Flexible Transparency With Smart Materials

A study on adaptive thin glass façade developed with SMA

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Tendency towards SMART, LIGHT, TRANSPARENT design solutions is growing

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Ultra-Thin Glass

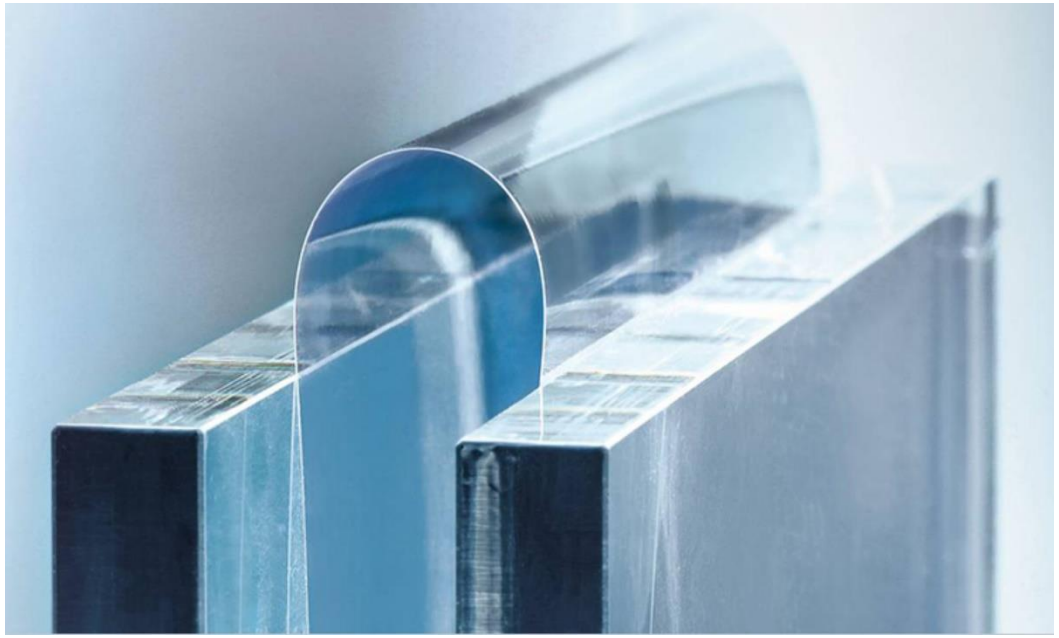
Thin glass→ t < 2 mm

Ultra thin glass→ t < 0.1 mm

Tendency towards SMART, LIGHT, TRANSPARENT

design solutions is growing

Ultra-Thin Glass



Tendency towards SMART, LIGHT, TRANSPARENT design solutions is growing

Smart Materials

Breathing Facade

Adaptiveness

|

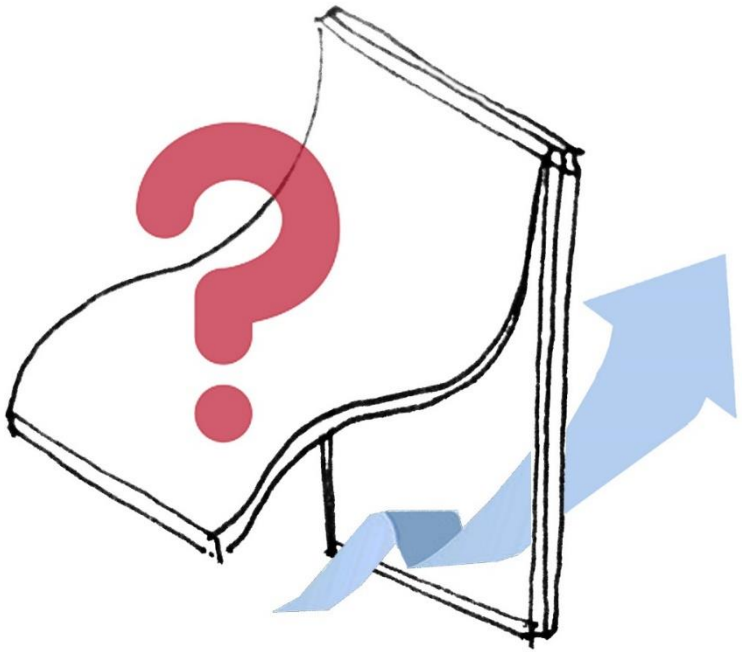
Thin Glass Deformation

|

Actuator

Research Question

How can a thin glass skin be applied as an adaptive façade developed by smart materials?



Research Structure

Literature Review

Design Exploration

Material Analysis

Practical Feasibility

Case Study

Conclusion

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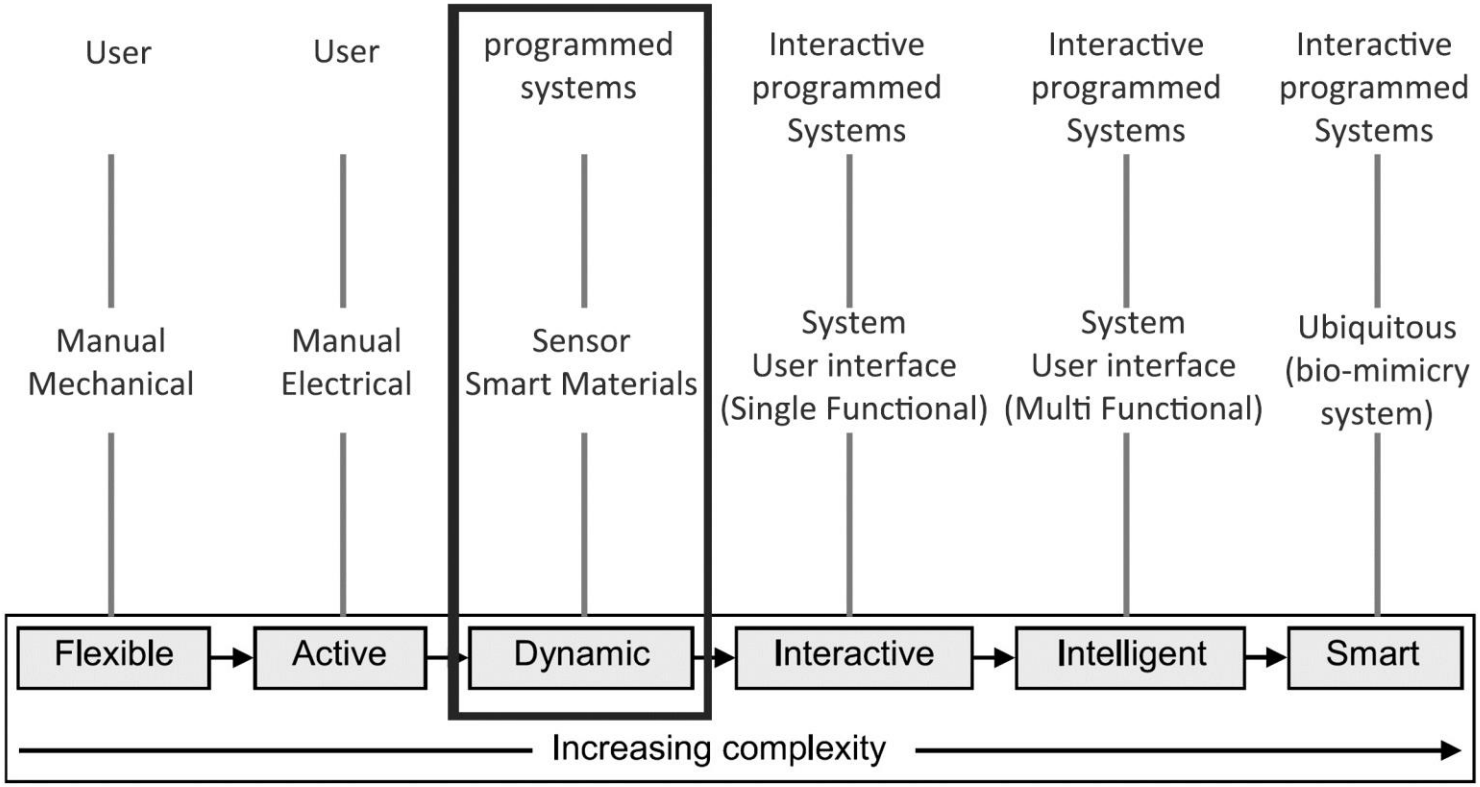
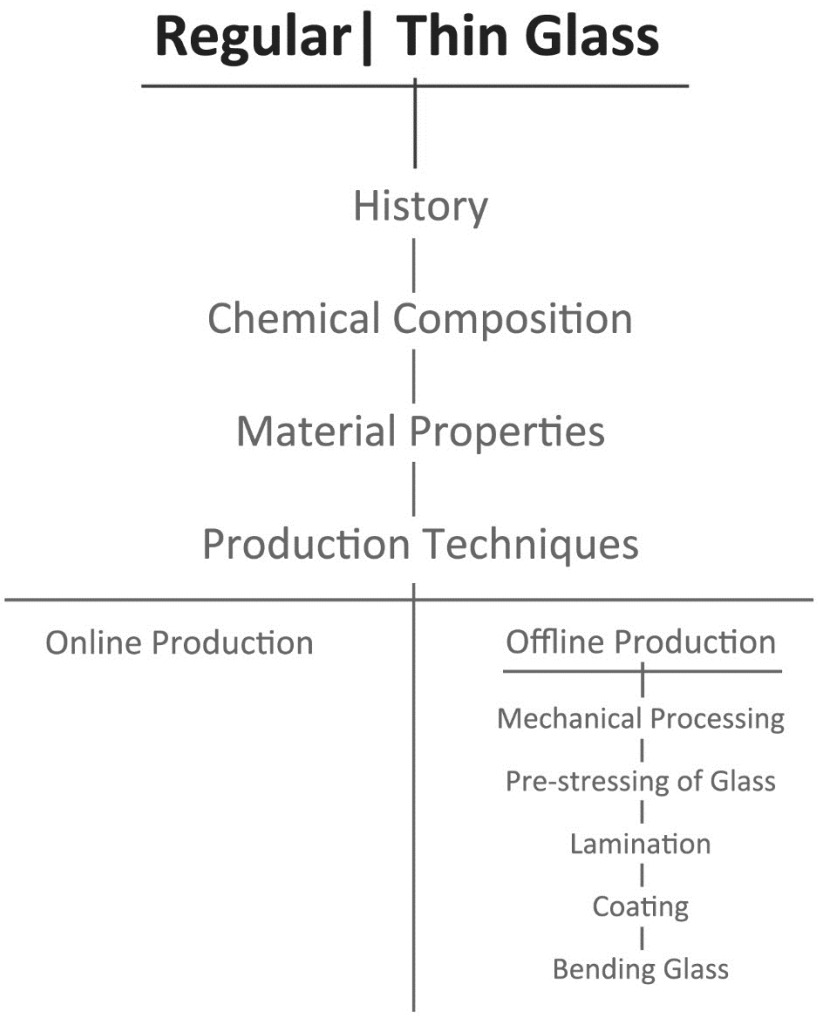
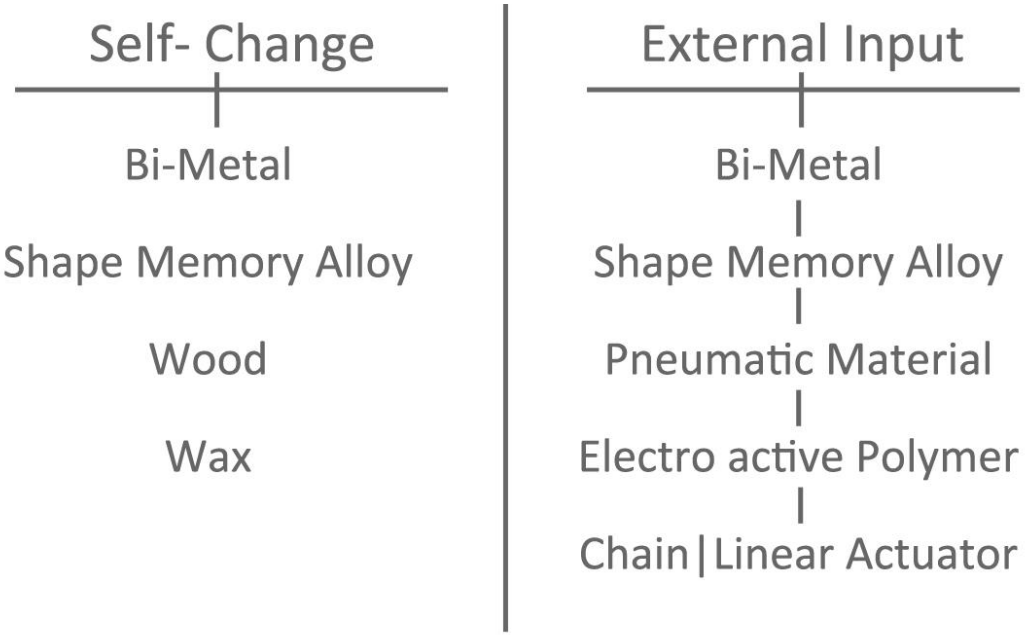
Breathing System



Glass


Regular| Thin Glass
History
Chemical Composition
Material Properties
Production Techniques
Online Production
Offline Production
Mechanical Processing
Pre-stressing of Glass
Lamination
Coating
Bending Glass

Actuator System



Actuator System

BI-Metal

Actuator System

Shape Memory Alloy

Actuator System

Wax

Actuator System

Wood

Actuator System

Pneumatic

Actuator System

Linear| Chain Actuator

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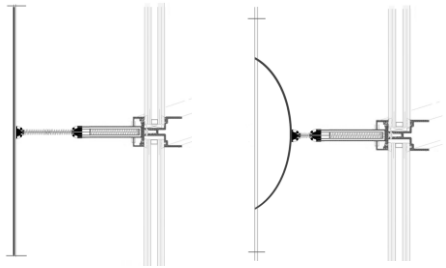
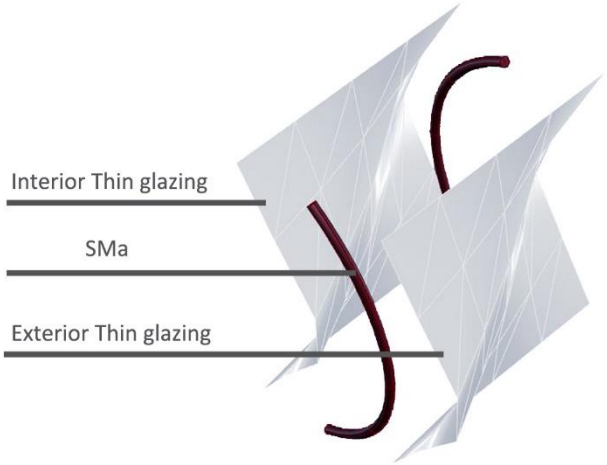
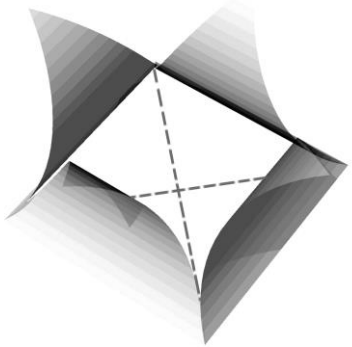
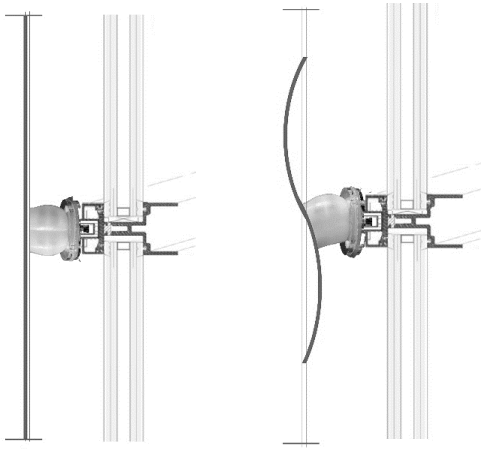
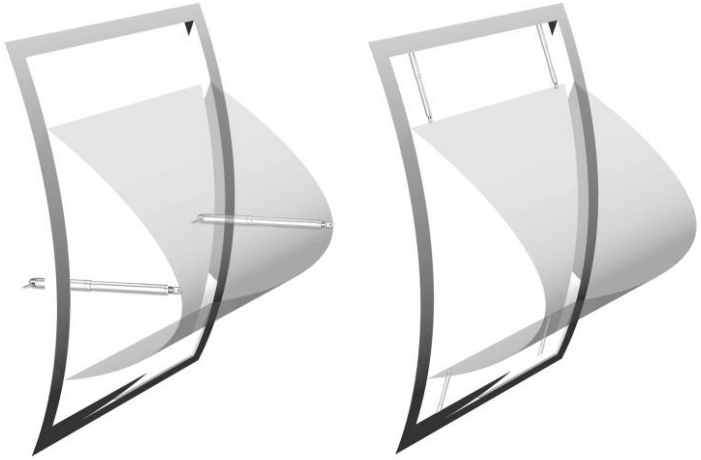
Design Ideas



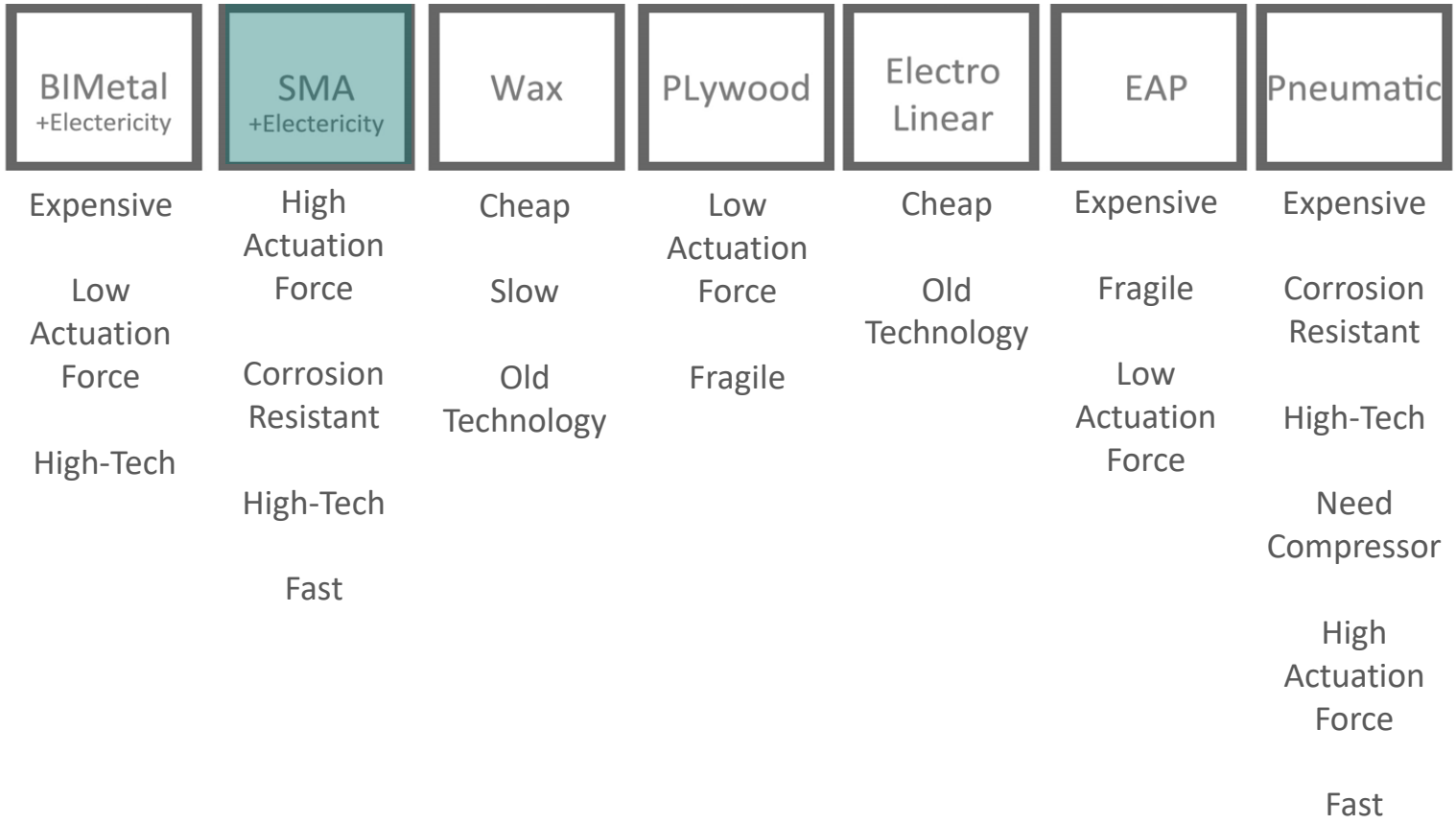








Selected Actuator System



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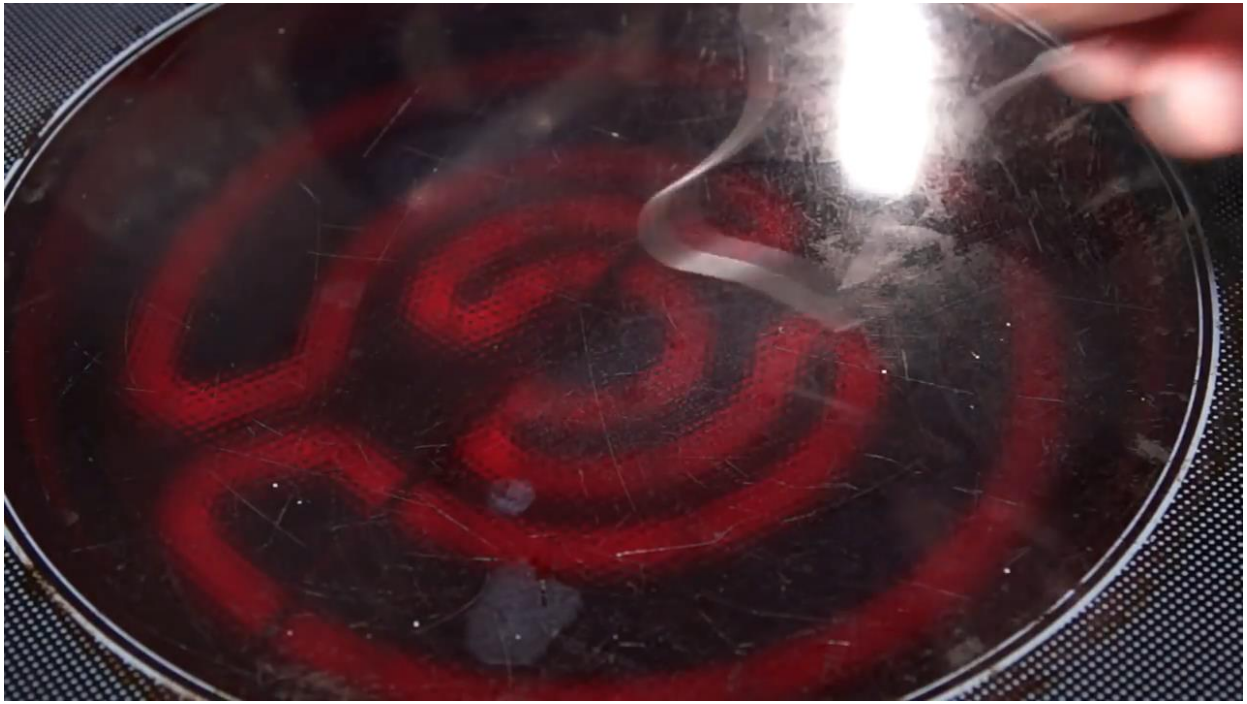
SMA Behavior

