Flexible Transparency

A study on thin glass adaptive facade panels

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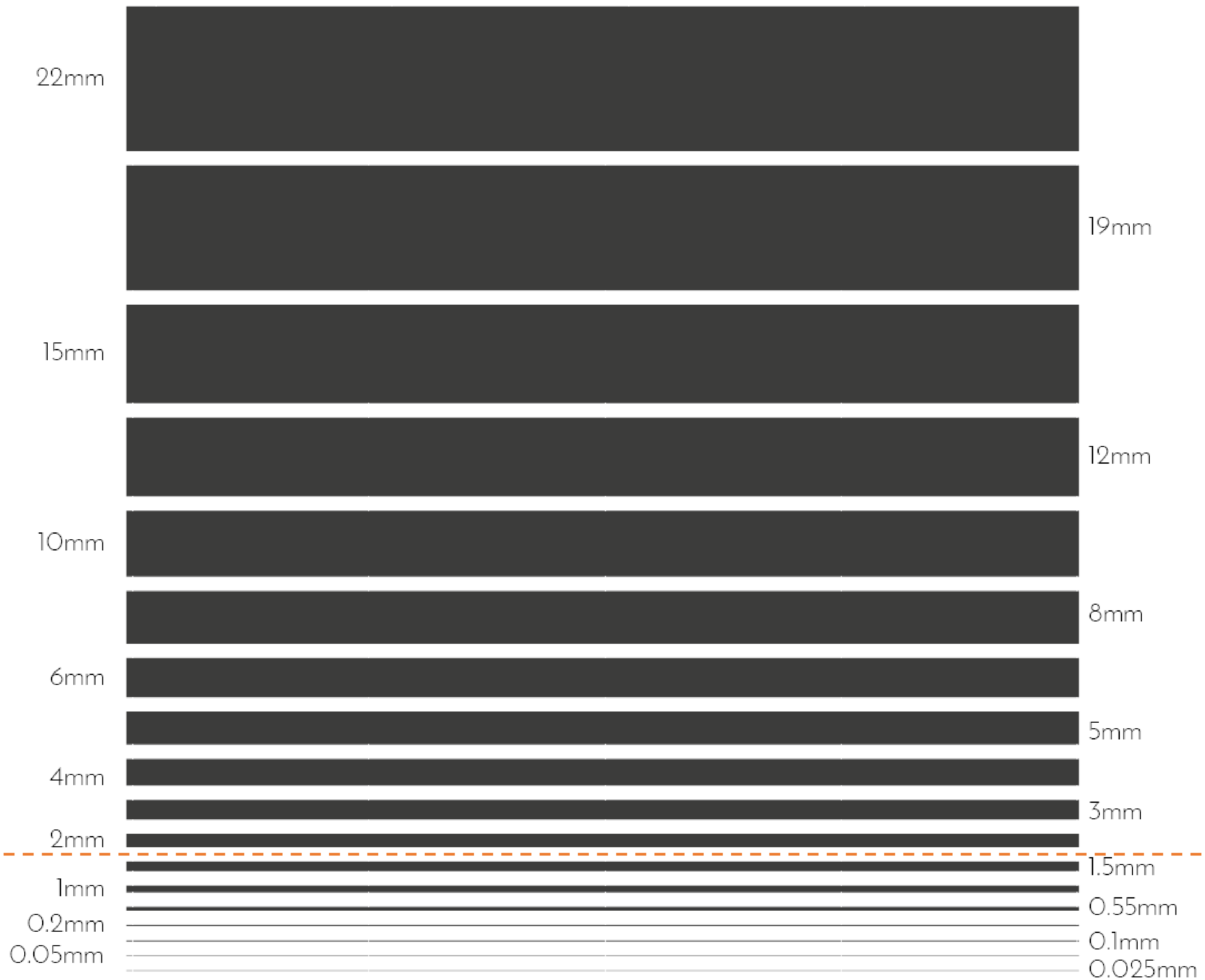

22mm
19mm
15mm
12mm
10mm
8mm
6mm
5mm
4mm
3mm
2mm
1.5mm
1mm
0.55mm
0.2mm
0.1mm
0.05mm
0.025mm

Asahi Glass-Glasstec Dusseldorf
2014

Thin Glass

Built environment

GLASS PANE SIZE TECHNOLOGY

70 AD - 0.5 x 0.3 m
Herculaneum

1226 - Broad Sheet
produced in Sussex

1330 - Crown Glass
Rouen

1620 - Brown Plate
London - mirrors

1688 - Polished plate
France

1700s - Introduction of
soda to the composition.
More strength and
transparency.
Costs reduced

1790 - 0.6 x 0.38 m
Maximum sizes of Crown
glass

1790 - 0.72 x 0.6 m
0.84 x 0.54 m
Maximum sizes available
in Belgium

1800 - Polished
plate using steam
power
England

1834 - Improved Cylinder Sheet
Germany

1843 - Early float glass
invented - expensive and not
sucessful commercially

1845 - 1.2 x 0.72 m
Maximum size
increase

1847 - Rolled plate
Used for large railway
stations

1870 - 1.44 x 0.96 m
Cylinder glass
production

1874 - Tempered glass method is
patented

1888 - Machine rolled glass
allows the introduction of
patterns

1898 - Wired Cast glass
Pilkington

1903 - Machine drawn
cylinder technique
U.S.

1903 - Laminated glass
is invented
France

1906 - 3.8 x 1.9 m
Fourcault process

1913 - Flat drawn sheet technique
Belgium

1923 - Polished plate
England

1925 - 4 x 2.3 m
Fourcault process improved

1927 - 4 x 2.5 m
Pilkington process

1951 - 15.24 x 2.4 m
Exhibition glass
Britain, power and
production pavilion

1959 - Float glass
Pilkington

1970 - 6 x 3.21 m
Jumbo float glass

2009 - 9 x 3.21 m
New Jumbo float glass

2010 - 18 x 3.3 m
Insulated glass at
Glasstec

Chart 1- Evolution of glass
Based on chart by Alejandro
Zaera Polo in [12]

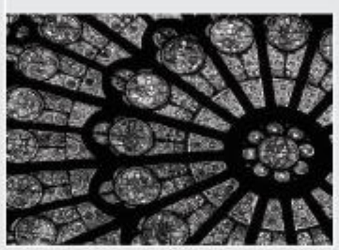


Figure 2-Notre Dame de Paris - 1260


Figure 3-Victorian houses - ca. 1850


Figure 4-Crystal Palace - 1851


Figure 5-Glass Pavilion - 1914


Figure 6-Bauhaus Dessau - 1928


Figure 7-Apple Istambul - 2014

2mm Alumino silicate

Alumino silicate - 1720

Density (kg/m³)		2520
Thickness (m)		0,002
Weight (kg)		5,04
Embodied energy, primary production	13,95	70,308
CO2 footprint, primary production	0,9405	4,74012
Water usage	21,15	106,596
Glass molding energy	11,15	56,196
Processing energy, CO2 footprint & water		
Glass molding CO2	0,892	4,49568
Glass molding water	3,94	19,8576
Grinding energy (per unit wt removed)	33,8	170,352
Grinding CO2 (per unit wt removed)	2,535	12,7764
CO2	KG	22,0122
WATER	LITER	126,4536
ENERGY	MJ	226,548

6mm Soda lime

Soda lime - 0080

Density (kg/m³)		2470	
Thickness (m)		0,006	
Weight (kg)		14,82	
Embodied energy, primary production	10,6	157,092	
CO2 footprint, primary production	0,758	11,23356	
Water usage	14,35	212,667	
Glass molding energy	8,655	128,2671	
Processing energy, CO2 footprint & water			
Glass molding CO2	0,6925	10,26285	
Glass molding water	3,06	45,3492	
Grinding energy (per unit wt removed)	26,95	399,399	
Grinding CO2 (per unit wt removed)	2,02	29,9364	
CO2	KG	51,43281	234%
WATER	LITER	258,0162	204%
ENERGY	MJ	527,6661	233%

Estimation based on data from:

CES Edupack 2015. Soda lime – 0080, Alumino silicate - 1720 (Granta Design Limited). 2015.

Hundevad (2014)

20 % energy reduction demands for a $10m^2$ roof

6mm heat tempered x 1mm Chemically tempered glass

		2 x 6mm Heat Tempered glass					**2 x 1mm Chem temp Glass.**				Source
		1000					1000				
Weight		30	30000	kg			5	5000	kg		
Float Glass	30 MJ/kg	30	900000	MJ	69%		30	150000	MJ	69%	
Tempering	1 MJ/kg	1	30000	MJ	2%		1	5000	MJ	2%	Xinology.com
Shipping	Assume 5000km	2500	375000	MJ	29%		2500	62500	MJ	29%	US Trade Dept.
	Road 2500 kJ/t km										
	TOTAL		**1305000**	**MJ**				**217500**	**MJ**		
Gallons of Gas		*122 MJ/gal*	*10697*	*Gallons*				*1783*	*Gallons*		
House Consumption USA Average		*10500 kWh*	*37800*	*MJ*				*37800*	*MJ*		
			35	*Households*				*6*	*Households*		

Thin Glass

Built environment

Research question

How can a thin glass double skin façade panel be made adaptive?

How can a thin glass double skin façade panel be made adaptive?

1. To what purposes can a thin glass panel be made adaptive?
2. How does bending influences the stress generation in the thin glass panel?
3. What are the influences of bending and thickness on the load resistance of the thin glass panel?
4. What are the possibilities of movement for this panel?
5. How can supports influence the movement and geometry of the thin glass adaptive panel?
6. How to translate the necessary degrees of freedom for the movement of the panel to its detailing?

Research structure

Literature Review and definition of research focus

Understand the behavior of the material in the context of façade adaptive panel

Development of an example of a thin glass adaptive façade panel

Research structure

Literature Review and definition of research focus

- Analyze current applications
- Explore different possibilities, to understand the material and possible applications

Research structure

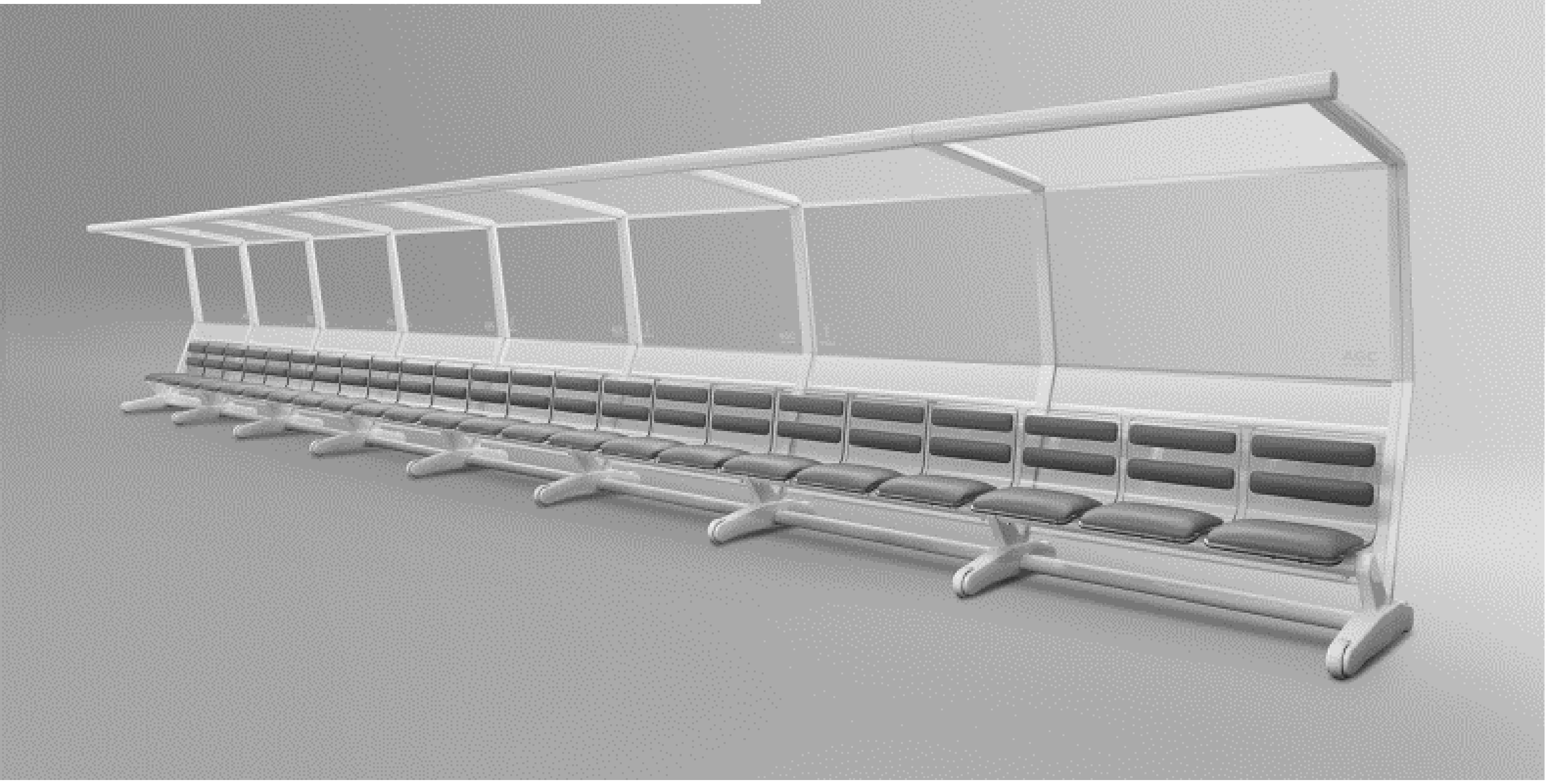
Understand the behavior of the material in the context of façade adaptive panel

- Study models and Numerical models for the simulation of bending
- Numerical models applying wind loads to the thin glass panel.
- Study of possible movements and supports by numerical models

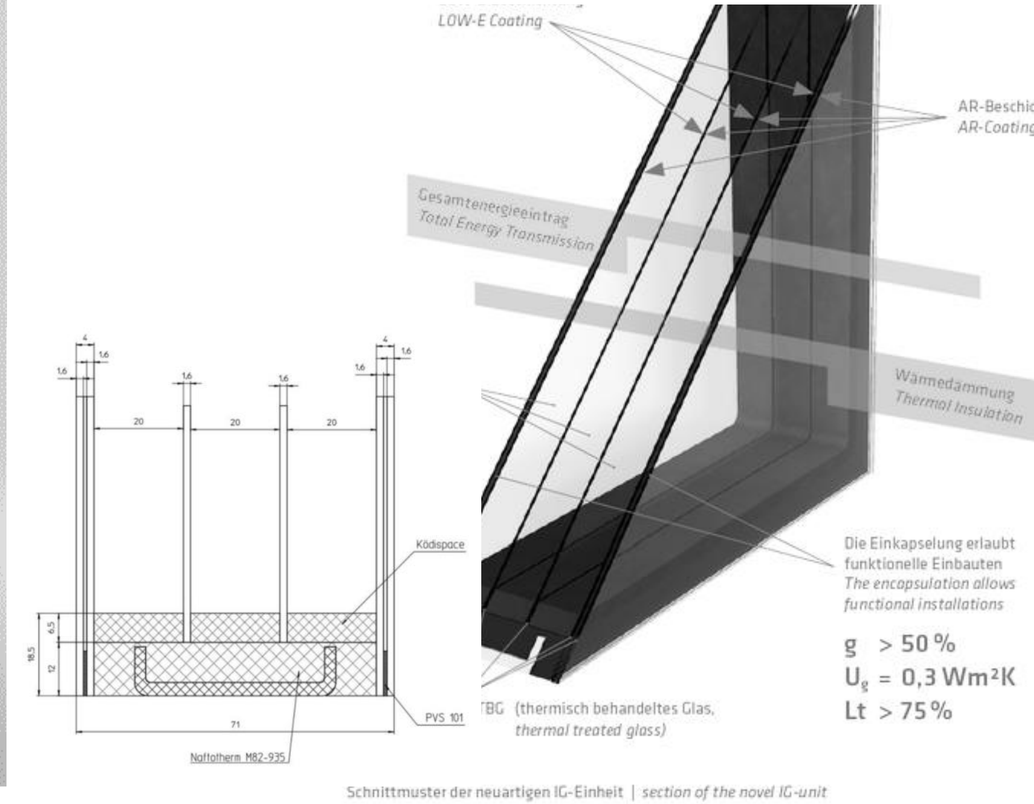
Research structure

Development of an example of a thin glass adaptive façade panel
• Analyze possible design strategies based on developed knowledge • Select most suitable design strategy for detailing

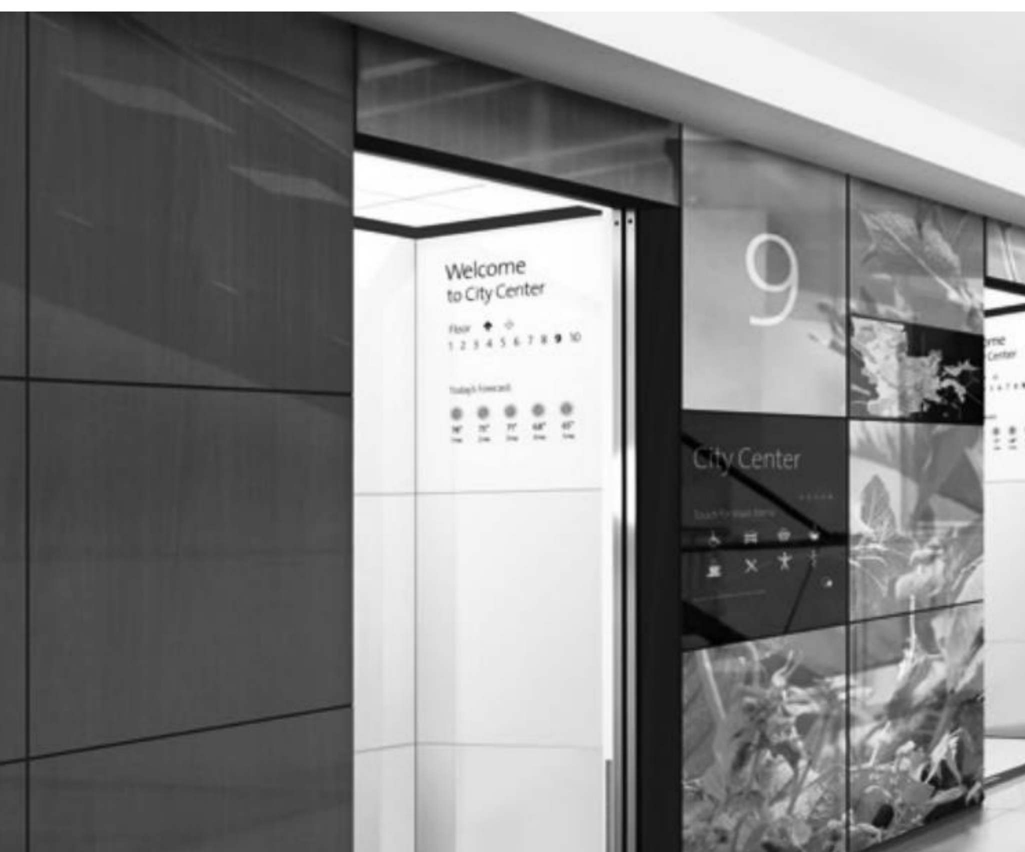
Impact and weather resistant



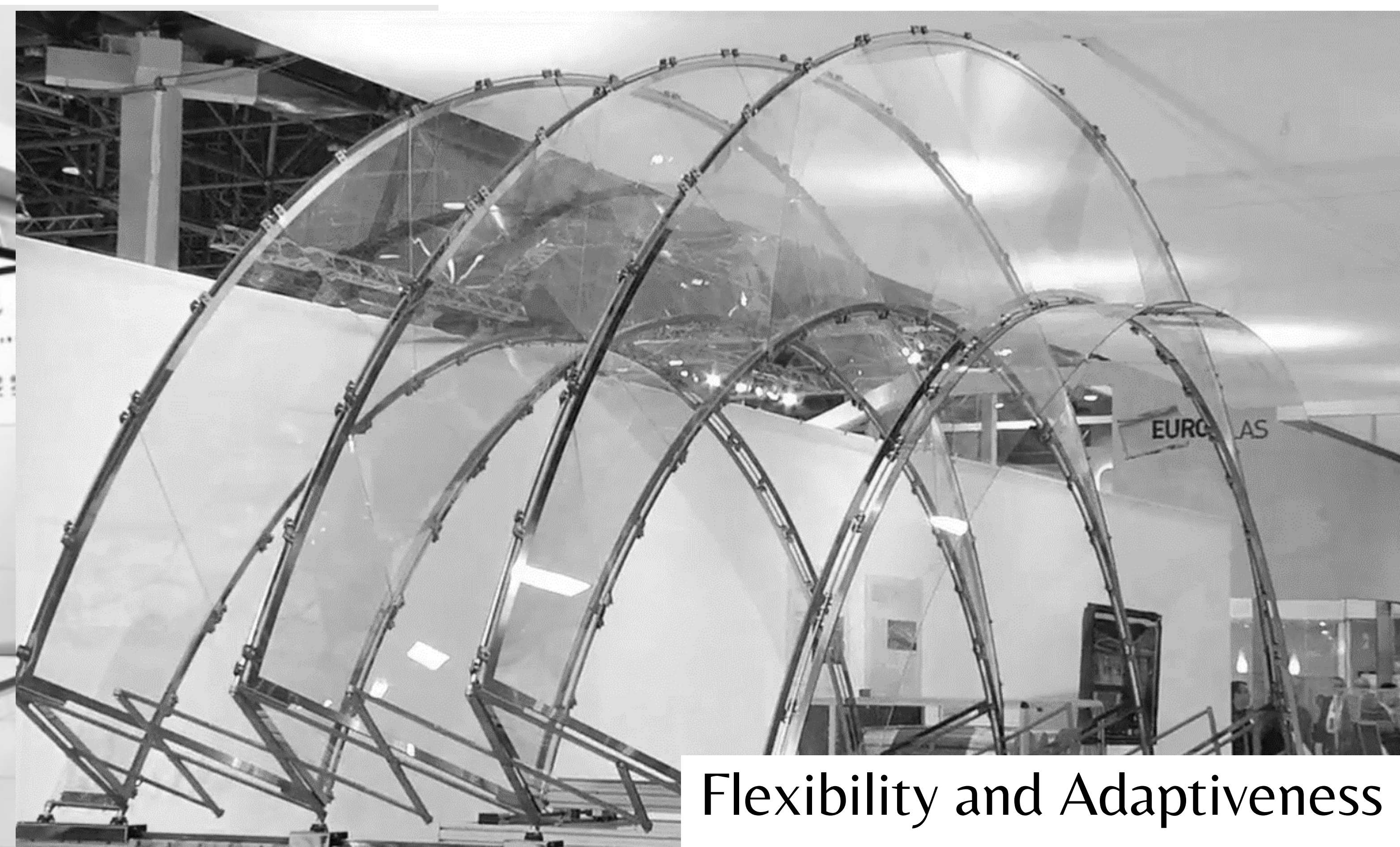
Light weight



Current use in the built environment



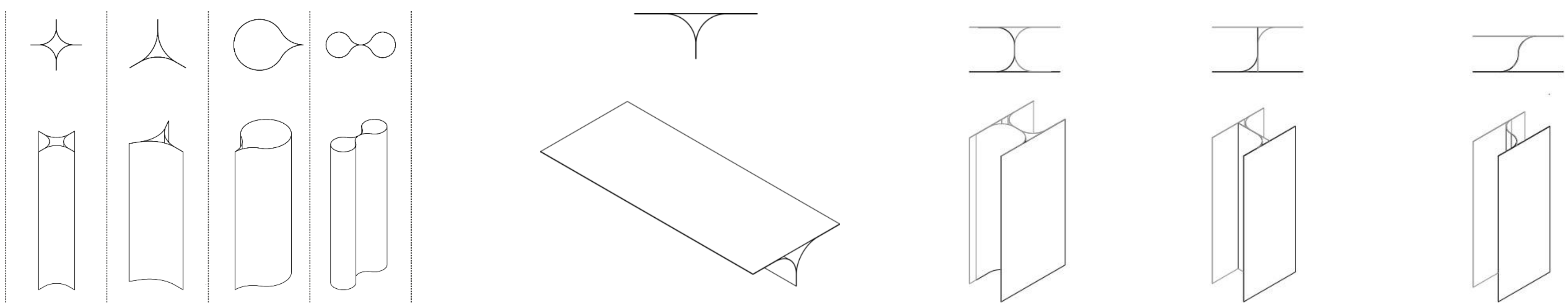
Impact and damage resistant



Flexibility and Adaptiveness

Geometry Exploration

- Structural Elements
- Planar panels
- Single Radius
- Double Curvature



Unique characteristics

- Transparency
- Adaptability
- Flexibility

Development of low mass adaptive panels/structures

Adaptive Structures/Facades

- Change of properties/shape;
- Respond to the necessities of the building;
- Enhance the performance of a building;
- And/or the comfort of the occupants.

Adaptive Structures/Facades

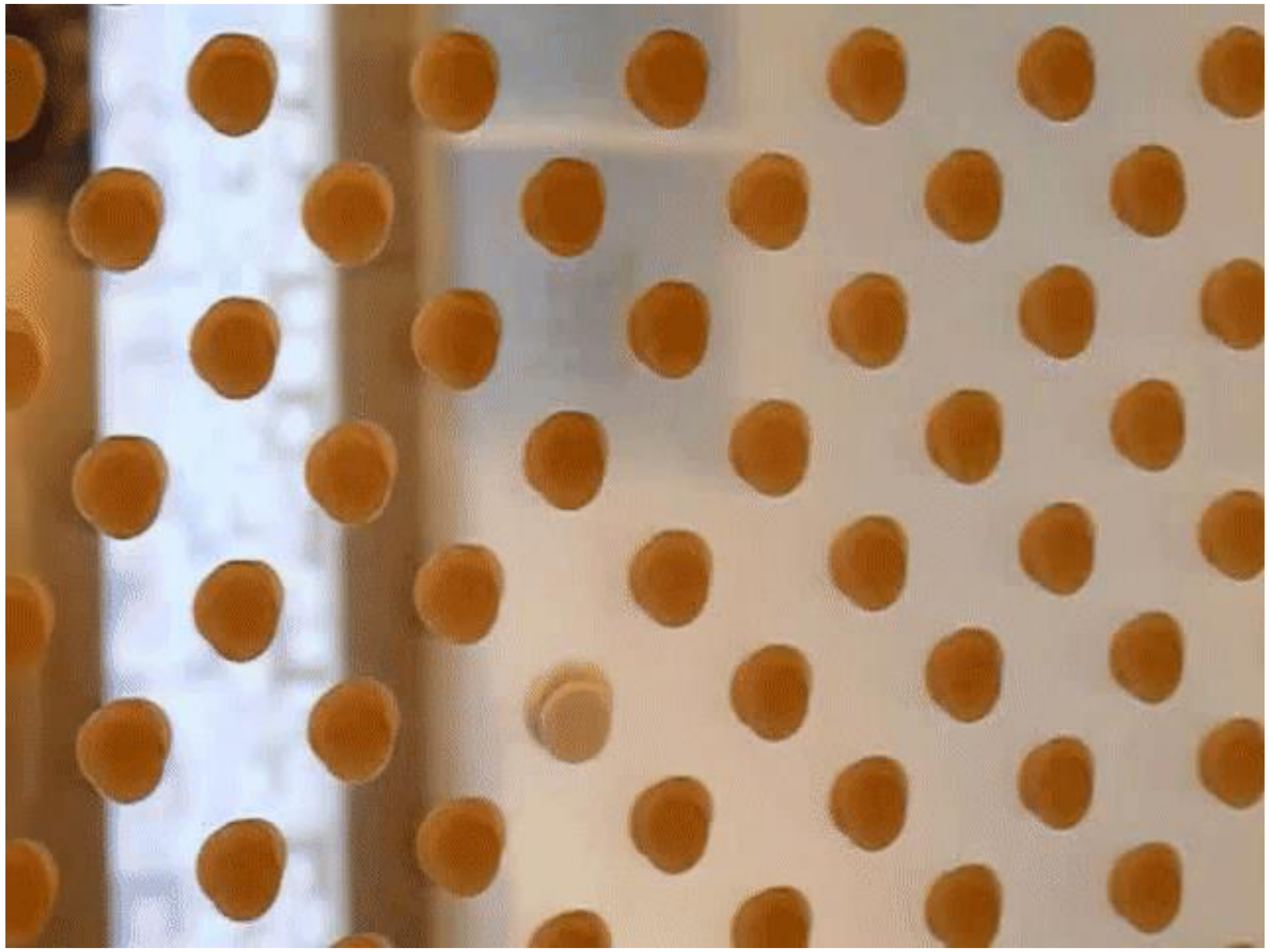
- Active Bending

EXPO 2012

(KNIPPERS, J. et al. **Kinetic media Façade consisting of GFRP louvers**. 20

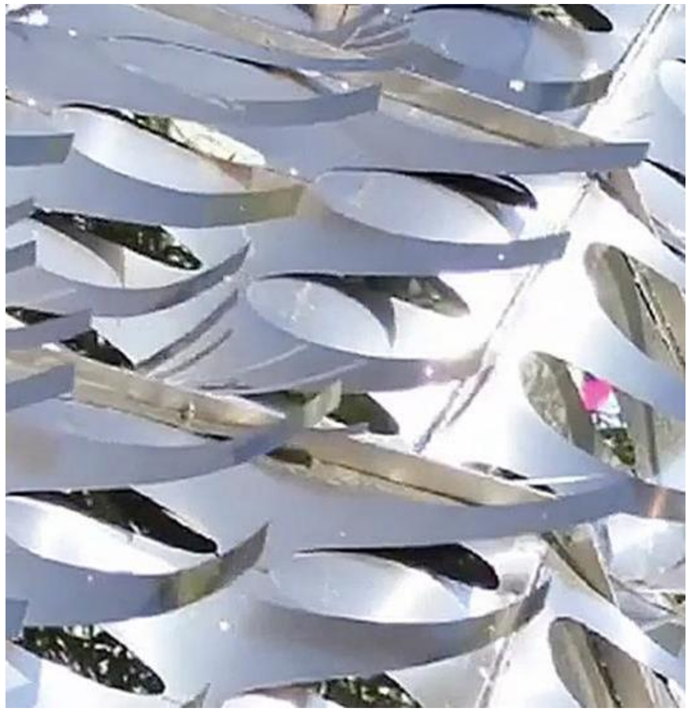
Adaptive Structures/Facades

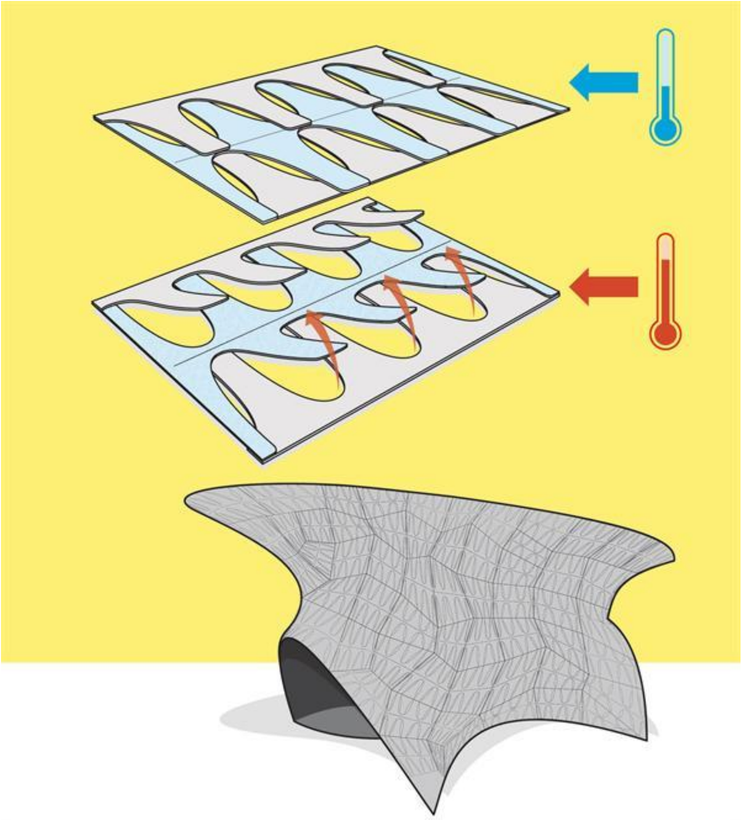
- Adaptive fritting



Adaptive Structures/Facades

- Control - Material





(Sung, D. et al. **Bloom**. 2011)

Adaptive Structures/Facades – Thin Glass

Façade

- Adapt without obstructing the view;
- Light weight – lower loads on the main structure.

Adaptive Structures/Facades – Thin Glass

Facade

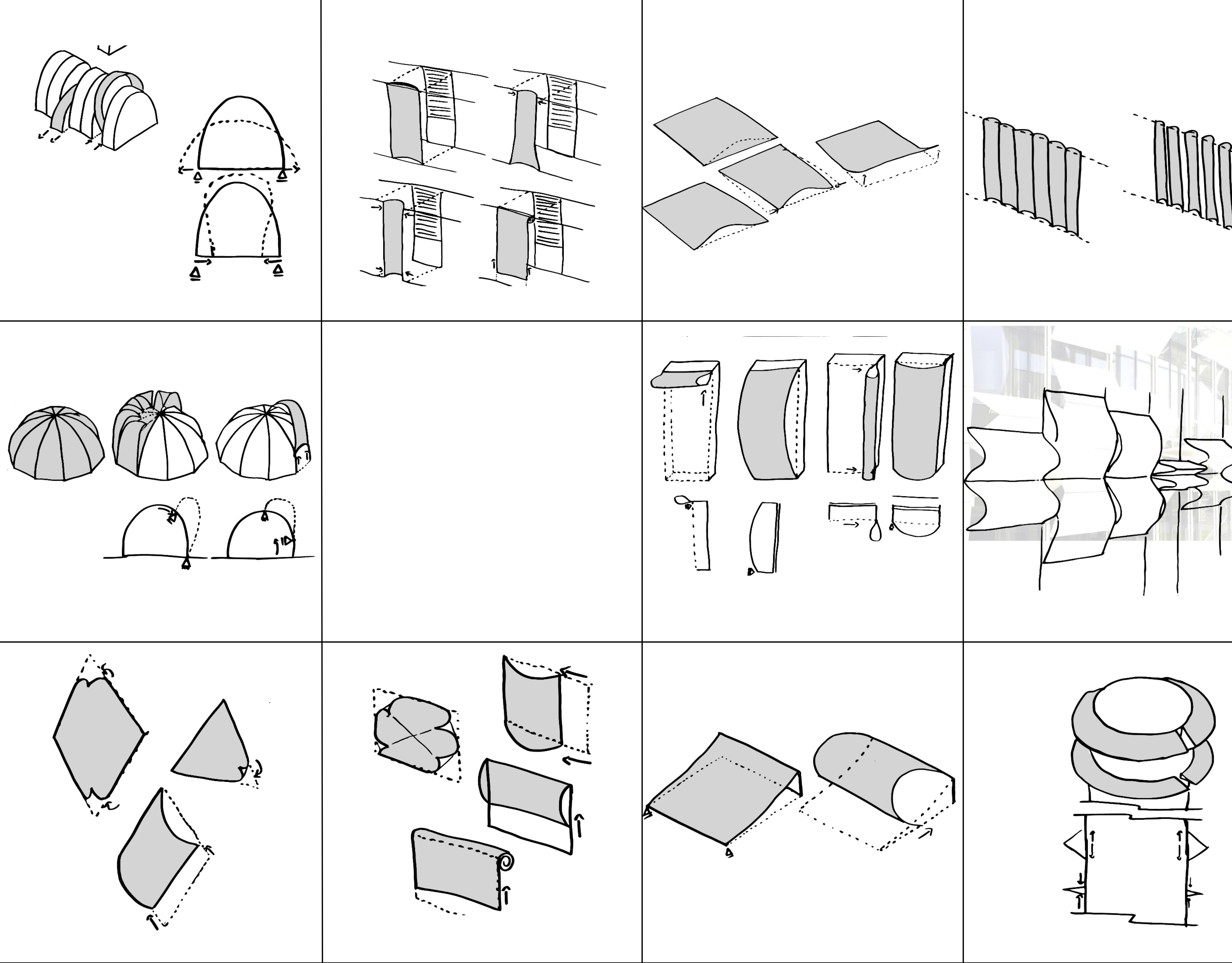
- Ventilation
- Wind load reduction (Adaptive Façade for Wind load reduction in High-rise, P. Vongsingha 2015)
- Acoustic (Acoustical Invisible Envelopes, Holger Techen, 2015)
- Sun shading (fritting –Agbar Tower)
- Visual

