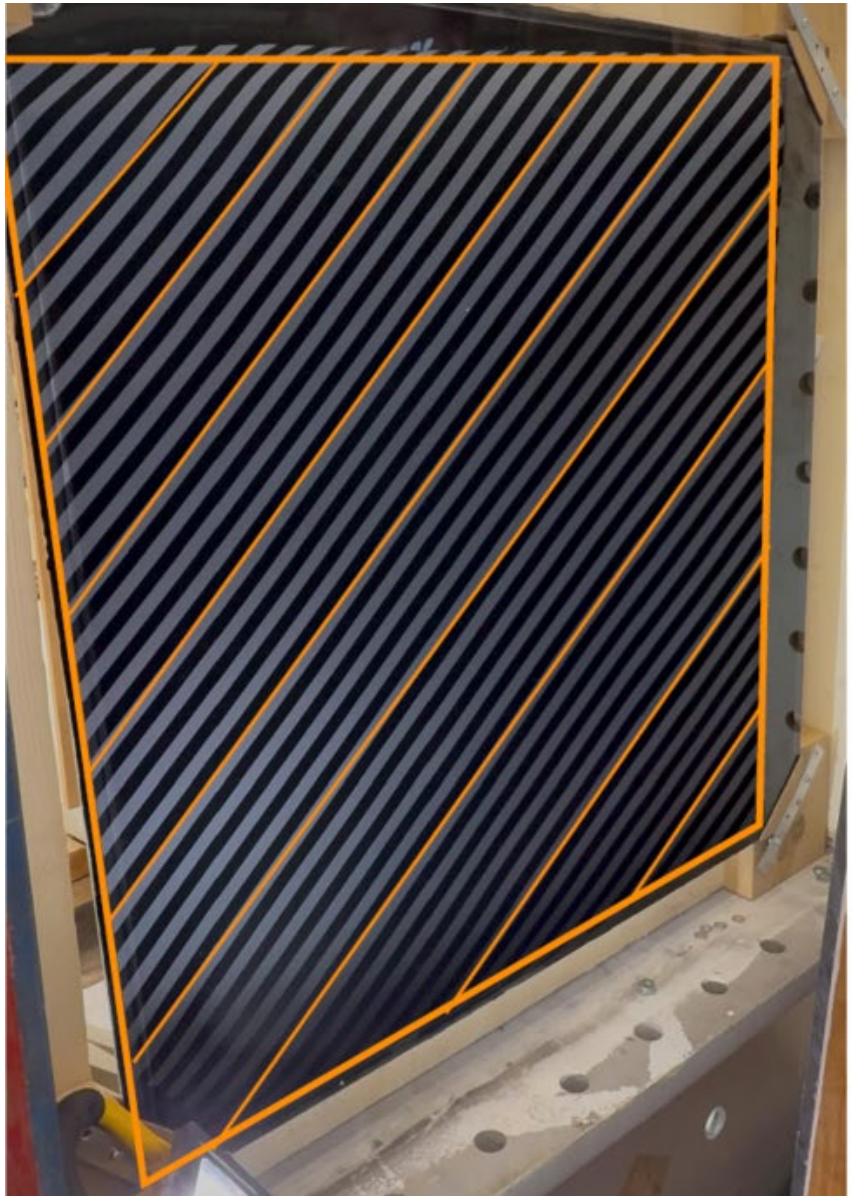
Deformation of outer pane = 0.4 cm

Part III: Reflection

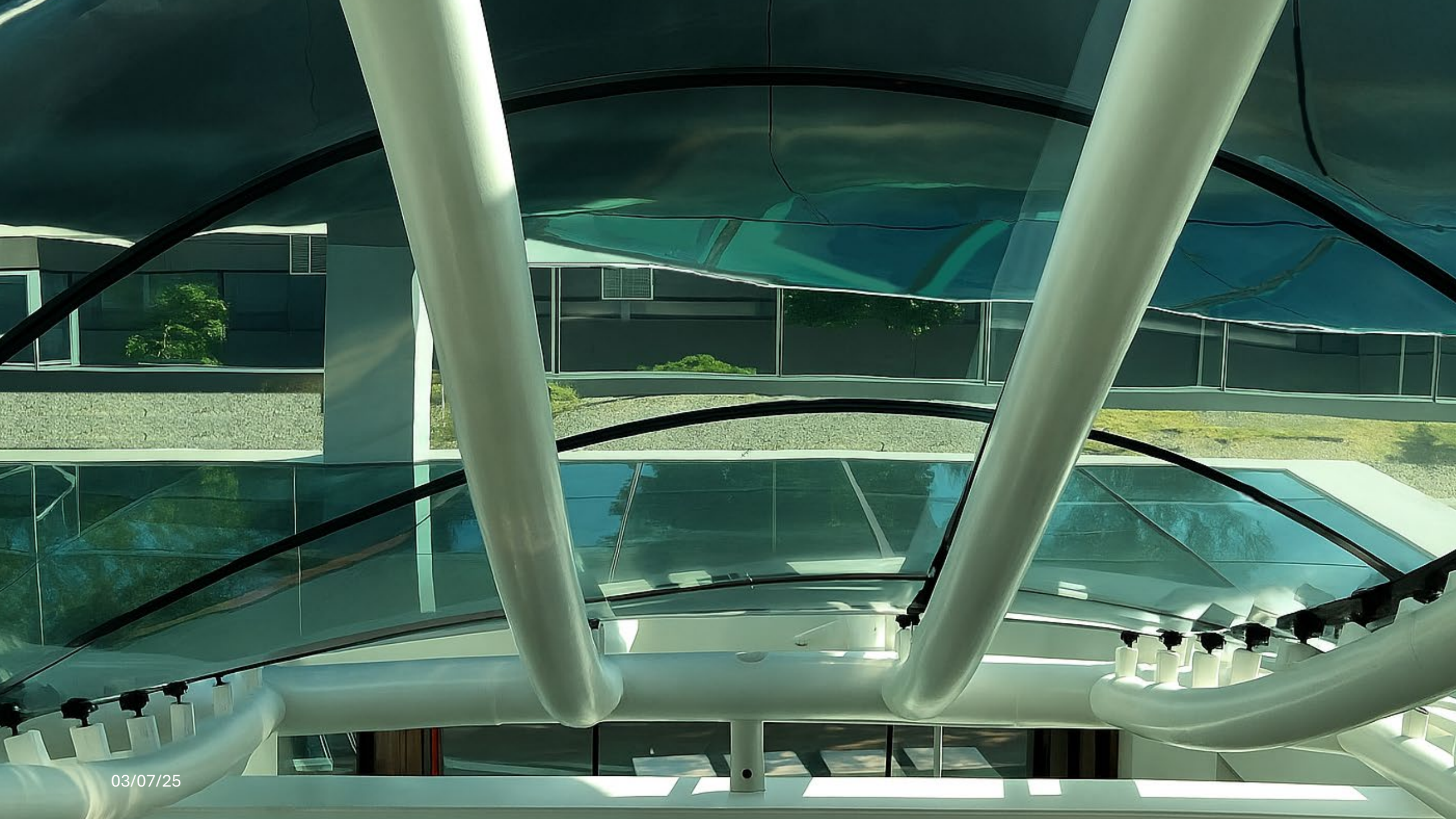
Reflection test

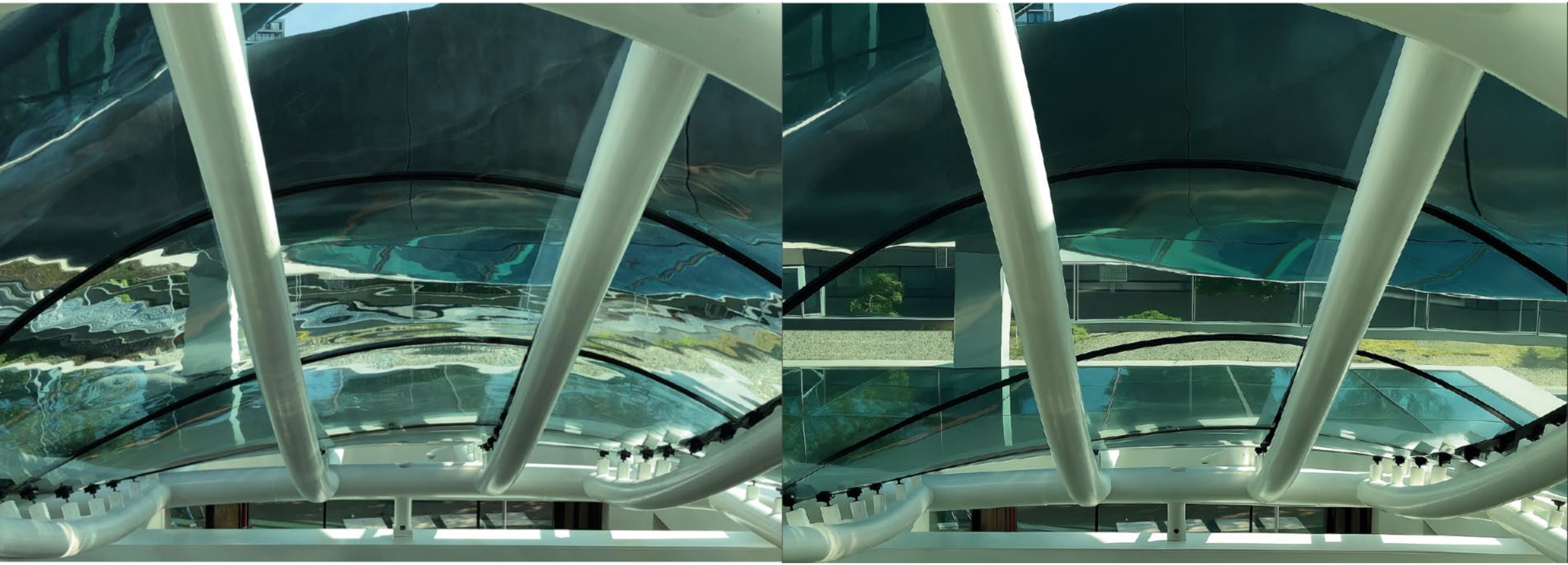






03/07/25


03/07/25



Conclusion

- Thin glass IGU's can be bend up to a corner displacement ratio 0f **0.102,** much