Super Elasticity

SMA Behavior

Super Elasticity
Shape Memory Effect



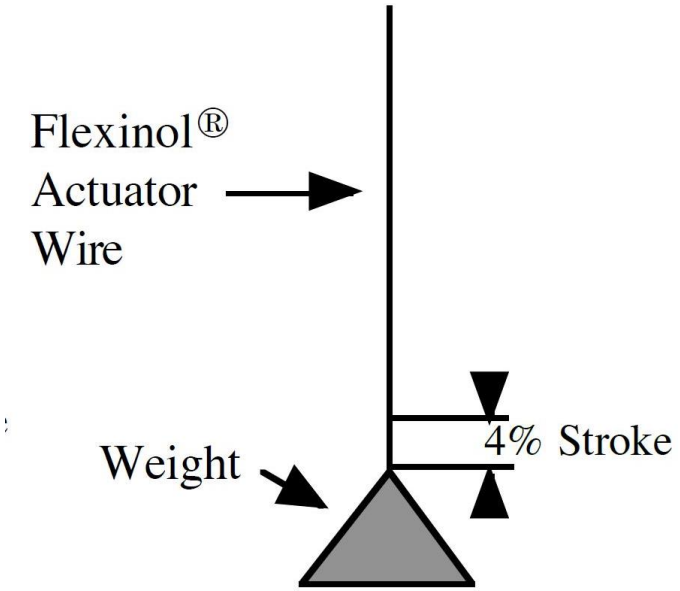
SMA Selection

Flexinol

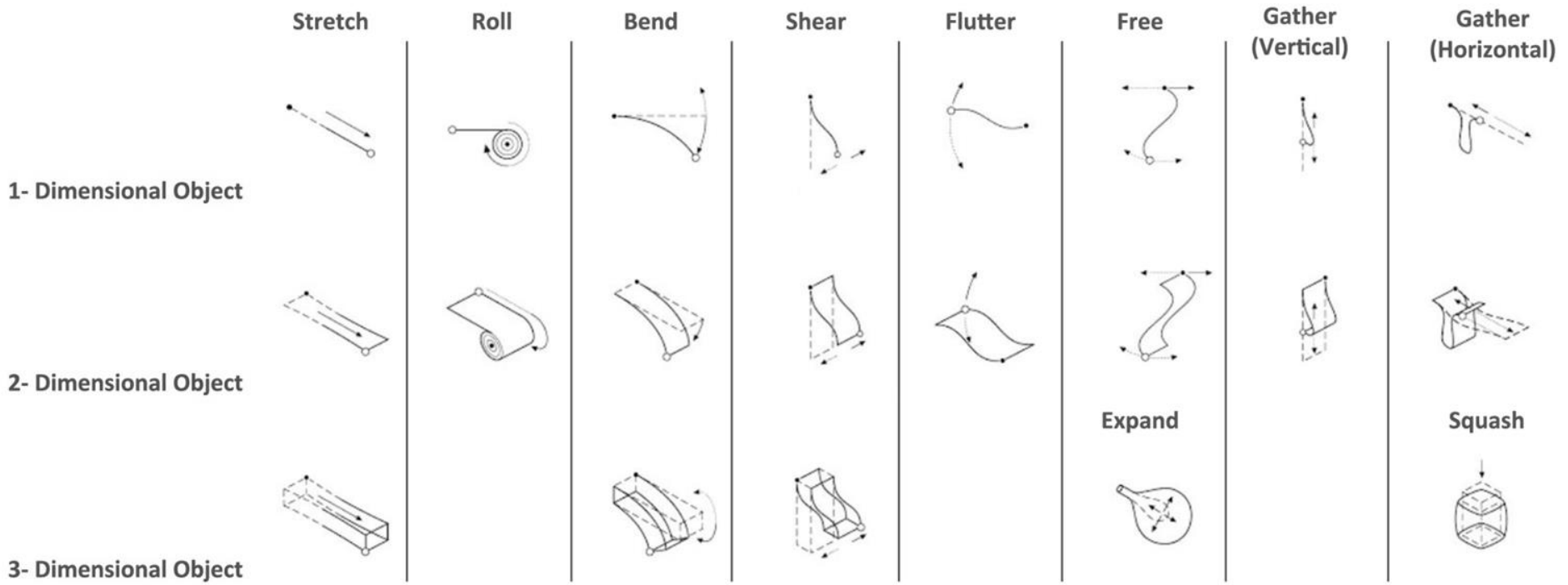
3-5 % stroke

Need no training

Linear Motion



Types of Movement



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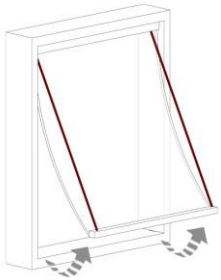
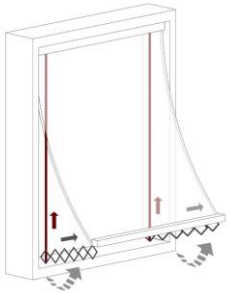
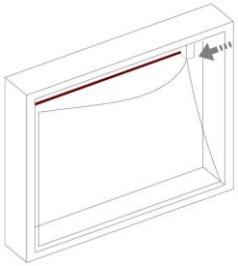
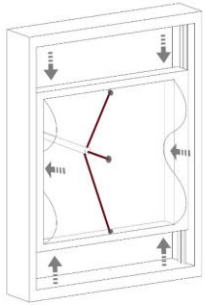
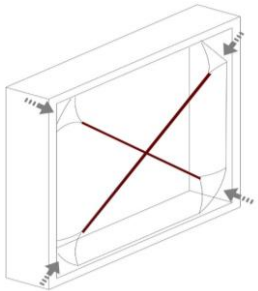
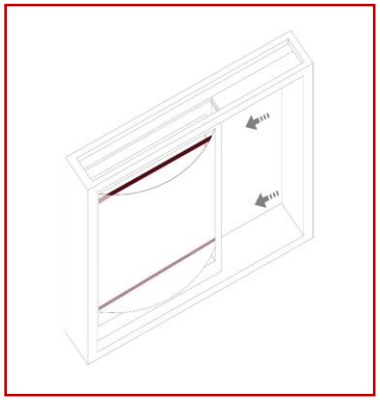
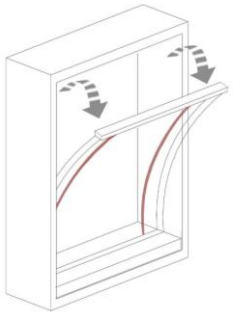
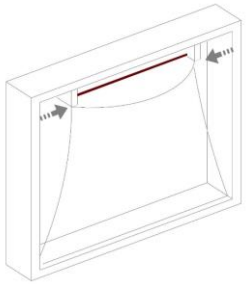
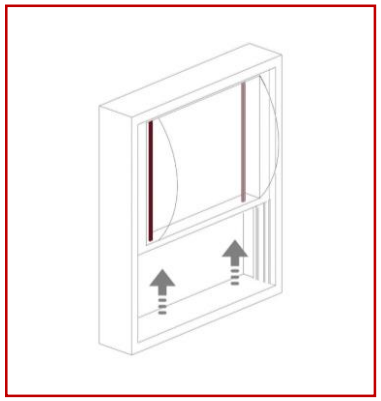
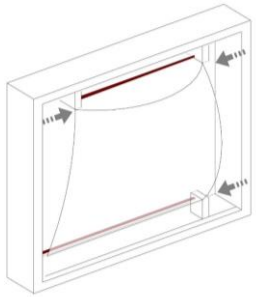
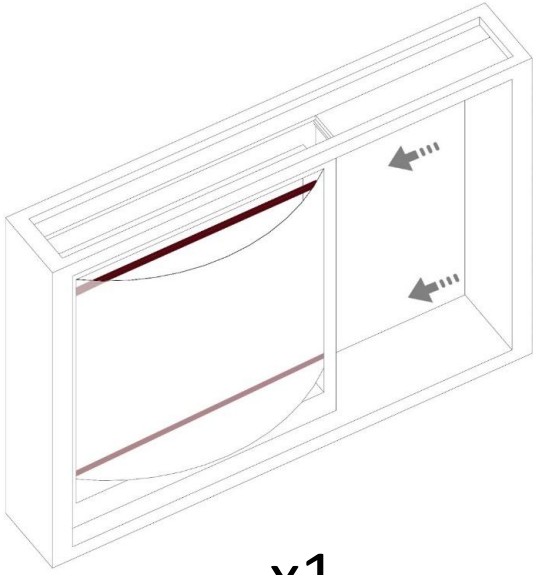
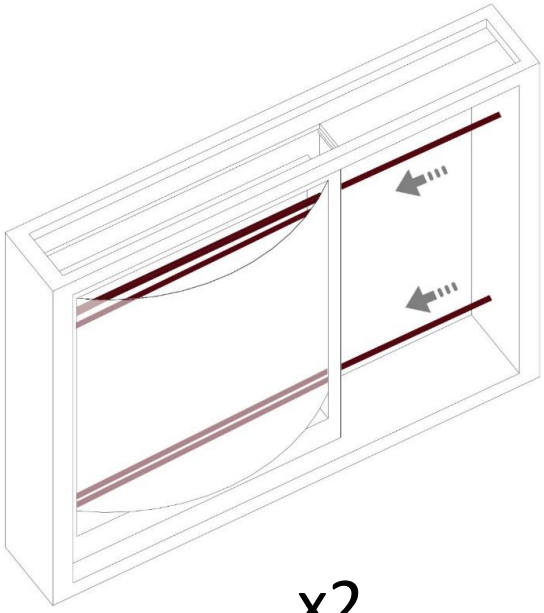











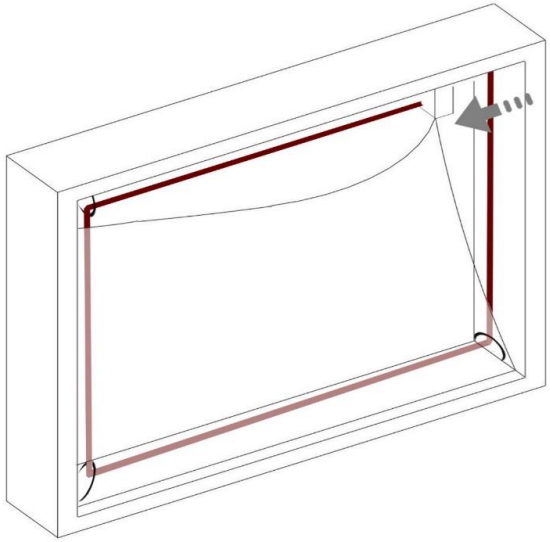
Stroke



x1



x2



x4

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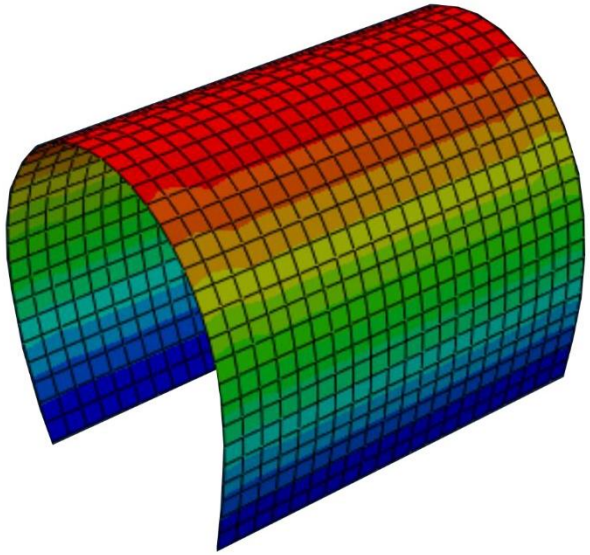
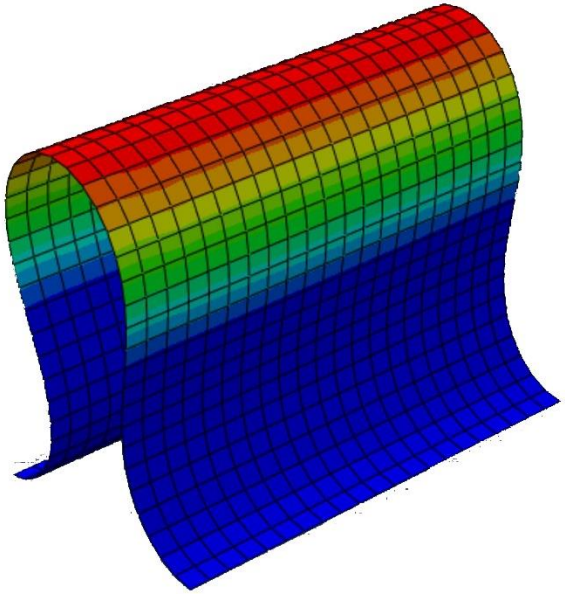
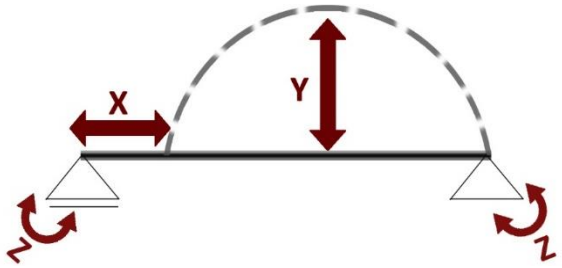
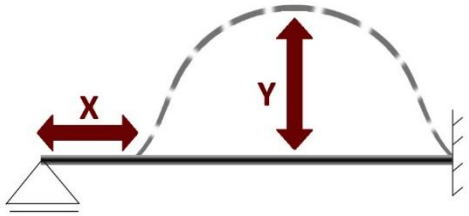
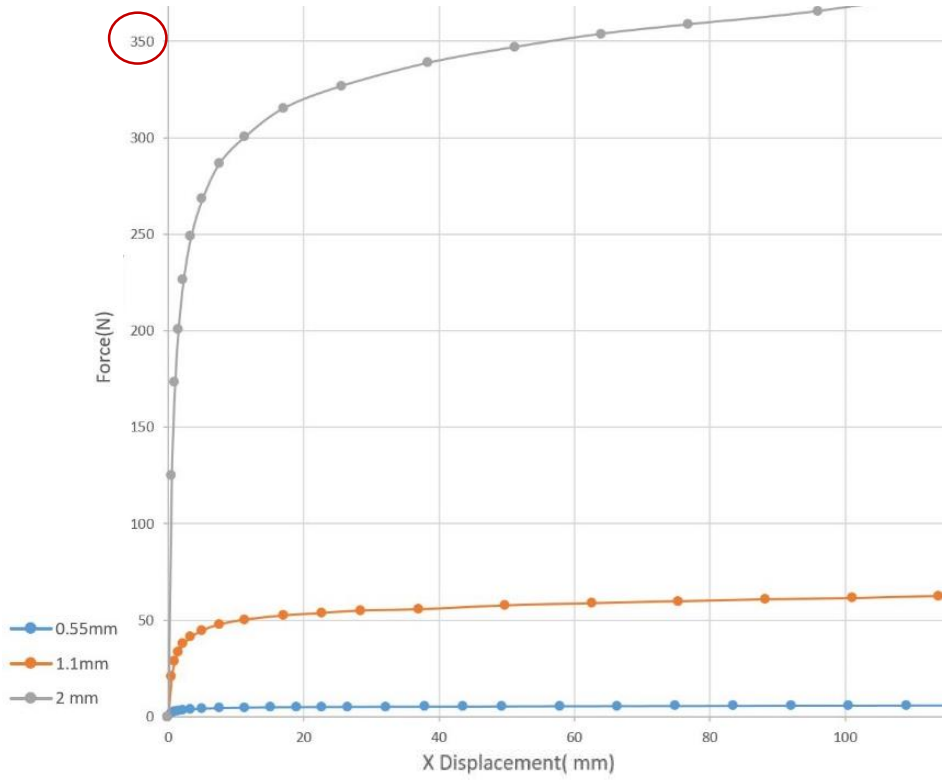


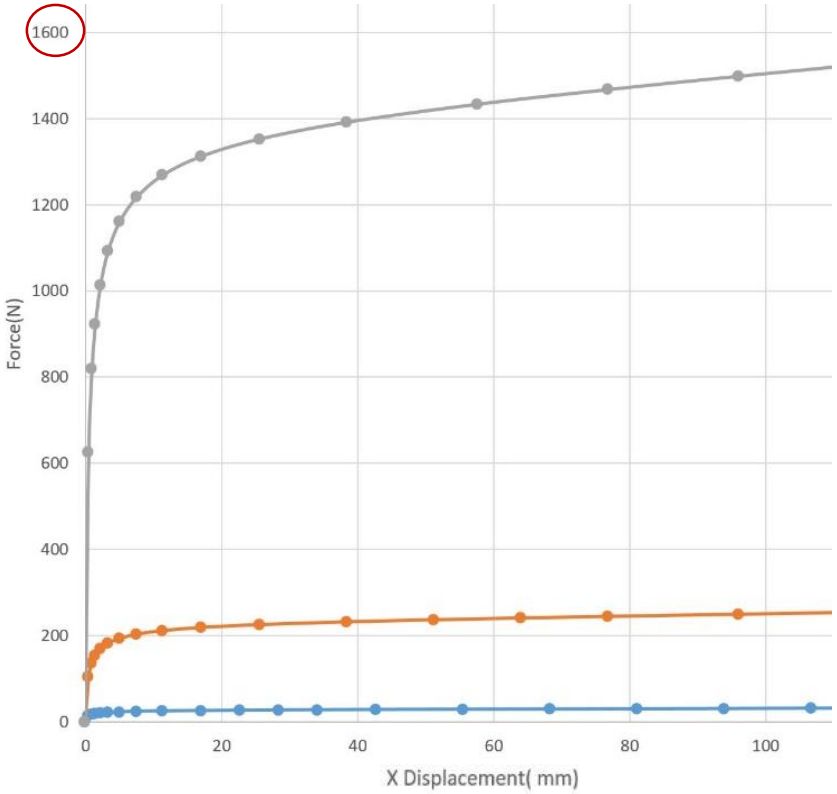


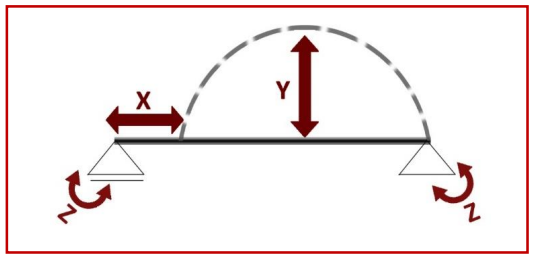


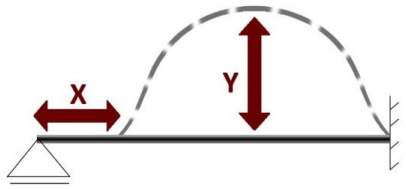


Structural Analysis

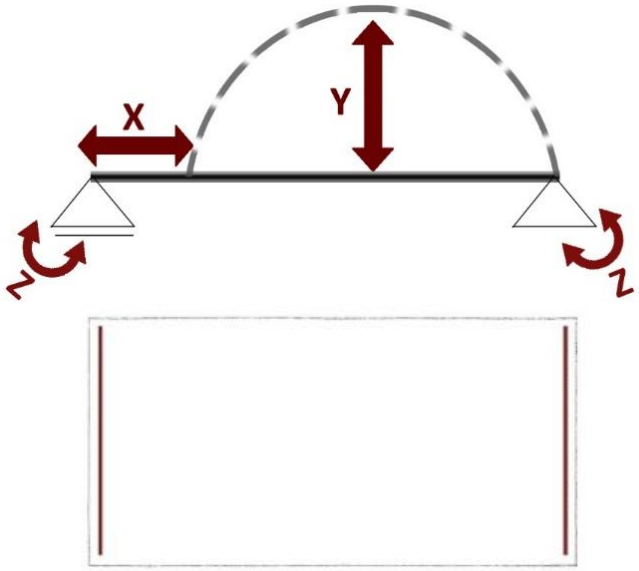




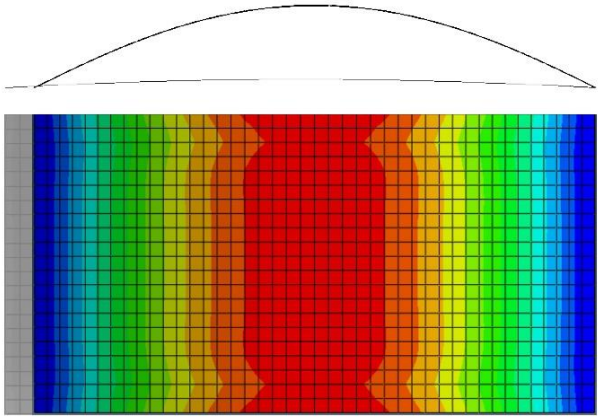




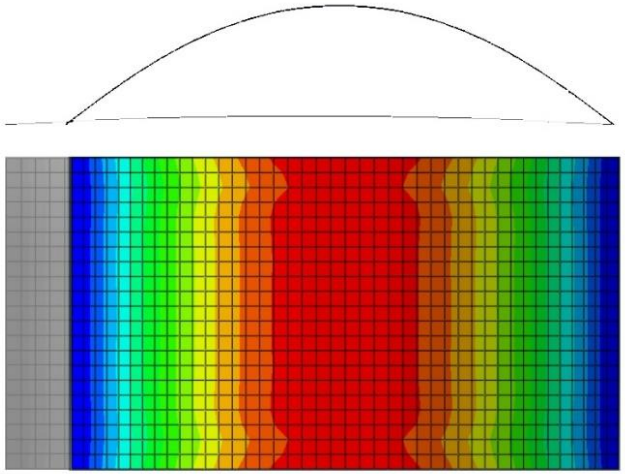
Structural Analysis



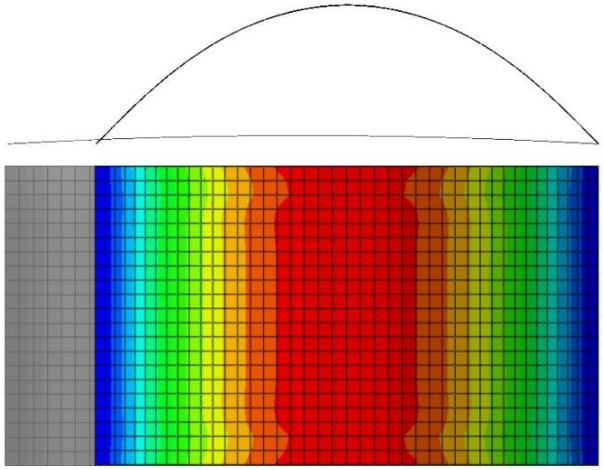
Length:	**710 mm**
Width:	**360 mm**
Thickness:	**1.1 mm**
Initial Bending:	**10 mm**



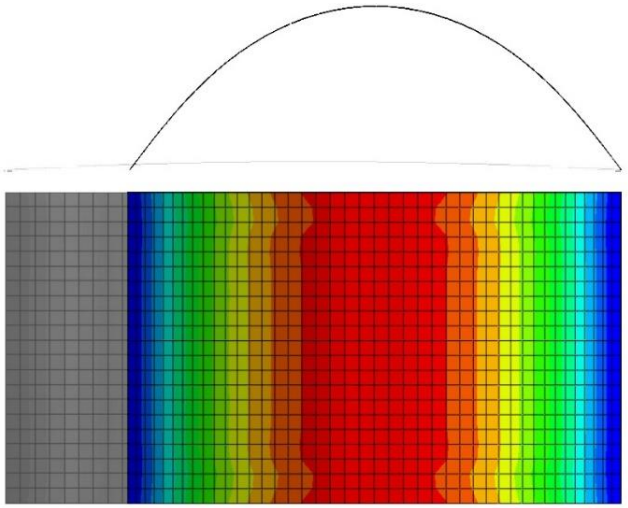
Stroke:	35 mm
U2:	89 mm
Max. Principal stress top layer:	77 Mpa
Force:	55.5 N
No. Wires:	2
Length of Wire:	710 mm



Stroke:	71 mm
U2:	120 mm
Max. Principal stress top layer:	114 Mpa
Force:	59 N
No. Wires:	2
Length of Wire:	1420 mm

