EXOSKELETWINDOW

Thin-glass window embedded with soft pneumatic actuator

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Mentor team

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External mentors from ABT(computational design): Frank Huijben and Chris van der Ploeg

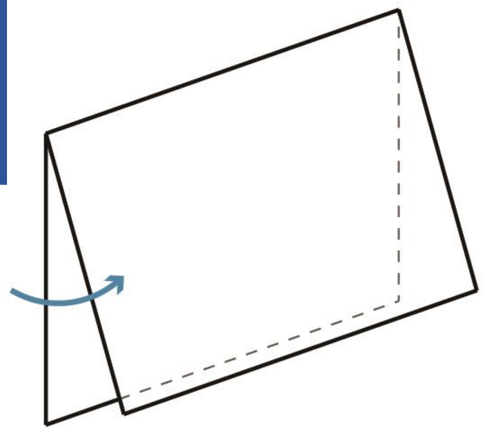
Prototype

Content

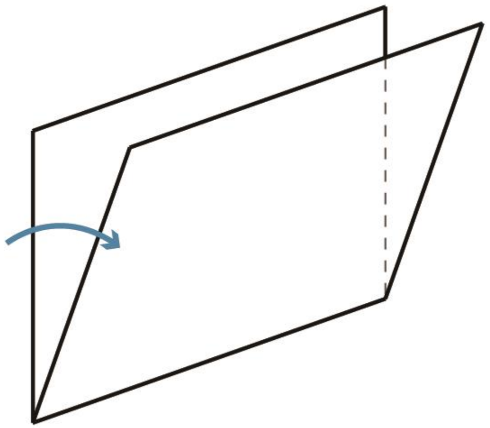
Part 1

Introduction

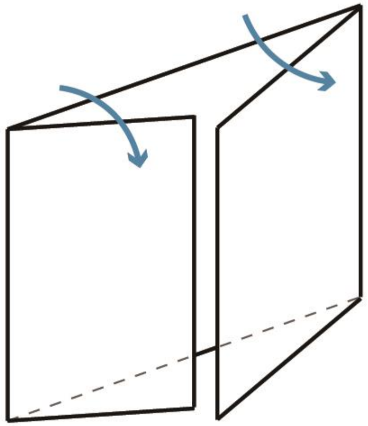
How window open for natural ventilation nowadays



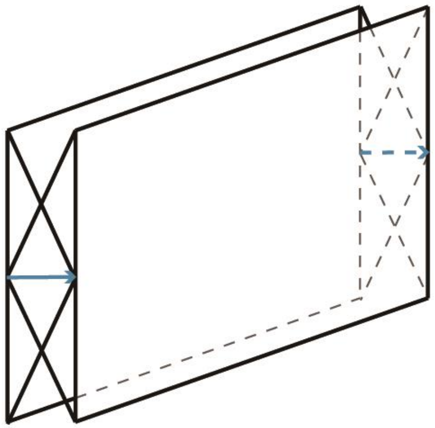
Top hung window open to outside



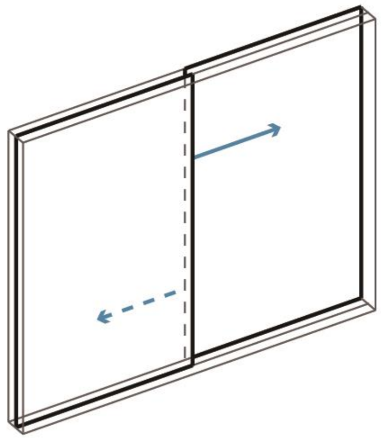
Bottom hung window open to outside



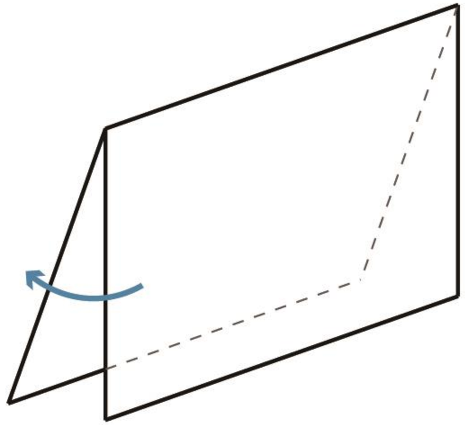
Common window open to outside



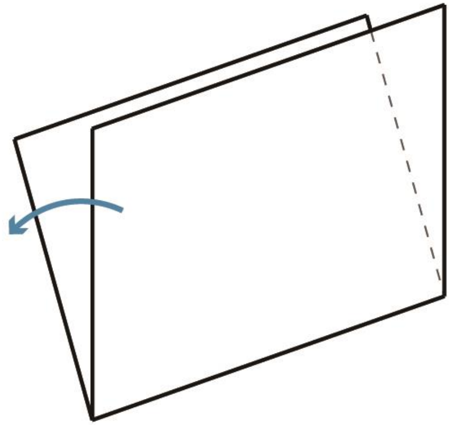
Push-out window



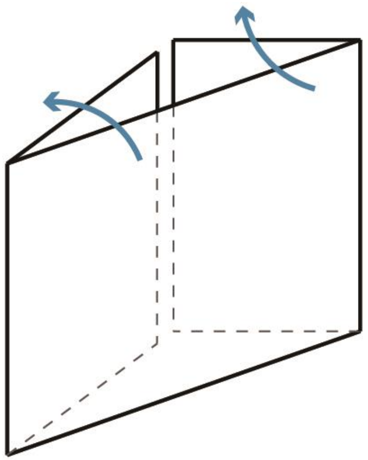
Frameless sliding glass window



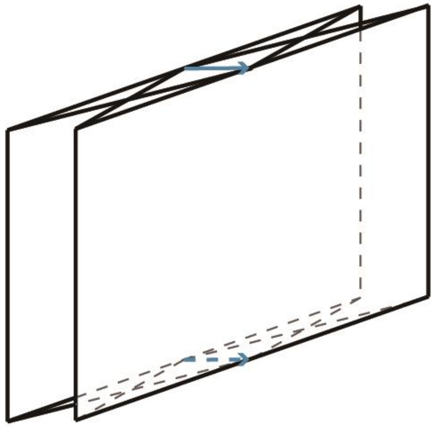
Top hung window open to inside



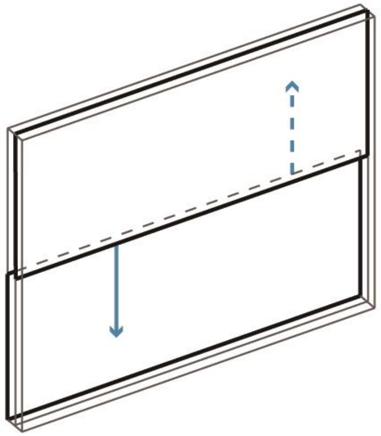
Bottom hung window open to inside



Common window open to inside



Push-out window



Double Hung Double-Glazed Sash-less Window

- Unpredictable wind
- Monotonous window openings
- Difficult to control inlet air velocity and direction

Main questions

How can soft pneumatic actuator(SPA) bend thin-glass windows structurally for natural ventilation?

Sub-questions

- How to prove curved window can decrease predict dissatisfied percentage due to draft (PPDR)
- Considering natural ventilation function, which window configuration can be developed
- What is the relationship between SPA geometry, air pressure and bending radius.
- How to design window frame

Part 1.1

Methodology

Proof of Concept (POC)

Hypothesis

A: Soft pneumatic actuator can bend insulating thin glass window

B: Curved window can improve predict dissatisfied percentage due to draft

Proof of Concept (POC)

Hypothesis

A: Soft pneumatic actuator can bend insulating thin glass window

B: Curved window can improve predict dissatisfied percentage due to draft

Hypothesis based Research

A: Soft Pneumatic Actuator, thin glass and Window detail

B: Aerodynamic theory and Draught model

Proof of Concept (POC)

Hand calculation based approximation

A: Structure mechanism, SPA morphology generation

B: Inlet air flow rate

Proof of Concept (POC)

Hand calculation based approximation

A: Structure mechanism, SPA morphology generation

B: Inlet air flow rate

Simulation based approximation

A: Soft Fiber-Reinforced Bending Actuator, SPA

B: Mean air velocity and predict dissatisfied percentage due to draft(PPDR)

Proof of Concept (POC)

Experiment based evaluation

A: Model making by increase air pressure to test bending behavior

Part 2

Hypothesis-based research

- High strength
- Flexibility
- Lightweight

Source: (Schott, 2016)

Previous research on thin glass topic

Thin glass adaptive facade

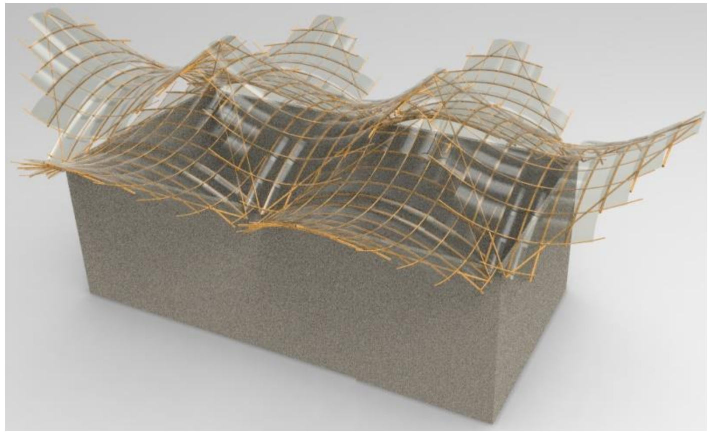
Source: (Rafael, 2016)

Water and air tight bending facade

Source: (Özhan, 2017)

Folding-canopy roof

Source: (Prof. Jürgen Neugebauer, 2014)



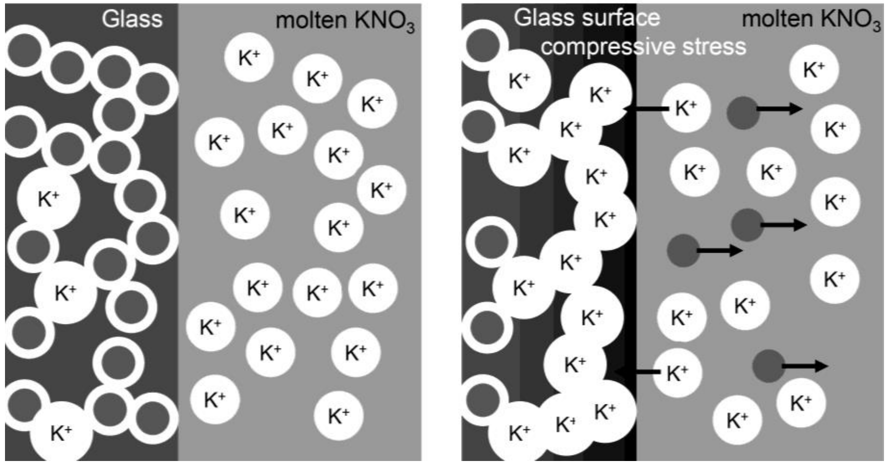
Bamboo and thin glass roof

Source: (Priyanka, 2016)

Thin glass sandwich panel

Source: (Iris, 2017)

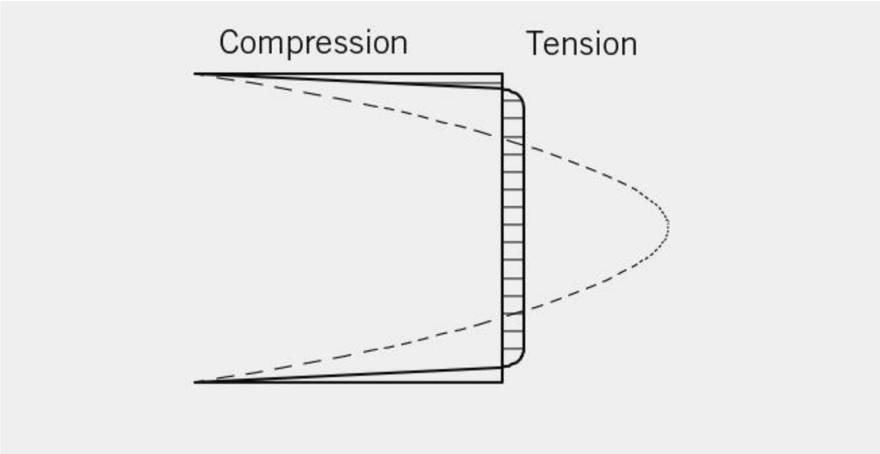
Chemically strengthened borosilicate glass



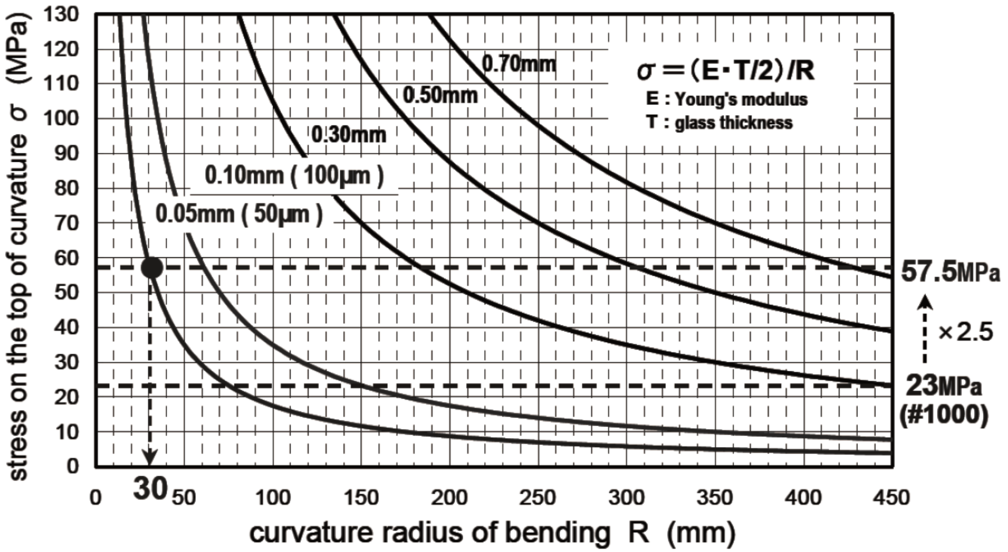
Chemical strengthened process

	Leoflex (0.85mm)	Thermally tempered (3.2mm)
MECHANICAL CHARACTERISTICS		
Strength / Marginal stress　短期許容応力 (MPa)	260	80
Young modulus　ヤング率 (GPa)	74	70
Poisson ratio　ポアッソン比	0.23	0.2
Density　密度 (g/cm³)	2.48	2.5

Thin glass mechanical properties

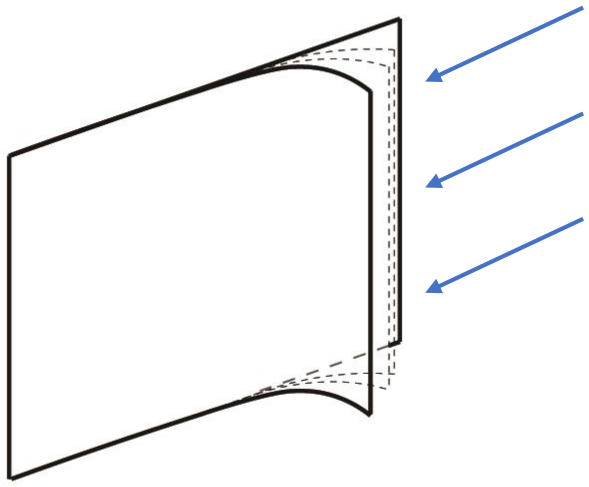


Stress cross-sectional of chemically strengthened glass

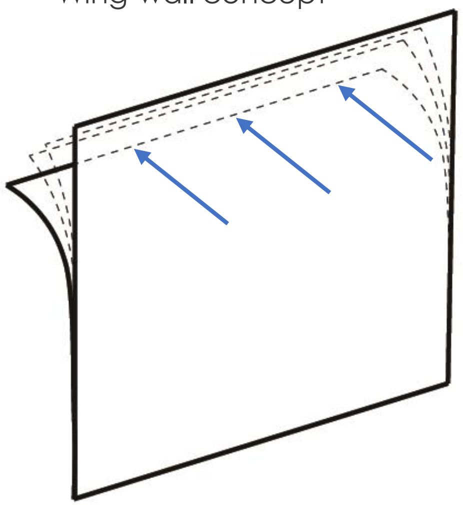


Stress on surface by bending curvature

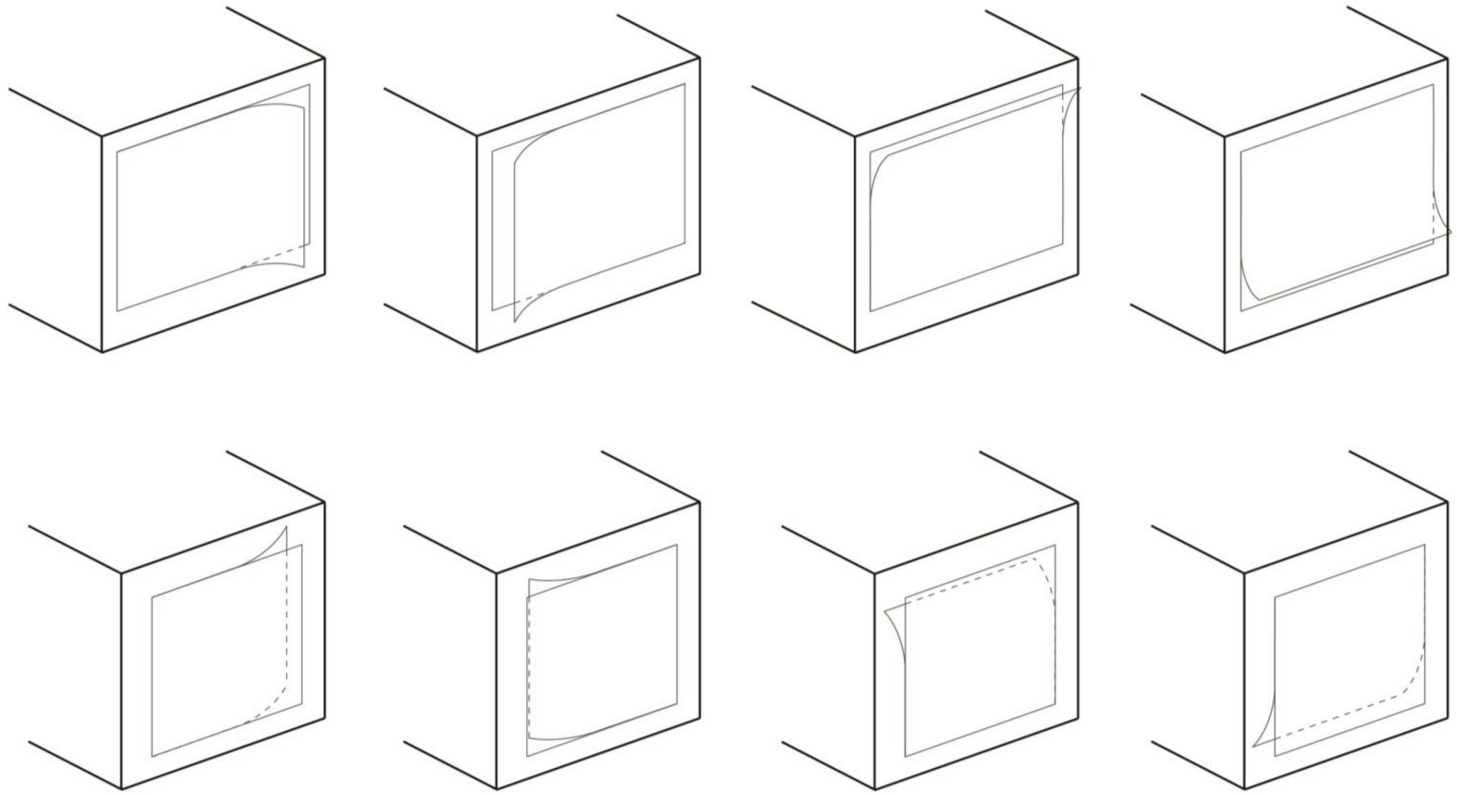
New material possibilities



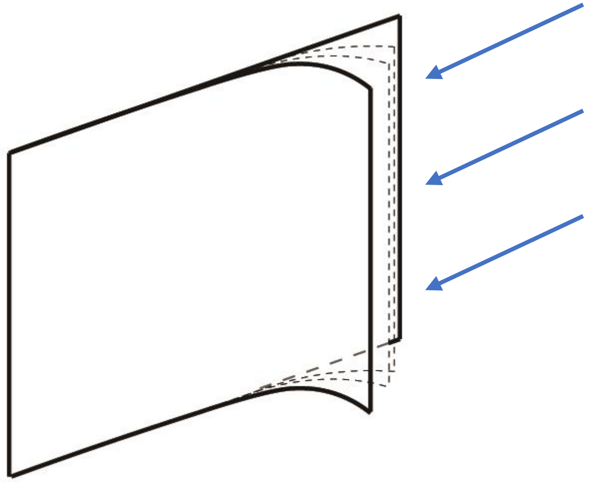
Wing-wall concept



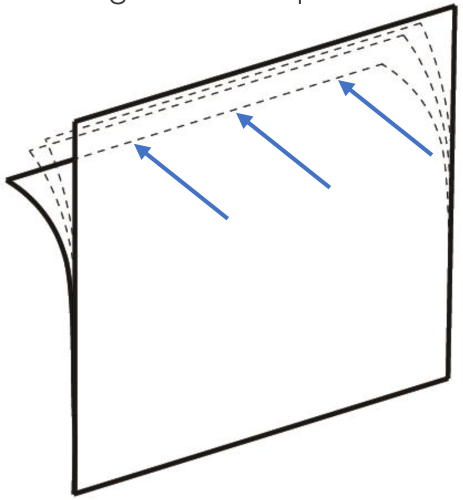
Tilt and turn window concept



New material possibilities



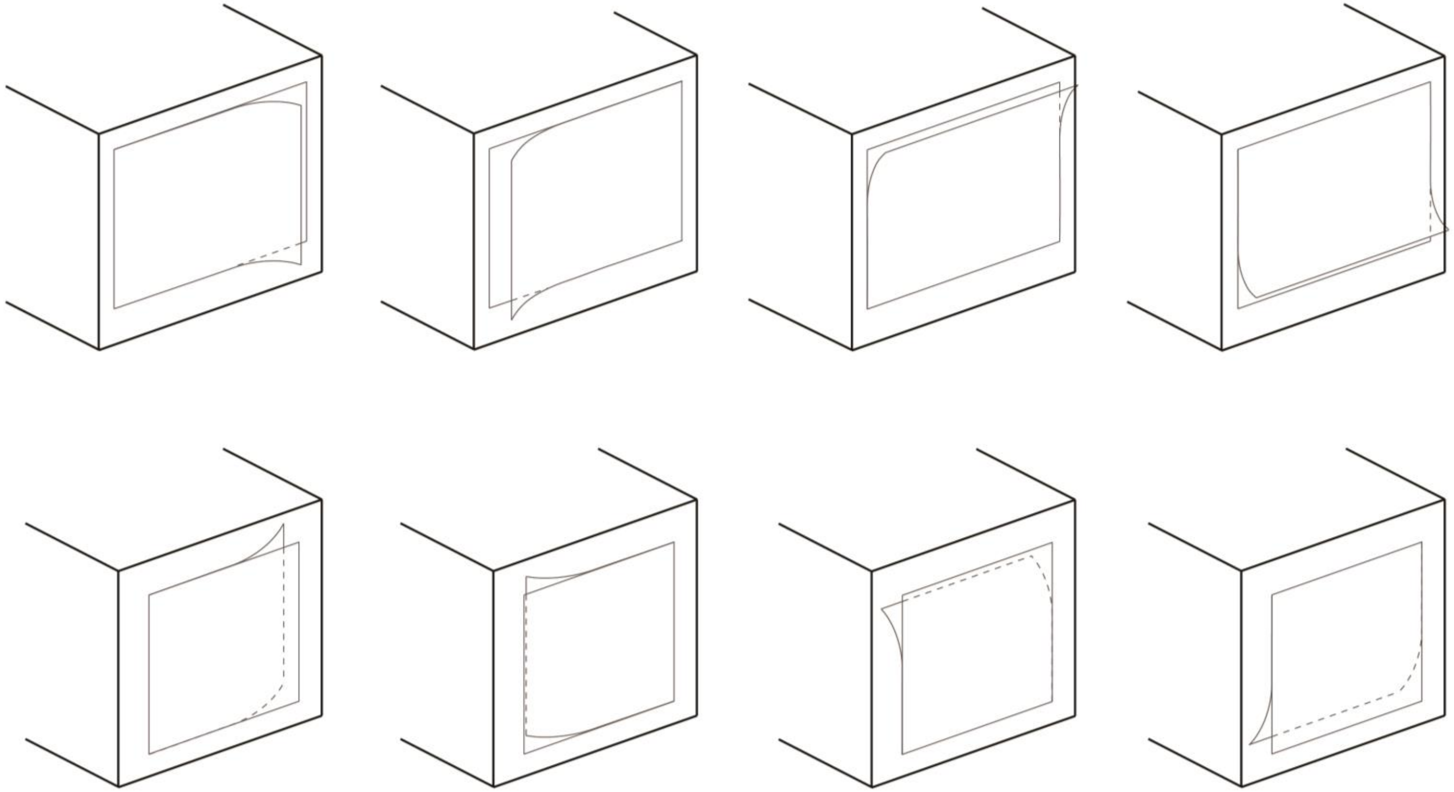
Wing-wall concept



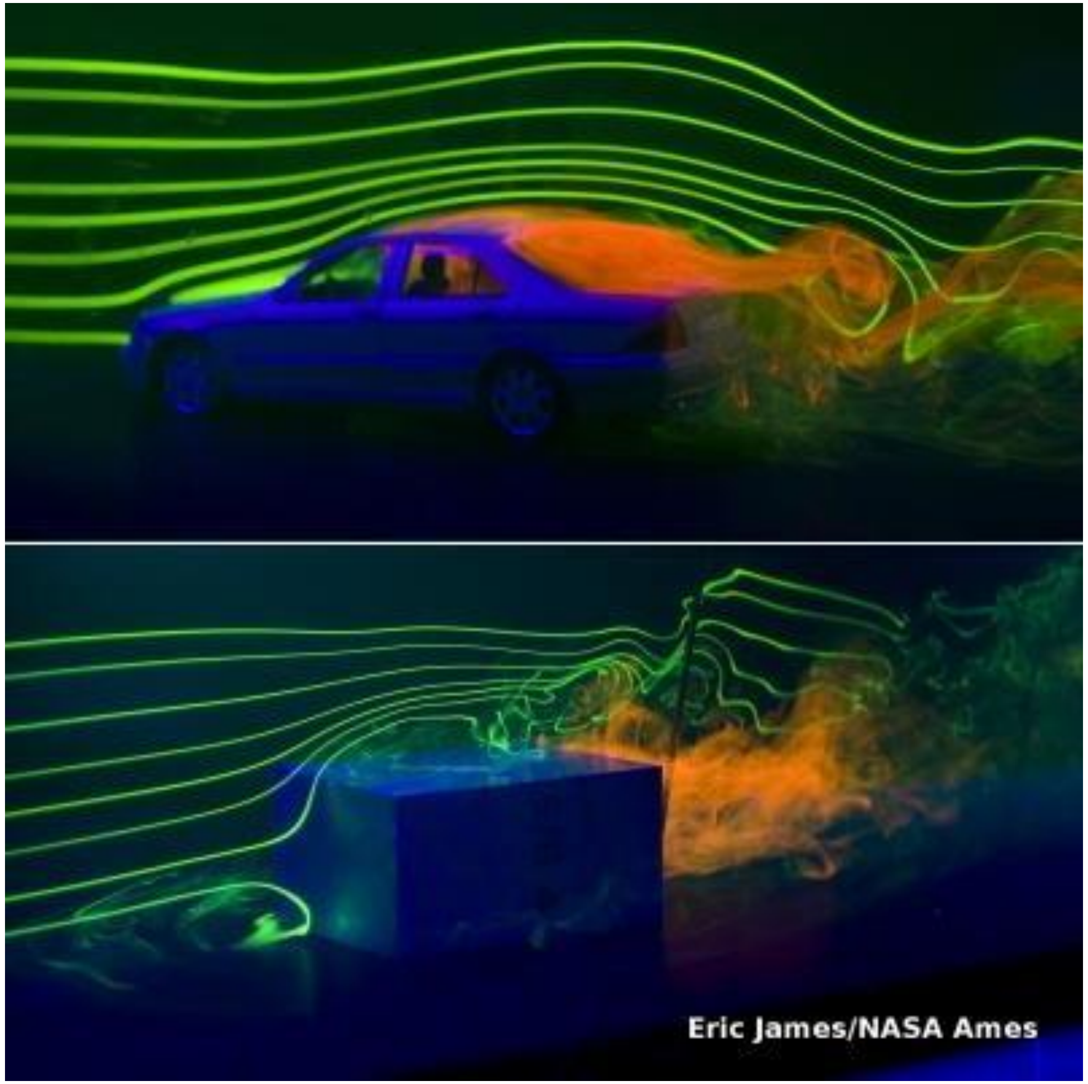
Tilt and turn window concept

Variable opening radius adaptable to external environment

$$Q = C_d A v$$

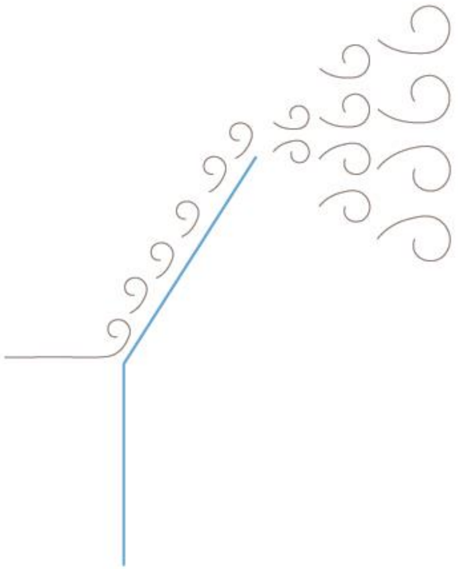


CFD simulation comparison

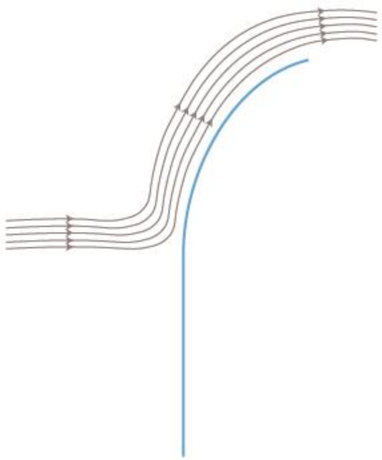


Why curved window

Aerodynamics theory

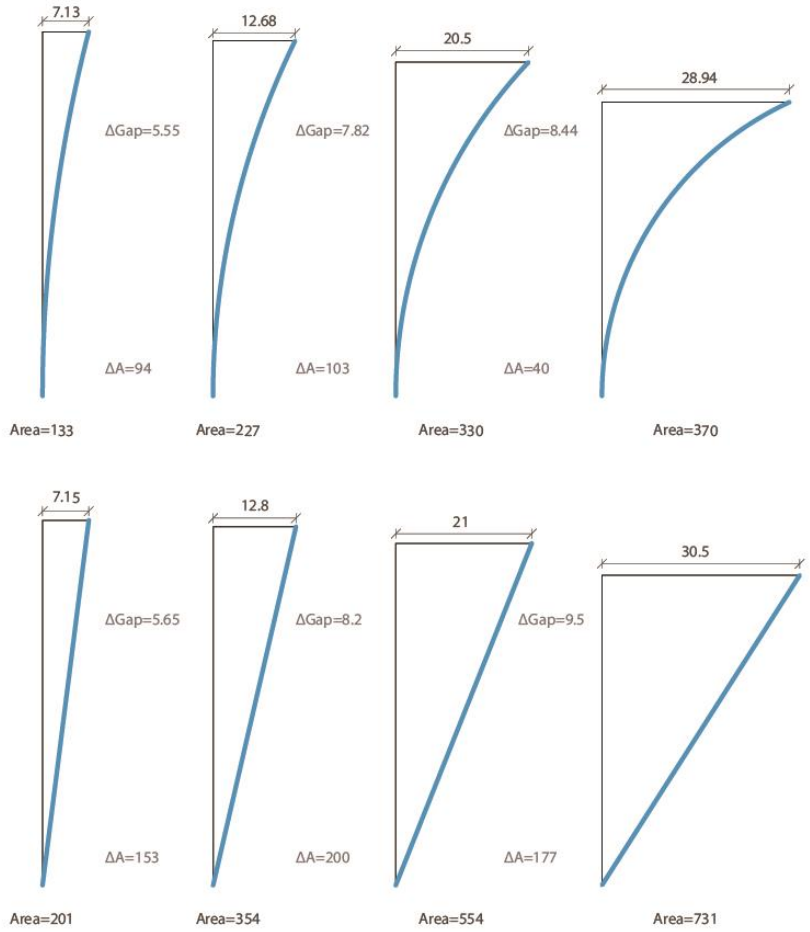


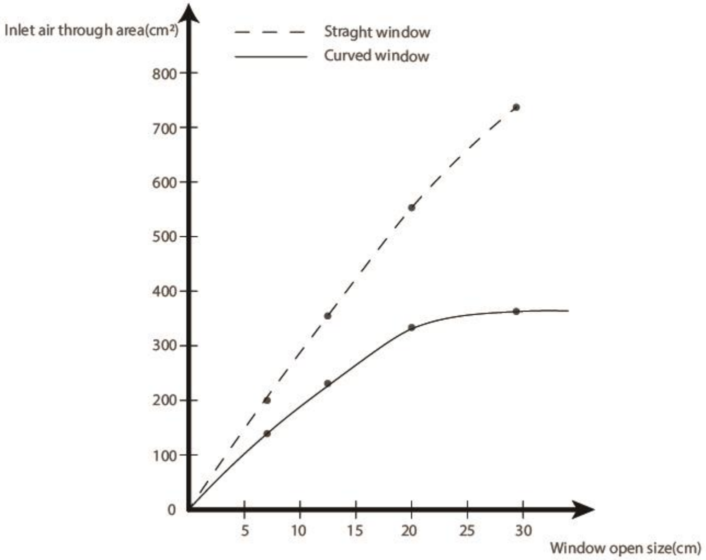
Form drag- turbulent flow



Friction drag- laminar flow

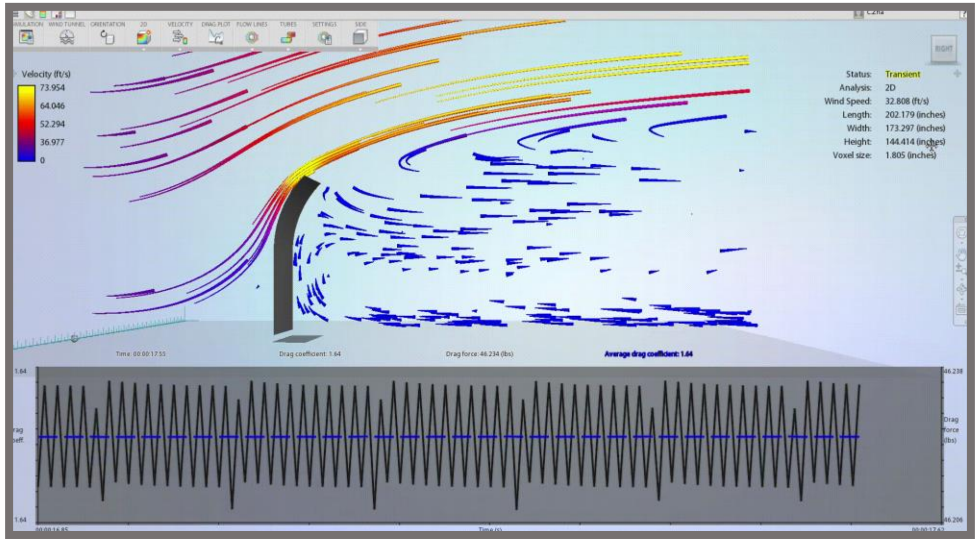
Inlet airflow rate changing ratio



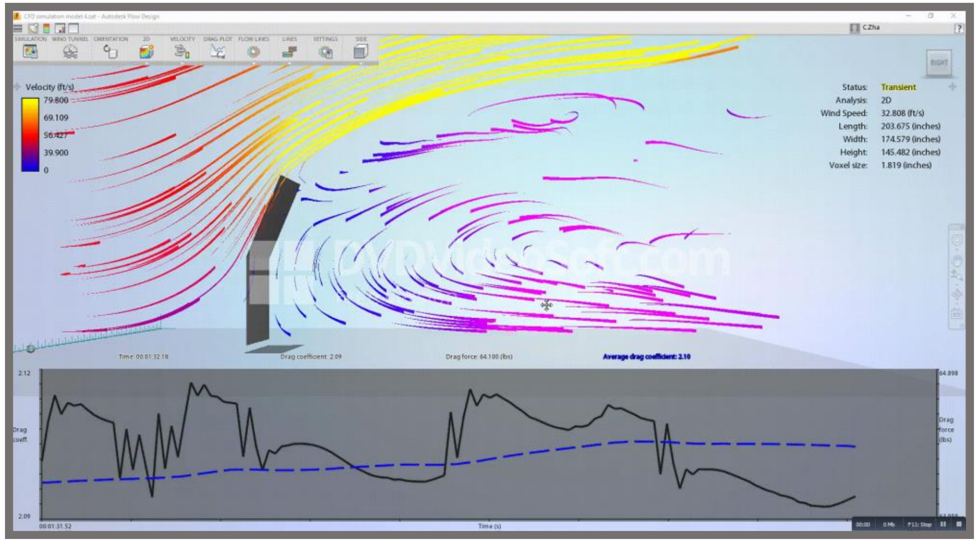


Fanger and Pedersen(1977) experiments shows that a fluctuating air flow is more uncomfortable than a constant flow with the same mean velocity.

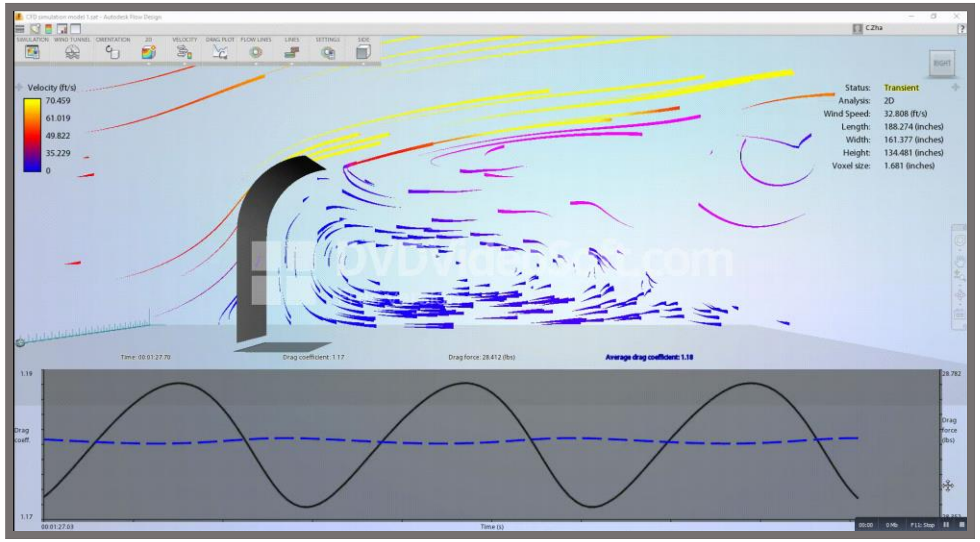
CFD simulation comparison



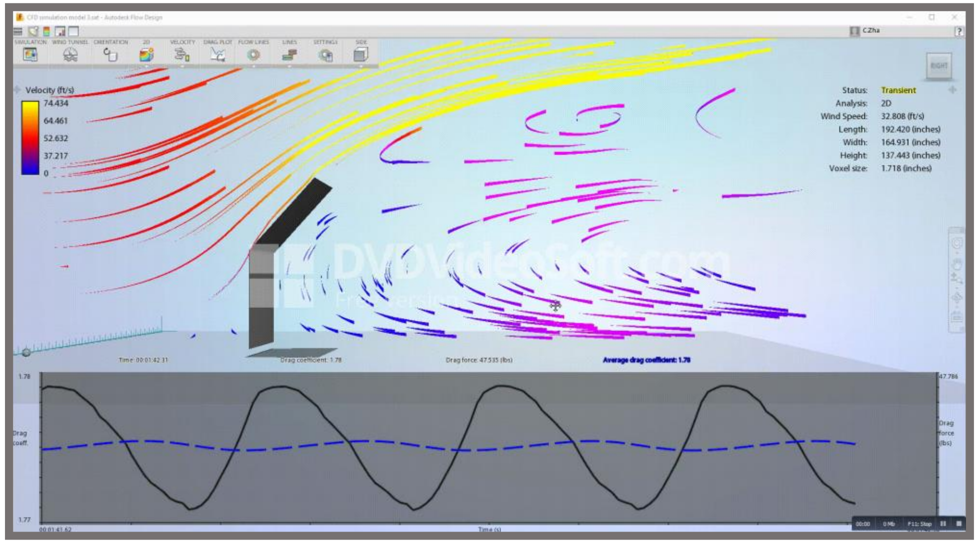
Opening size-A/ Drag force 46/ Drag coefficient 1.64



Opening size-A/ Drag force 64/ Drag coefficient 2.10



Opening size-B/ Drag force 28/ Drag coefficient 1.18



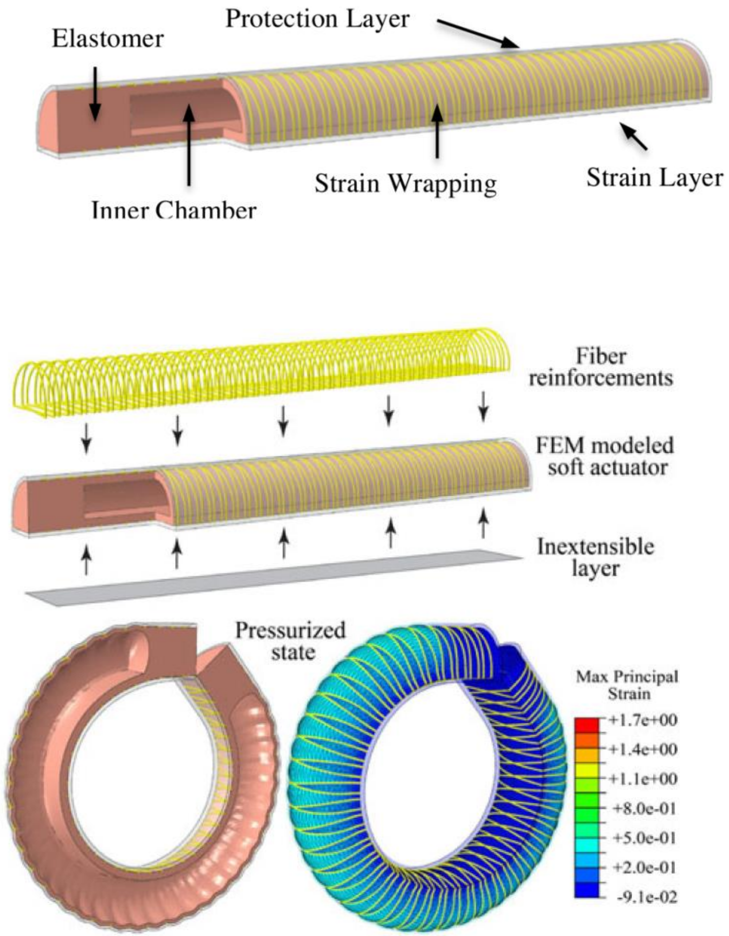
Opening size-B/ Drag force 47/ Drag coefficient 1.78

Soft robotics

Source: (soft robotic toolkit, 2015)