further than **thick tempered glass** or **thinner regular glass.**
- **Using thin-glass cold bending reduces:**
  - **Energy use → reduces carbon emissions**
  - **Project time**
  - **Raw material usage**
- High curvature cold bending will **not cause major surface distortions**
- Extreme wind loads **cause too high deformations at flat panels**, but panels are **stiff enough after cold bending**

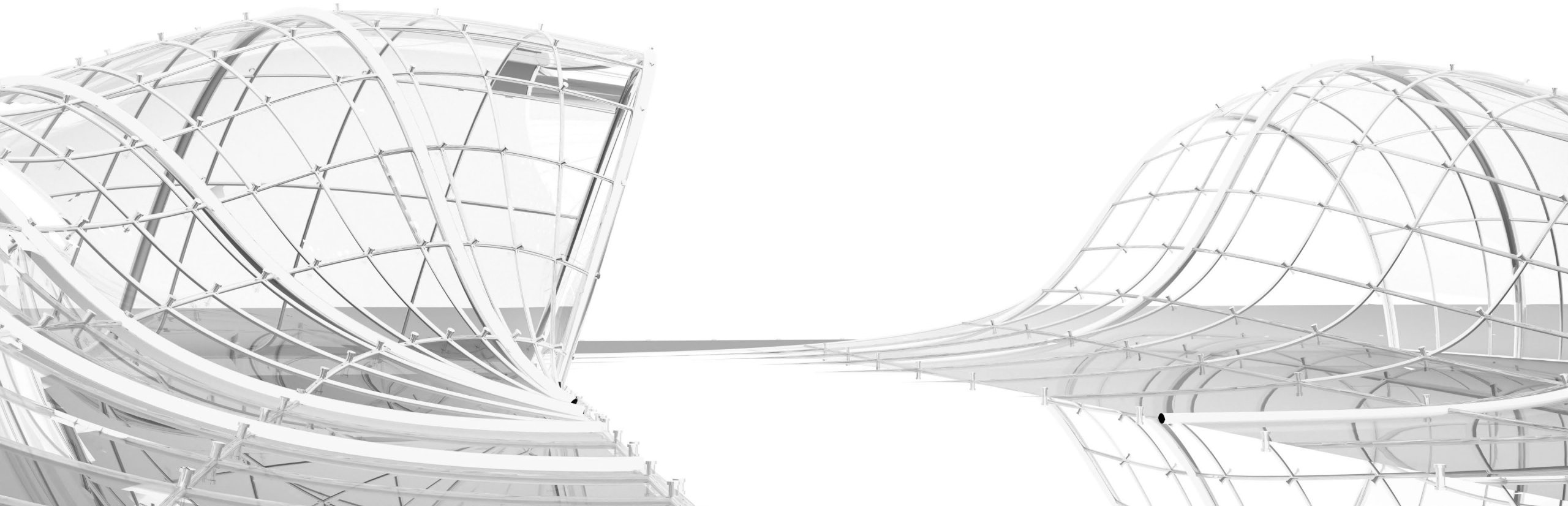
Discussion

- Strain gauges do not offer the most accurate data.
- Numerical model could be expanded upon and improved for optimal cold bending curvatures.
- Actual tensile stress data TBD.