Case Studies

Literature Review

Material Behavior

Design example



Conclusions

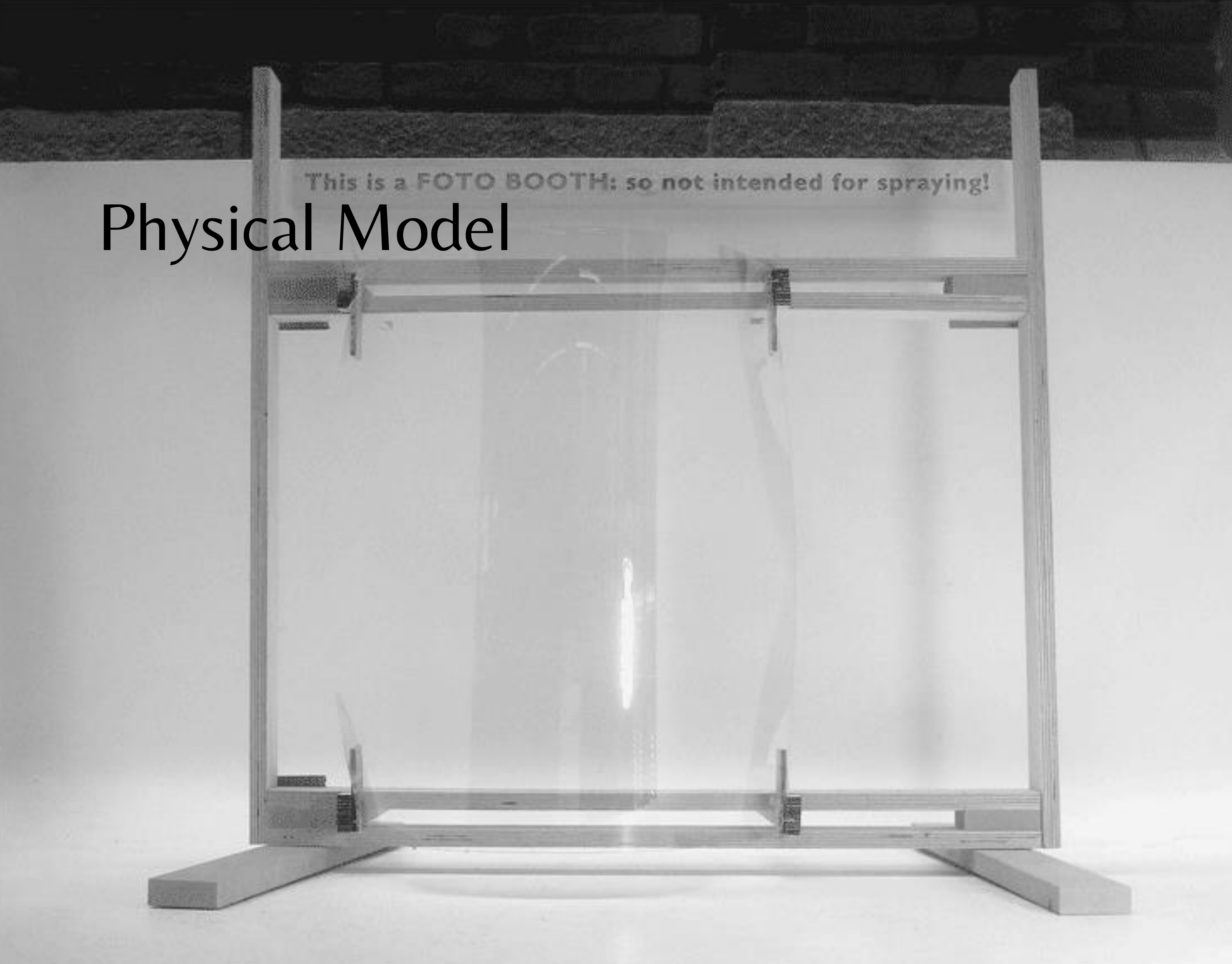
- Façade
- Double skin

Development of transparent low mass adaptive panels in a double skin façade

Study Models

- Physical Model
- Numerical Models

Physical Model

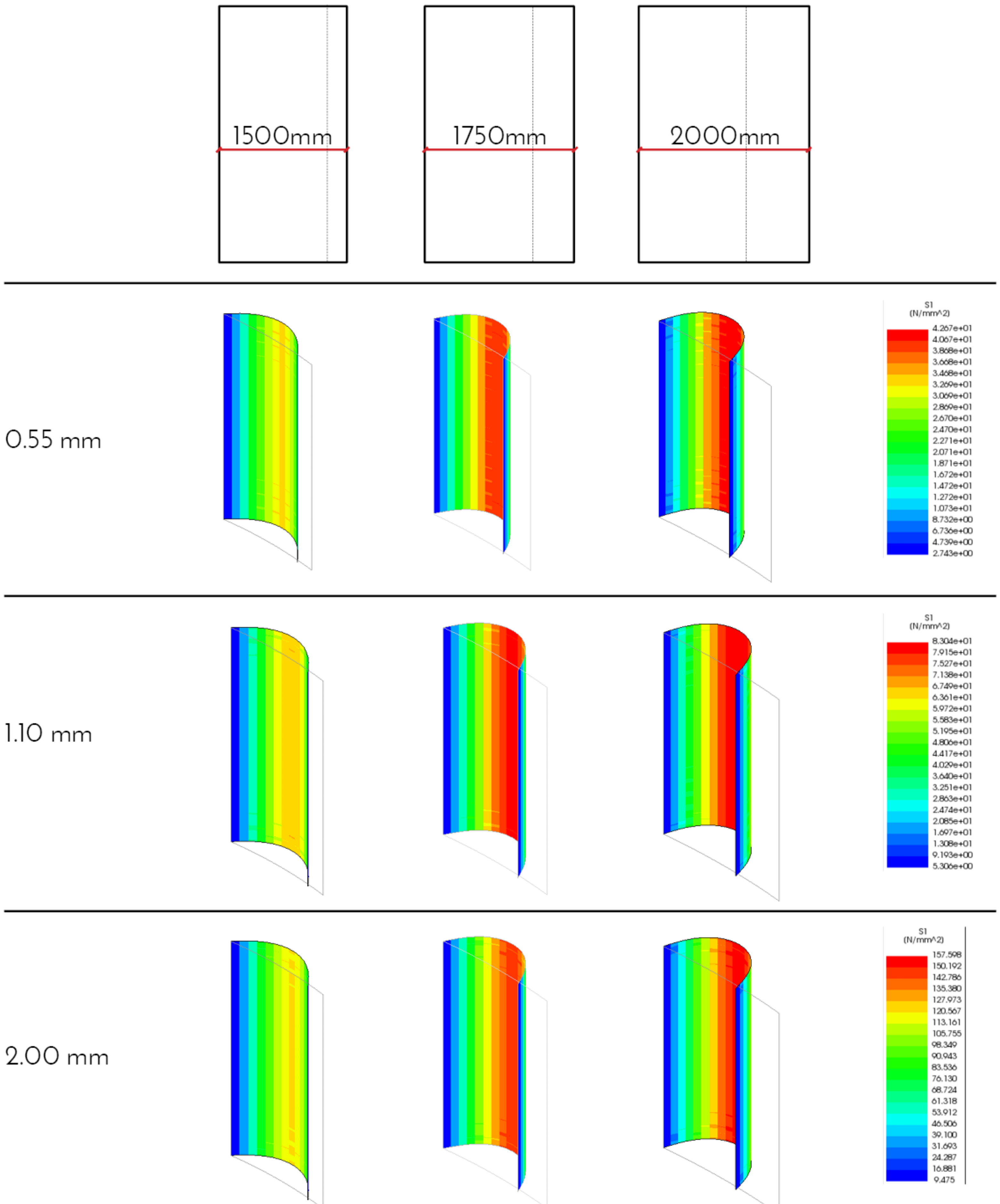


Numerical models

- Initial bending
- Movement bending
- Wind loads

Numerical models

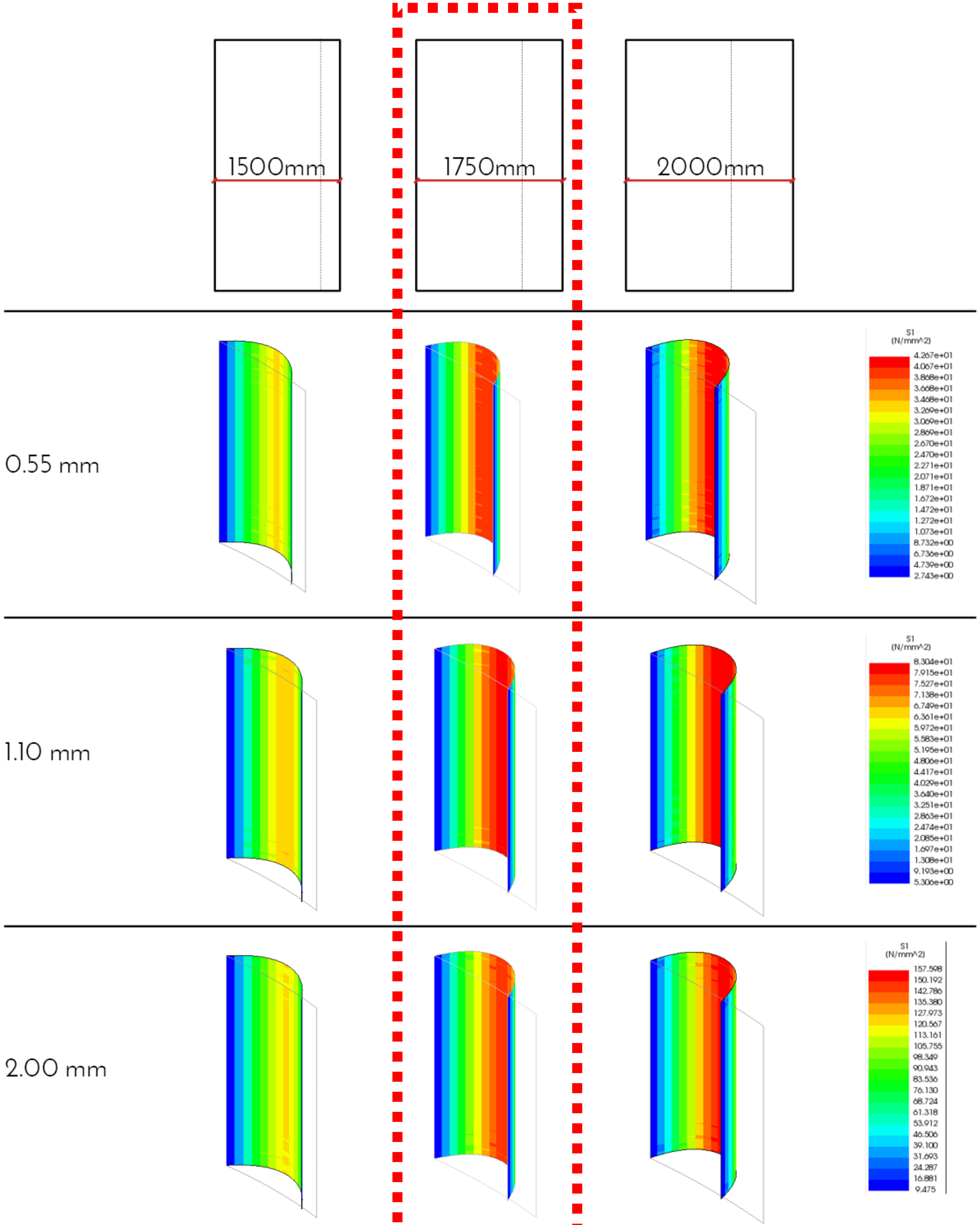
- Definition of plate size



2.73 – 42.6 N/mm^2

5.30 – 83.04 N/mm^2

9.47 – 157.59 N/mm^2



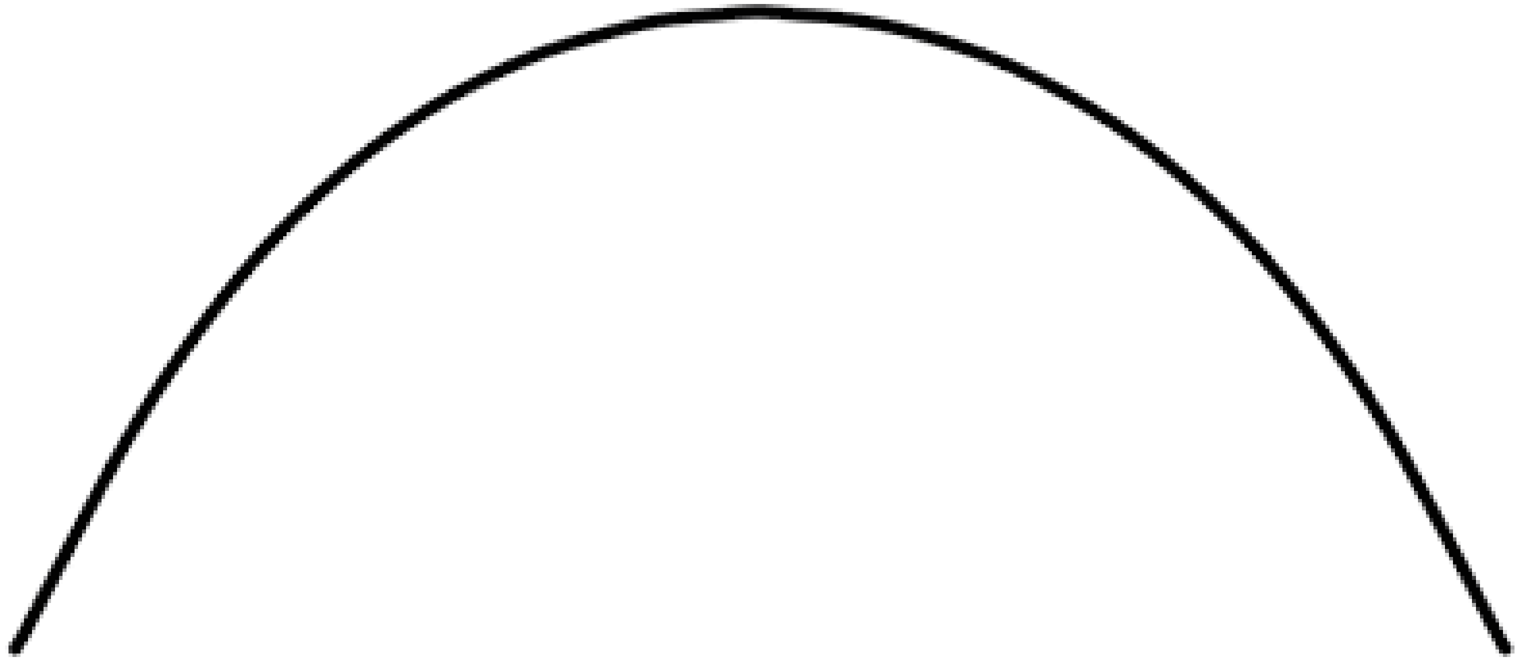
2.73 – 42.6 N/mm^2

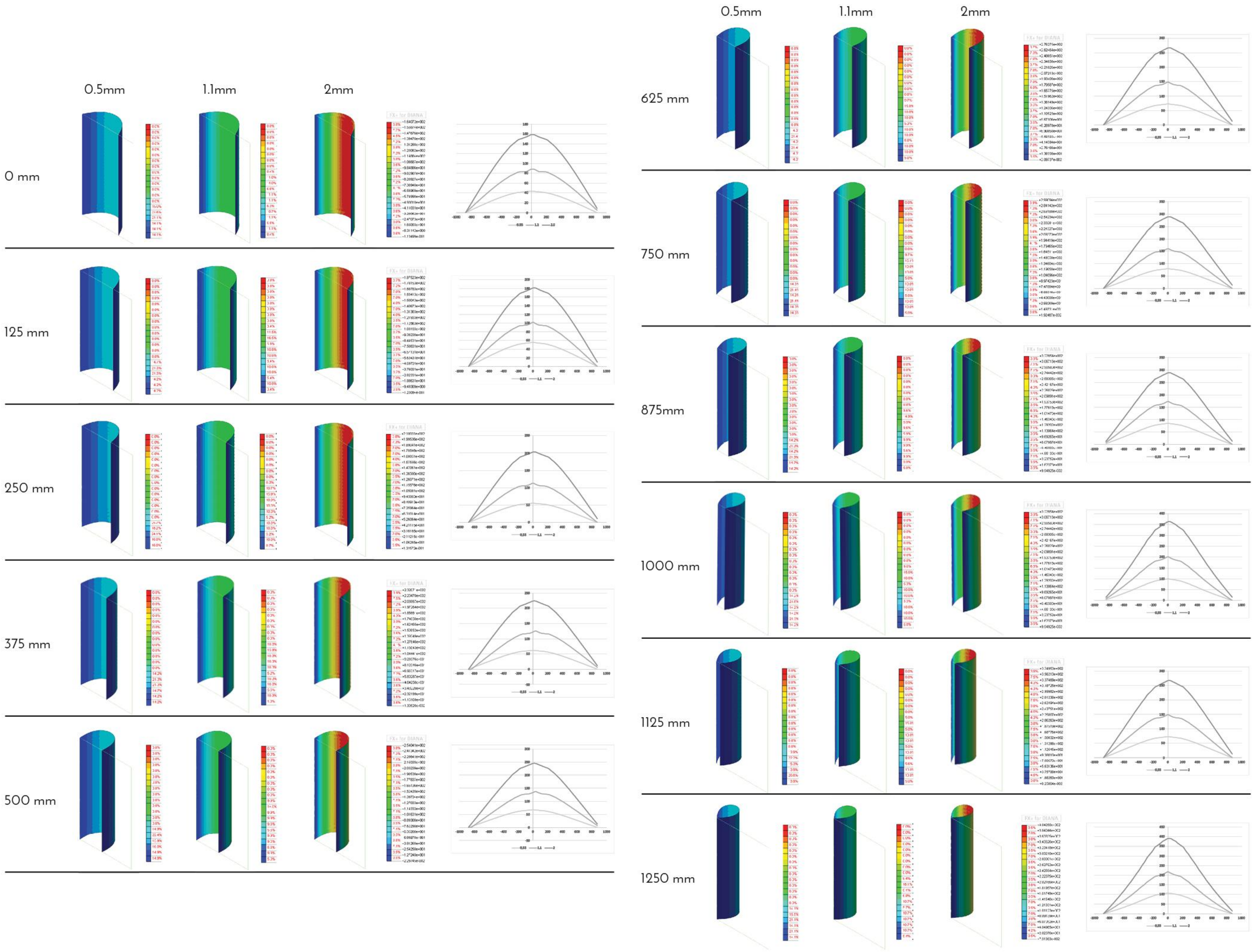
5.30 – 83.04 N/mm^2

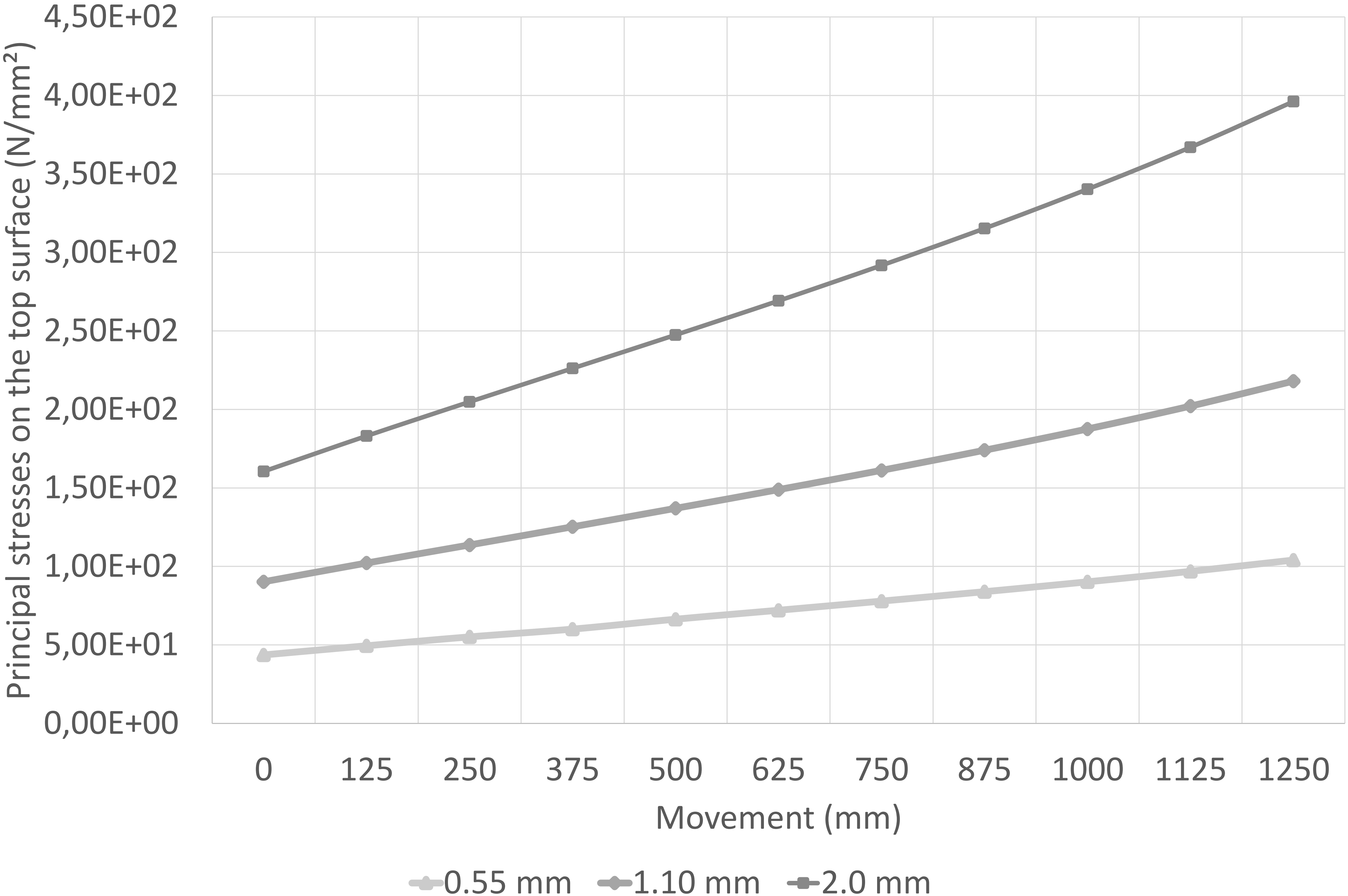
9.47 – 157.59 N/mm^2

Numerical models

- Initial bending
- Movement bending




0.5mm
1.1mm
2mm
0 mm
125 mm
250 mm
375 mm
500 mm
625 mm
750 mm
875mm
1000 mm
1125 mm
1250 mm
FX+ for DIANA

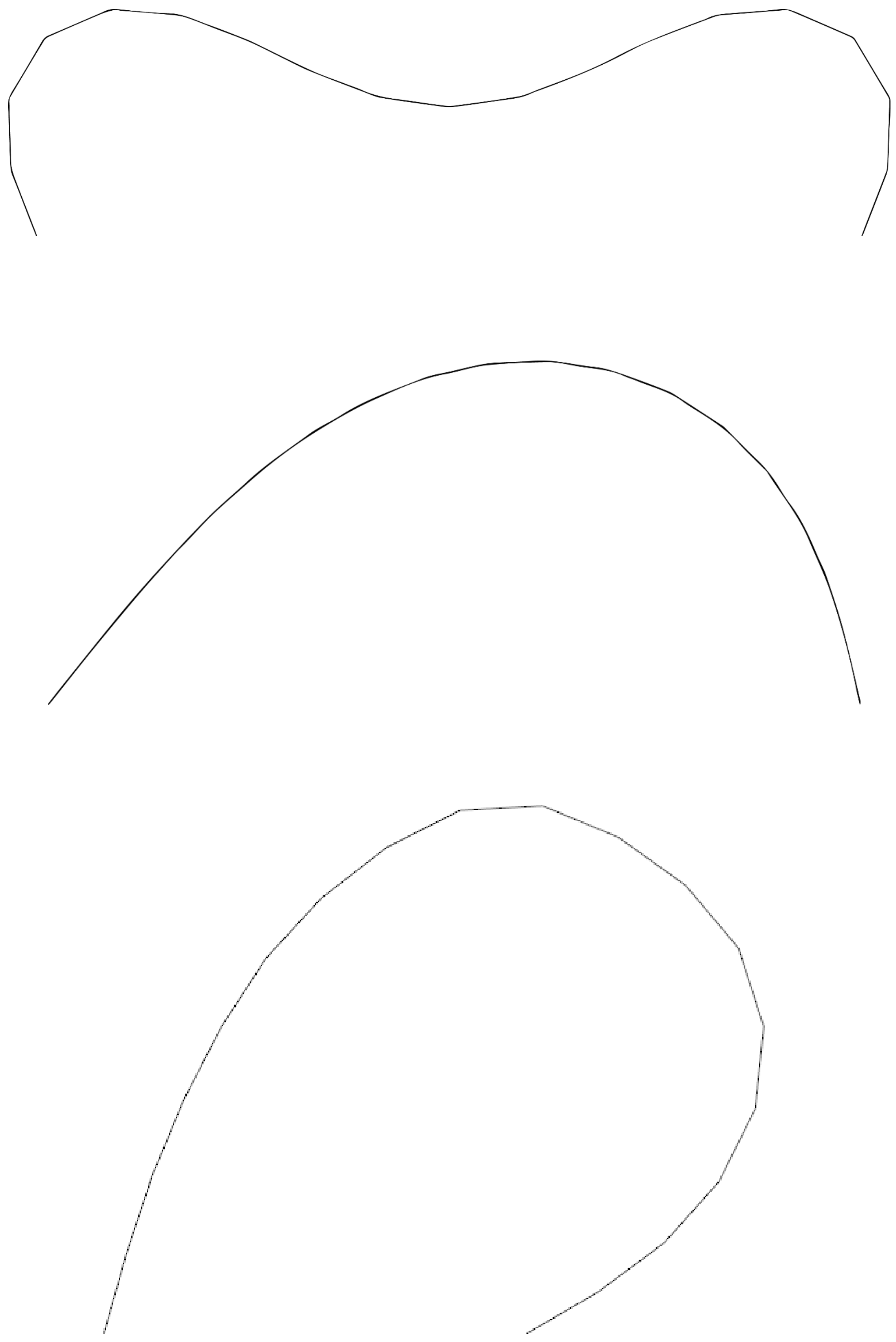

4,50E+02
4,00E+02
3,50E+02
3,00E+02
2,50E+02
2,00E+02
1,50E+02
1,00E+02
5,00E+01
0,00E+00
Principal stresses on the top surface (N/mm²)
0
125
250
375
500
625
750
875
1000
1125
1250
Movement (mm)
0.55 mm
1.10 mm
2.0 mm

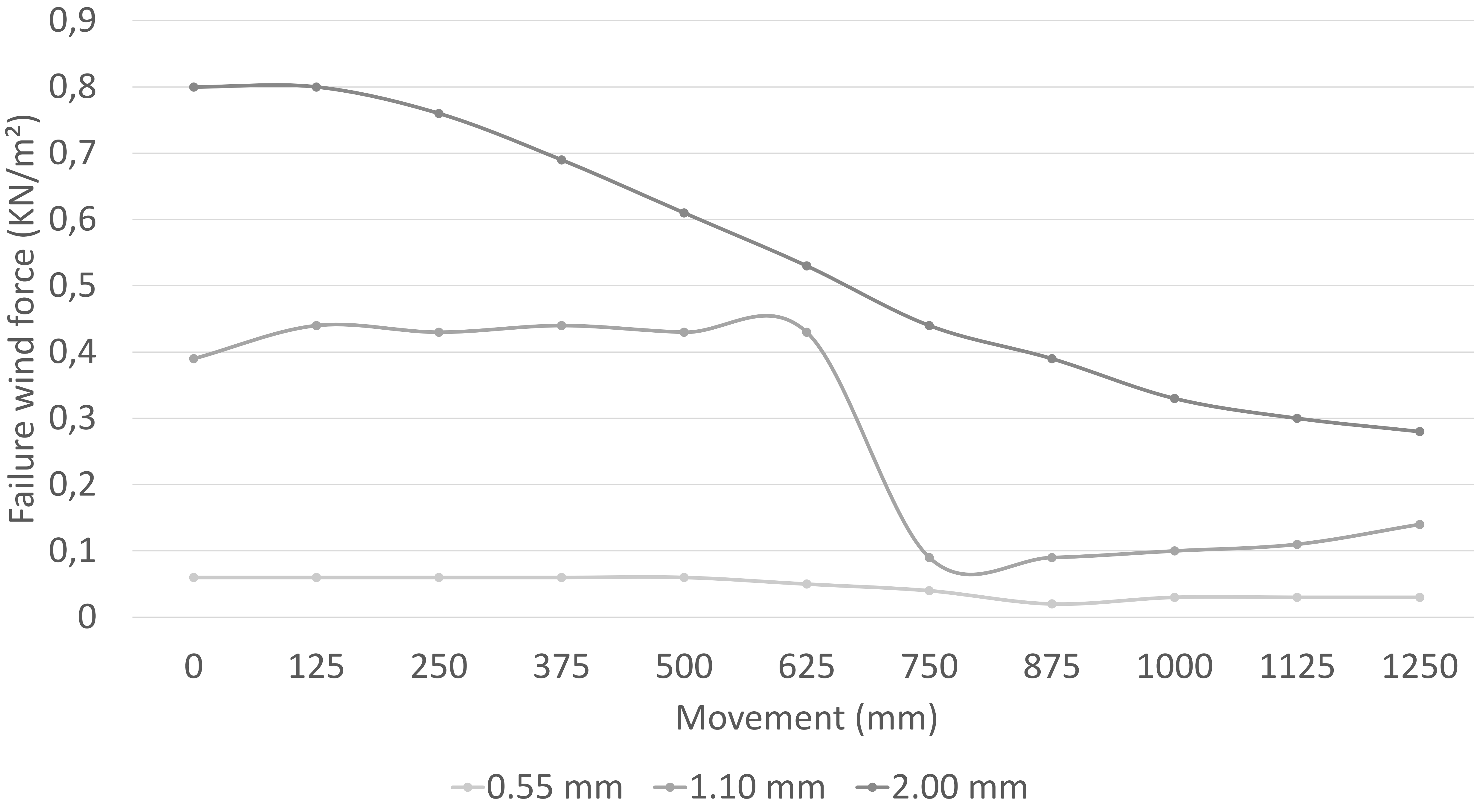
Numerical models

- Wind Load
- 1 KN/m^2 perpendicular pressure

Wind load

- Non convergence





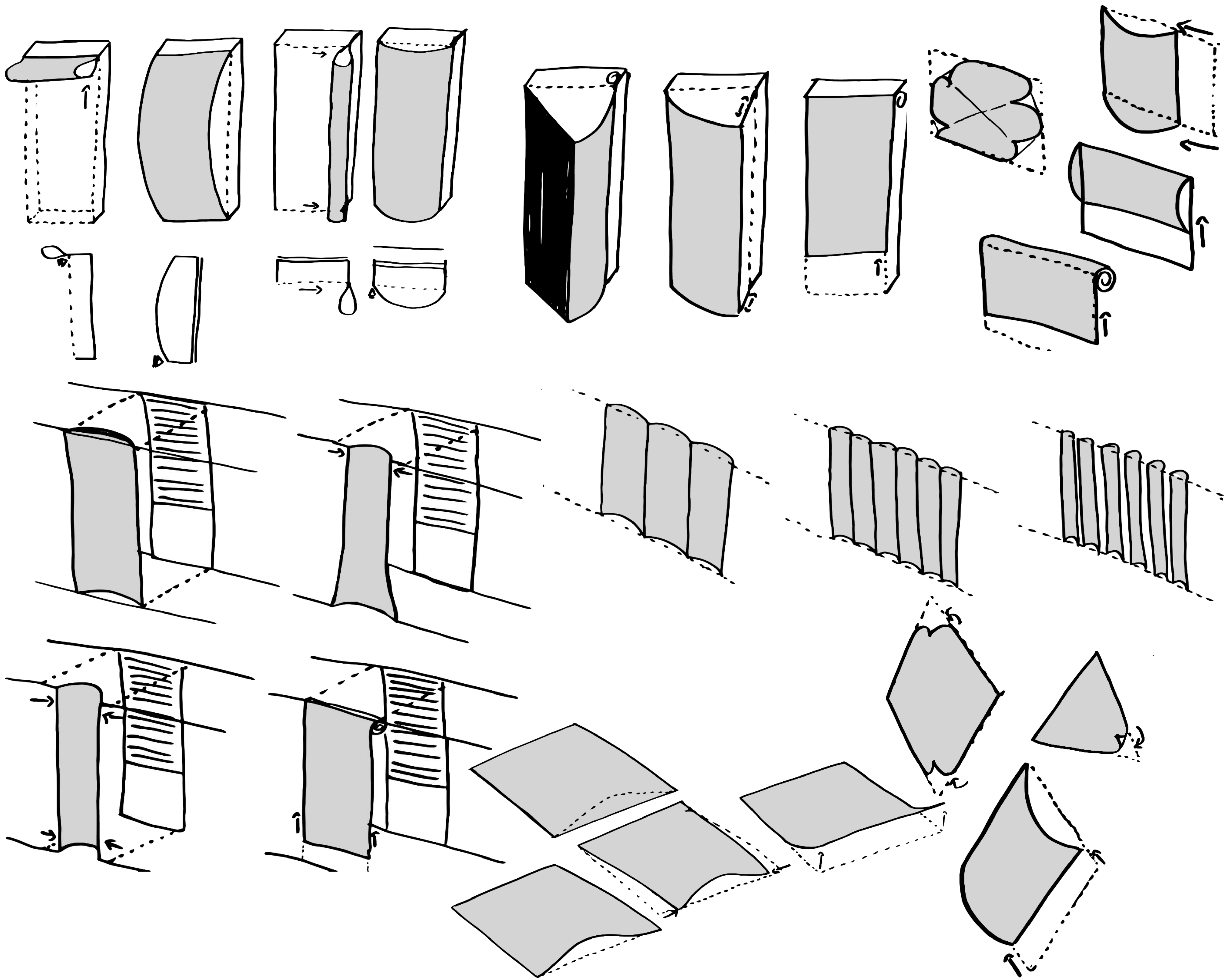
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Failure wind force (KN/m²)
0
125
250
375
500
625
750
875
1000
1125
1250
Movement (mm)
0.55 mm
1.10 mm
2.00 mm

Numerical models

- 1750 mm wide thin glass plate
- 1.1mm thick glass

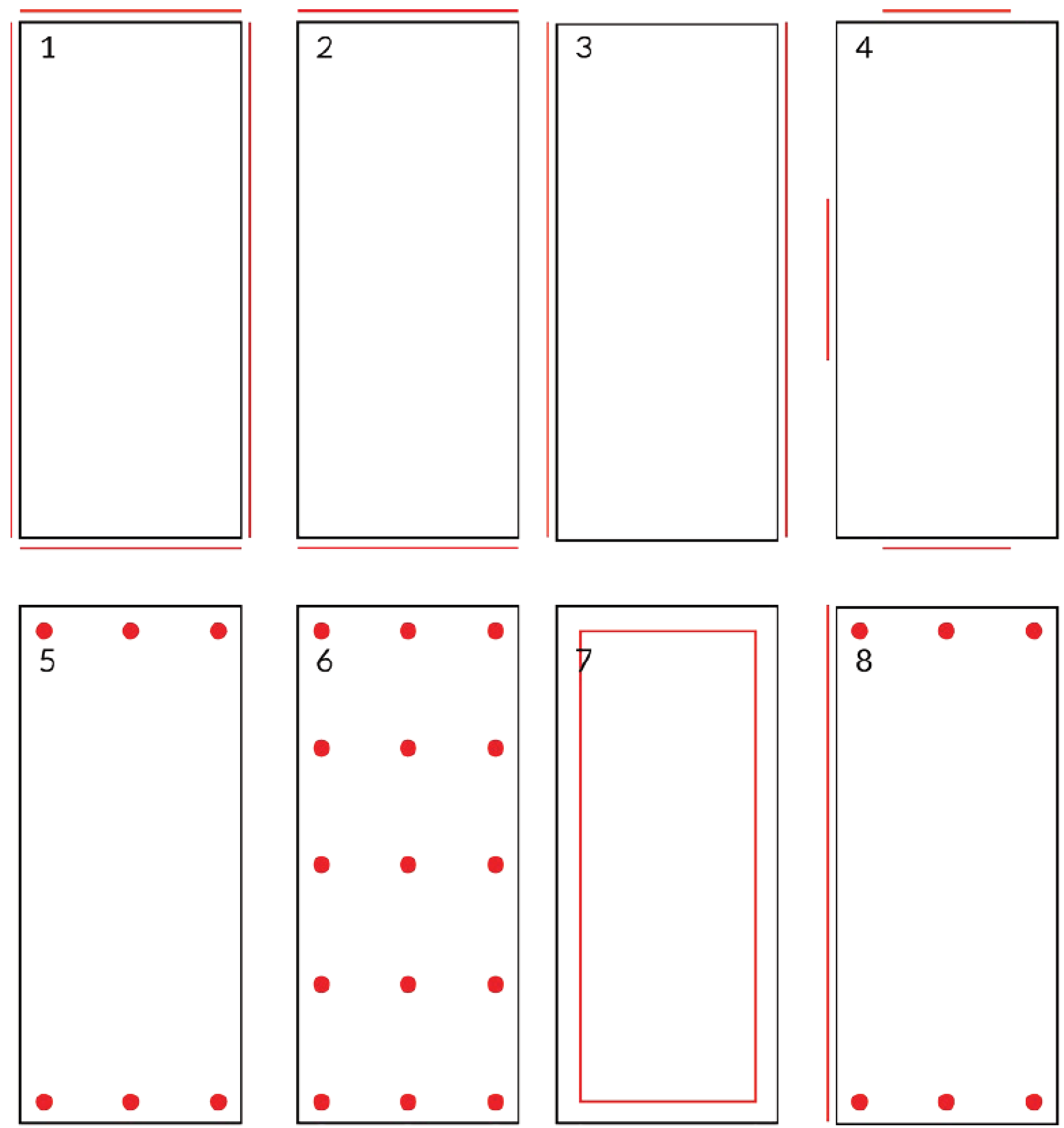
Thin Glass Adaptive panel

- Support
- Move
- Degrees of Freedom



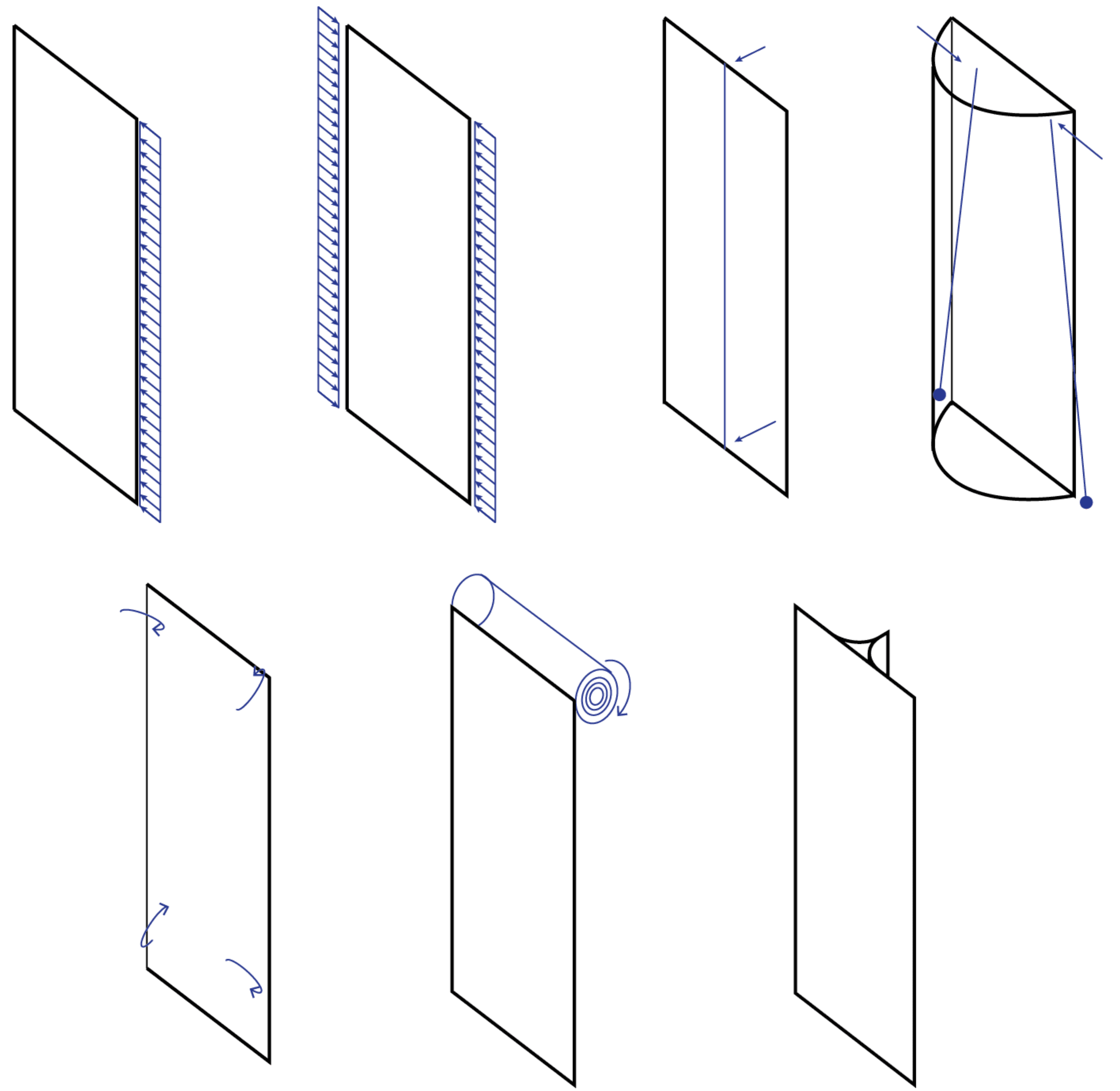
How to Support

- Protect edges
- Avoid stress concentration
- Allow movement
- Avoid blocking the view