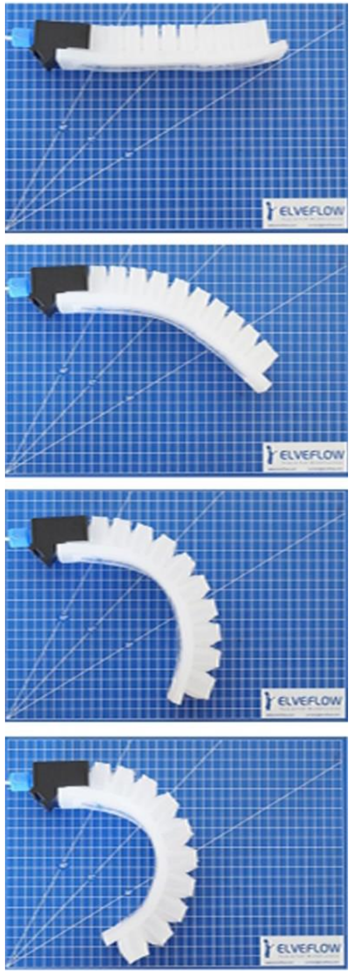
Two soft actuators comparison

Soft Fiber-Reinforced Bending Actuators

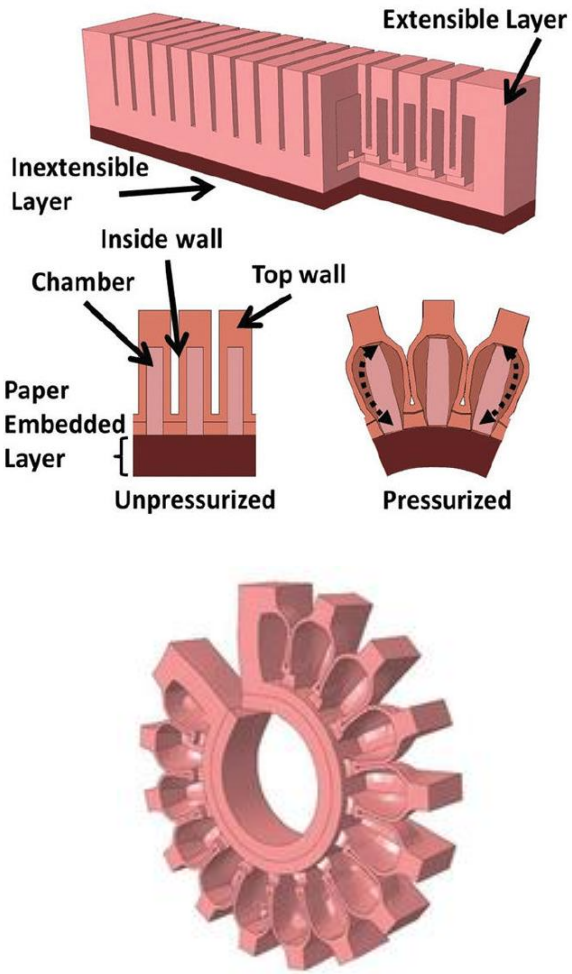


Source: (soft robotic toolkit, 2015)

Soft Pneumatic Actuator

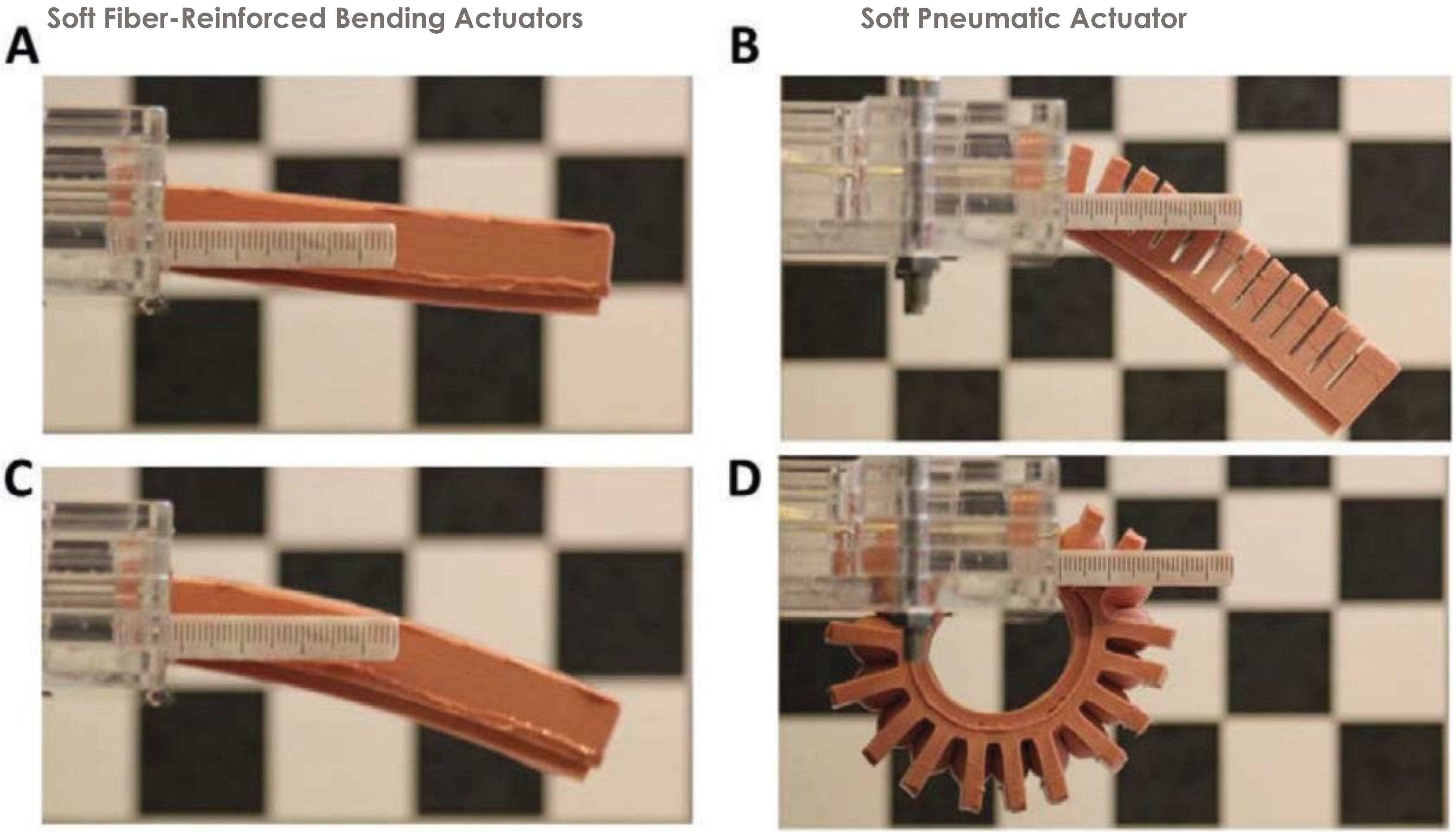


Source: (soft robotic toolkit, 2015)



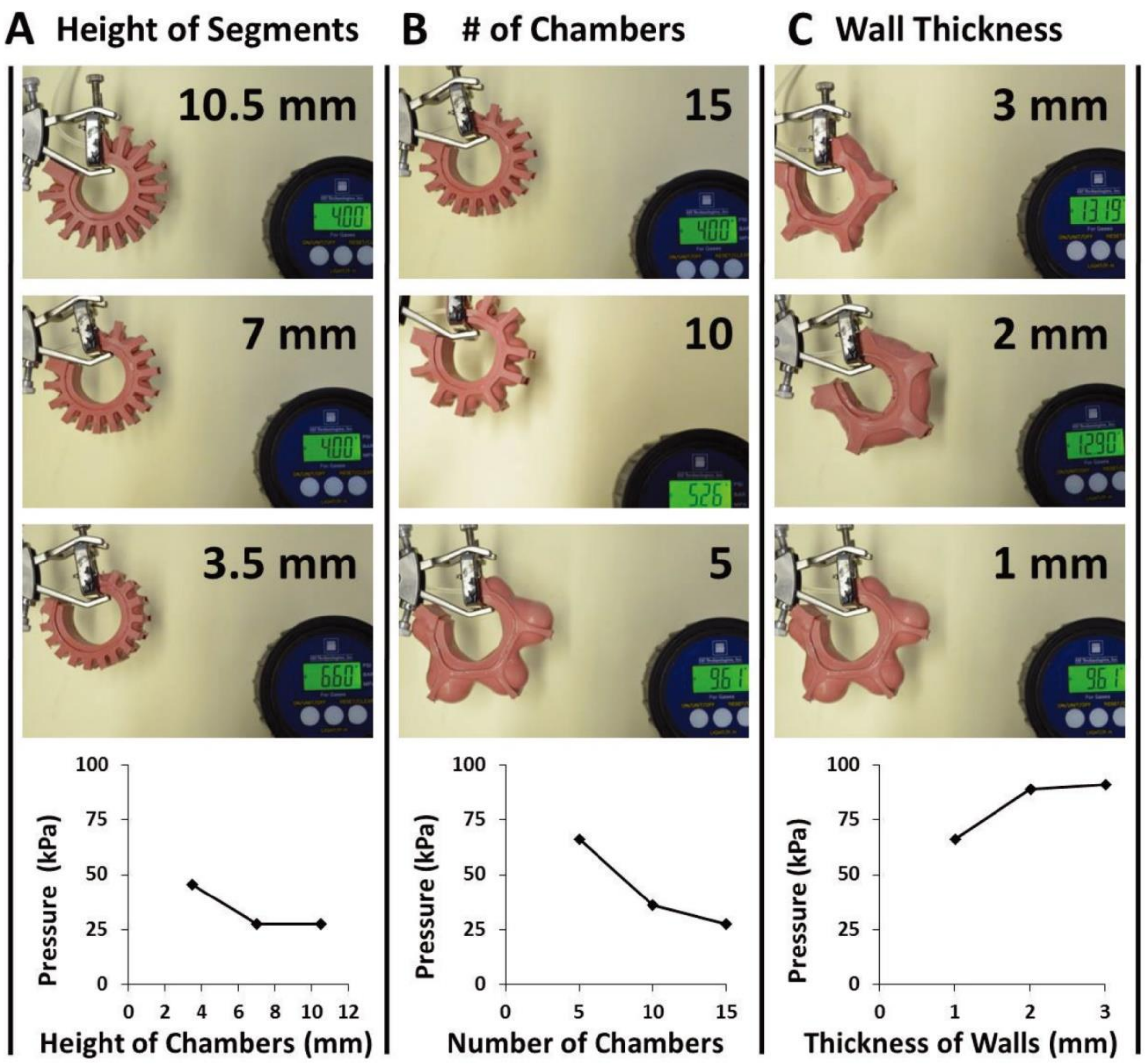
Source: (soft robotic toolkit, 2015)

Two soft actuators comparison



Source: (soft robotic toolkit, 2015)

Relative Research- SPA- Actuator morphology influences air pressure



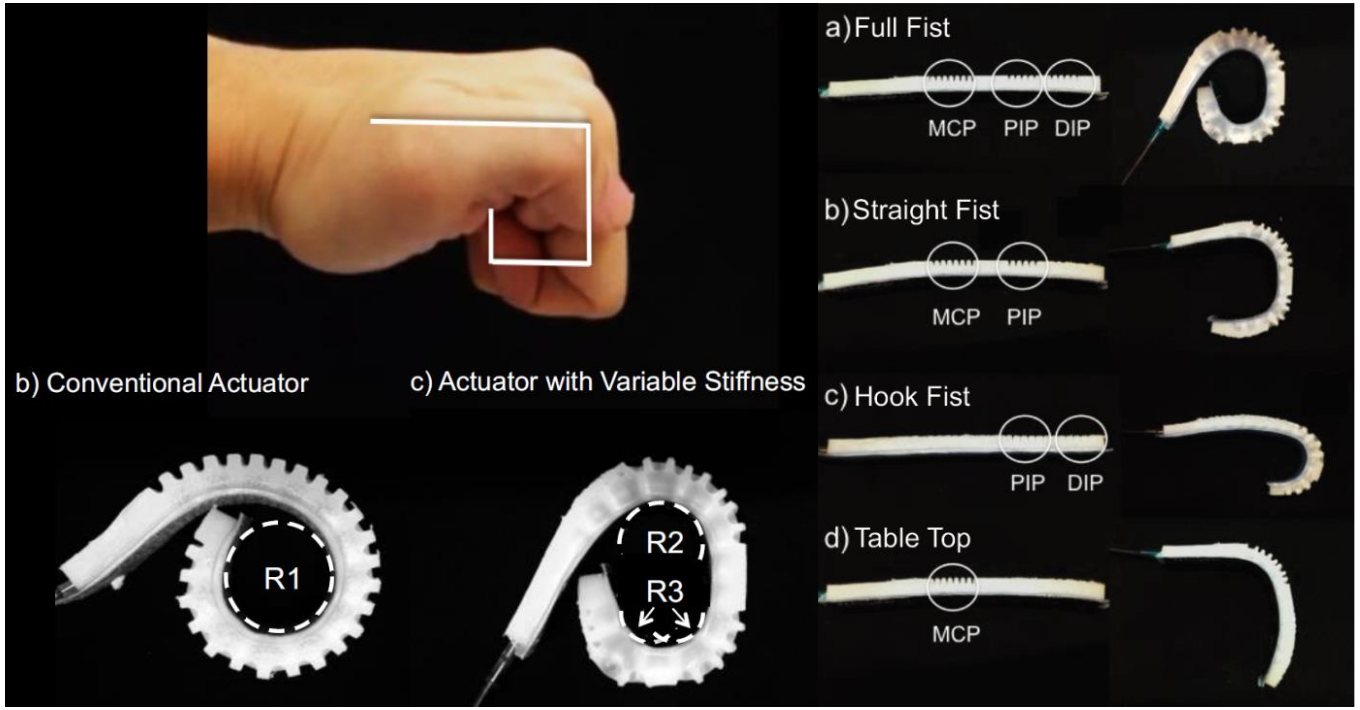
Source: (Mosadegh et al., 2014)

Conclusion

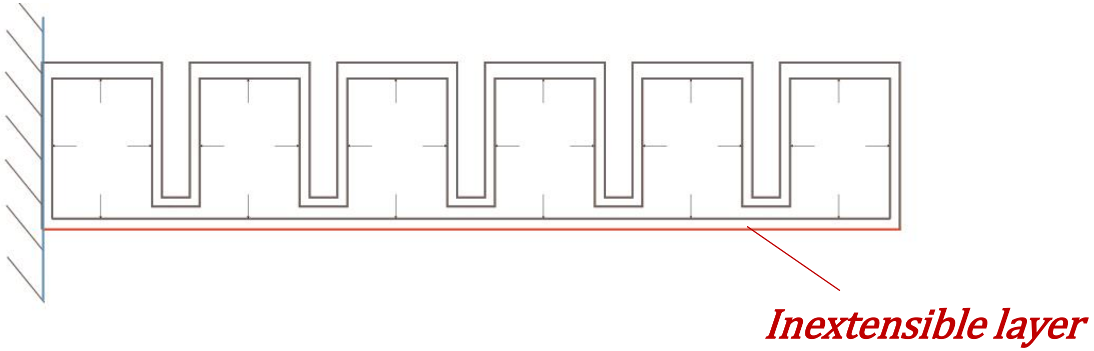
To achieve full bending motion,

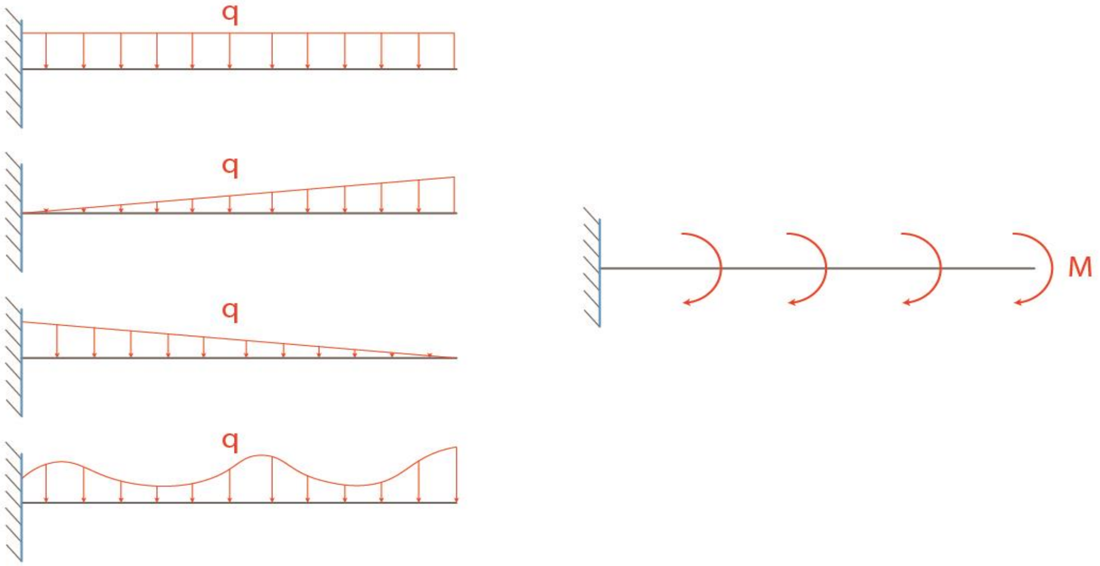
Thinner wall, more chamber numbers and higher segments requires least air pressure

Relative Research- SPA- Variable Stiffness at different localities to conform to the shape

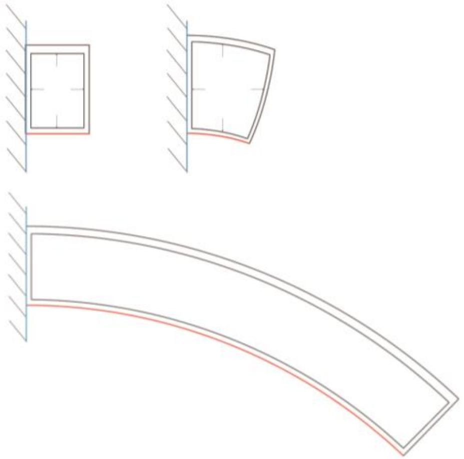


Structural mechanism



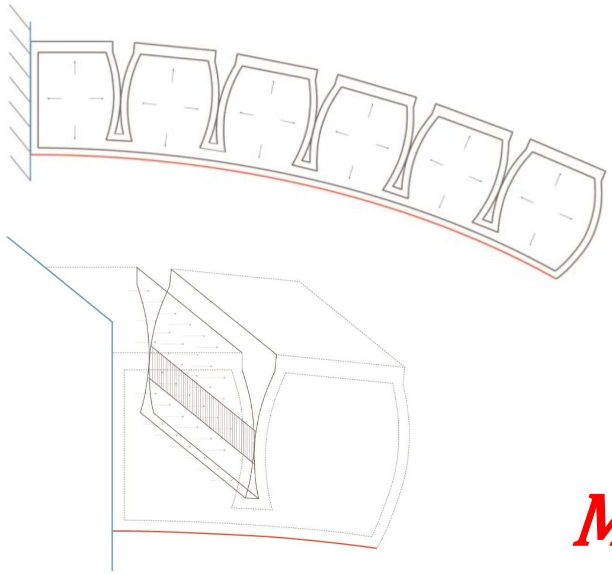


Stretching based bending



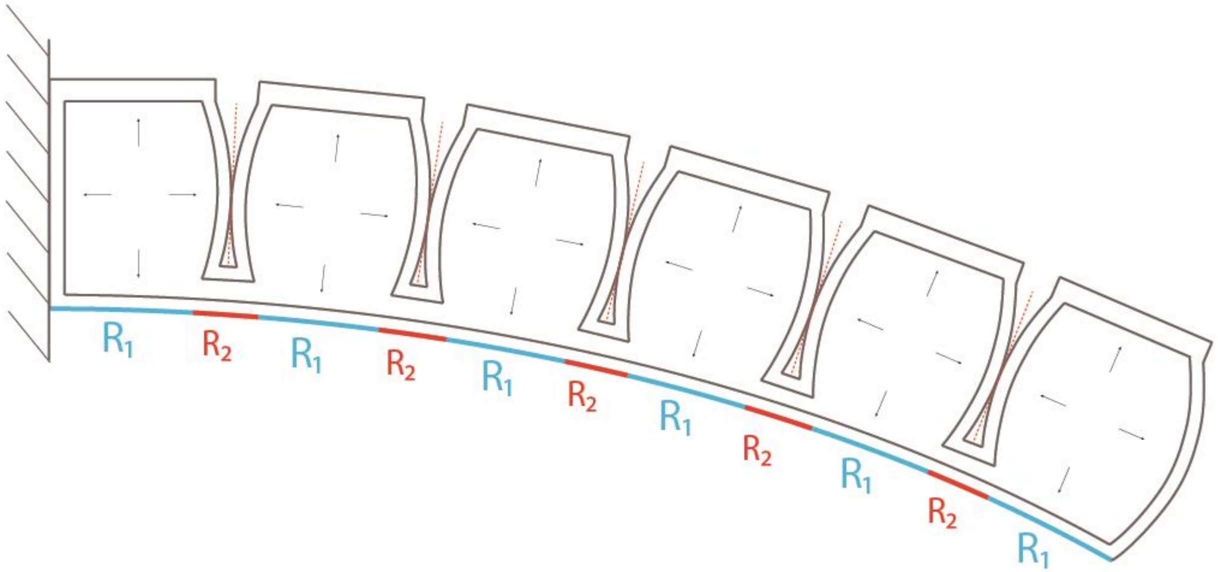
$M_{stretch} = ?$

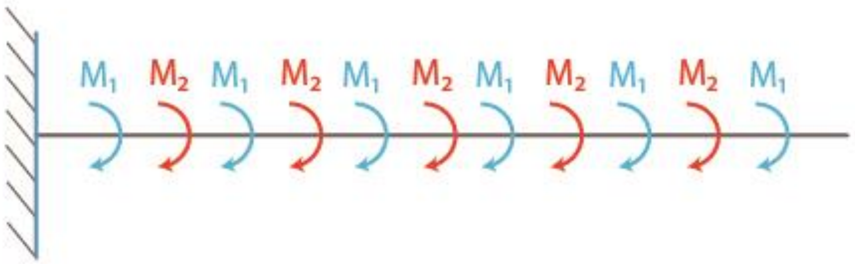
Contacting based bending



$M_{contact} = ?$

Structural mechanism

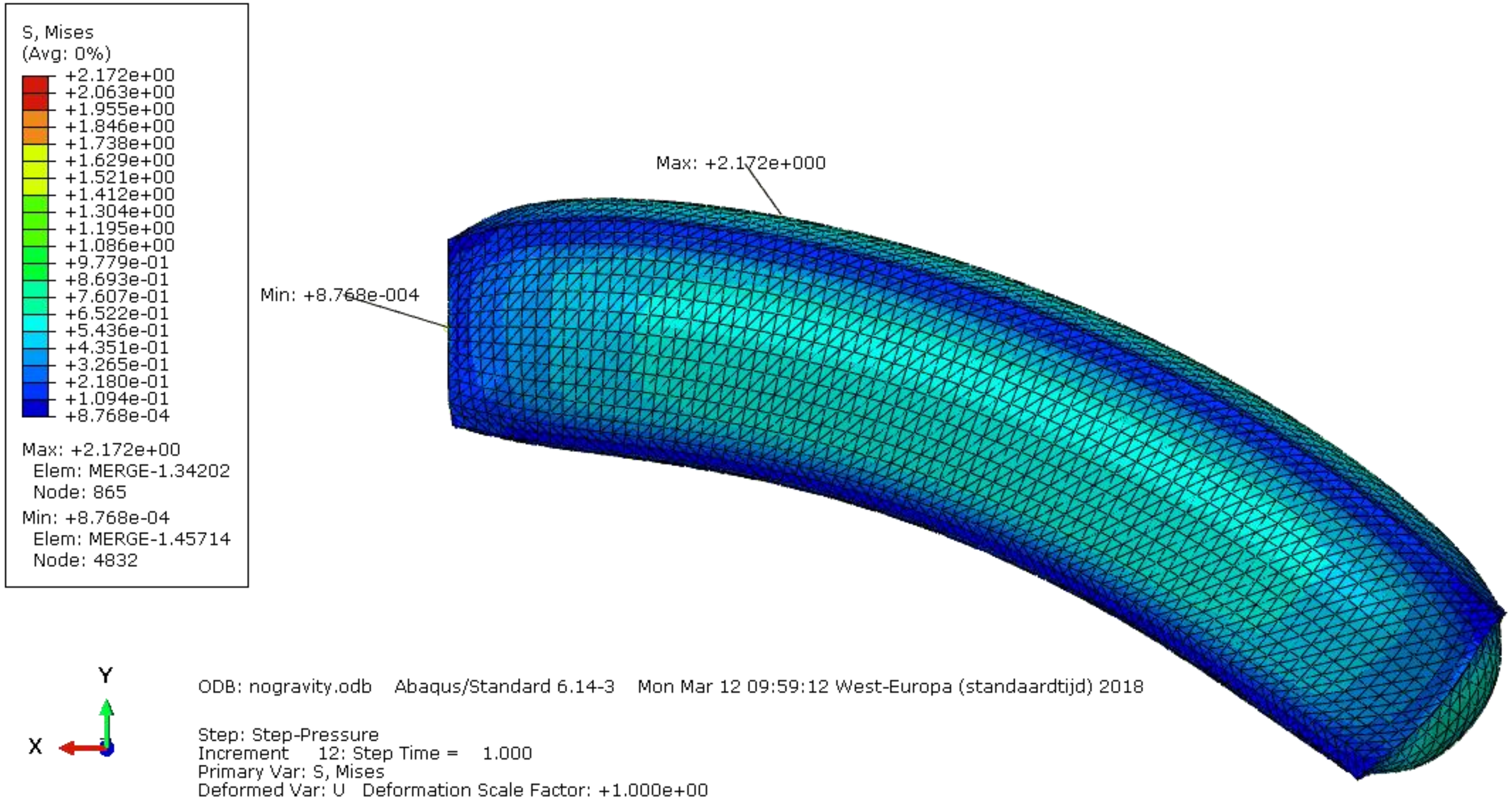




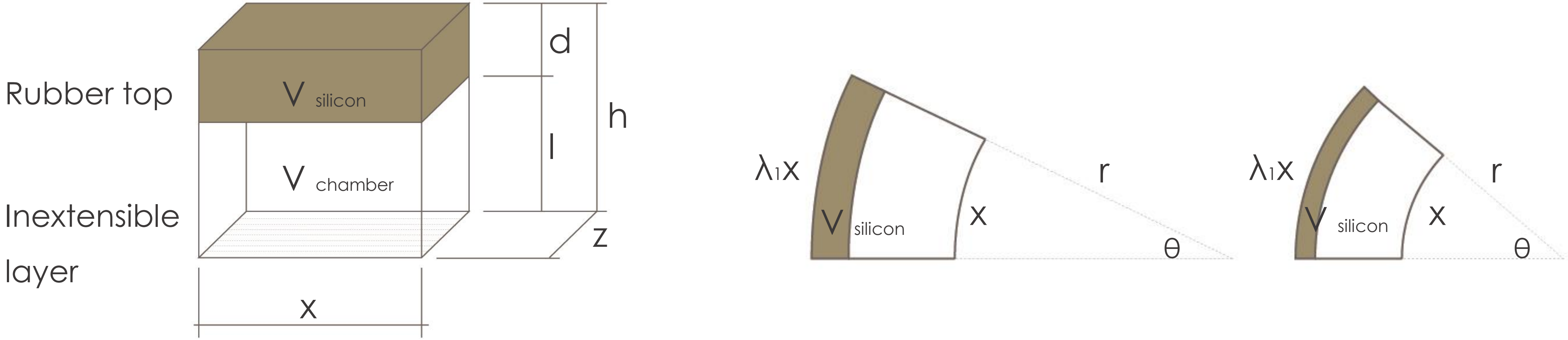
$$\frac{1}{R_1} = \frac{M_{stretch}}{EI} \qquad \frac{1}{R_2} = \frac{M_{contact}}{EI}$$

- Bending moment (M) by pressure
- Rubber tensile stress (σ)
- Thin glass tensile stress(σ)
- End edge deflection(δ)

Product mechanism- stretching model



Product mechanism- strain energy method

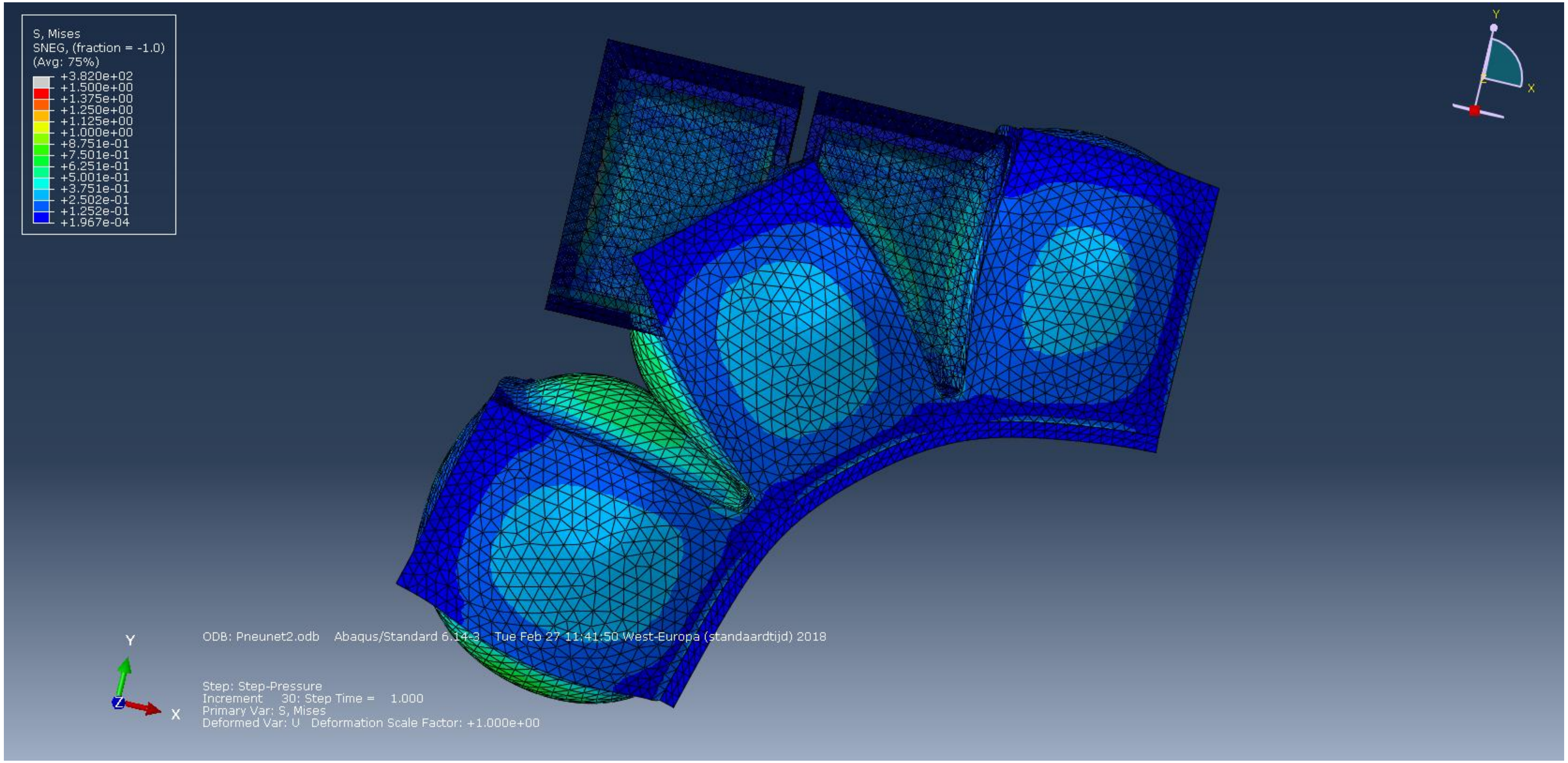


- Gas compression
- Elastic rubber deformation
- Work added by an external load

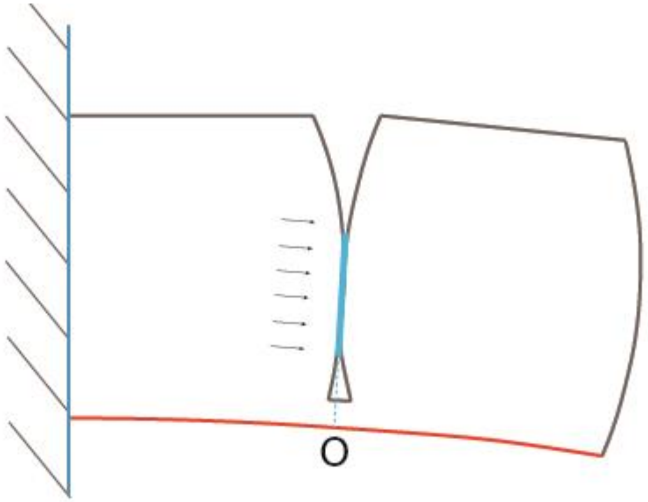
$W = W_{air} + W_{silicom} + W_{load}$ $h = 50mm$ $P = 0.55MPa$

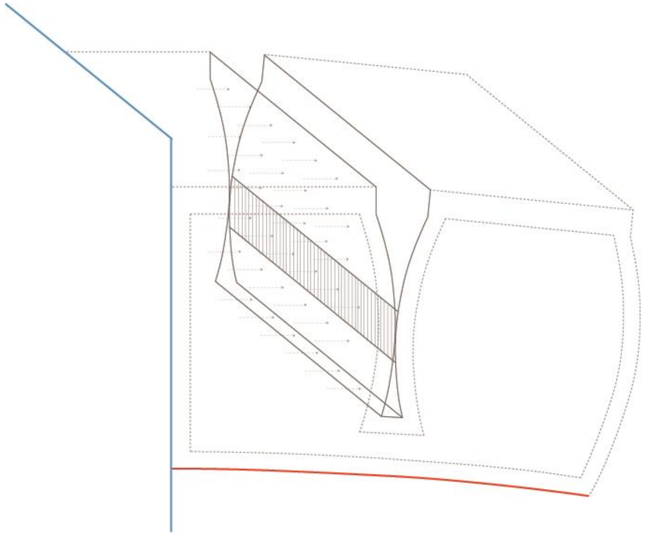
$\frac{\delta W_{silicon}}{\delta \lambda_1} + \frac{\delta W_{air}}{\delta \lambda_1} + \frac{\delta W_{load}}{\delta \lambda_1} = 0$ $d = 8mm$ $M_{stretch} = 189Nmm$

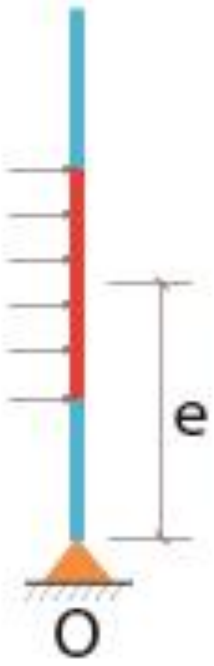
Product mechanism- contacting model



Product mechanism- contacting model







h = 50mm

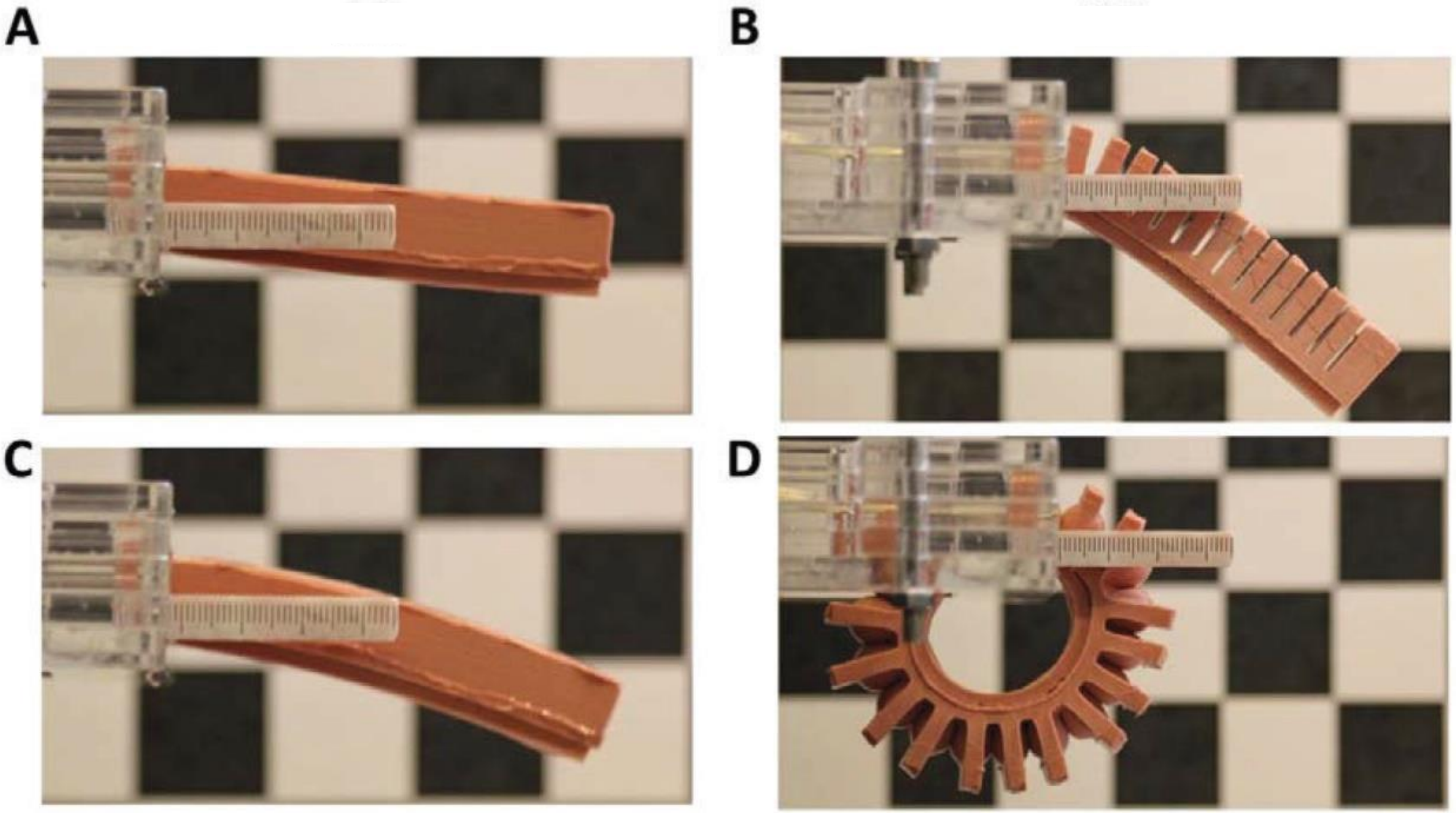
d = 8mm

$M_{contact}$ = PAe=2775Nmm

A= Contacting area

P= Air pressure

Product mechanism- stretching and contacting model

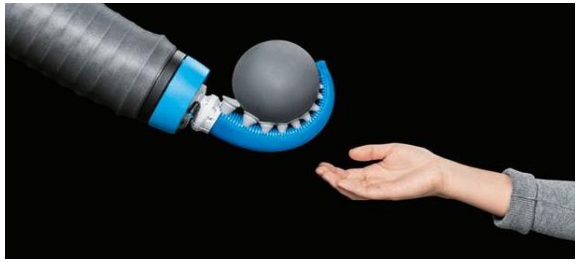


$M_{stretch} = 189Nmm$

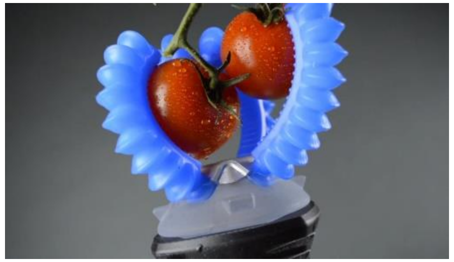
$M_{contact} = PAe = 2775Nmm$

Soft Robotics Technology Utilities

- Gripper



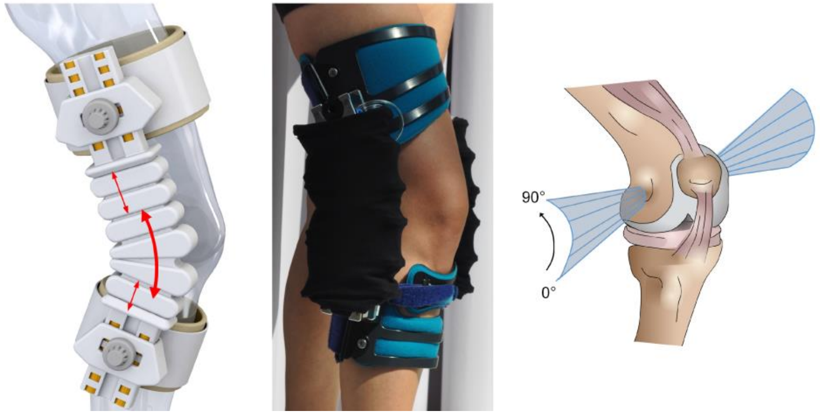
Octopus gripper- Festo



Soft Robotics gripper

Soft Robotics gripper

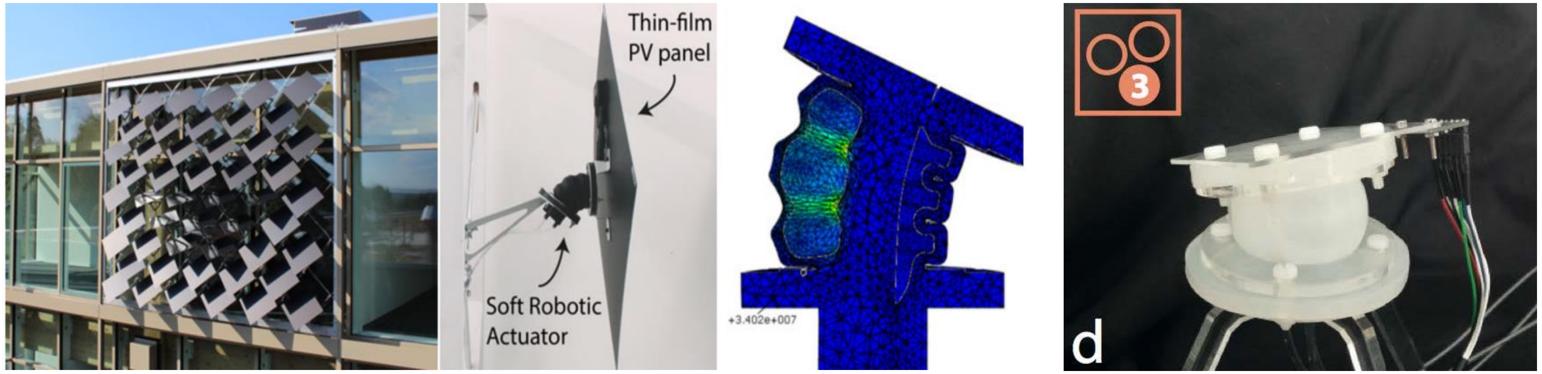
- Rehabilitation



Skewed rotary elastic chambers bending actuator

Soft robotic glove

- Sun shading



Adaptive Solar Façade installed at ETH House of Natural Resources

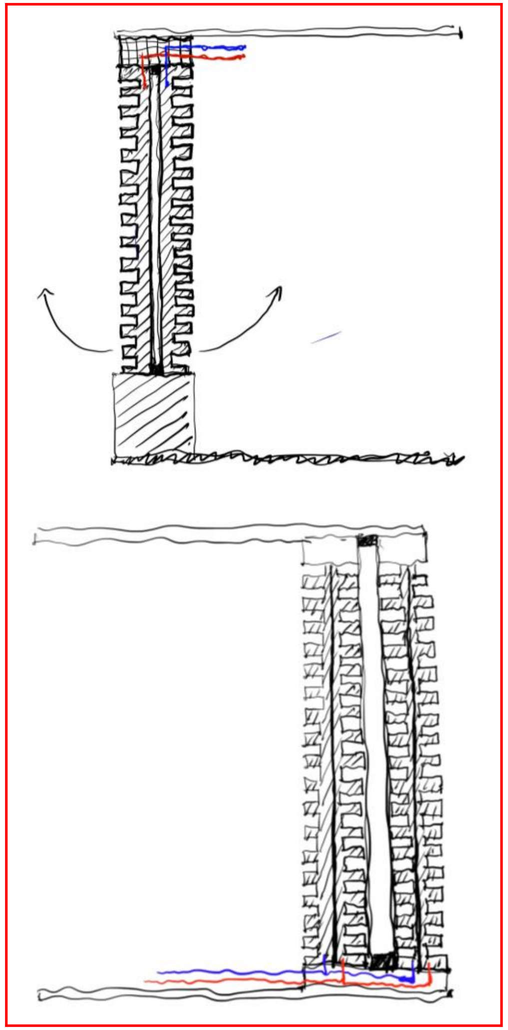
Soft Pneumatic Actuator-benefit

- Curvature adaptive
- Continuous form change
- Lightweight
- Easily controlled and measured
- Less mechanical equipment