Further research

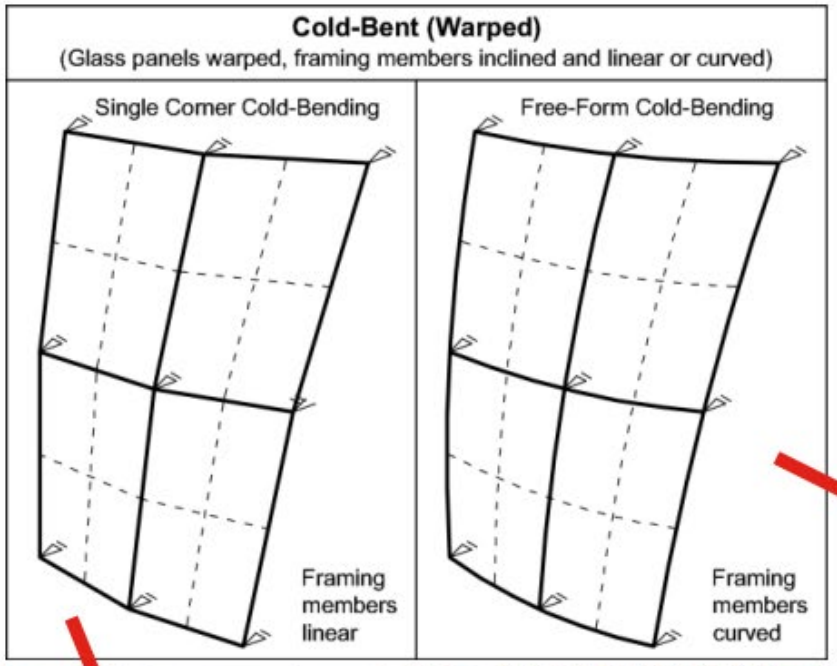
- Long term adhesive performance
- Interlayer influence and performance with high curvature cold bending
- Free form cold bending with curved edges

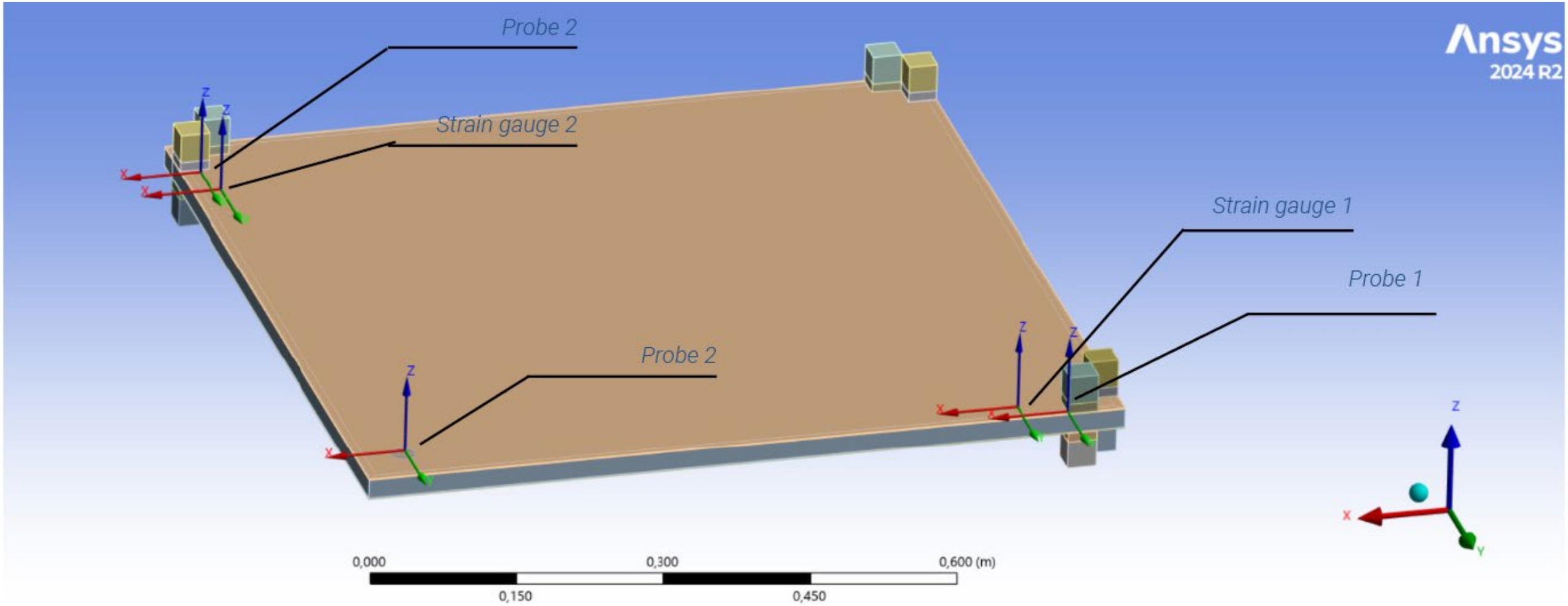
Thank you



Complex Geometry – Cold-Bending Options

Single Corner Cold-Bending vs. Free-Form Cold Bending:




Probe 2
Strain gauge 2
Strain gauge 1
Probe 1
Probe 2
Ansys
2024 R2
0,000
0,300
0,600 (m)
0,150
0,450