1
2
3
4
5
6
7
8

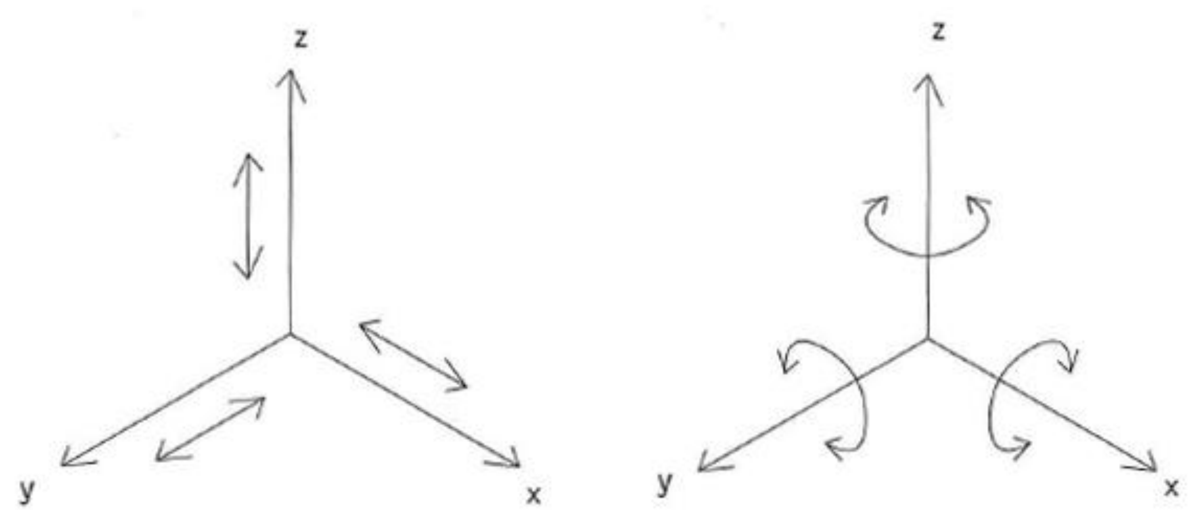
How to Move

- Evidence of movement
- Avoid multiple actuators
- Increase stiffness by geometry
- Double curvature is constrained by the strain of the glass plate



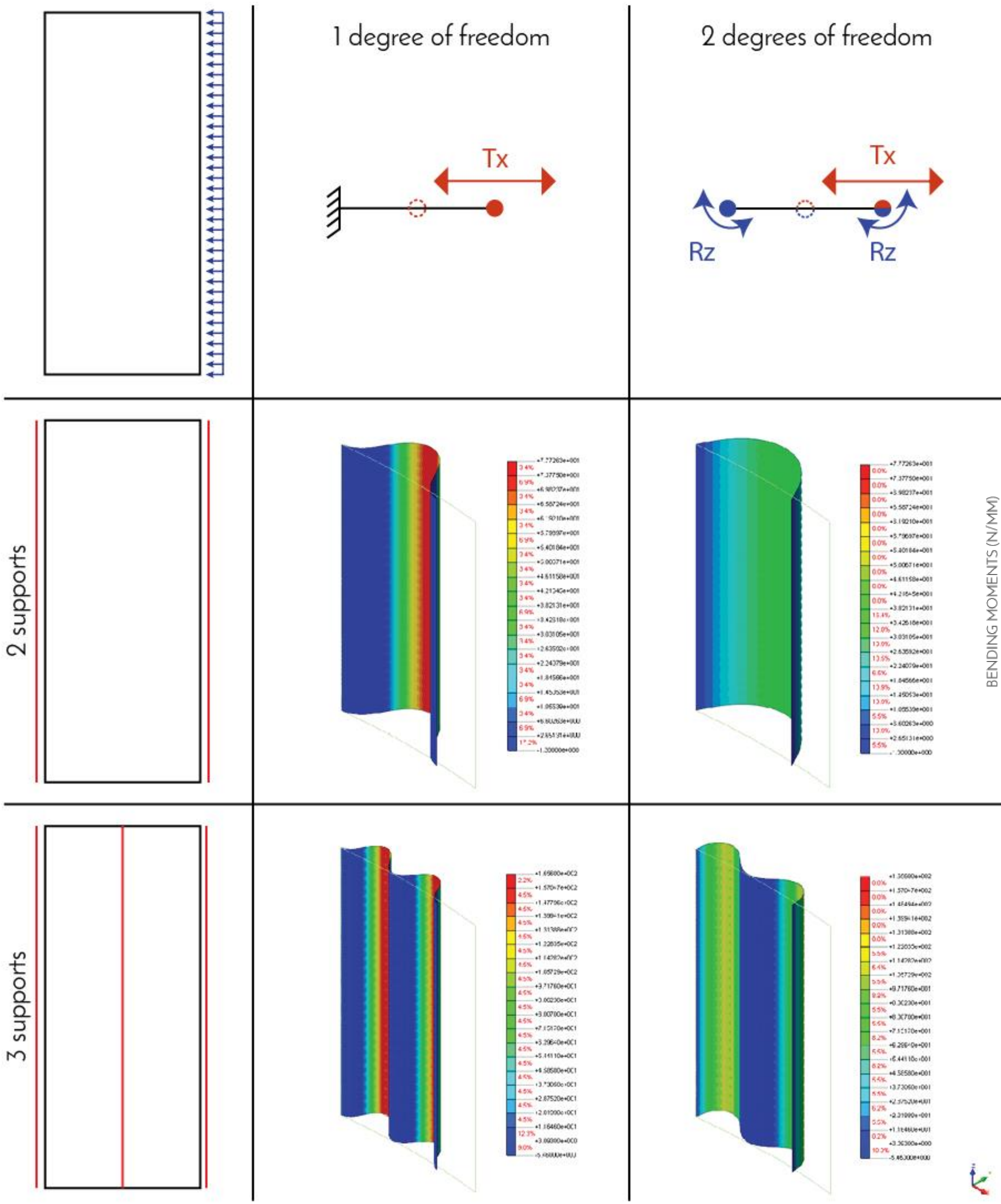
Move and Support

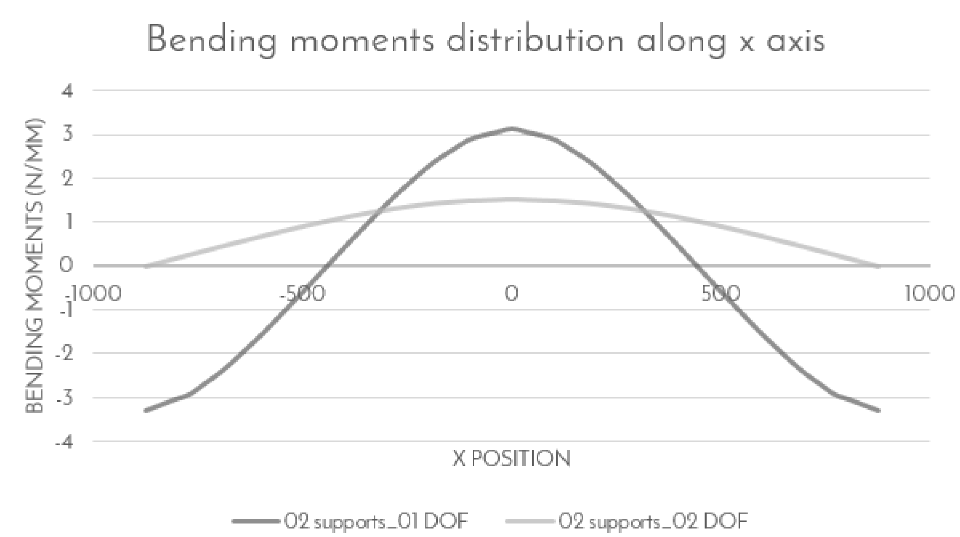
- Degrees of freedom

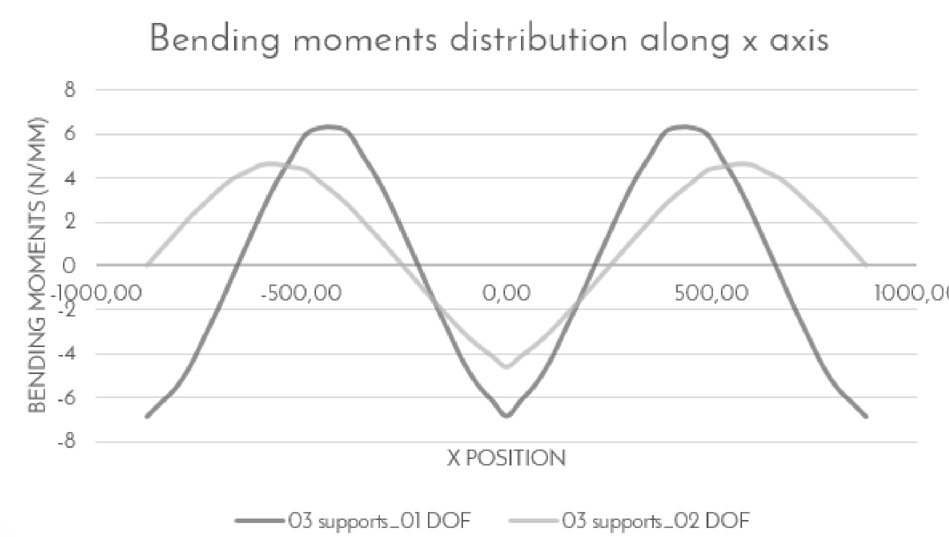


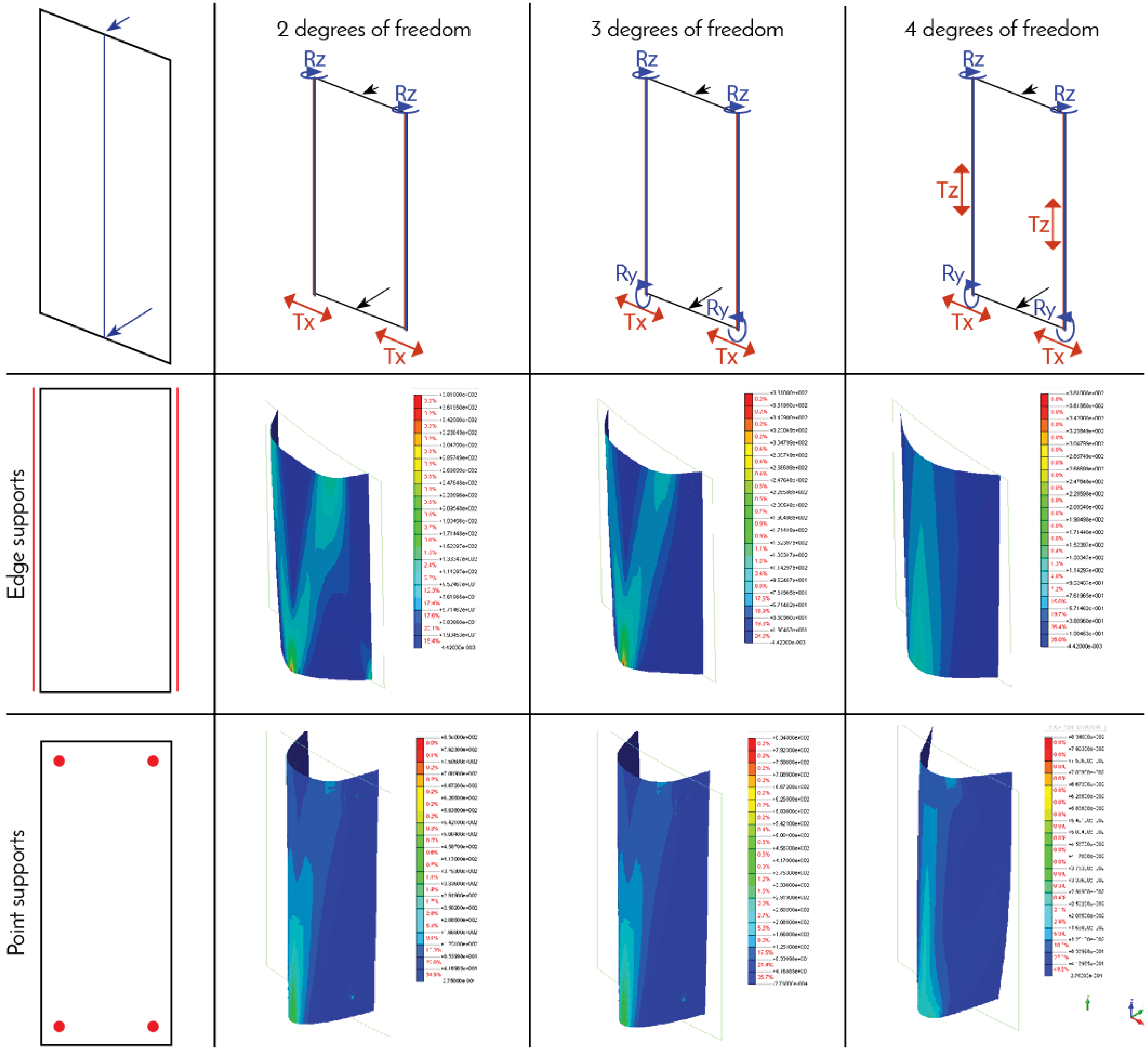
Three degrees of freedom of translation

Three degrees of freedom of rotation


1 degree of freedom
2 degrees of freedom
Tx
Rz
Tx
Rz
2 supports
3 supports

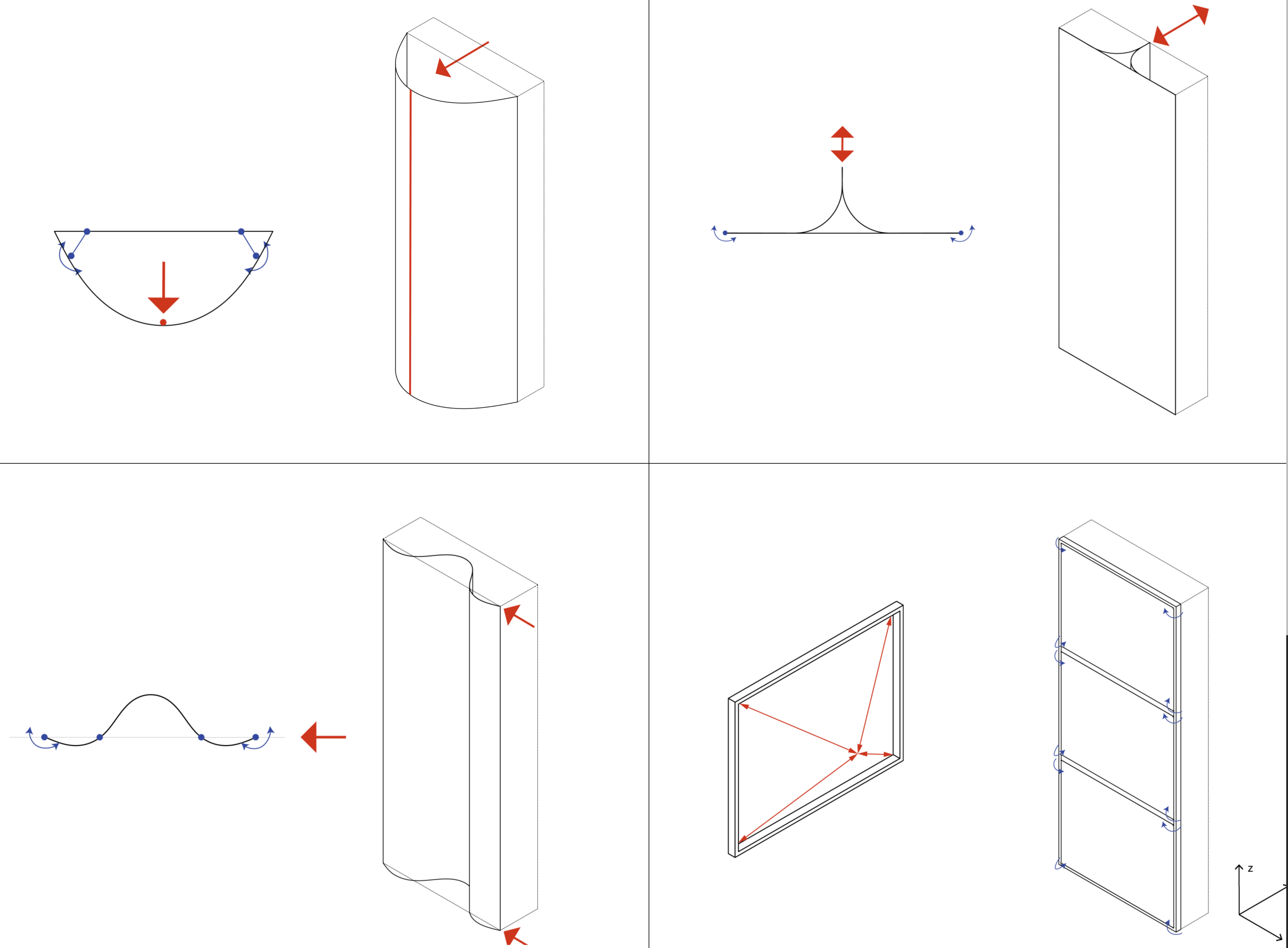

Bending moments distribution along x axis
BENDING MOMENTS (N/MM)
4
3
2
1
0
-1
-2
-3
-4
-1000
-500
0
500
1000
X POSITION
02 supports_01 DOF
02 supports_02 DOF


Bending moments distribution along x axis
BENDING MOMENTS (N/MM)
8
6
4
2
0
-2
-4
-6
-8
-1000,00
-500,00
0,00
500,00
1000,00
X POSITION
03 supports_01 DOF
03 supports_02 DOF


2 degrees of freedom
3 degrees of freedom
4 degrees of freedom
Rz
Ry
Tx
Tz
Edge supports
Point supports

Move and Support

- Number and type of supports can influence the geometry
- Fewer degrees of freedom - stress concentration
- More degrees of freedom – excess of complexity on design or unpredictability
- Suitable type of support and degrees of freedom depends on the desired movement and geometry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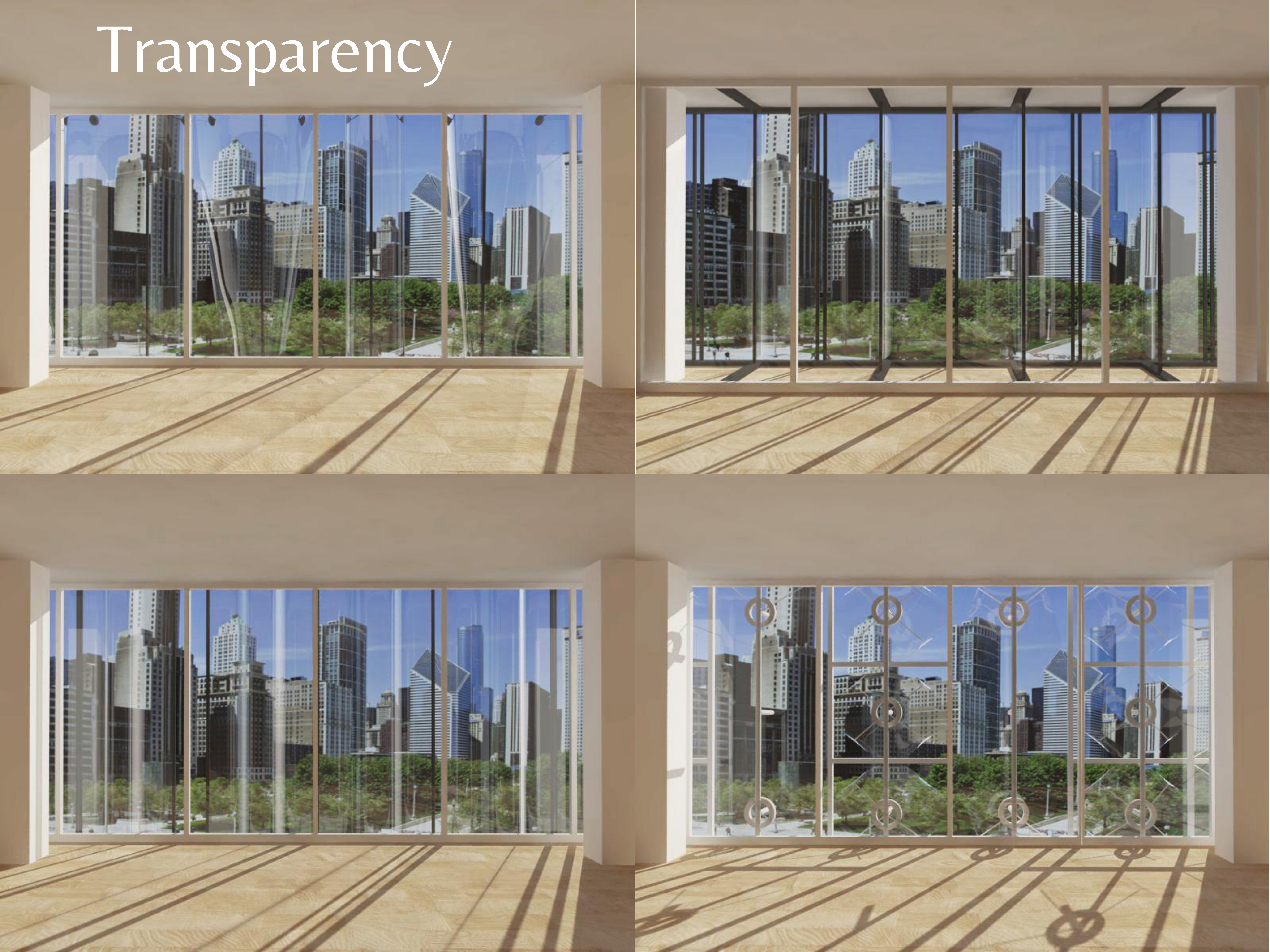
Parameters for design solution

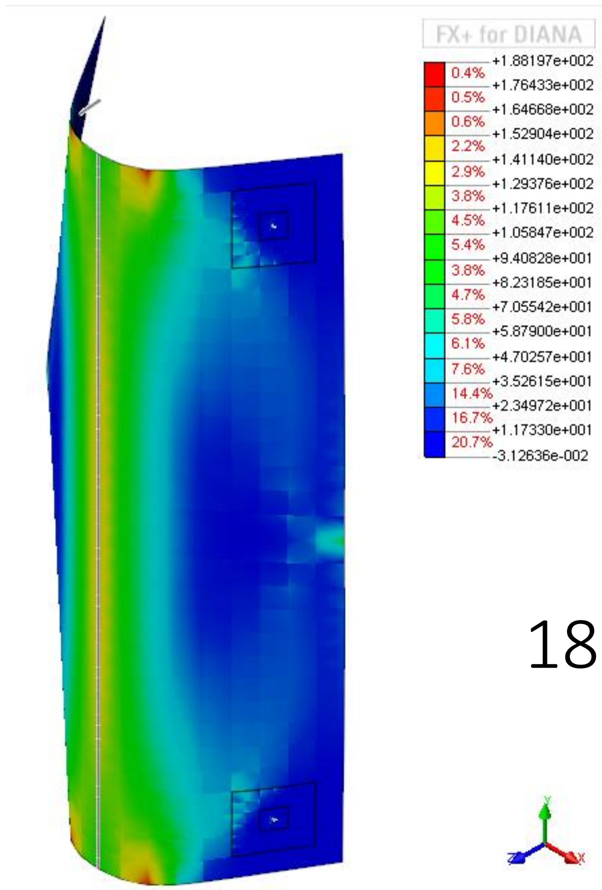
- Transparency
- Stiffness
- Adaptiveness
- Feasibility