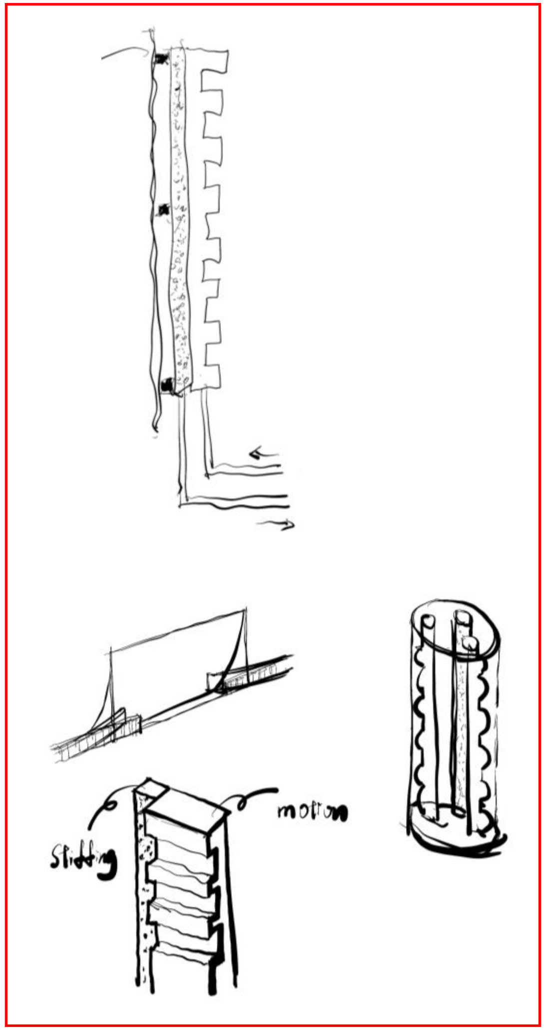
Part 3

Draft design

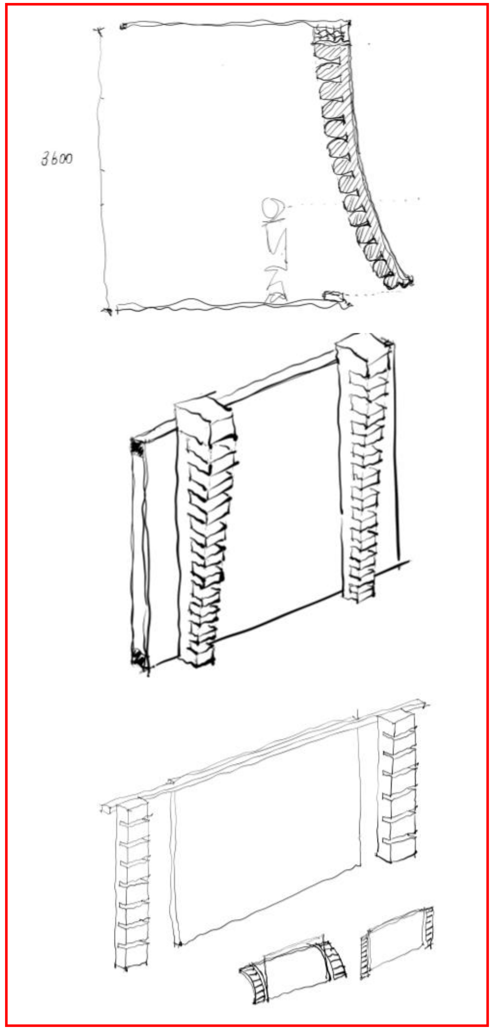
Hand sketches



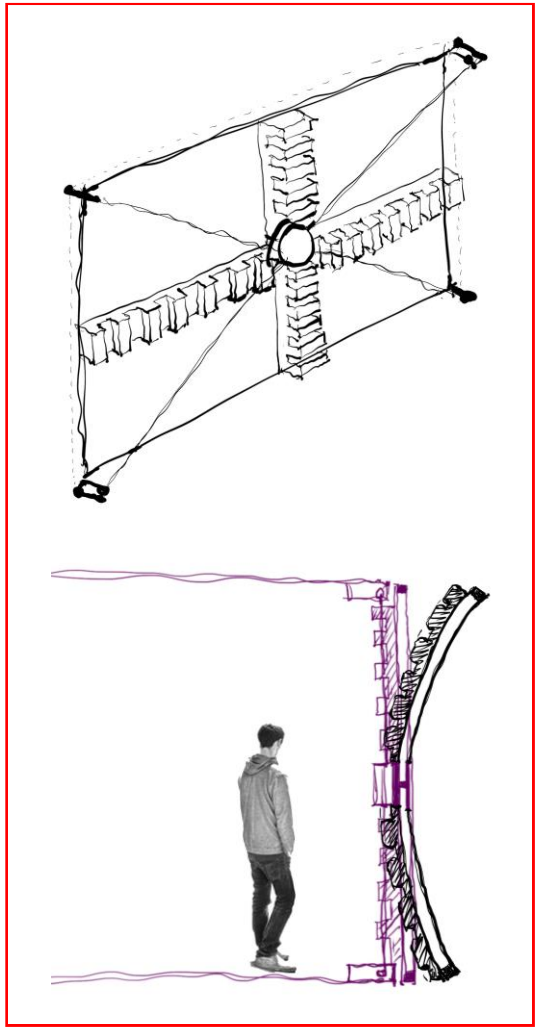
Bi-direction opening window



Variable stiffness with jamming chamber

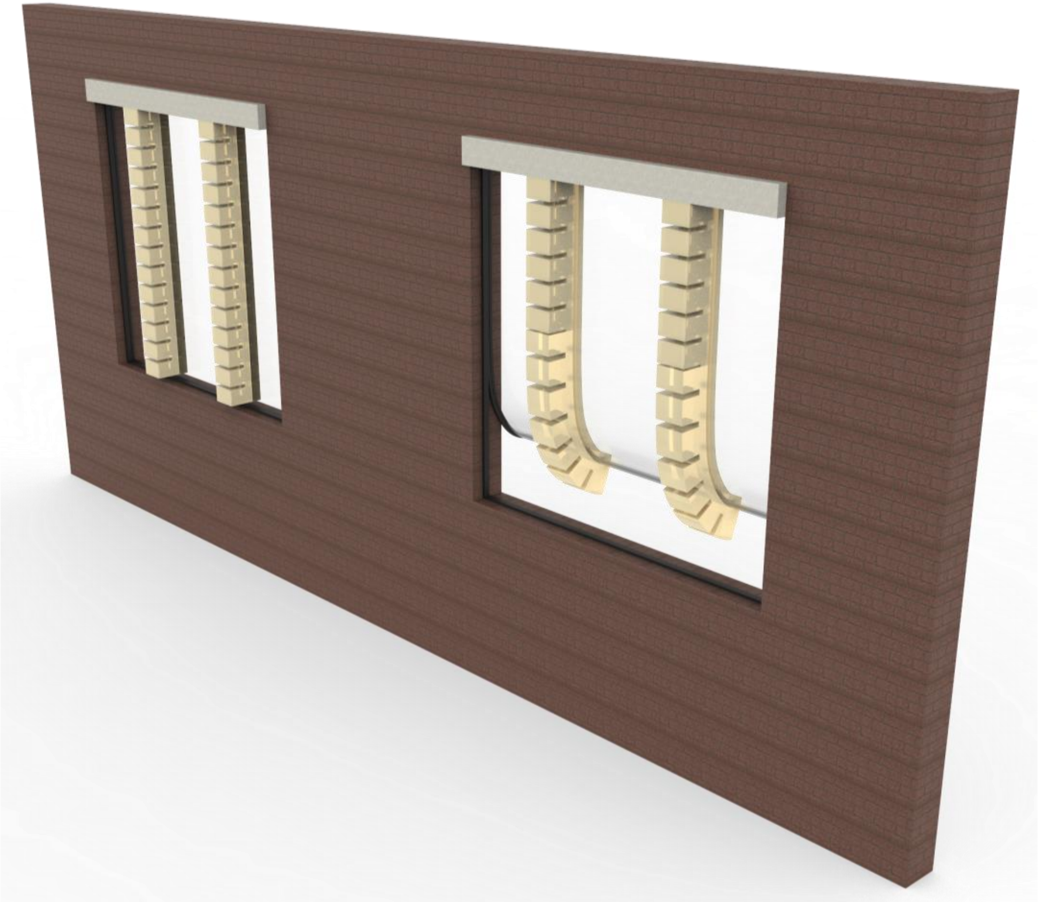


Top hung window



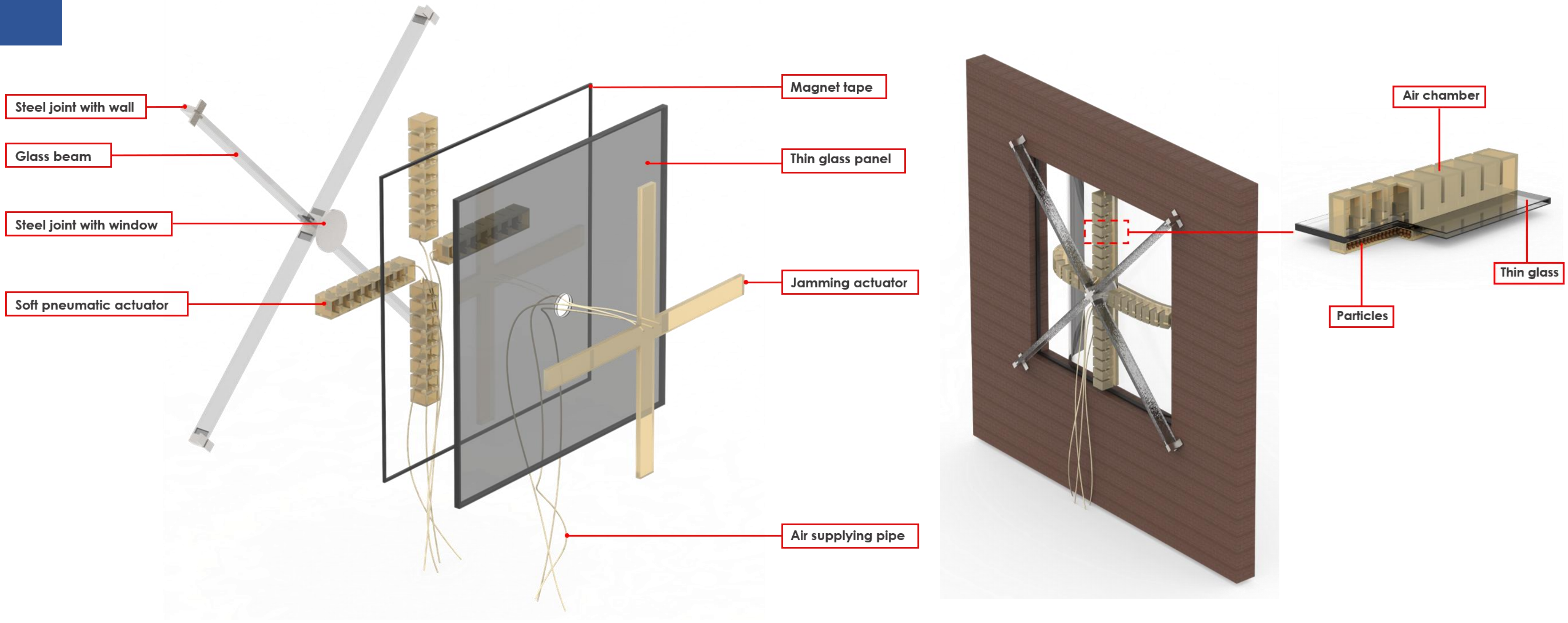
Four opening directions prototype

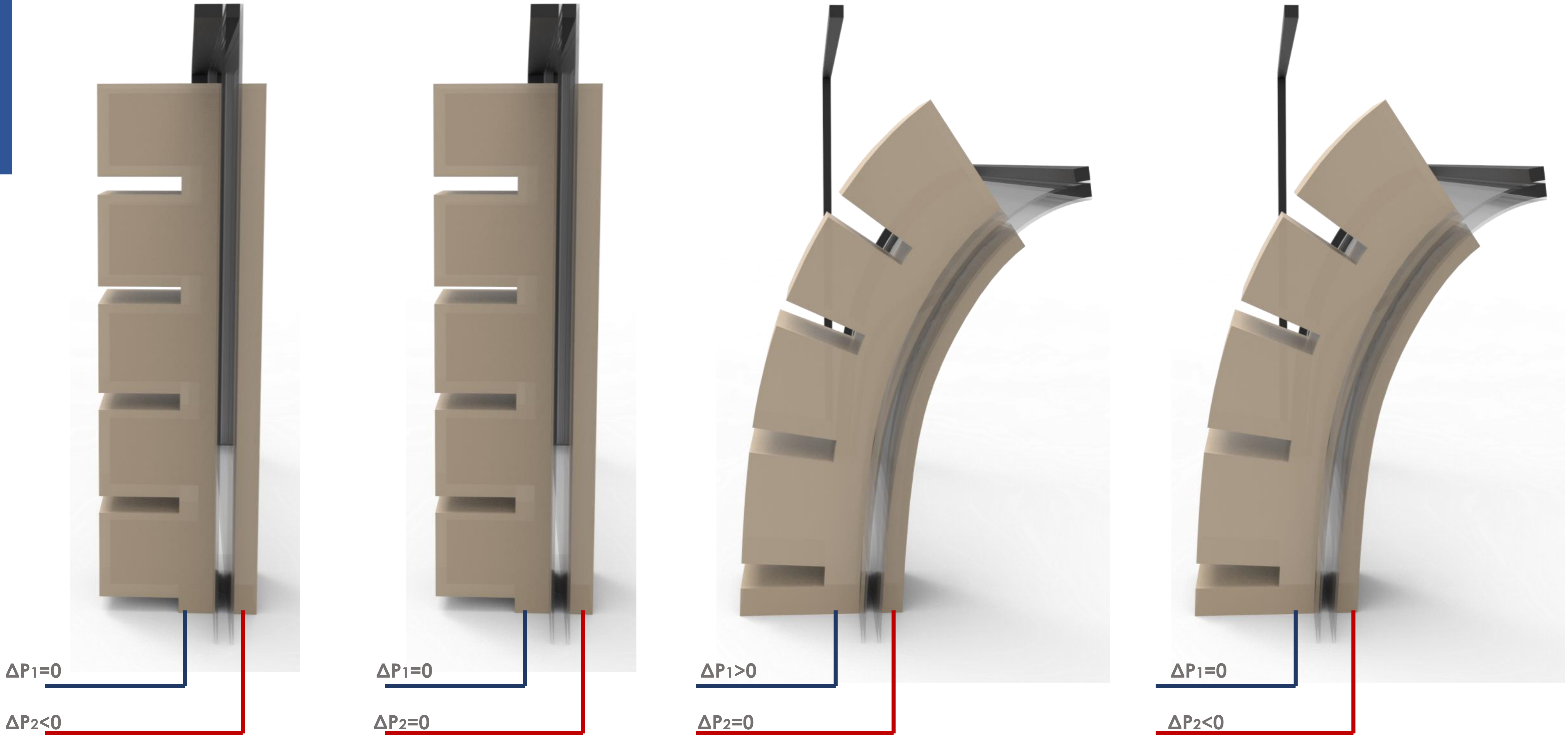
Design A



Design B

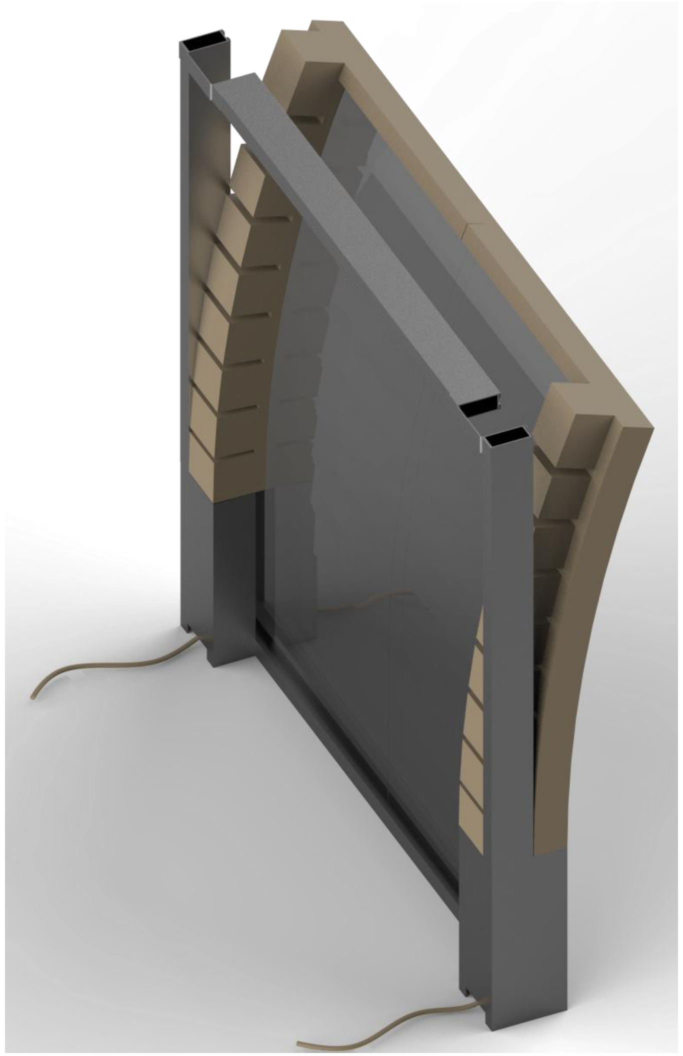
Design C

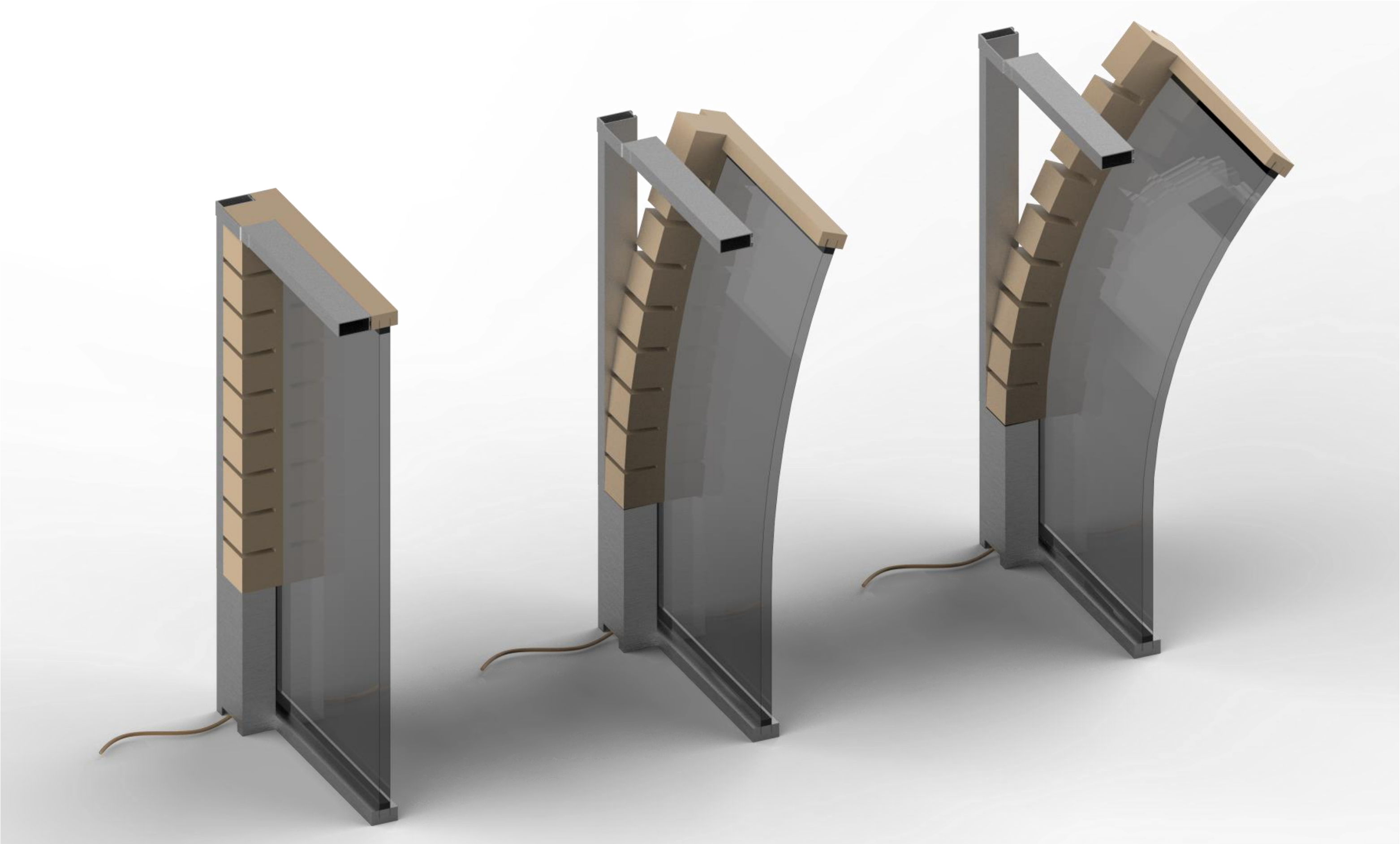

Steel joint with wall
Glass beam
Steel joint with window
Soft pneumatic actuator
Magnet tape
Thin glass panel
Jamming actuator
Air supplying pipe
Air chamber
Thin glass
Particles



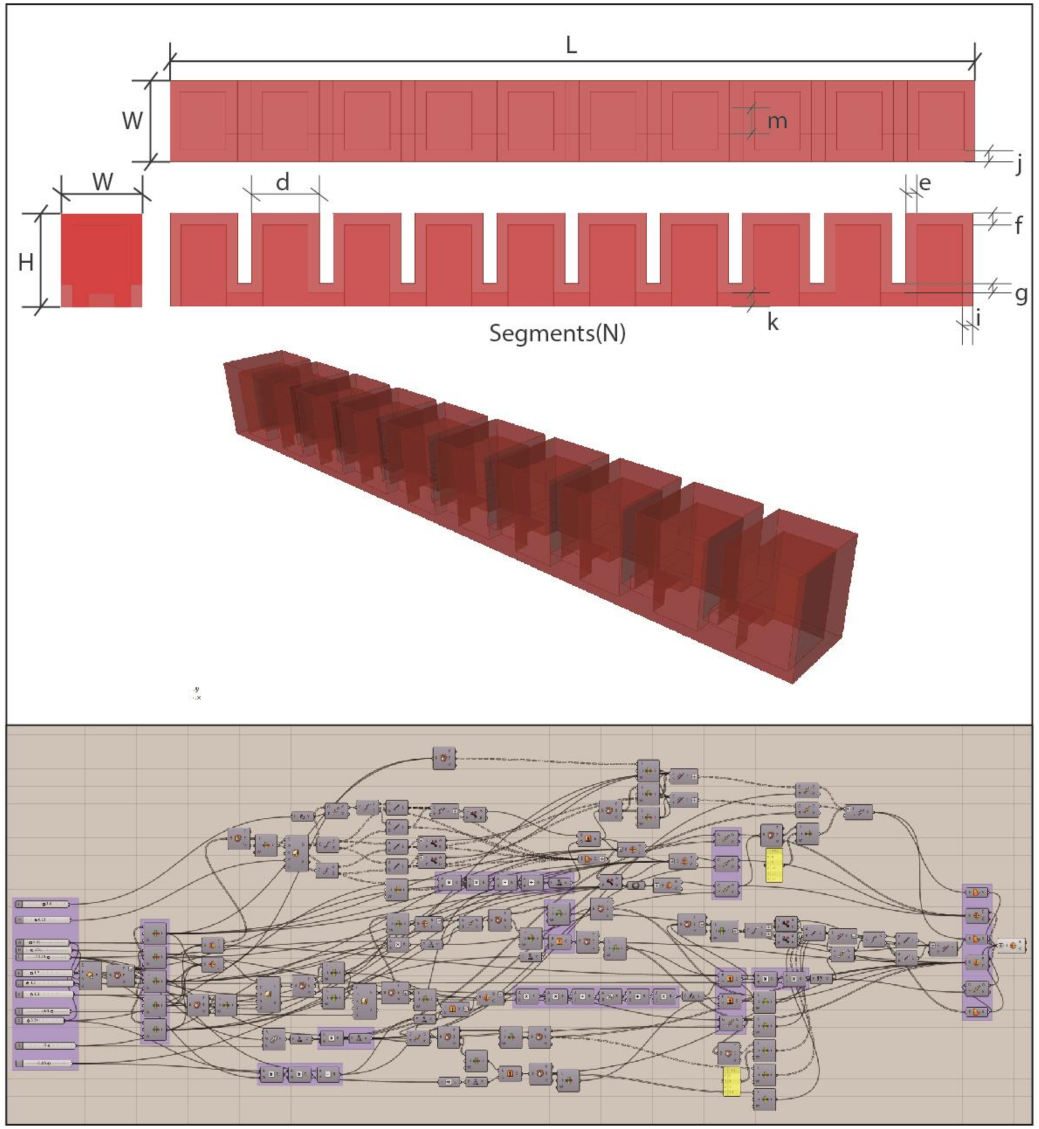
Phase 1: Closed | Phase 2: Prepare opening | Phase 3: Start opening | Phase 4: Keep opened

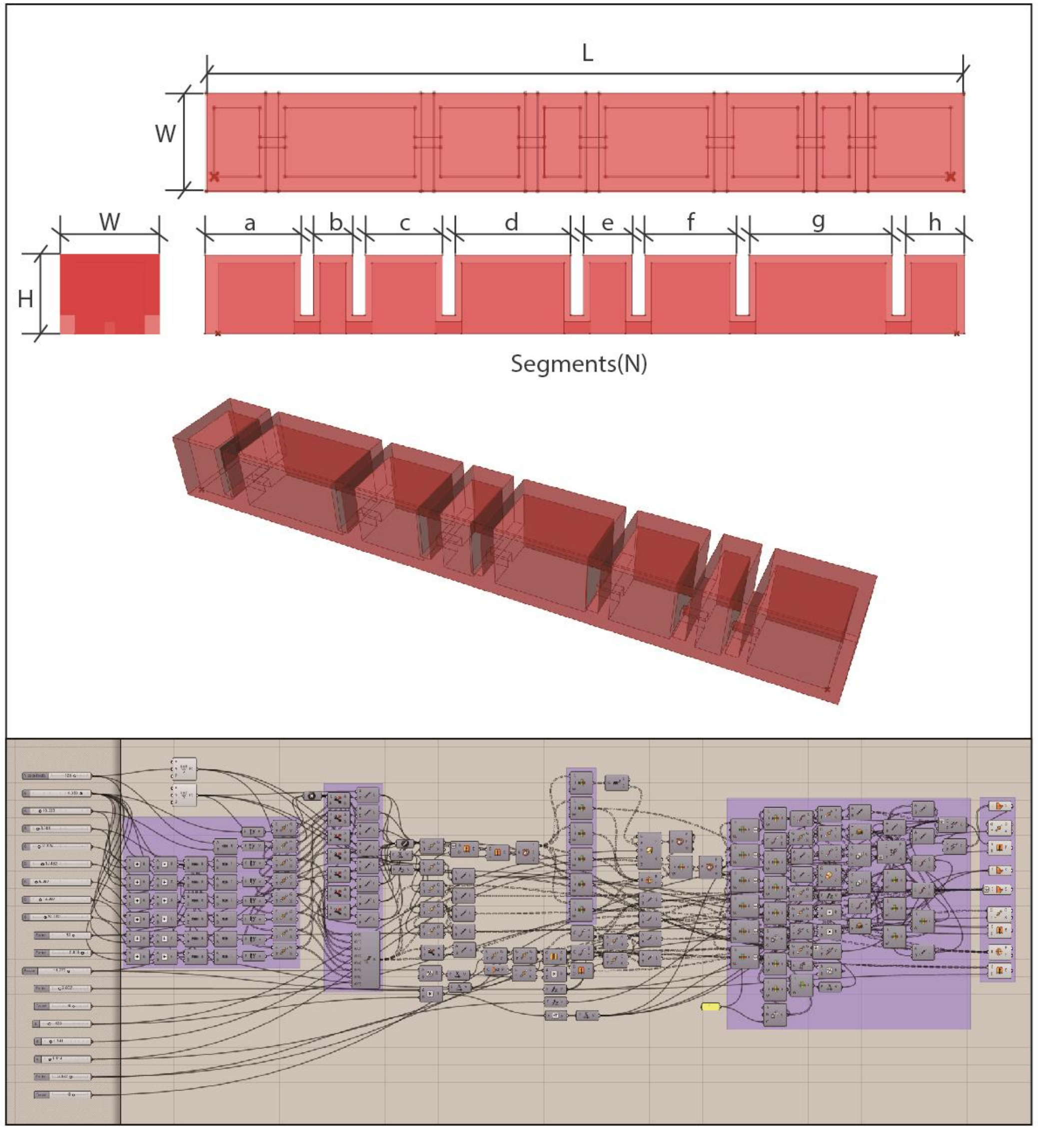
Design D





Parametric geometry generation

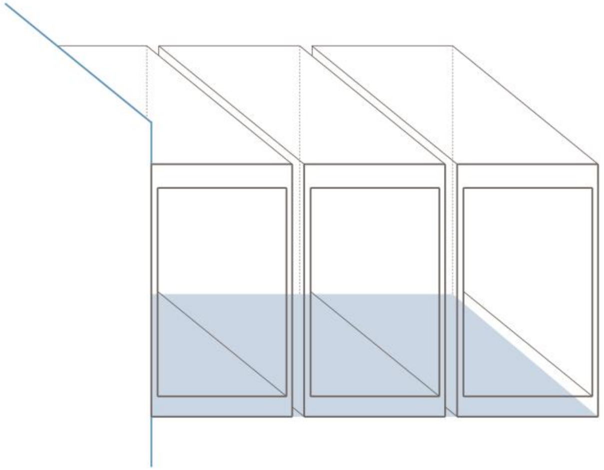


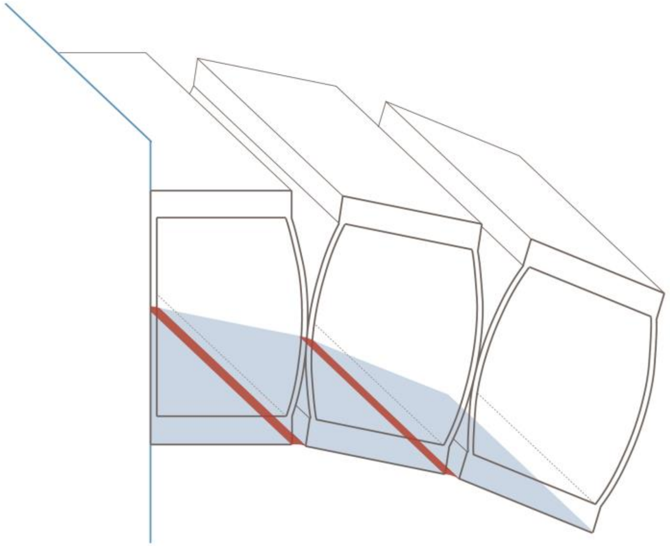


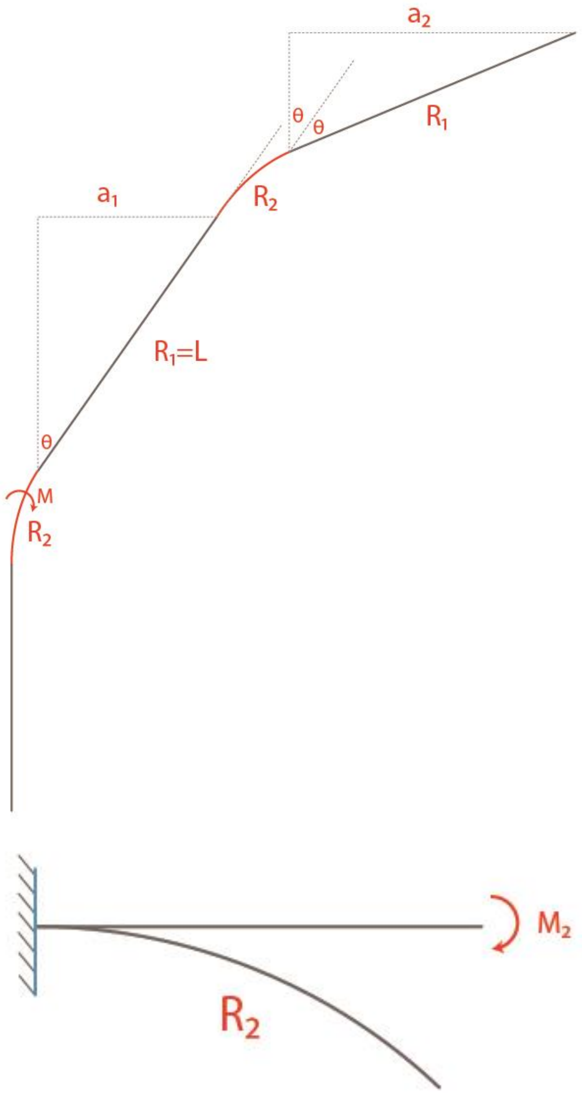
Part 4

Mathematical model and assumption

Opening size calculation





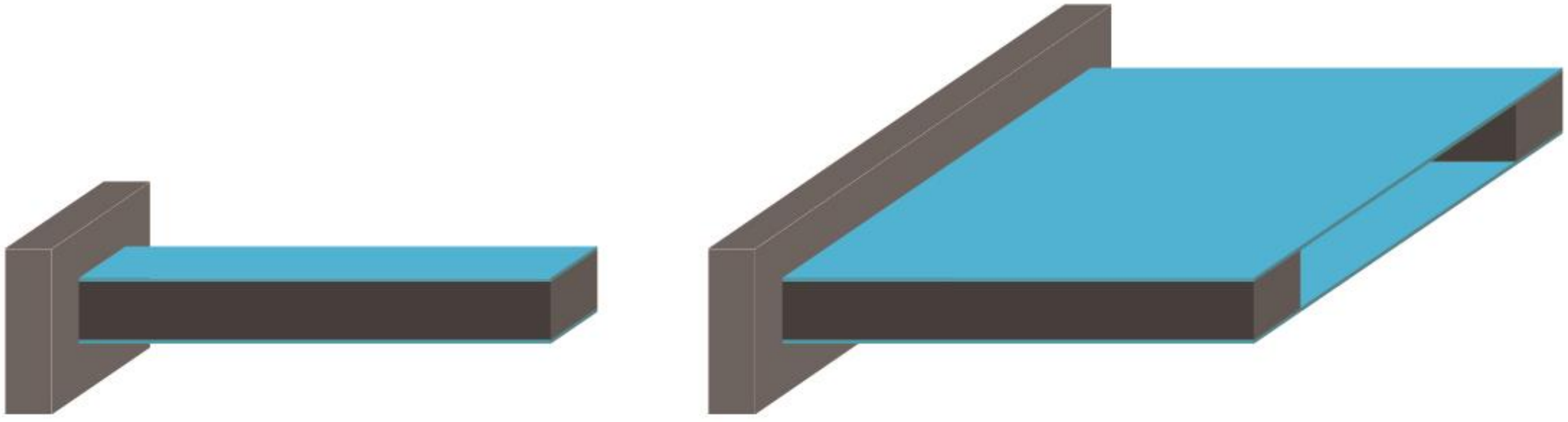


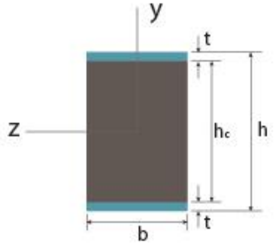
$$\text{Opening size} = L(\sin\theta + \sin 2\theta + \sin 3\theta + \ldots\ldots + \sin n\theta)$$

$$\theta = L_2/R_2$$

$$\sigma = \frac{ET}{2R_2} \qquad \theta = \frac{LM_2}{EI} = \frac{L}{R}$$

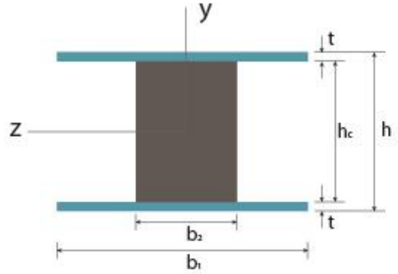
Product mechanism- rigid spacer





$$I_1 = \frac{b}{12}(h^3 - h_c^3)$$

$$I_2 = \frac{b}{12} h_c^3$$



$$I_1 = \frac{b_1}{12}(h^3 - h_c^3)$$

$$I_2 = \frac{b_2}{12} h_c^3$$

Flexural rigidity $= E_1 I_1 + E_2 I_2$

$$\sigma_{1max} = \pm \frac{M(h/2)E_1}{E_1 I_1 + E_2 I_2}$$

$$\sigma_{2max} = \pm \frac{M(h_c/2)E_2}{E_1 I_1 + E_2 I_2}$$

$$R = \frac{E_1 I_1 + E_2 I_2}{M}$$

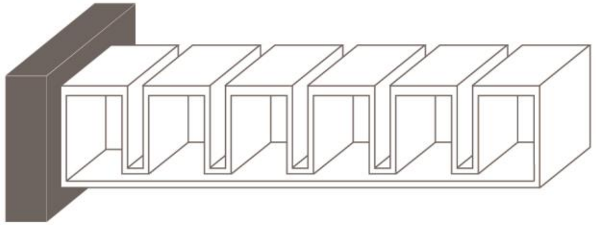
$t = 0.55mm$

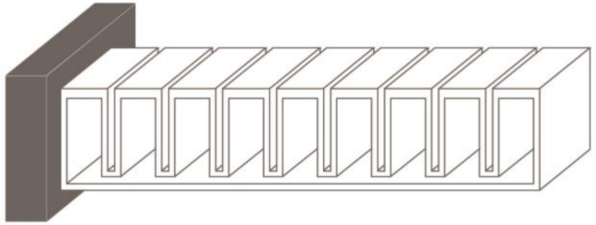
$h_c = 12mm$

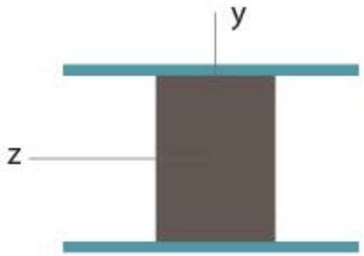
$M = 2775Nmm$

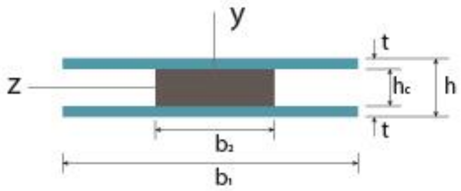
$R = 346m$

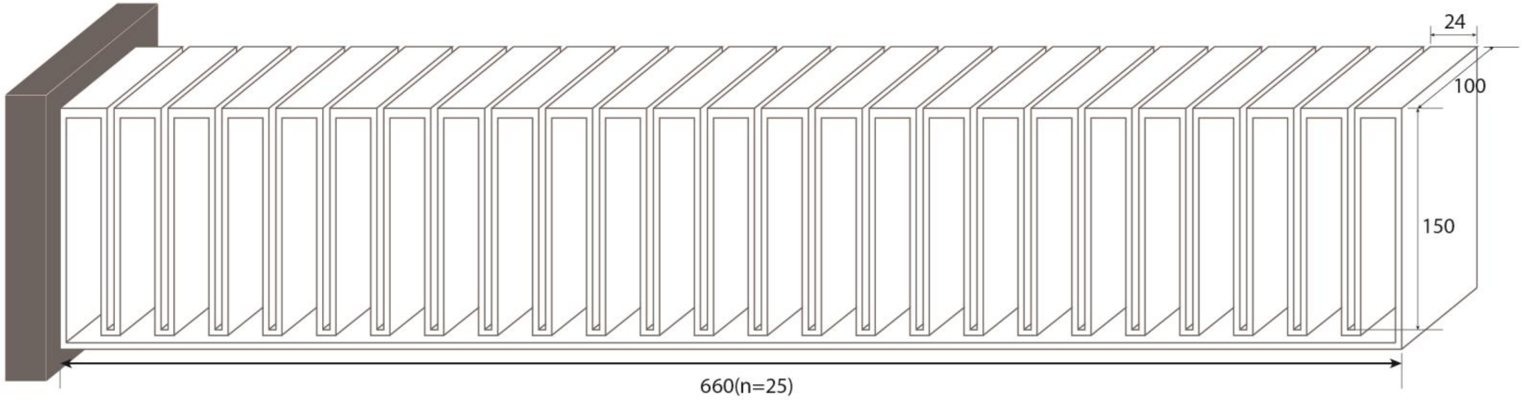
Correction: Soft actuator morphology-enlarge bending moment











h_c= 4mm

n= 25

M= 210000Nmm

Spacer material-super spacer edgetech

Edgetech
A Quanex Building Products Company

CHANGE REGION

Contact +44 (0) 2476 639931
Email: ukenquiries@edgetechig.com

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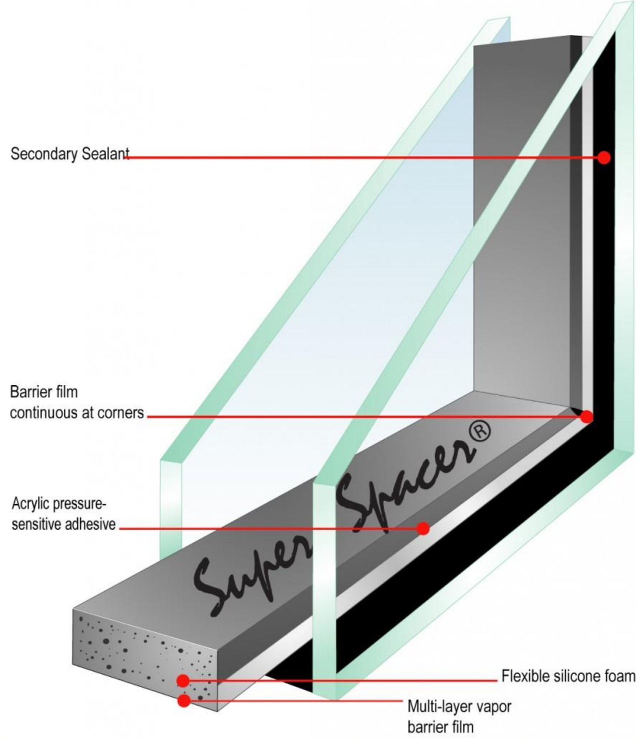
Energy Efficient

80% of the energy lost through a window occurs at the edge of the glass because of the highly conductive nature of aluminium spacer. Super Spacer® is 950 times less conductive, blocking heat loss and reducing energy costs. Super Spacer reduces window U-values by up to 0.2W/m2K allowing windows to achieve the highest Window Energy Ratings.