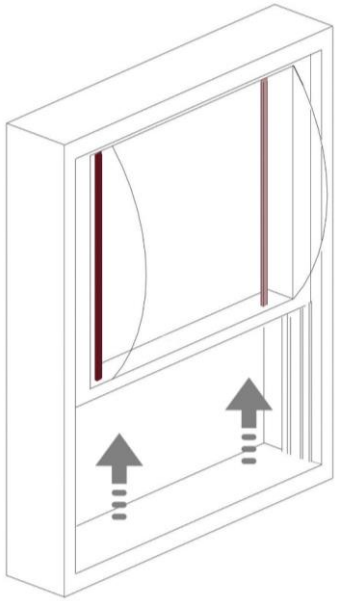


Stroke:	106.5 mm
U2:	150 mm
Max. Principal stress top layer:	143 Mpa
Force:	61.5 N
No. Wires:	2
Length of Wire:	2130 mm



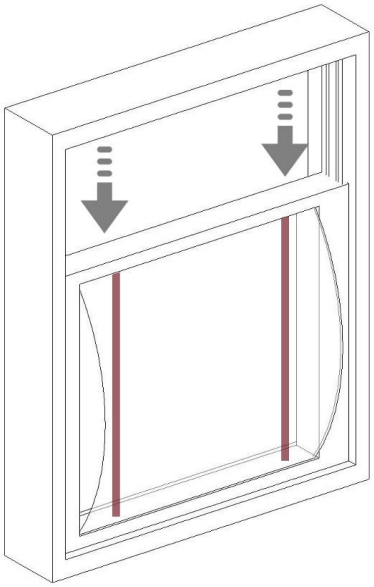
Stroke:	142 mm
U2:	181 mm
Max. Principal stress top layer:	168 Mpa
Force:	64.5 N
No. Wires:	2
Length of Wire:	2840 mm

Structural Analysis



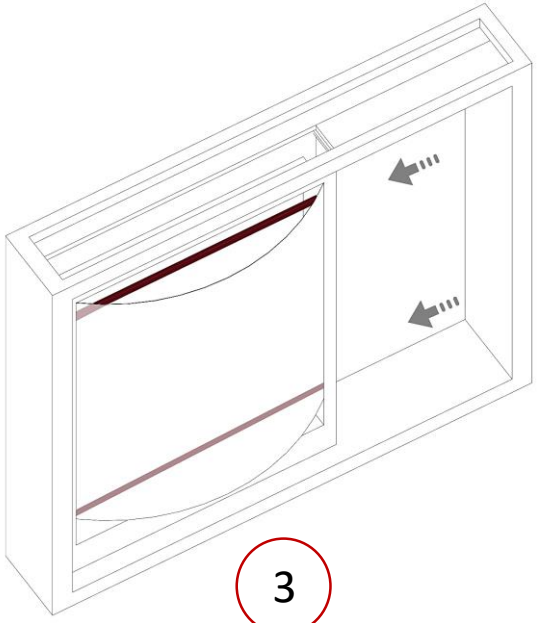
F total= F displacement + W glass

1



F total= F displacement

2



3

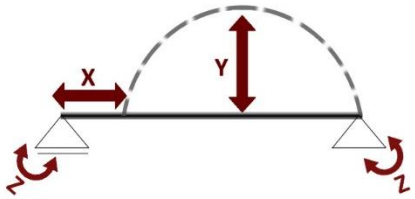
Structural Analysis

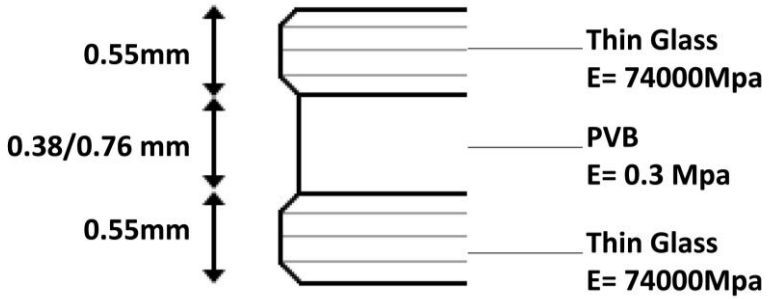
Lamination

PVB Type No.	Young's Modulus E [MPa]	Shear Modulus G [MPa]	PVB Type	Temperature [°C]	Load Duration
E1	2030	700	Trosifol Extra Stiff	10	3 sec
E2	1450	500	Trosifol Extra Stiff	10	5 min
E3	943	325	Other Stiff PVB	20	3 sec
E4	435	150	SentryGlas	20	1 d
E5	0.3	0.1	Trosifol PVB	30	1 mo

Structural Analysis

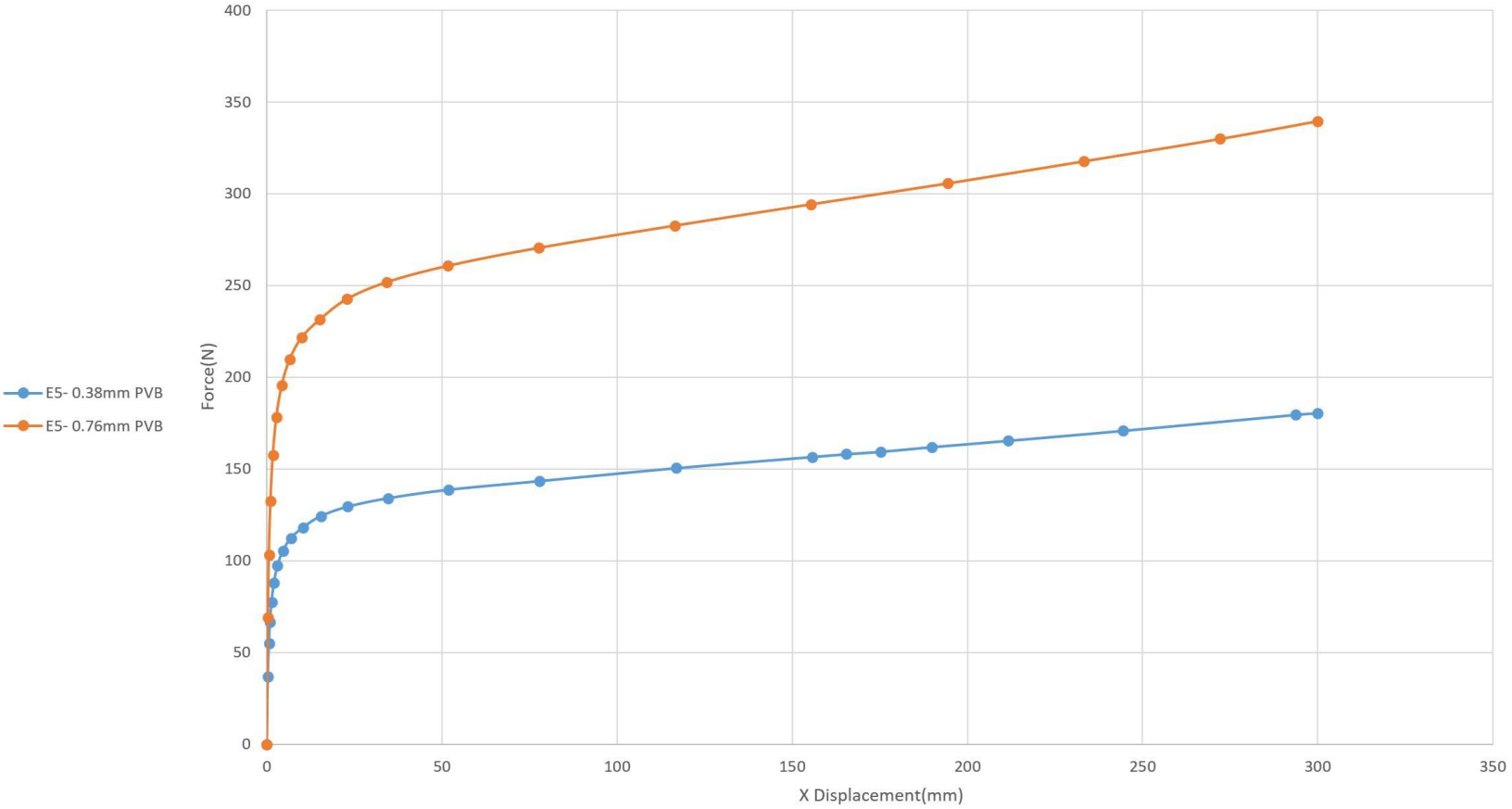
Lamination





Structural Analysis

Lamination



Electrical Analysis

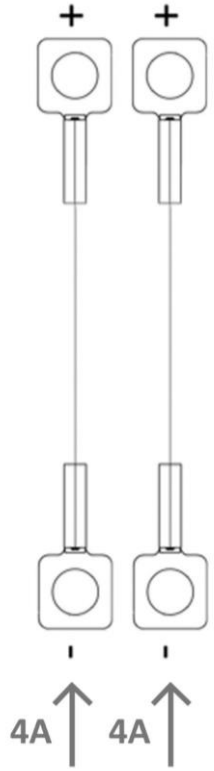
Recommended Current in one second: 4 A

Lower current:

Slower contraction

Higher power consumption

Chance of overheating



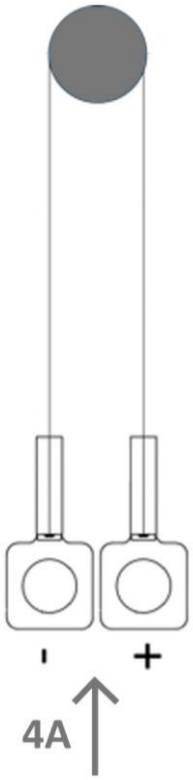
Electrical Analysis

Strategy for low Current

2x the effective pull force of the wire

2x the voltage requirement

the current requirement remains the same



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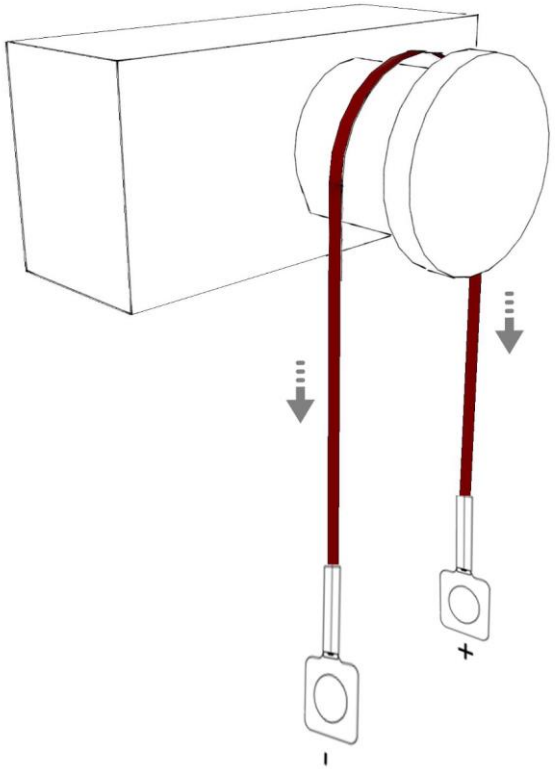
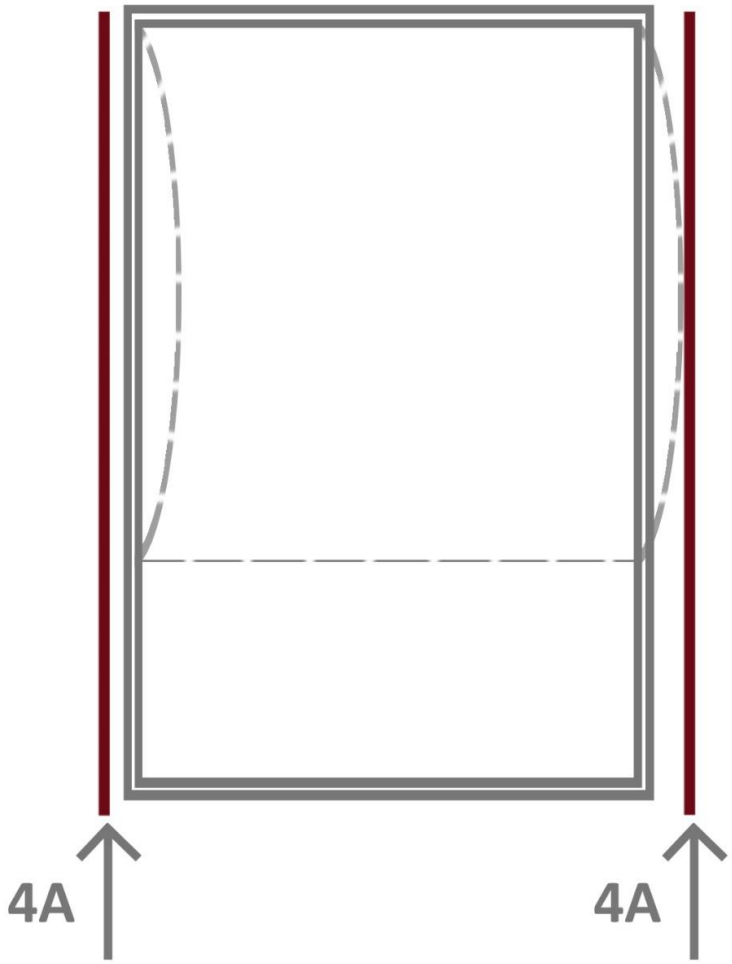


Electrical Analysis



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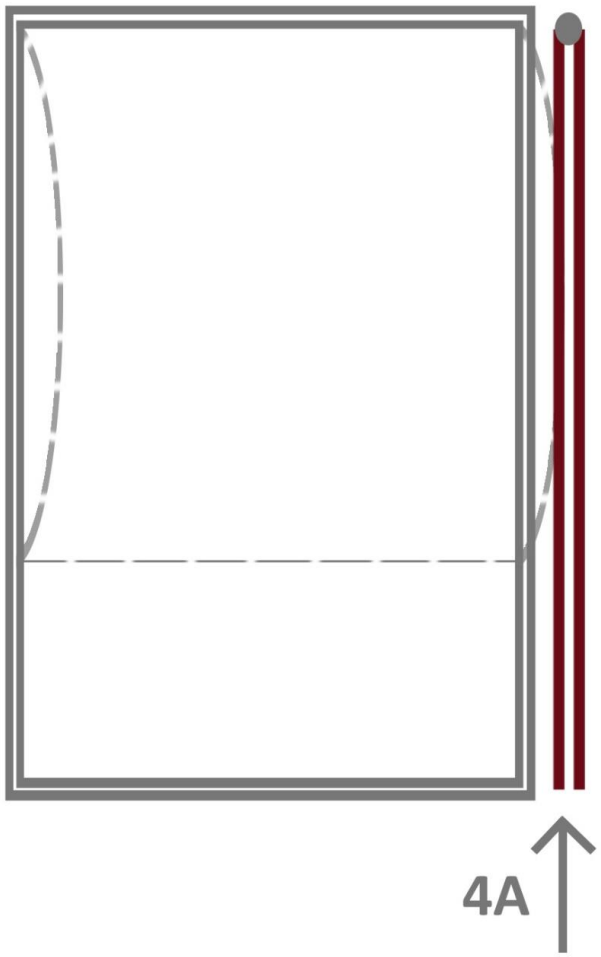


Experimental Setup

Test 1- Stroke, Force

Experimental Setup

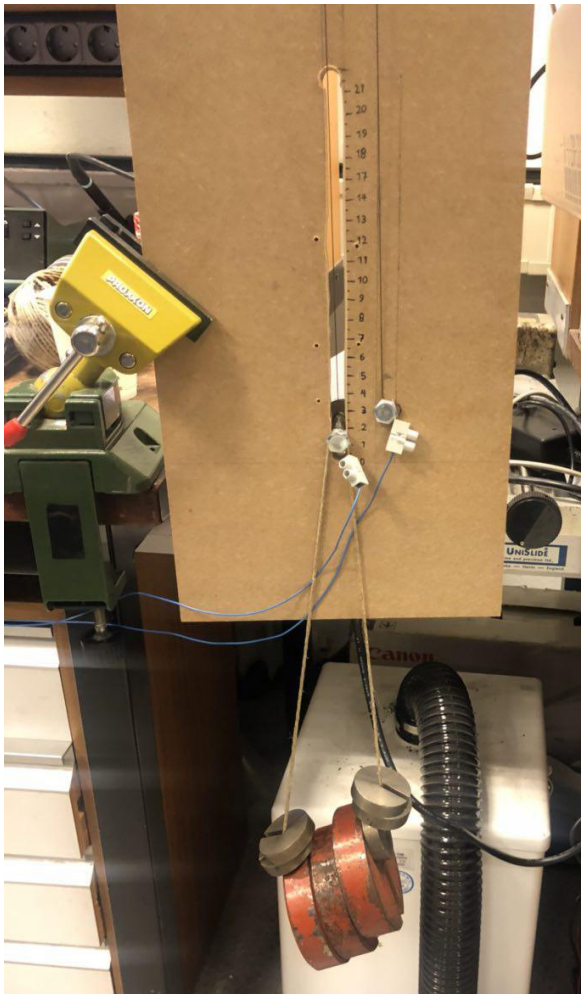
Test 2- Stroke, Force

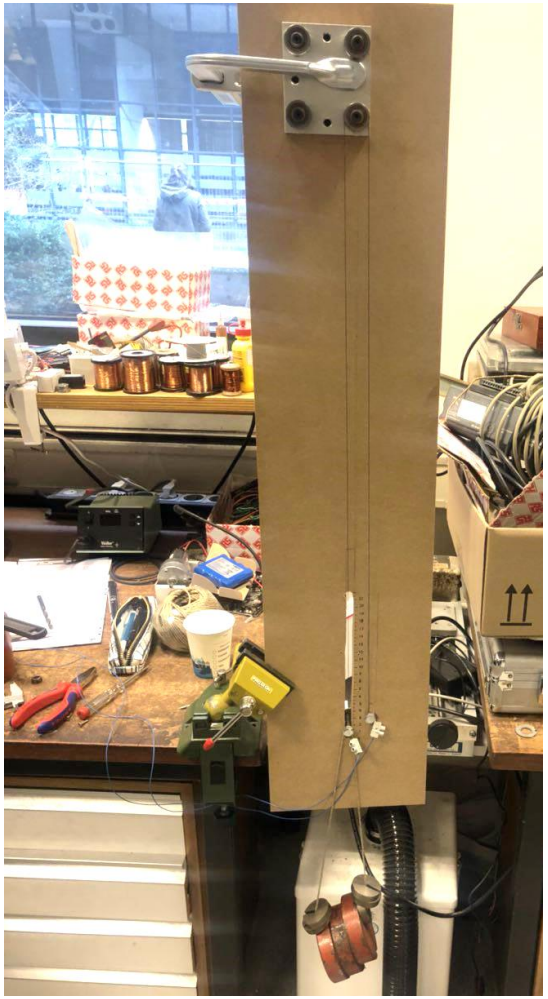
Current	Voltage	Performance
4	12	1 sec ✓✓ ✓
0.5	2	X
1.4	5.4	11 sec ✓✓
0.9	4	120 seconds ✓

Length of the wire= 71cm

Experimental Setup

Test 2- Double Stroke





Experimental Setup

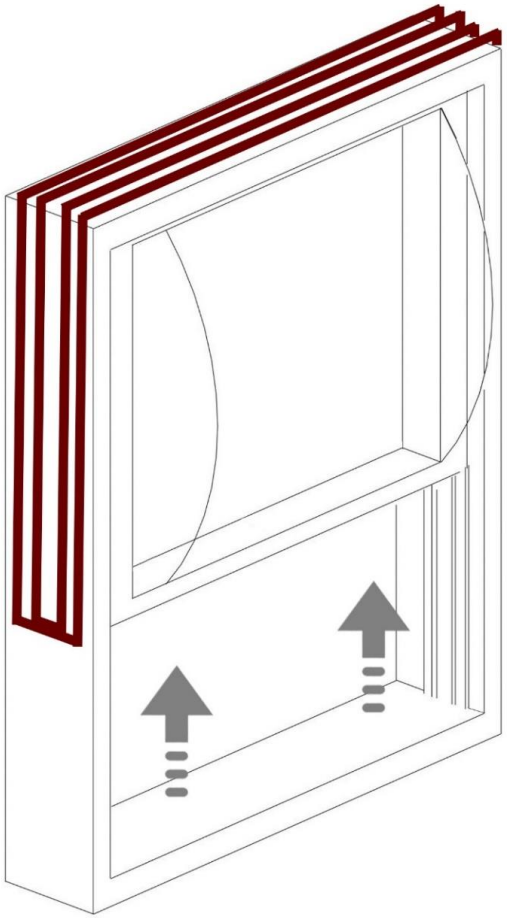
Test 2- Double Stroke

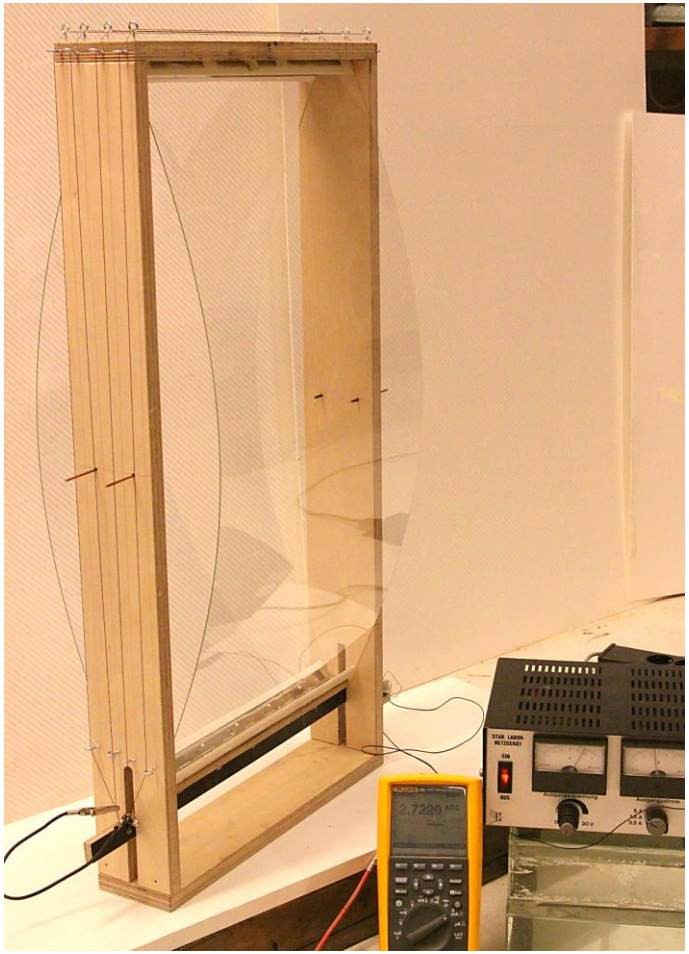
I	V	Performance
4	24	1 sec ✓✓ ✓
1.4	5.4	300 sec ✓
1.4	10	13 sec ✓✓