Transparency

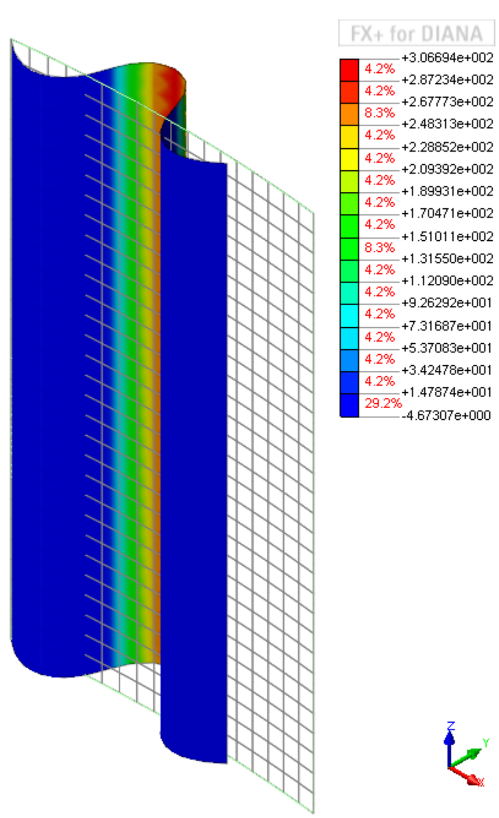


Stiffness

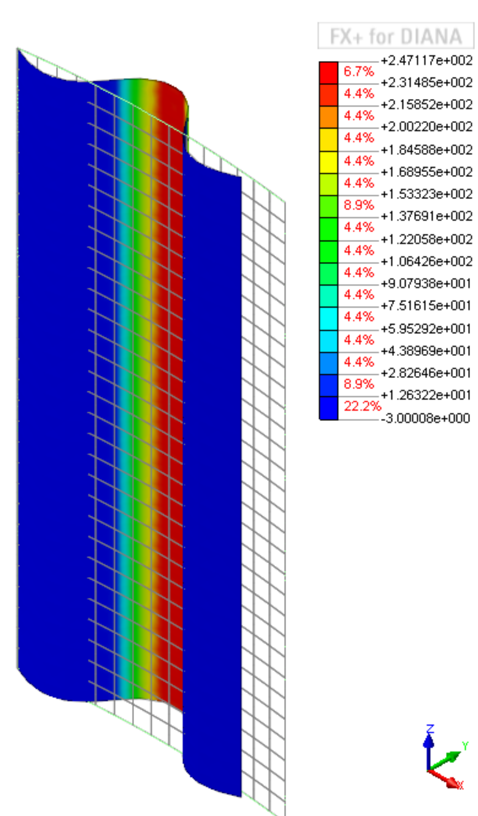
Initial bending stress



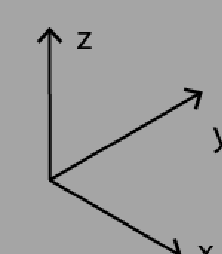
180MPa

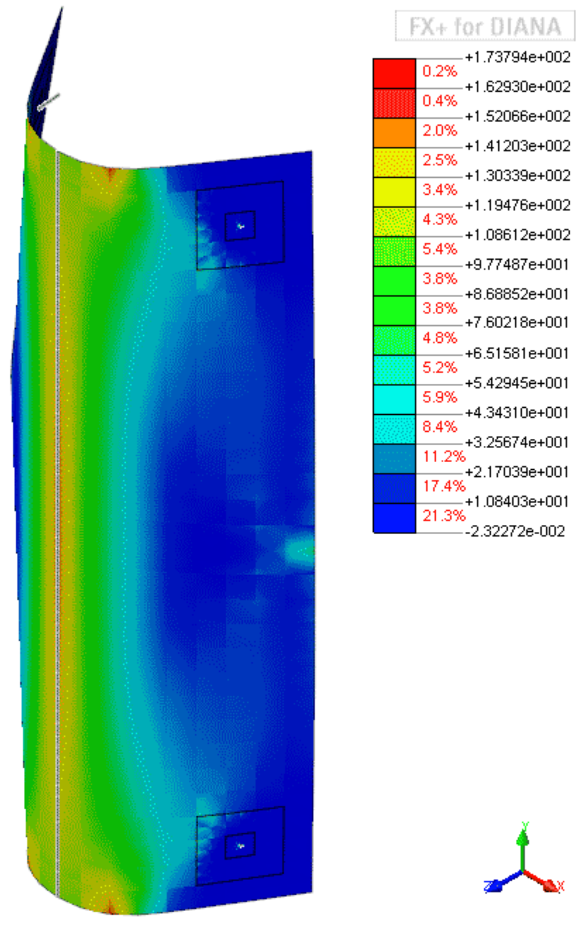


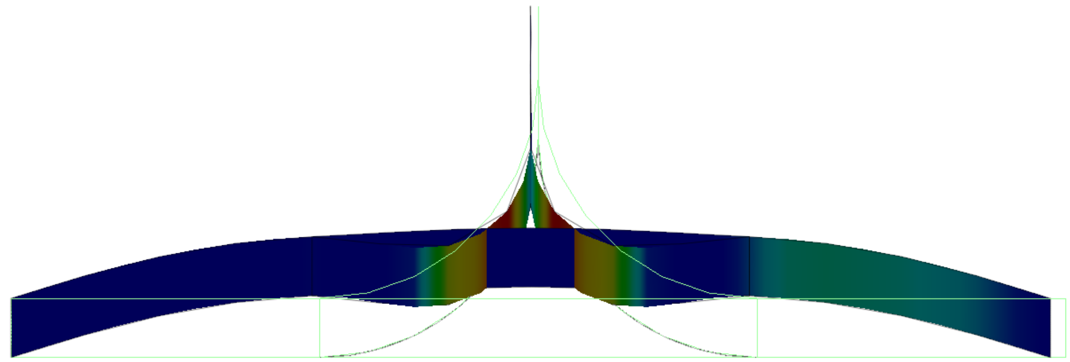
300MPa

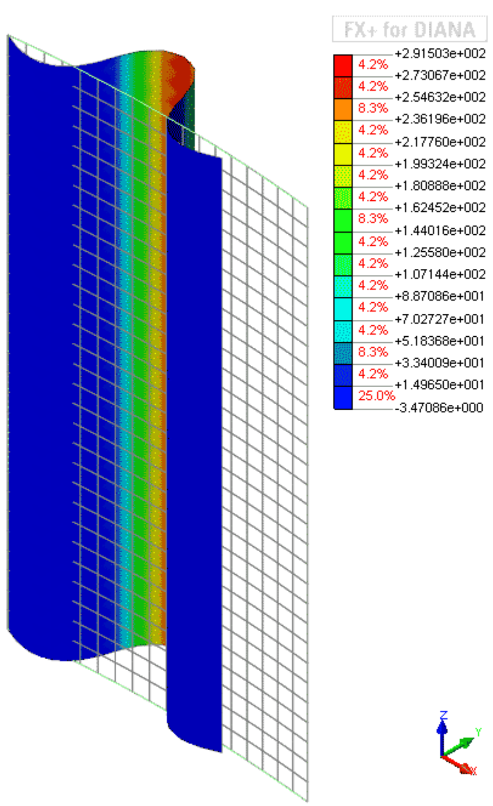


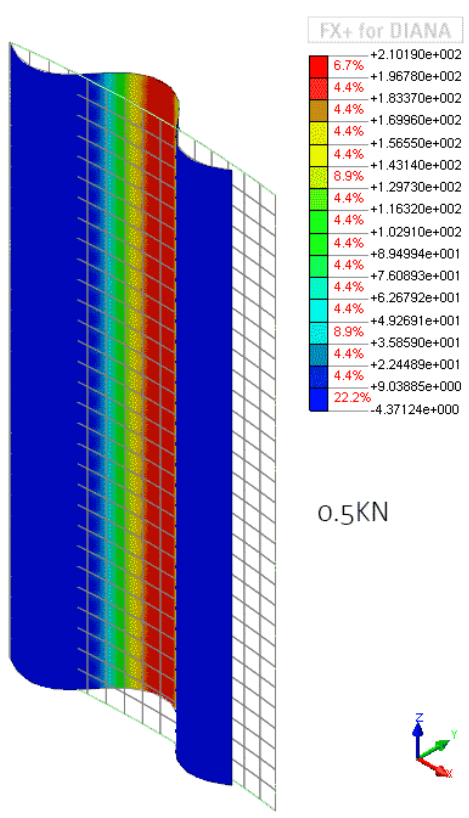
240MPa









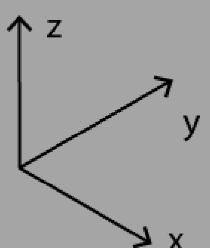


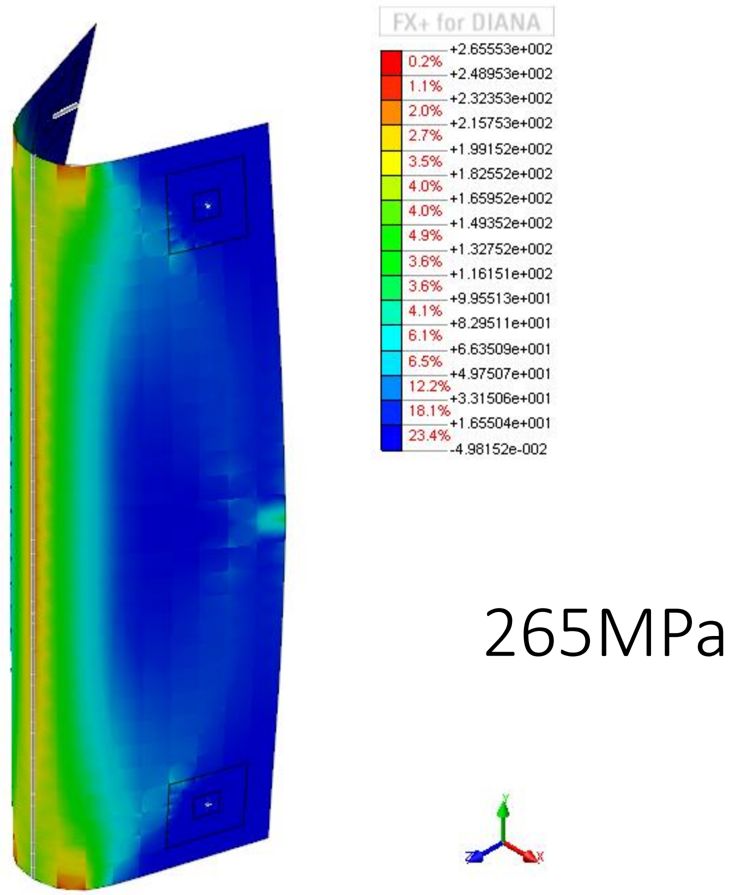
0.5KN

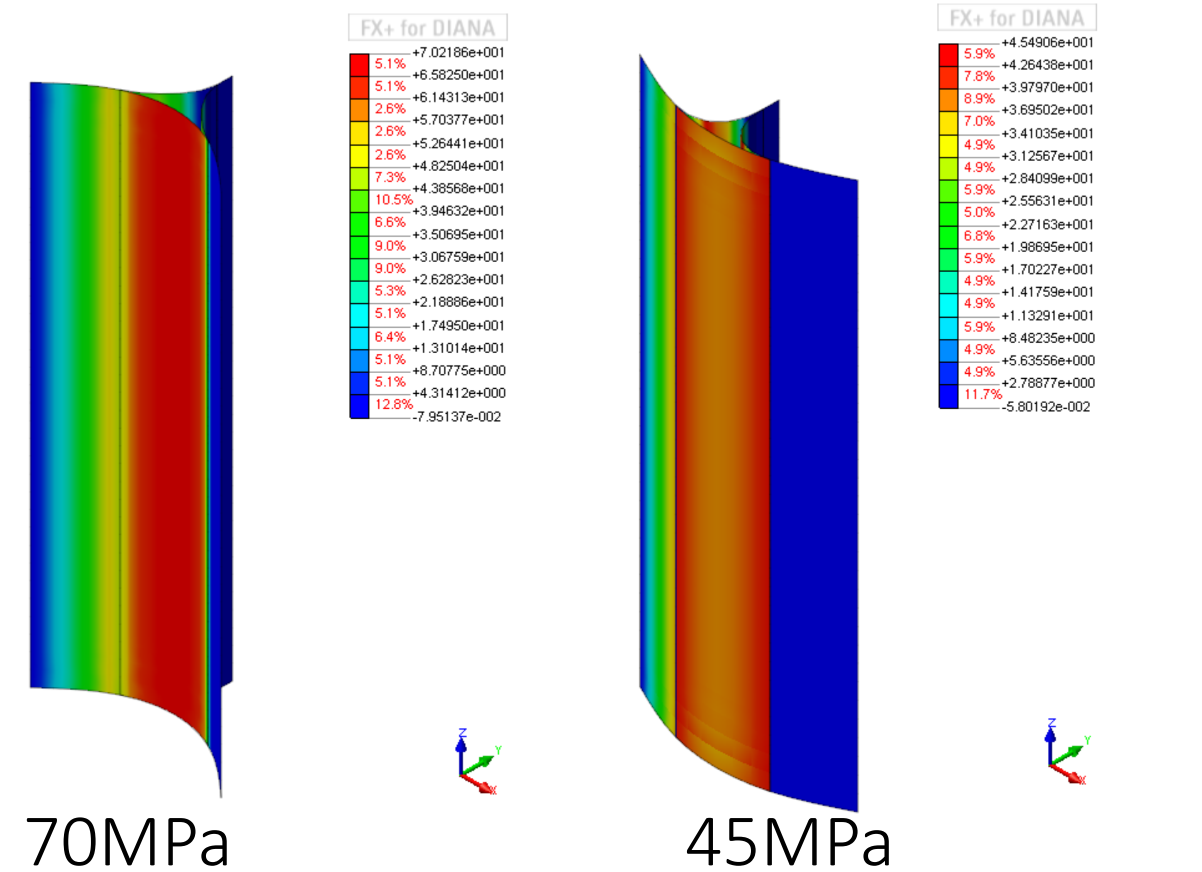
Stiffness

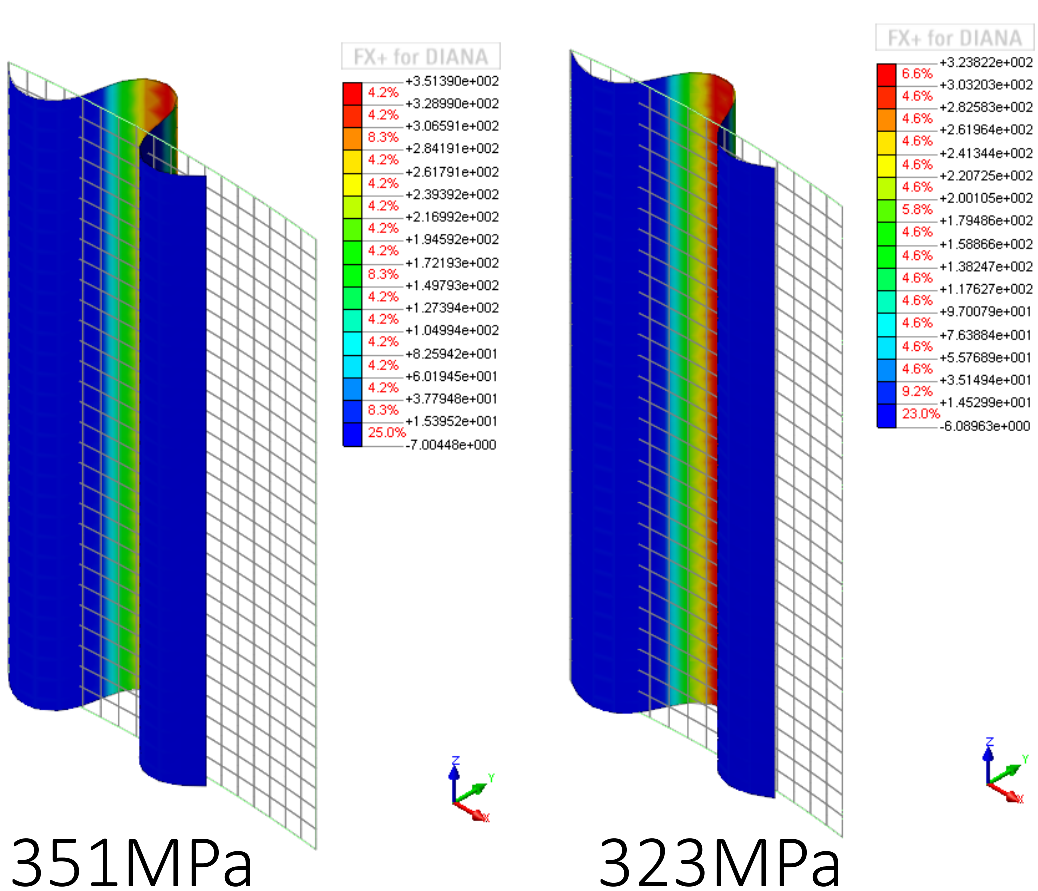
Wind bending stress

On initial bending



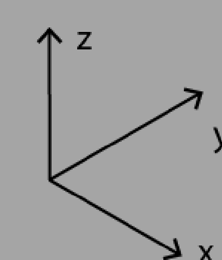


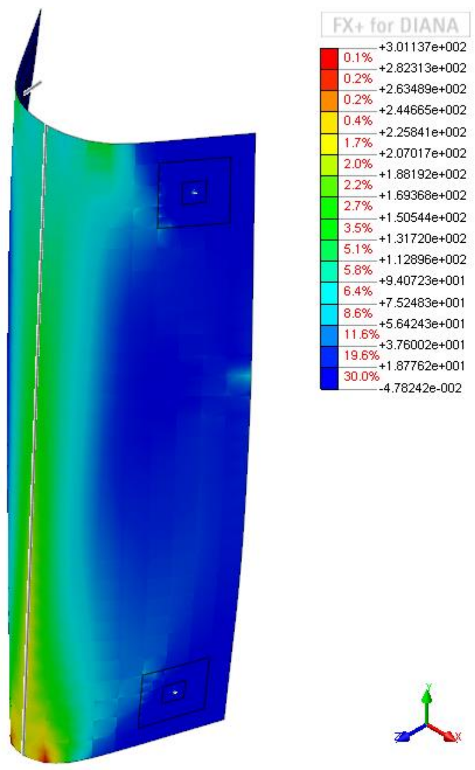




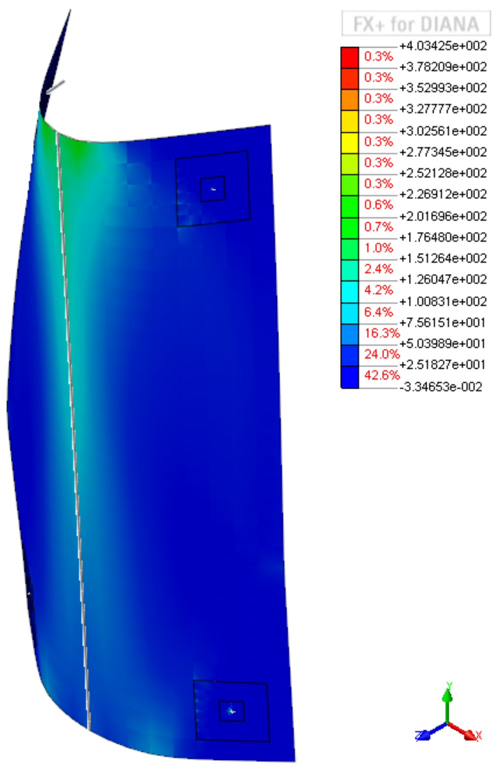
Stiffness

Increased bending stress

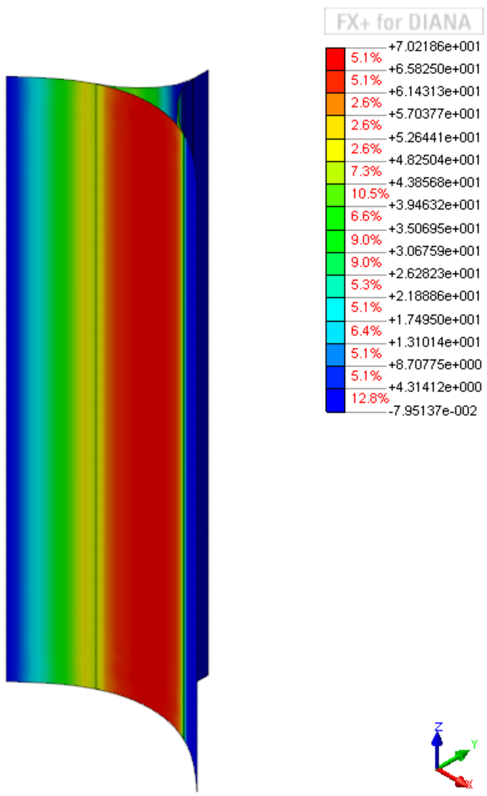




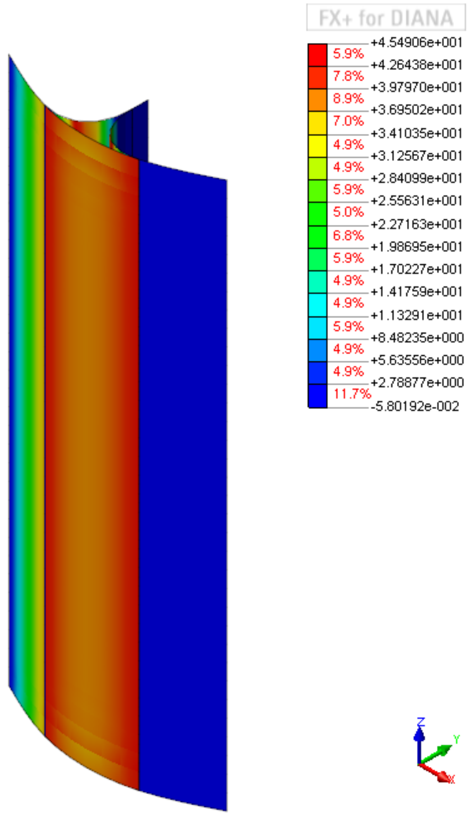
300MPa



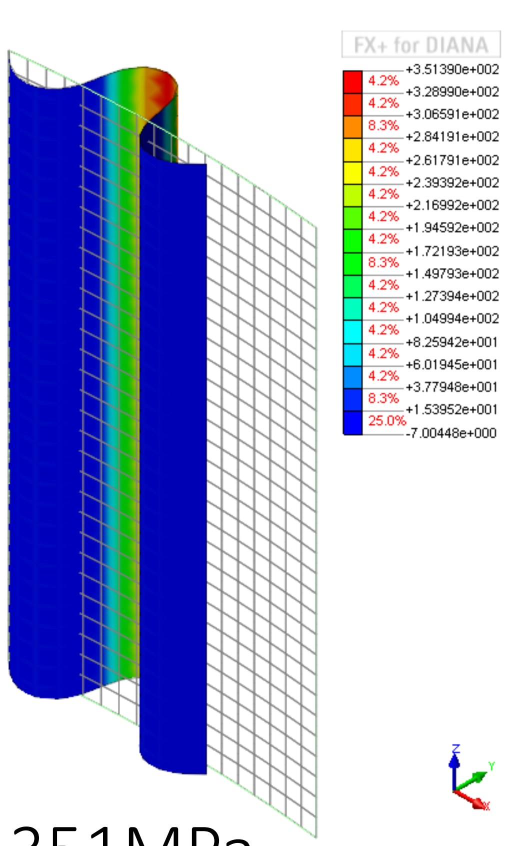
260MPa



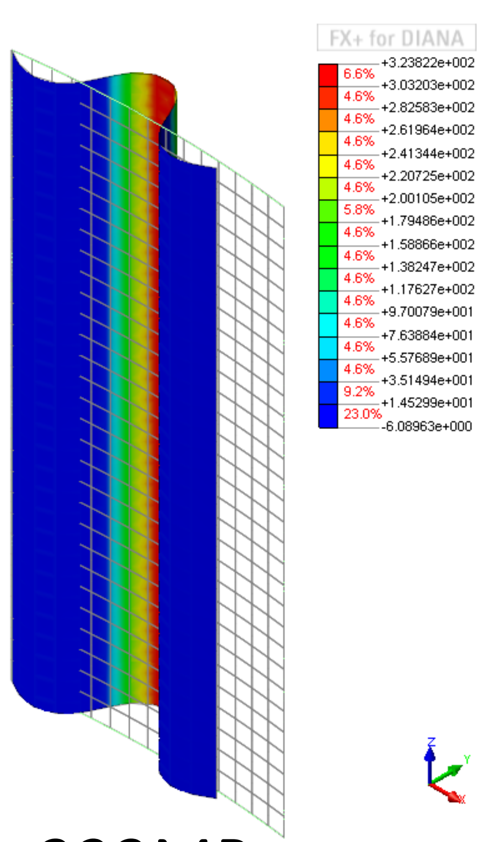
70MPa



45MPa



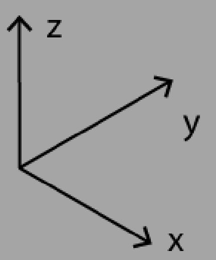
351MPa

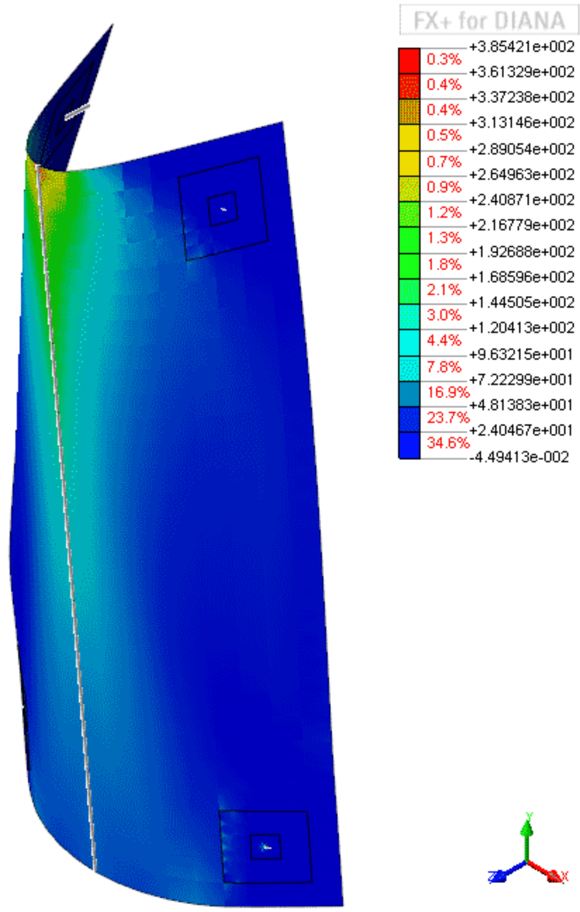


323MPa

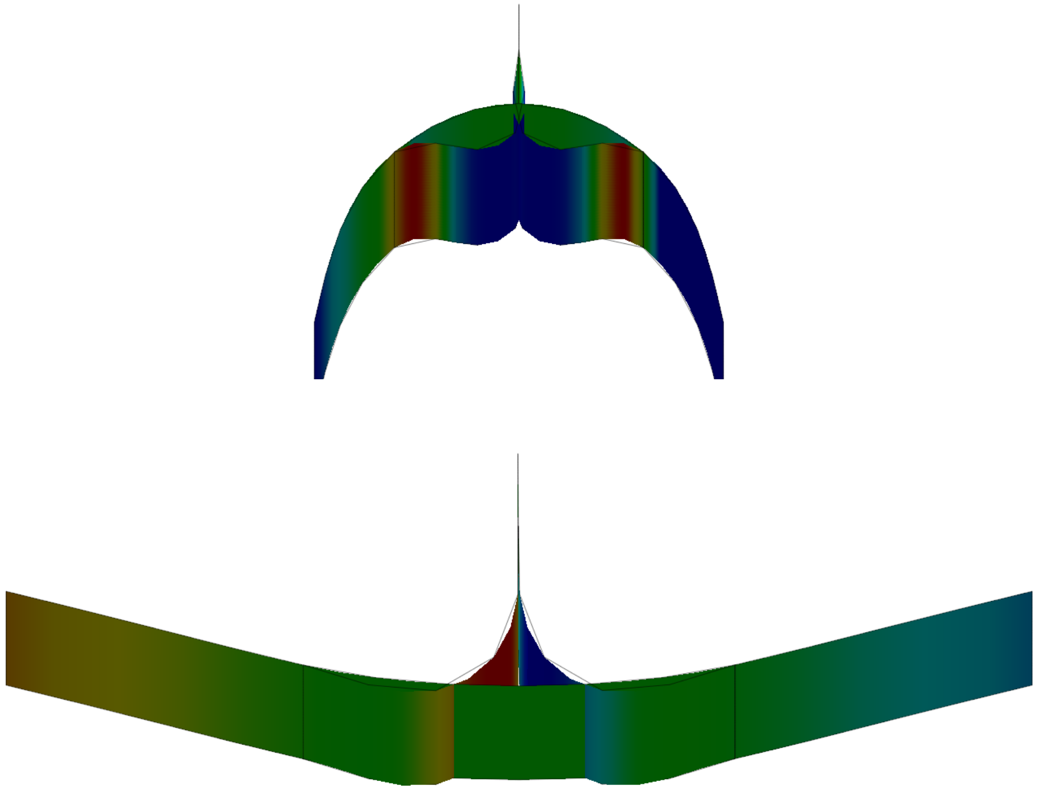
Stiffness

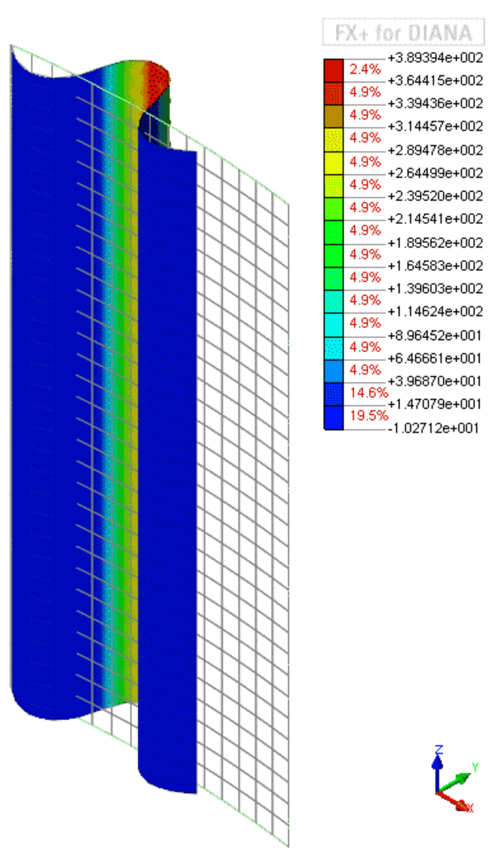
Increased bending stress





300MPa

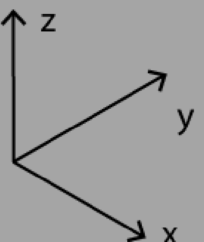


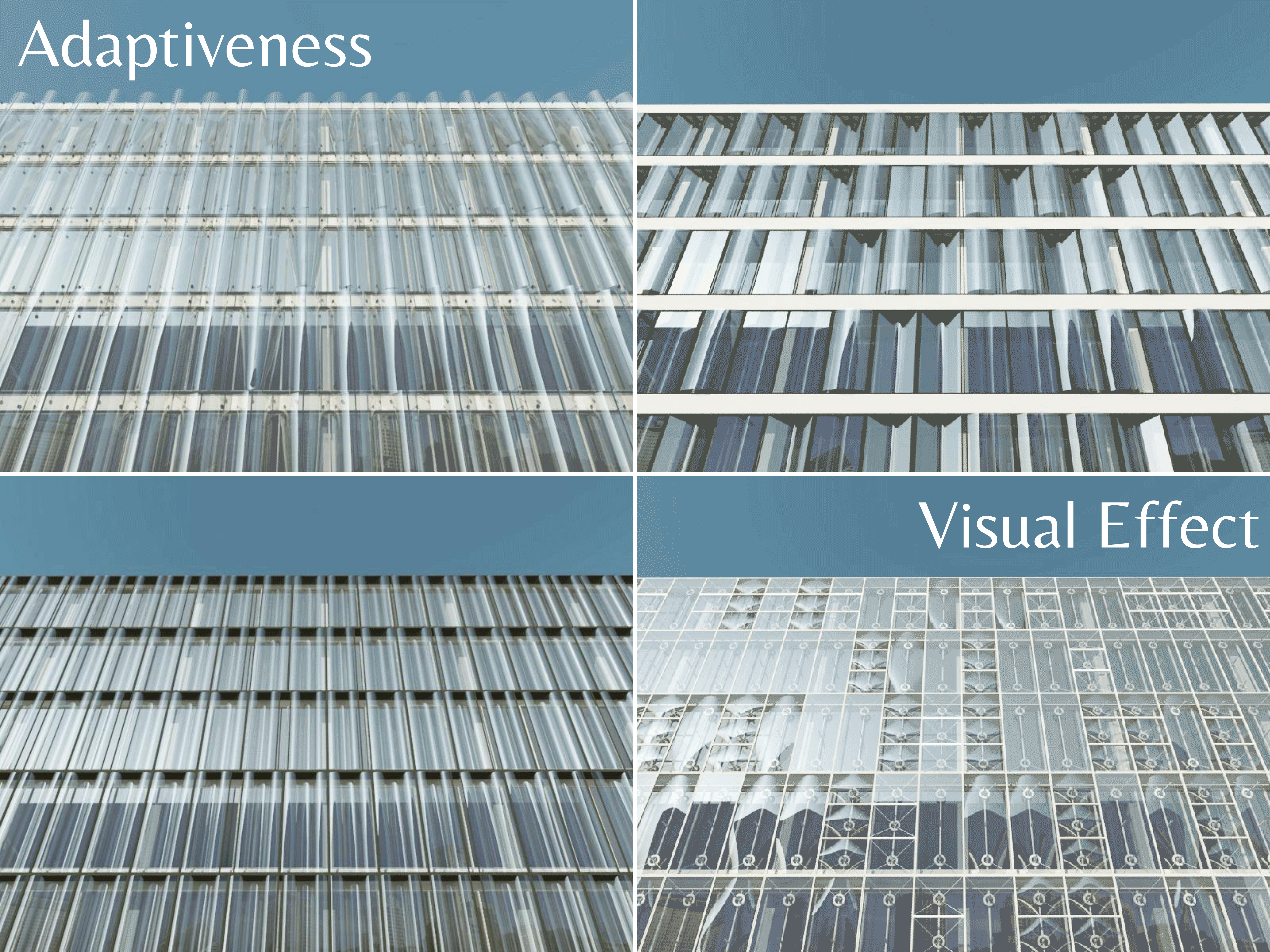


Stiffness

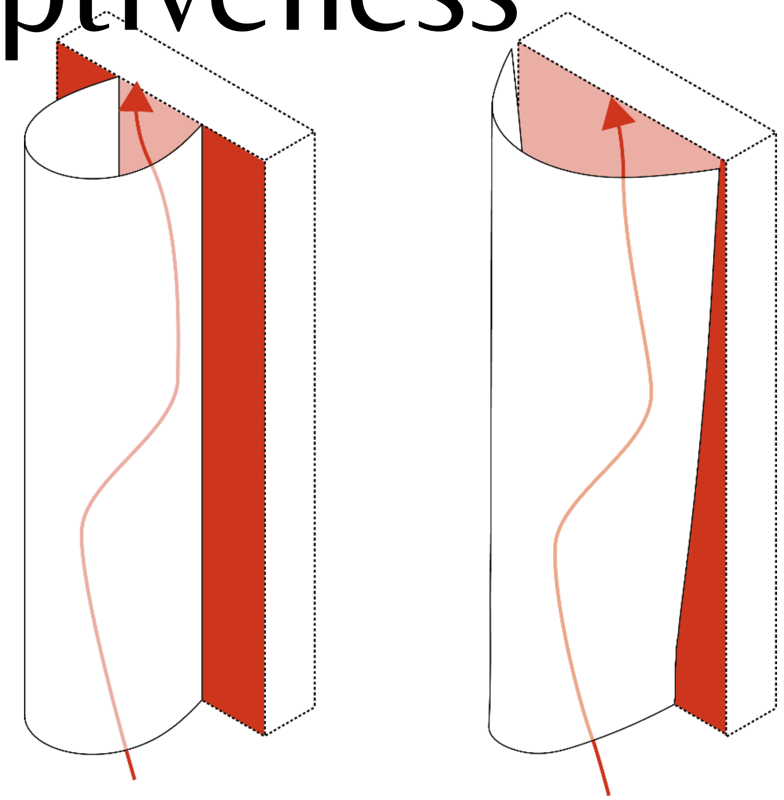
Wind bending stress

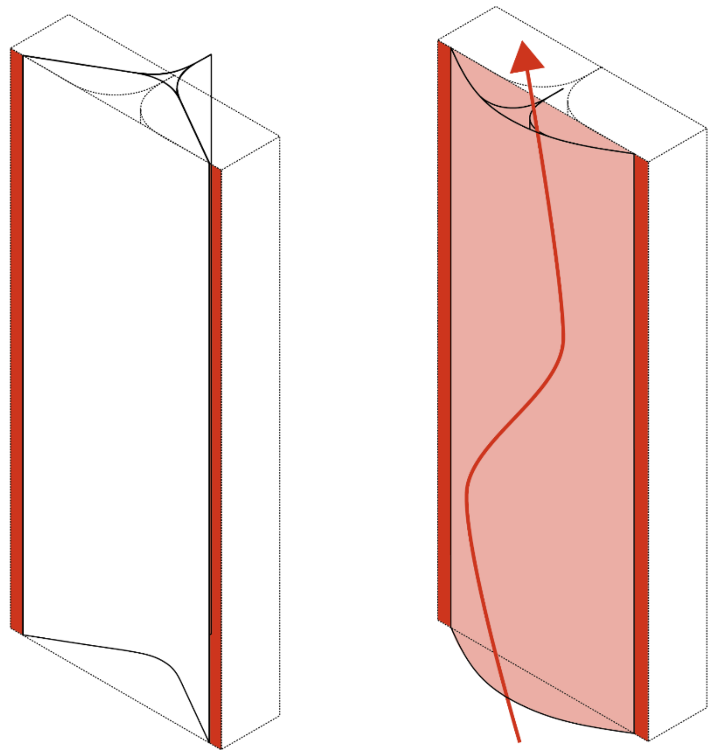
On increased bending

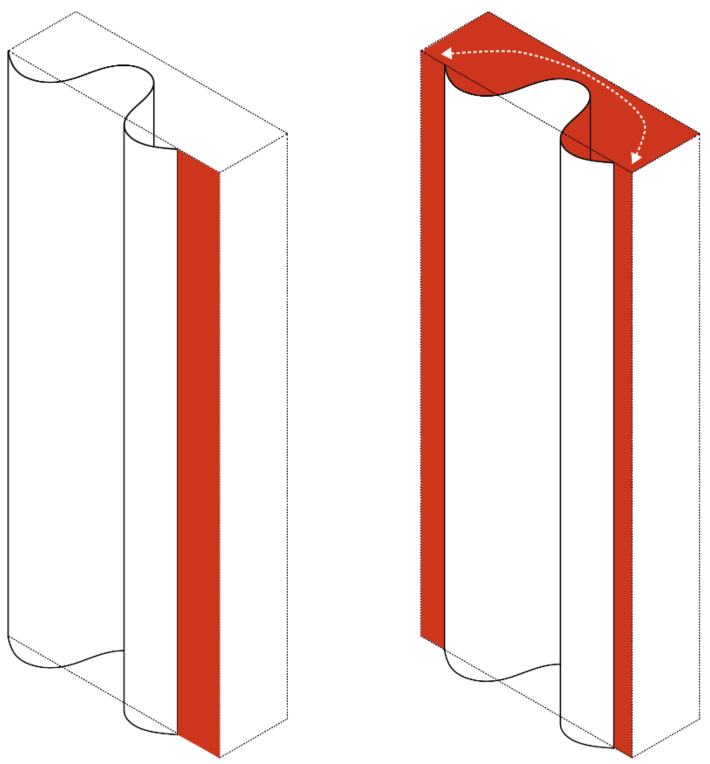



Adaptiveness
Visual Effect

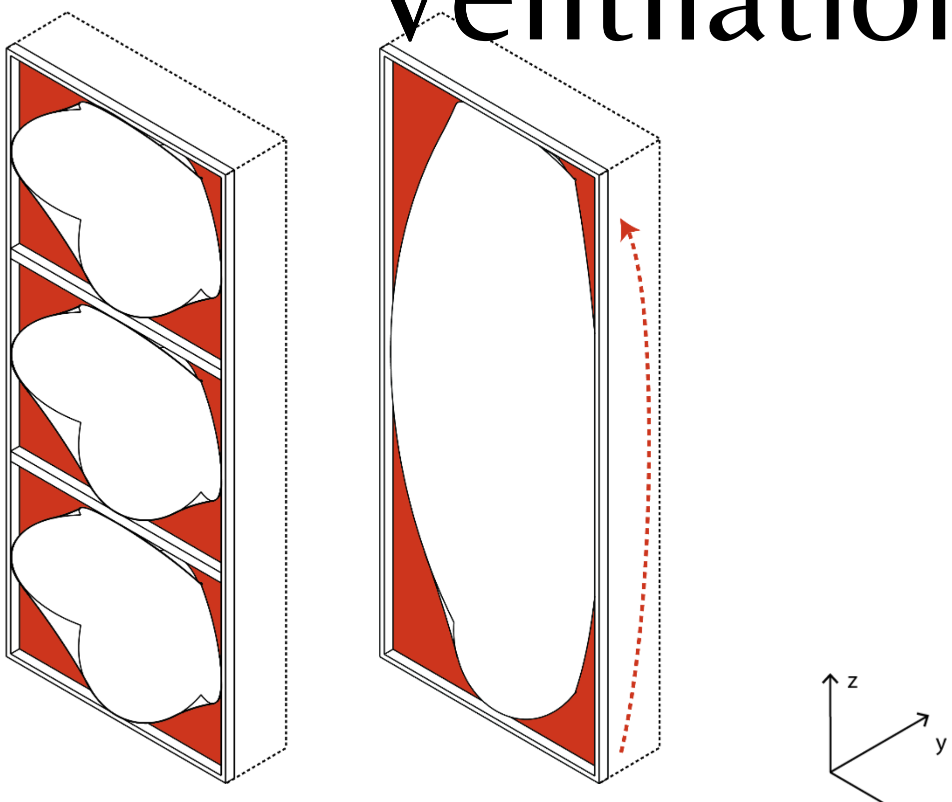
Adaptiveness



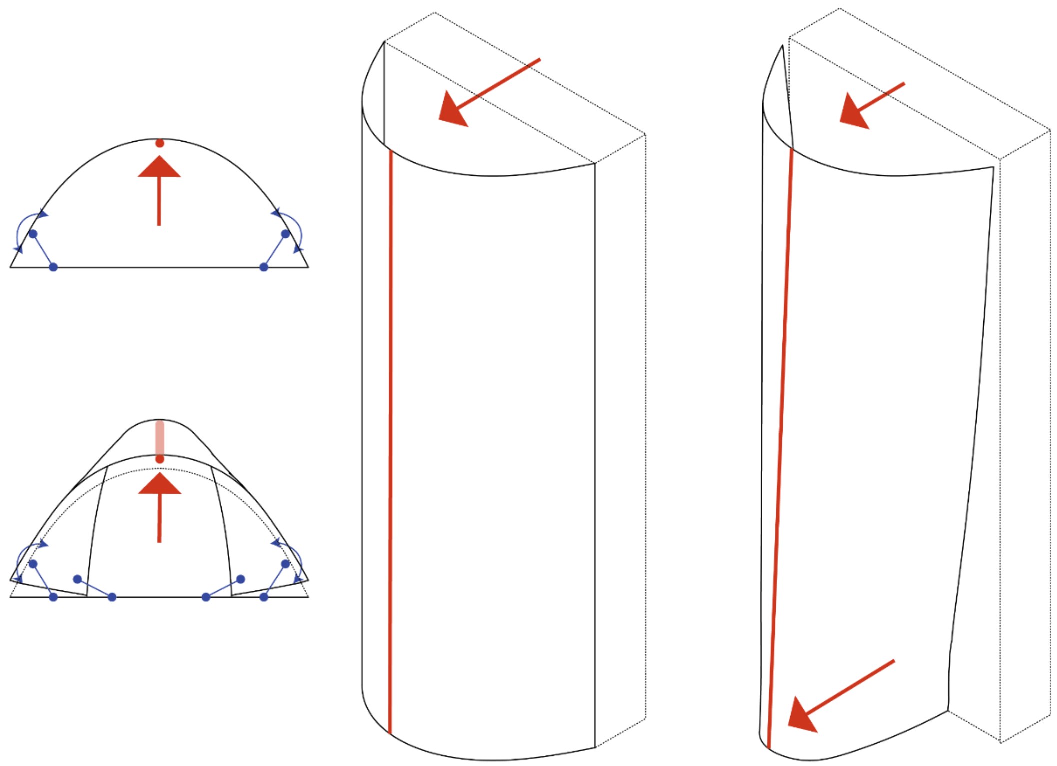


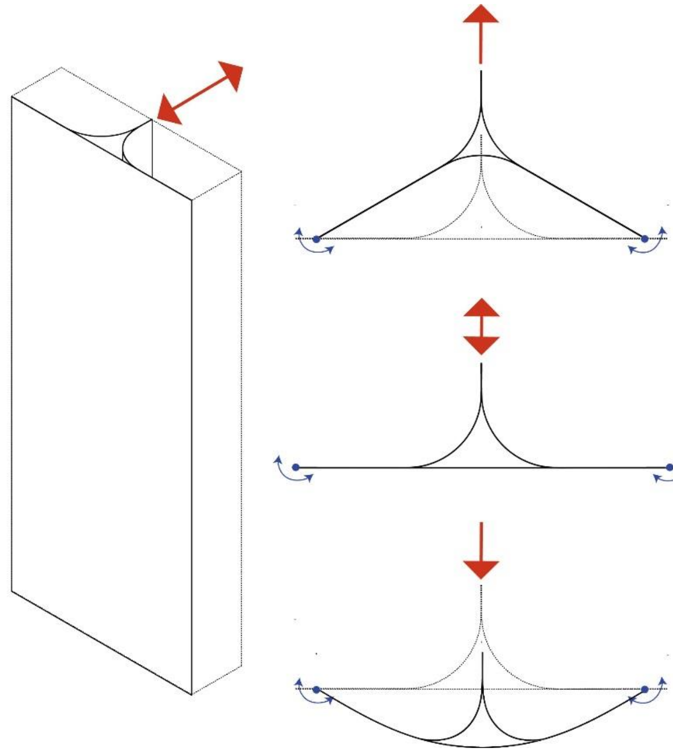


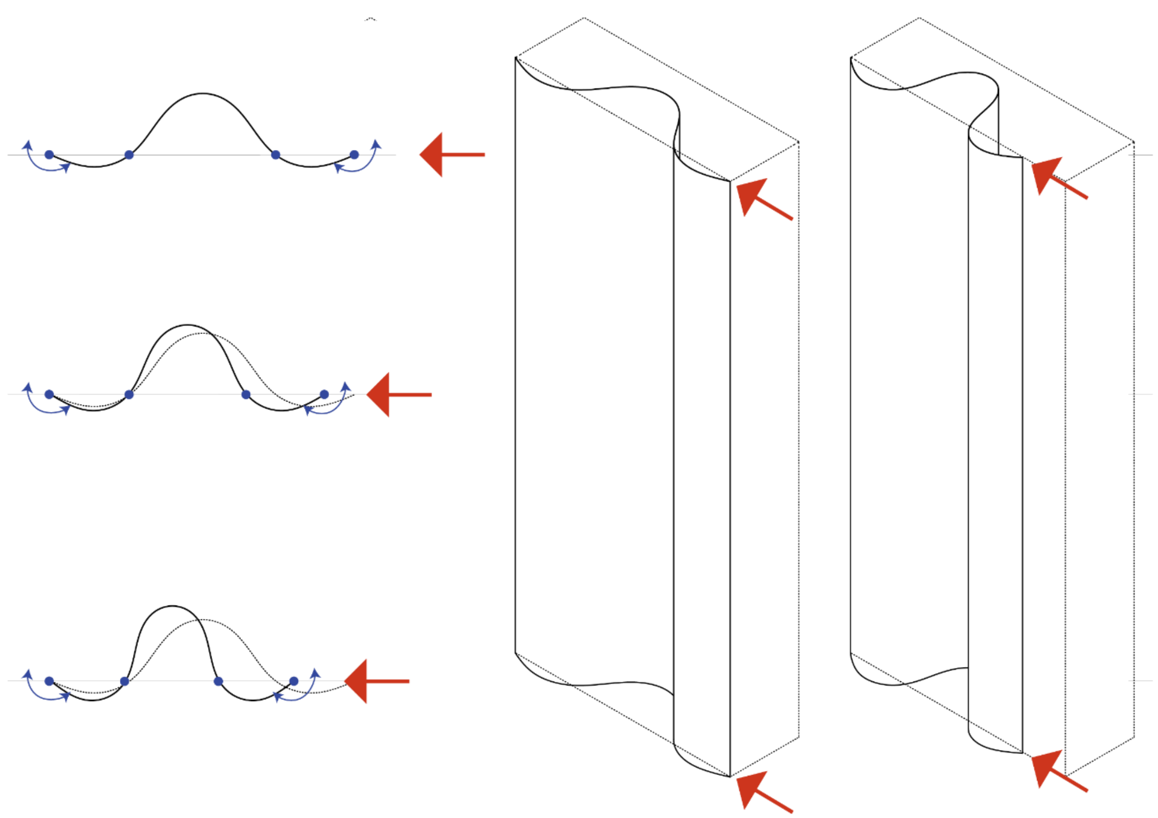
Ventilation

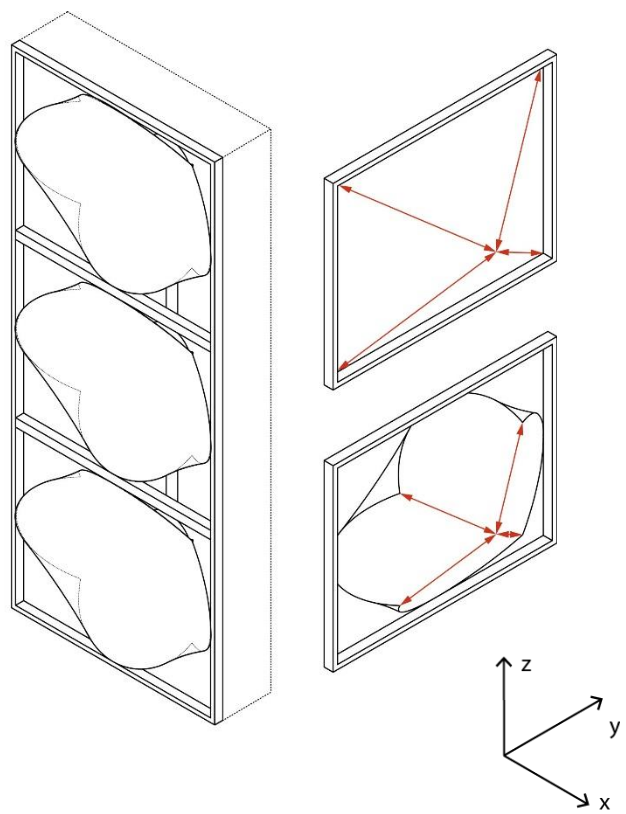


Feasibility

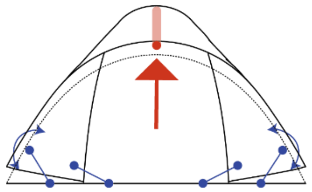




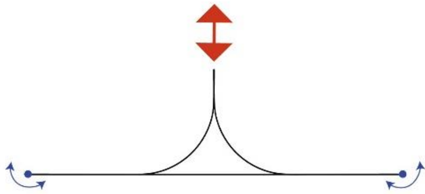




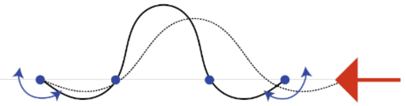
Conclusions



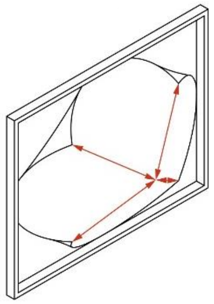
- Pros:
  - Transparency, visual effect, stiffness, feasibility
- Cons:
  - Feasibility



- Pros:
  - Stiffness, feasibility
- Cons:
  - Transparency, visual effect, feasibility



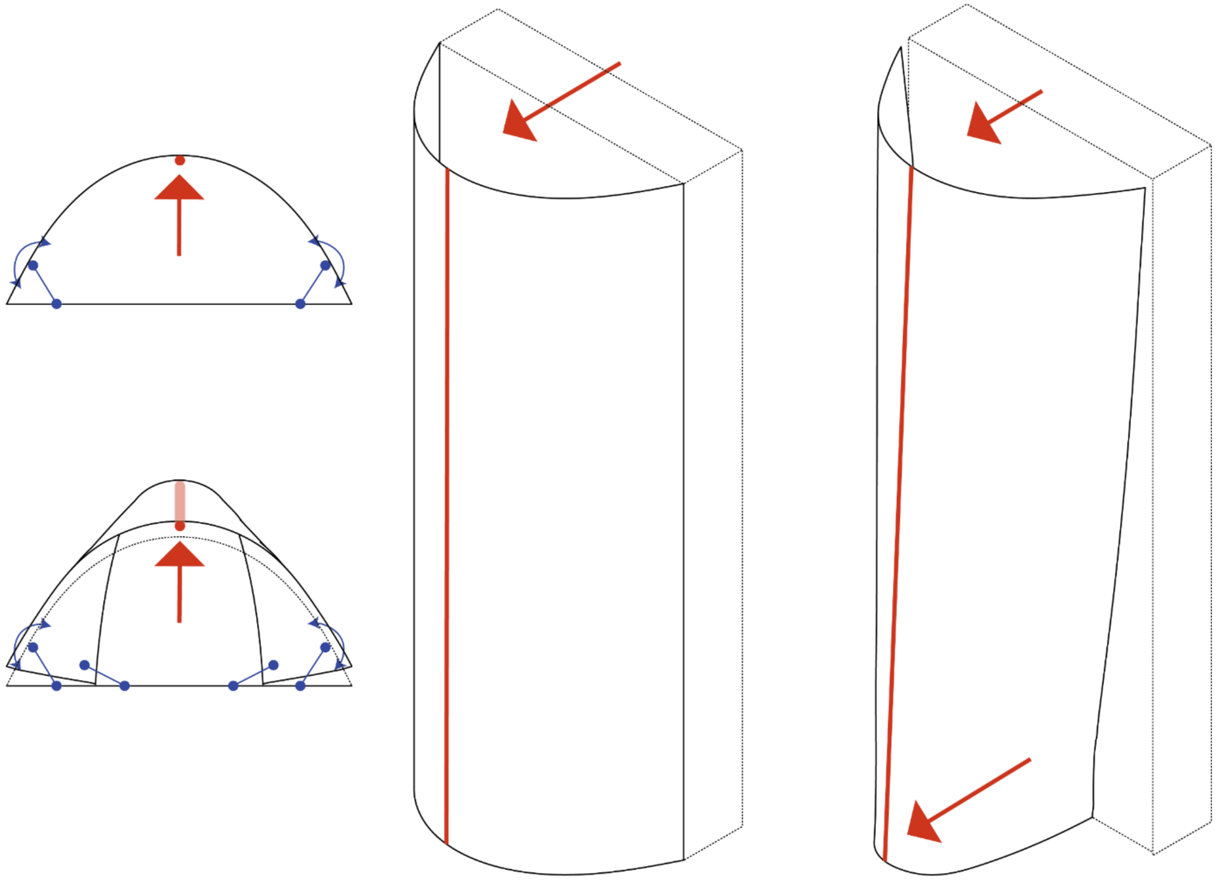
- Pros:
  - Transparency, stiffness, feasibility
- Cons:
  - Visual effect, stiffness, feasibility