Download the leaflet



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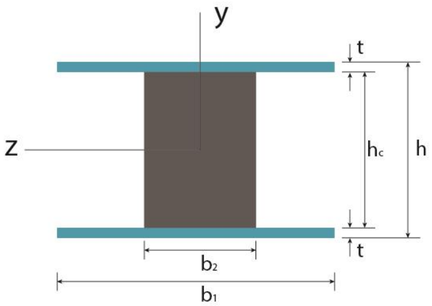
Accept

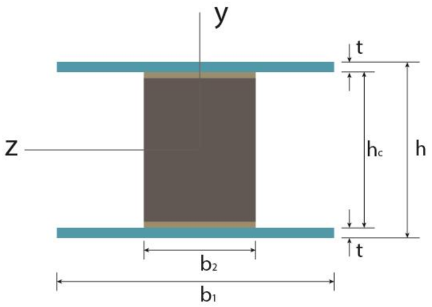
Product mechanism- effective flexural stiffness of insulating window-correction

0.55mm thickness thin glass and 12mm super spacer



$$I_1 = \frac{b_1}{12}\left(h^3 - h_c^3\right)$$

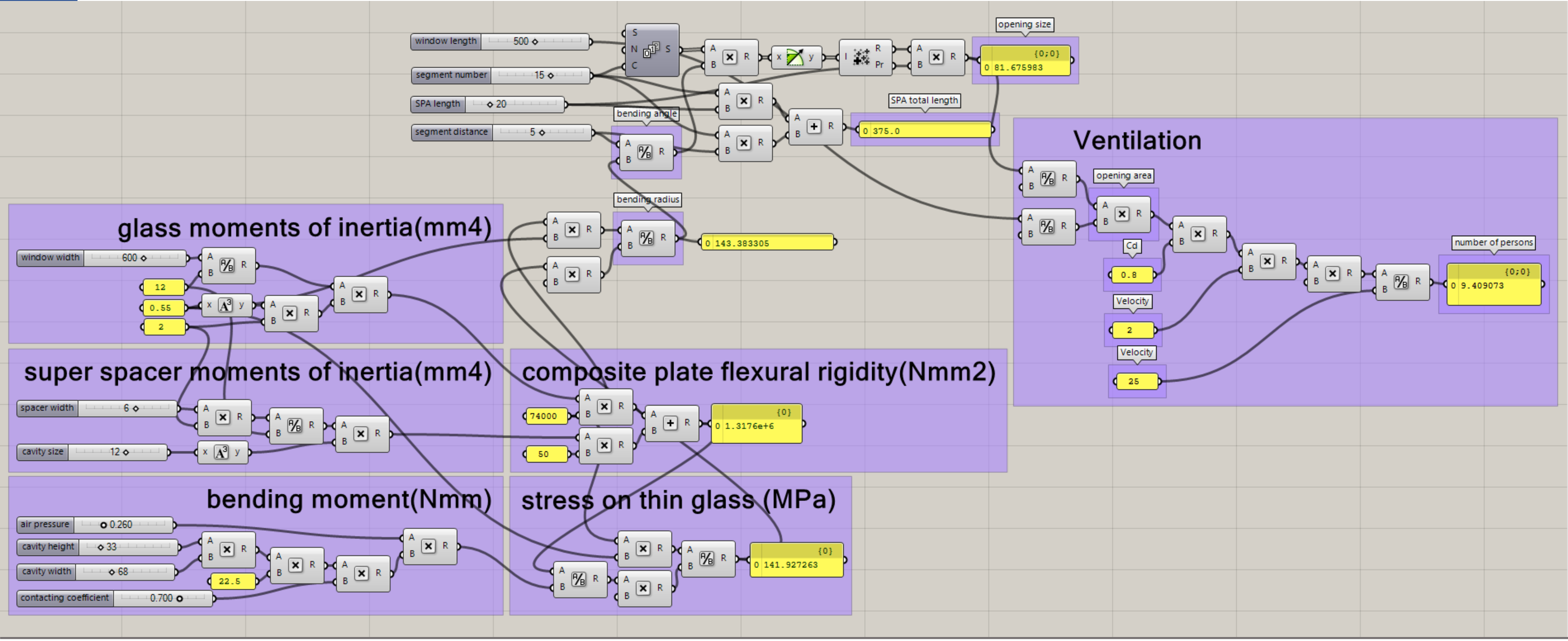
$$I_2 = \frac{b_2}{12} h_c^3 \qquad \text{Flexural rigidity} = E_1 I_1 + E_2 I_2 = 1.9 * 10^9 \text{ N mm}^2$$



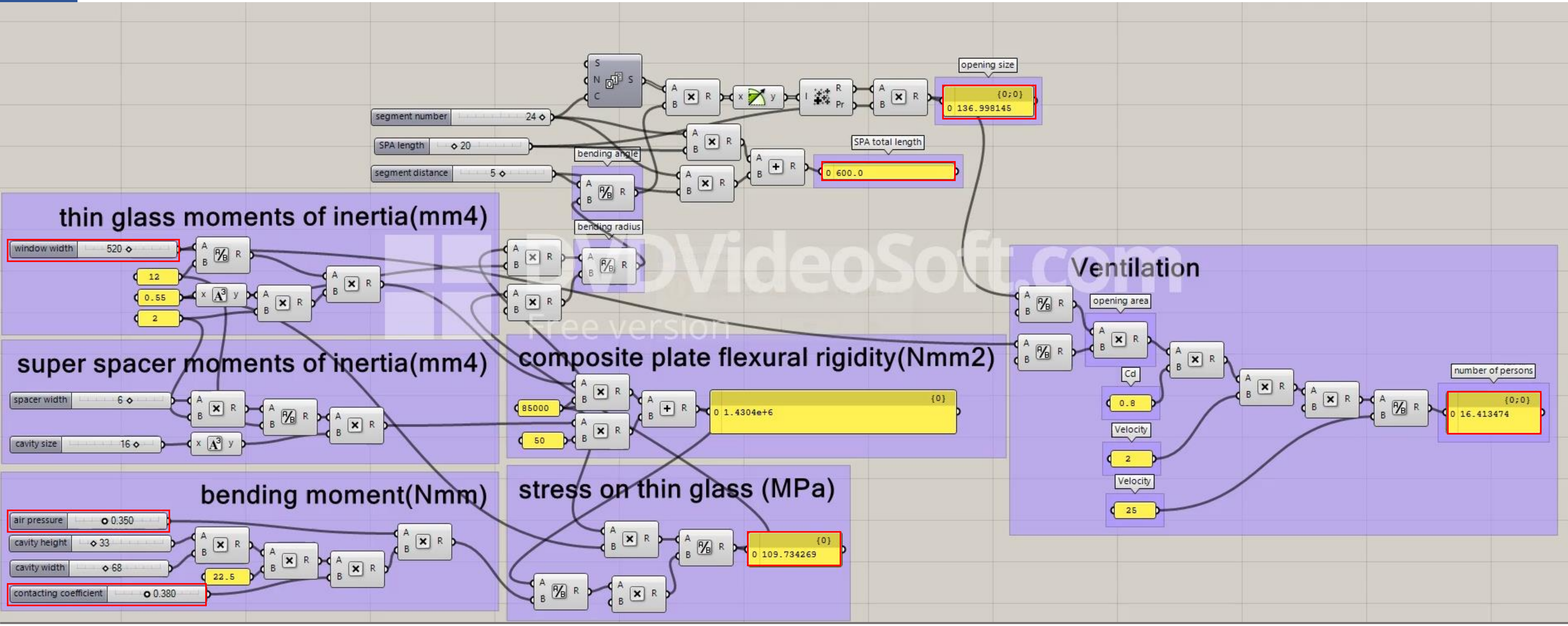
$$I_1 = \frac{b_1}{12} t^3$$

$$I_2 = \frac{b_2}{12} h_c^3 \qquad \text{Flexural rigidity} = 2E_1 I_1 + E_2 I_2 = 1.3 * 10^6 \text{ N mm}^2$$

Calculation integration



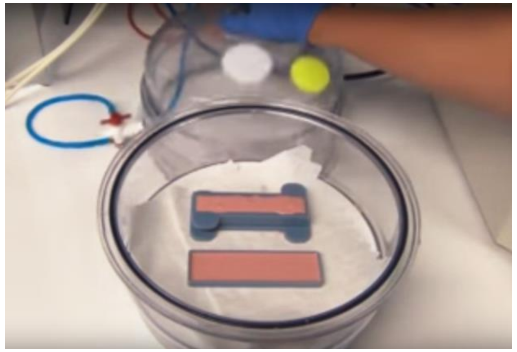
Calculation integration



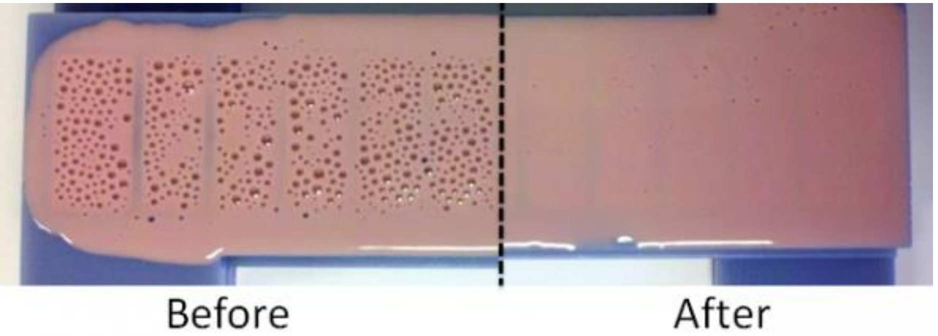
Part 4.1

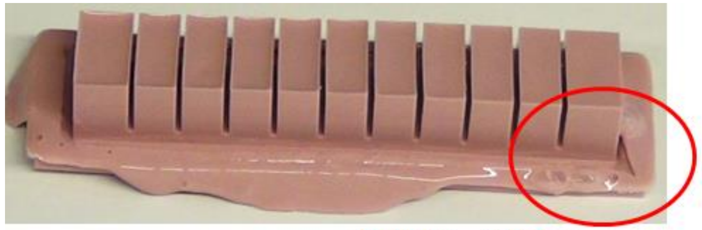
Draft experiment

Pouring



De-gas





Bubbles – may be a weak spot. Inspect closely.

Cure

Material property

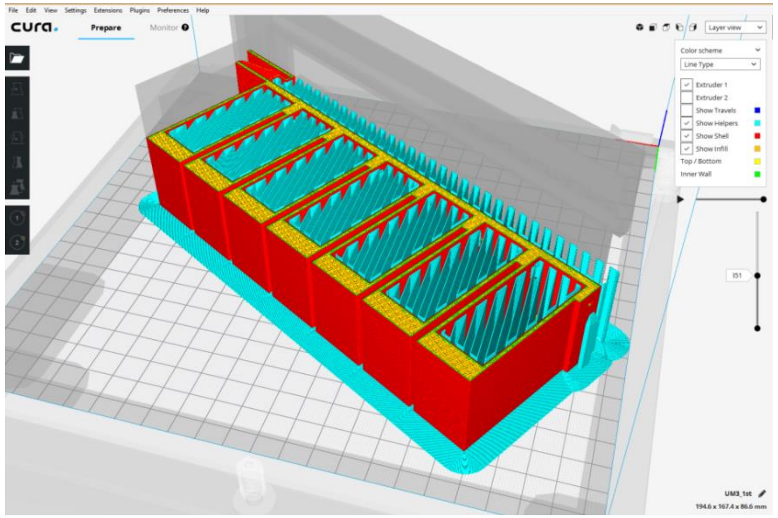
Tensile strength: 6.5MPa

Elongation at break: 700%

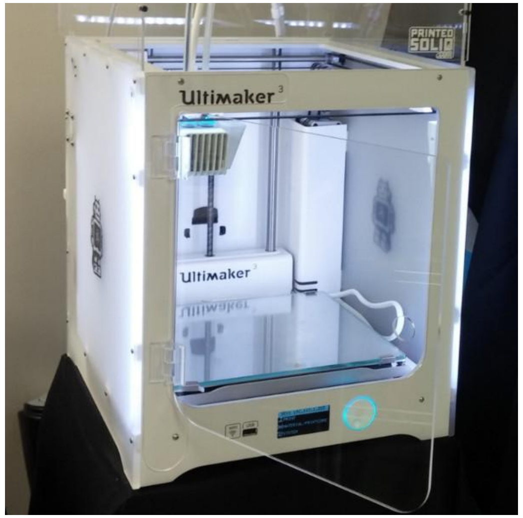
Break at air pressure: 1 bar

Disadvantage

Low tensile strength: 6.5MPa

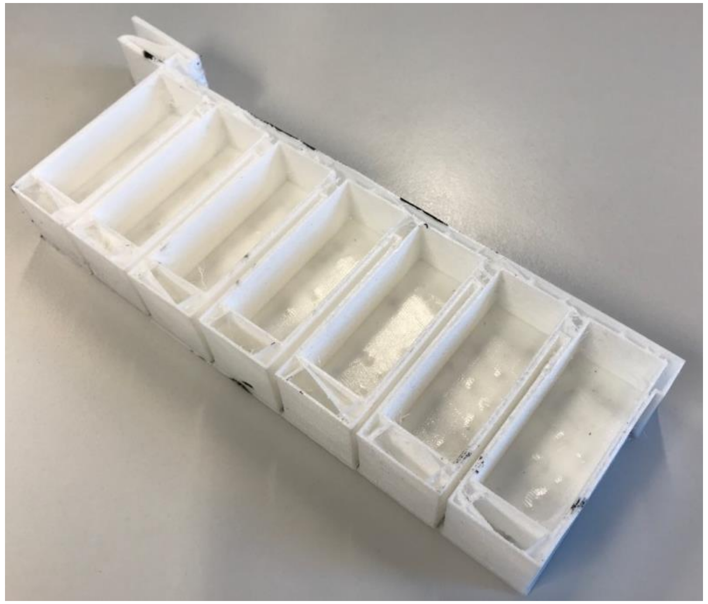


Cura simulation



Ultimaker 3

TPU 95A



Soft robotics prototype

Material property

Tensile stress at yield: 8.6MPa

Elongation at break: 580%

Maximum air pressure: 4 bars

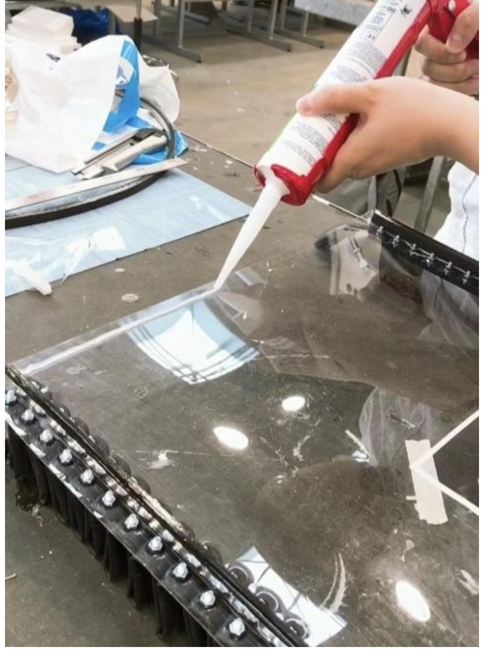
Disadvantage

High tensile modulus: 26MPa

Leakage between layers

Production and cost

	Description	x | y | z extents (mm)	Quantity	Unit
	FDM: Material= Nylon 12	77.209*46.511*30 0.000	1	$377
	FDM: Material= ABS	77.209*46.511*30 0.000	1	$324



Material property

Tensile stress at yield: 11MPa

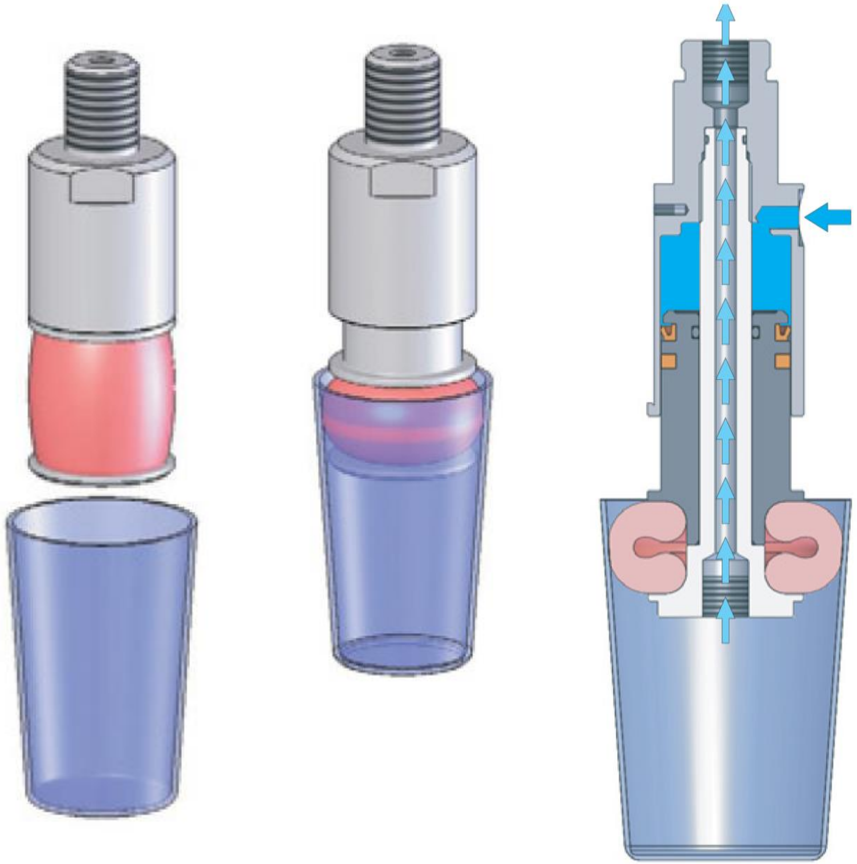
Elongation at break: 600%

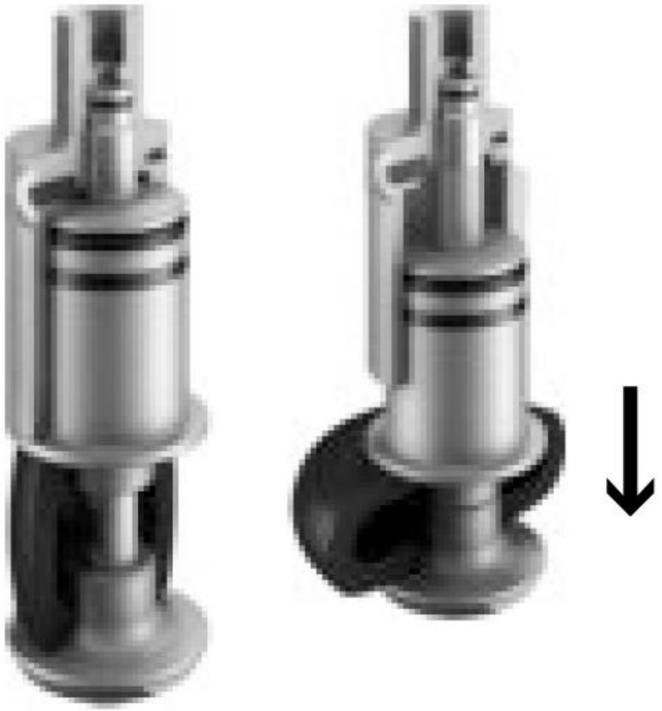
Maximum air pressure: 7 bars

Part 4.2

Further design

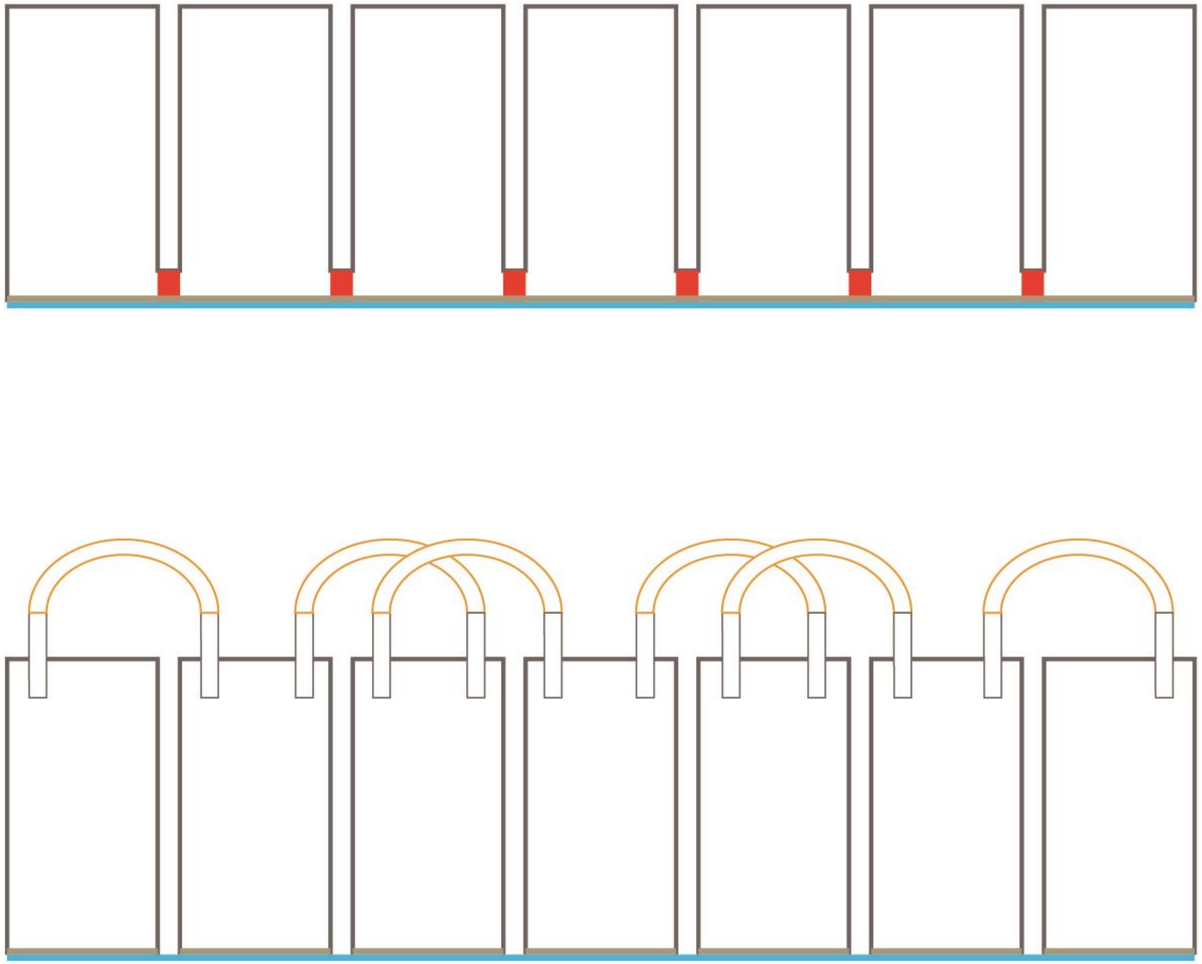
Inspiration- Bellows grippers Festo





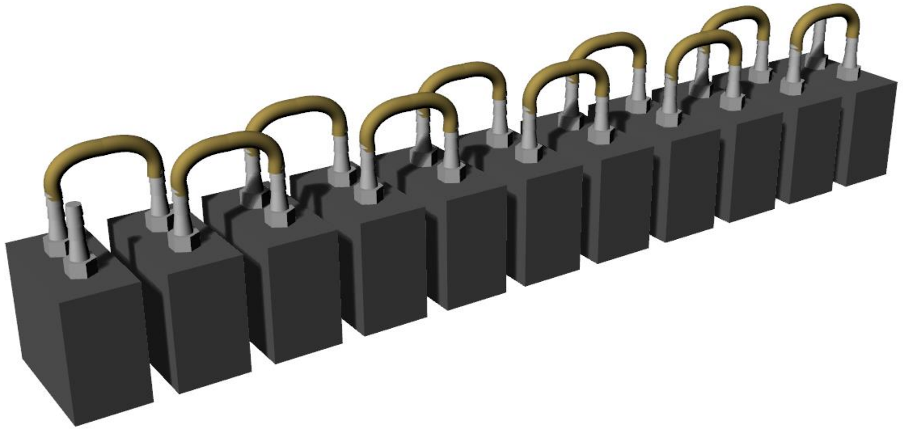
Inspiration- Bellows grippers Festo

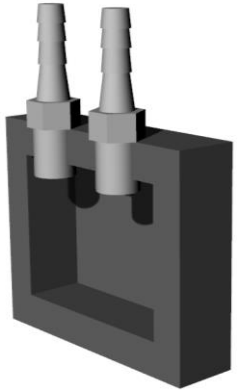
Bellows connection remove



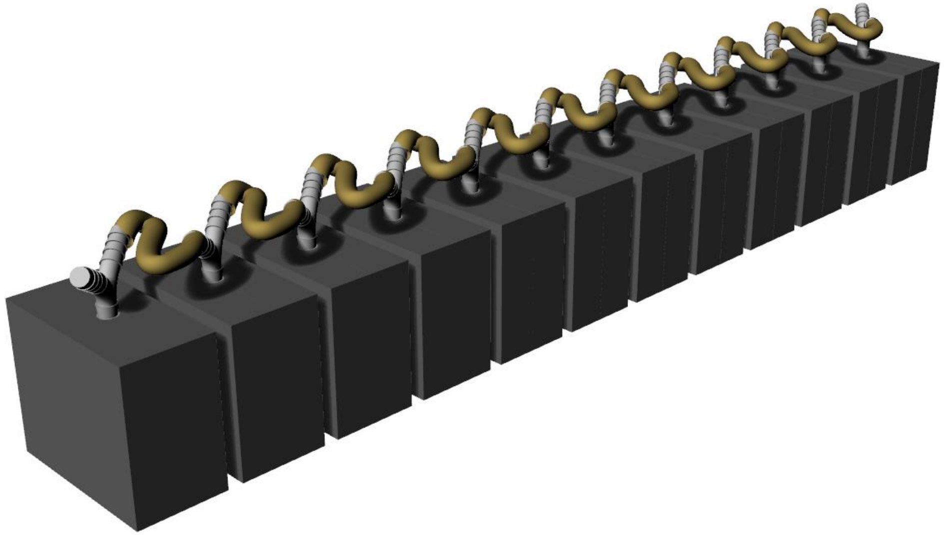
Bellows geometry generation

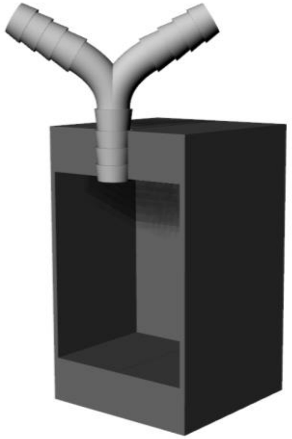
Design A

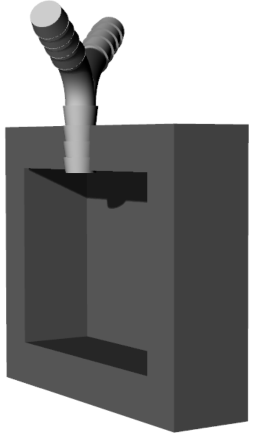


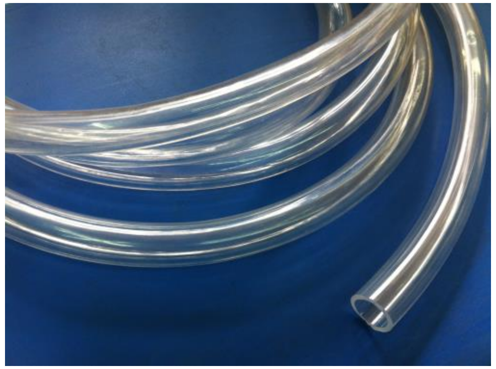


Design B

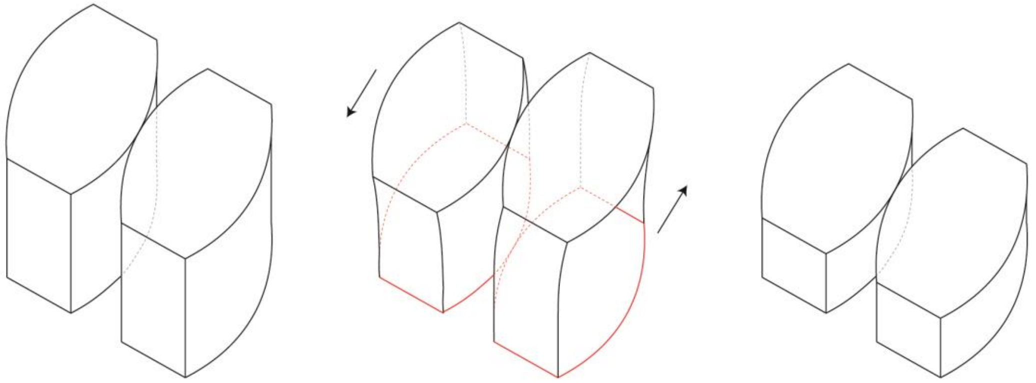








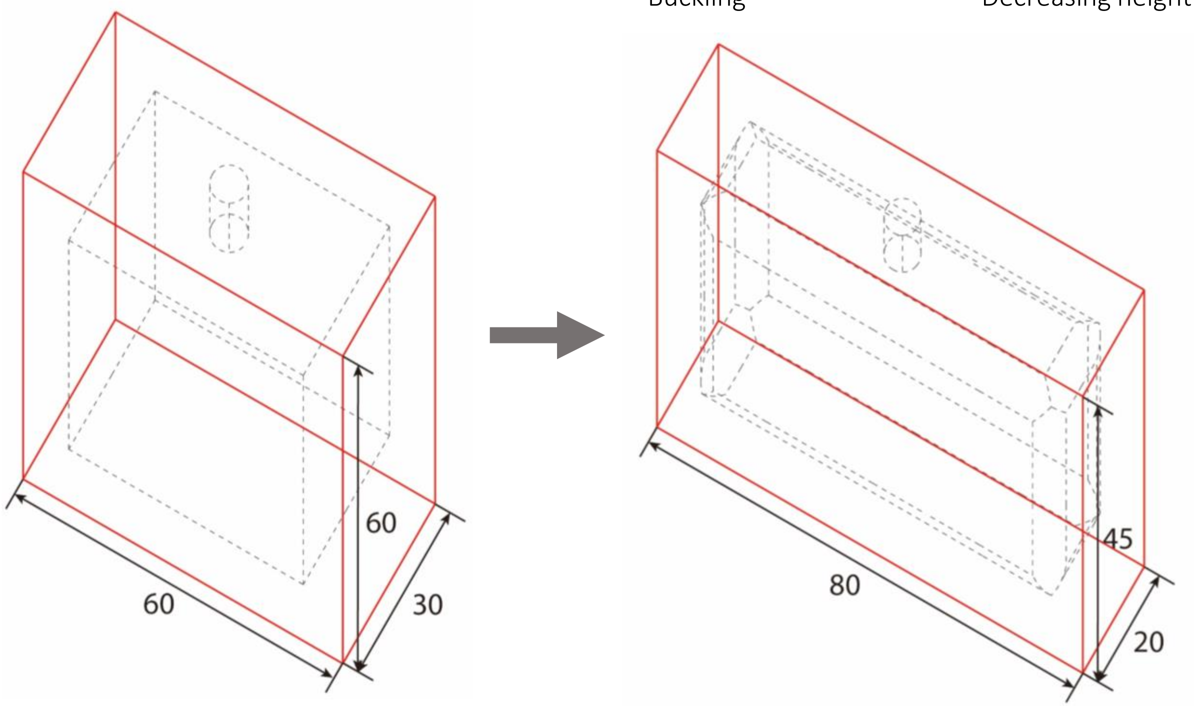
Bellows geometry generation

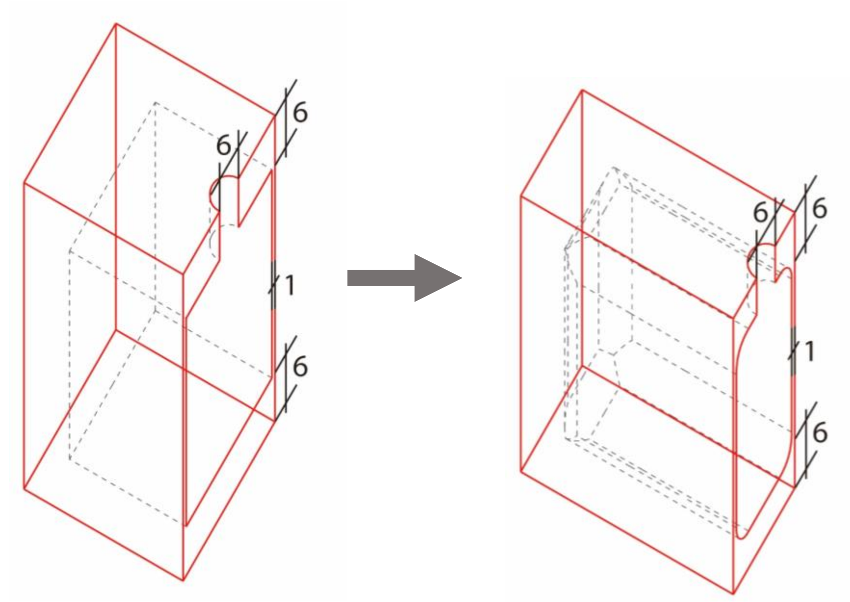


Buckling

Decreasing height

- Decreasing segments height
- Keep contacting area same
- Decreasing segments thickness
- Fillet bellow corners