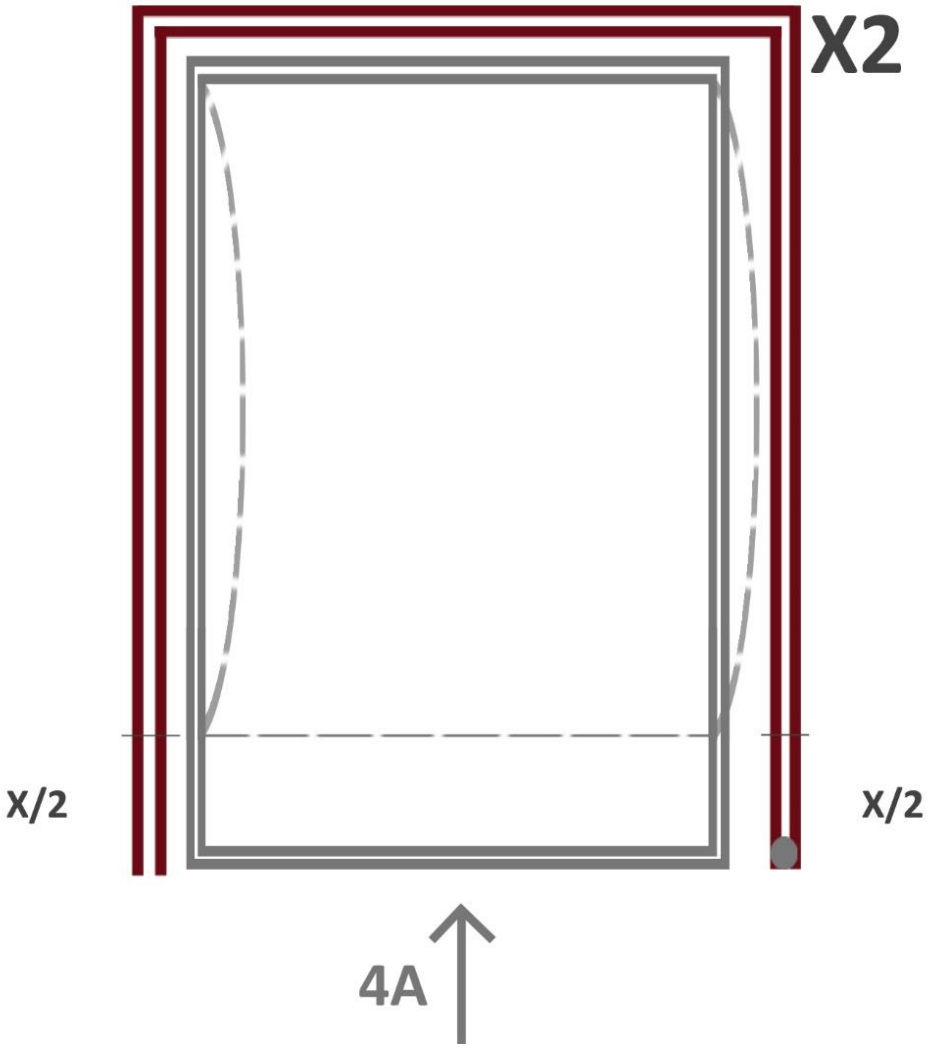
Length of the wire= 142cm

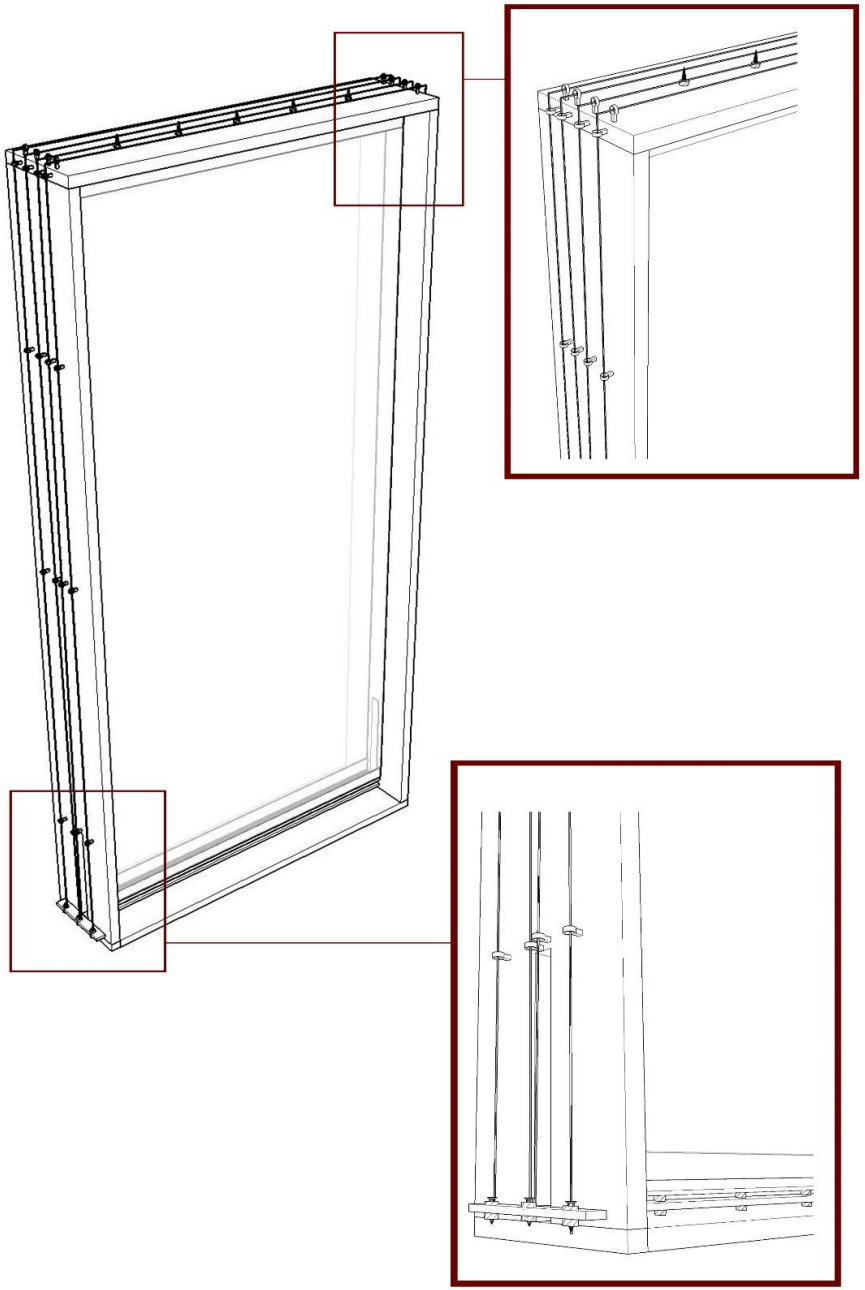
Experimental Setup

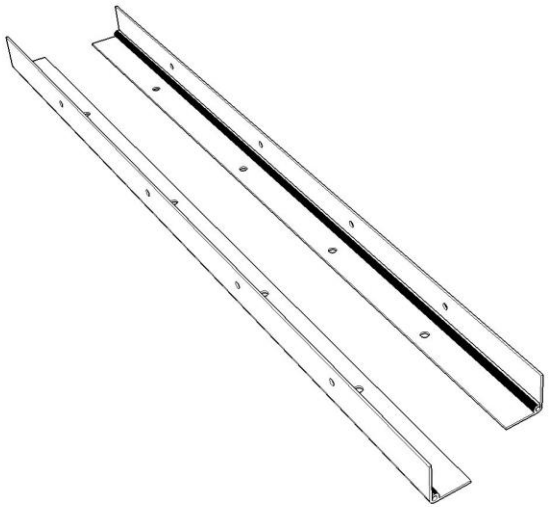
Test 3- Mock-up 1

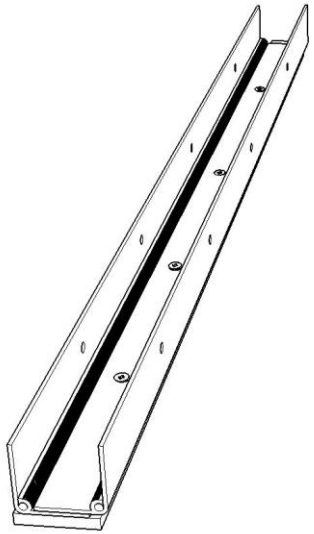


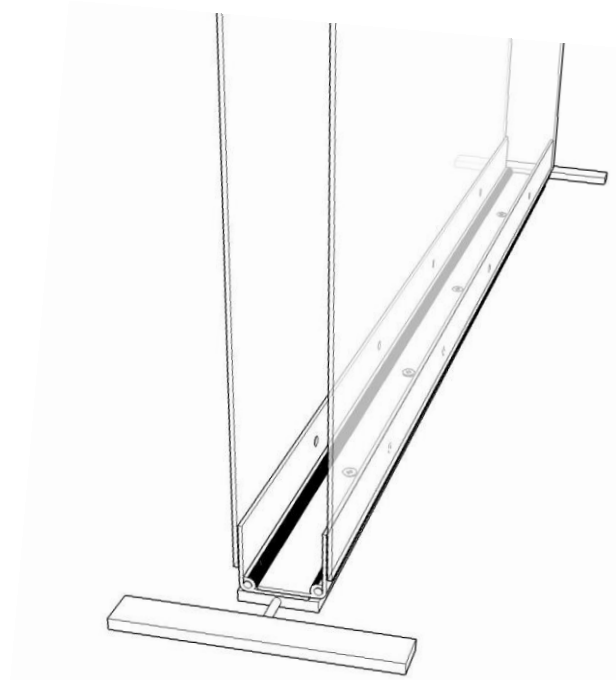


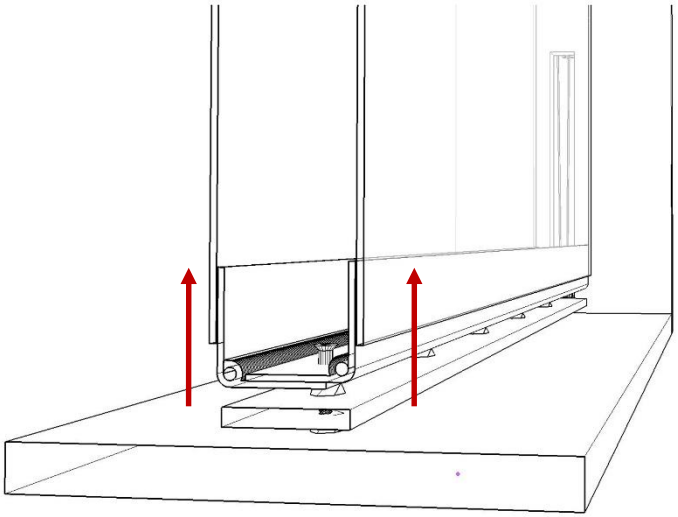

X2
X/2
X/2
4A



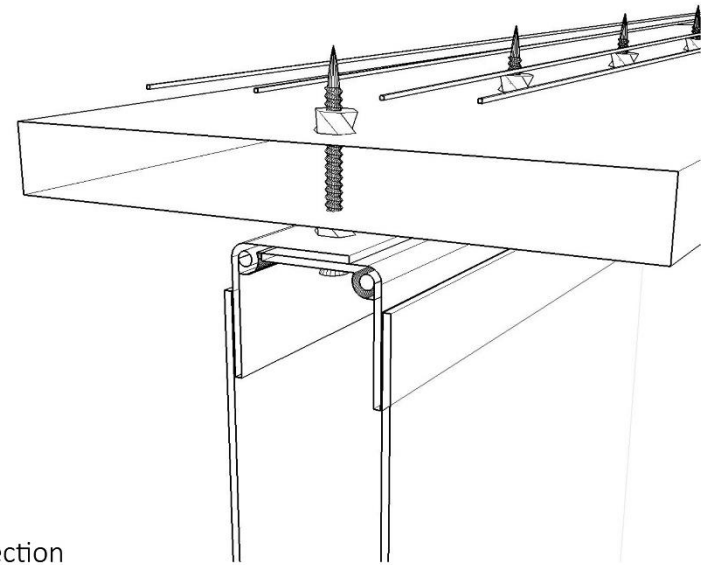






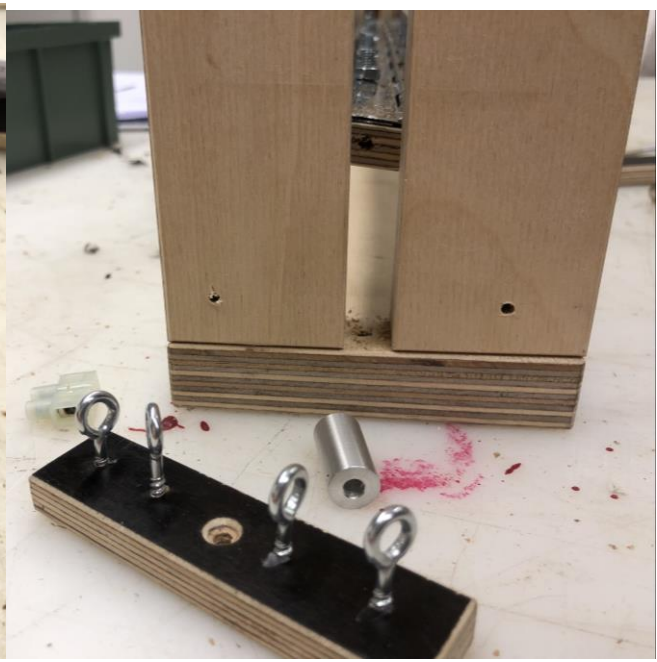


Bottom Connection

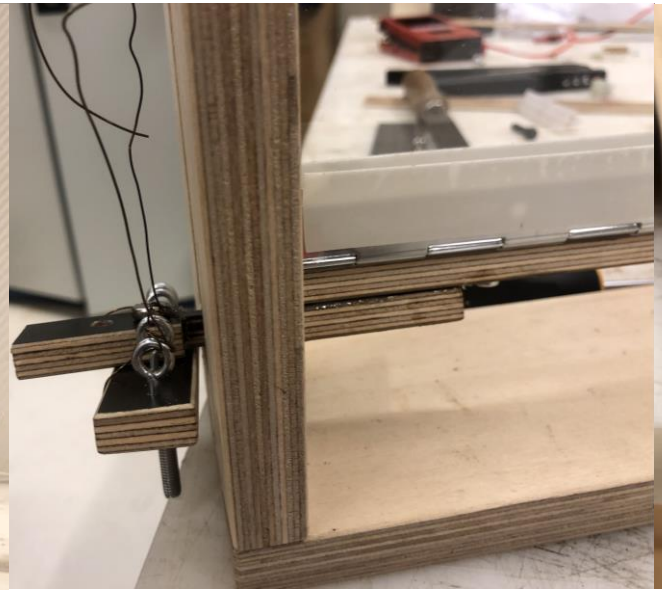


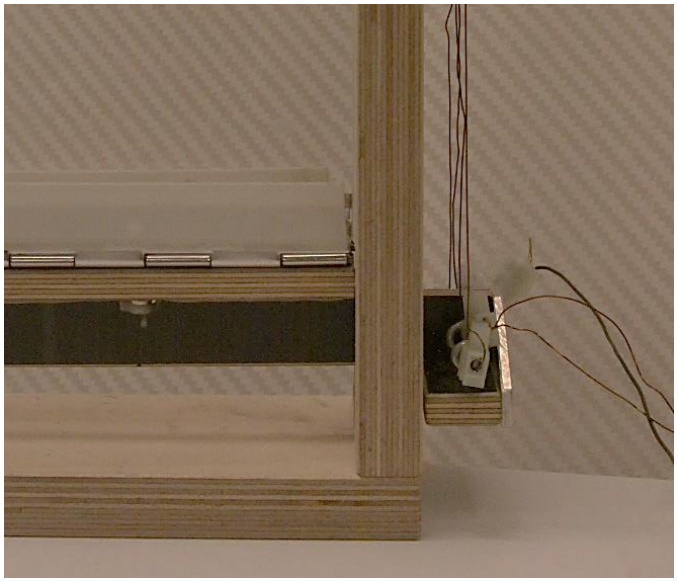
Top Connection

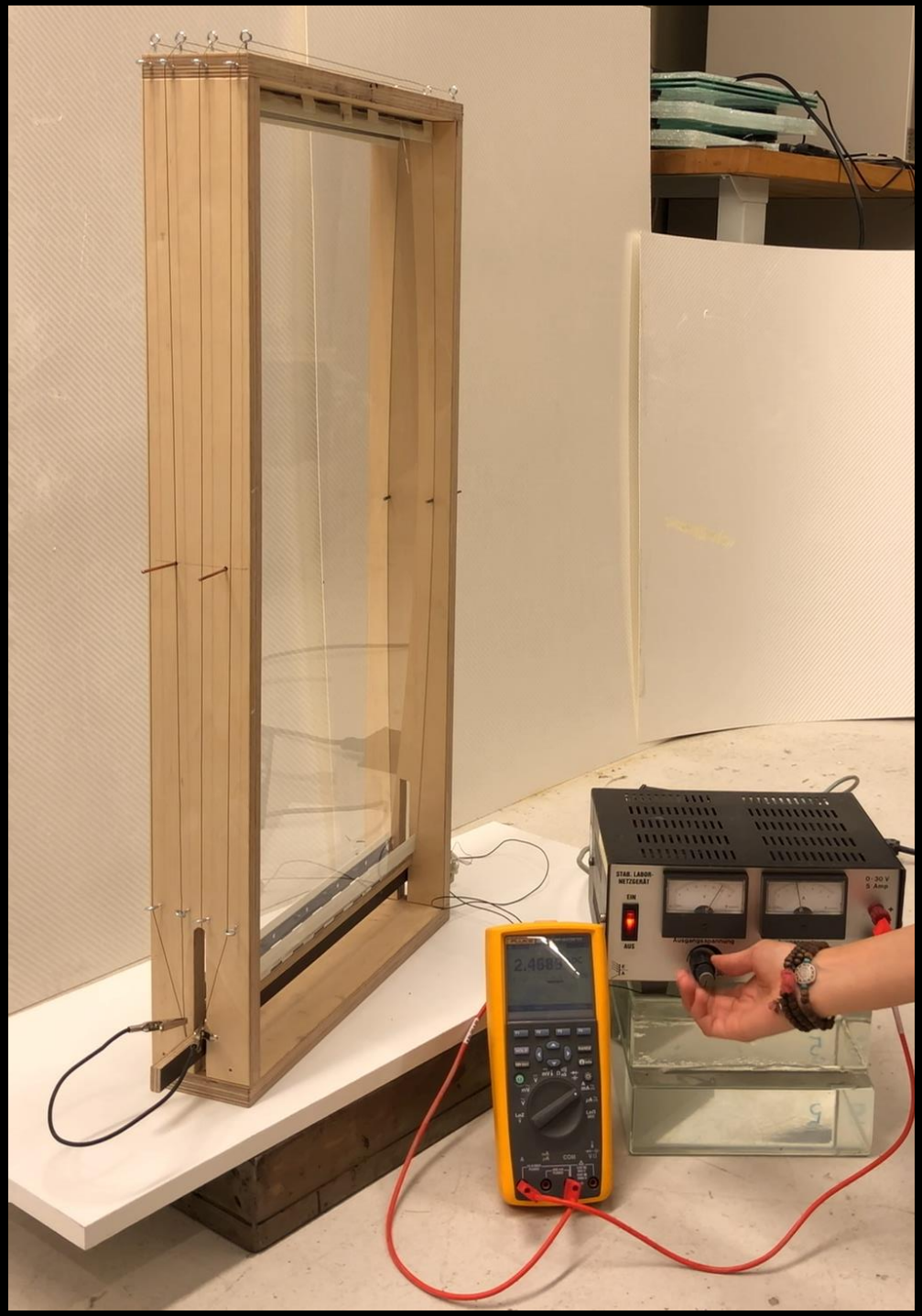
1



2






STABIL. LABOR-
NETZGERÄT
EIN
AUS
0 - 30 V
5 Amp

Experimental Setup

Test 3- Mock-up 1

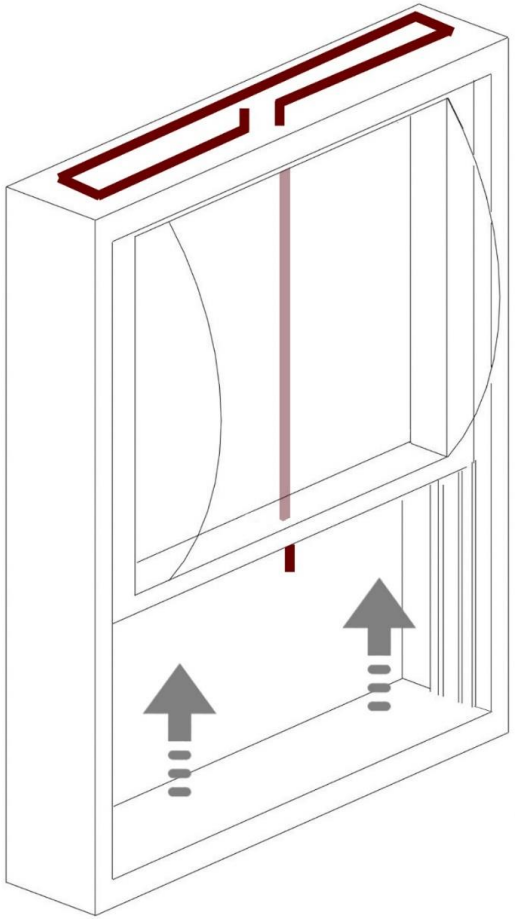
Current	Voltage	Performance
2.8	25	10 sec ✓✓ ✓
1.7	17	X
2.4	23	15 sec ✓✓
2.2	22	25 sec ✓✓
2	20	60 sec ✓