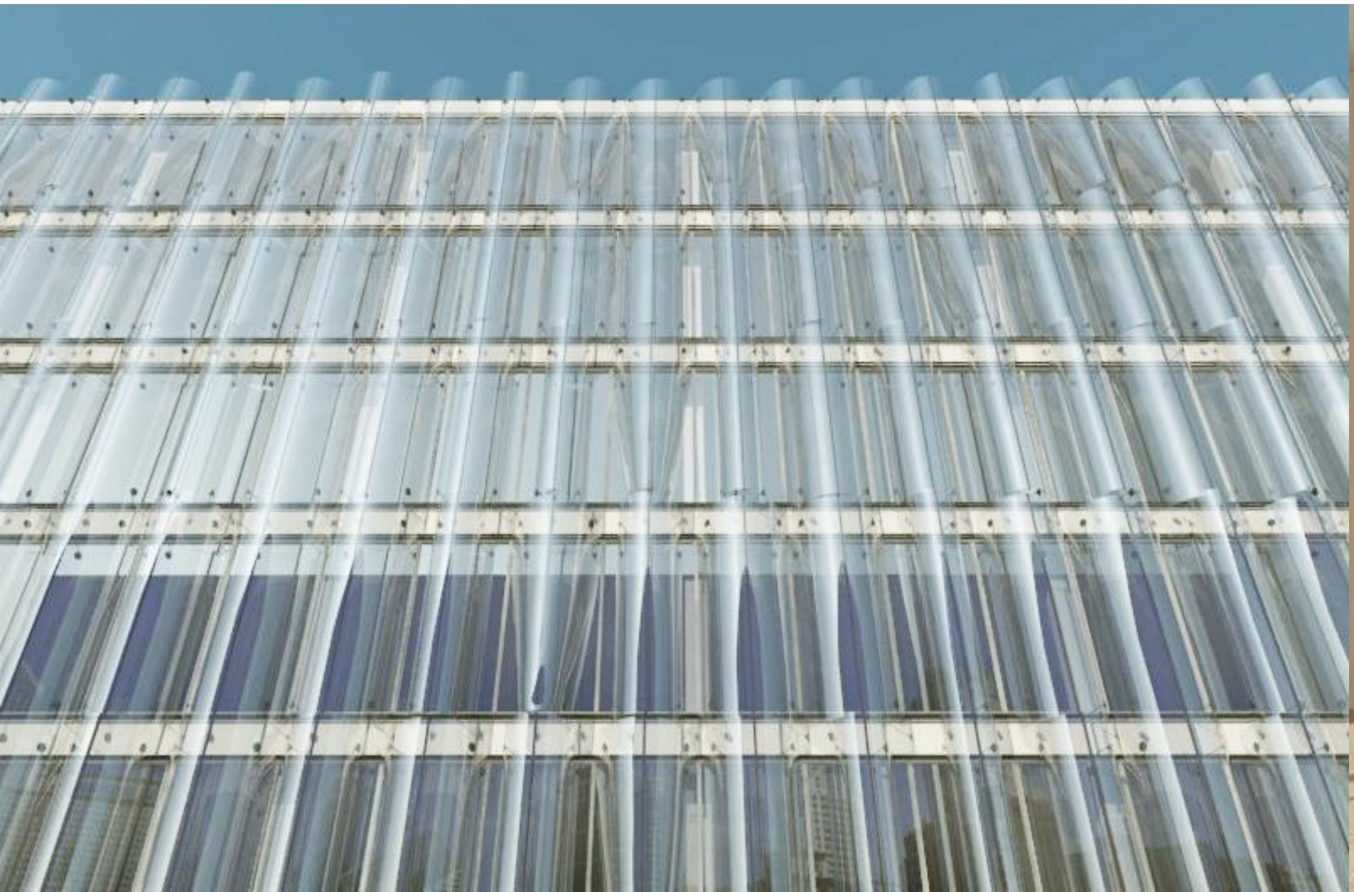


- Pros:
  - Visual effect
- Cons:
  - Transparency, feasibility

Conclusions

- Adjust this design strategy to reduce peak stresses and facilitate feasibility of the concept

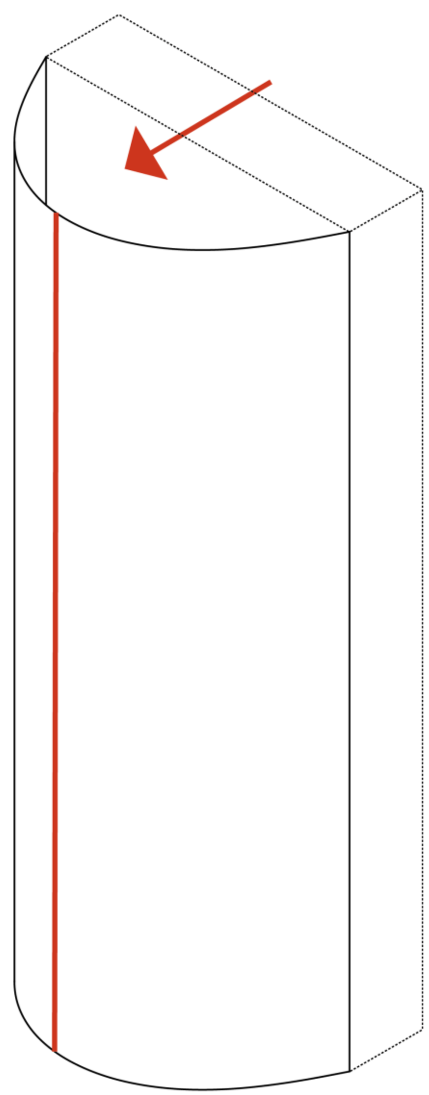


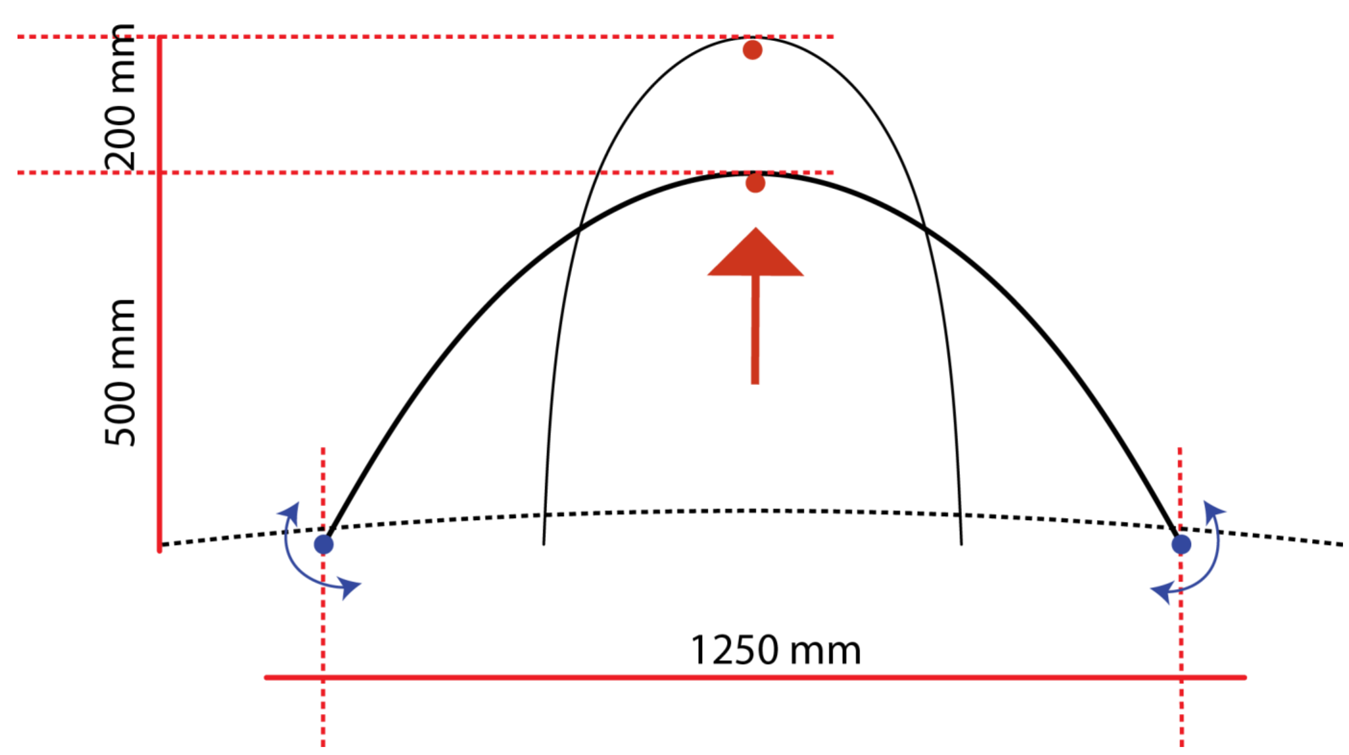


Analysis of the design strategy

- Movement and Support
- Necessary degrees of freedom
- Fem analysis
- Translation in design

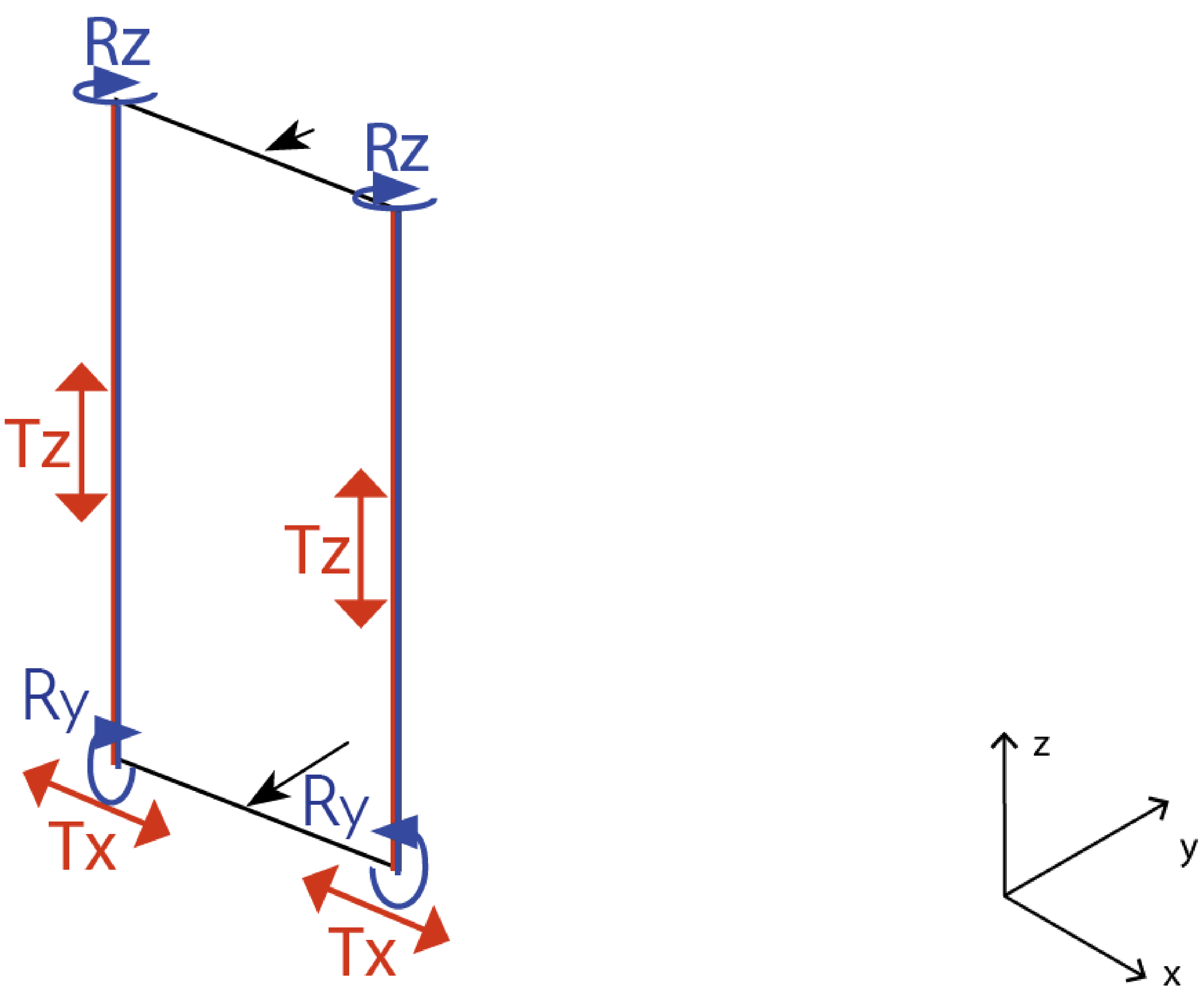
Movement and support





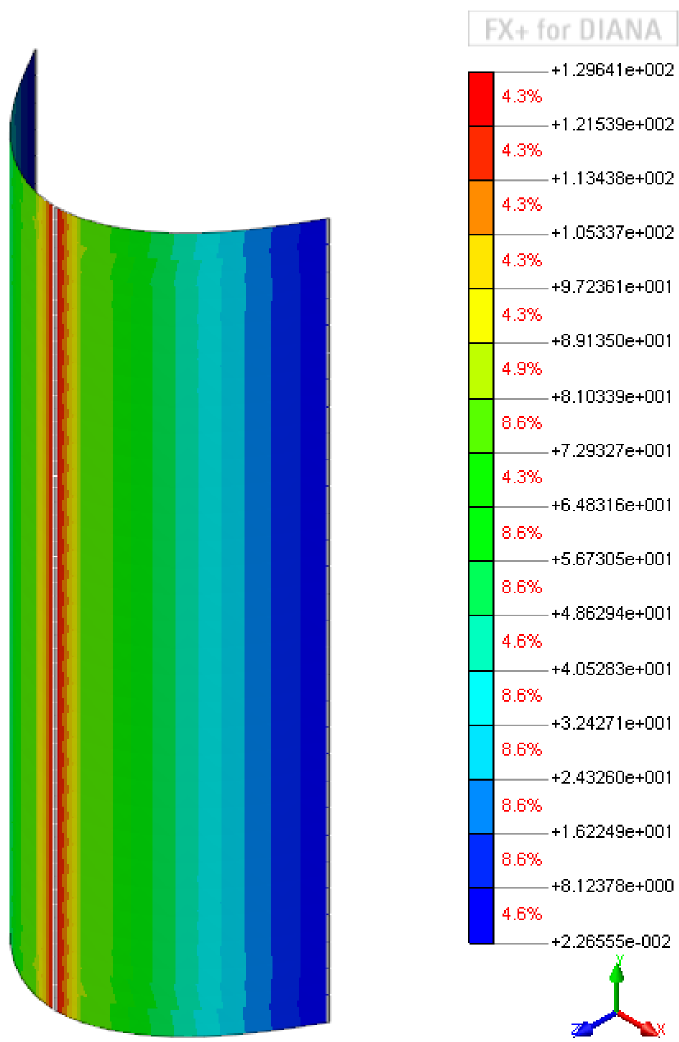
Analysis of the panel degrees of freedom

4 degrees of freedom

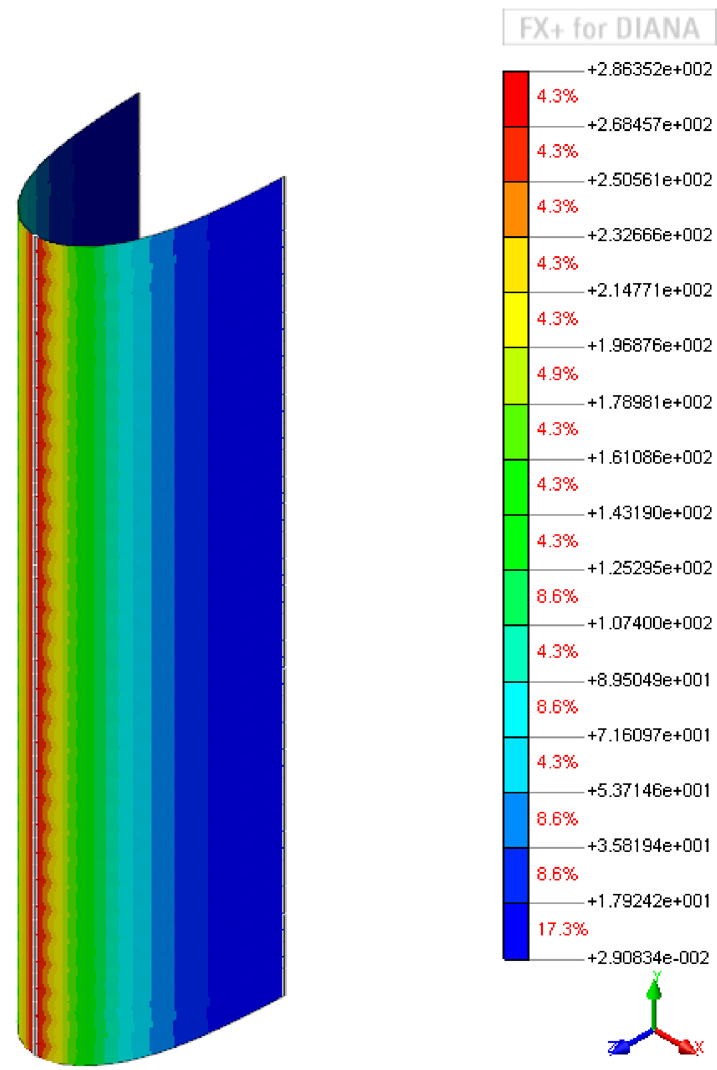


Bending Stresses

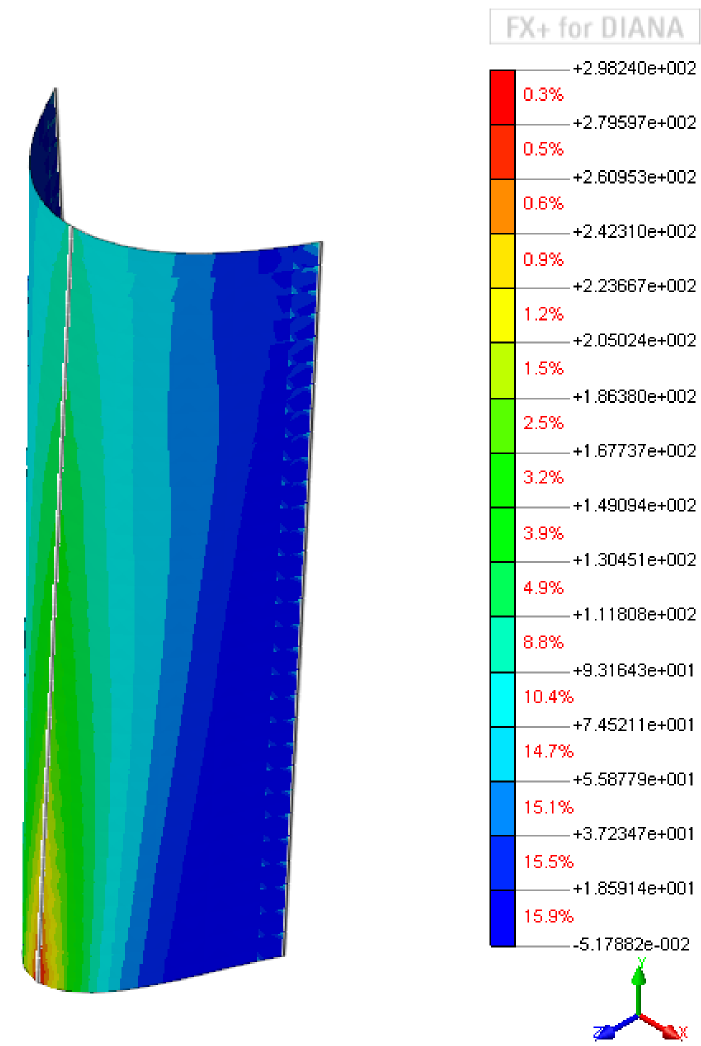
Initial Bending



Increased Bending



Asymmetric Bending

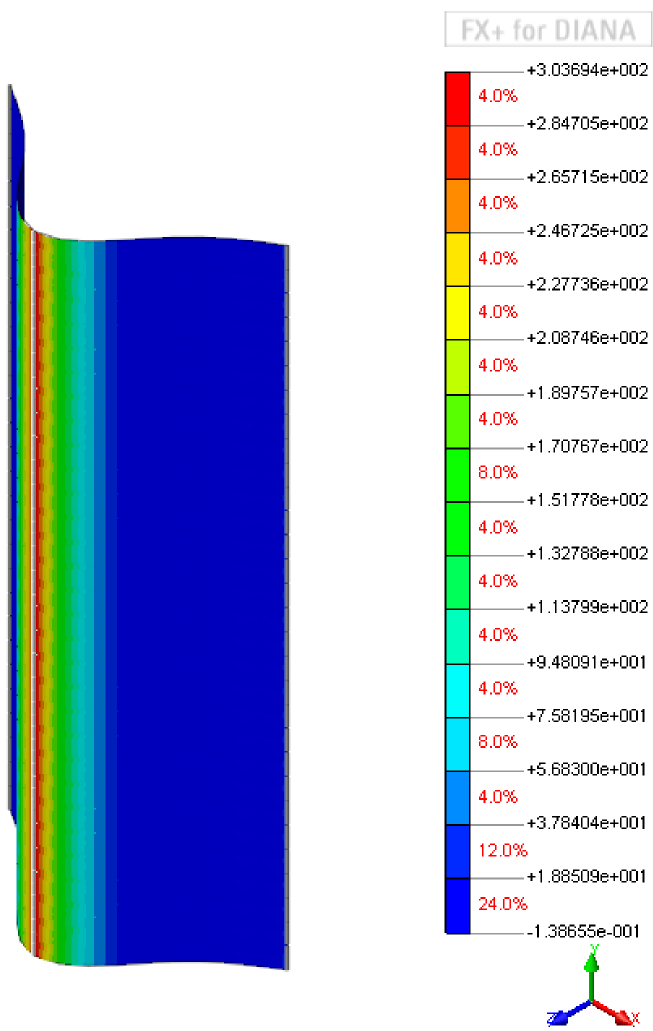


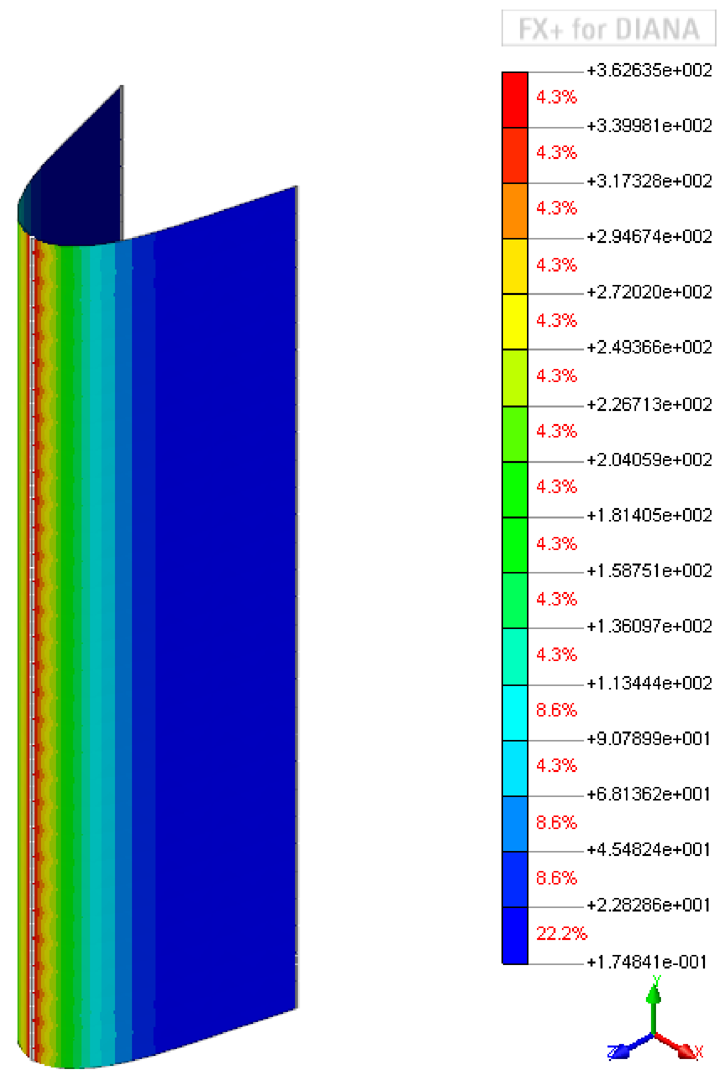
Absolute tensile stress on the top surface

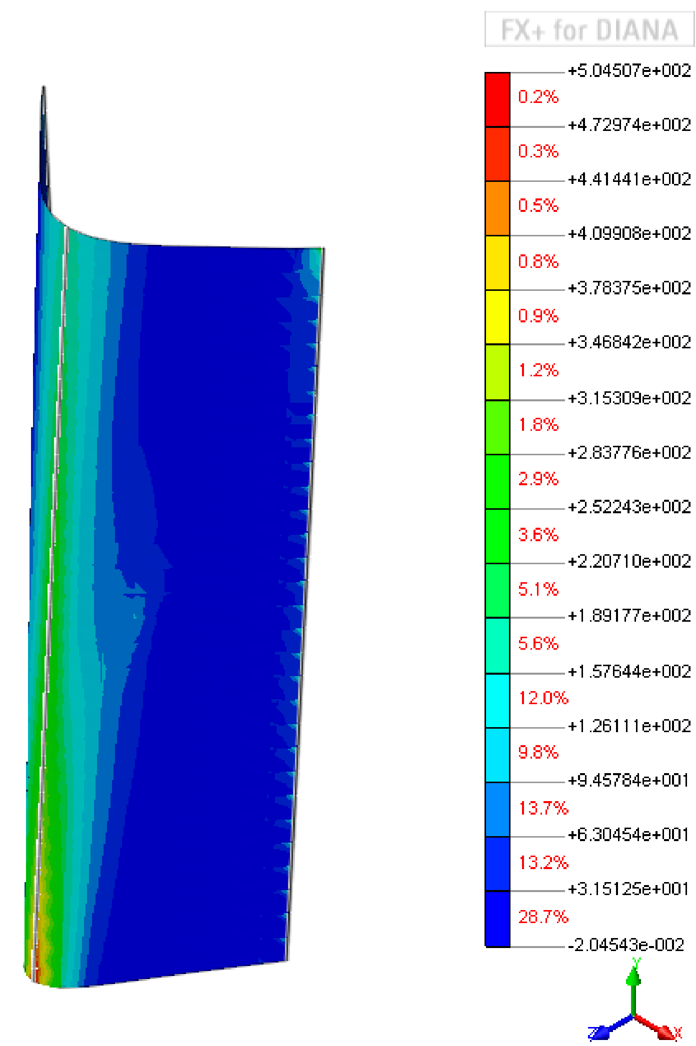
130 N/mm^2 | 280 N/mm^2 | 300 N/mm^2

Wind 0.5 KN/m²

Initial Bending Increased Bending Asymmetric Bending





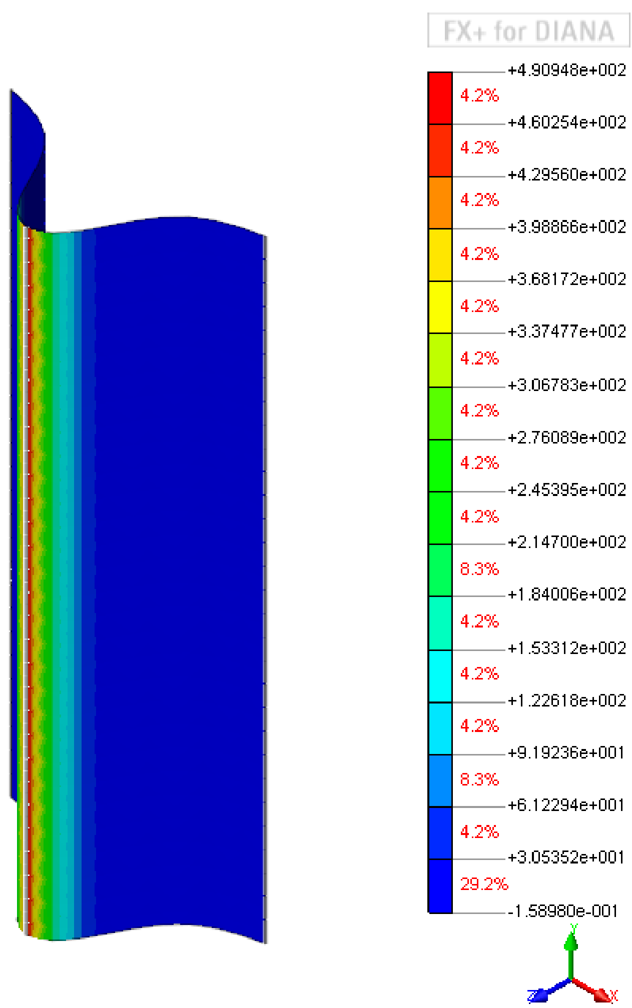


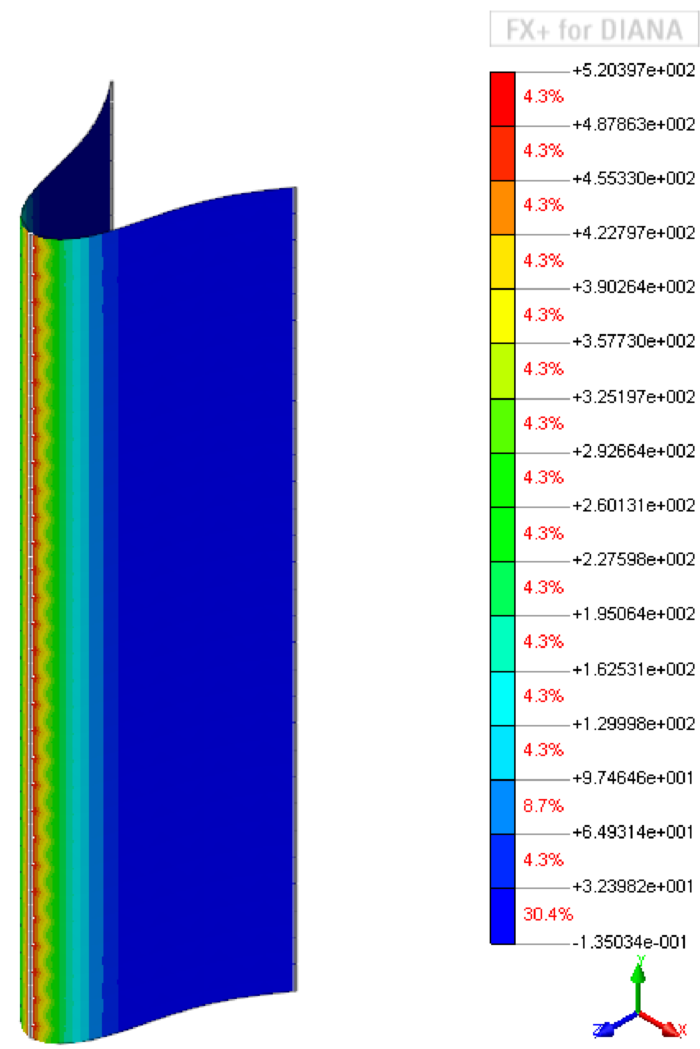
Absolute tensile stress on the top surface

303 N/mm² 362 N/mm² 504 N/mm²

Wind 1 KN/m²

Initial Bending | Increased Bending | Asymmetric Bending





Absolute tensile stress on the top surface

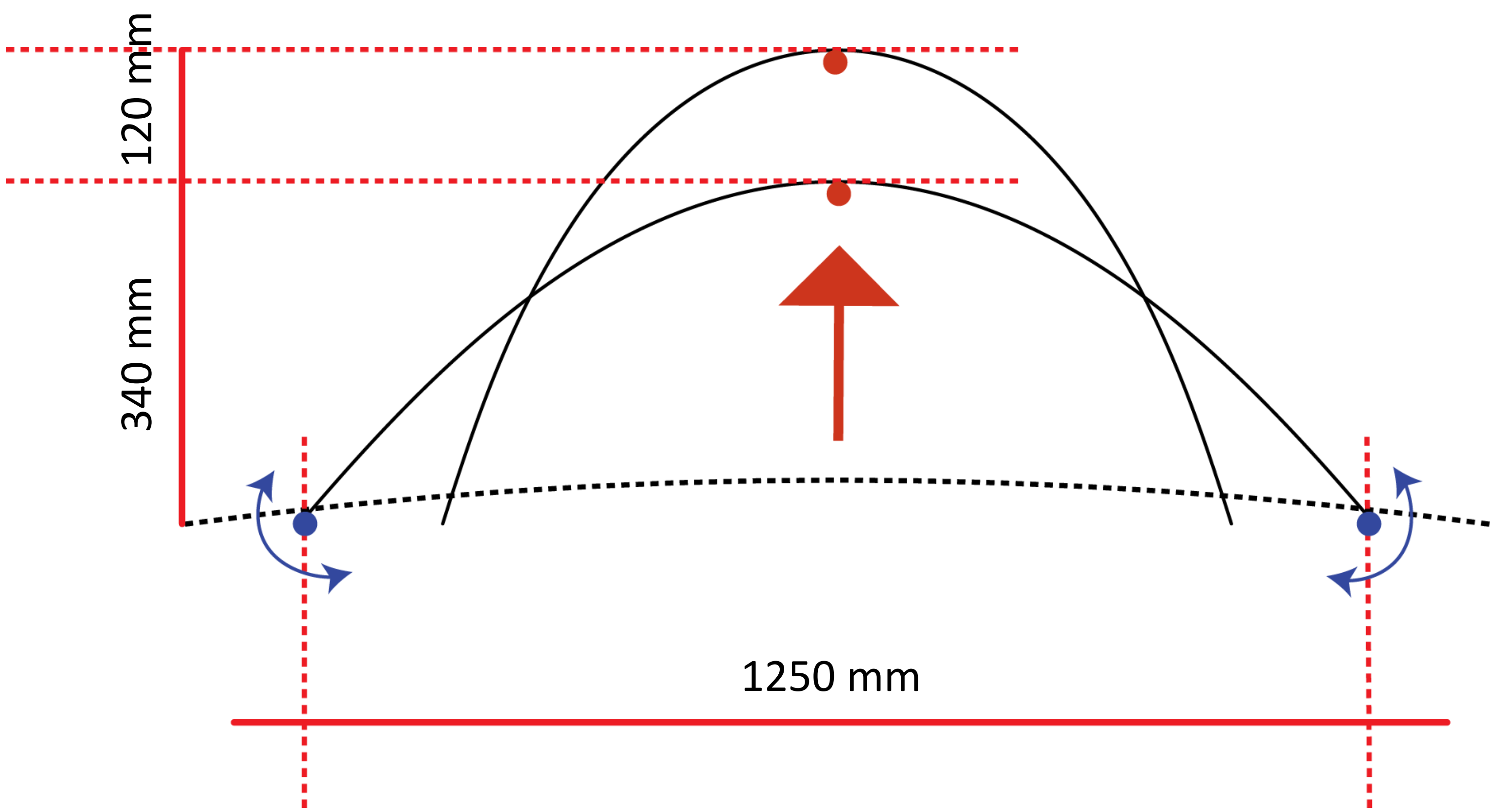
490 N/mm²

520 N/mm²

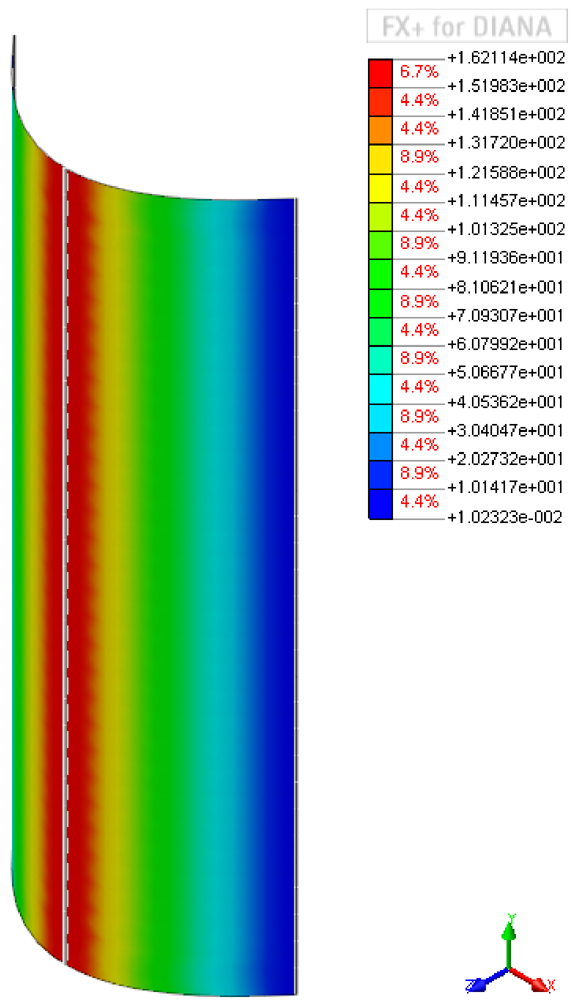
Changes to increase stiffness

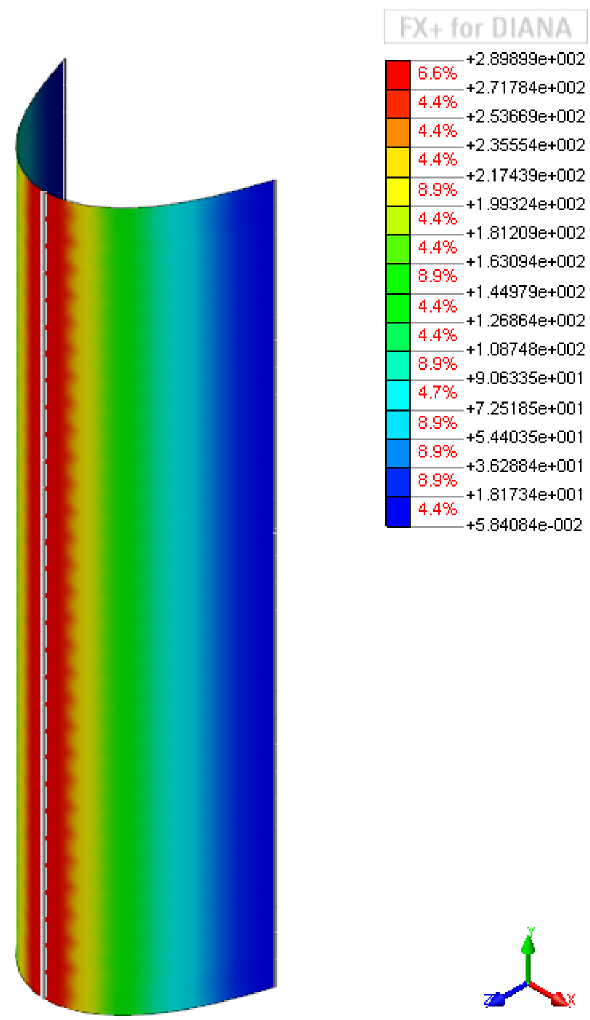
- Thickness to 2 mm
- Plate size reduction to 1500mm