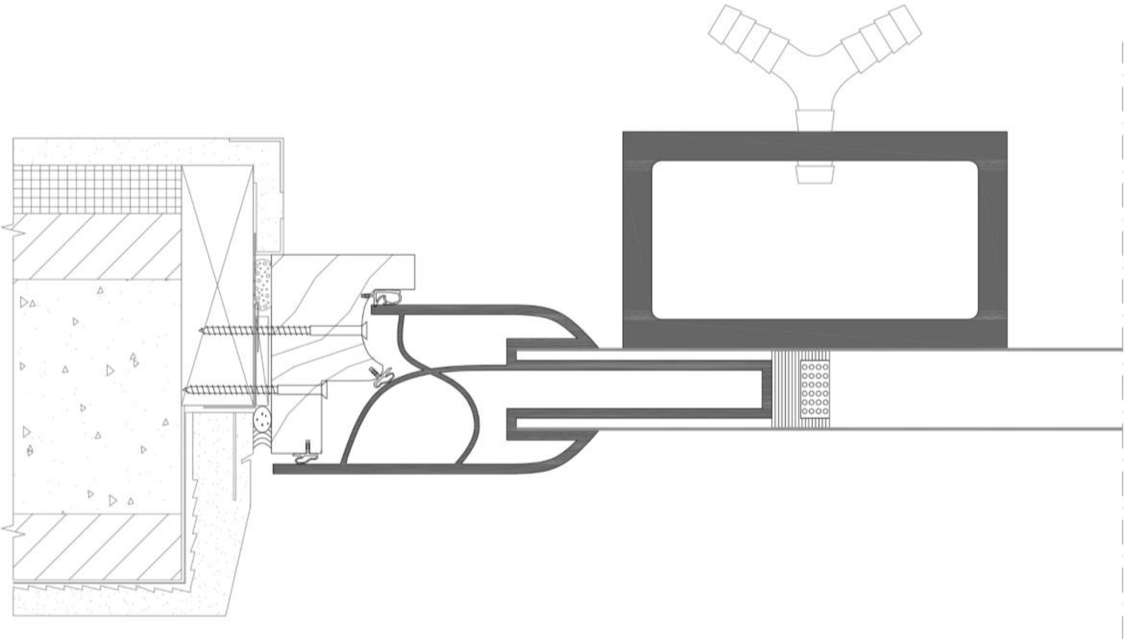




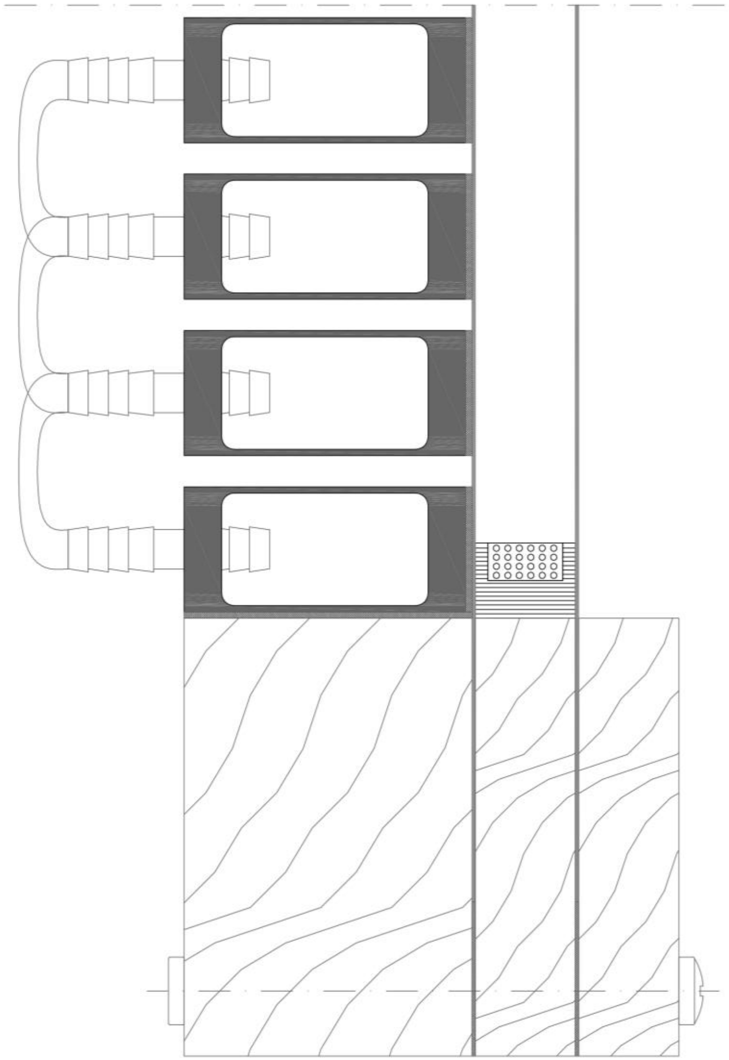
Mould making and Production

Mould making and Production

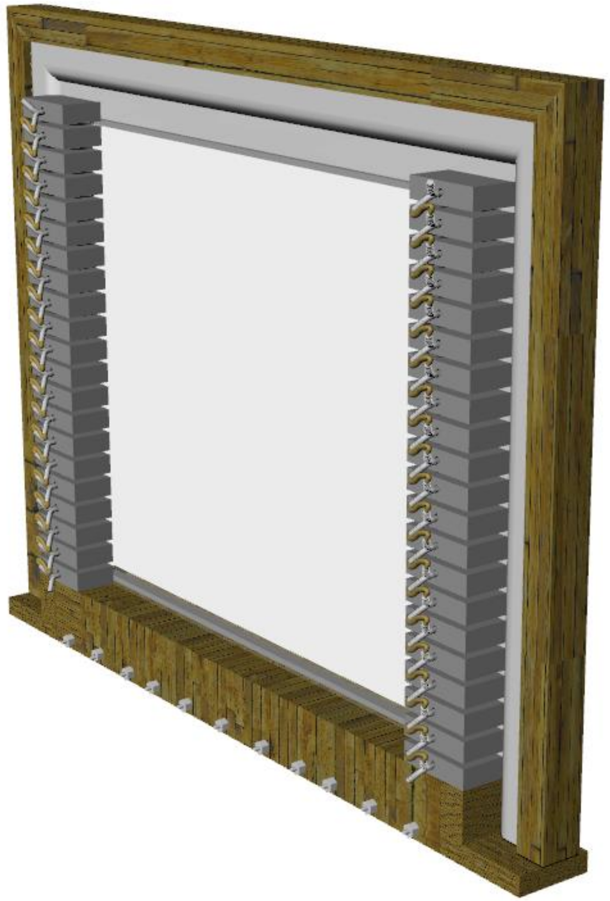
Design A



Top view

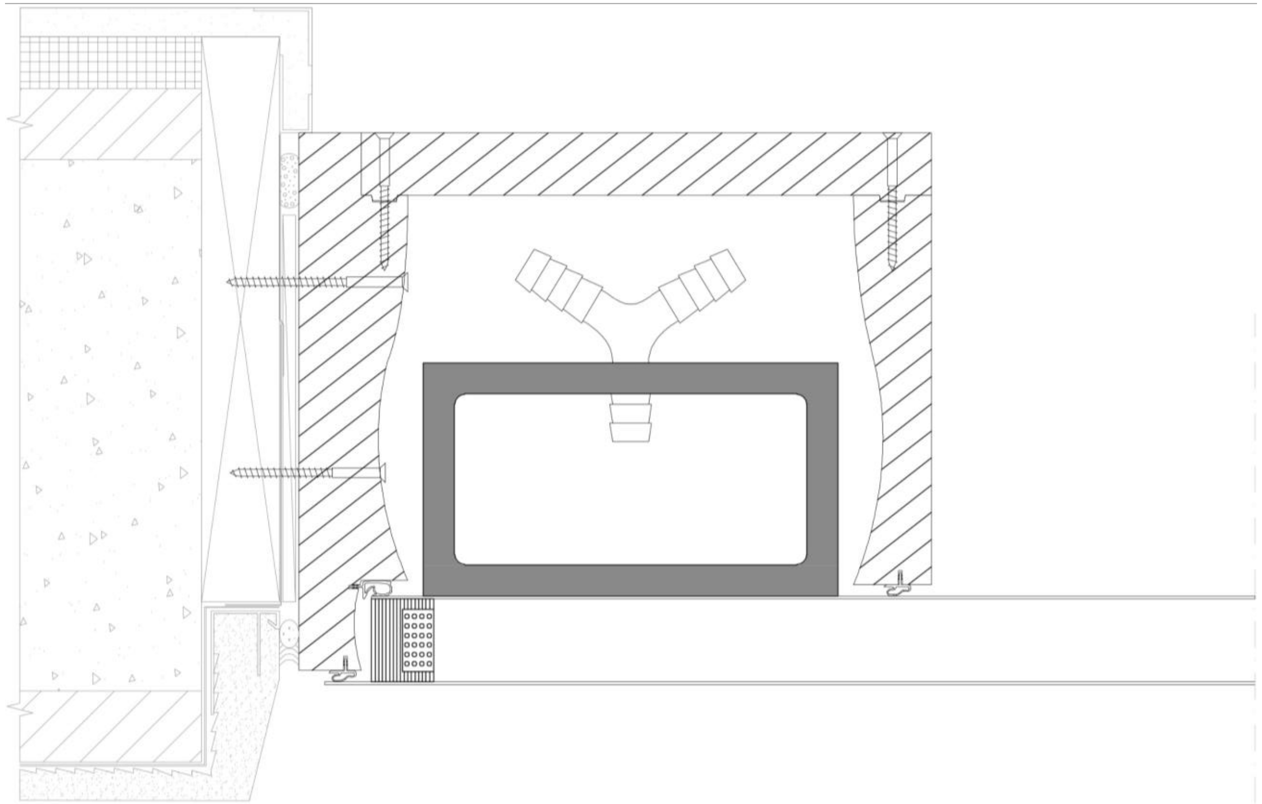


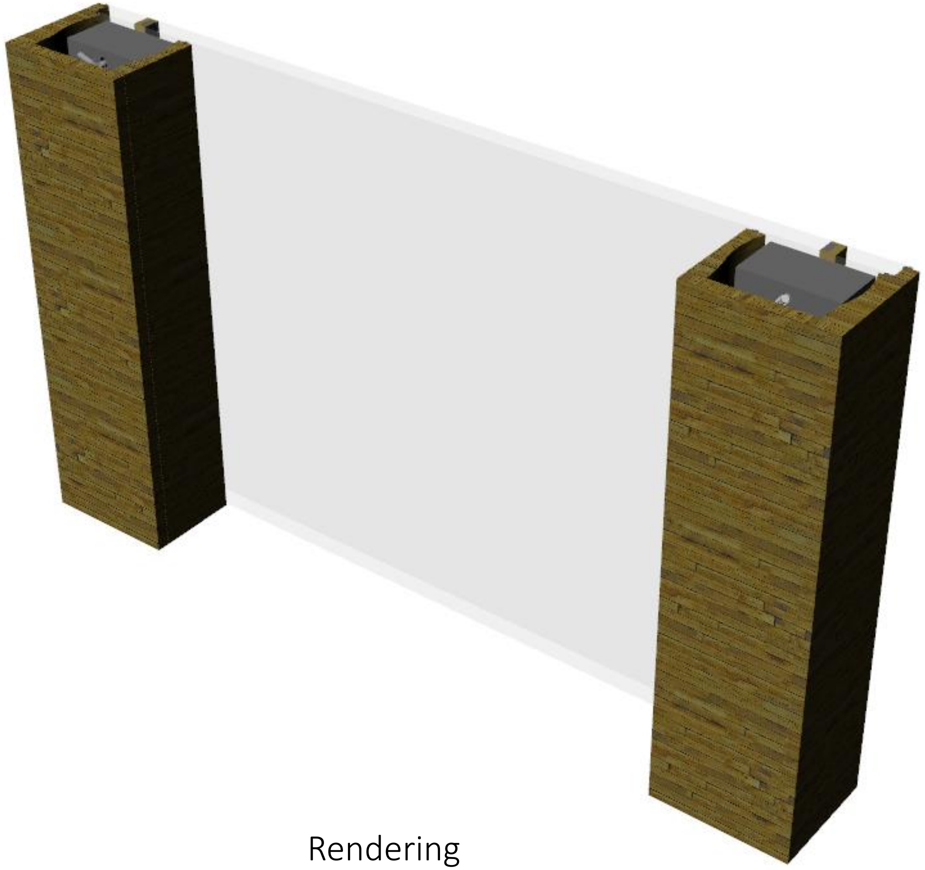
Clamping edge



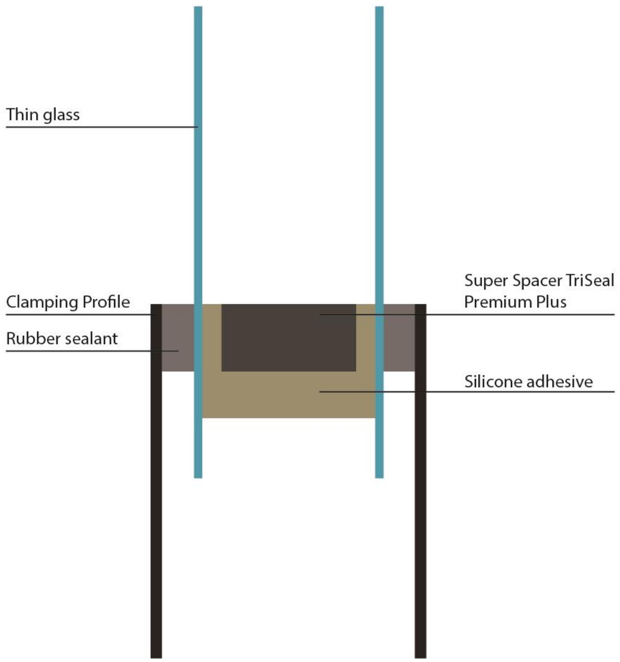
Rendering

Design B

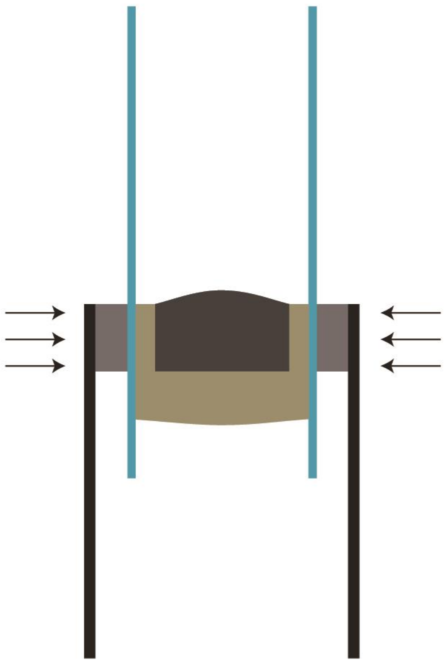

Top view


Rendering

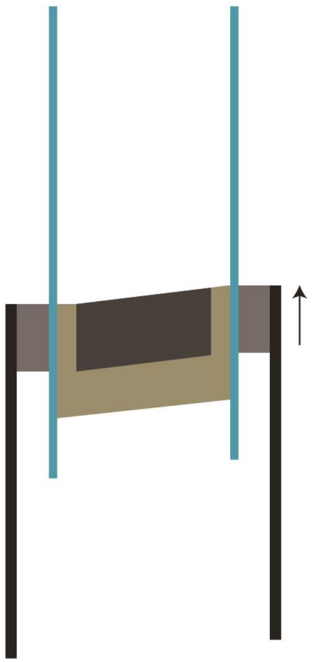
Design C- bottom edge clamping method



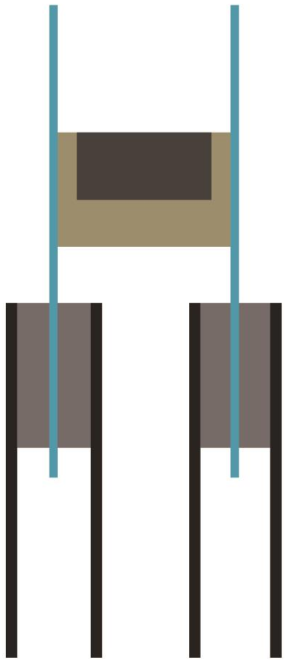
Clamping method A



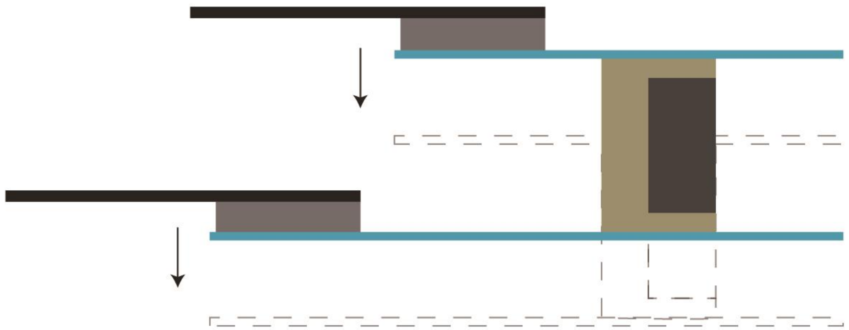
Compression state



Shear state

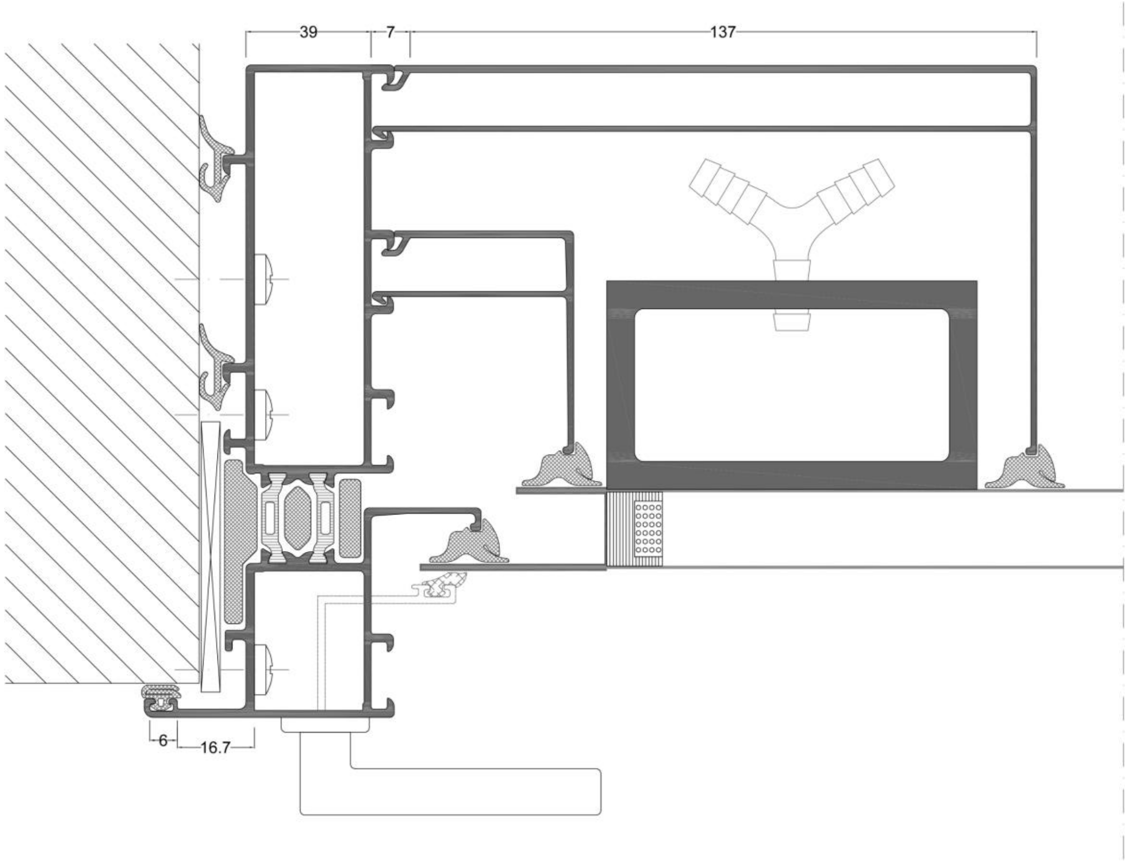


Clamping method B

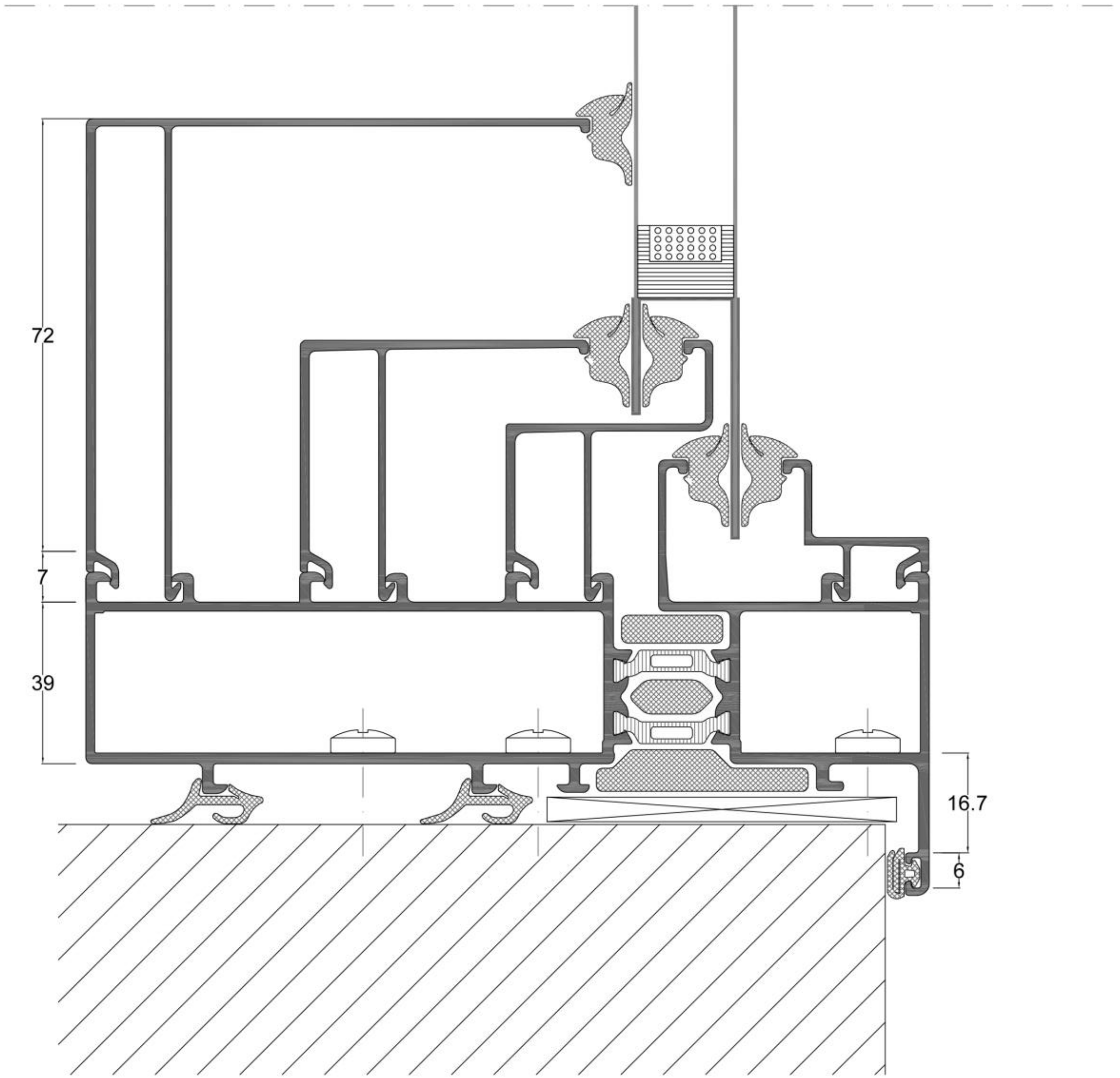


Opening on side edge

Design C

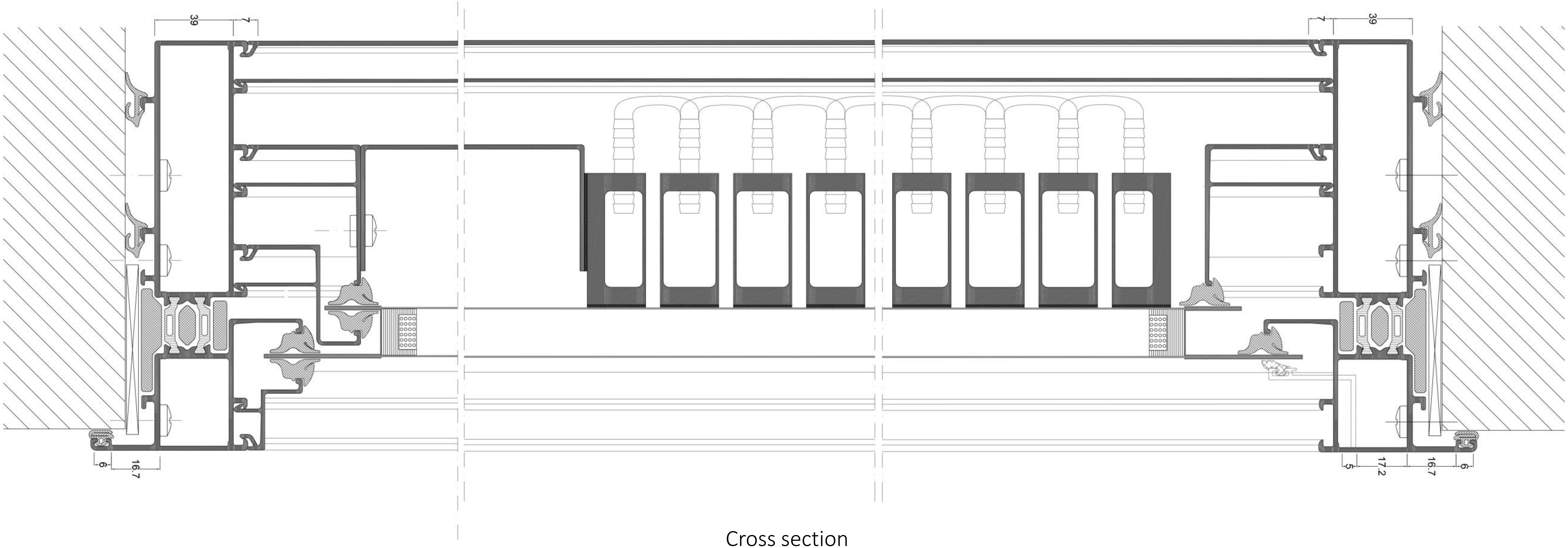


Side edge



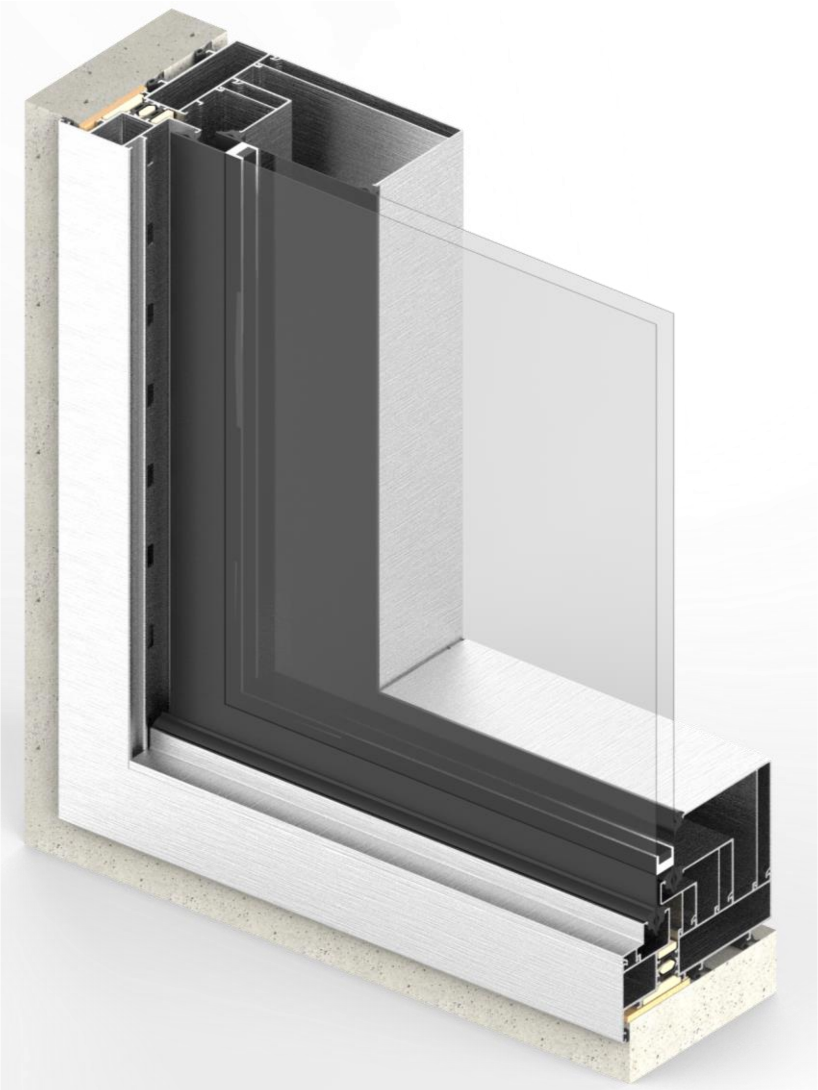
Bottom edge

Design C



Cross section

Design C

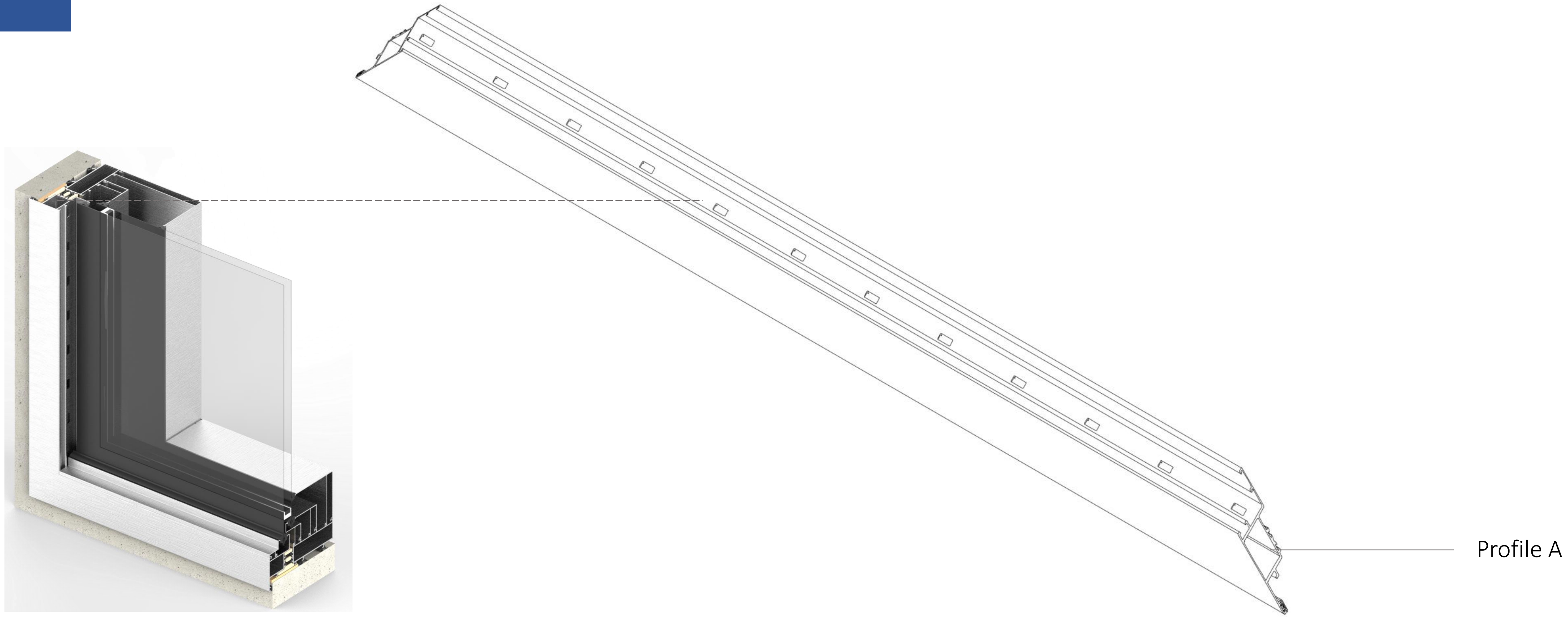


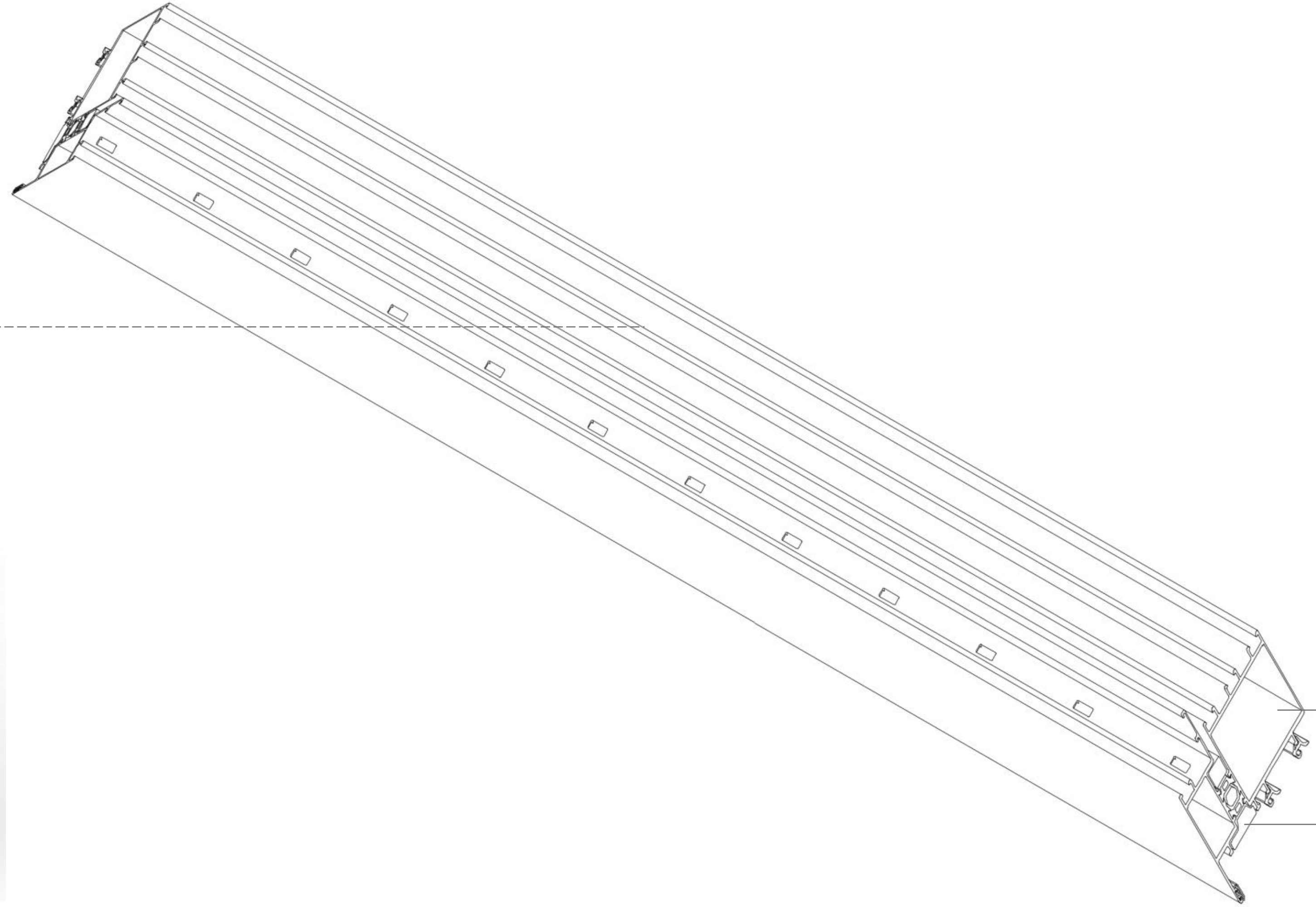
Inside view

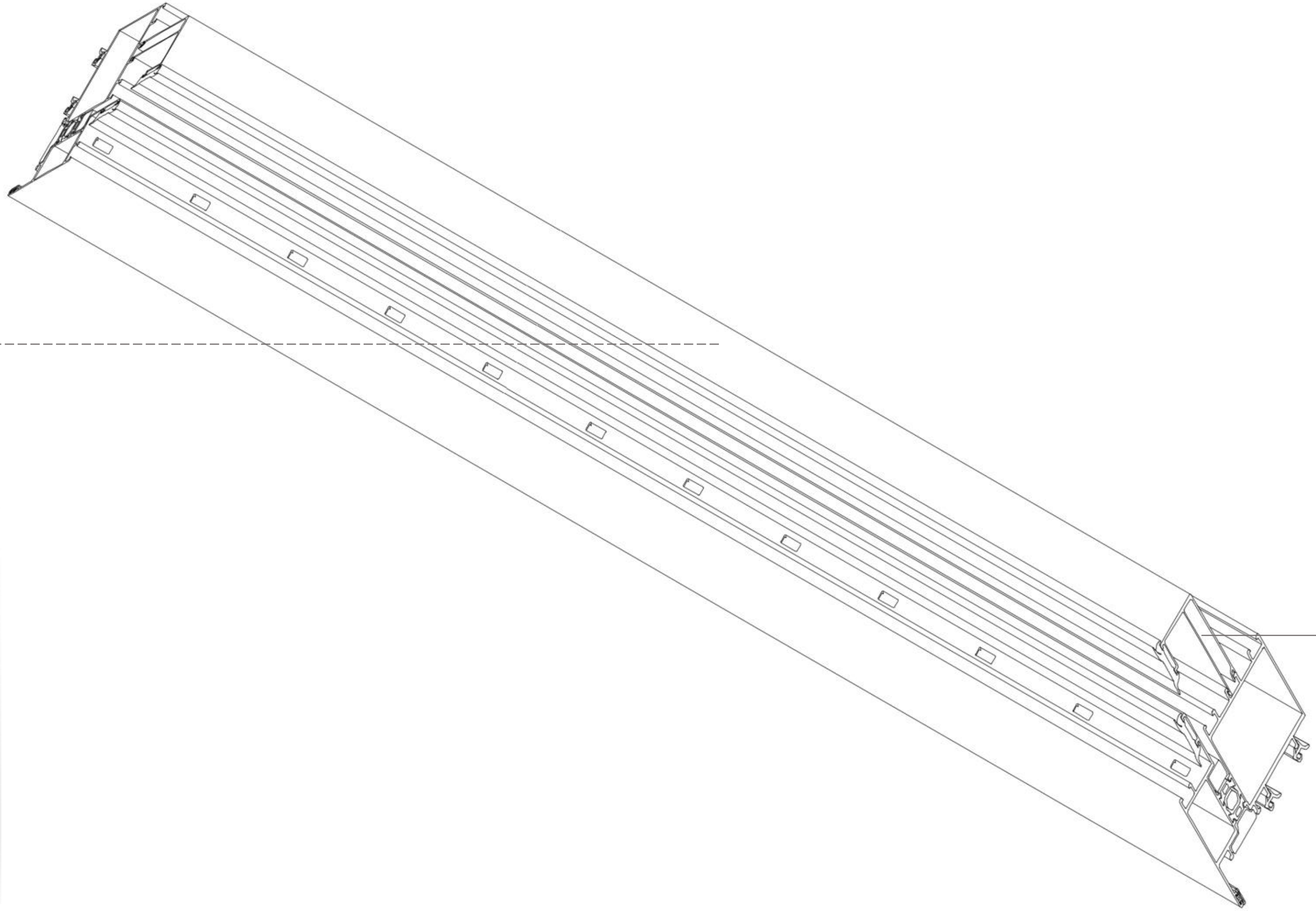
Outside view

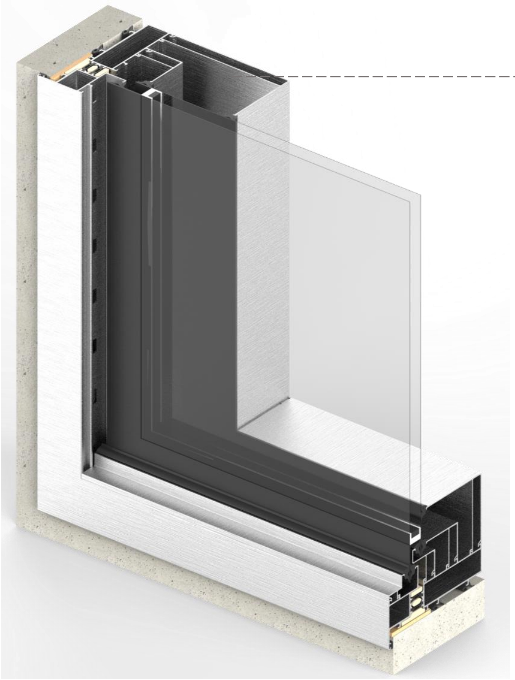
Part 4.3

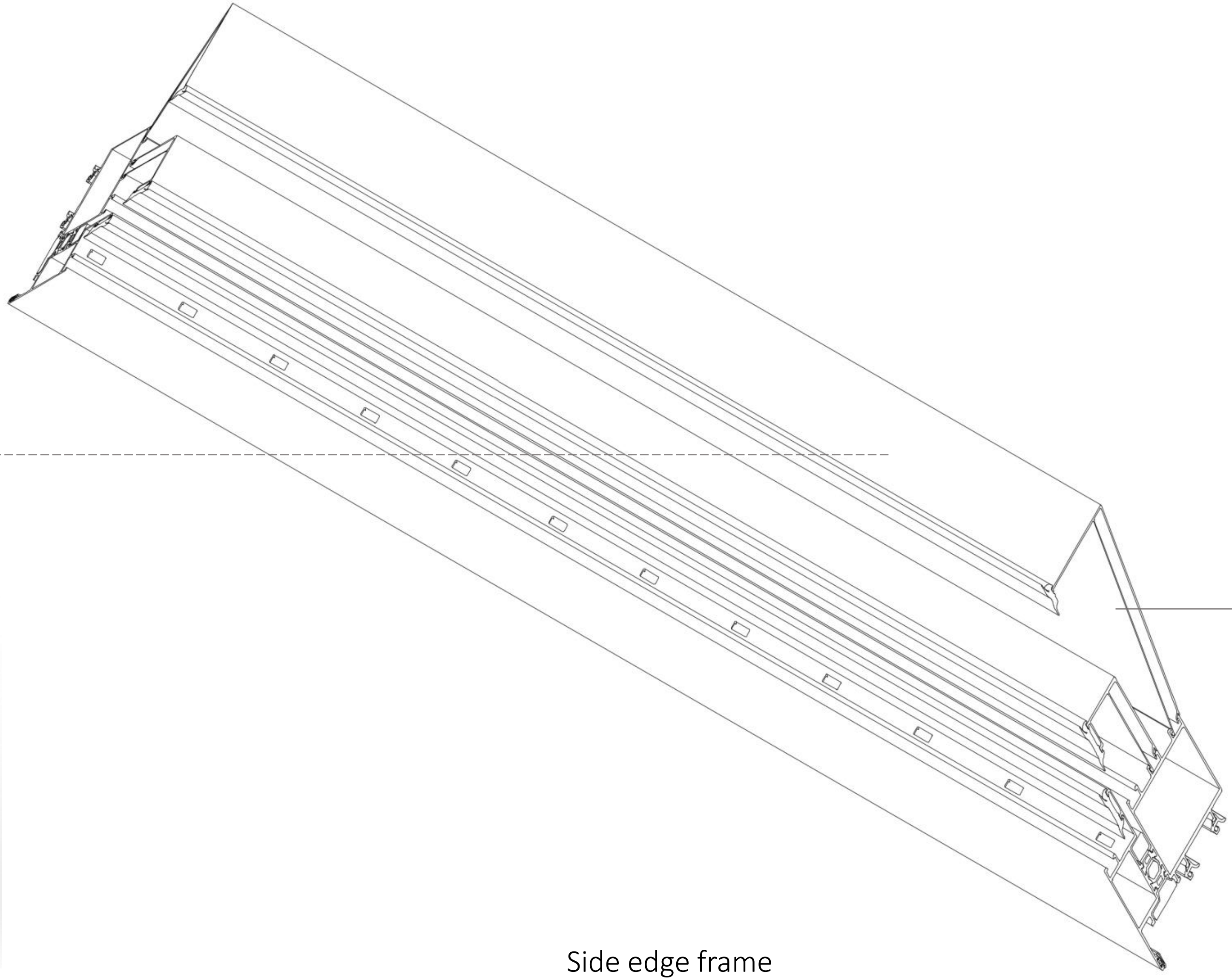
Installing process


Profile A

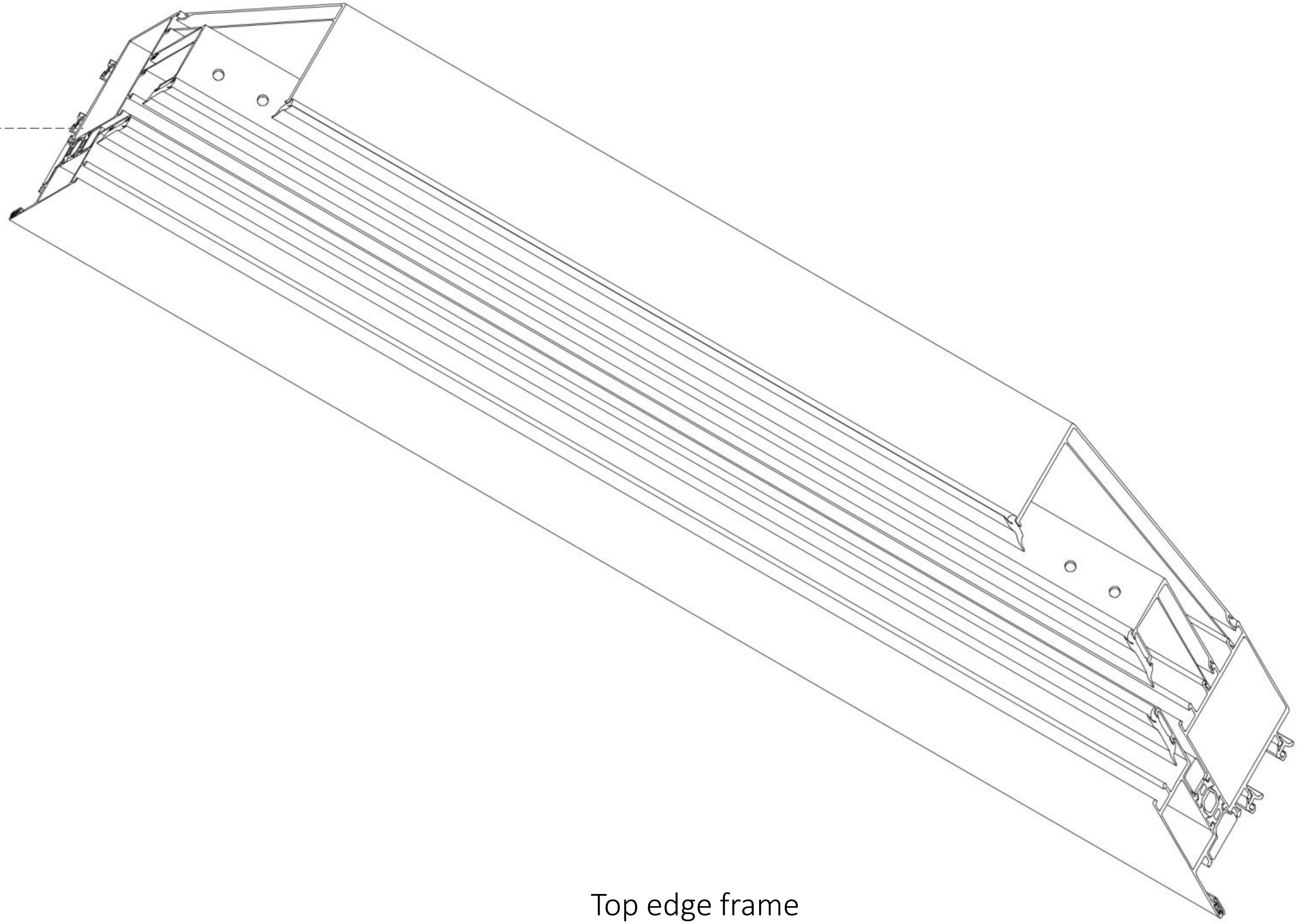

Profile B
Thermal
insulation


Profile C

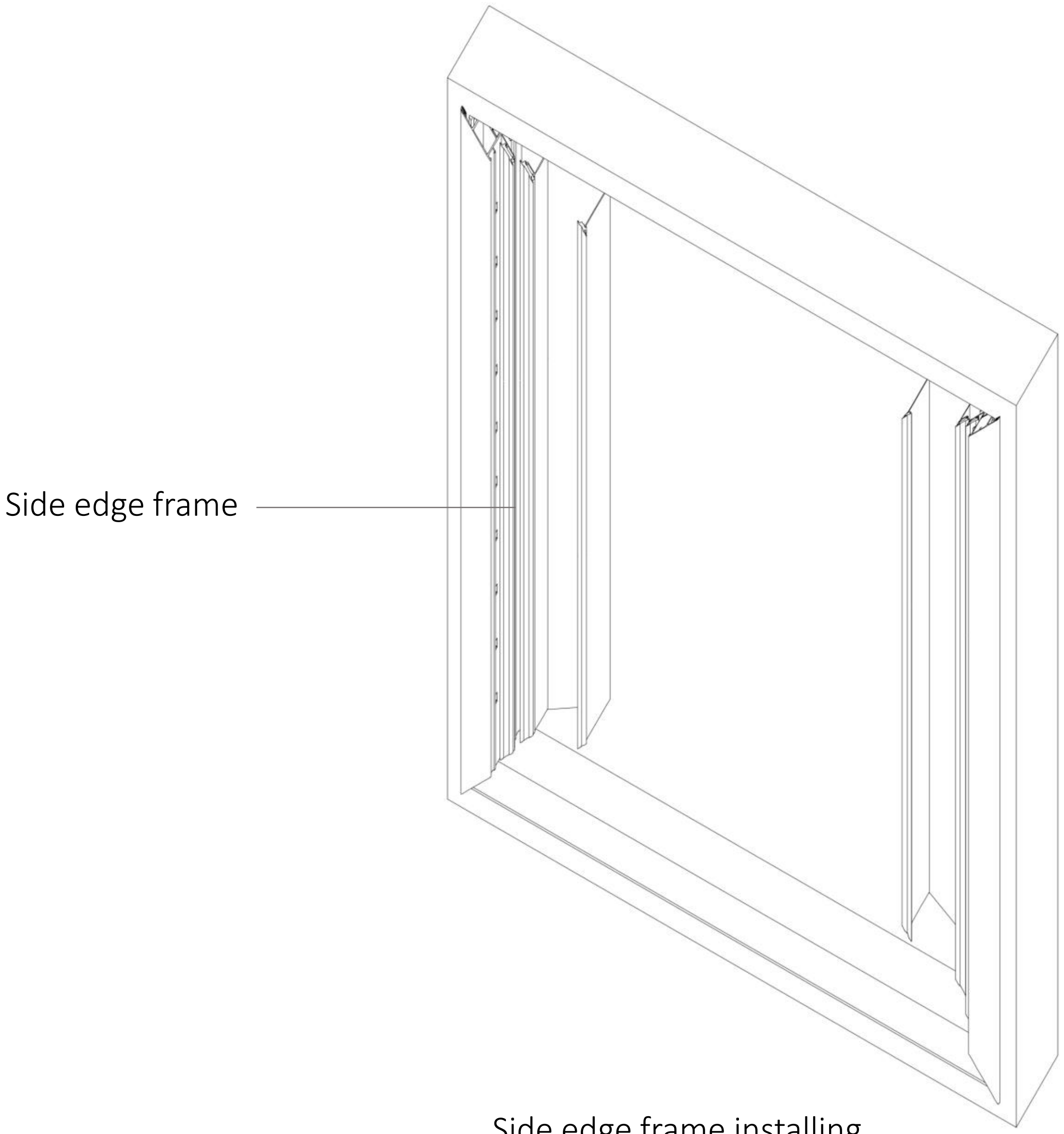




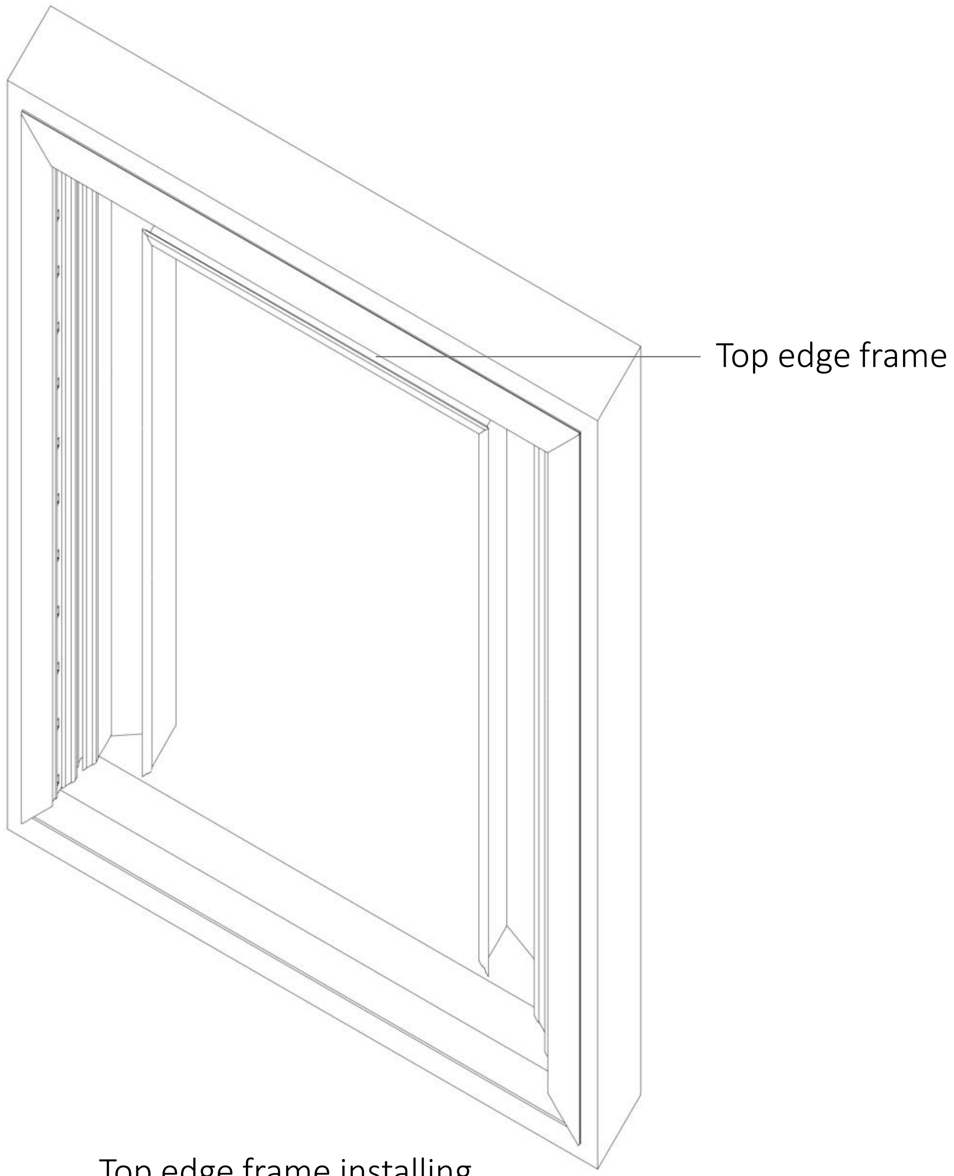
Side edge frame



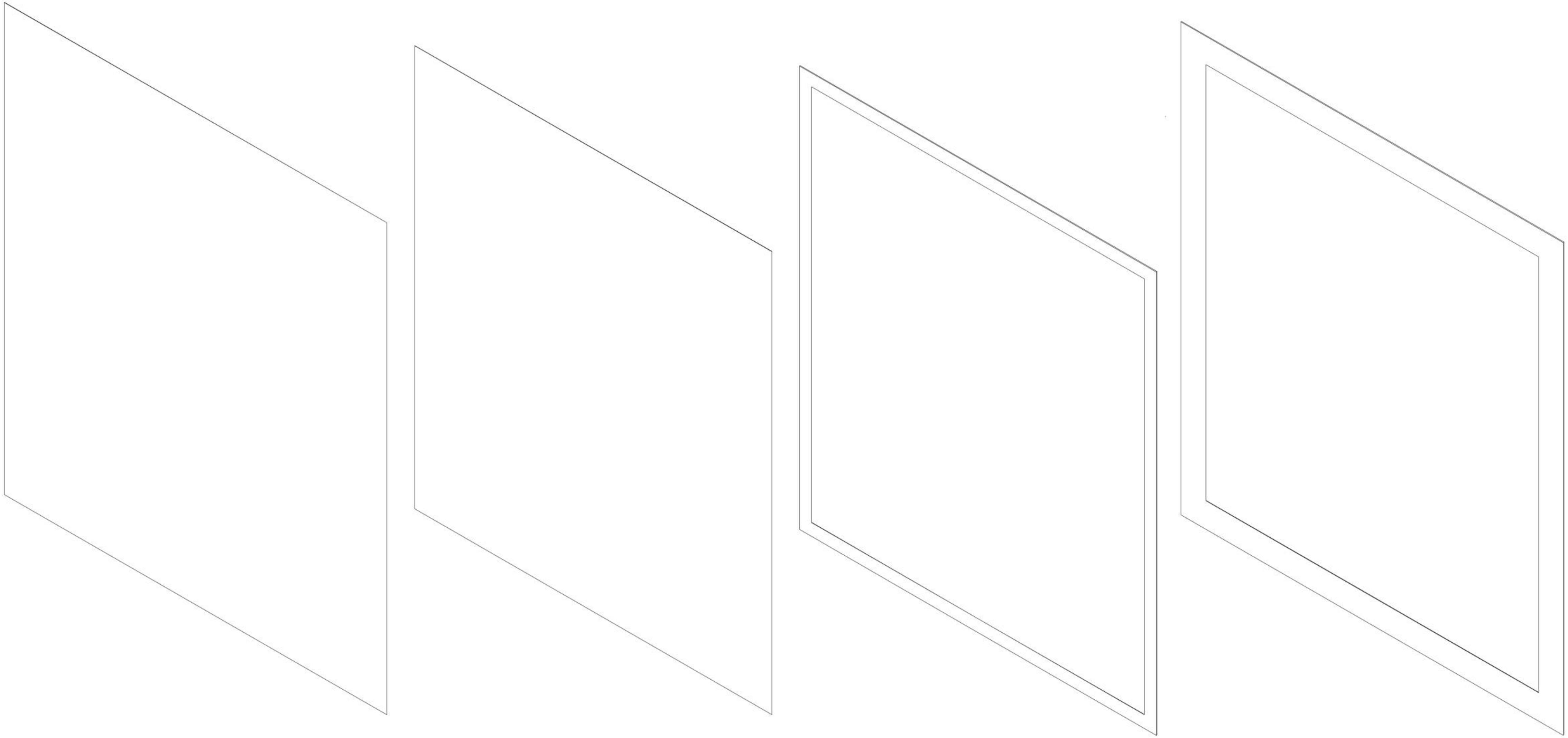
Top edge frame



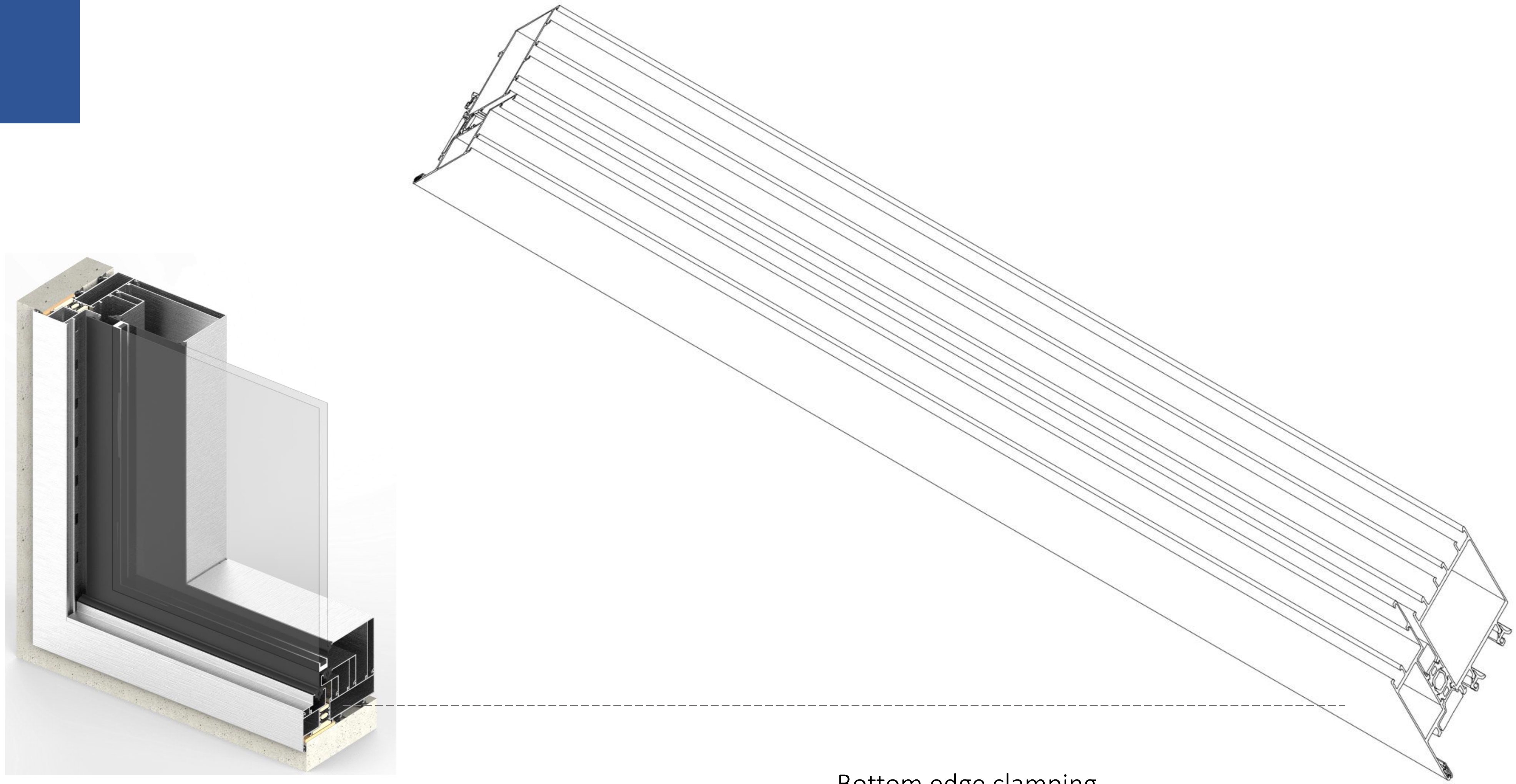
Side edge frame installing



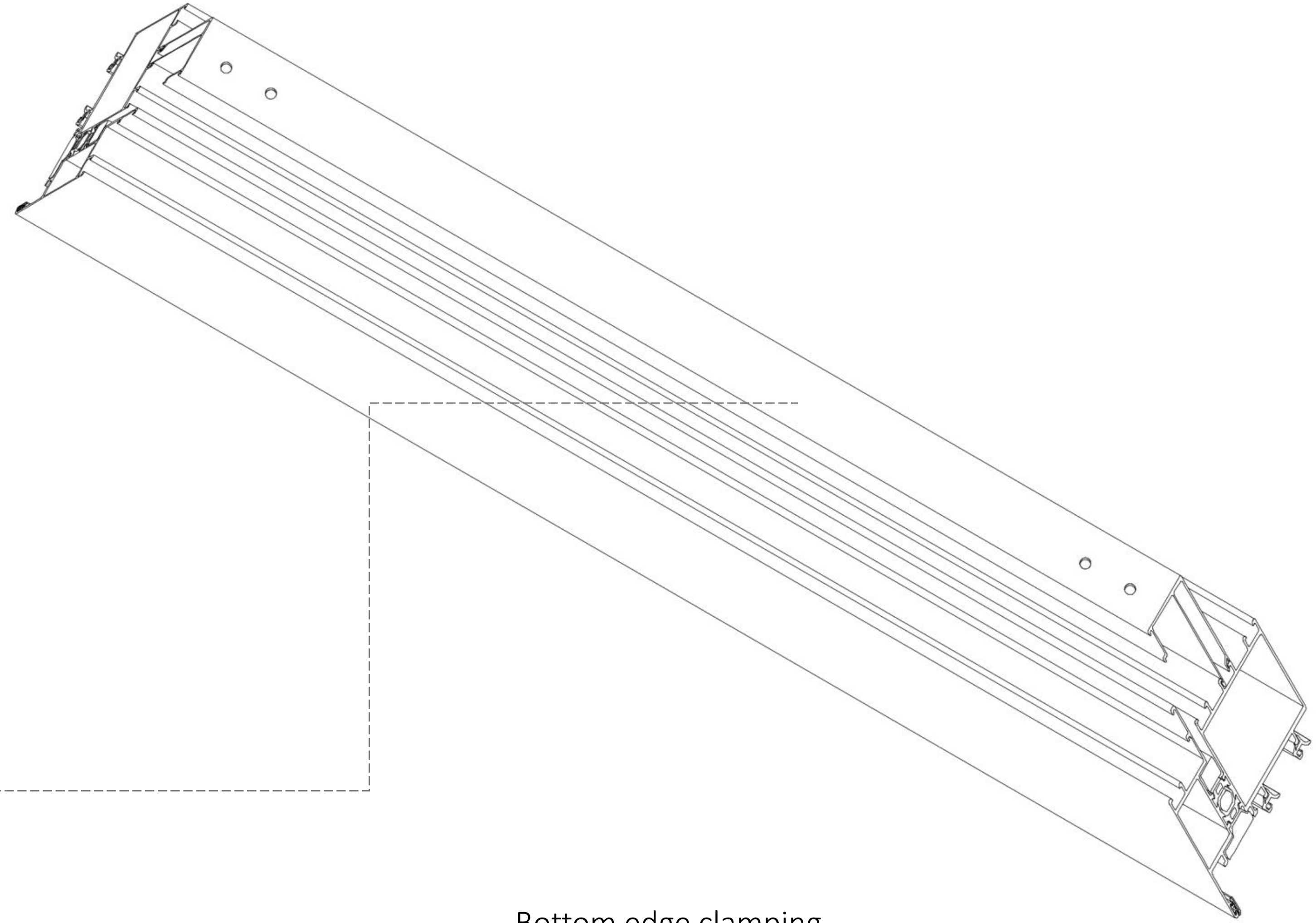
Top edge frame installing



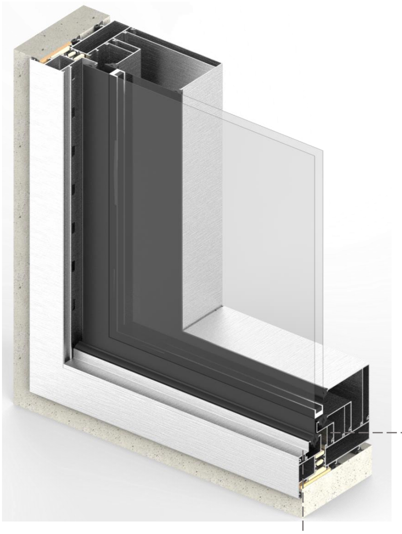
Thin glass panel edge painting

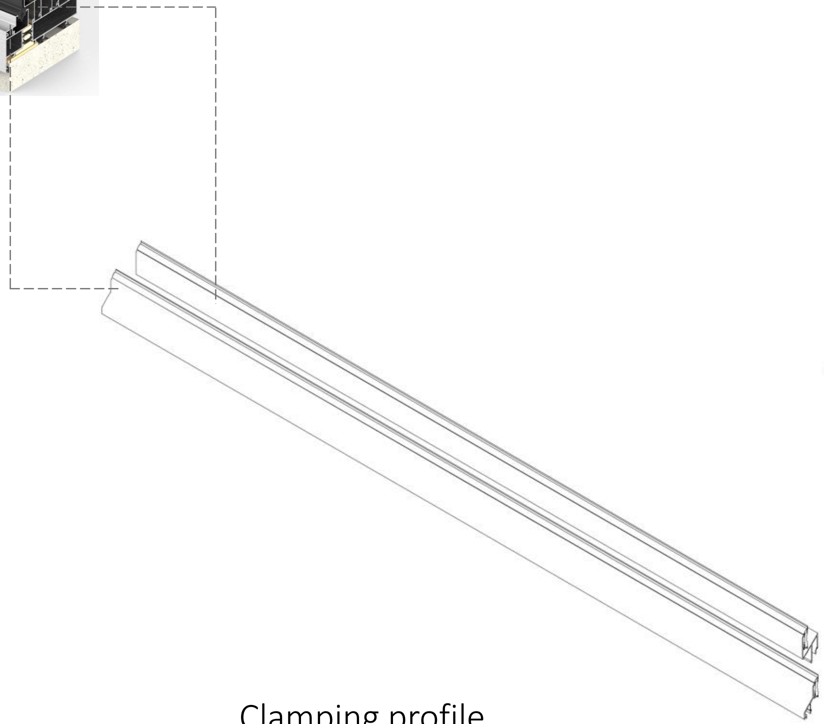


Bottom edge clamping

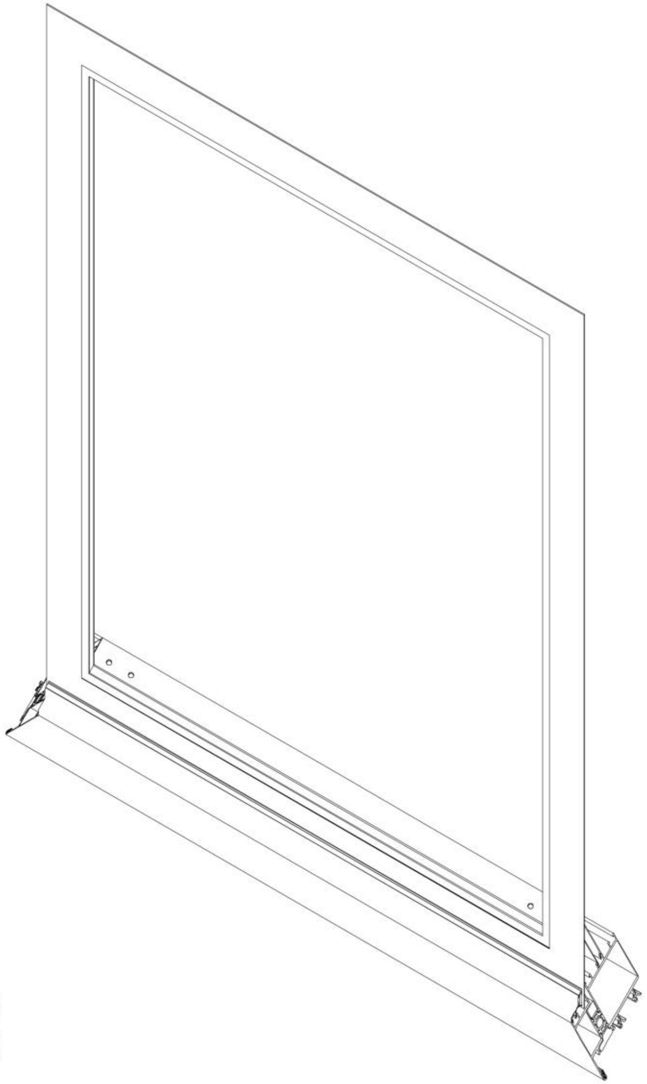


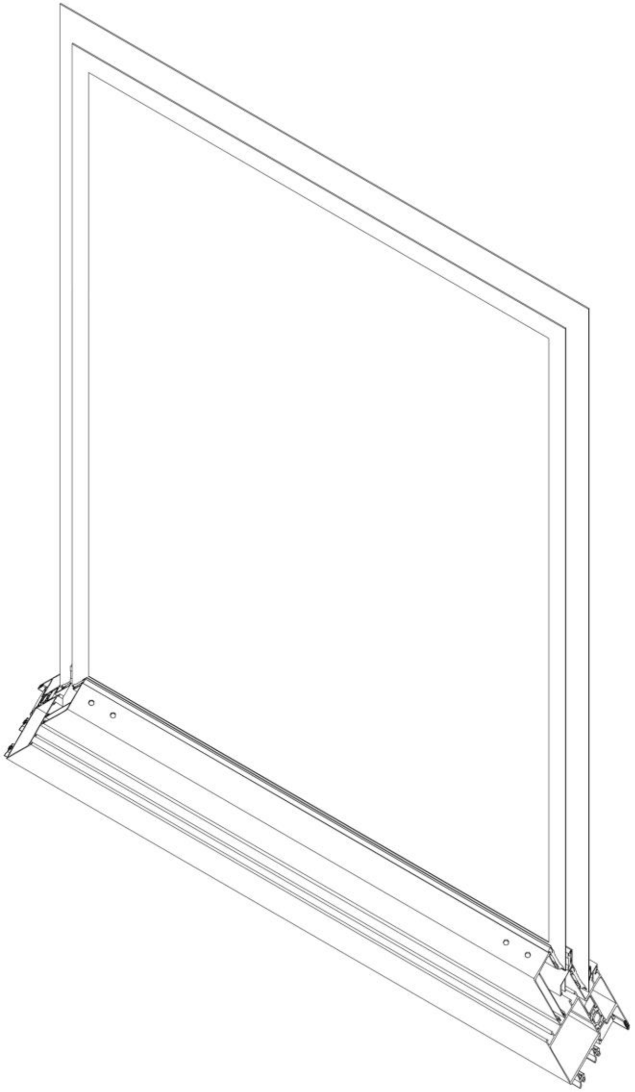