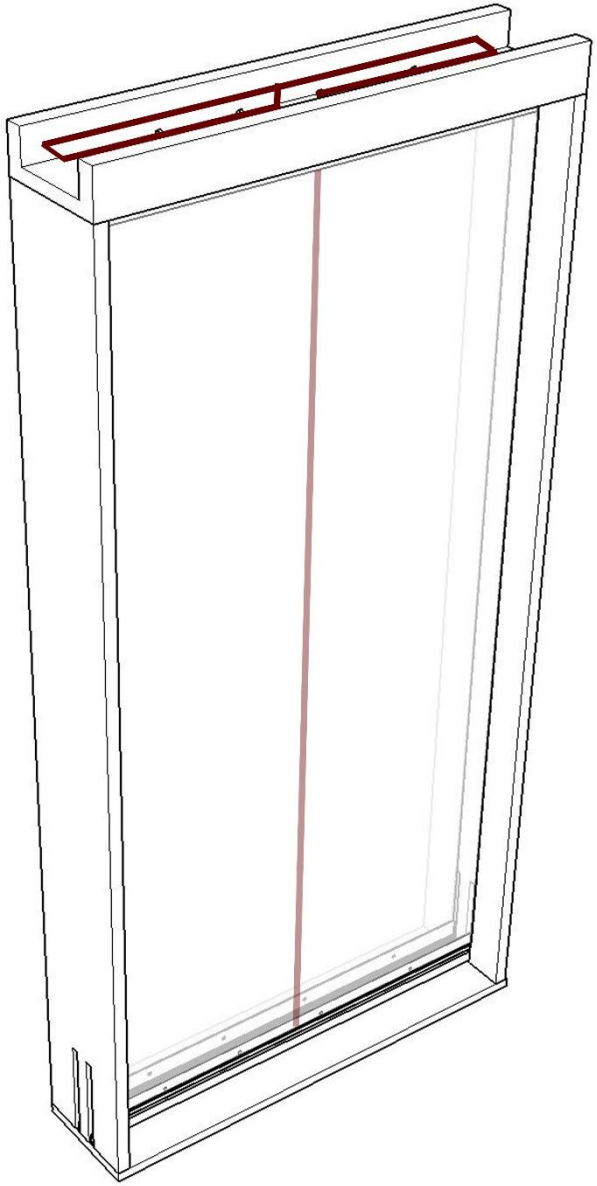
Number of wires: 2

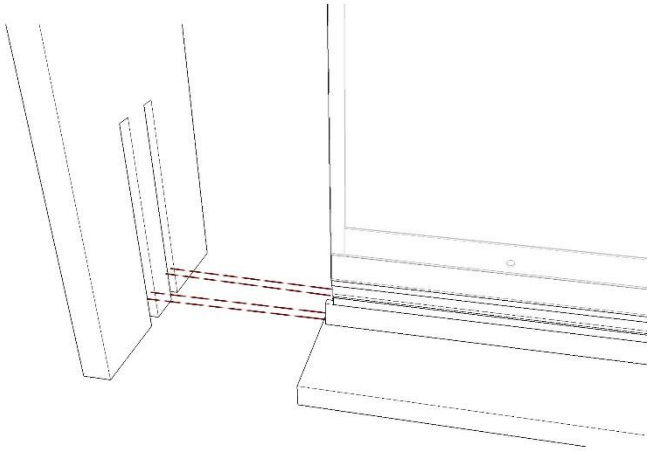
Length of one wire= 184cm

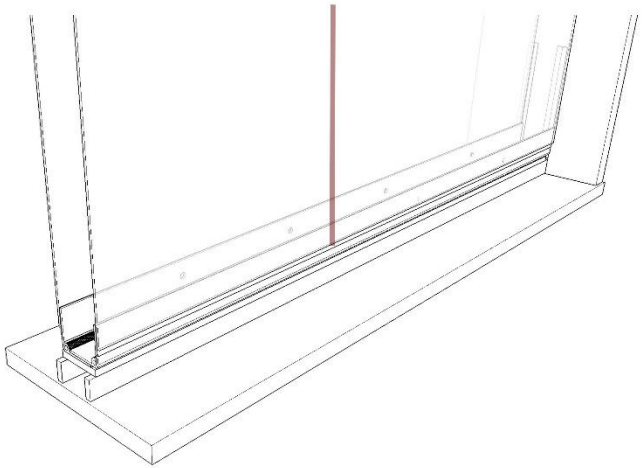
Experimental Setup

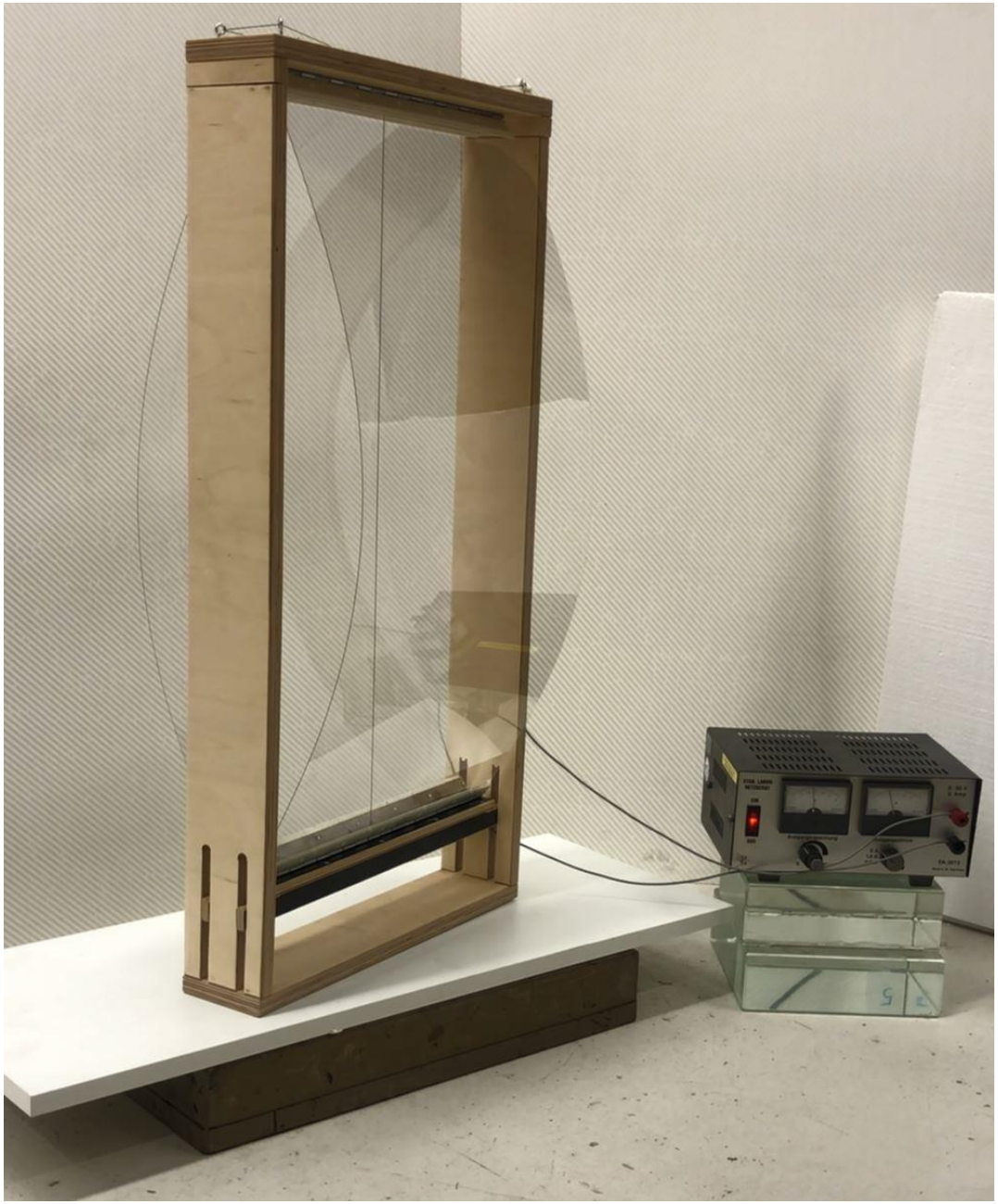
Test 4- Mock-up 2

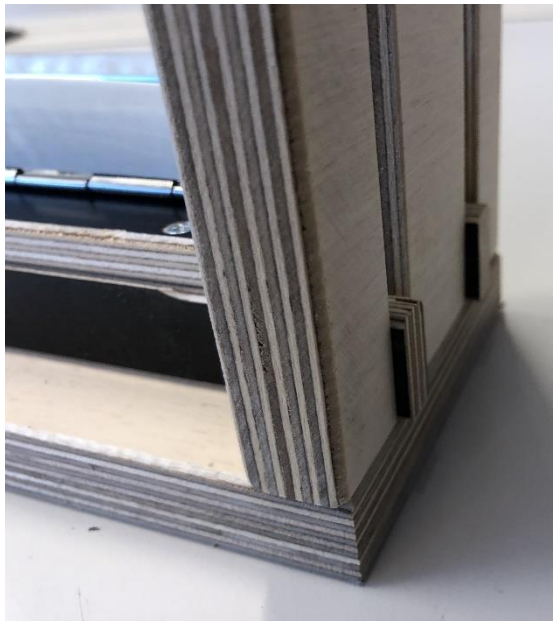


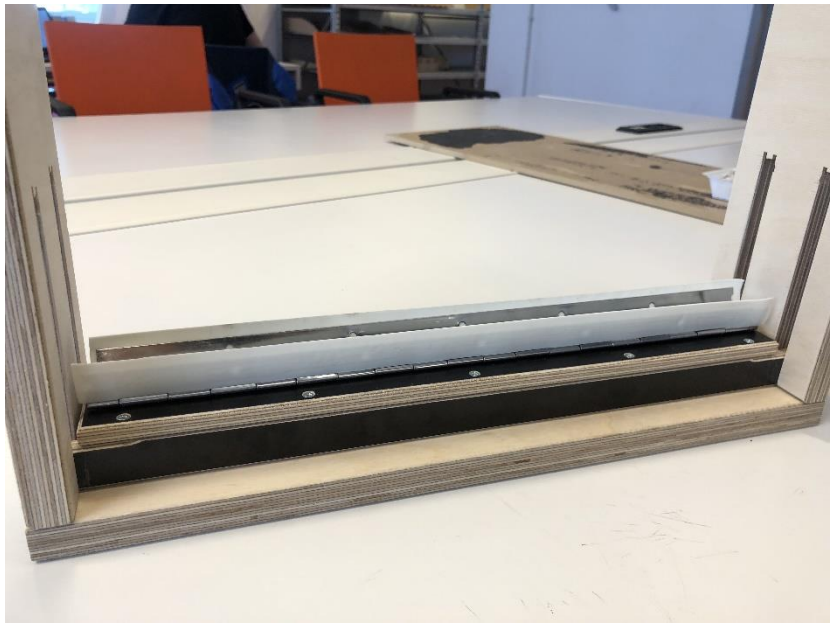


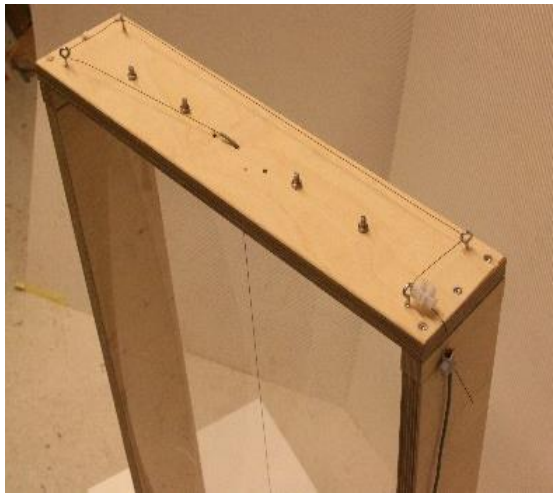


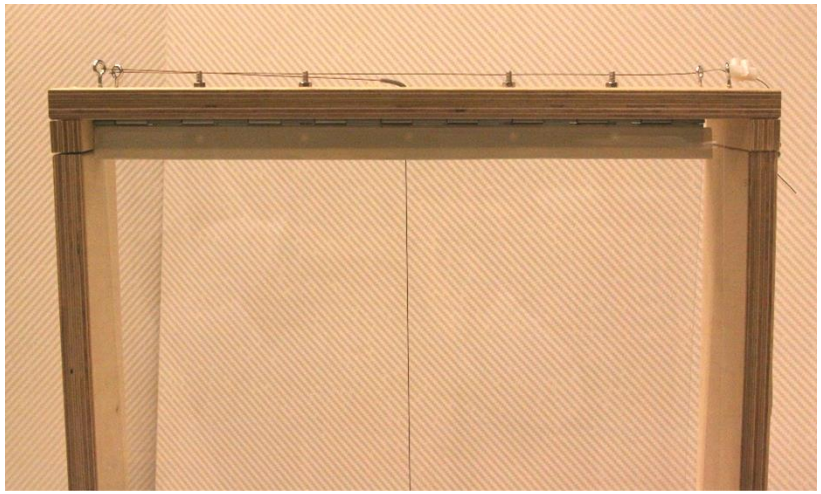












Experimental Setup

Test 4- Mock-up 2

I	V	Performance
4	24	1 sec ✓✓ ✓
1.4	5.4	300 sec ✓
1.4	10	13 sec ✓✓

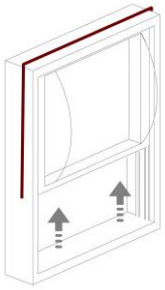
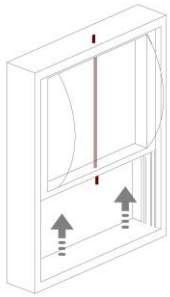
Length of the wire= 142cm

Experimental Setup

Comparison

Experimental Setup

Comparison

			
+	-	+	-
Possibility of insulating the wires	Long wires	Possibility of activation by solar radiation	Impossible for single glazing layer
Wire protection	Thick frame	Short wires	
Applicable for single glazing layer	Complex system	Thin Frame	
	High power consumption	Simple system	
	Slow reaction time	Visibility of the system	
		Low power consumption	
		Fast reaction time	

Research Structure

Literature Review

Design Exploration

Material Analysis

Practical Feasibility

Case Study

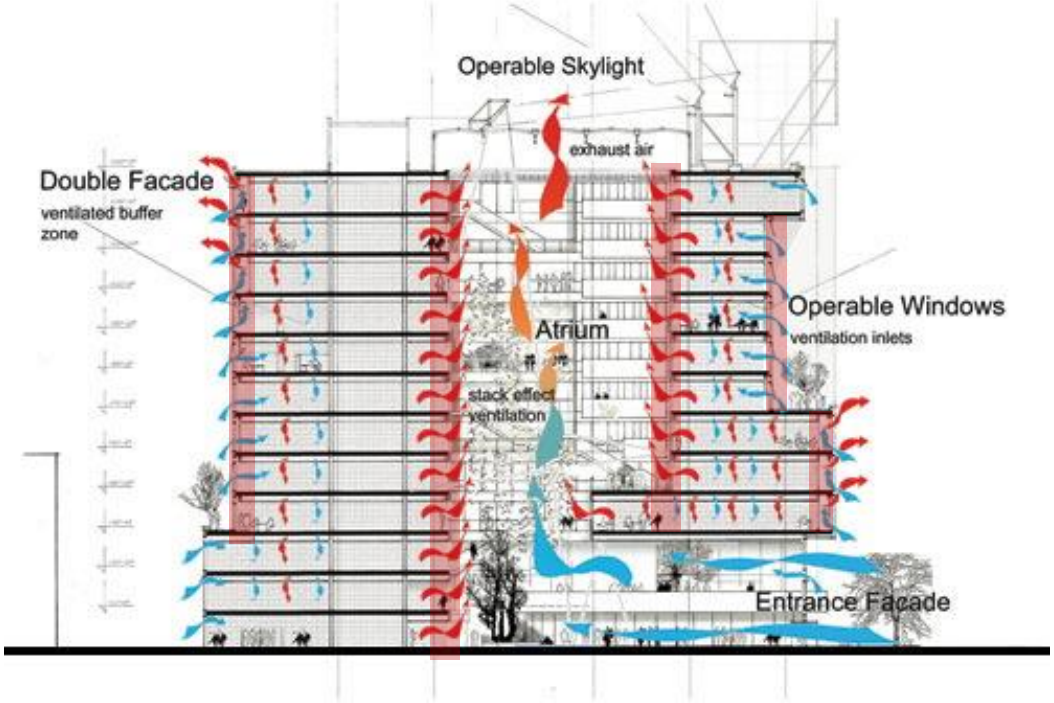
Conclusion

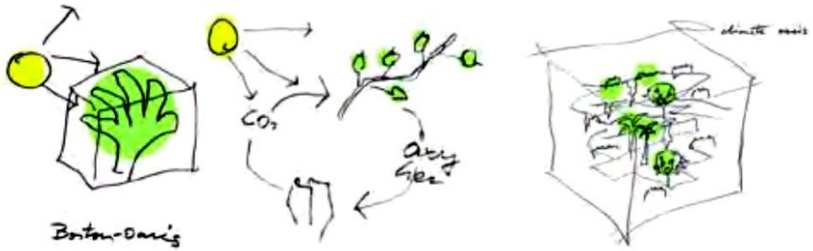
Selected Case Study

Genzyme Center

Location: Cambridge, Massachusetts
Main usage: Office
Storeys: 12
Architect: Behnisch Architects

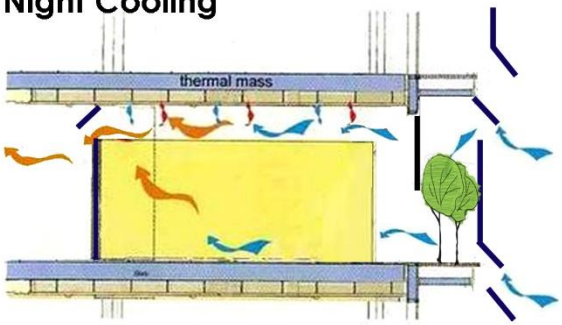
Selected Case Study



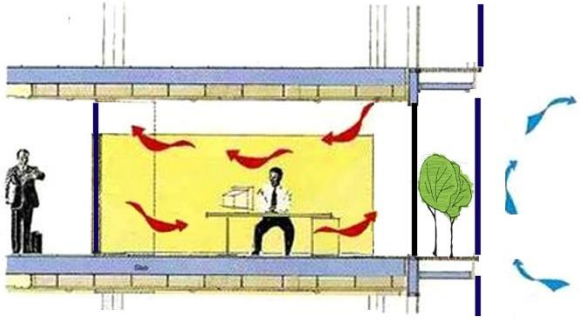


Current Situation

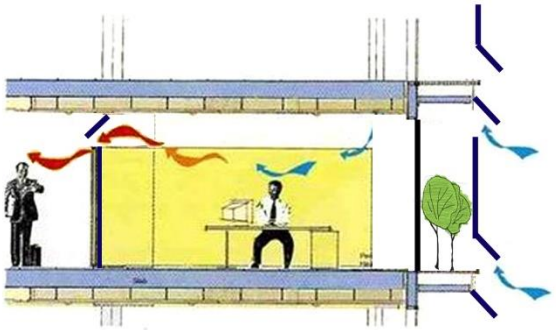
Summer Night
Night Cooling



Winter Day
Insulated Buffer Zone

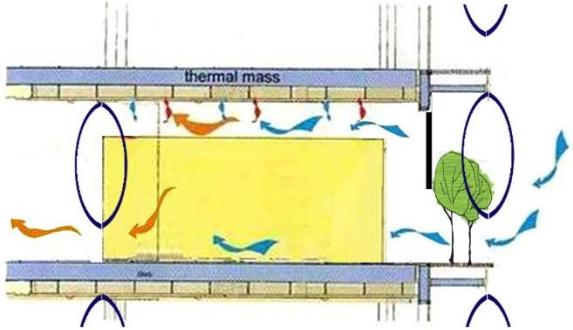


Summer Day
Ventilated Buffer Zone

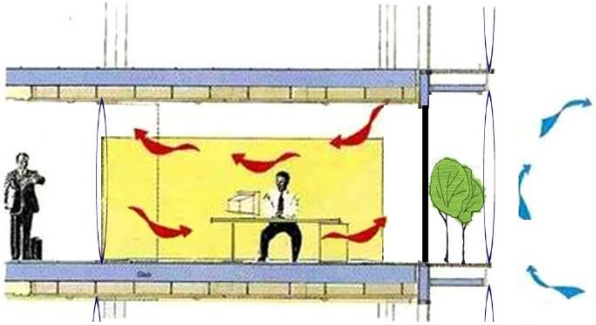


Proposed Situation

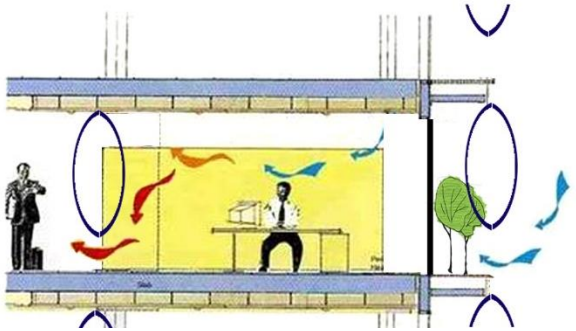
Summer Night
Night Cooling



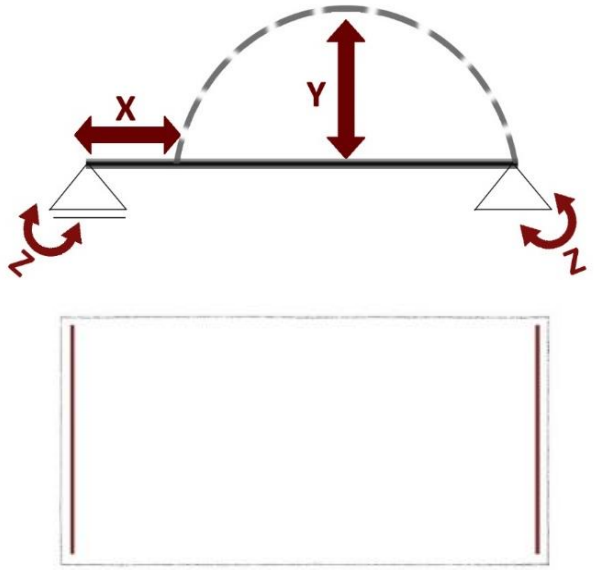
Winter Day
Insulated Buffer Zone



Summer Day
Ventilated Buffer Zone



Structural Analysis



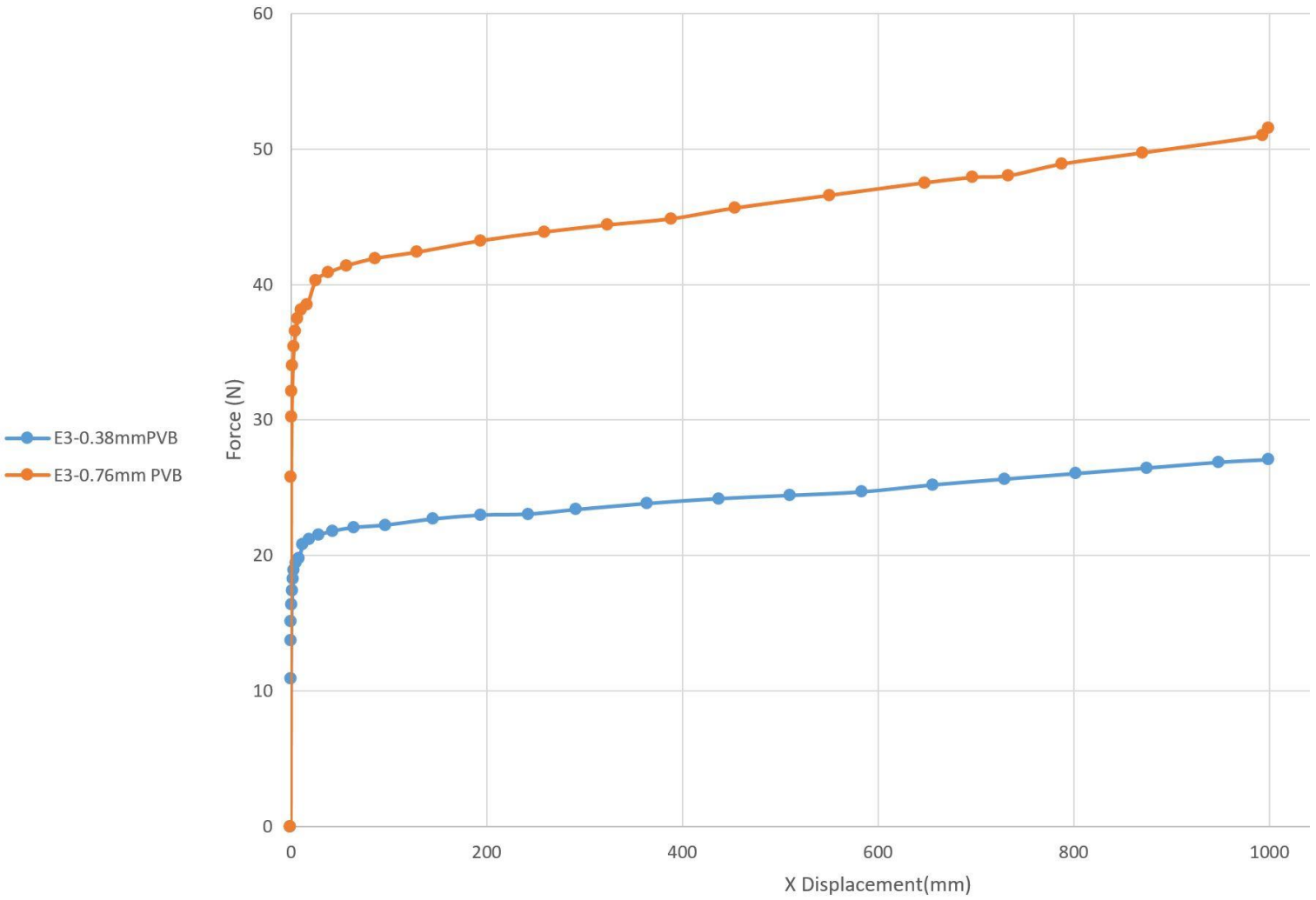
Length:	**3000 mm**
Width:	**1000 mm**
Thickness:	
Thin Glass 1:	**0.55 mm**
PVB:	**0.38 mm**
Thin Glass2:	**0.55 mm**
Initial Bending:	**10 mm**