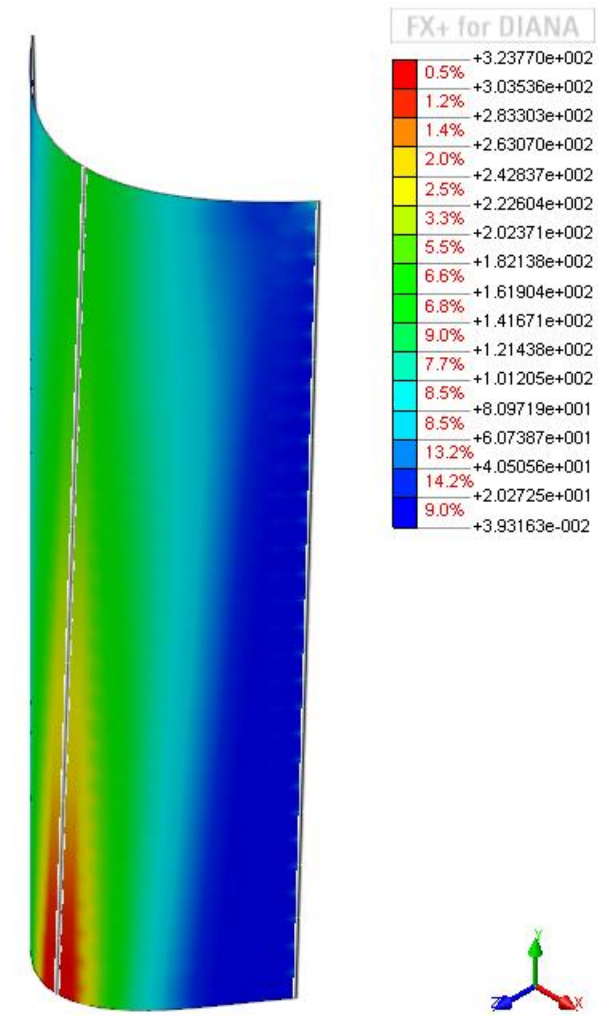
Movement magnitude



Initial Bending   Increased Bending   Asymmetric Bending





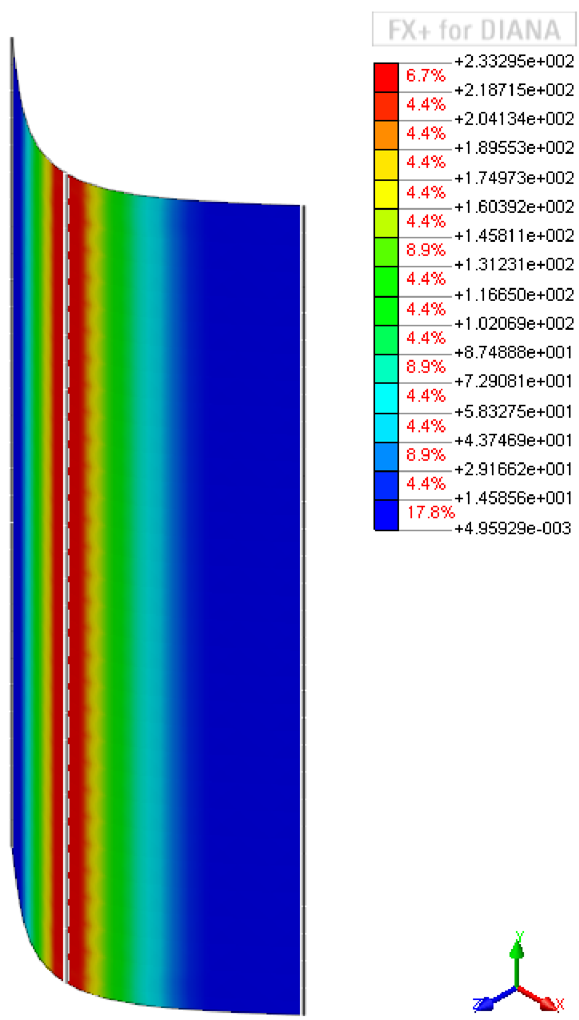


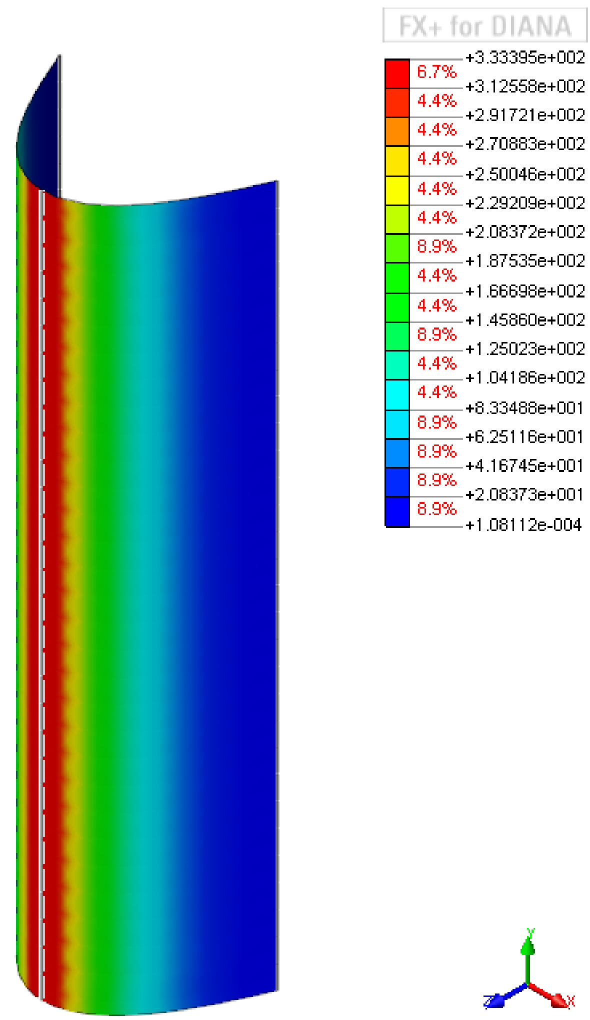
Absolute tensile stress on the top surface

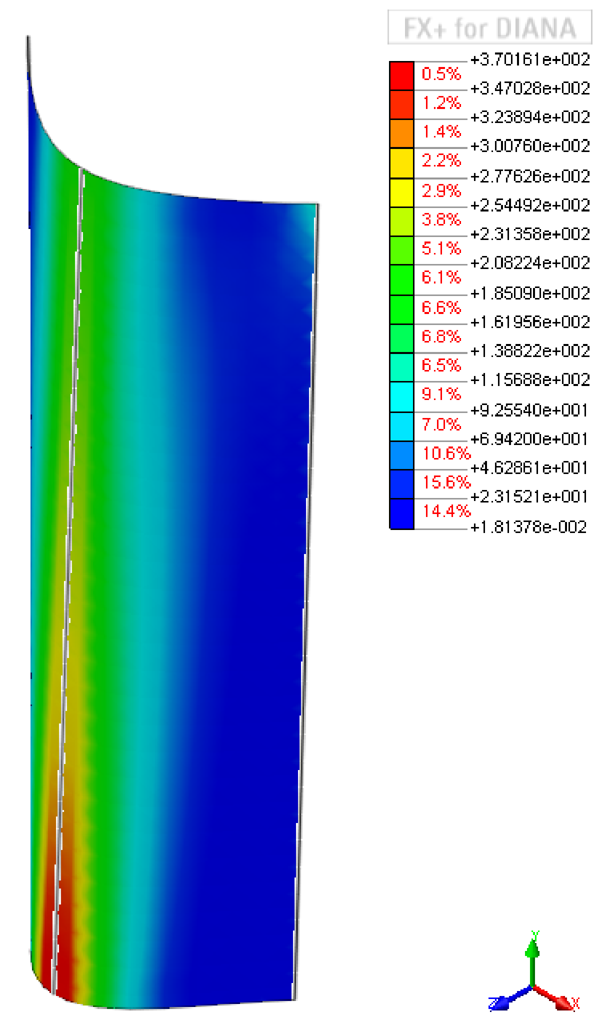
162N/mm^2 289 N/mm^2 320 N/mm^2

Wind 1 KN/m²

Initial Bending | Increased Bending | Asymmetric Bending





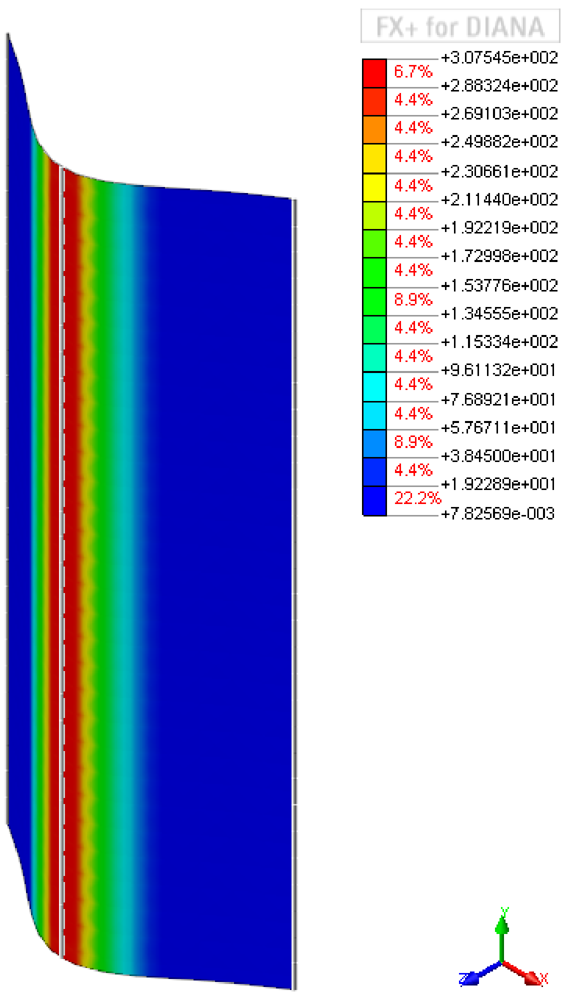


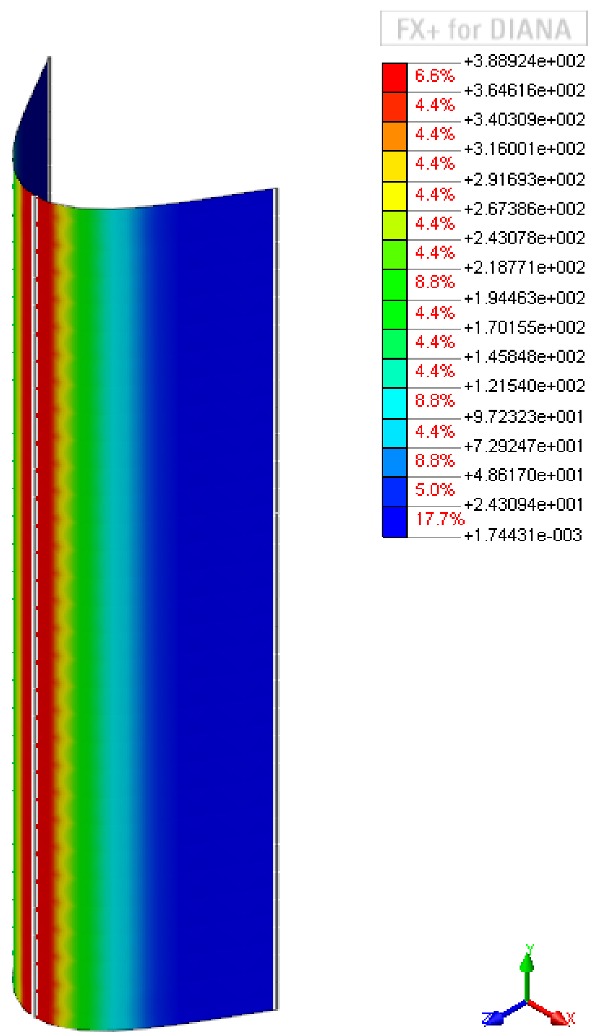
Absolute tensile stress on the top surface

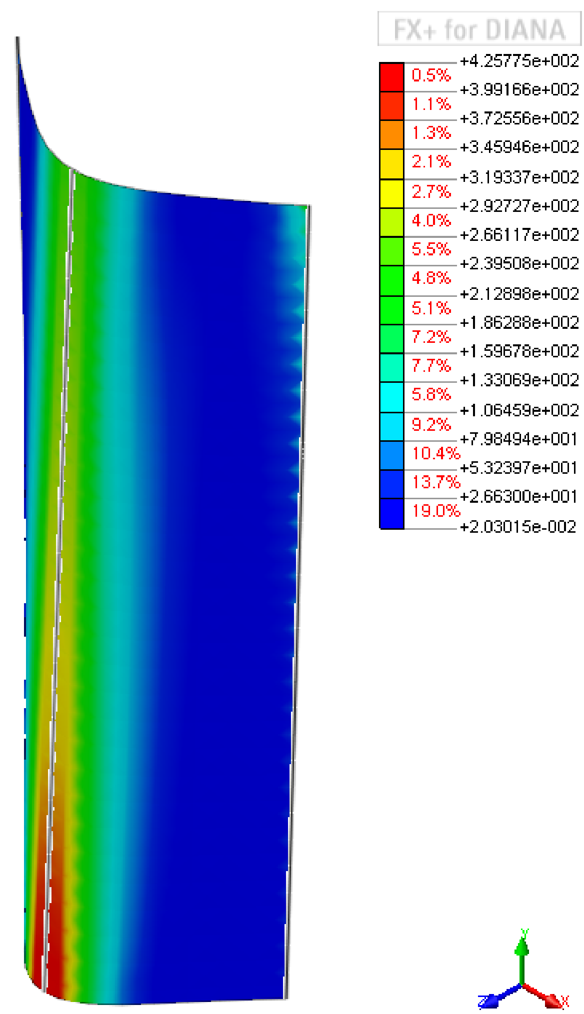
233 N/mm² | 333 N/mm² | 370 N/mm²

Wind 2 KN/m^2

Initial Bending	Increased Bending	Asymmetric Bending





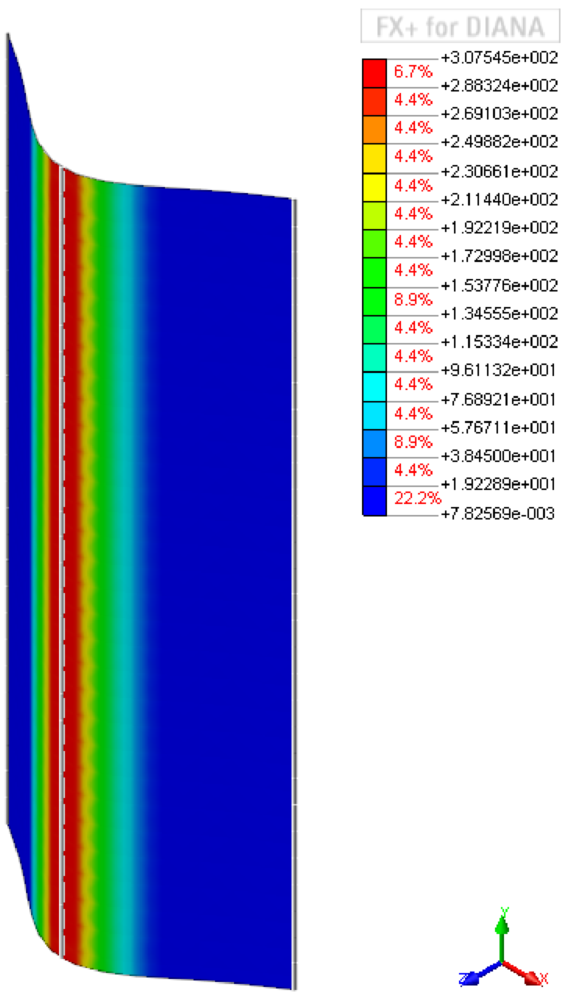


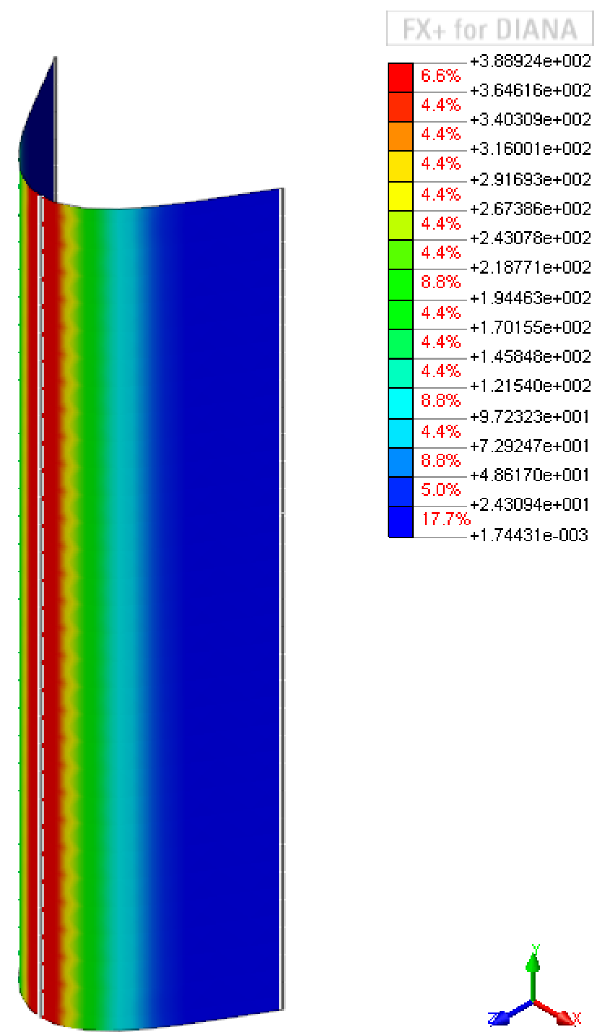
Absolute tensile stress on the top surface

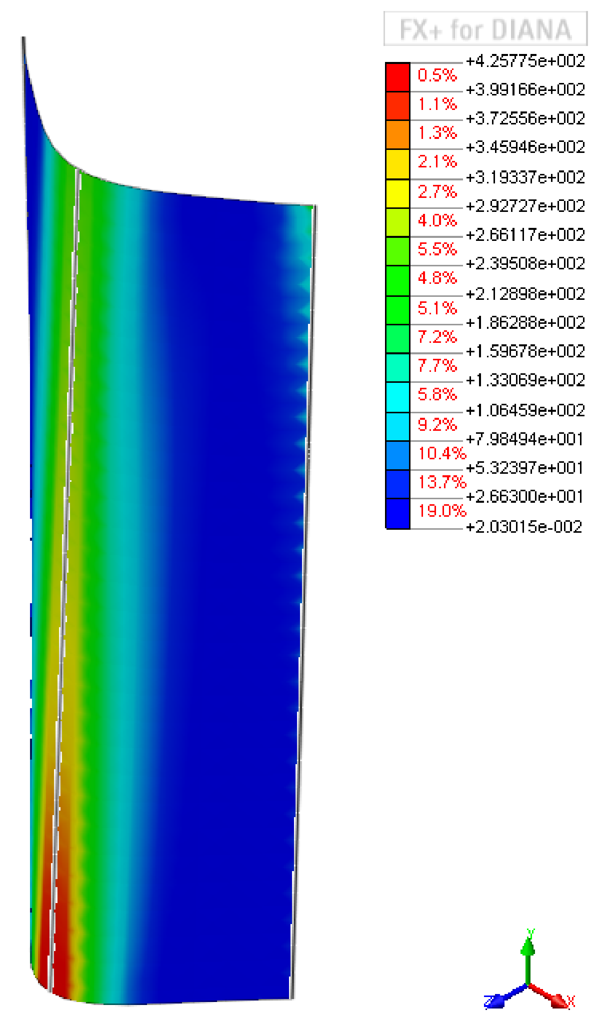
307 N/mm^2	388 N/mm^2	425 N/mm^2

Wind 2 KN/m^2

Initial Bending | Increased Bending | Asymmetric Bending





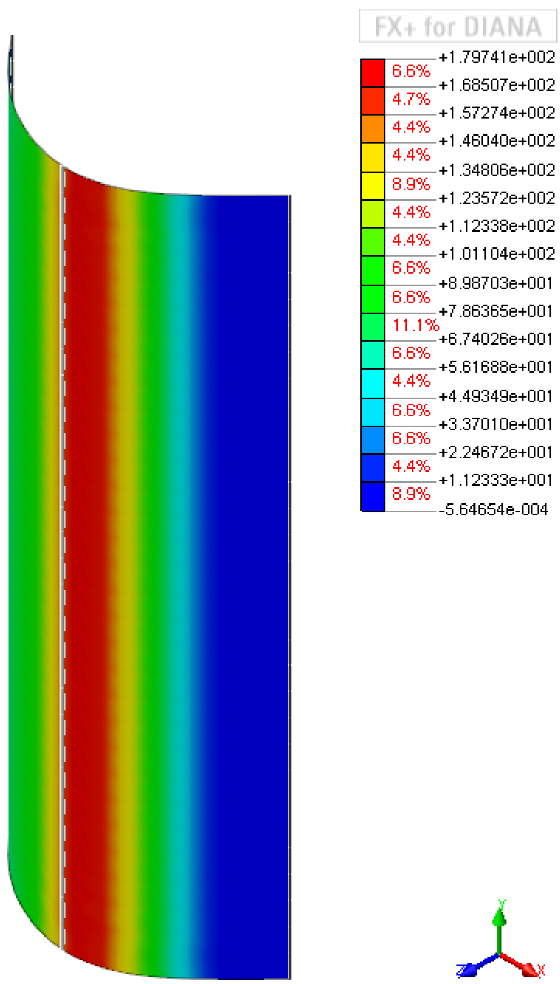


Absolute tensile stress on the top surface

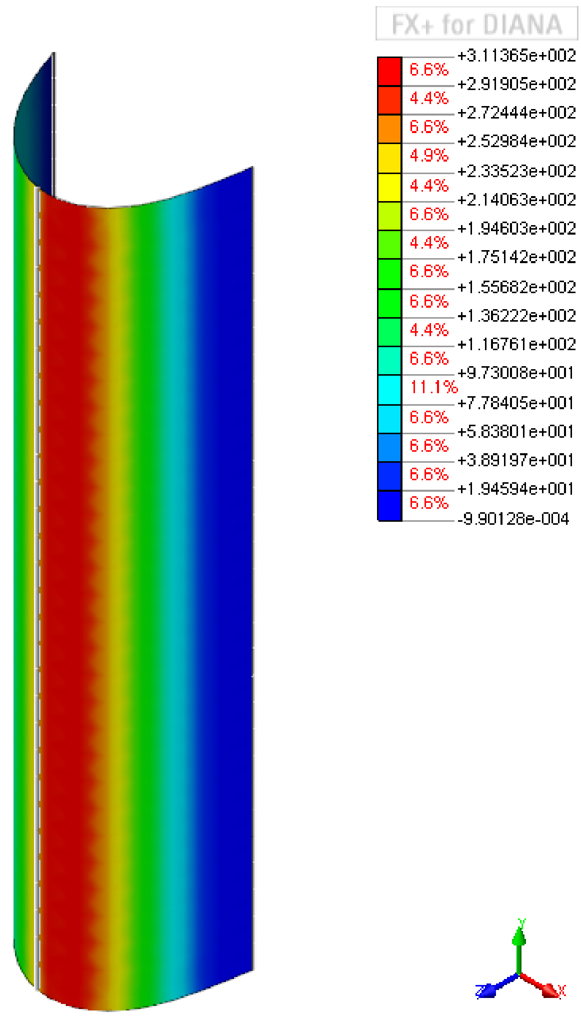
307 N/mm^2 | 388 N/mm^2 | 425 N/mm^2

Wind 2 KN/m^2 one side

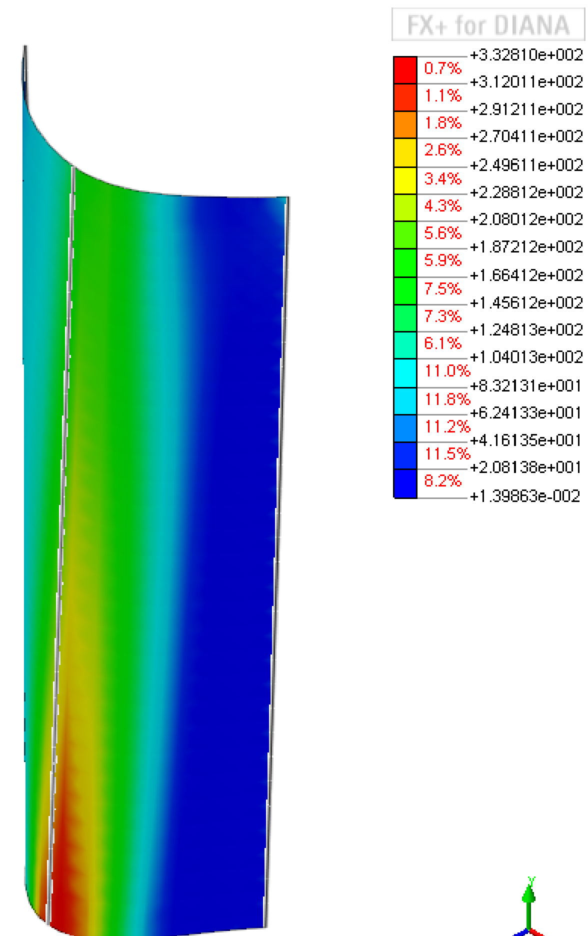
Initial Bending



Increased Bending



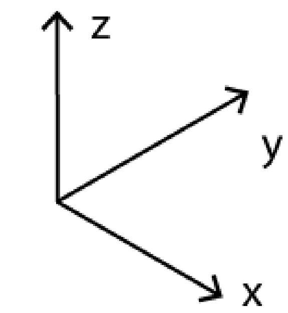
Asymmetric Bending

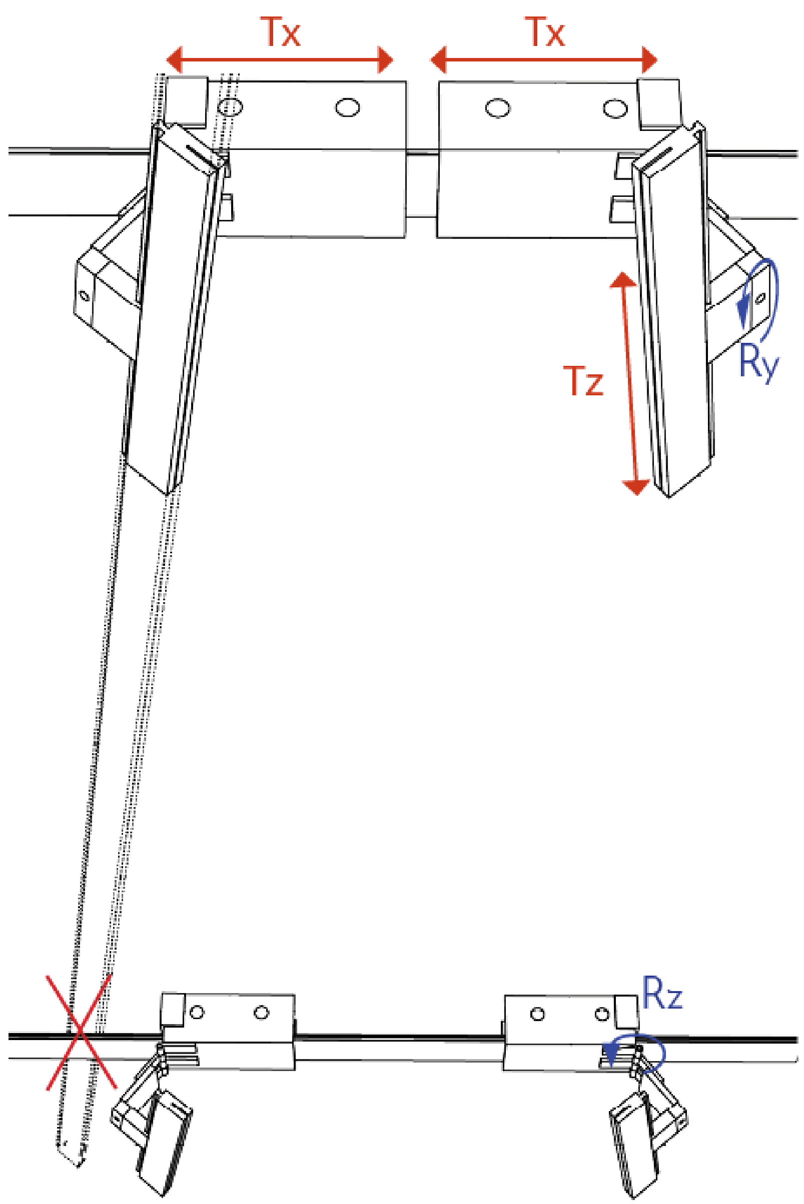


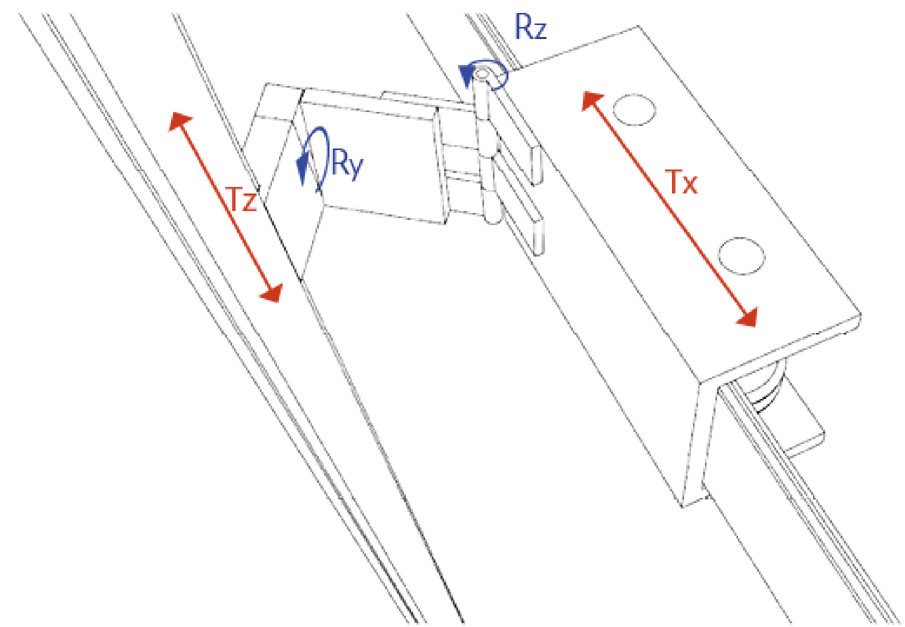
Absolute tensile stress on the top surface