Bottom edge clamping

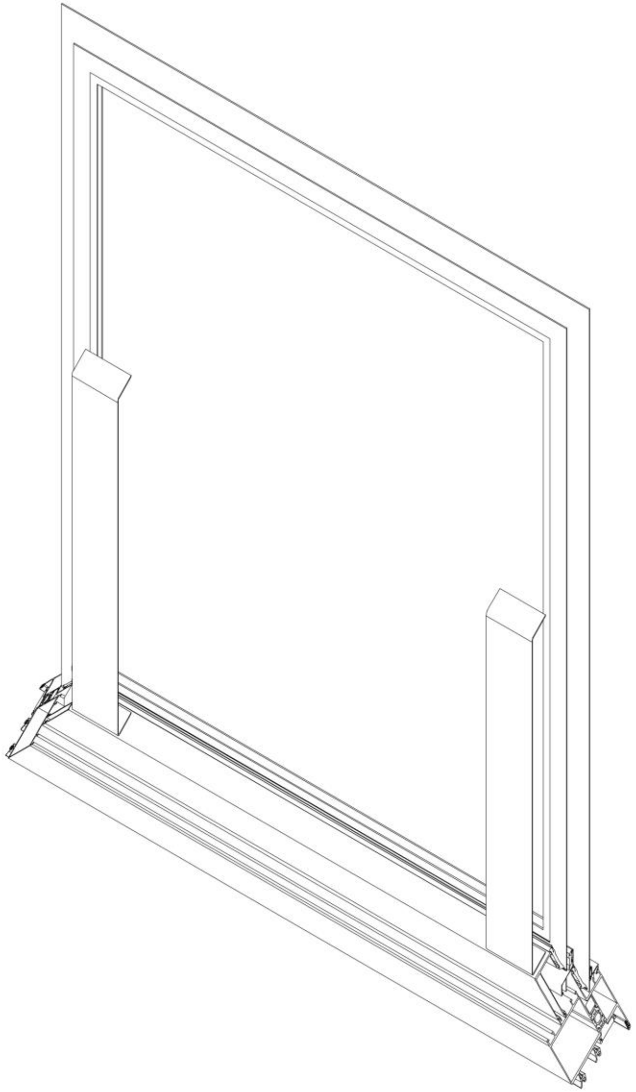




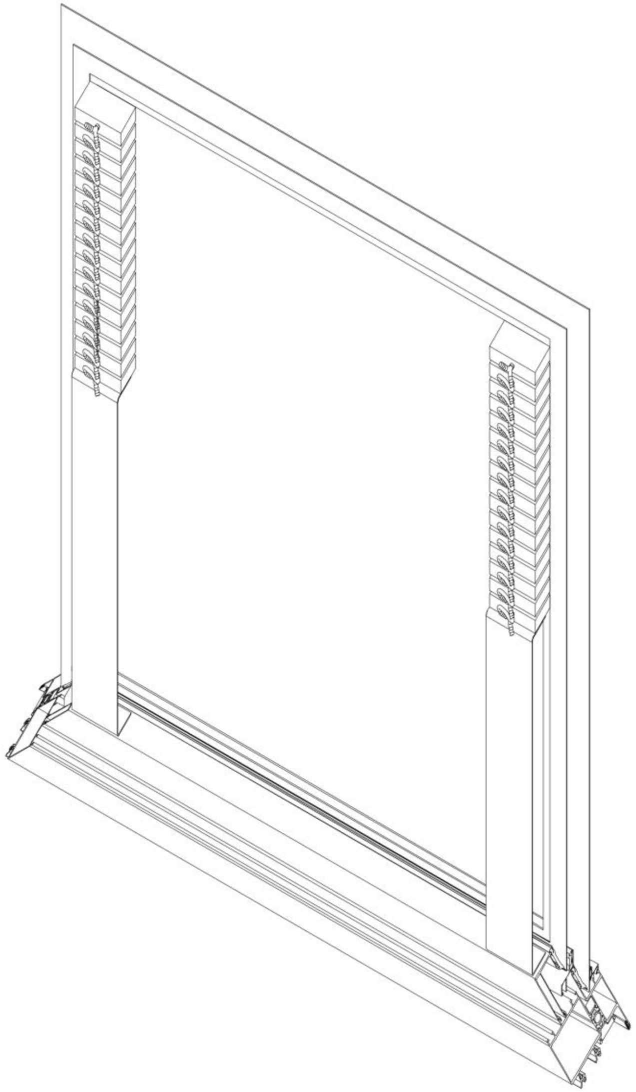
Clamping profile



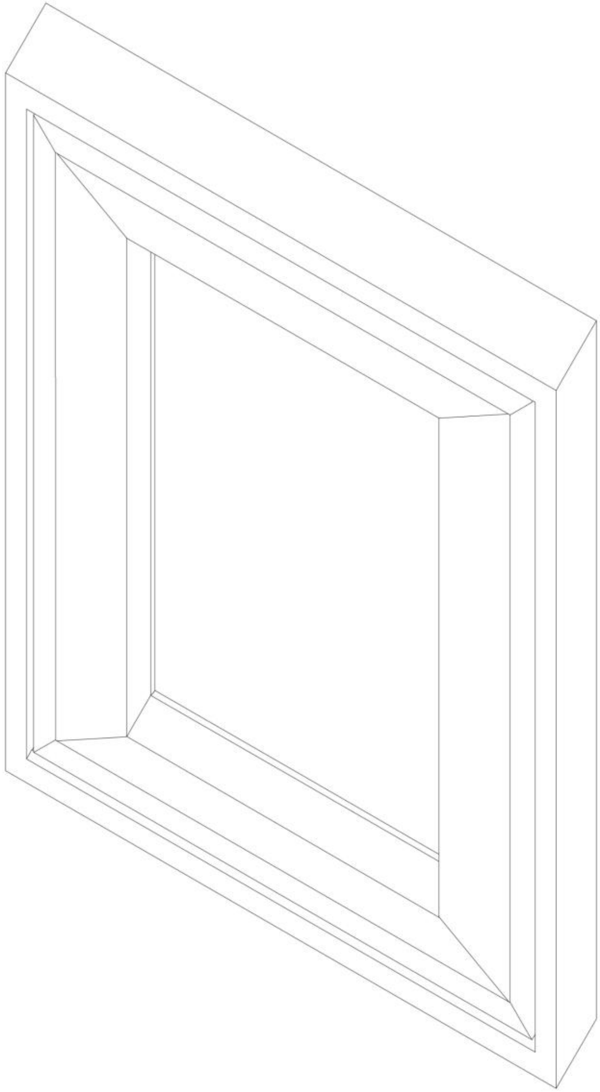




SPA support installing



SPA installing

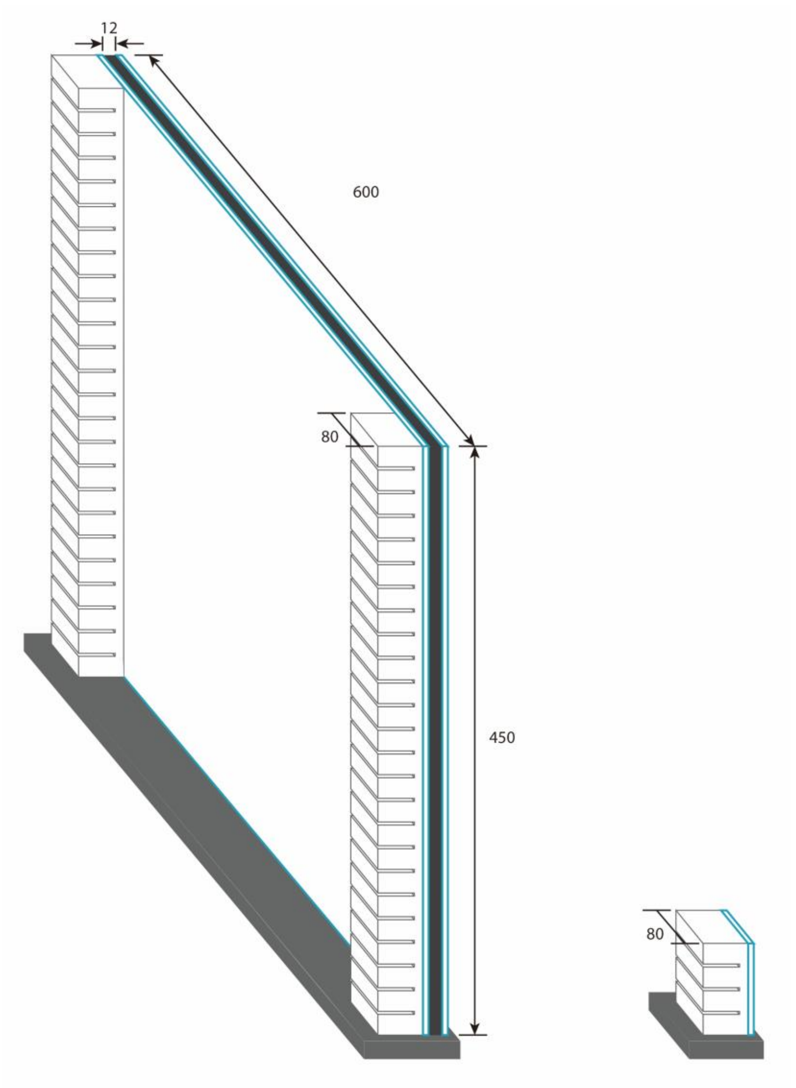


Finishing

Part 5

Simulation

Structure equivalent



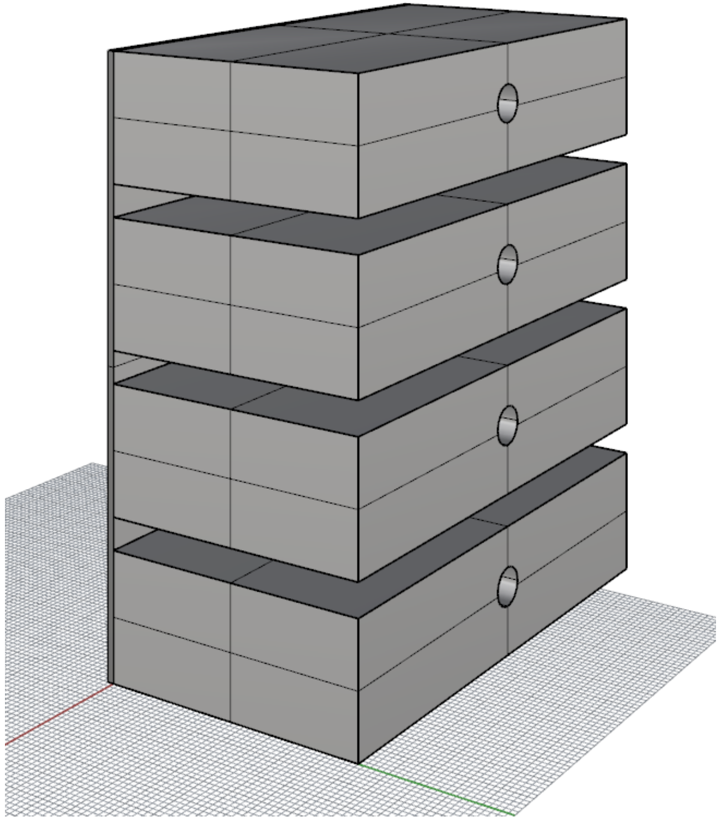
$$\text{Flexural rigidity} = 2E_{\text{thin glass}}\, I_{\text{thin glass}} + E_{\text{super spacer}}\, I_{\text{super spacer}}$$

$$= E_{\text{equivalent}}\, I_{\text{equivalent}}$$

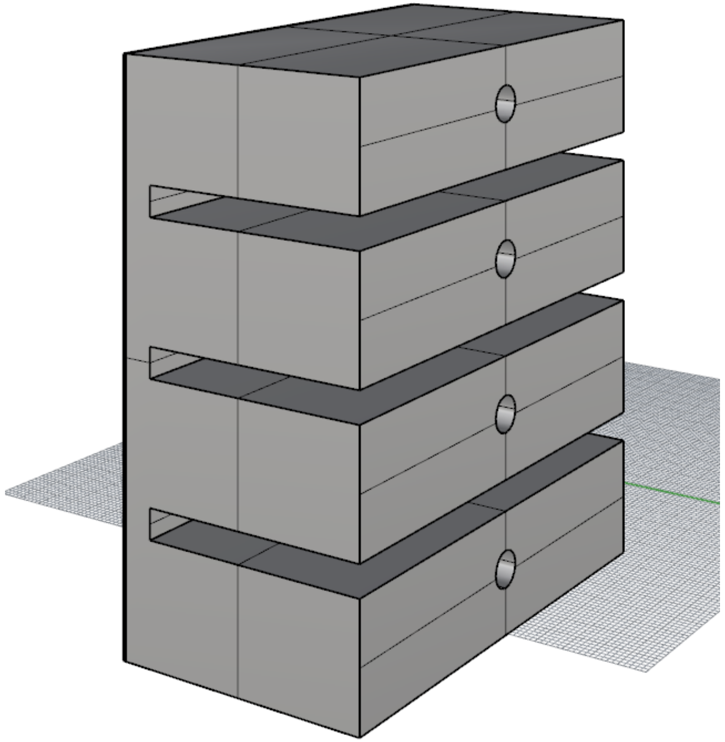
$$\text{Thickness} = 1.1\text{mm}$$

$$E_{\text{equivalent}} = 84556\text{MPa}$$

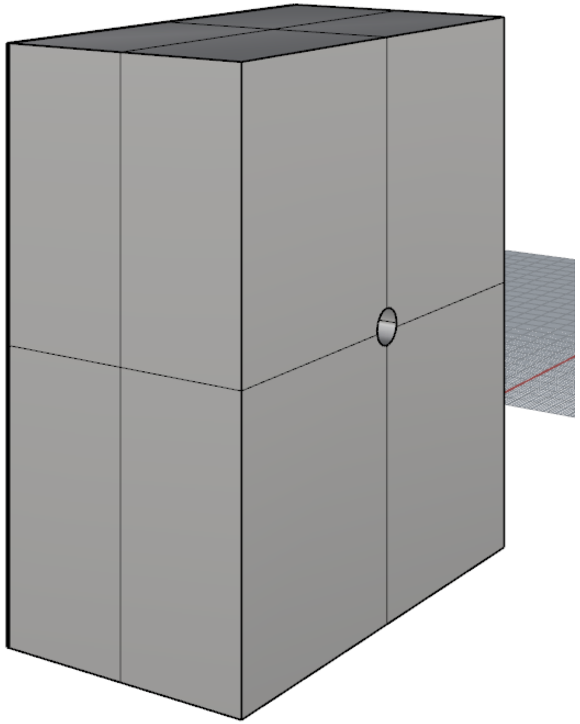
Geometry



Separate segments

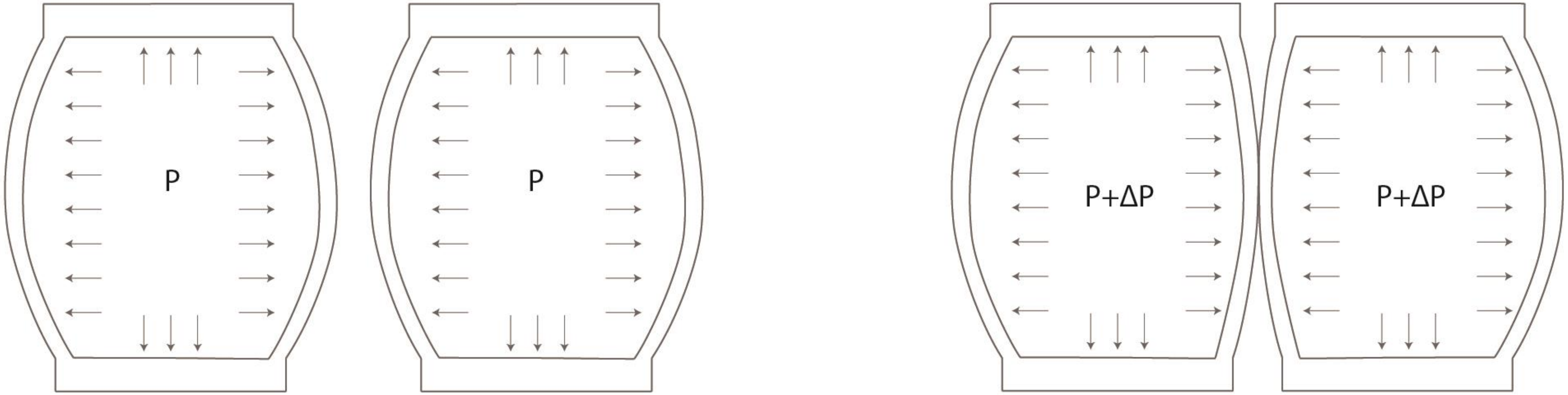


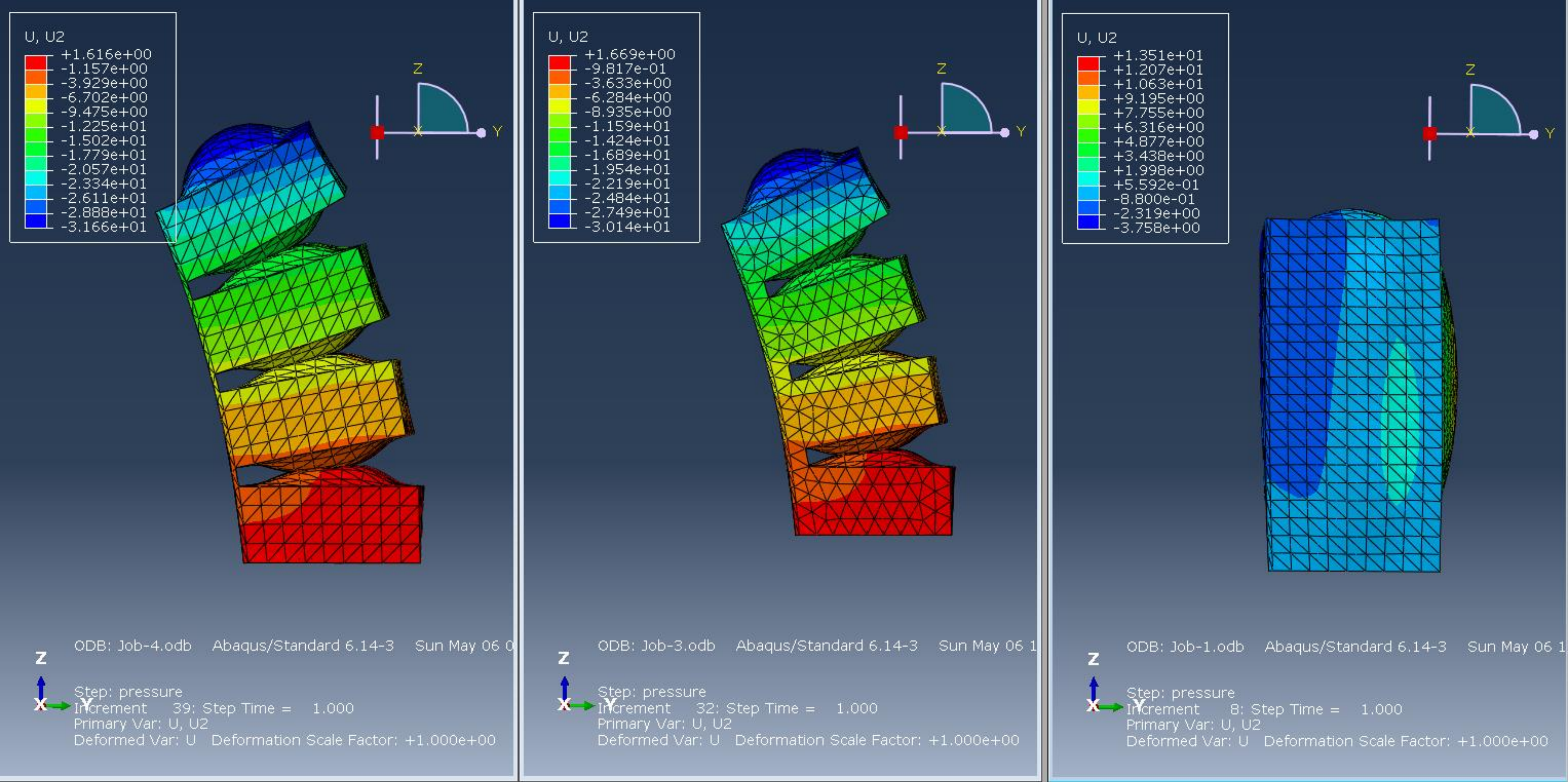
Connected segments

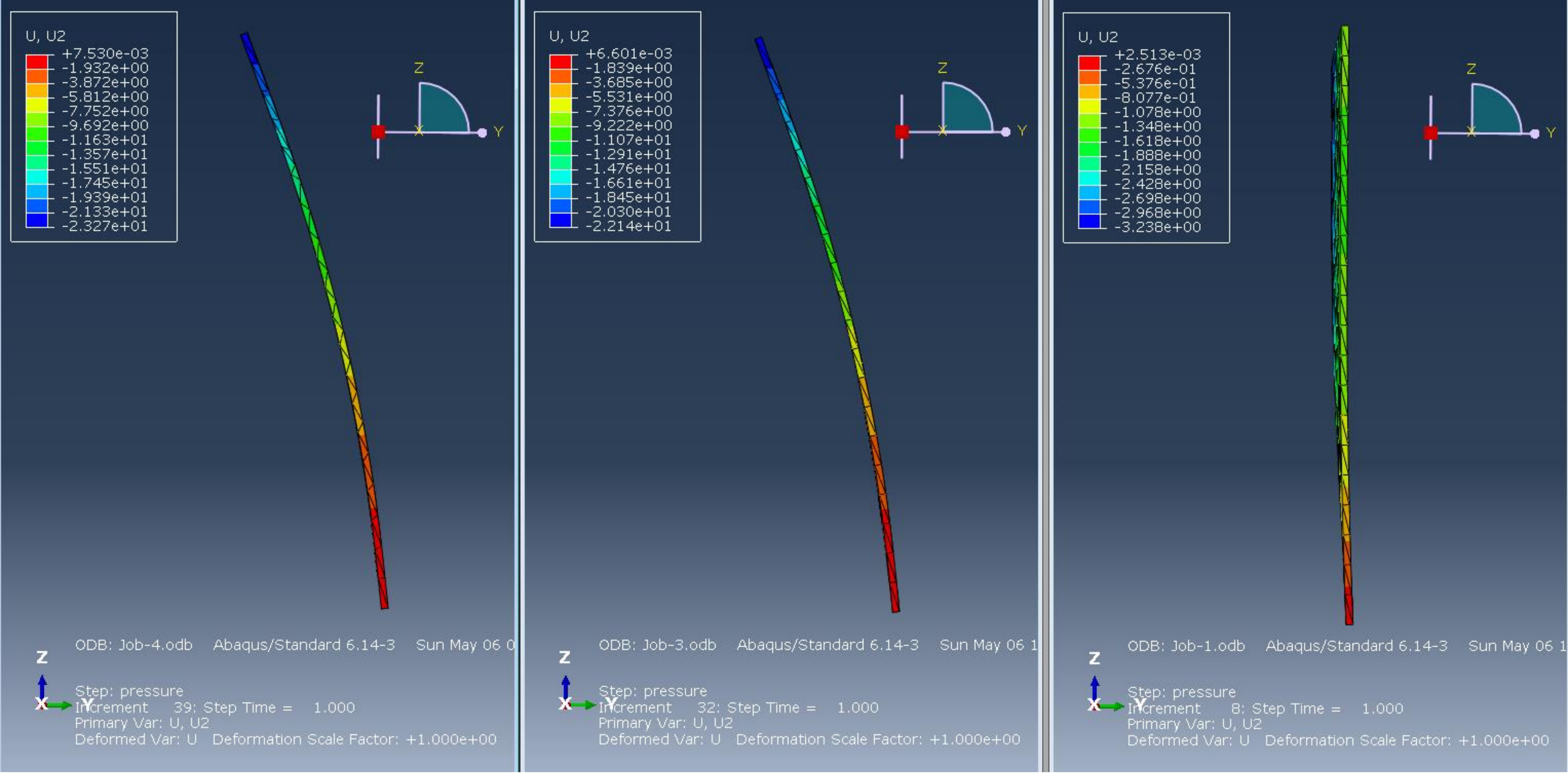


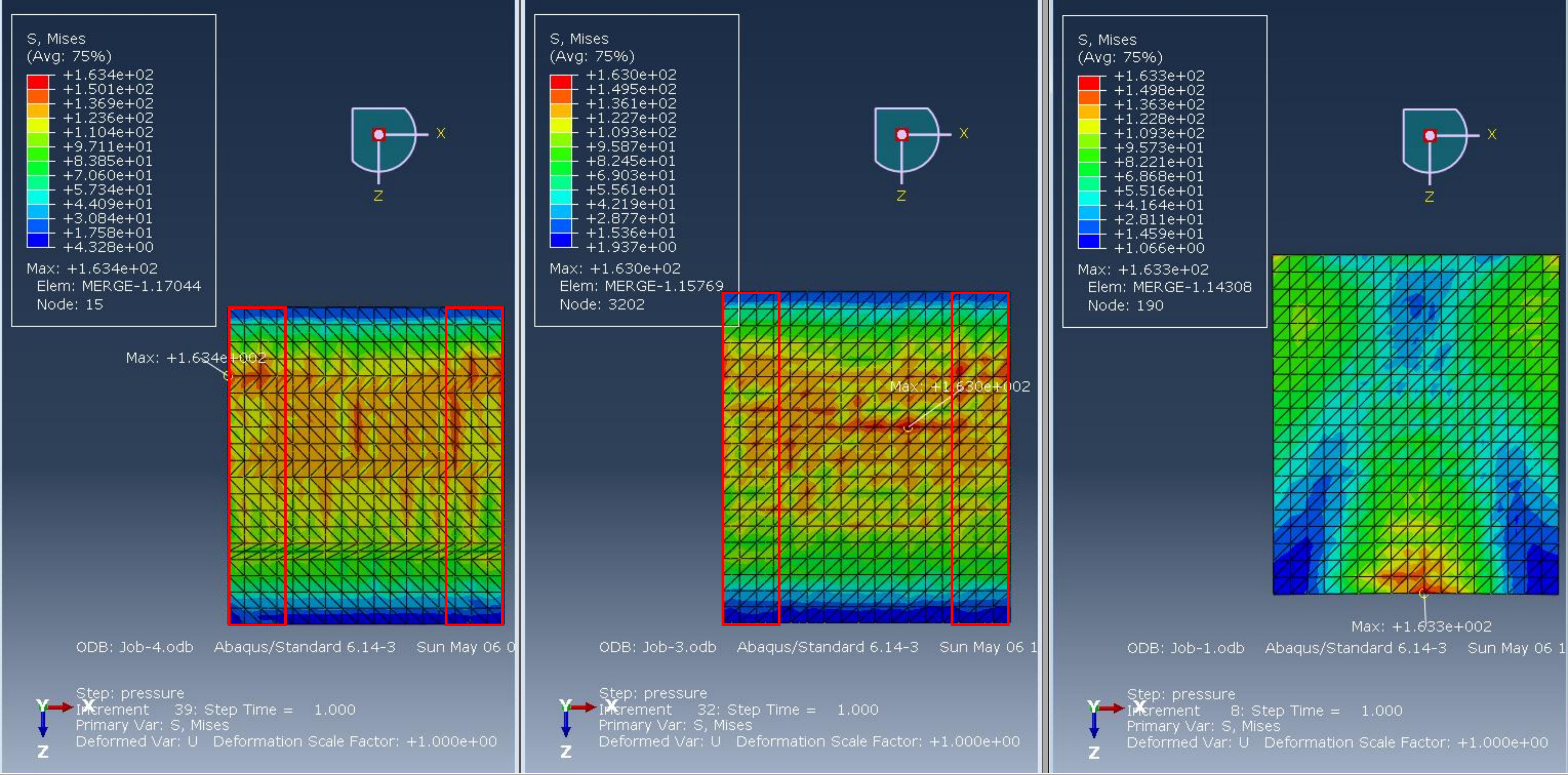
Whole segment

Pressure correction

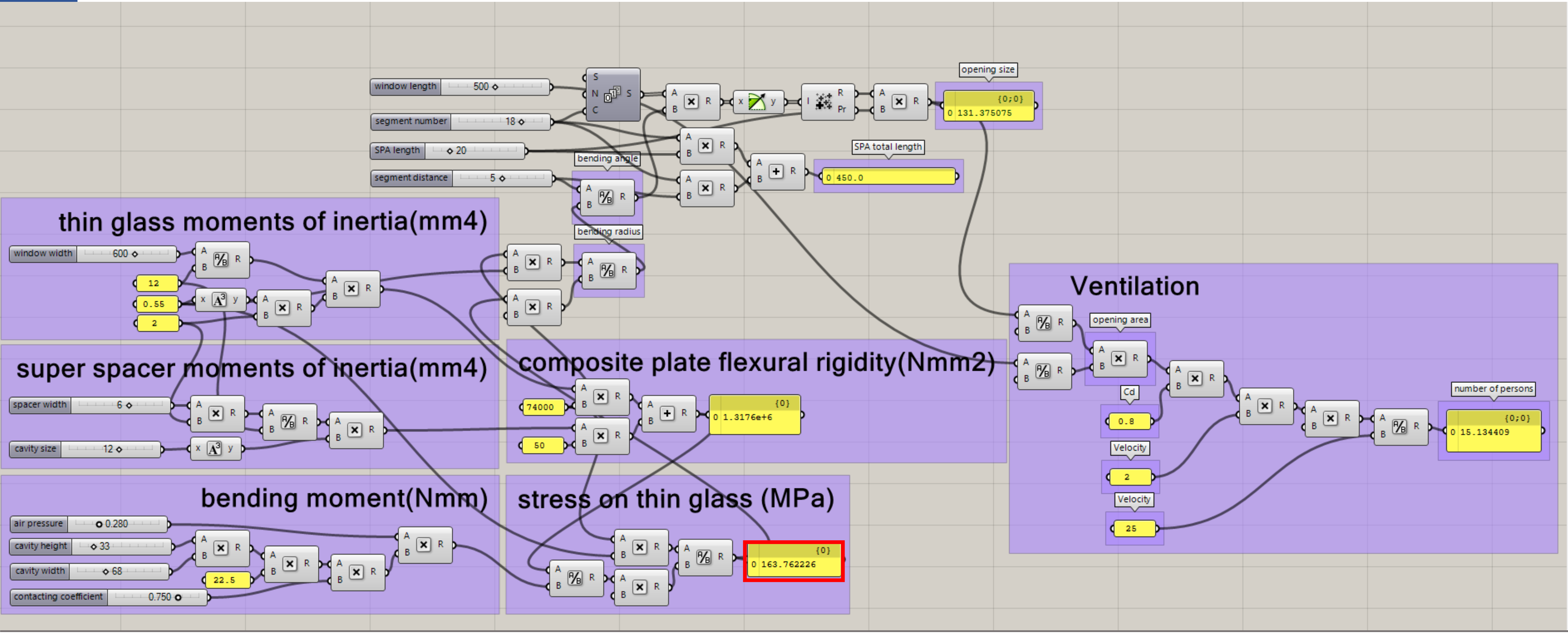



U, U2
+1.616e+00
-1.157e+00
-3.929e+00
-6.702e+00
-9.475e+00
-1.225e+01
-1.502e+01
-1.779e+01
-2.057e+01
-2.334e+01
-2.611e+01
-2.888e+01
-3.166e+01
ODB: Job-4.odb Abaqus/Standard 6.14-3 Sun May 06 0
Step: pressure
Increment 39: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00
U, U2
+1.669e+00
-9.817e-01
-3.633e+00
-6.284e+00
-8.935e+00
-1.159e+01
-1.424e+01
-1.689e+01
-1.954e+01
-2.219e+01
-2.484e+01
-2.749e+01
-3.014e+01
ODB: Job-3.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 32: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00
U, U2
+1.351e+01
+1.207e+01
+1.063e+01
+9.195e+00
+7.755e+00
+6.316e+00
+4.877e+00
+3.438e+00
+1.998e+00
+5.592e-01
-8.800e-01
-2.319e+00
-3.758e+00
ODB: Job-1.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 8: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00