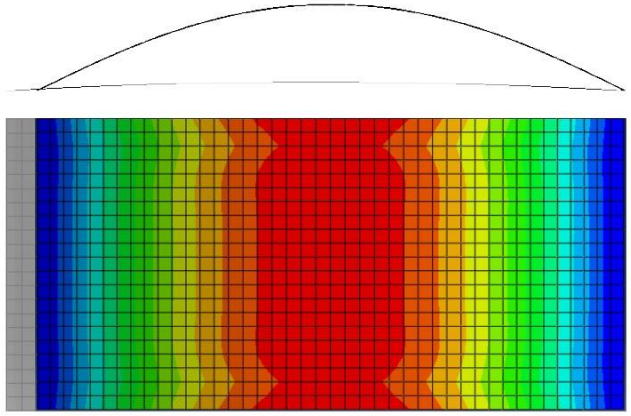
Structural Analysis

Lamination

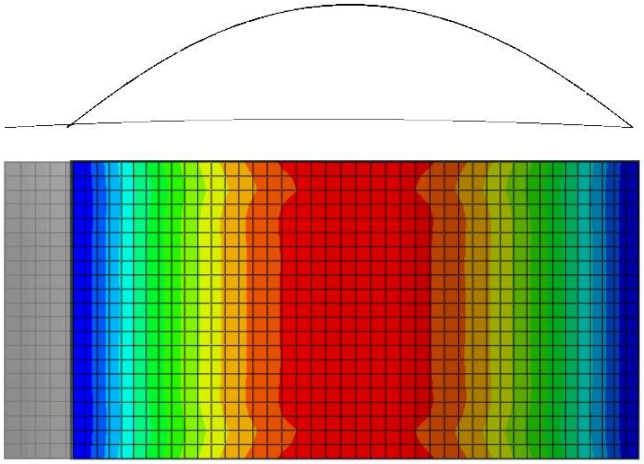
PVB Type No.	Young's Modulus E [MPa]	Shear Modulus G [MPa]	PVB Type	Temperature [°C]	Load Duration
E1	2030	700	Trosifol Extra Stiff	10	3 sec
E2	1450	500	Trosifol Extra Stiff	10	5 min
E3	943	325	Other Stiff PVB	20	3 sec
E4	435	150	SentryGlas	20	1 d
E5	0.3	0.1	Trosifol PVB	30	1 mo

Structural Analysis

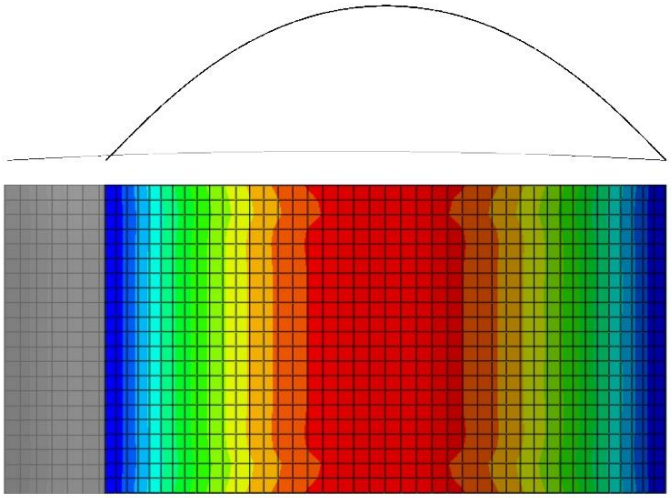




Stroke:	150 mm
U2:	410 mm
Max. Principal stress top layer:	27 Mpa
Force:	22.8 N
No. Wires:	1
Length of Wire:	3000 mm



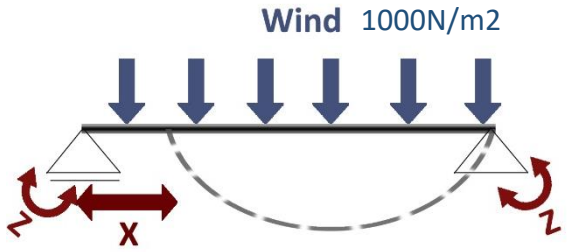
Stroke:	300 mm
U2:	570 mm
Max. Principal stress top layer:	39 Mpa
Force:	23.5 N
No. Wires:	1
Length of Wire:	6000 mm

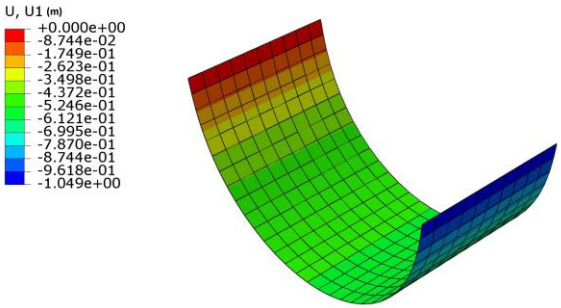


Stroke:	450 mm
U2:	692 mm
Max. Principal stress top layer:	48 Mpa
Force:	24.3 N
No. Wires:	1
Length of Wire:	9000mm

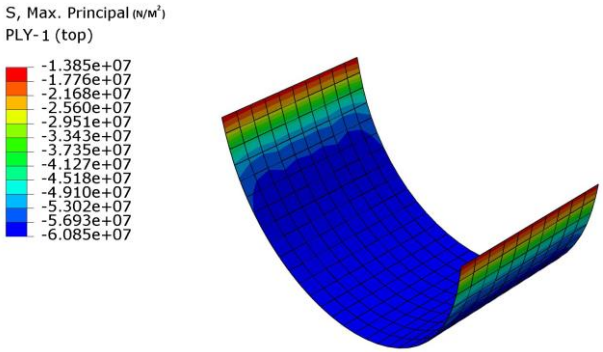
Structural Analysis

Wind

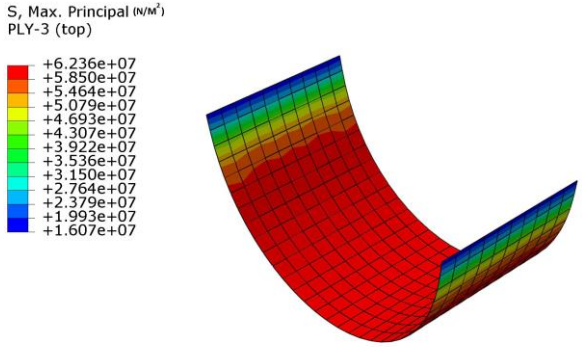




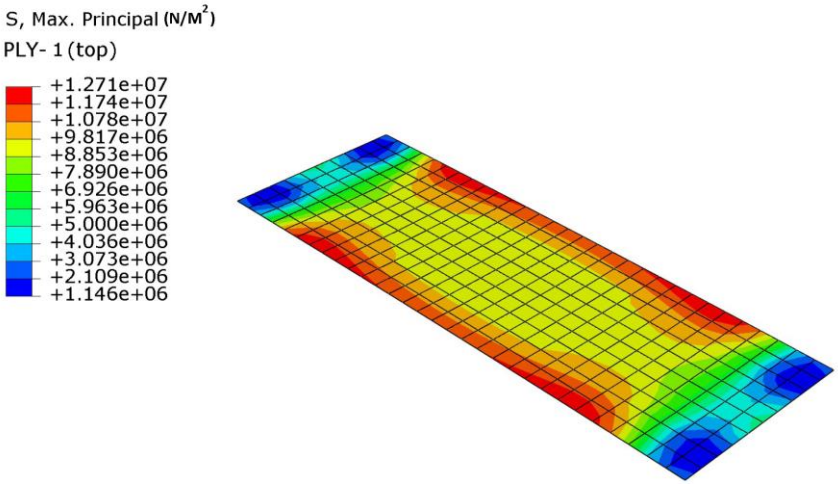
X Displacement



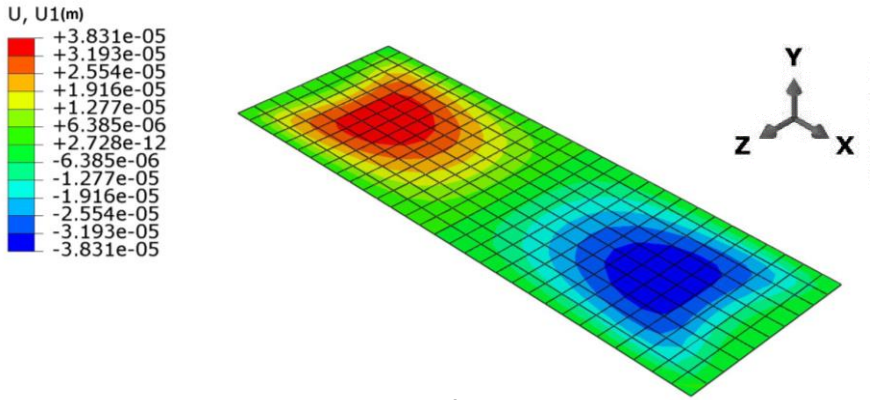
Max. Principal Stress
on top Layer 1



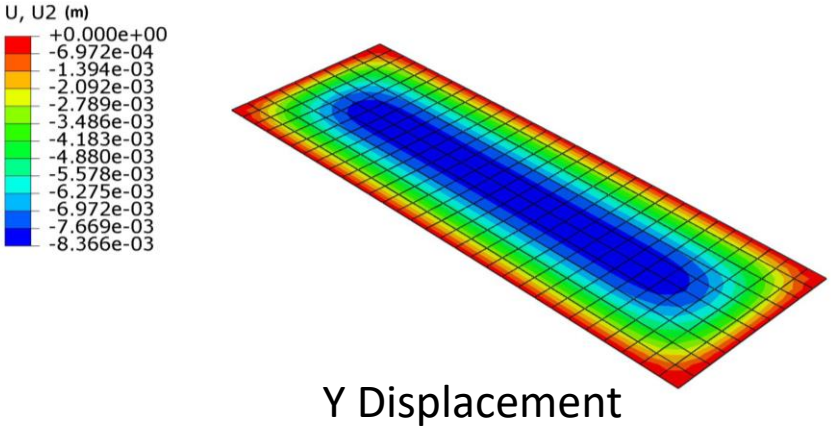
Max. Principal Stress
on top Layer 3



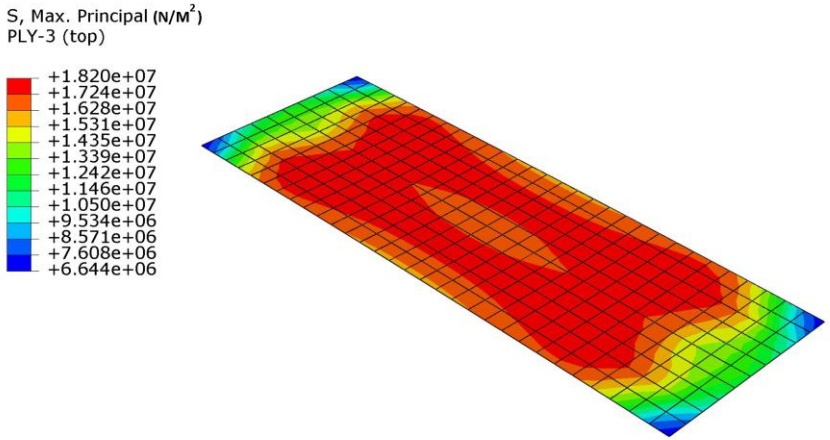
Max. Principal Stress on top Layer 1



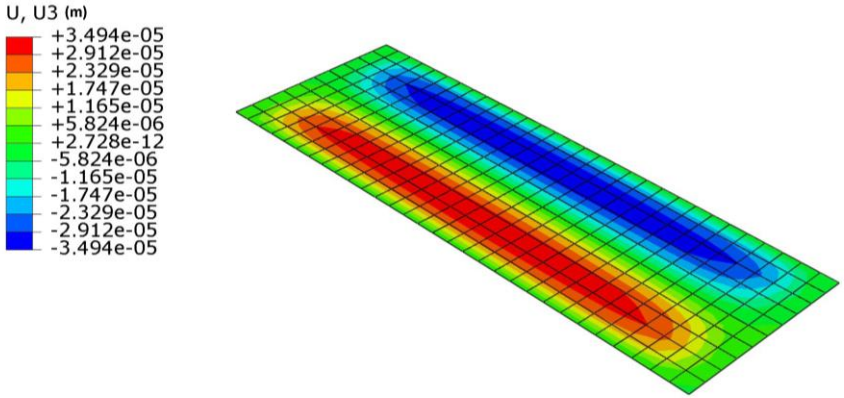
X Displacement



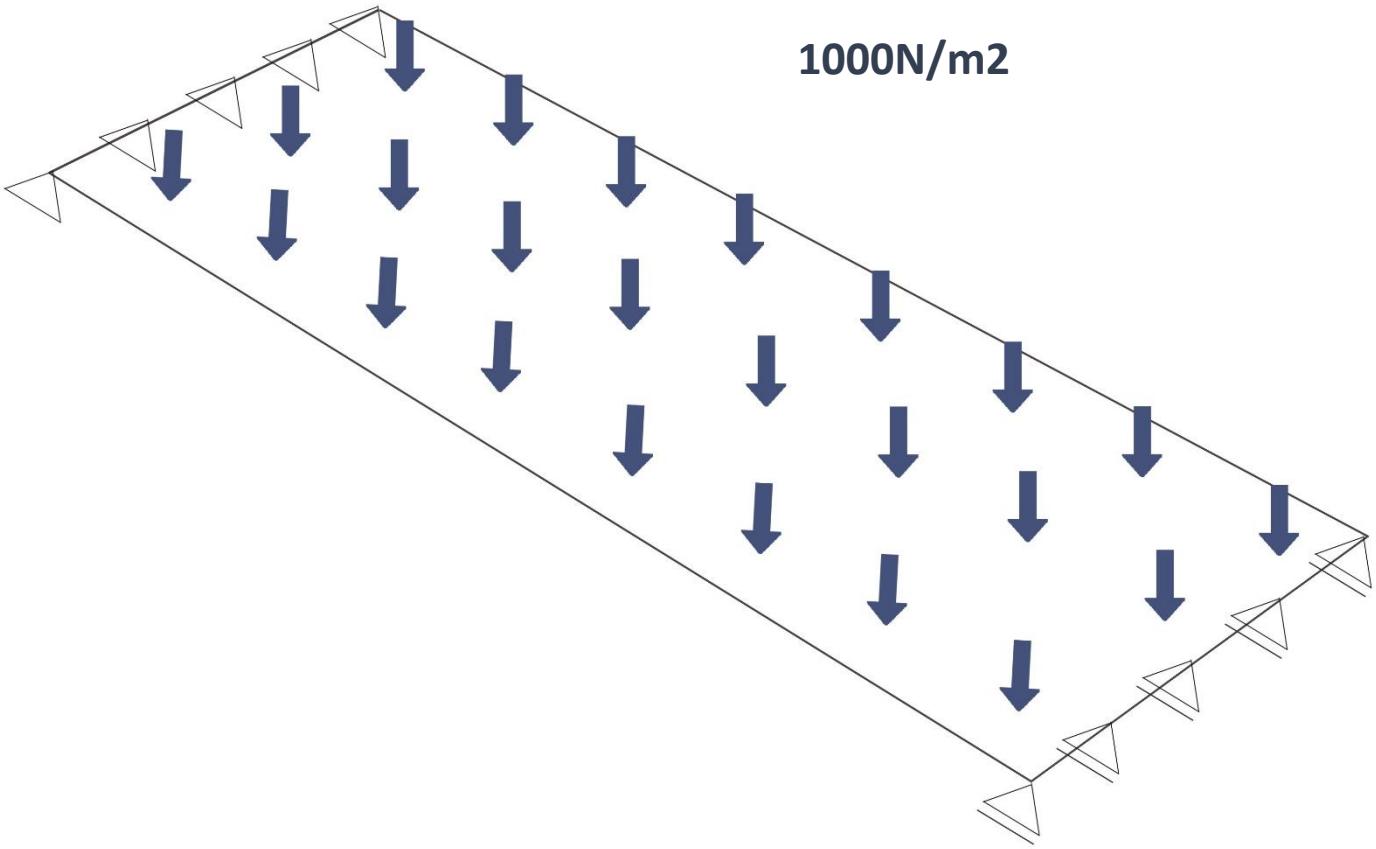
Y Displacement

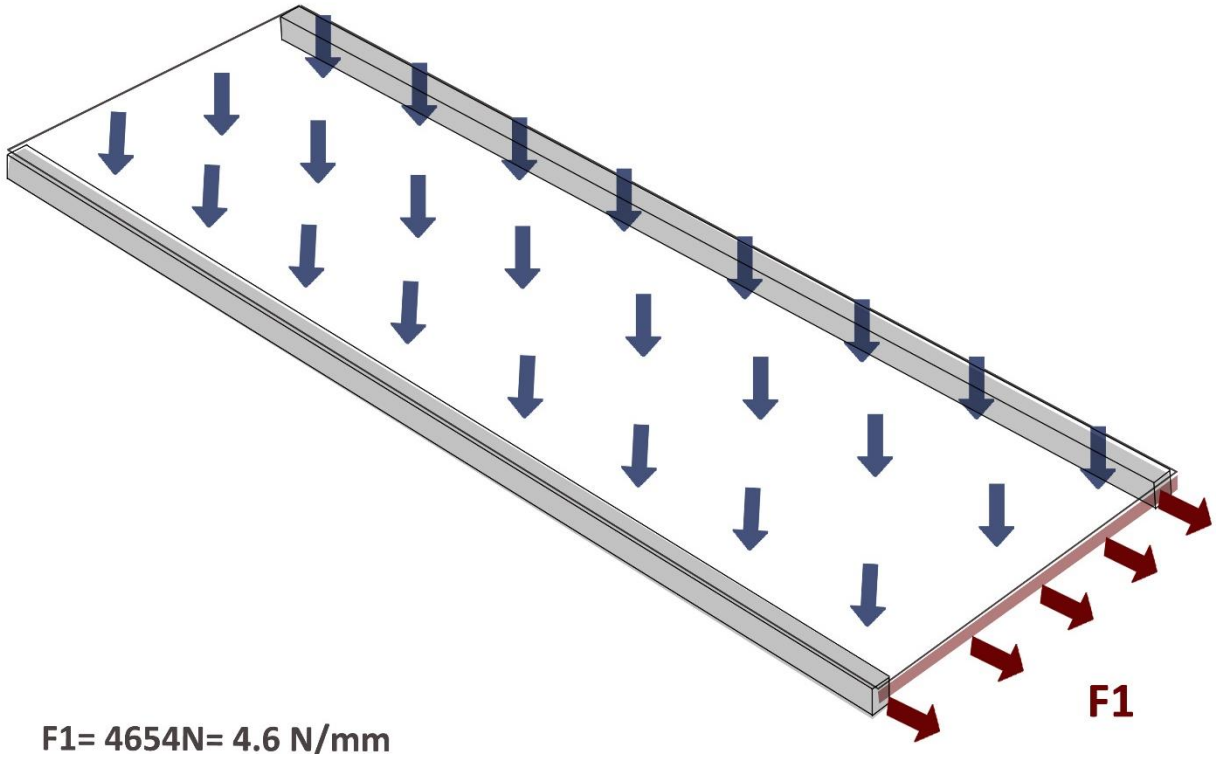


Max. Principal Stress on top Layer 3



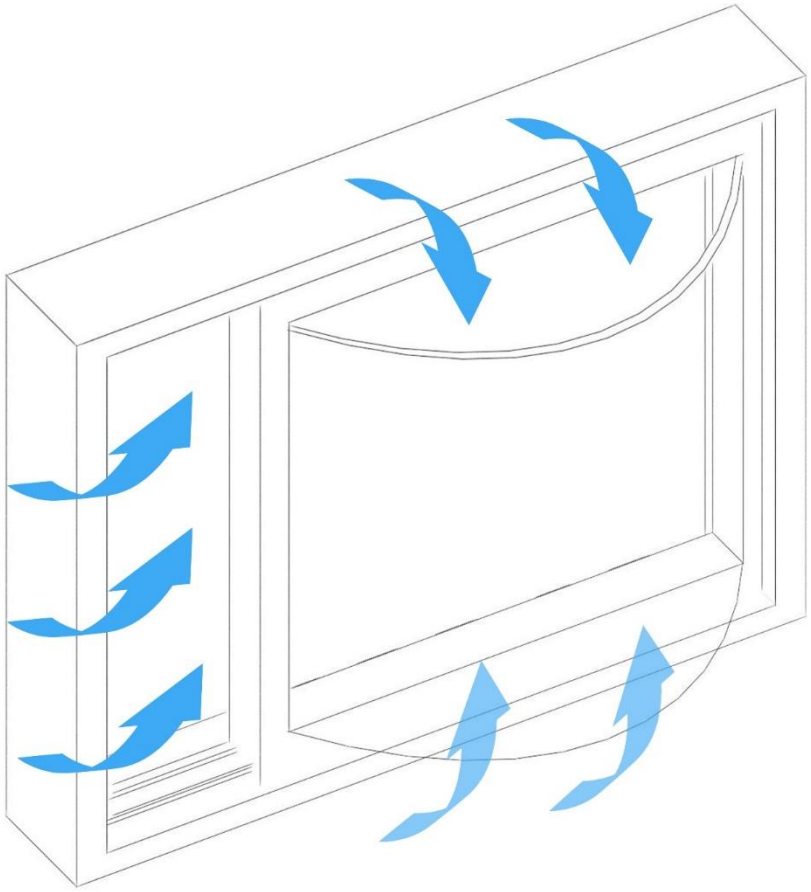
Z Displacement


1000N/m2



F1= 4654N= 4.6 N/mm

Climate Analysis



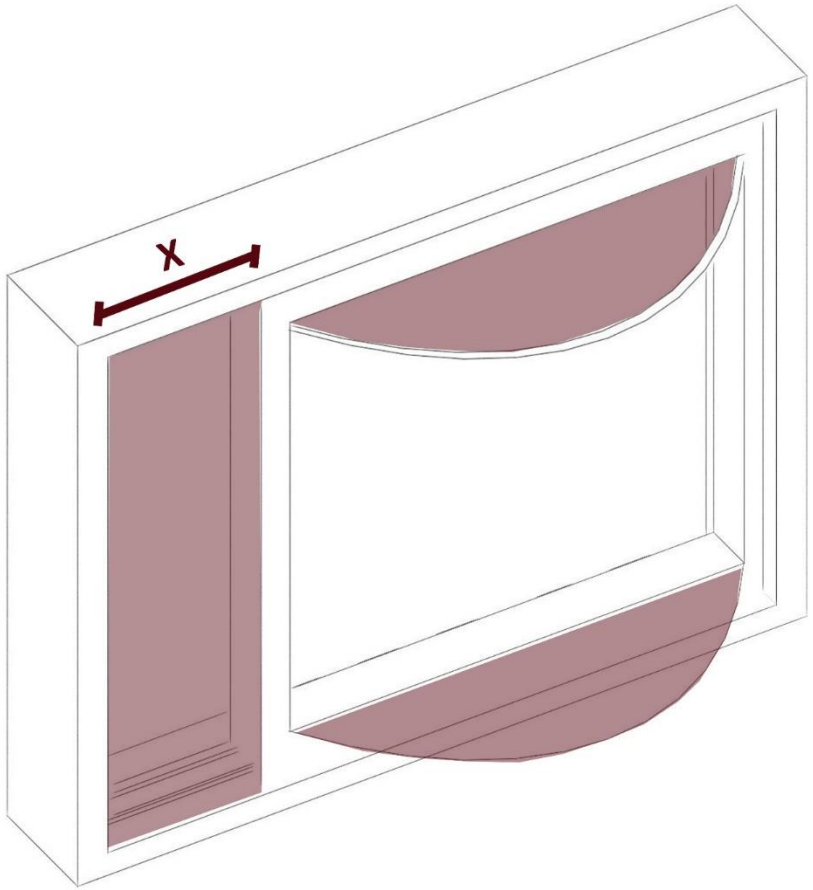
Climate Analysis

X= 15cm
2x 8116 cm^2
1x1500 cm^2

17732 cm^2
Q= 177320 cm^3 / s

X= 30cm
2x 10815 cm^2
1x3000 cm^2

24630 cm^2
Q= 246300 cm^3 / s

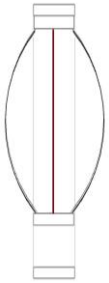


X= 45cm
2x 12589 cm^2
1x4500 cm^2

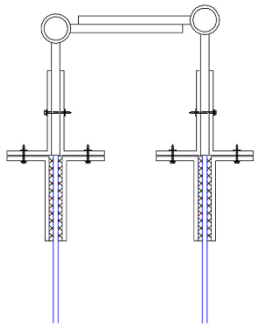
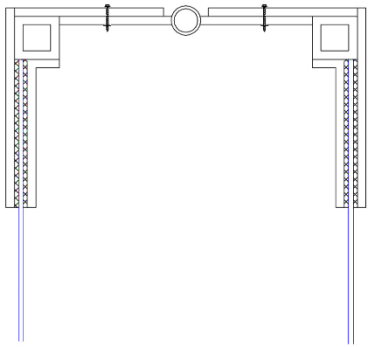
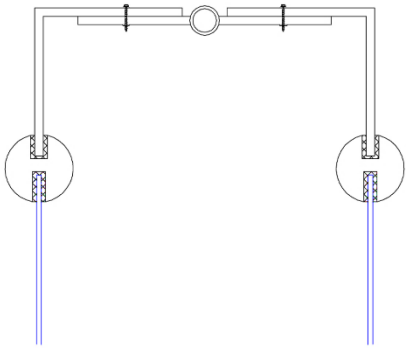
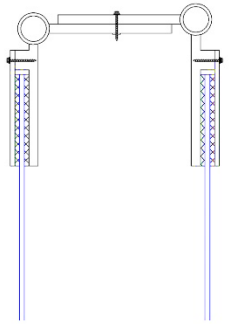
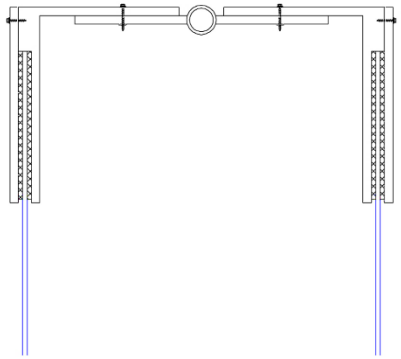
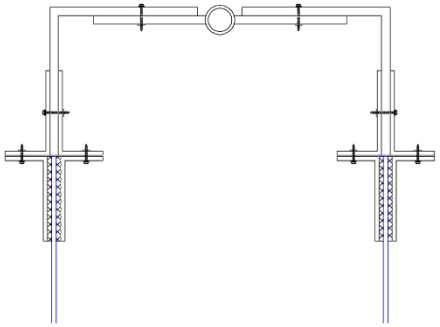
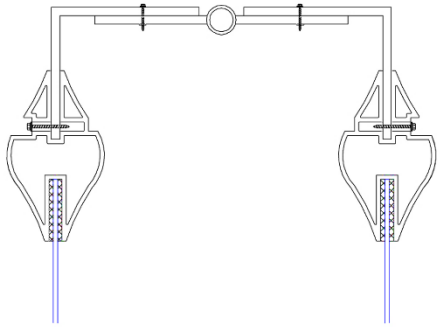
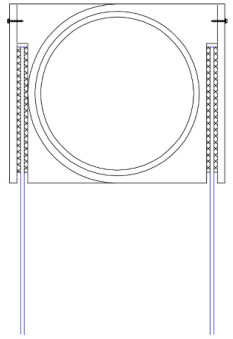
29678 cm^2
Q= 296780 cm^3 / s