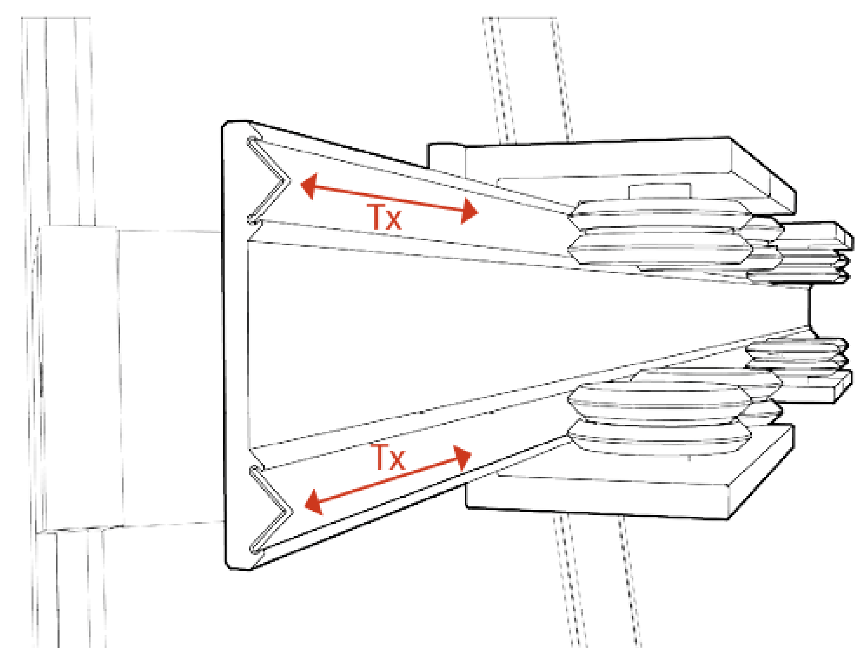
179 N/mm^2 | 311 N/mm^2 | 332 N/mm^2

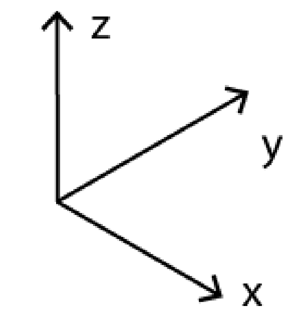
Translation in design



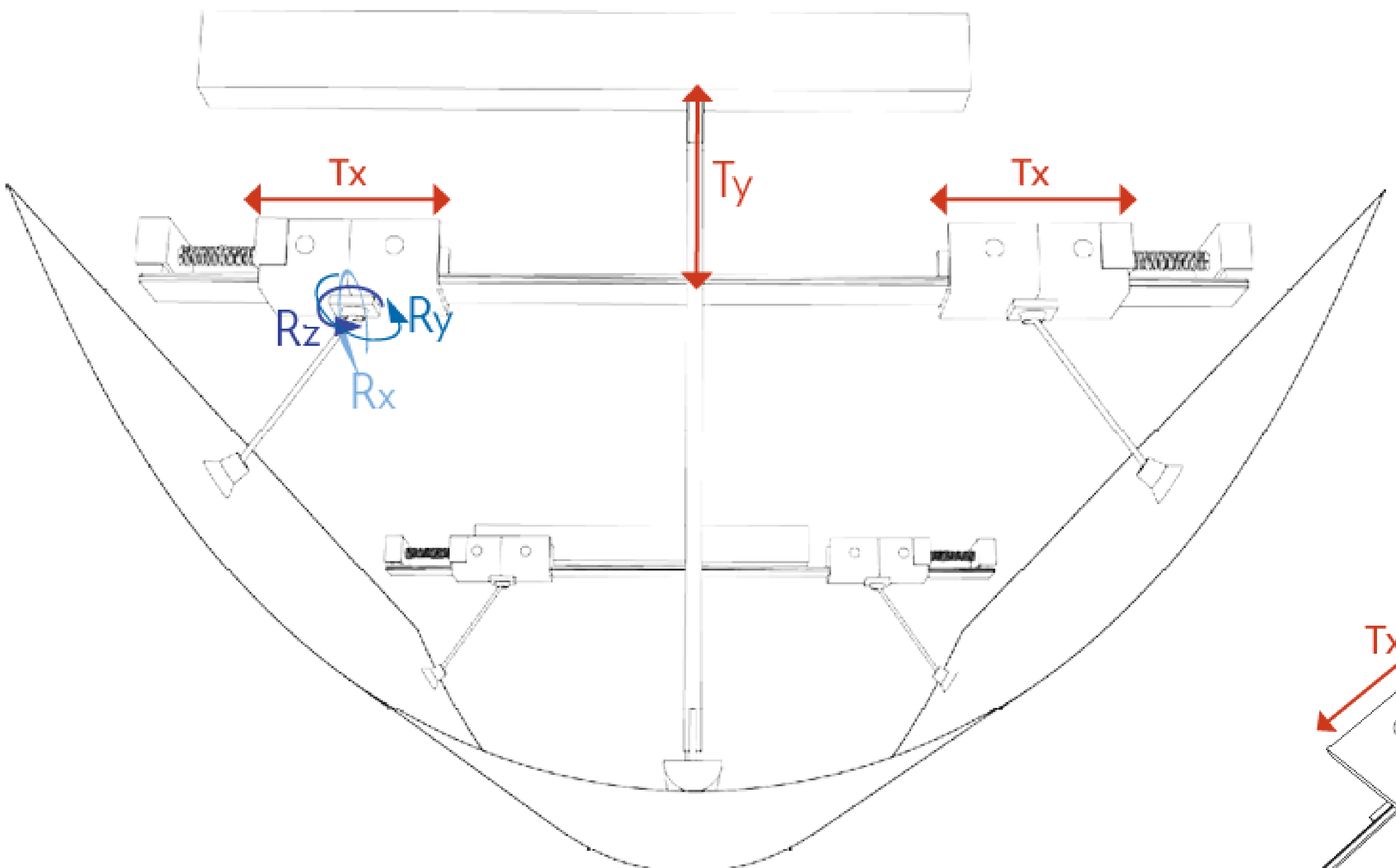


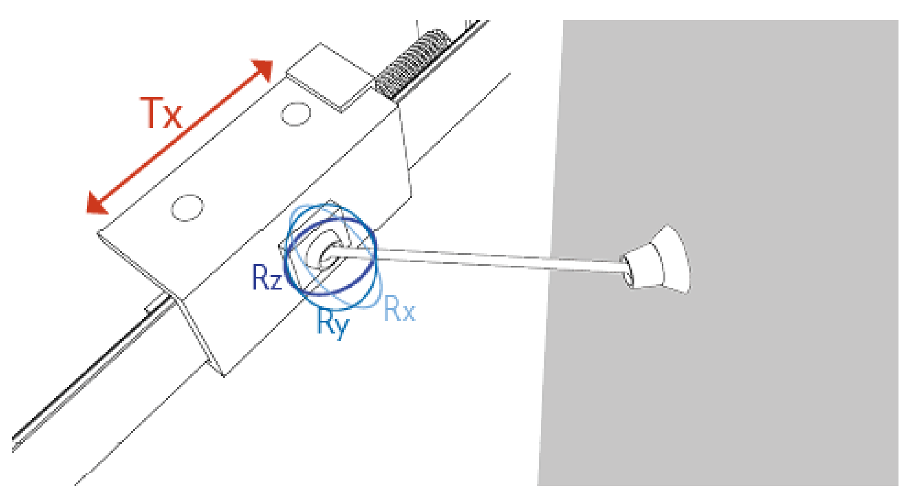


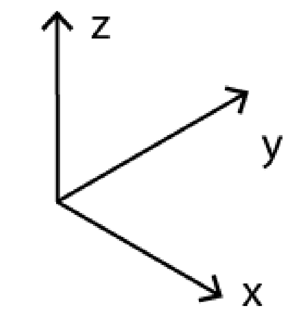




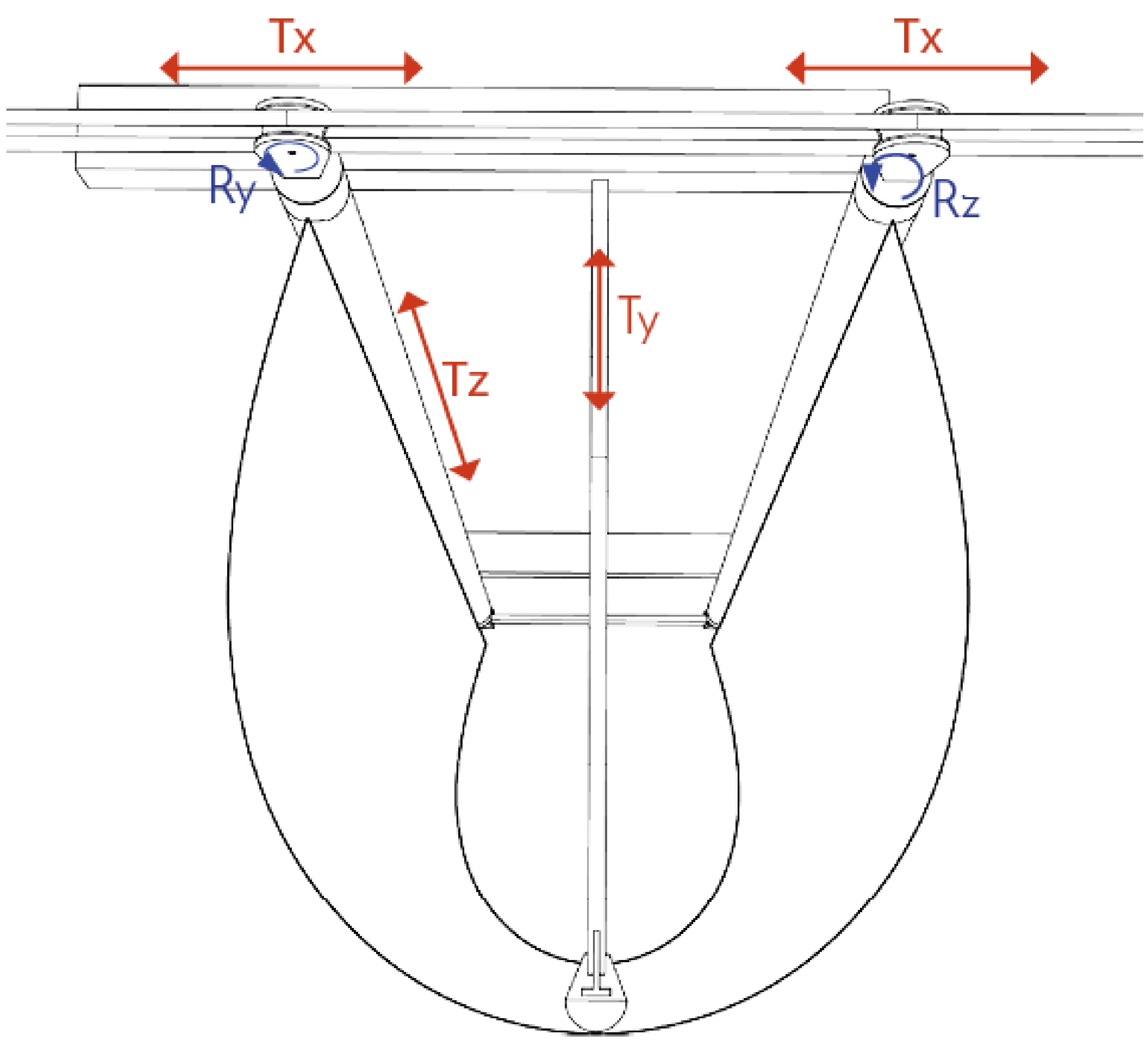
Translation in design

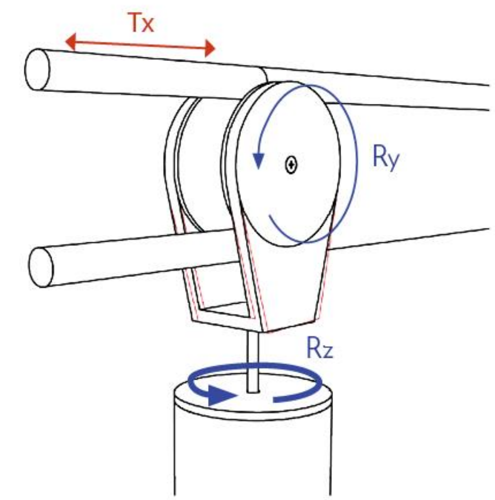


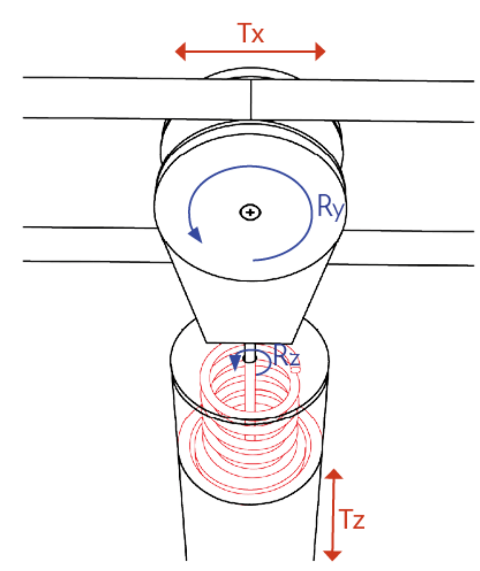




Translation in design

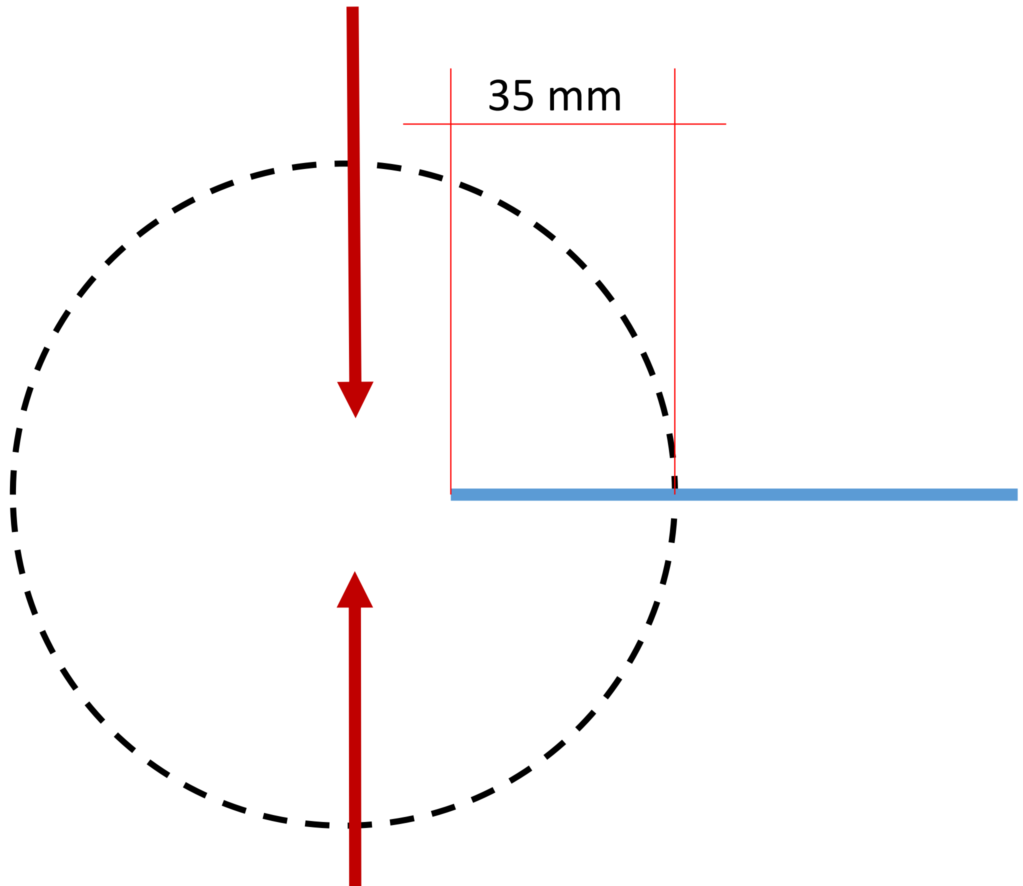


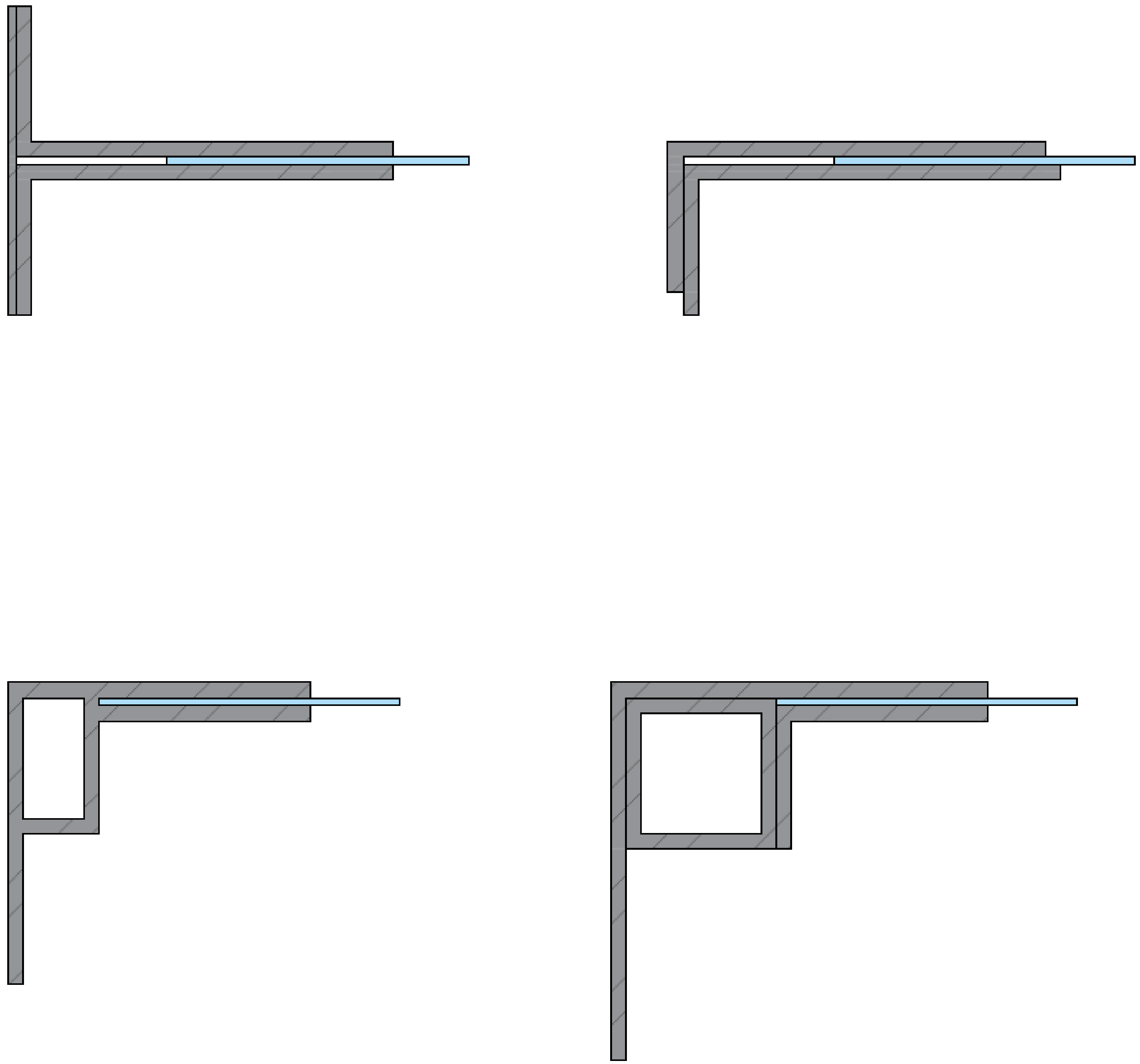


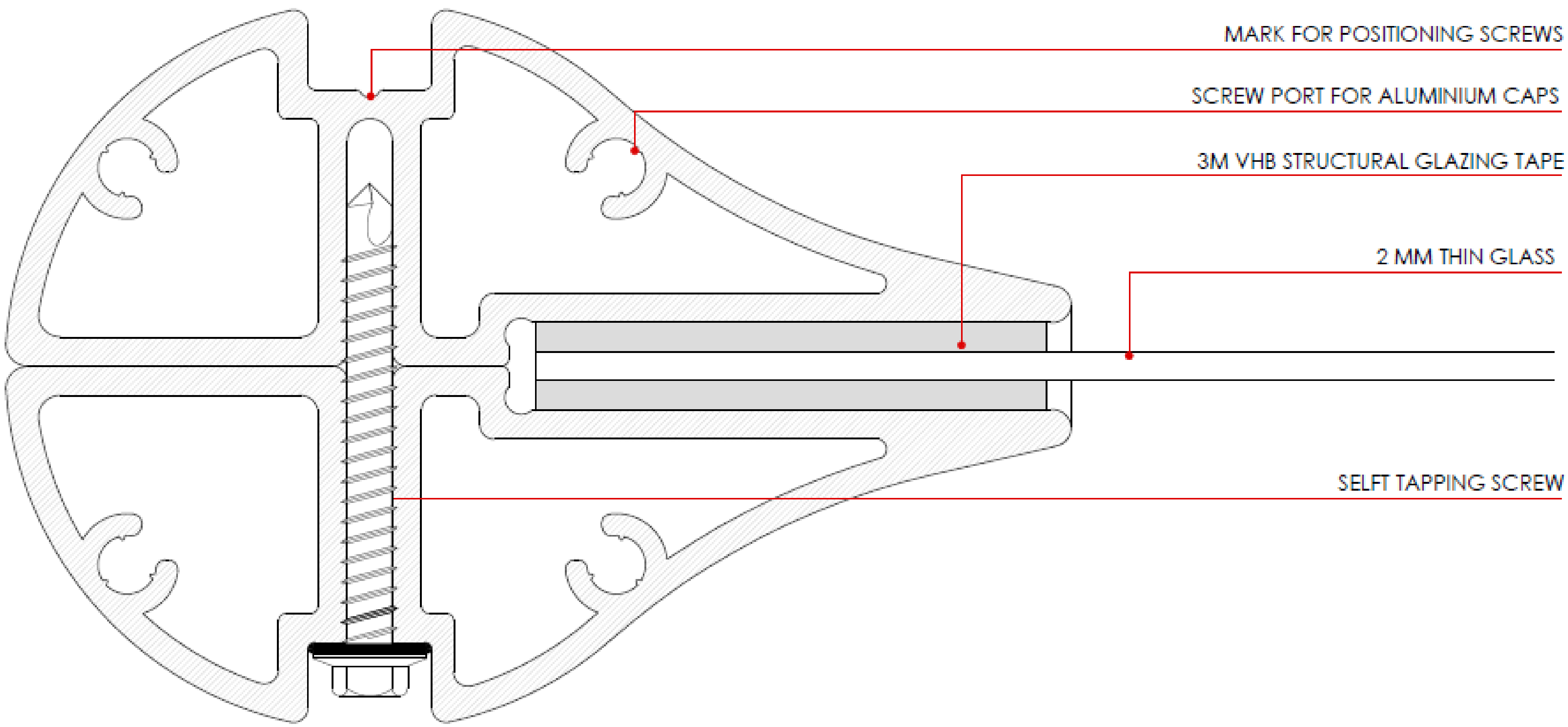


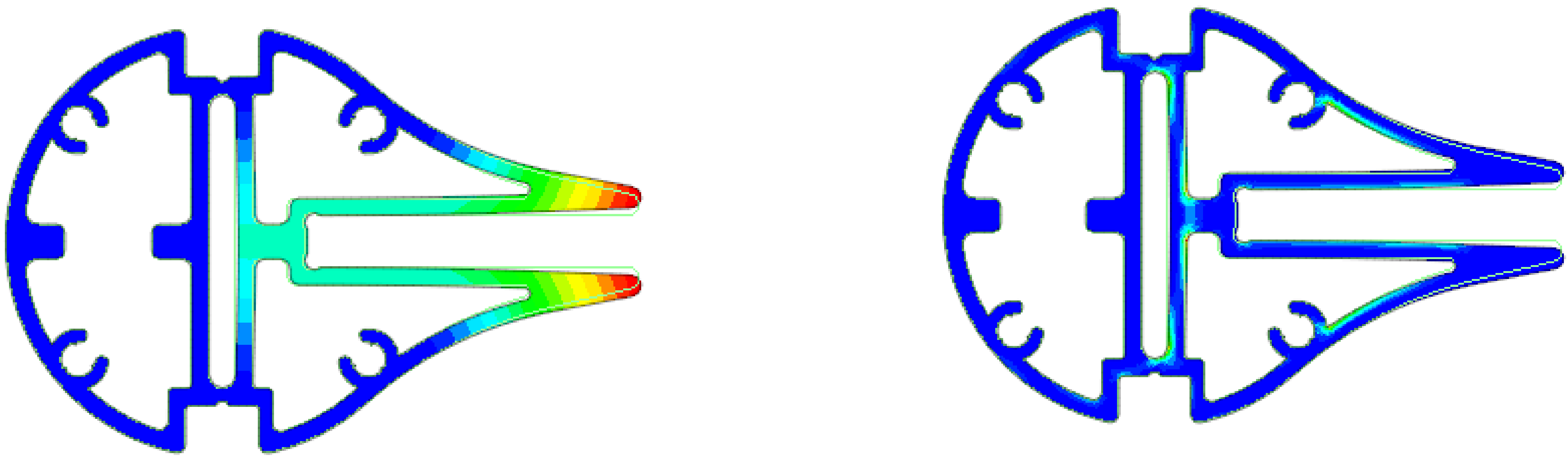
Profile exploration

- Clamp and adhesive
- Minimum structural glazing tape width 35mm
- Circular shape was difficult to adequate.

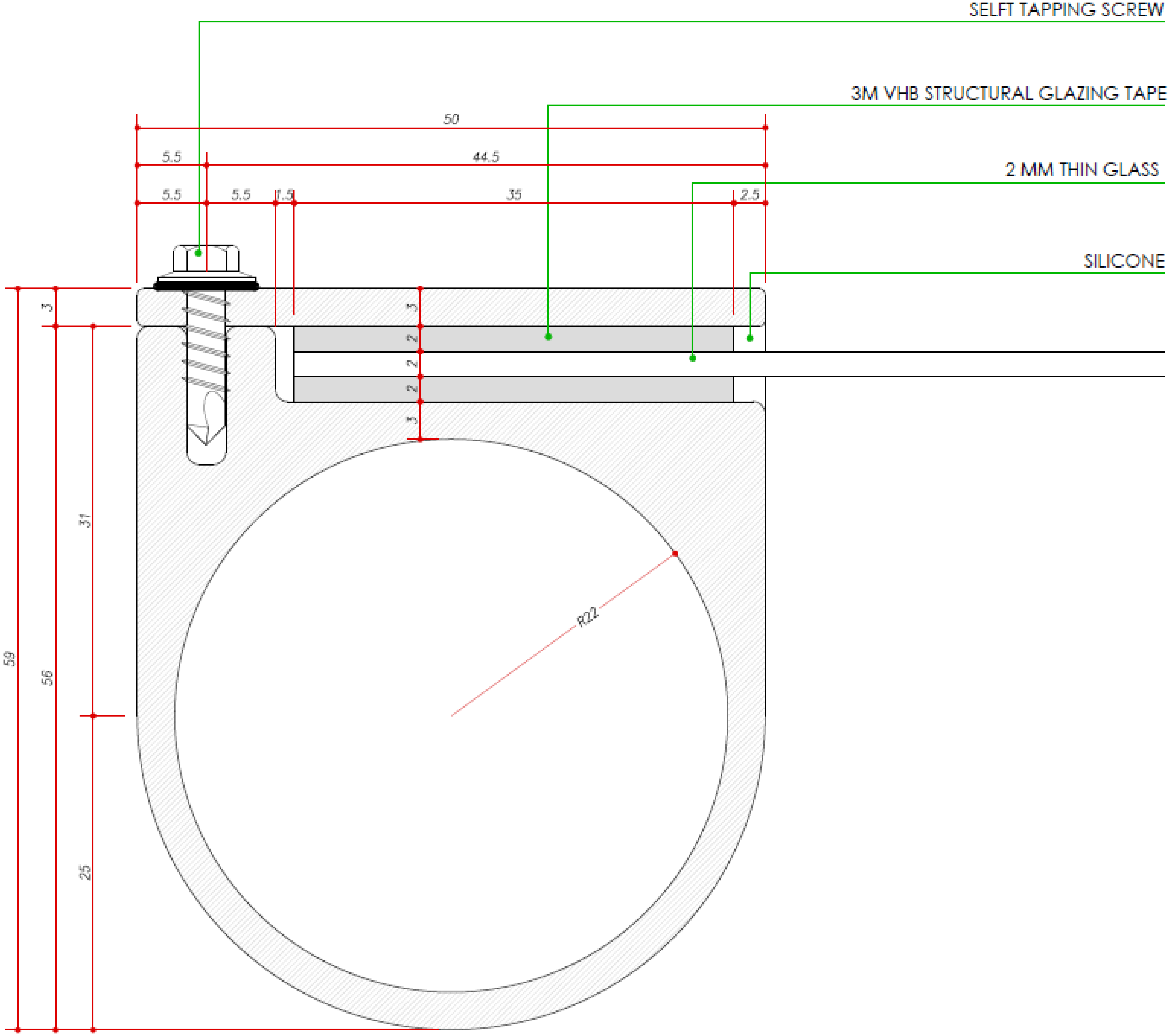


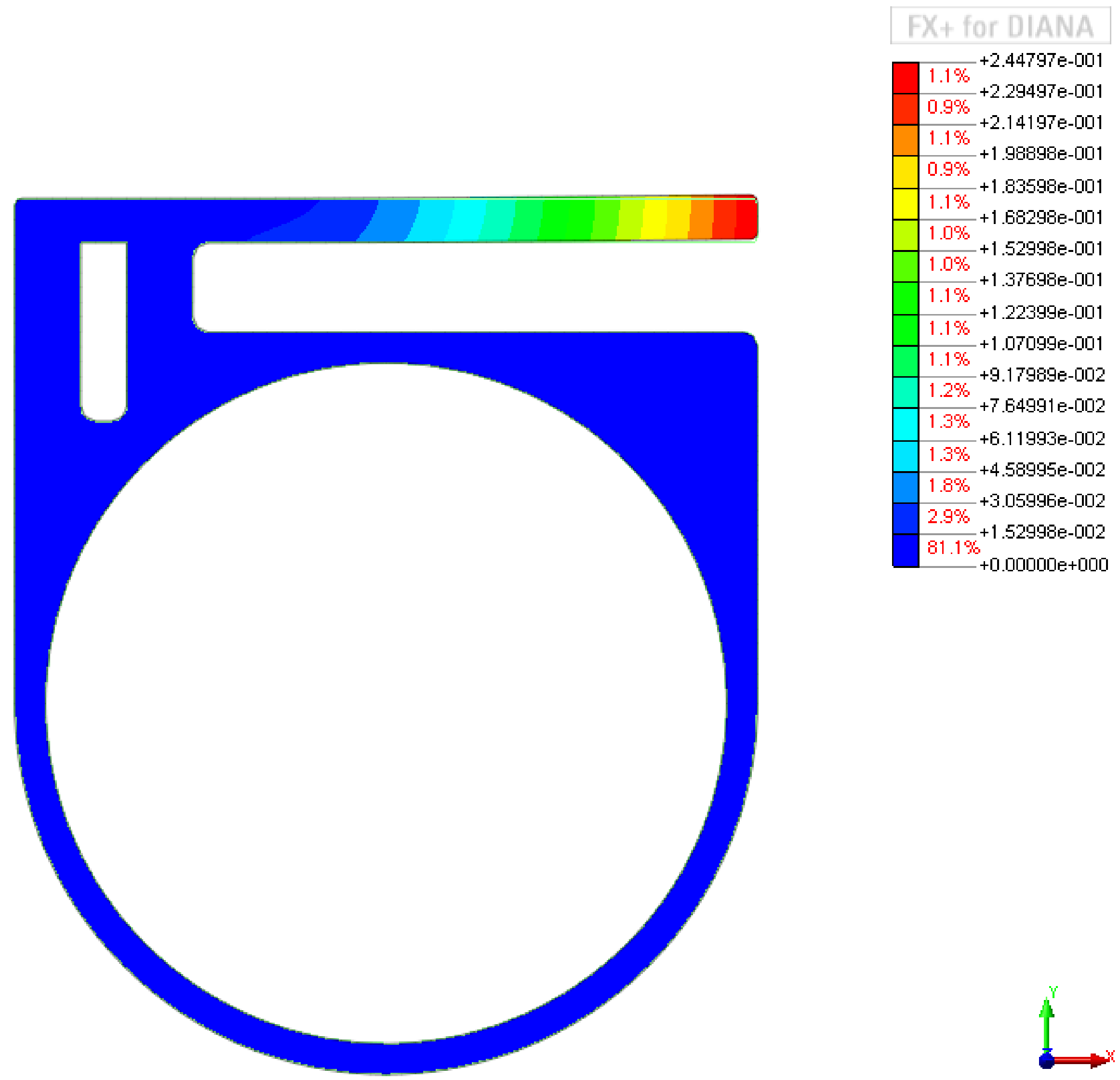



MARK FOR POSITIONING SCREWS
SCREW PORT FOR ALUMINIUM CAPS
3M VHB STRUCTURAL GLAZING TAPE
2 MM THIN GLASS
SELFT TAPPING SCREW



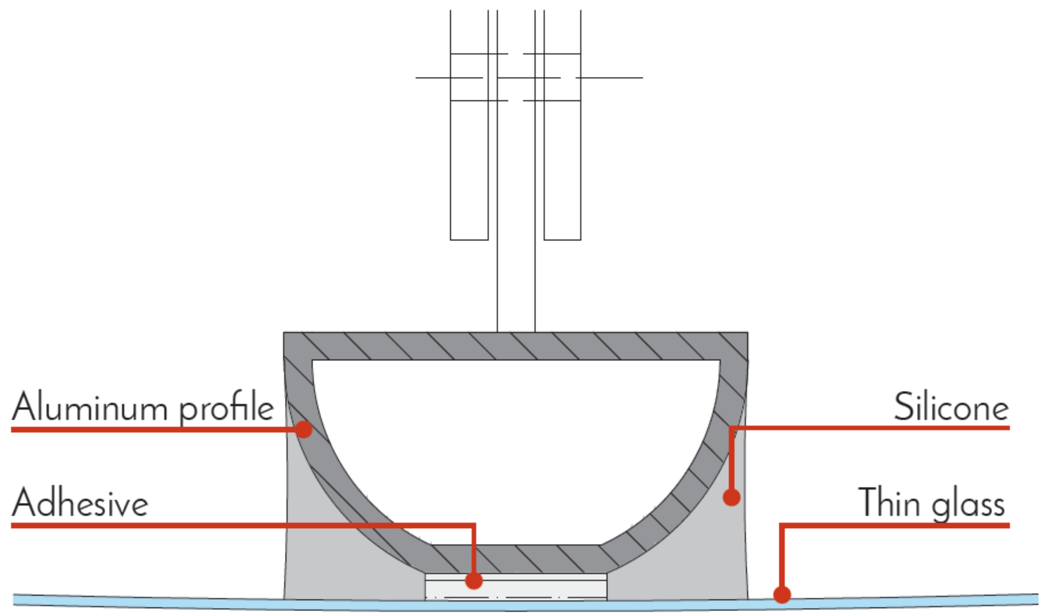
Displacement of 0.9mm > Tape compression (0.6mm)


SELFT TAPPING SCREW
3M VHB STRUCTURAL GLAZING TAPE
2 MM THIN GLASS
SILICONE
50
5.5
44.5
5.5
5.5
1.5
35
2.5
3
2
2
2
3
R22
59
56
31
25
3



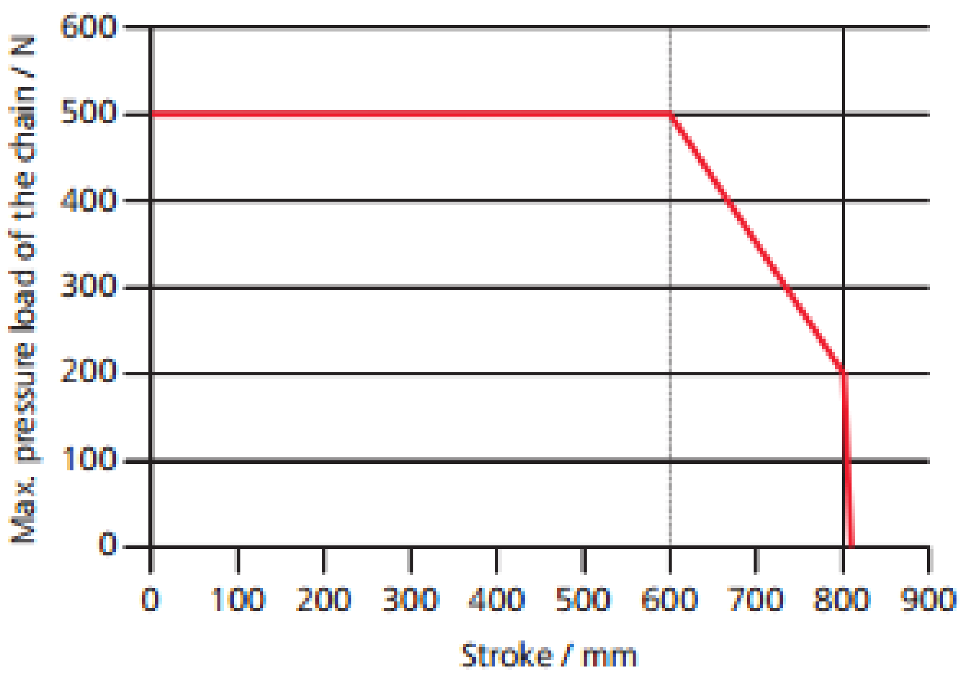
Displacement of 0.24mm < Tape compression (0.6mm)

Actuator



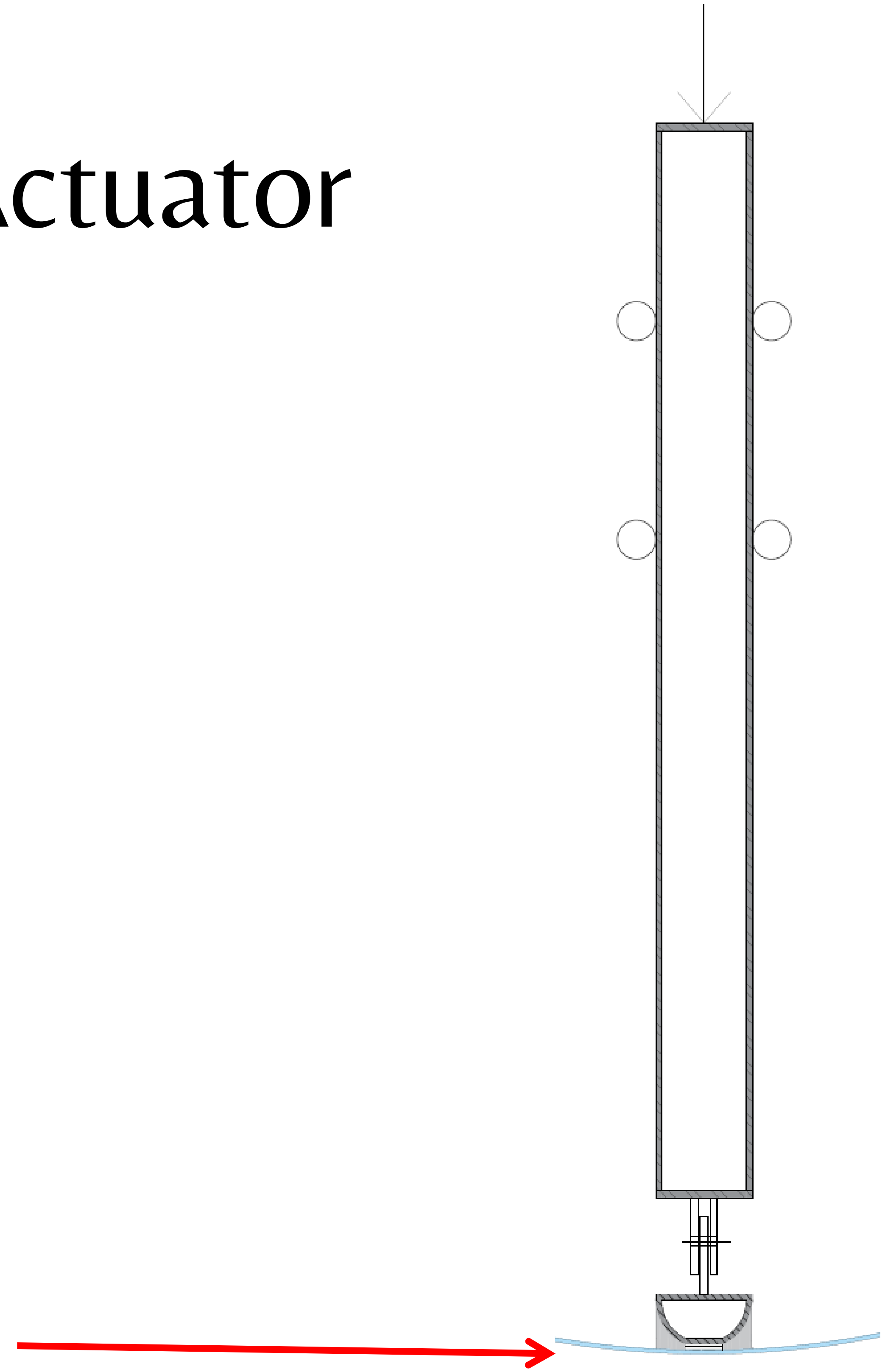
Actuator

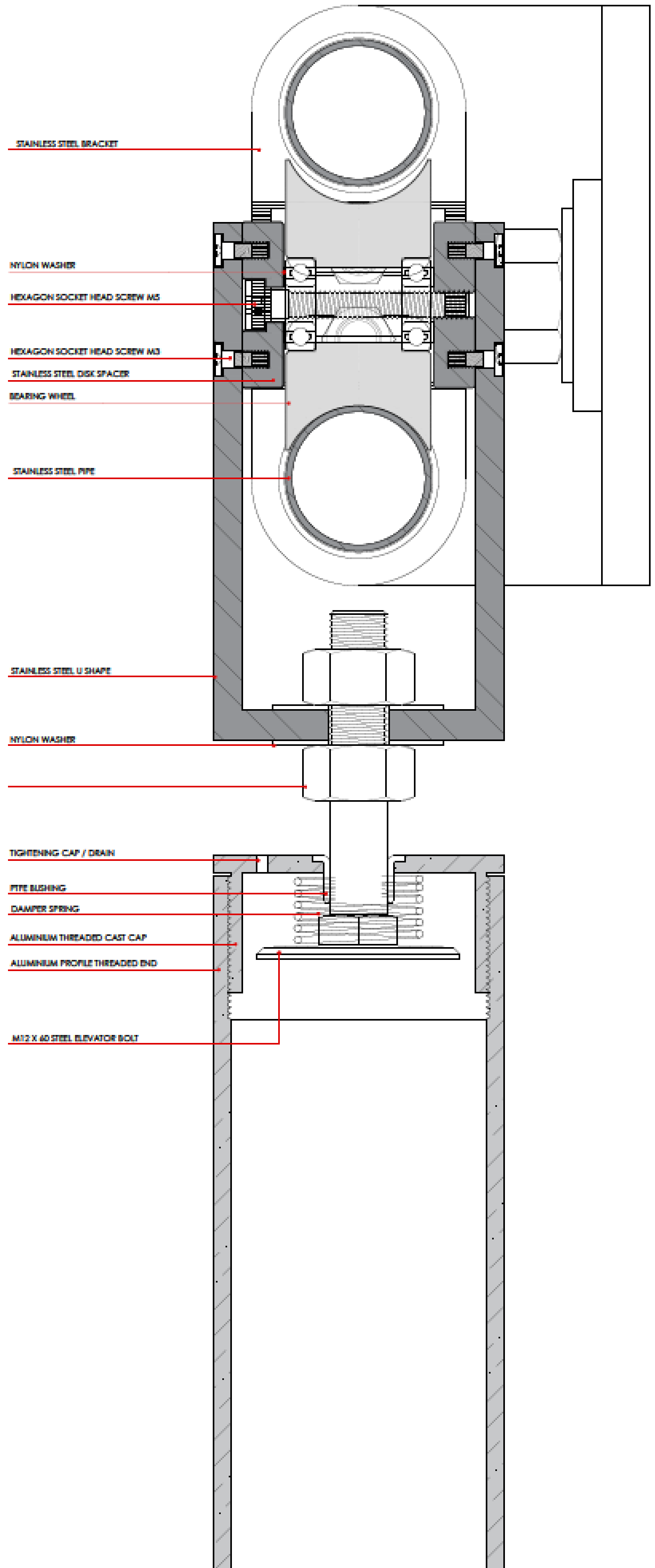
Pressure load diagram

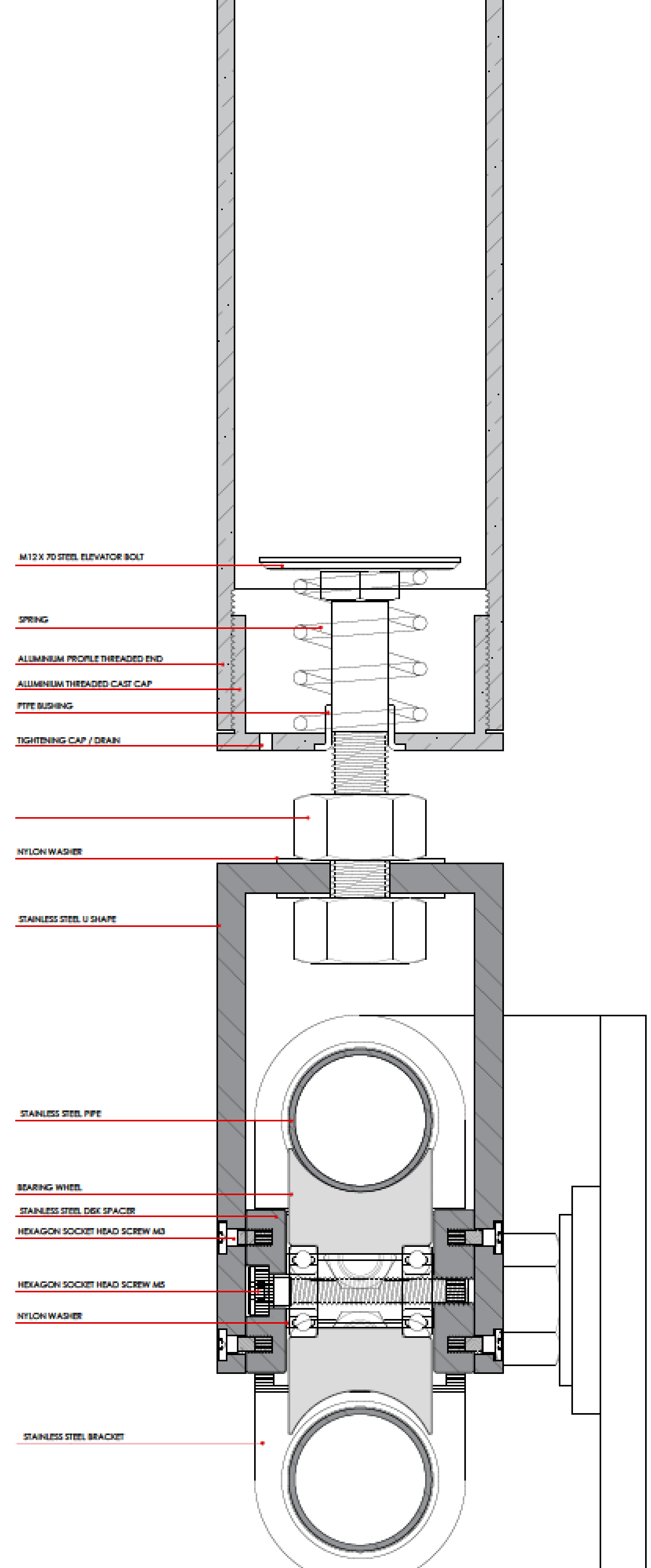


D+HE - KA 54-BSY – 500N forces

Actuator




STAINLESS STEEL BRACKET
NYLON WASHER
HEXAGON SOCKET HEAD SCREW M5
HEXAGON SOCKET HEAD SCREW M3
STAINLESS STEEL DISK SPACER
BEARING WHEEL
STAINLESS STEEL PIPE
STAINLESS STEEL U SHAPE
NYLON WASHER
TIGHTENING CAP / DRAIN
PTFE BUSHING
DAMPER SPRING
ALUMINIUM THREADED CAST CAP
ALUMINIUM PROFILE THREADED END
M12 X 60 STEEL ELEVATOR BOLT