U, U2
+7.530e-03
-1.932e+00
-3.872e+00
-5.812e+00
-7.752e+00
-9.692e+00
-1.163e+01
-1.357e+01
-1.551e+01
-1.745e+01
-1.939e+01
-2.133e+01
-2.327e+01
ODB: Job-4.odb Abaqus/Standard 6.14-3 Sun May 06 0
Step: pressure
Increment 39: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00
U, U2
+6.601e-03
-1.839e+00
-3.685e+00
-5.531e+00
-7.376e+00
-9.222e+00
-1.107e+01
-1.291e+01
-1.476e+01
-1.661e+01
-1.845e+01
-2.030e+01
-2.214e+01
ODB: Job-3.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 32: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00
U, U2
+2.513e-03
-2.676e-01
-5.376e-01
-8.077e-01
-1.078e+00
-1.348e+00
-1.618e+00
-1.888e+00
-2.158e+00
-2.428e+00
-2.698e+00
-2.968e+00
-3.238e+00
ODB: Job-1.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 8: Step Time = 1.000
Primary Var: U, U2
Deformed Var: U Deformation Scale Factor: +1.000e+00

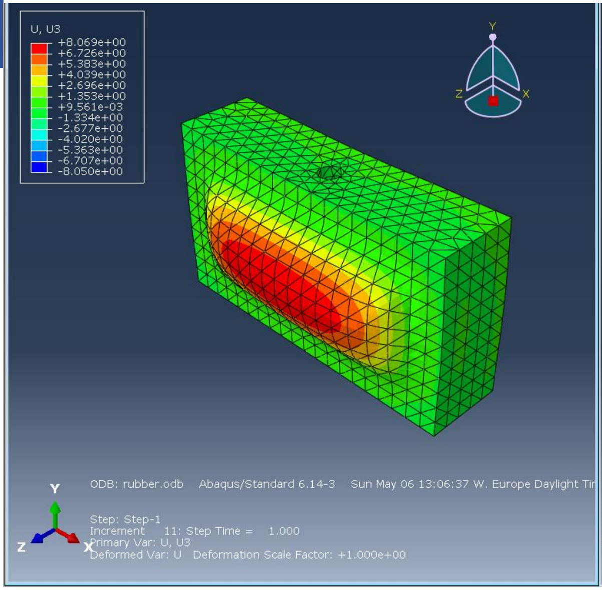

S, Mises
(Avg: 75%)
+1.634e+02
+1.501e+02
+1.369e+02
+1.236e+02
+1.104e+02
+9.711e+01
+8.385e+01
+7.060e+01
+5.734e+01
+4.409e+01
+3.084e+01
+1.758e+01
+4.328e+00
Max: +1.634e+02
Elem: MERGE-1.17044
Node: 15
X
Z
Max: +1.634e+002
ODB: Job-4.odb Abaqus/Standard 6.14-3 Sun May 06 0
Step: pressure
Increment 39: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
S, Mises
(Avg: 75%)
+1.630e+02
+1.495e+02
+1.361e+02
+1.227e+02
+1.093e+02
+9.587e+01
+8.245e+01
+6.903e+01
+5.561e+01
+4.219e+01
+2.877e+01
+1.536e+01
+1.937e+00
Max: +1.630e+02
Elem: MERGE-1.15769
Node: 3202
X
Z
Max: +1.630e+002
ODB: Job-3.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 32: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00
S, Mises
(Avg: 75%)
+1.633e+02
+1.498e+02
+1.363e+02
+1.228e+02
+1.093e+02
+9.573e+01
+8.221e+01
+6.868e+01
+5.516e+01
+4.164e+01
+2.811e+01
+1.459e+01
+1.066e+00
Max: +1.633e+02
Elem: MERGE-1.14308
Node: 190
X
Z
Max: +1.633e+002
ODB: Job-1.odb Abaqus/Standard 6.14-3 Sun May 06 1
Step: pressure
Increment 8: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00

Validation

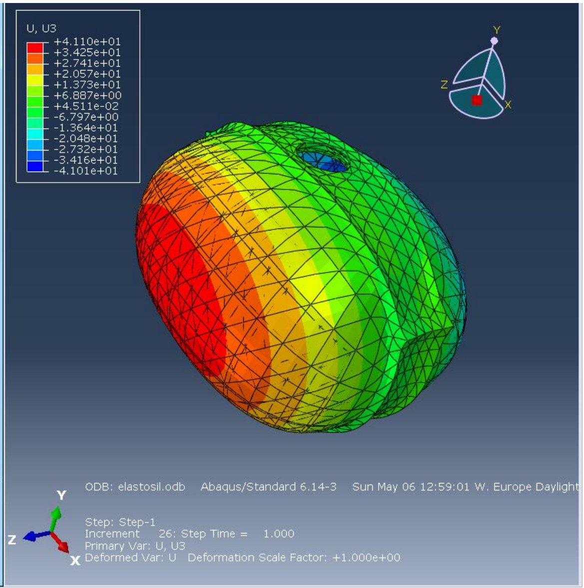

thin glass moments of inertia(mm4)
window width 600
12
0.55
2
super spacer moments of inertia(mm4)
spacer width 6
cavity size 12
bending moment(Nmm)
air pressure 0.280
cavity height 33
cavity width 68
22.5
contacting coefficient 0.750
window length 500
segment number 18
SPA length 20
segment distance 5
bending angle
bending radius
opening size
{0;0}
0 131.375075
SPA total length
0 450.0
composite plate flexural rigidity(Nmm2)
74000
50
{0}
0 1.3176e+6
stress on thin glass (MPa)
{0}
0 163.762226
Ventilation
opening area
Cd
0.8
Velocity
2
Velocity
25
number of persons
{0;0}
0 15.134409

Material inflating comparing

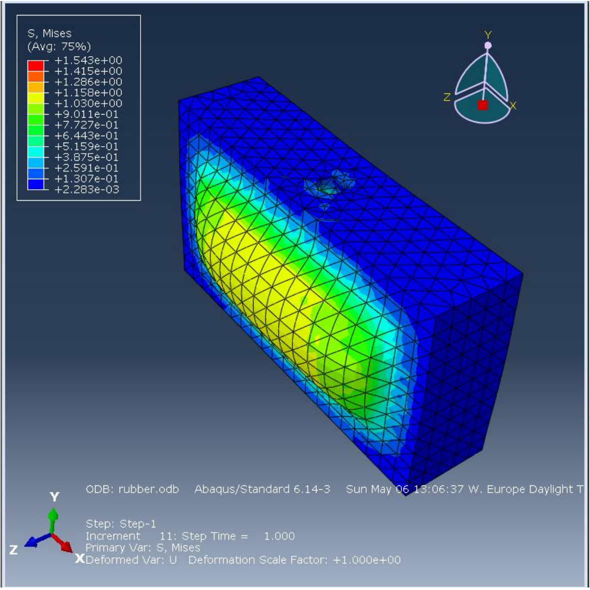
Natural rubber



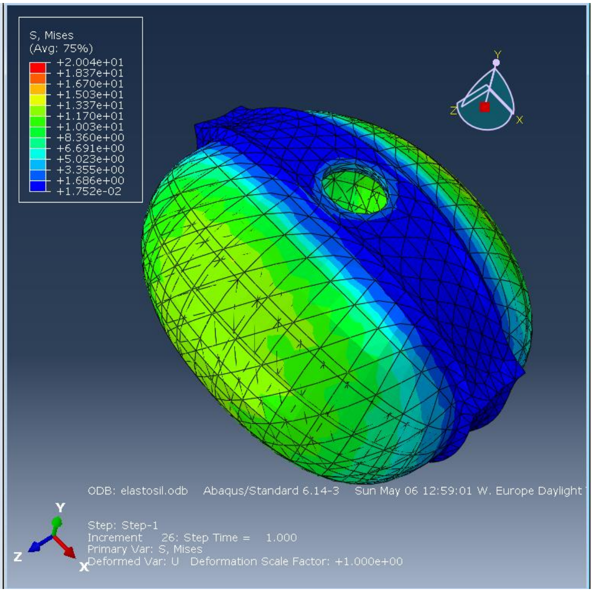
Elastosil silicone



Natural rubber



Elastosil silicone



Segments inflating deformation

Segments inflating stress simulation

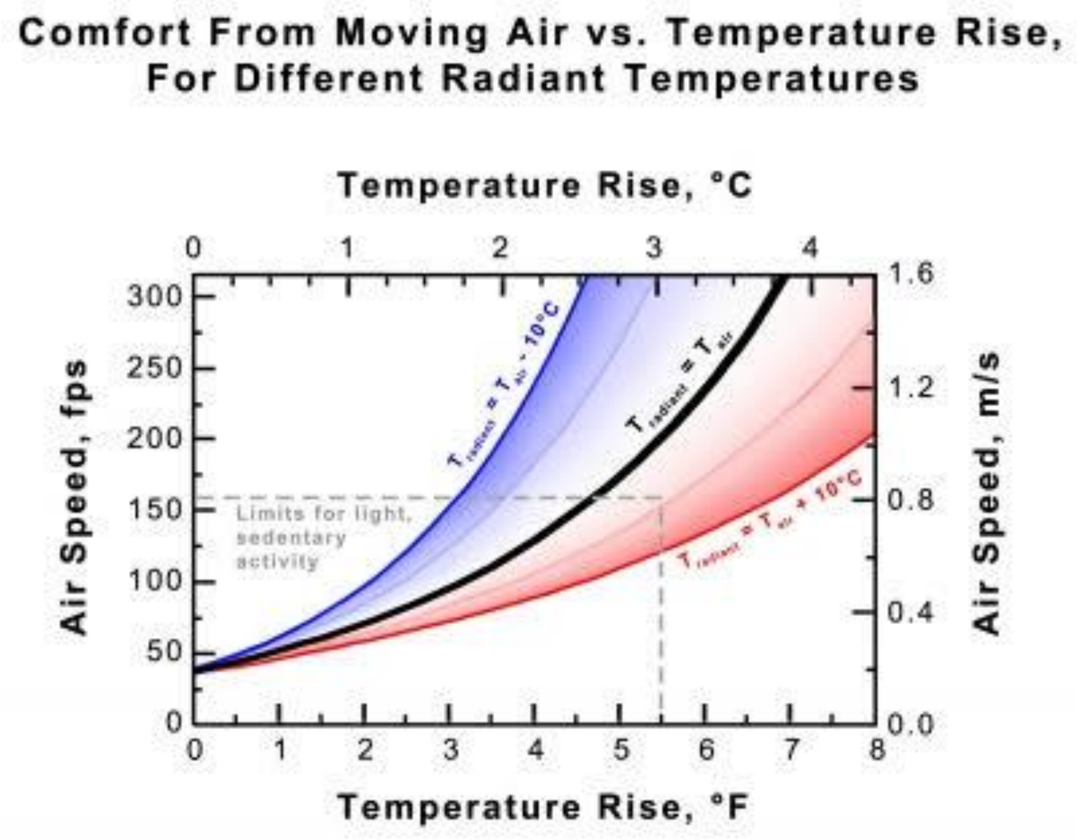
Tensile strength: Natural rubber 28MPa

Elastosil silicone 6.5MPa

Part 5.1

Indoor comfort simulation

Relationship between air speed and air temperature in comforting human



Inlet air temperature

5°C lower than radiant temperature

- 3°C increasing need 0.8m/s increasing

5°C higher than radiant temperature

- 3°C increasing need 1.6m/s increasing

- **Maximum allowable elevated airspeed is 1.5 m/s**

How to quantify indoor comfort by ventilation

- Air temperature (t_a)
- Mean air velocity ($\bar{v}$)
- Turbulence intensity (Tu)

Percentage Dissatisfied due to draft

$$PD = 3.143(34 - t_a)(\bar{v} - 0.05)^{0.6223} + 0.3696\bar{v}\,Tu(34 - t_a)(\bar{v} - 0.05)^{0.6223}$$

for $\bar{v} < 0.05$ m/s insert $\bar{v} = 0.05$ m/s

for PD>100% use PD=100%

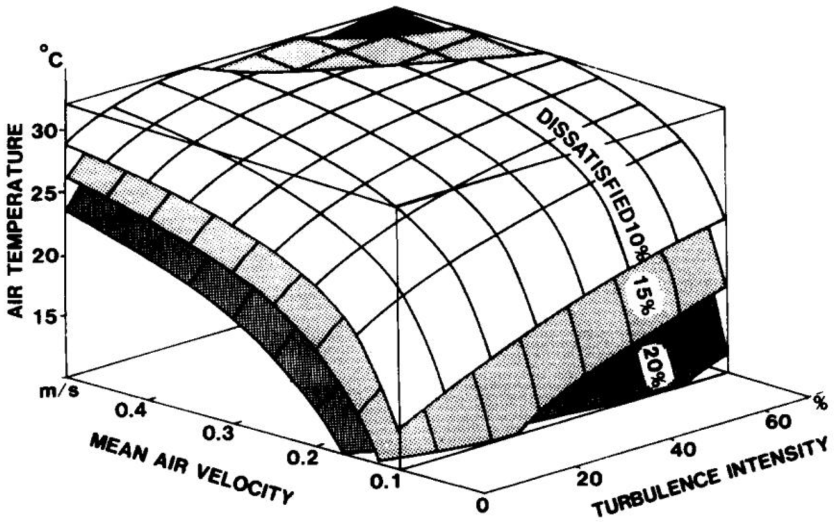
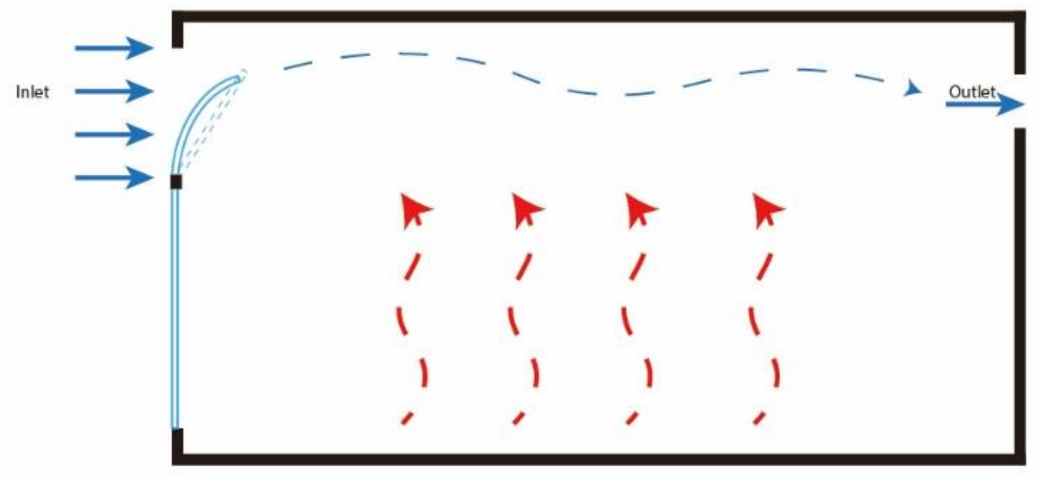


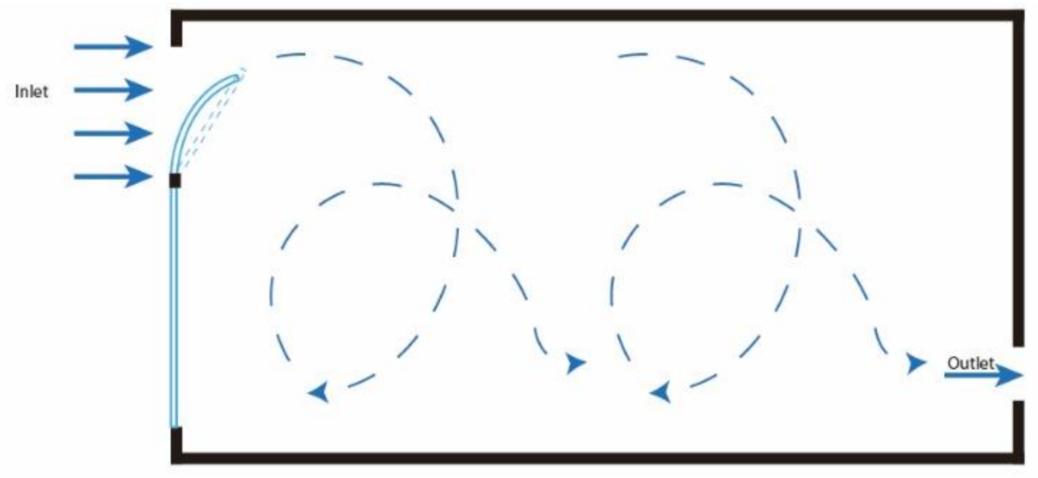
Fig. 19. A three-dimensional representation of the draught-risk model. The surfaces shown correspond to 10%, 15% and 20% dissatisfied respectively. The axes are turbulence intensity, mean air velocity and air temperature.

Source: (Fanger, 1988)