Details

Number of Glazing

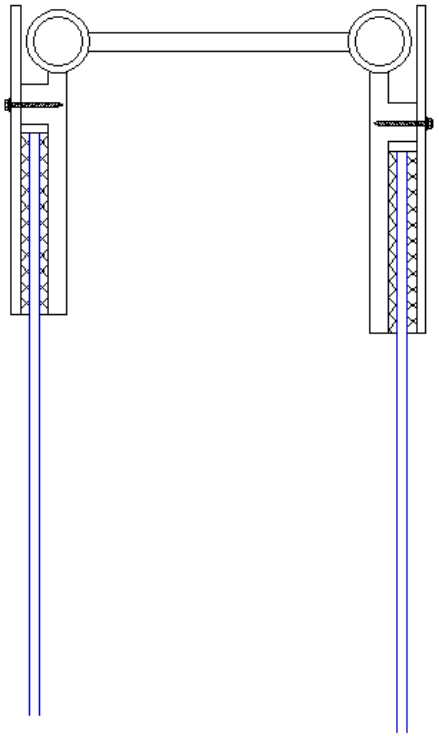
			
+	-	+	-
Less wire	Balance disorders	Improved balance	Extra wires for bending
Lower Electricity consumption	Covering the wire	Possibility of activation by solar radiation	Higher Electricity Consumption
Fast reaction time		Wire protection	Slower reaction time
		Higher airborne sound insulation	Occupy more space from inside
		Higher Thermal Resistance	Heavier

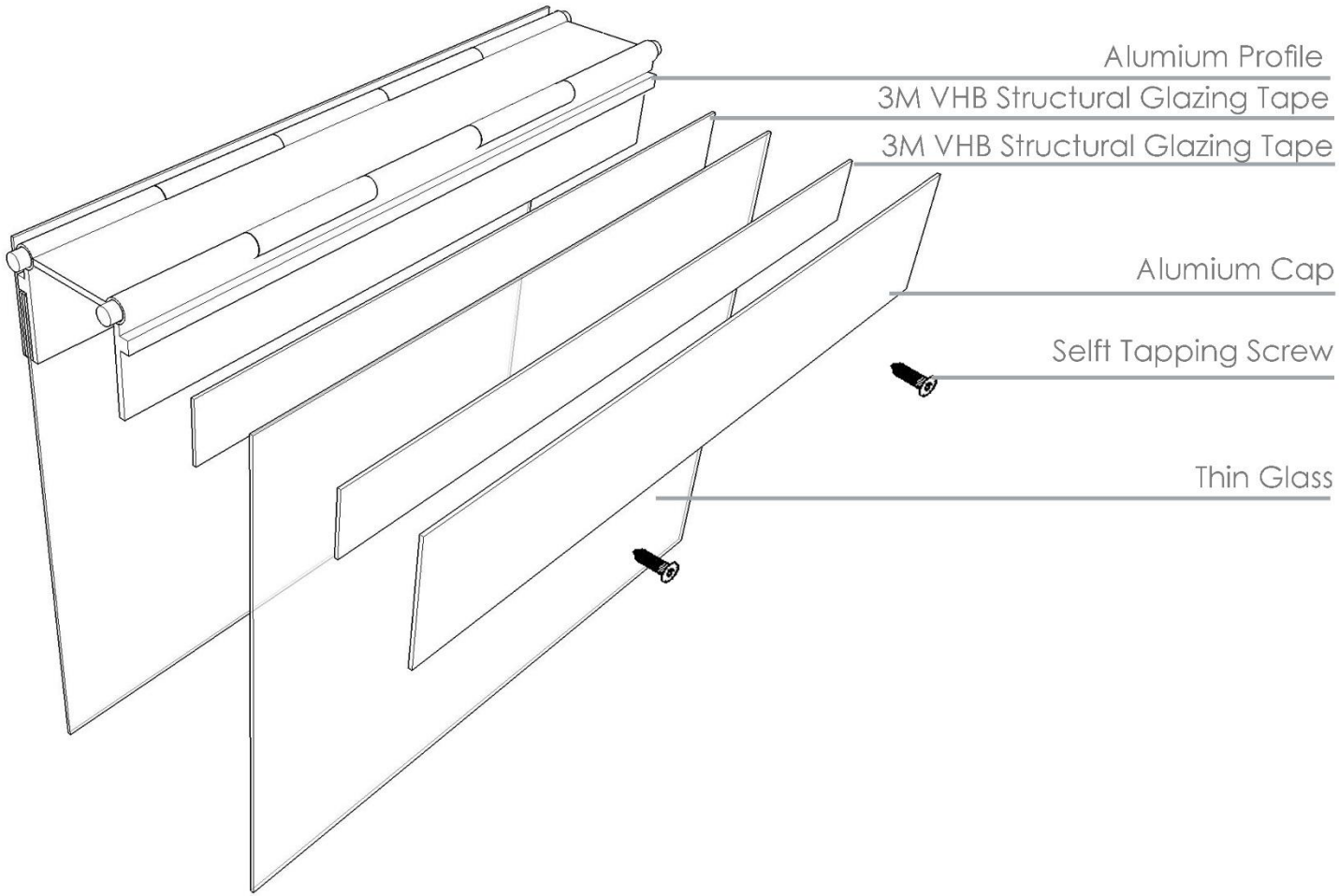
Details

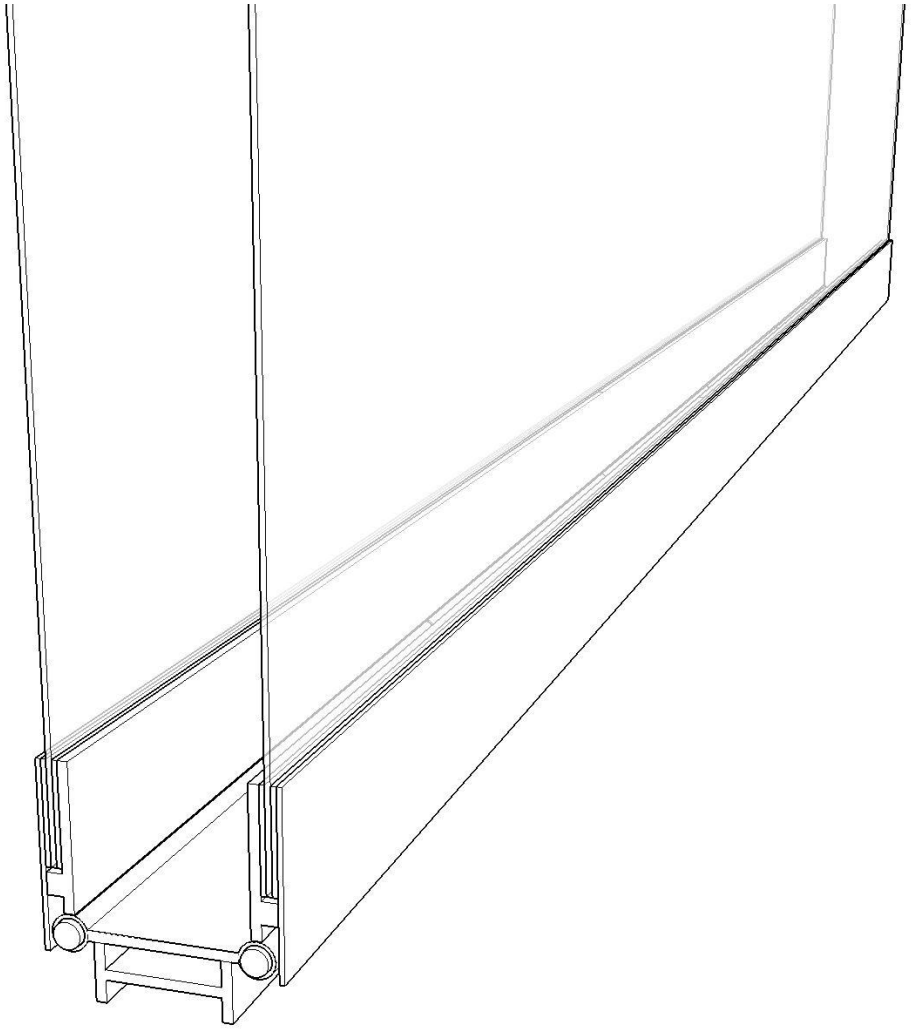









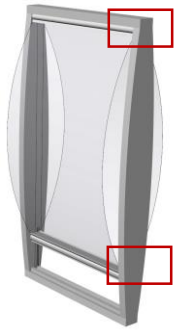
Details

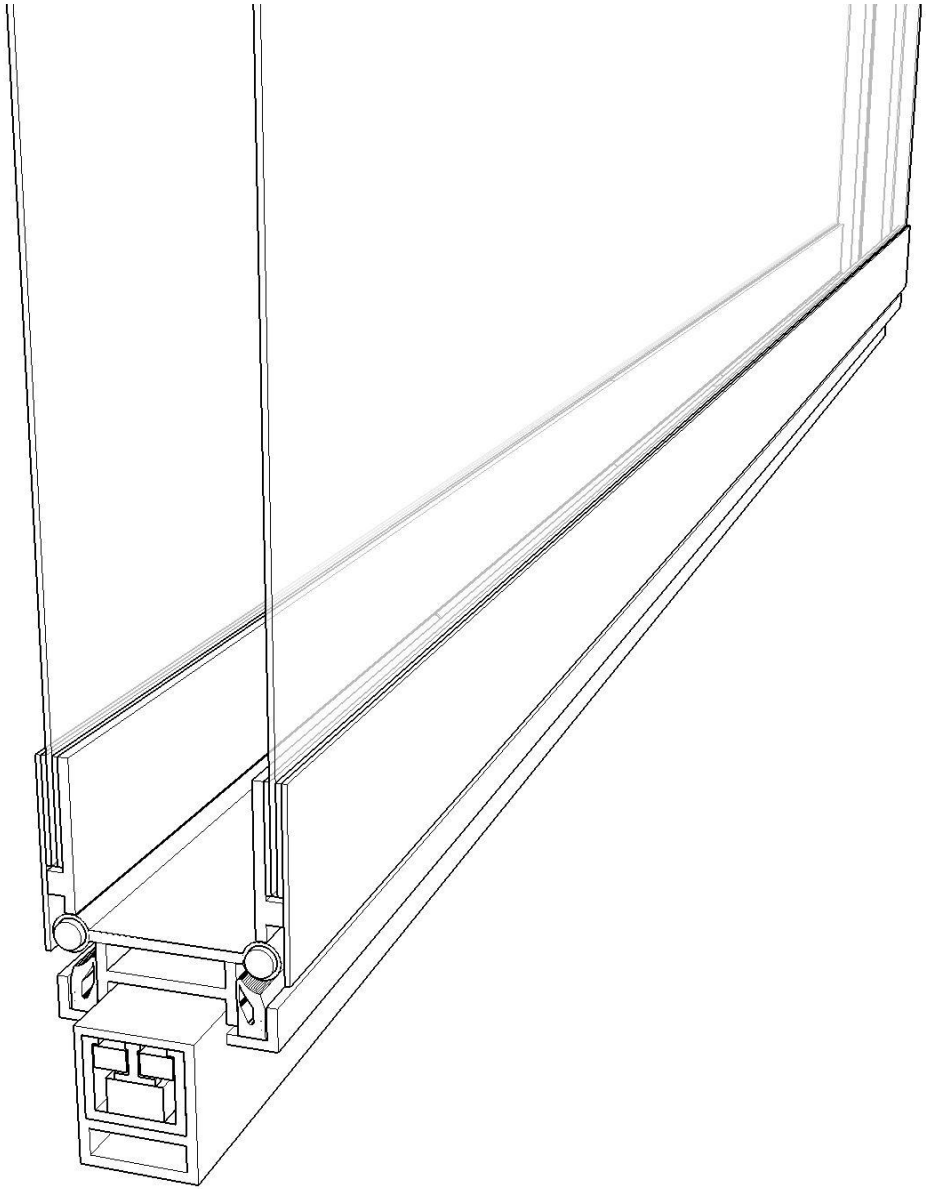
Selected Detail

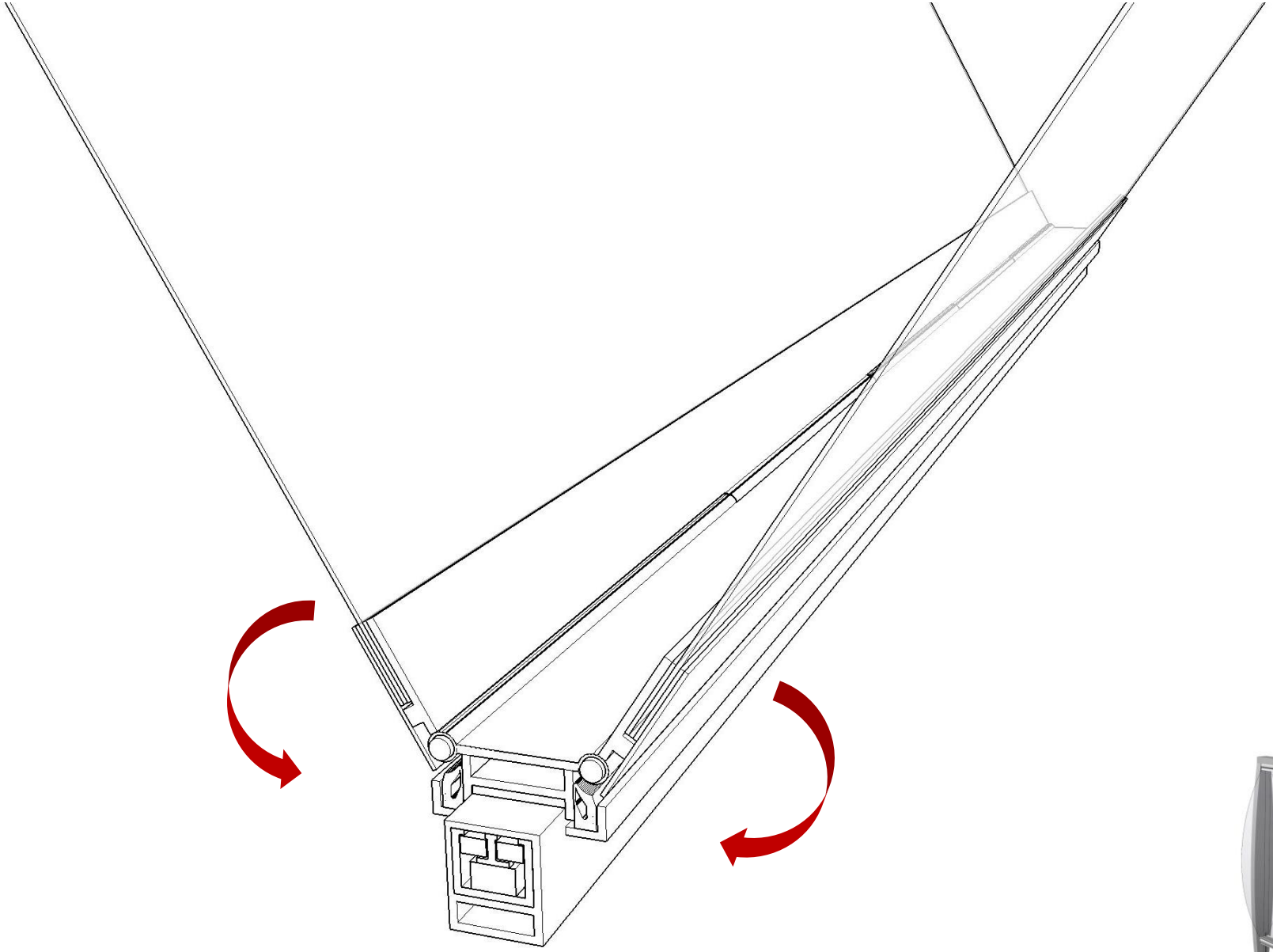


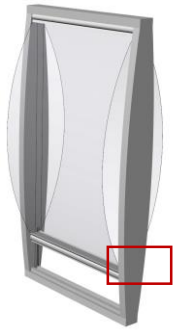

Alumium Profile
3M VHB Structural Glazing Tape
3M VHB Structural Glazing Tape
Alumium Cap
Selft Tapping Screw
Thin Glass