M12 X 70 STEEL ELEVATOR BOLT
SPRING
ALUMINIUM PROFILE THREADED END
ALUMINIUM THREADED CAST CAP
PTFE BUSHING
TIGHTENING CAP / DRAIN
NYLON WASHER
STAINLESS STEEL U SHAPE
STAINLESS STEEL PIPE
BEARING WHEEL
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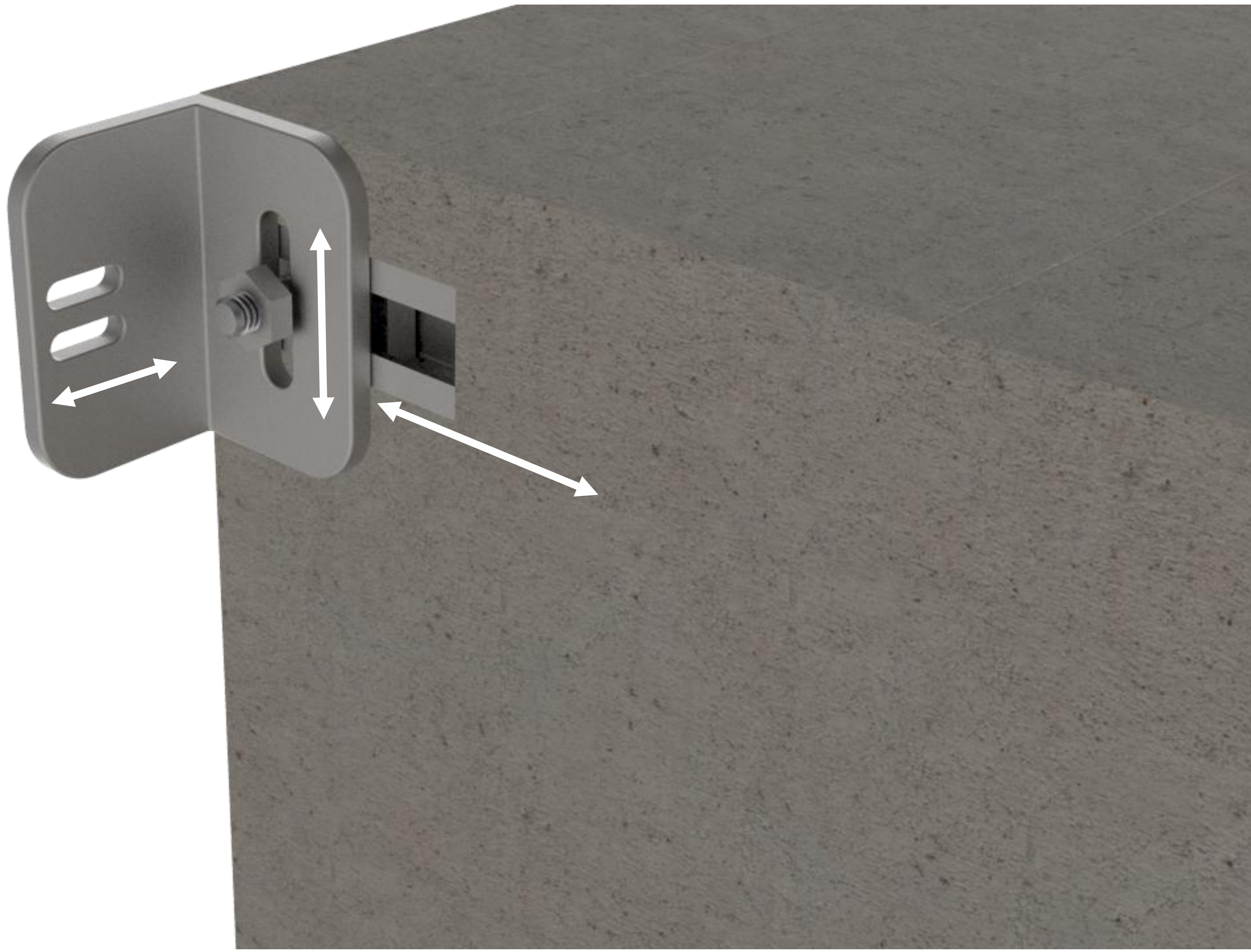
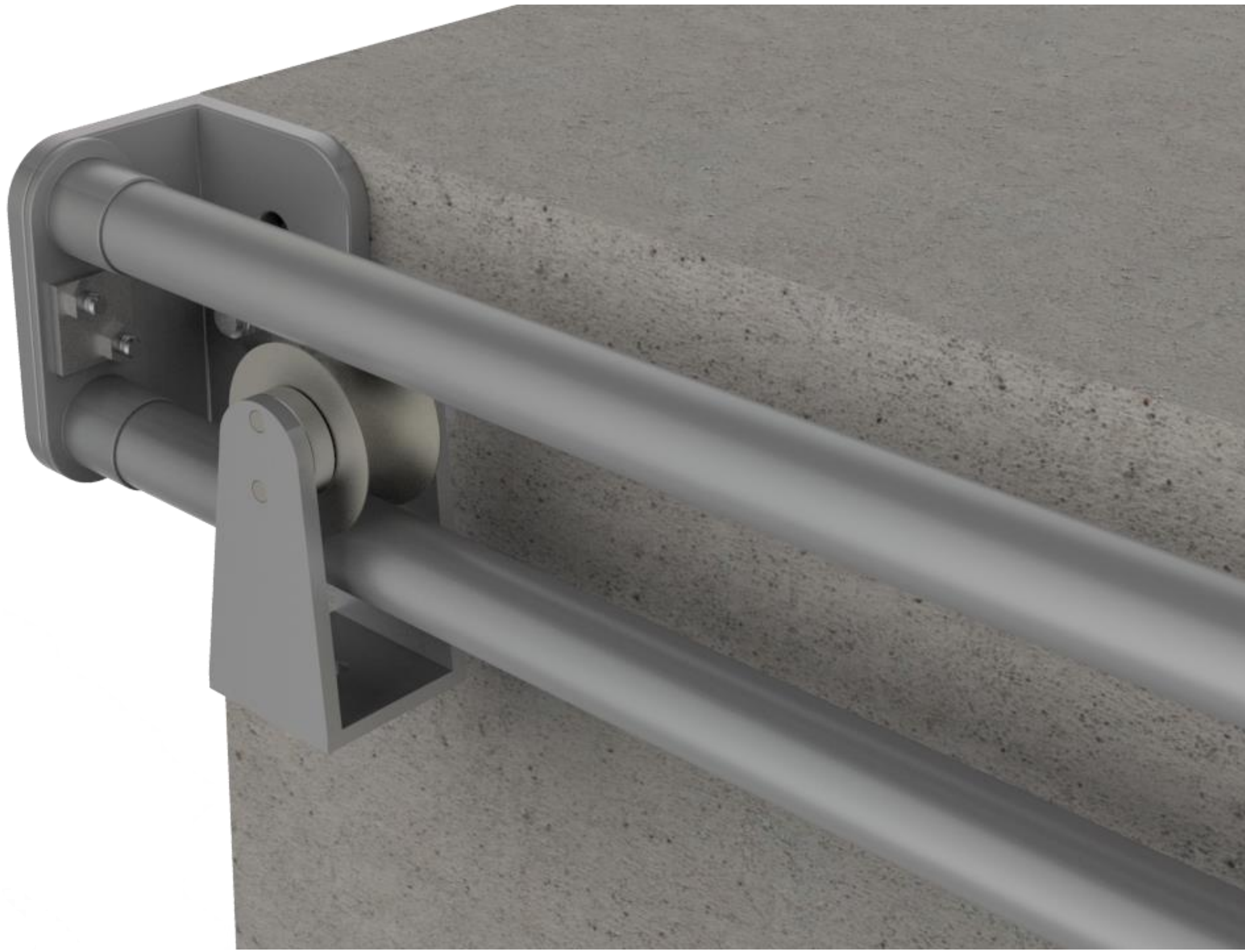
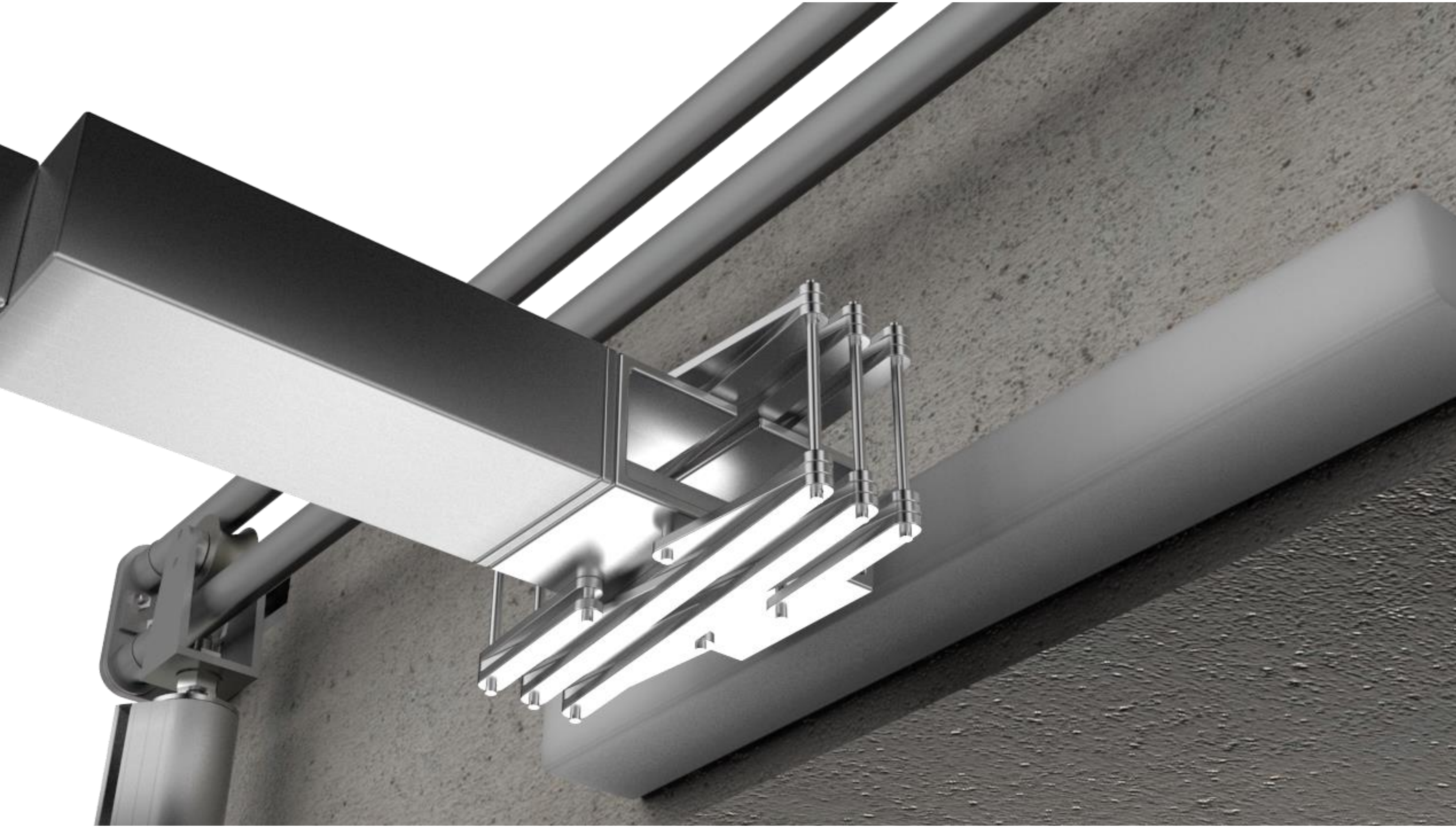
HEXAGON SOCKET HEAD SCREW M5
NYLON WASHER
STAINLESS STEEL BRACKET



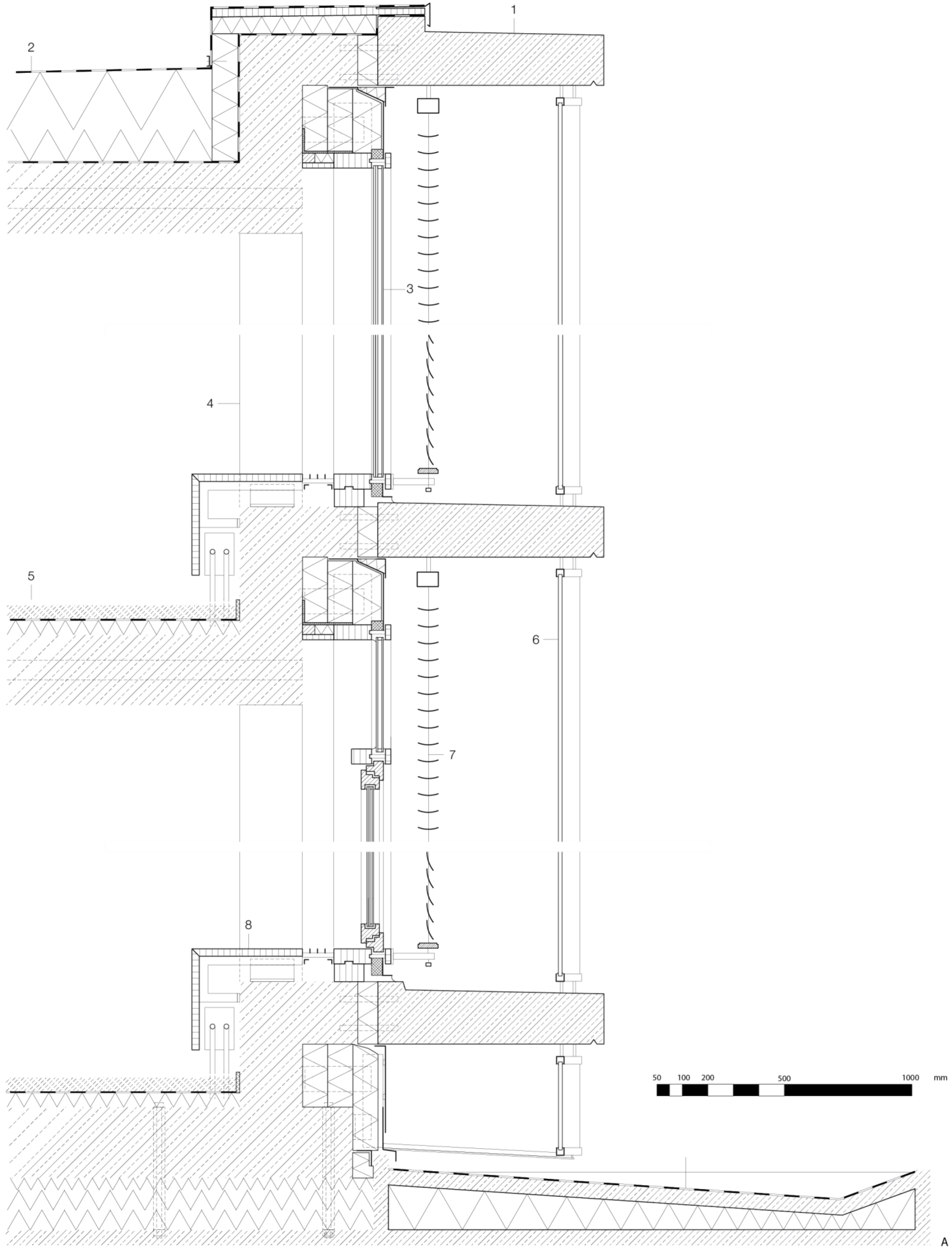




Case study - Vocational Schools in Recklinghausen

- Double skin glass façade panels as a permeable layer.

(Scholl Architekten Partnerschaft. **best of Detail: GLASS**. 2014)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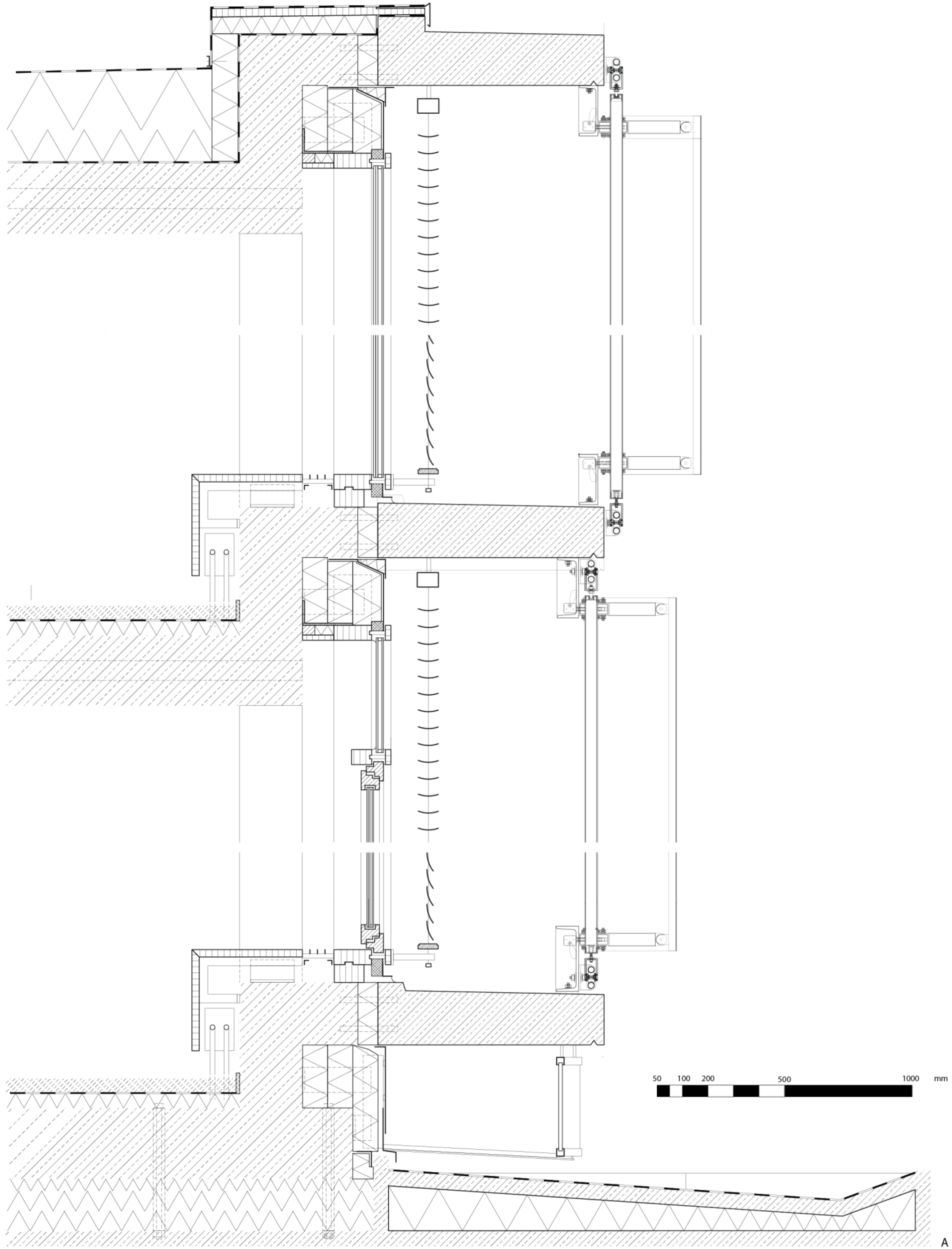
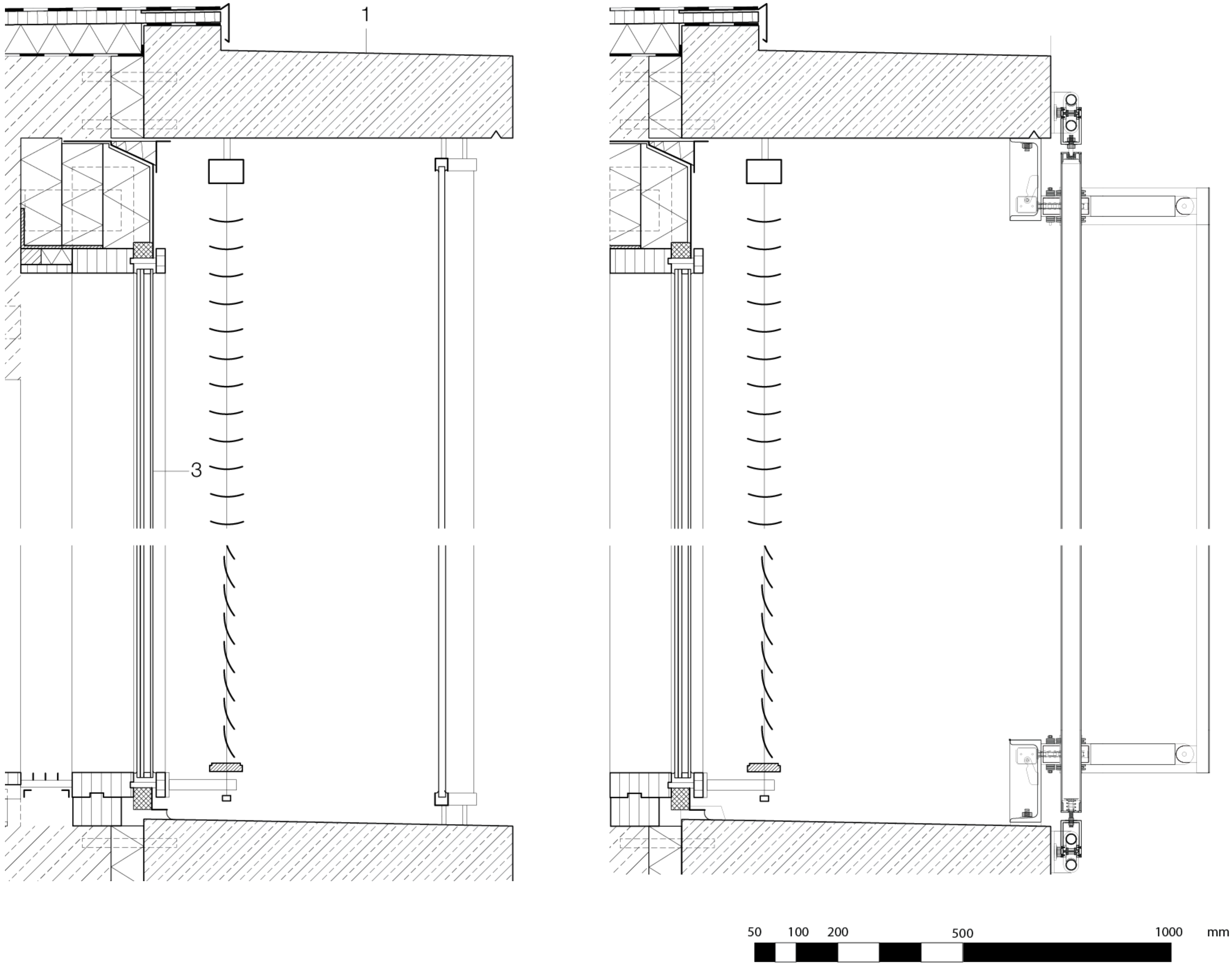

50 100 200 500 1000 mm
A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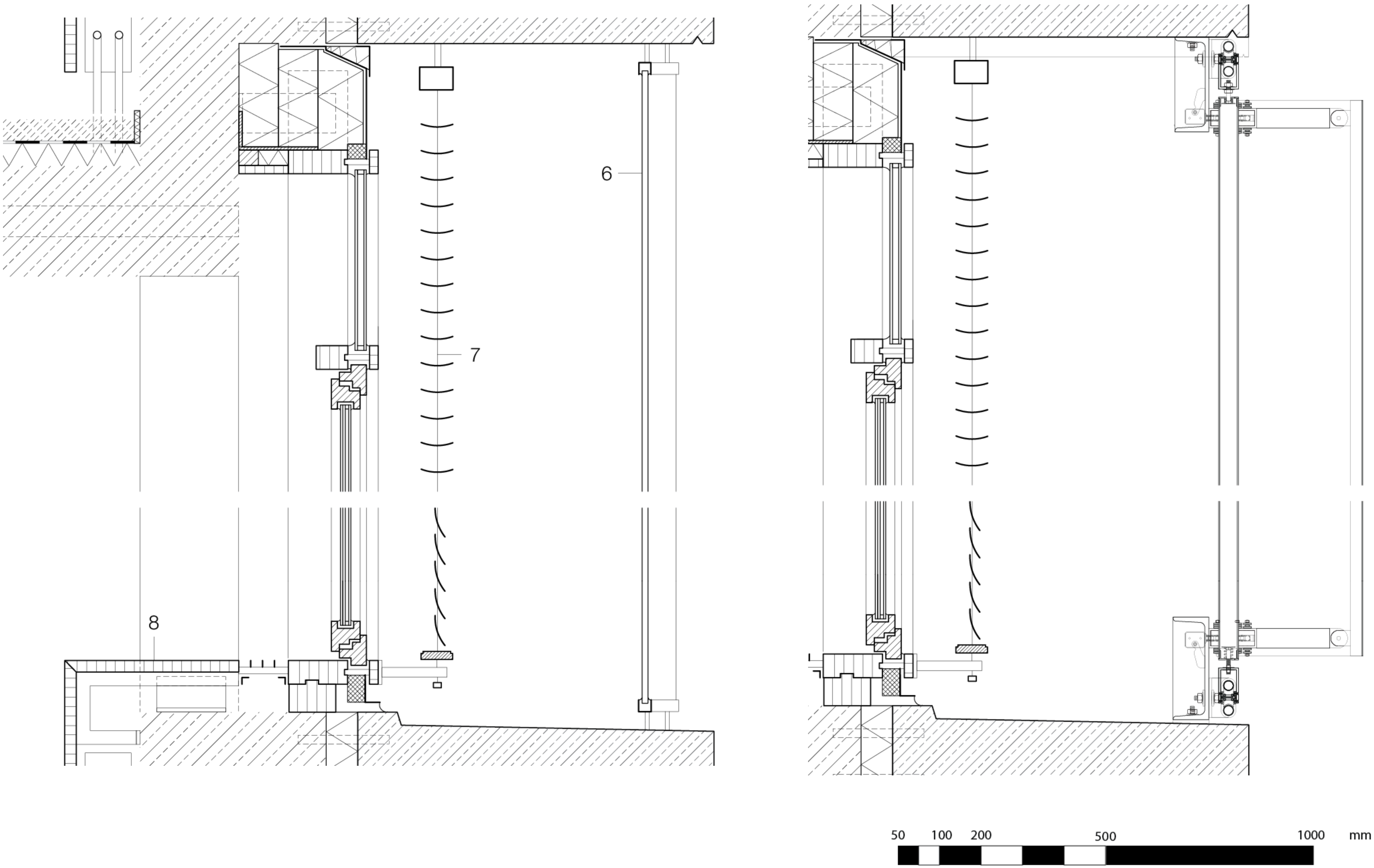
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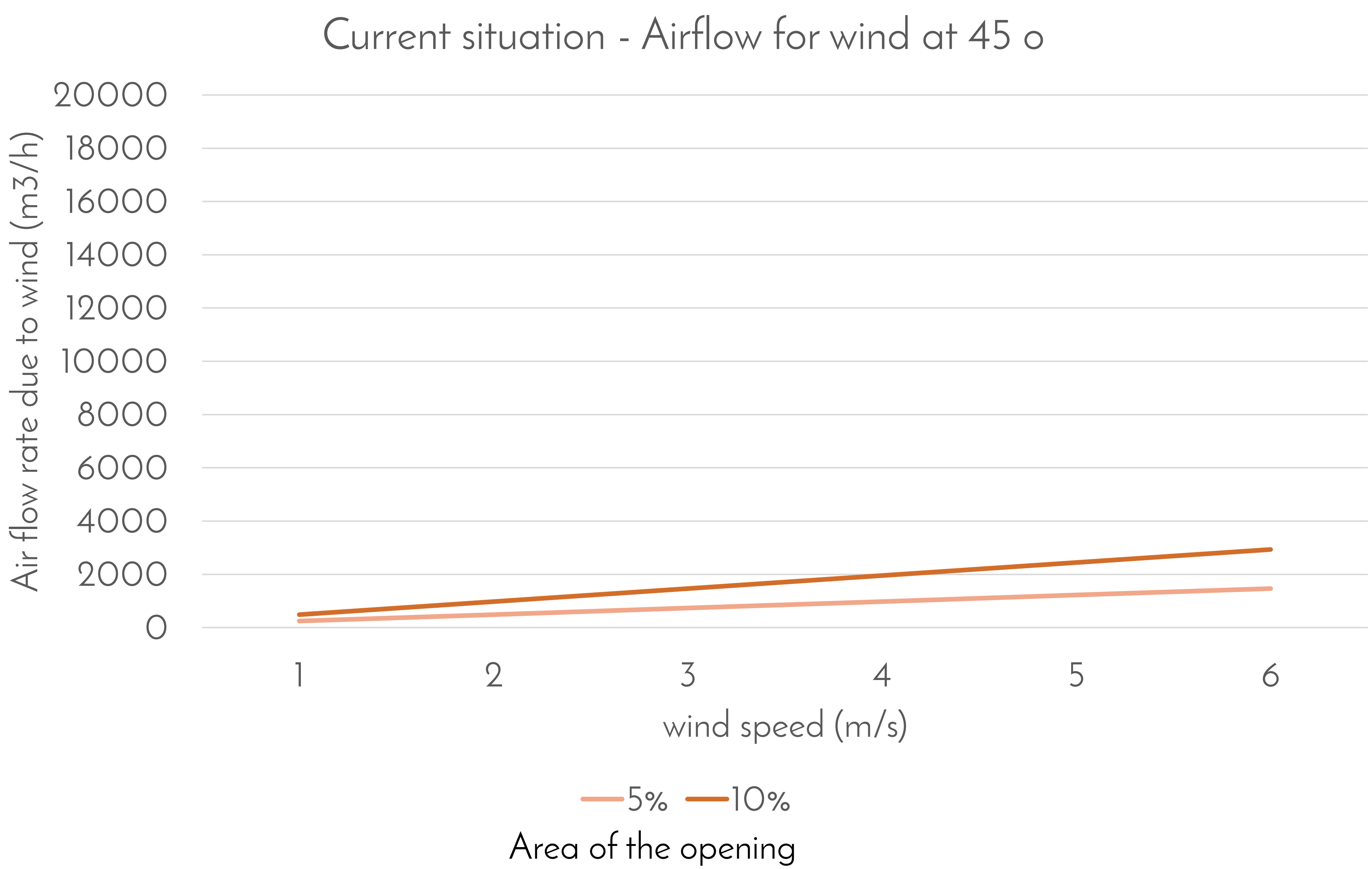
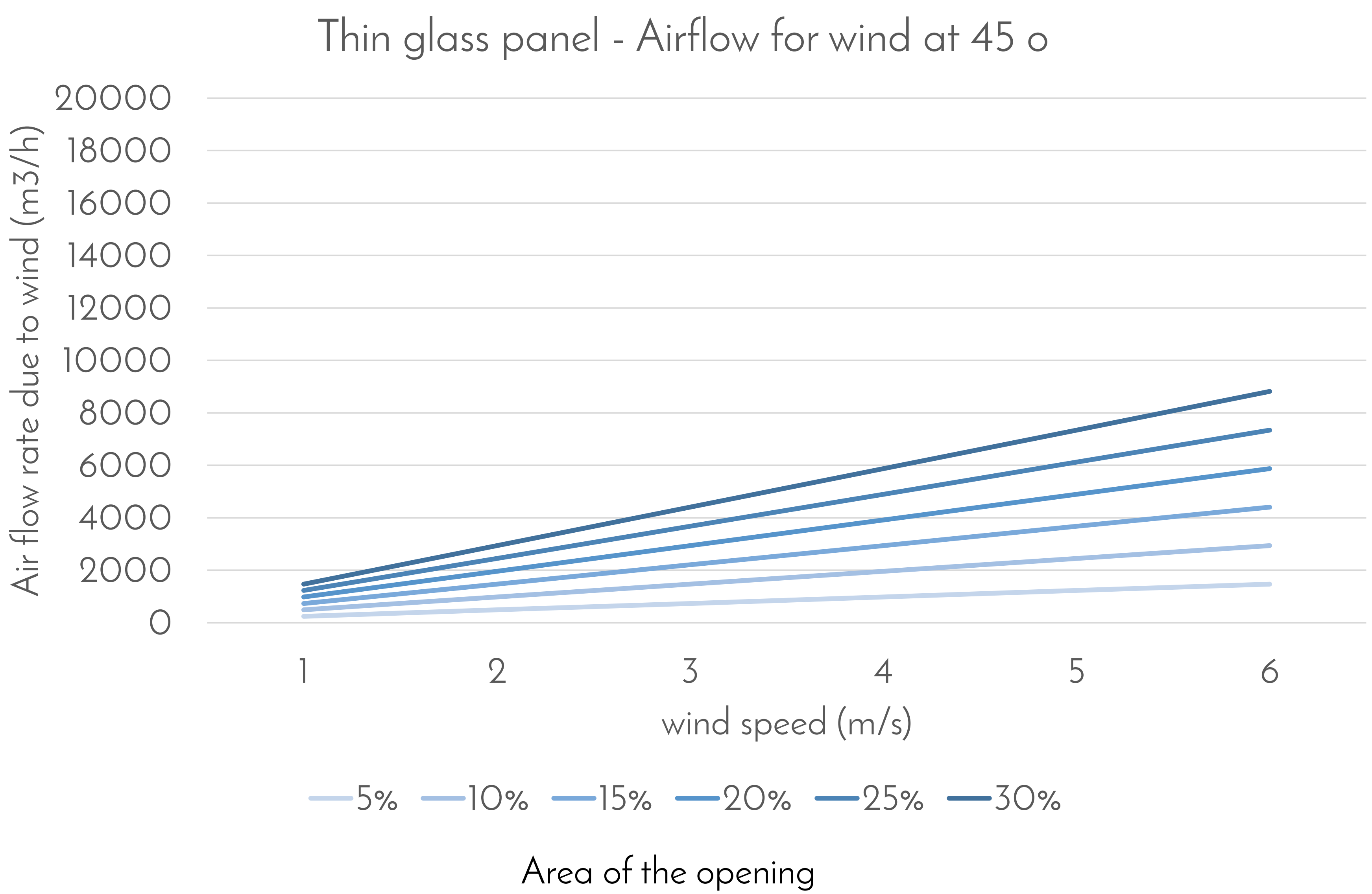
Ventilation estimation

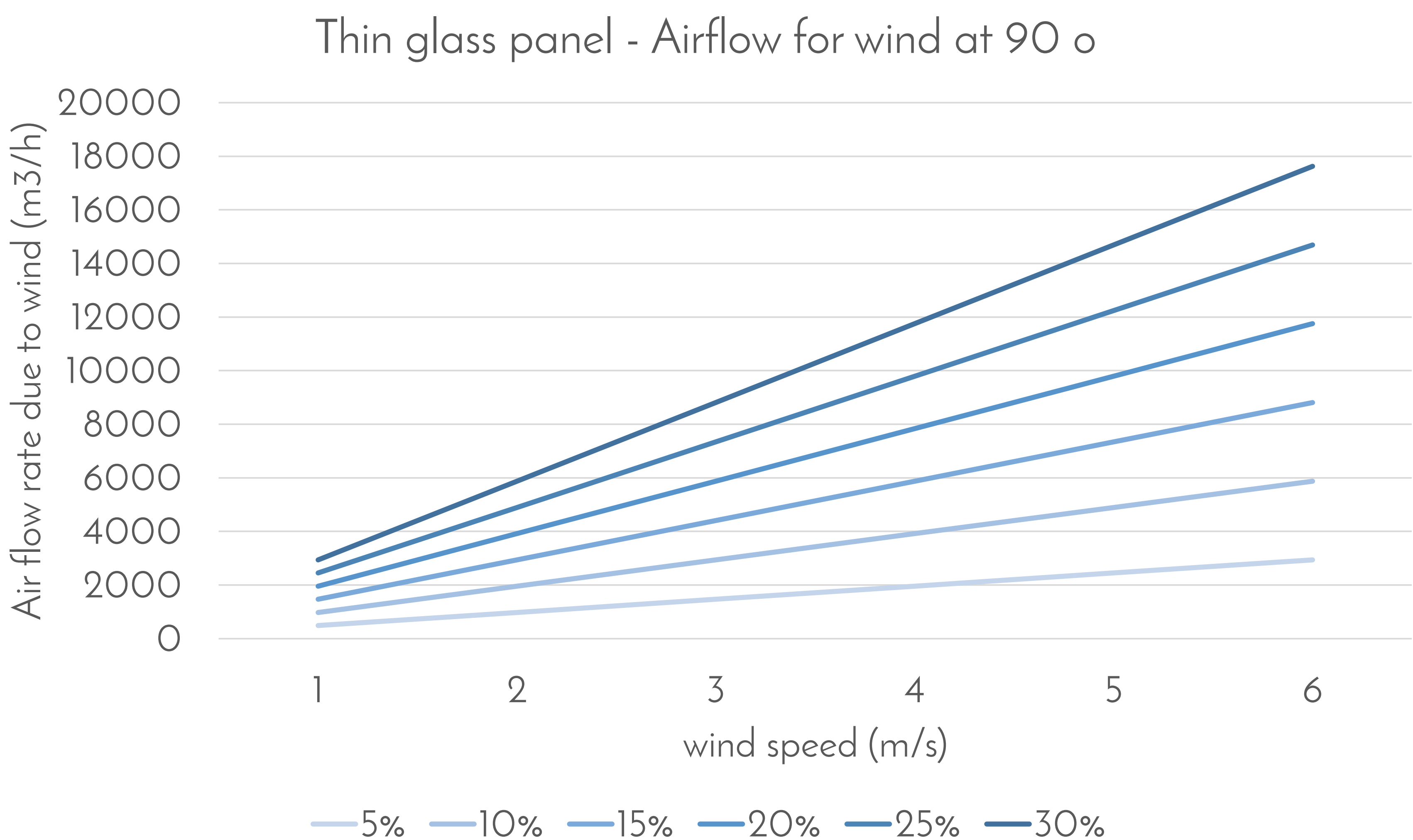
Ventilation estimation



Ventilation estimation



Ventilation estimation



Area of the opening

How can a thin glass double skin façade panel be made adaptive?

1. To what purposes can a thin glass panel be made adaptive?
2. How does bending influences the stress generation in the thin glass panel?
3. What are the influences of bending and thickness on the load resistance of the thin glass panel?
4. What are the possibilities of movement for this panel?
5. How can supports influence the movement and geometry of the thin glass adaptive panel?
6. How to translate the necessary degrees of freedom for the movement of the panel to its detailing?

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Conclusions of the research

- Thin glass as a building material
  - Research is still necessary to be applied in this context;
  - Is an alternative to common glass for sustainability aspects;
  - Opens new design possibilities which are not feasible by glass.

Conclusions of the research

- Thin glass as an adaptive façade panel
  - Challenge of the concept of glass as a static material;
  - Further research is still necessary to allow for large scale applications.

Conclusions of the research

- Contribution on the growth of knowledge over this material
  - Behavior of the material under simple bending and on assuming different shapes;
  - Applying this material to a façade context.

Suggestion further studies

- Study of material properties
  - Pre stresses on surface and edges;
  - Fracture behavior
- Lamination
  - Influence of lamination on the bending capacities;
  - Delamination by continuous bending.
- Integration with other materials
  - Bimetals as actuators;
  - Stiffening of the panel.

Thank you