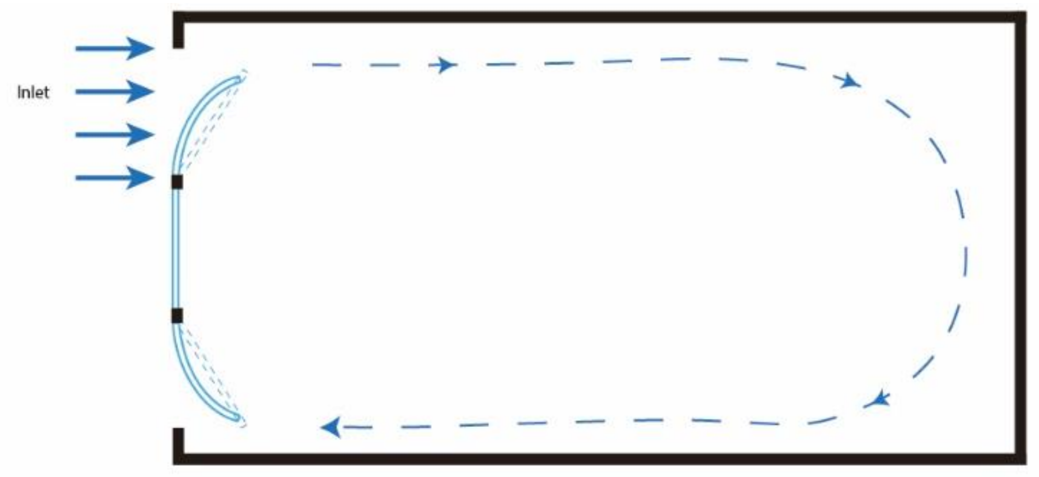
Standard room configurations



Air exhausting

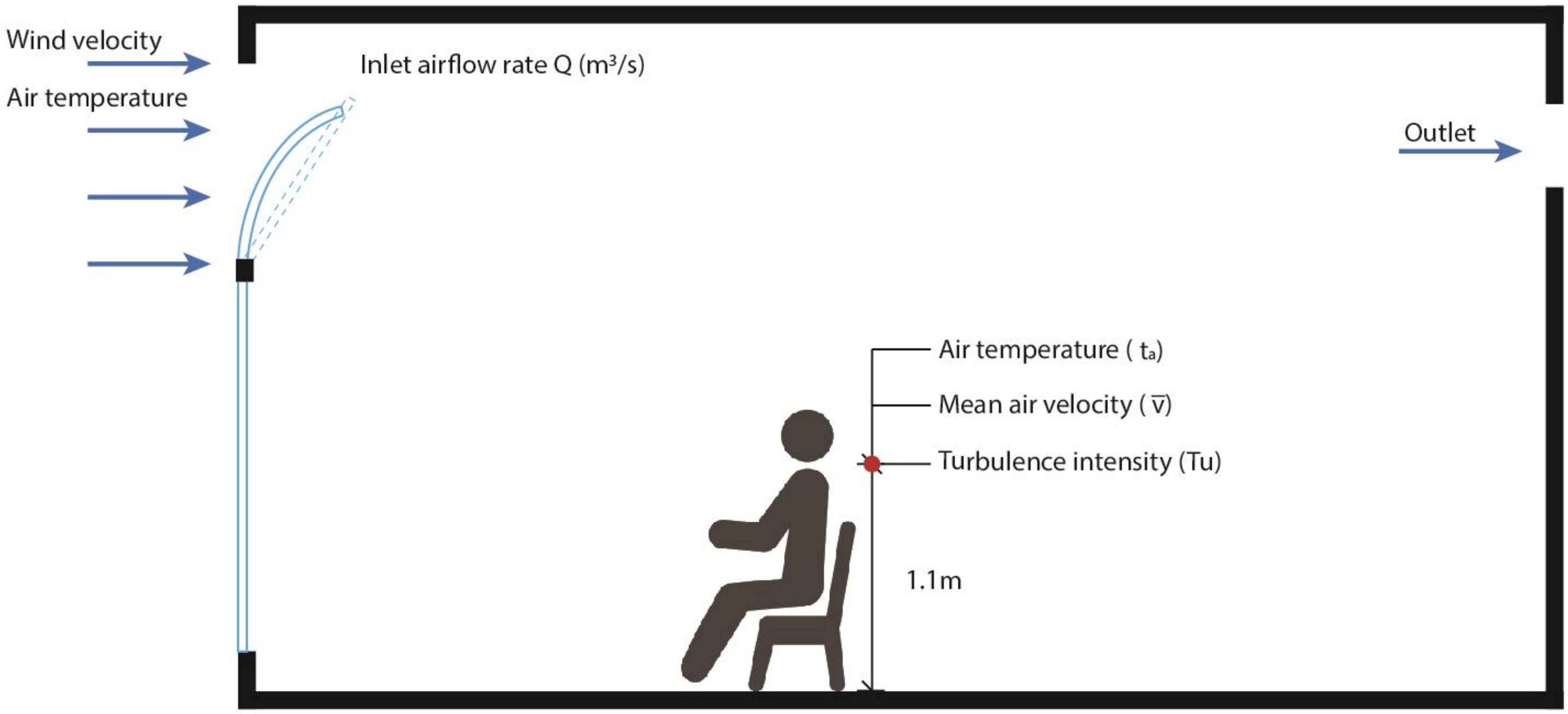


Air circulation



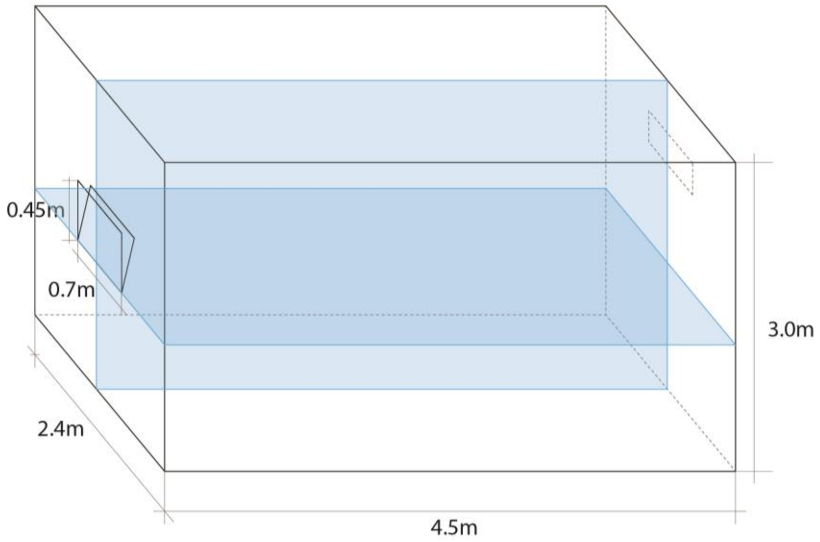
Single side ventilation

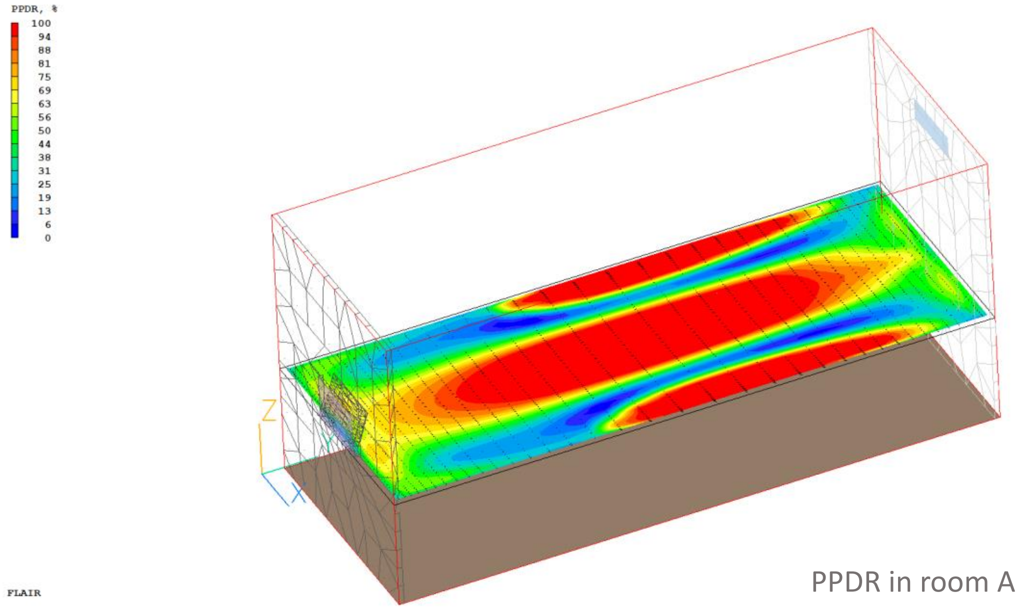
Standard room for simulation



Phoenics CFD simulation

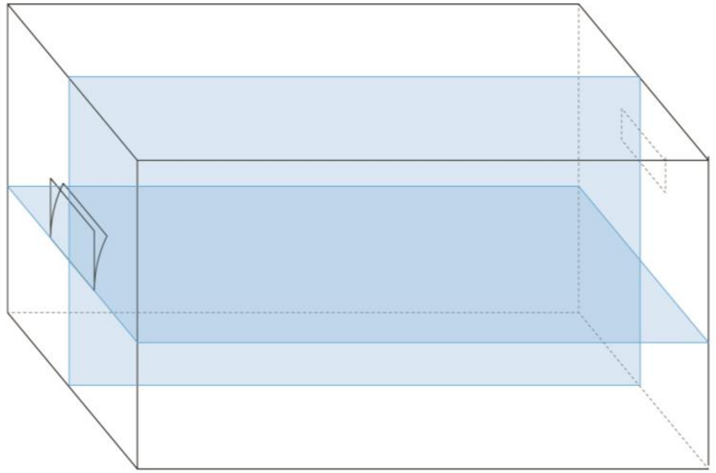
Room A

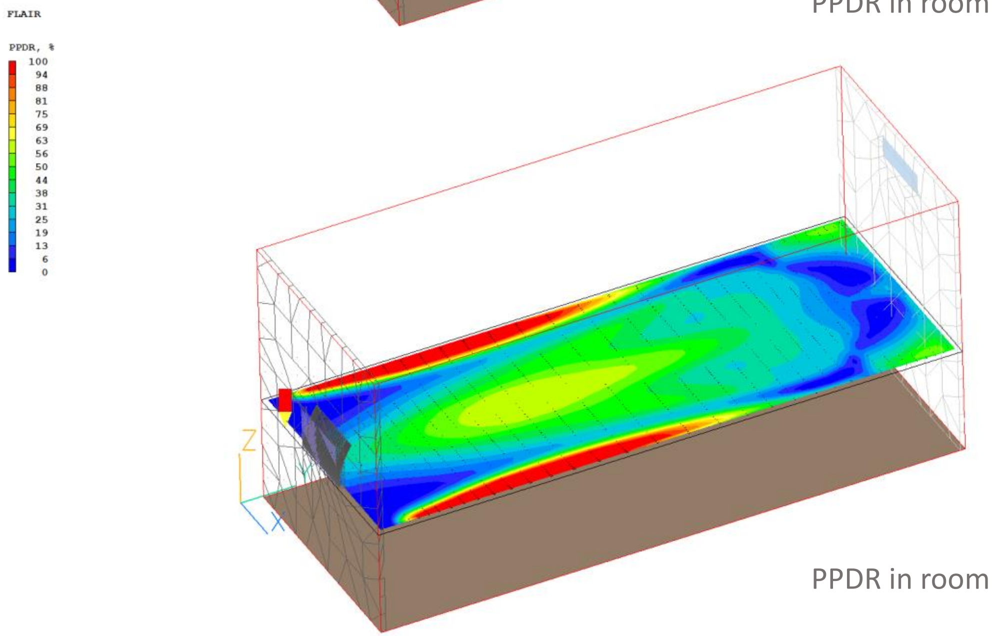




PPDR in room A

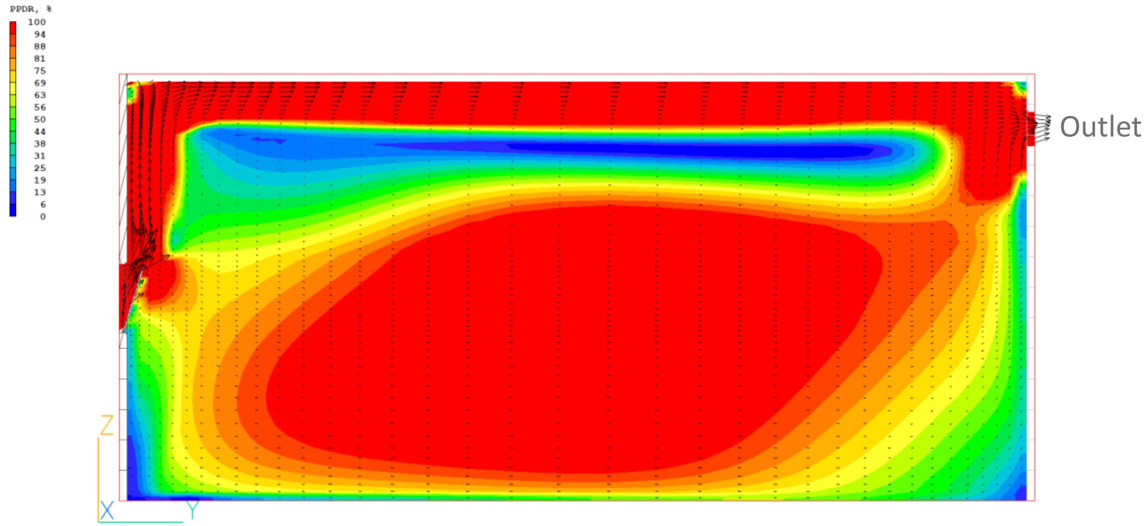
Room B



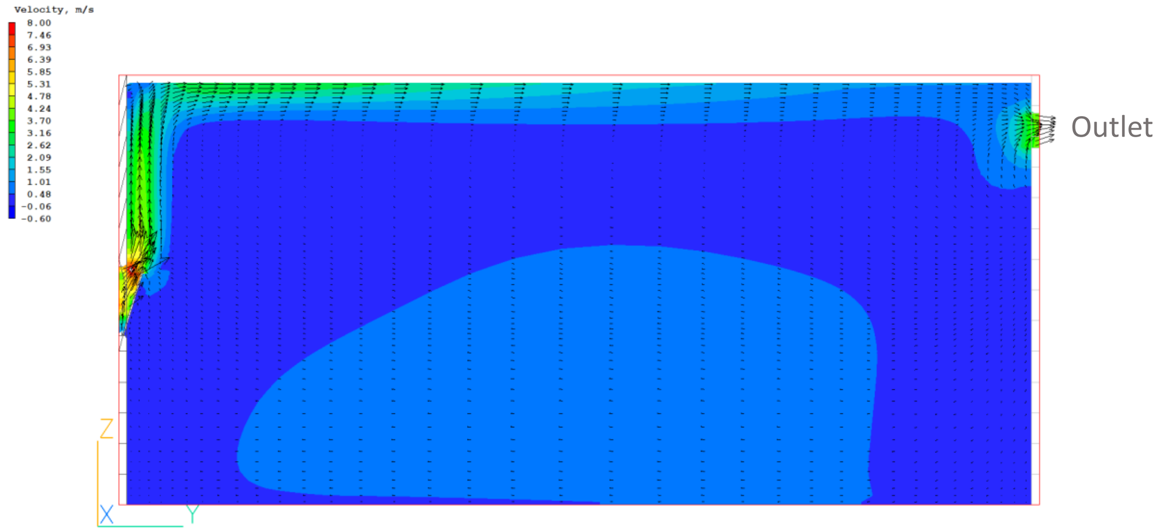


PPDR in room B

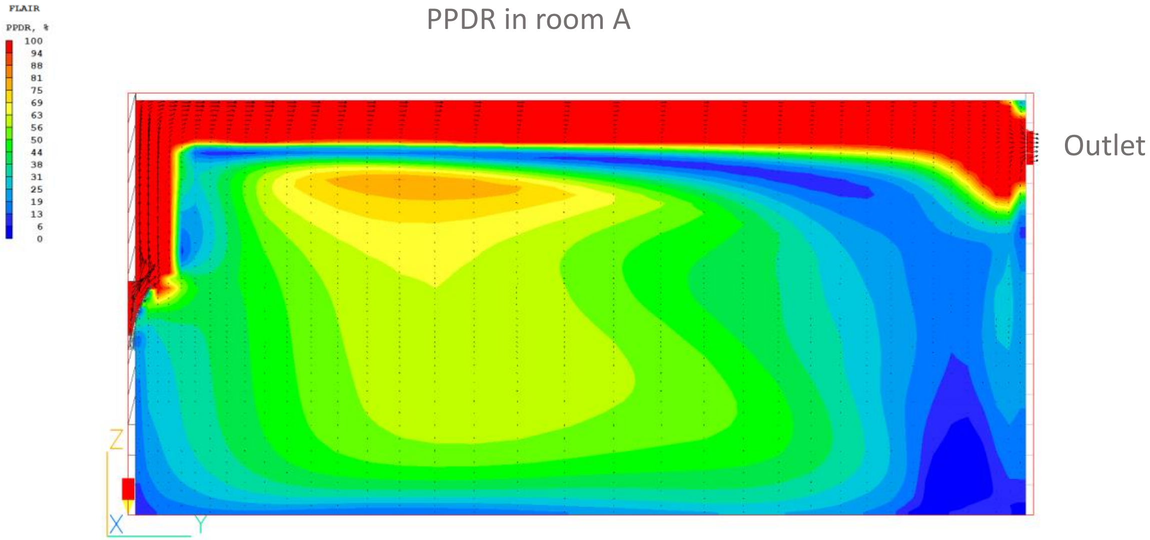
Phoenics CFD simulation



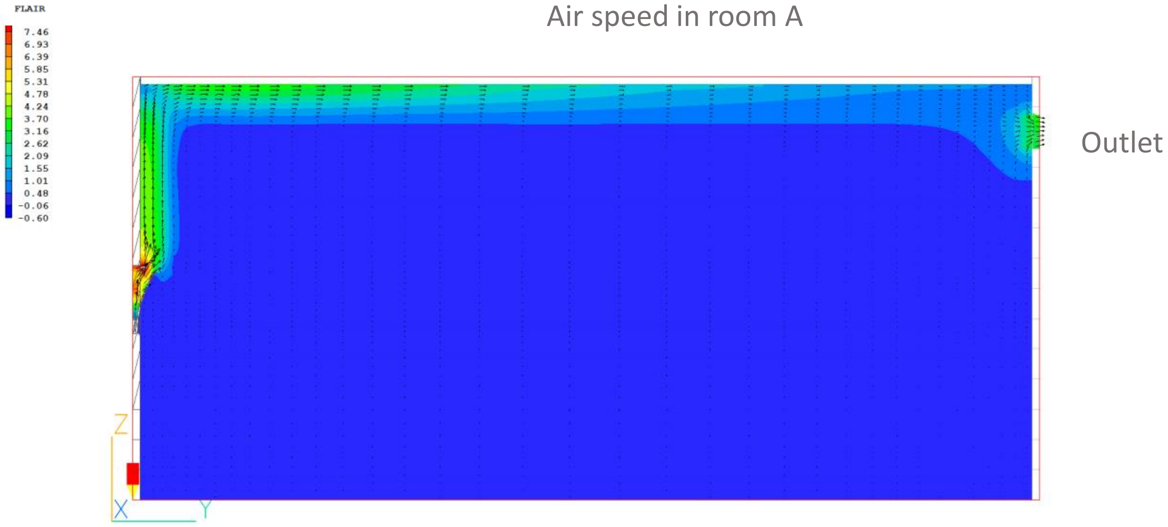
PPDR in room A



Air speed in room A

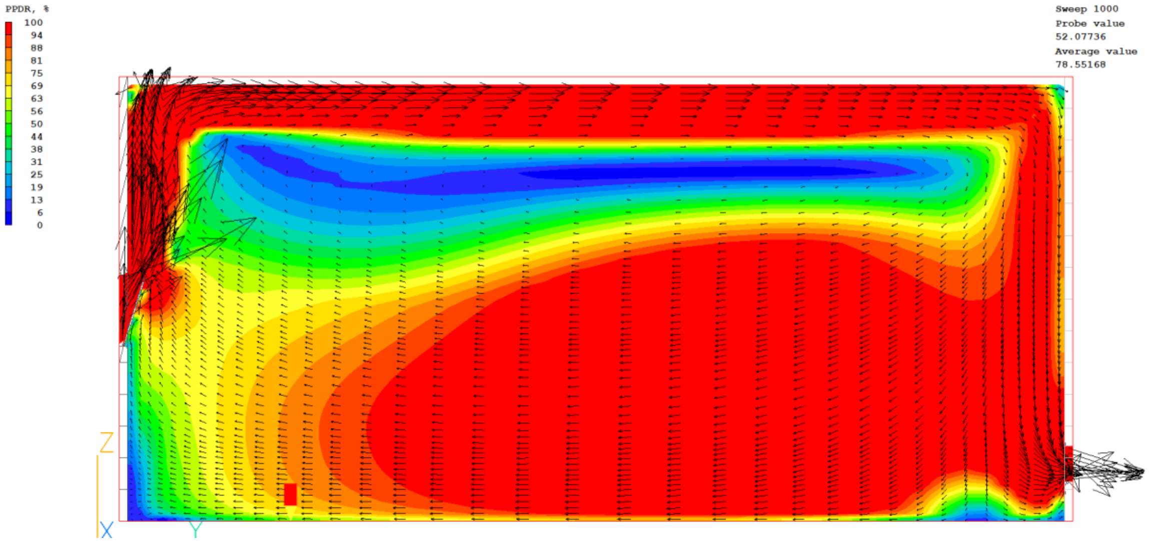


PPDR in room B

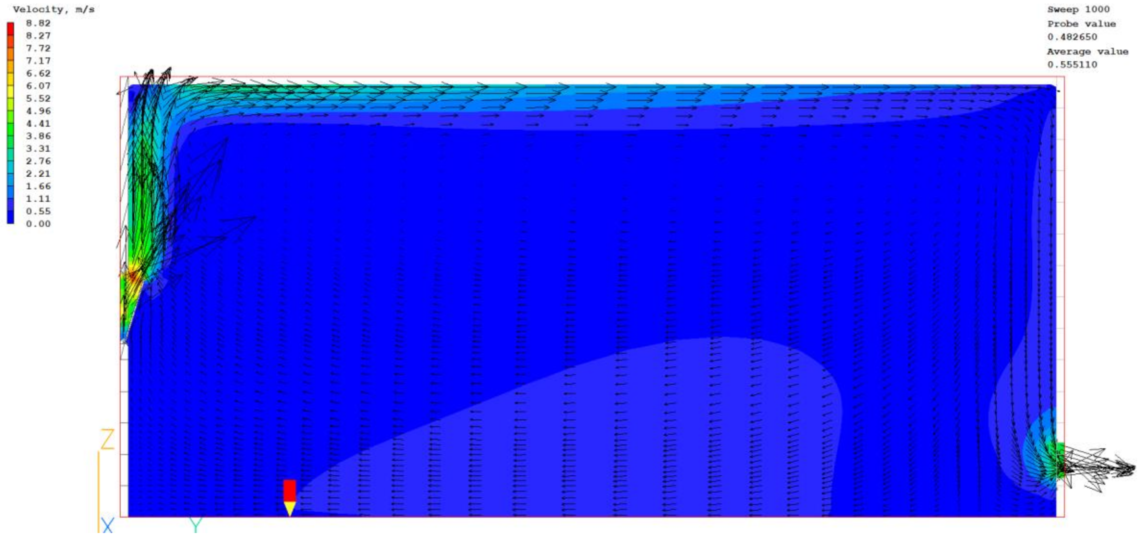


Air speed in room B

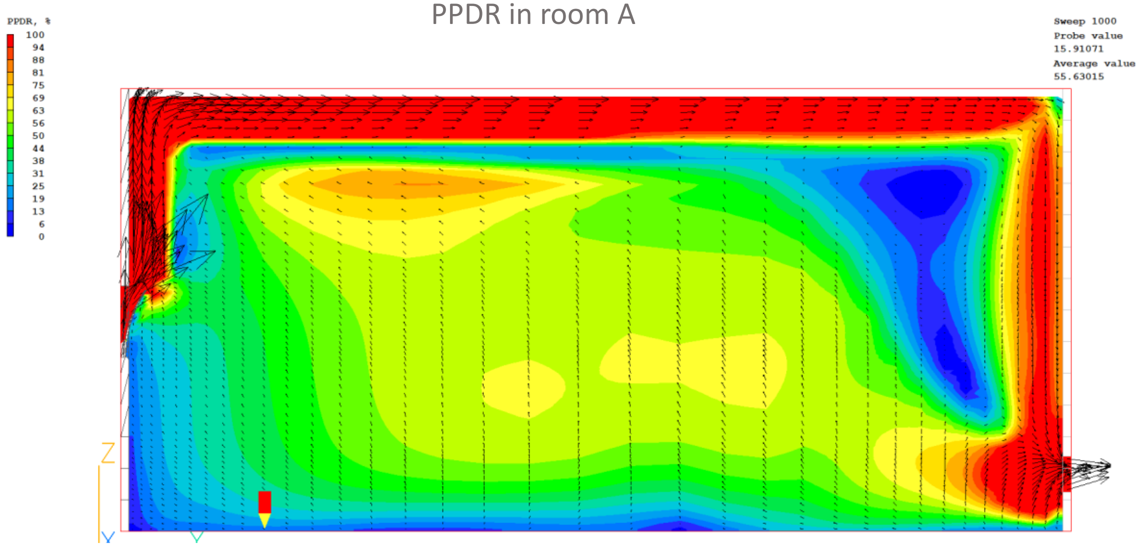
Phoenics CFD simulation



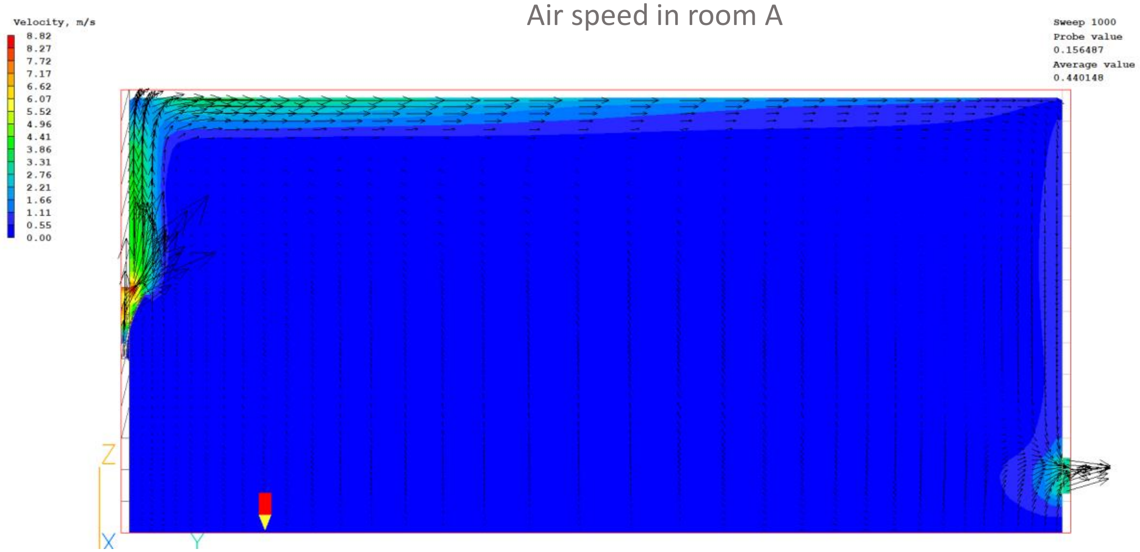
PPDR in room A



Air speed in room A



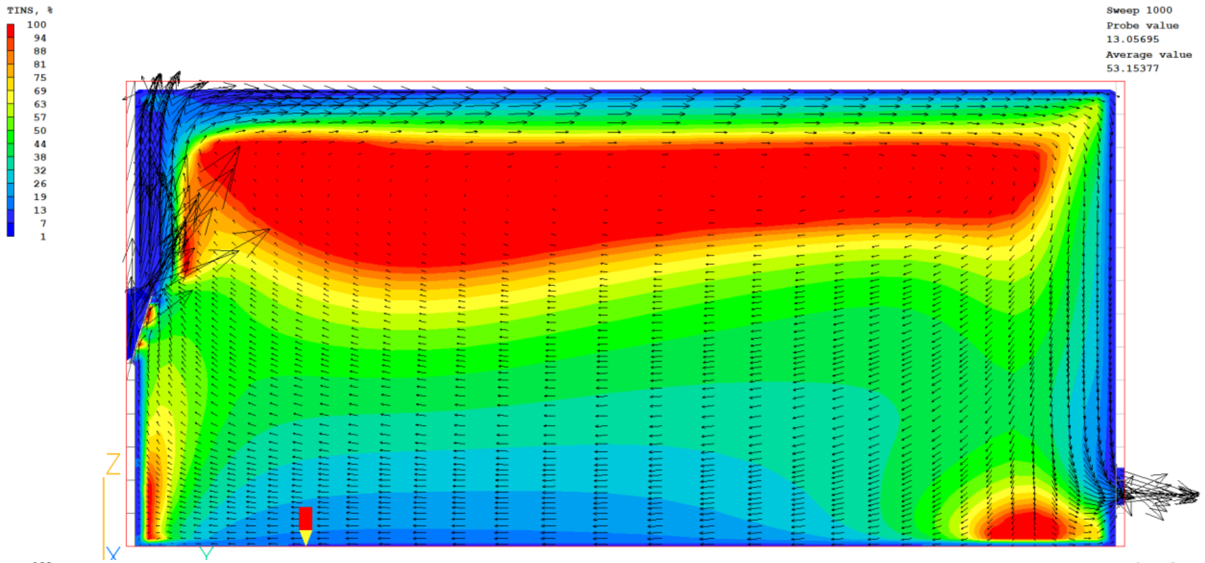
PPDR in room B



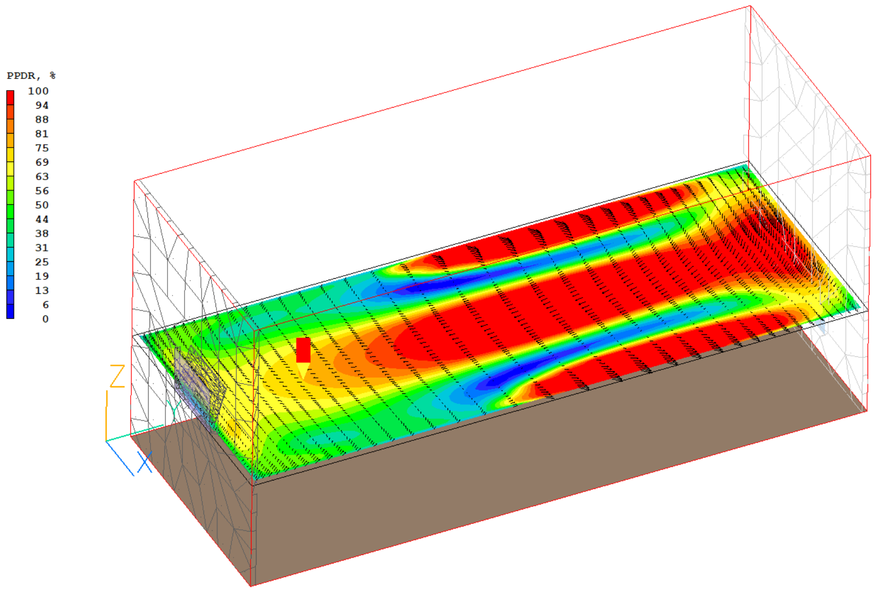
Air speed in room B

TU Delft Delft University of Technology

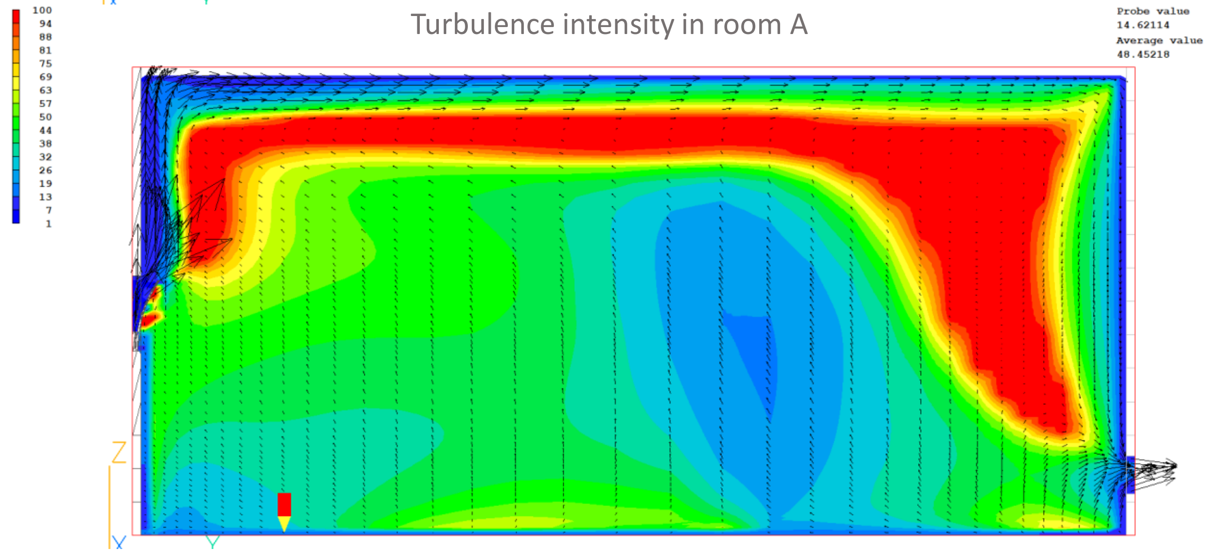
Phoenics CFD simulation



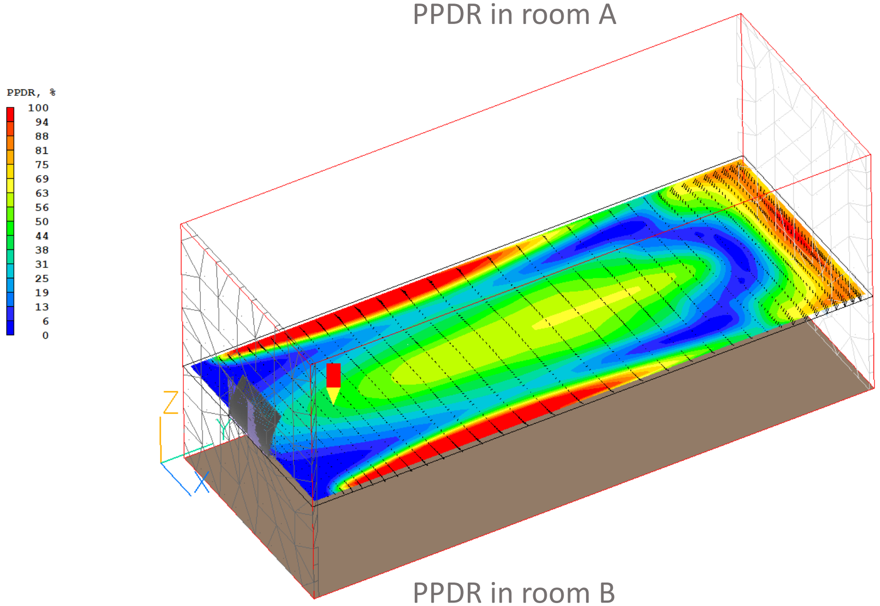
Turbulence intensity in room A



PPDR in room A



Turbulence intensity in room B

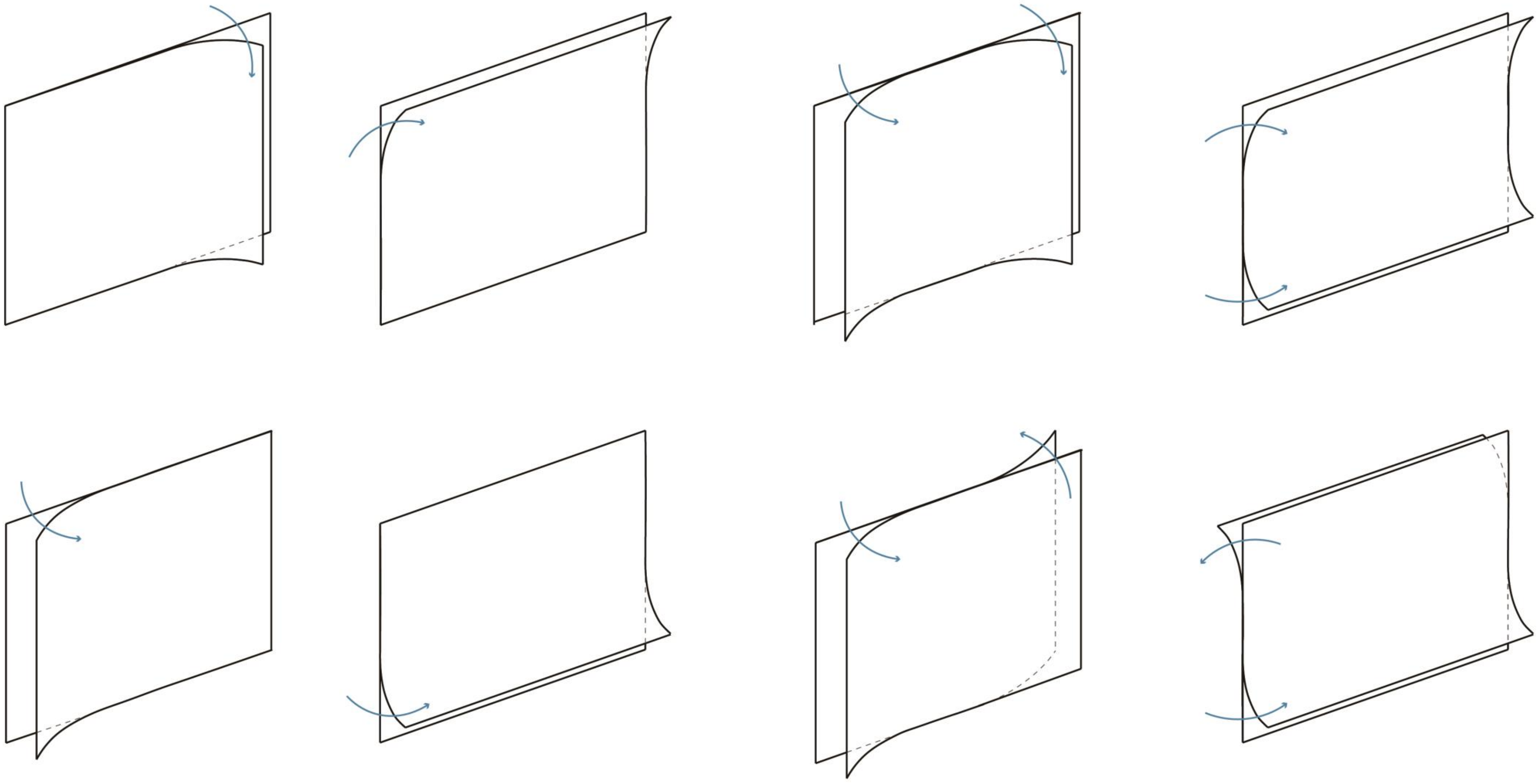


PPDR in room B

Part 5.2

Benchmark Exoskeletwindow

Window opening configurations

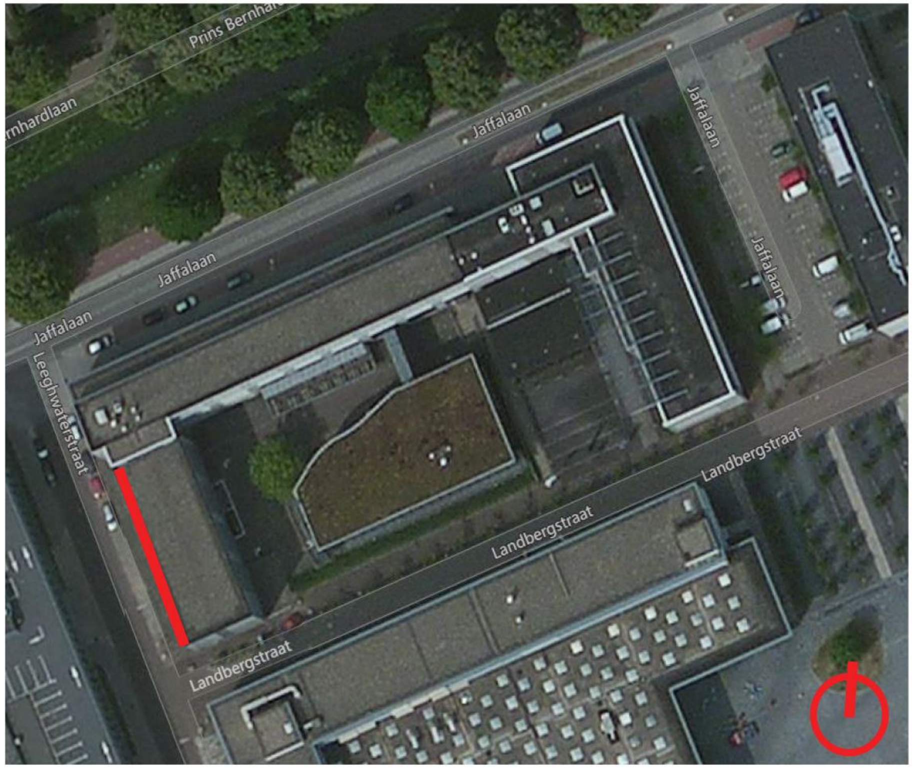


Product features

- Smooth air flow rate changing ratio
- Adaptive hinge system
- Low maintenance compared to kinetic façade
- Easy to control and measured
- Meet different architecture function and aesthetic

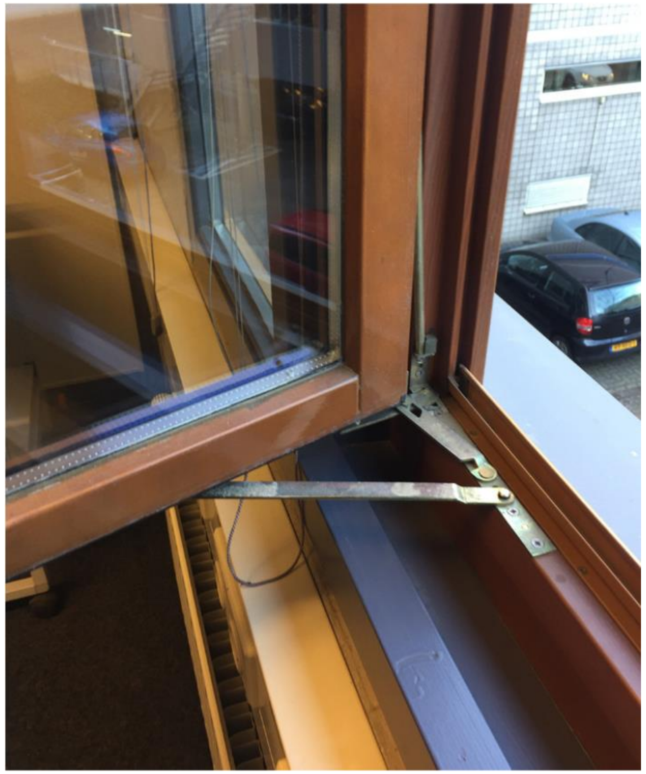
Part 5.3

Case study

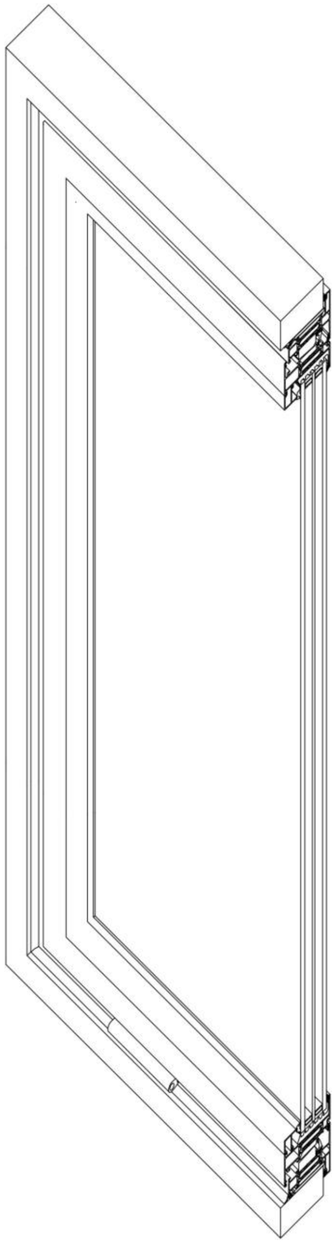


Google map view

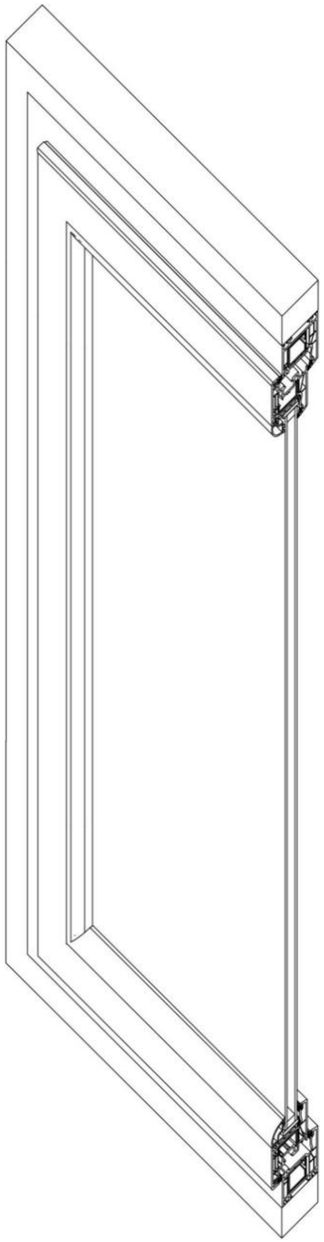
TPM Building facade



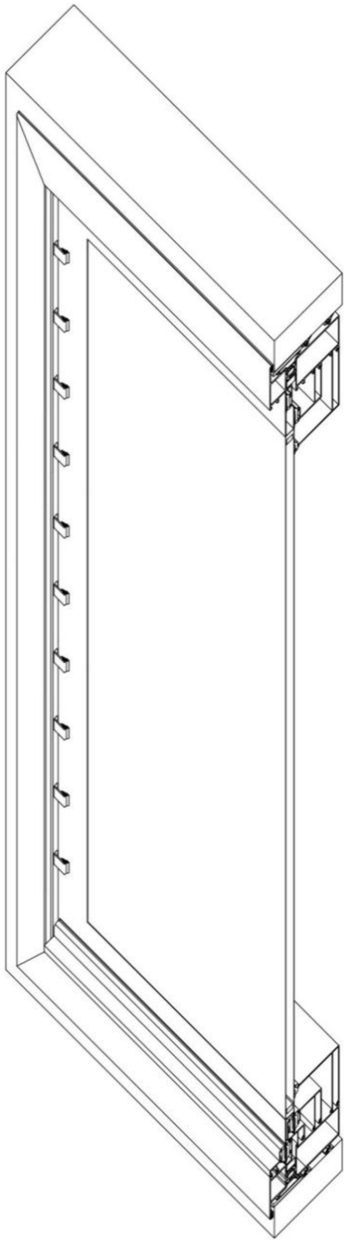
Window hinge system



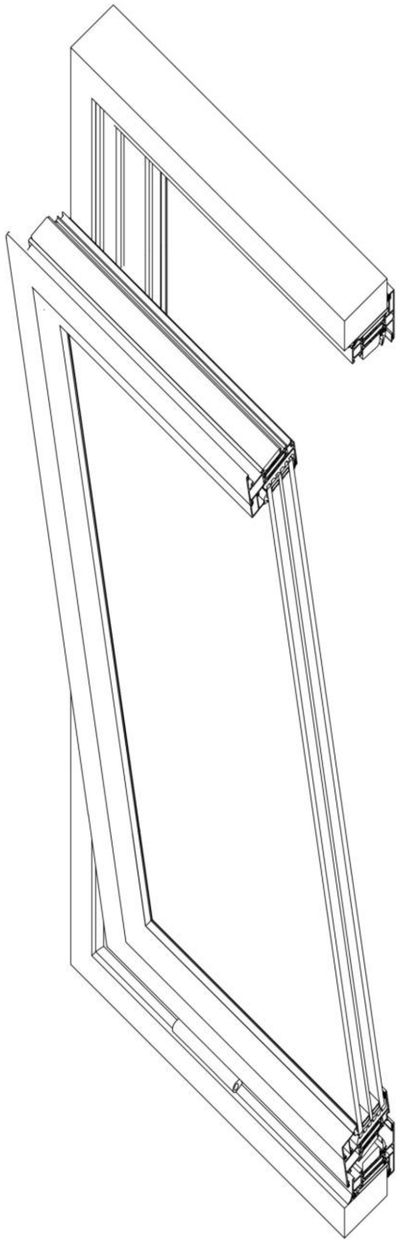
RT 82 HI+



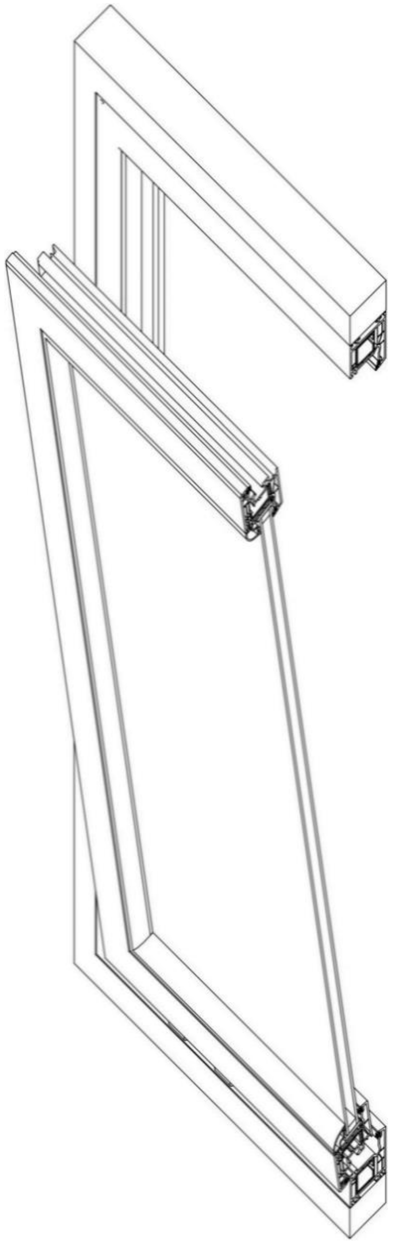
IDEAL 5000



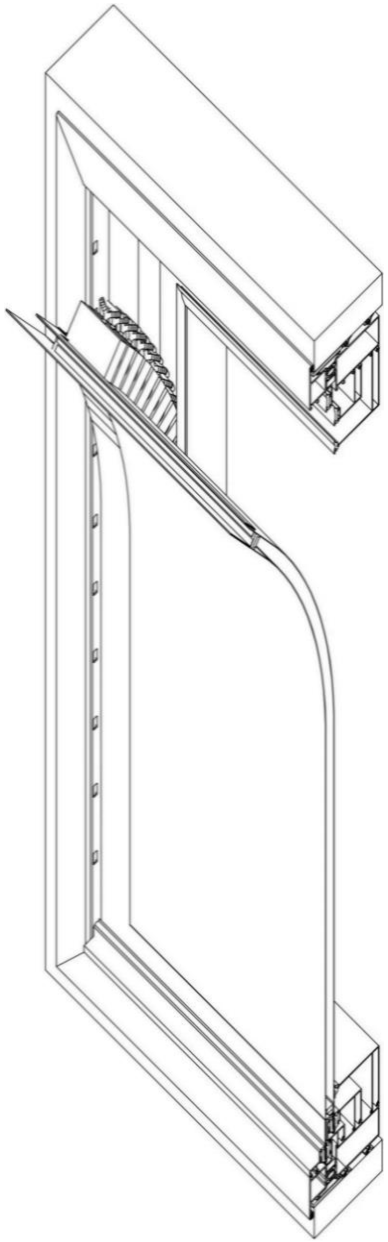
Exoskeletwindow



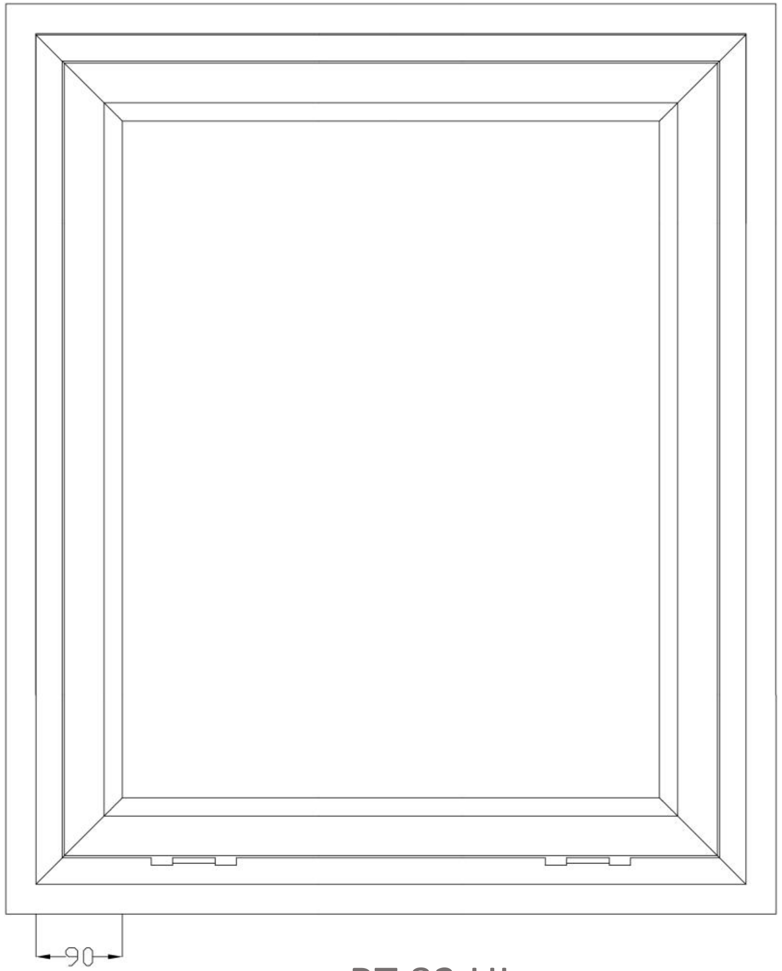
RT 82 HI+



IDEAL 5000



Exoskeletwindow



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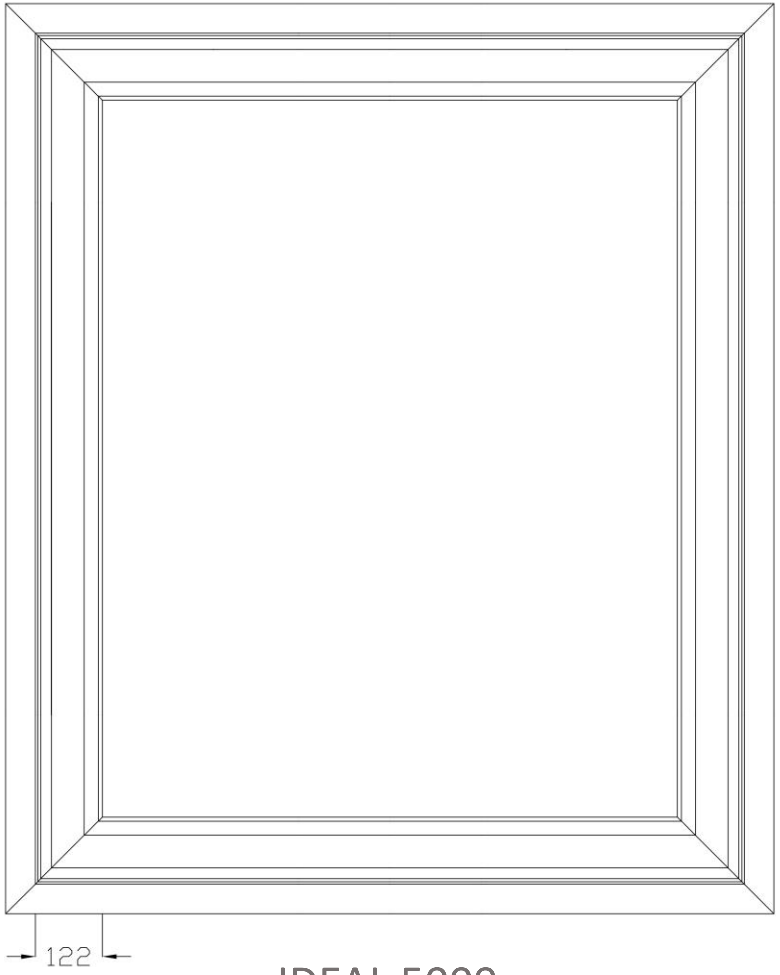

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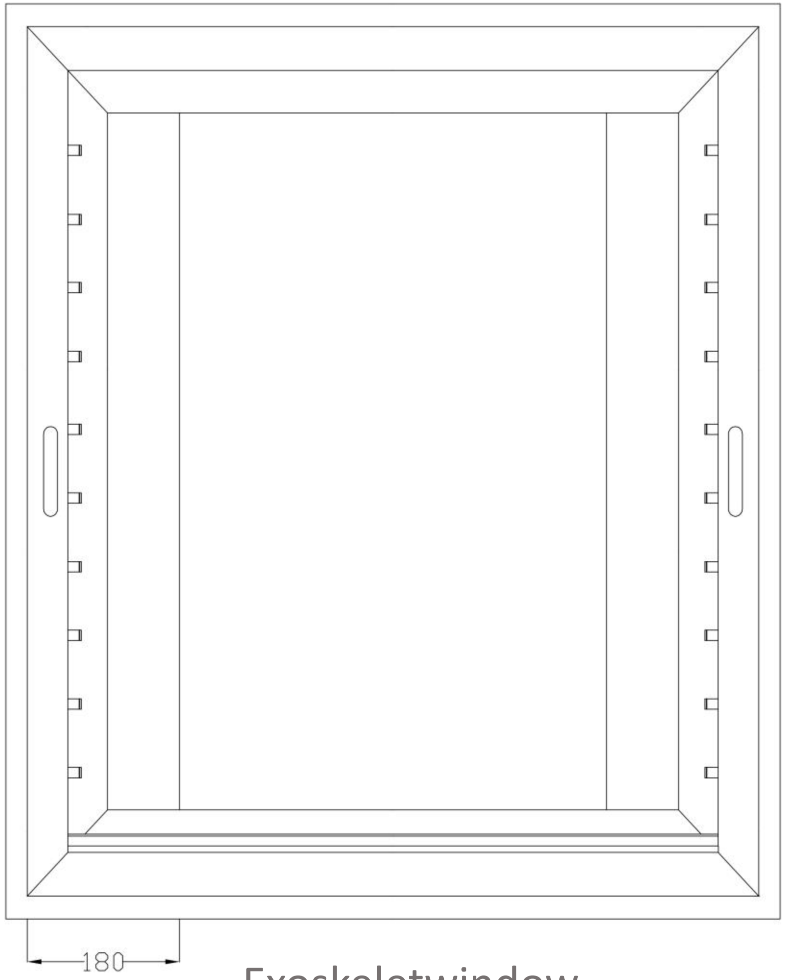


Exoskeletwindow

Future window

Future window

Part 6

Conclusion and discussion

Advantage

- Automatically indoor environment improving by responding to the external environment
- No motors and mechanical equipment
- Lightweight
- Potential on geometry generation

Disadvantage and limitation

- Low insulation value
- Too large window frame
- The low durability of rubber material
- Risk of delamination between silicone and thin glass

Conclusion: Not ready for the market, but worth further researching

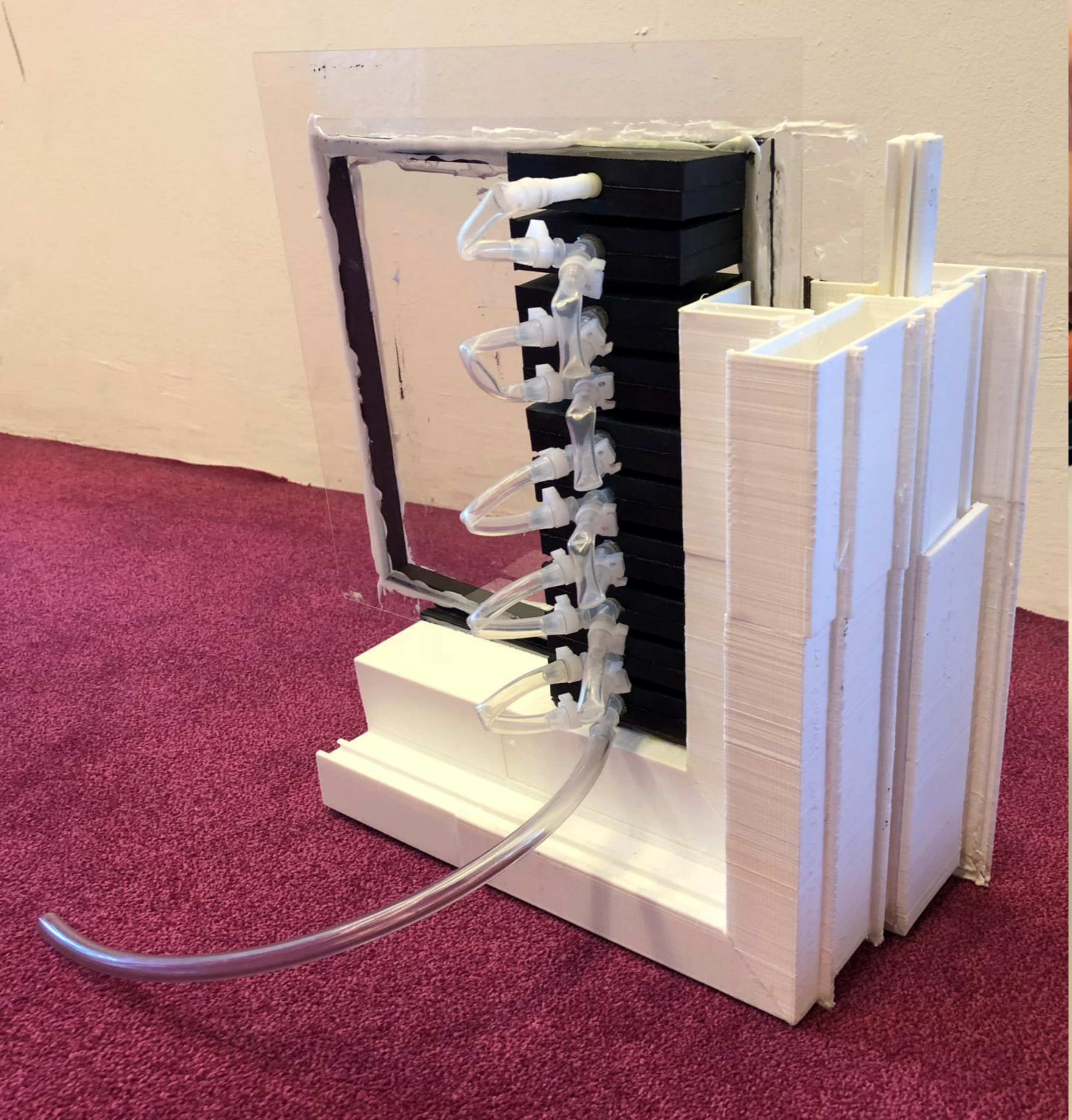
Limitation of research

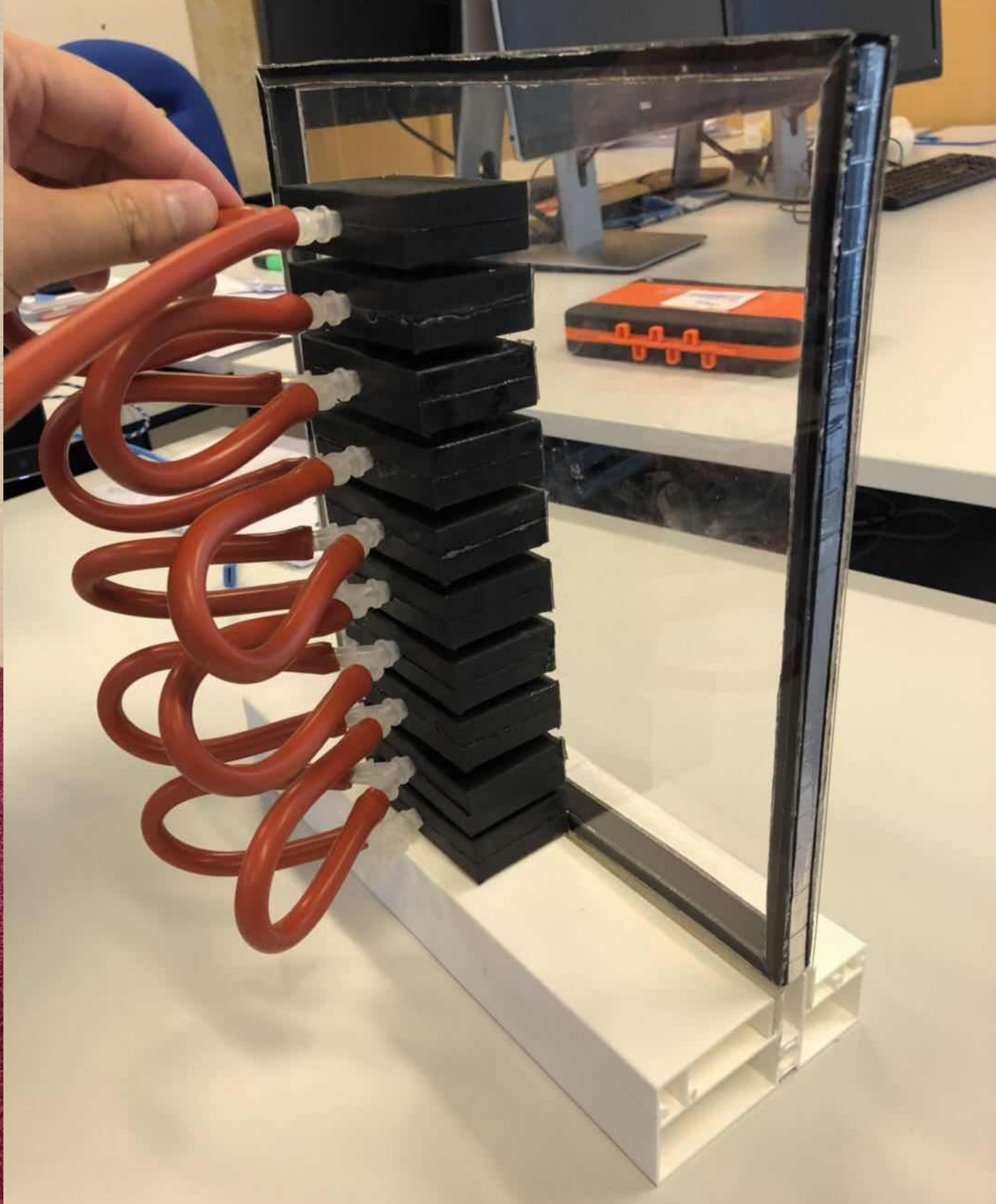
- Wind load and wind direction effect on structure are not considered
- Rubber material biaxial and uniaxial testing for Abaqus simulation
- CFD analysis in different configurations
    - Different window opening size
    - Different window locations
    - Different outlet locations

Future research

- Geometry generation
- Effects of wind load and direction
- Window location and opening size optimization to improve indoor comfort
- SPA material exploration
- Sun shading integration

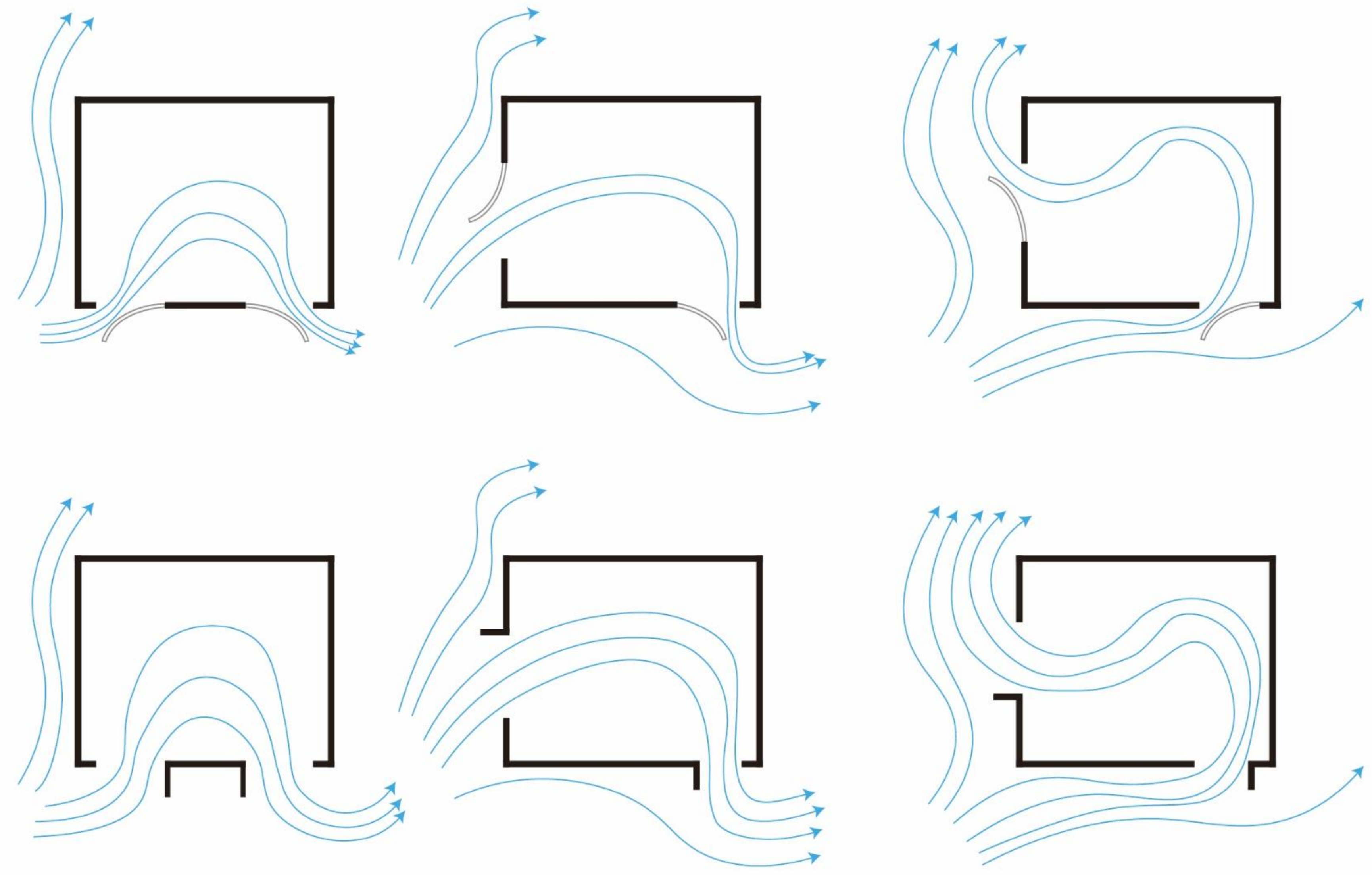
Physical model





Exploration

Wing wall configurations

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