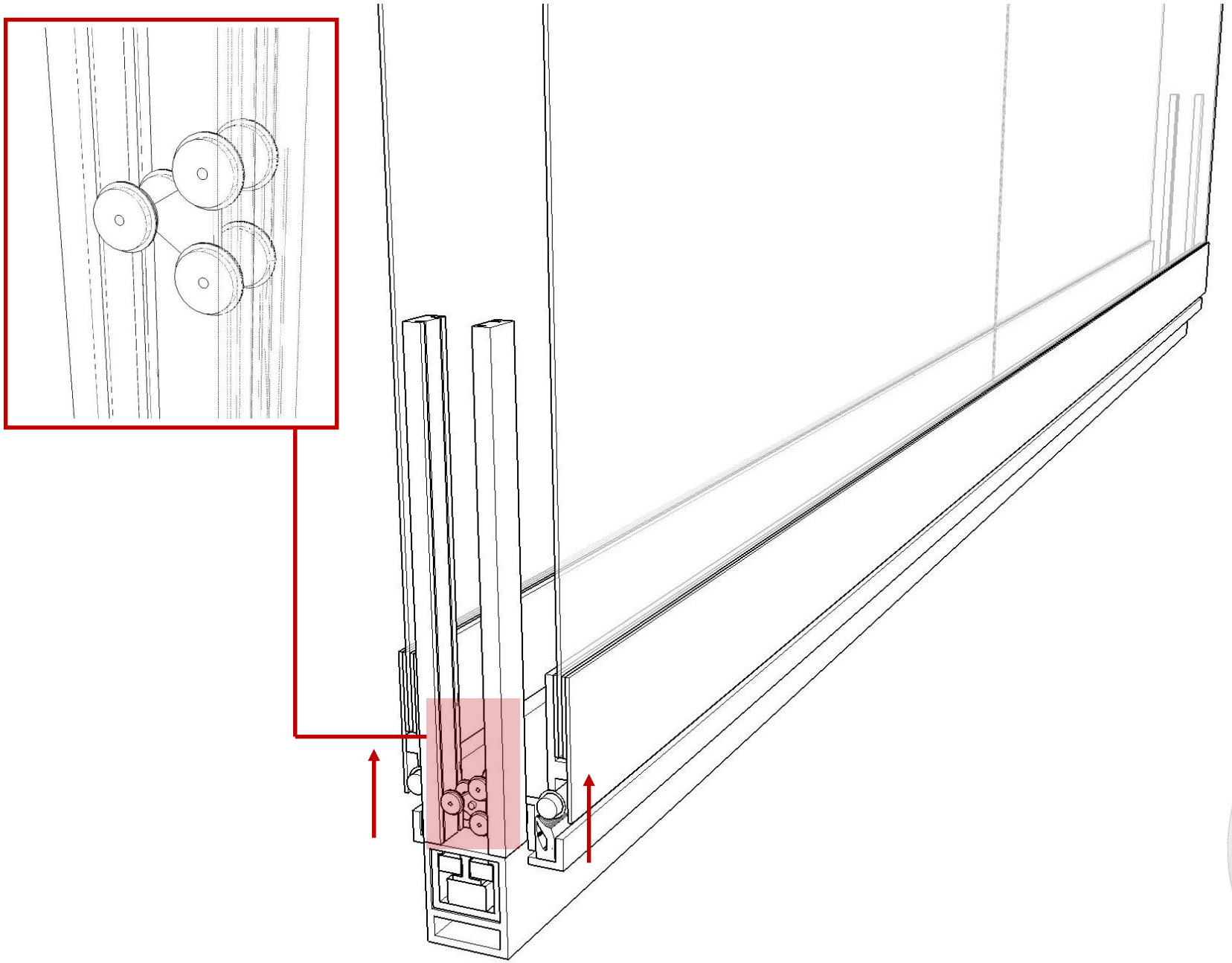


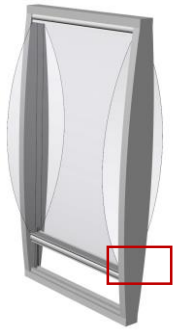


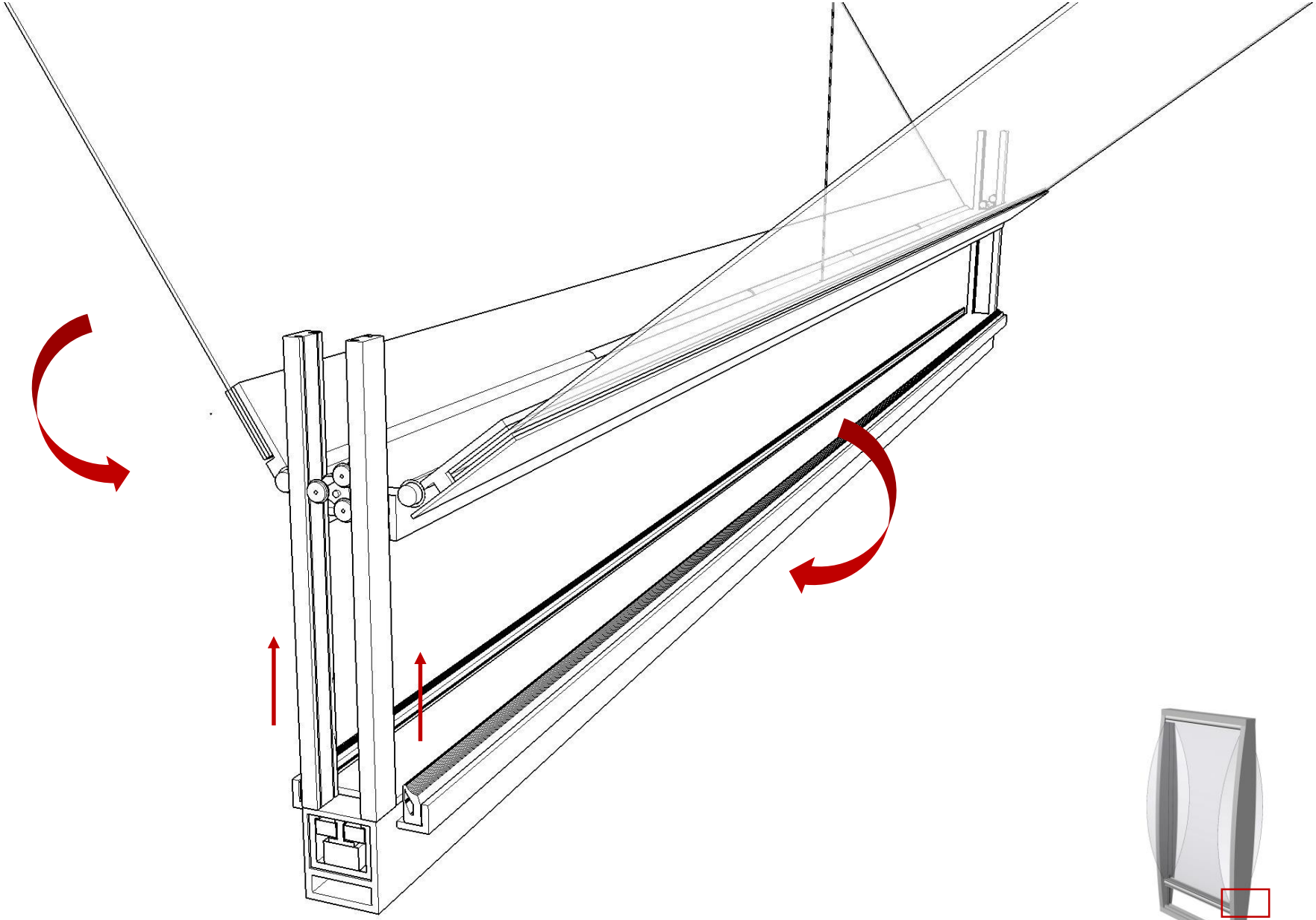








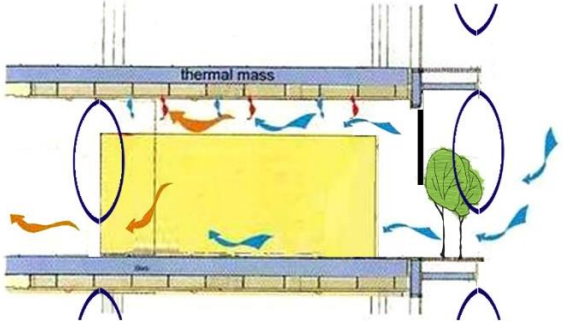




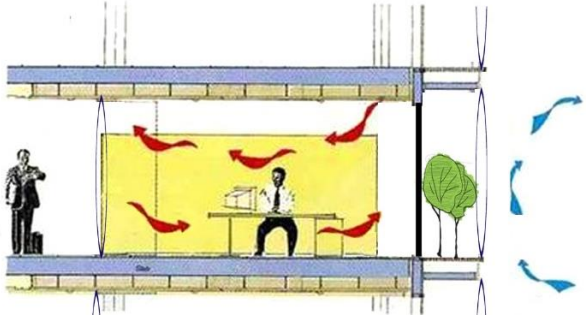
Details

Atrium Window Detail

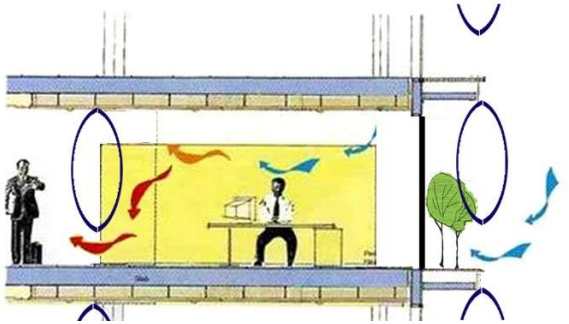
Summer Night
Night Cooling



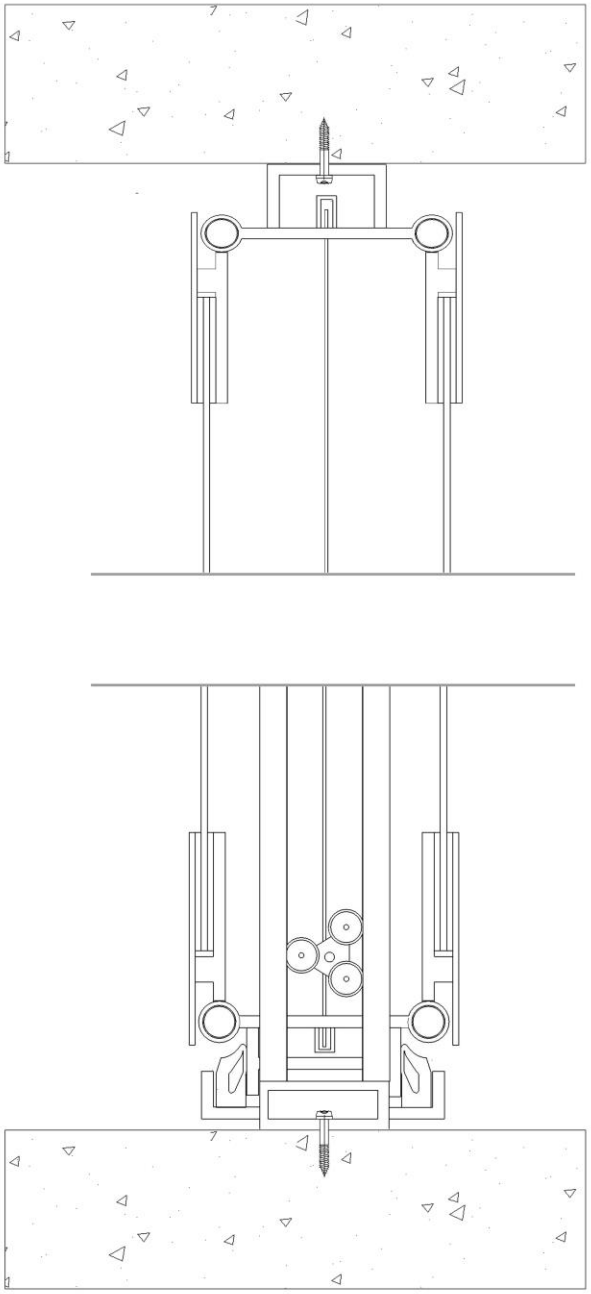
Winter Day
Insulated Buffer Zone

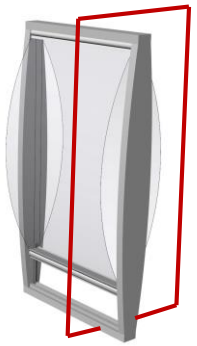


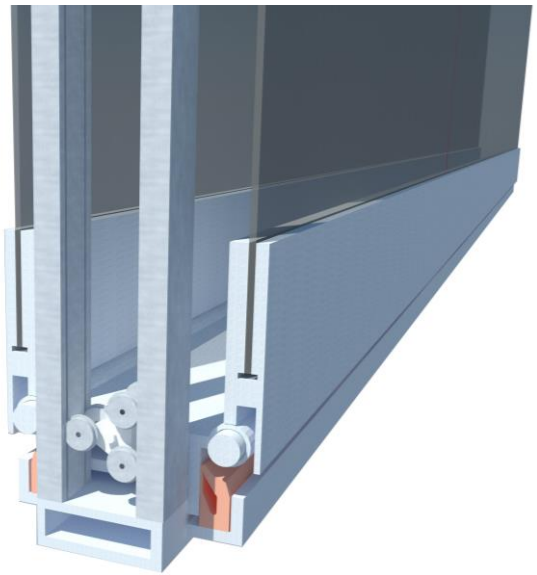
Summer Day
Ventilated Buffer Zone

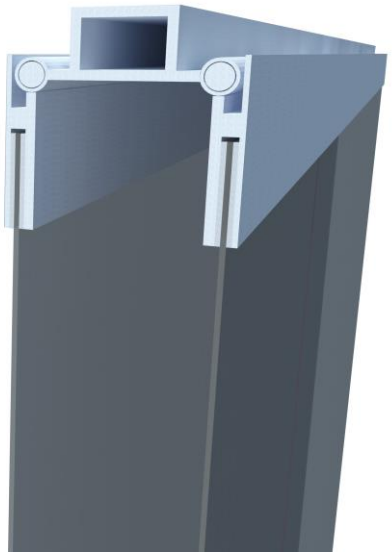


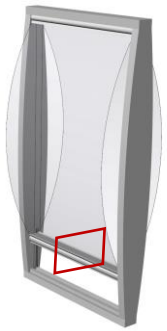
Requirements	
Thermal Insulation	☑
Stiffness for wind load	☒
Transparency	☑
Safety	☒
Natural Ventilation	☑
Airtightness	☒
Watertightness	☒
Acoustic Insulation	☑











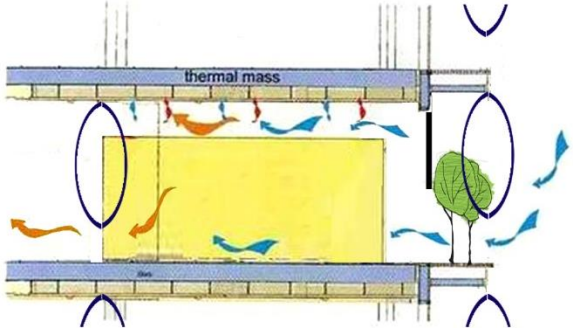

EXIT


EXIT

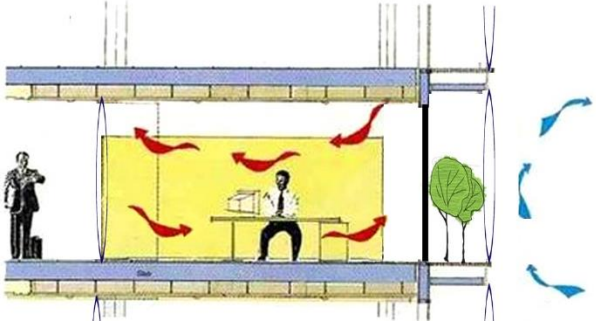
Details

Exterior Layer Of Double Façade Detail

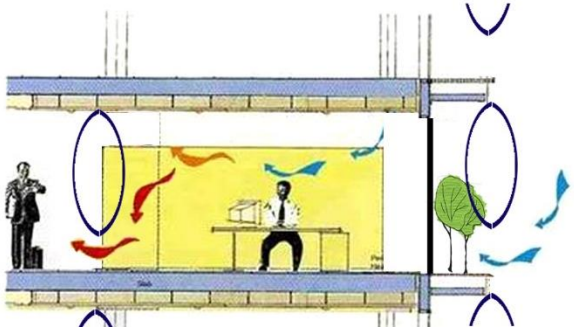
Summer Night
Night Cooling



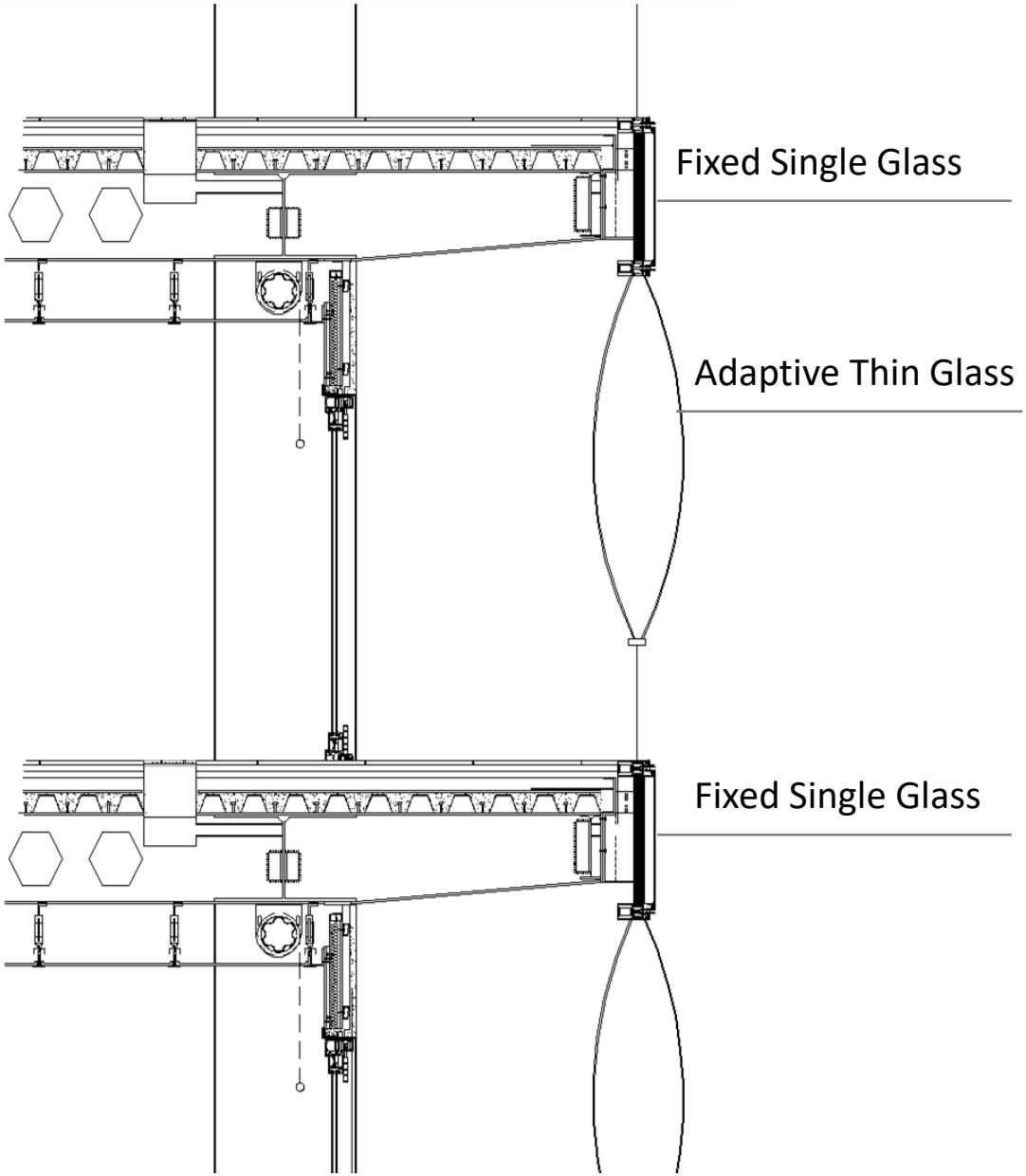
Winter Day
Insulated Buffer Zone

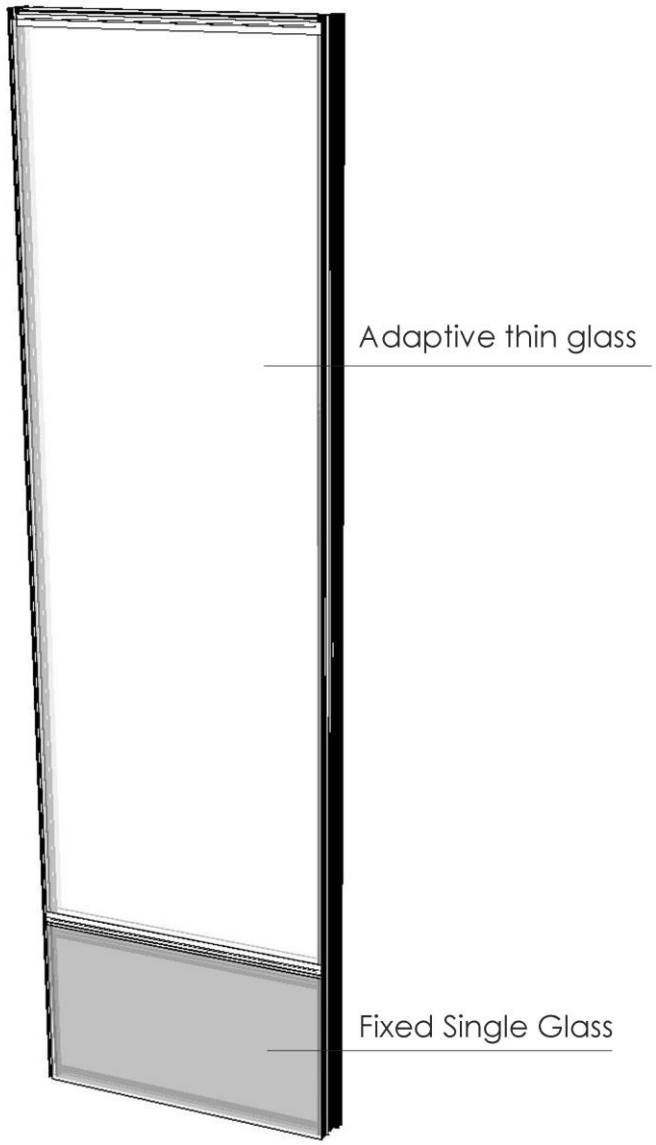


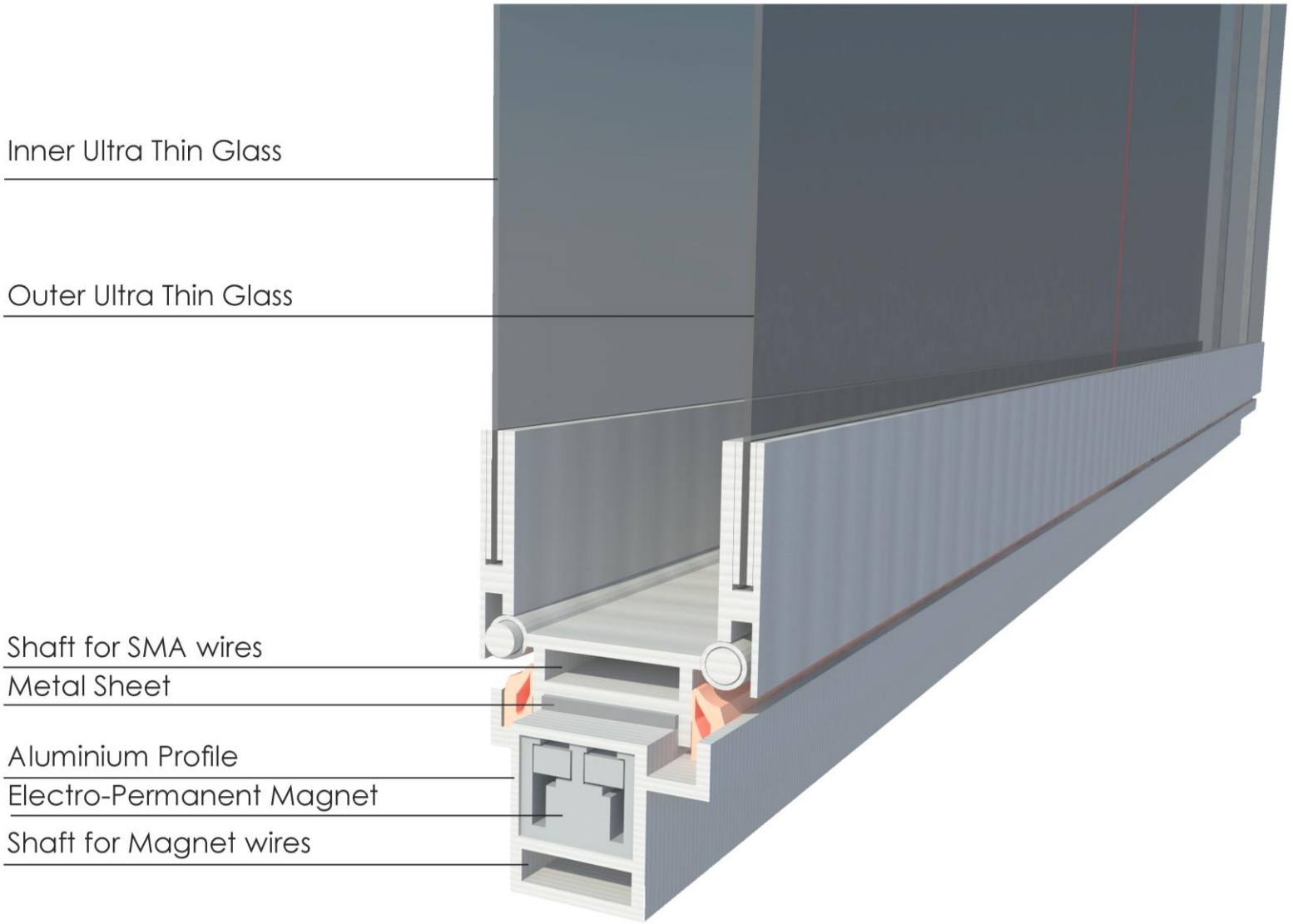
Summer Day
Ventilated Buffer Zone

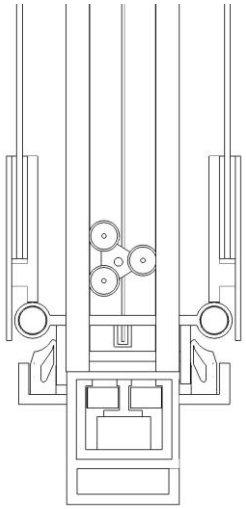


Requirements	
Thermal Insulation	☒
Stiffness for wind load	☑
Transparency	☑
Safety	☑
Natural Ventilation	☑
Airtightness	☒
Watertightness	☒
Acoustic Insulation	☒


Fixed Single Glass
Adaptive Thin Glass
Fixed Single Glass


Adaptive thin glass
Fixed Single Glass


Inner Ultra Thin Glass
Outer Ultra Thin Glass
Shaft for SMA wires
Metal Sheet
Aluminium Profile
Electro-Permanent Magnet
Shaft for Magnet wires



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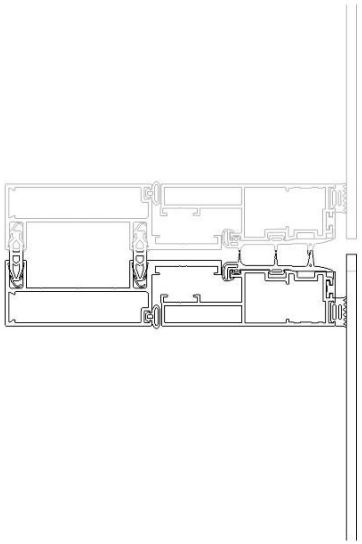
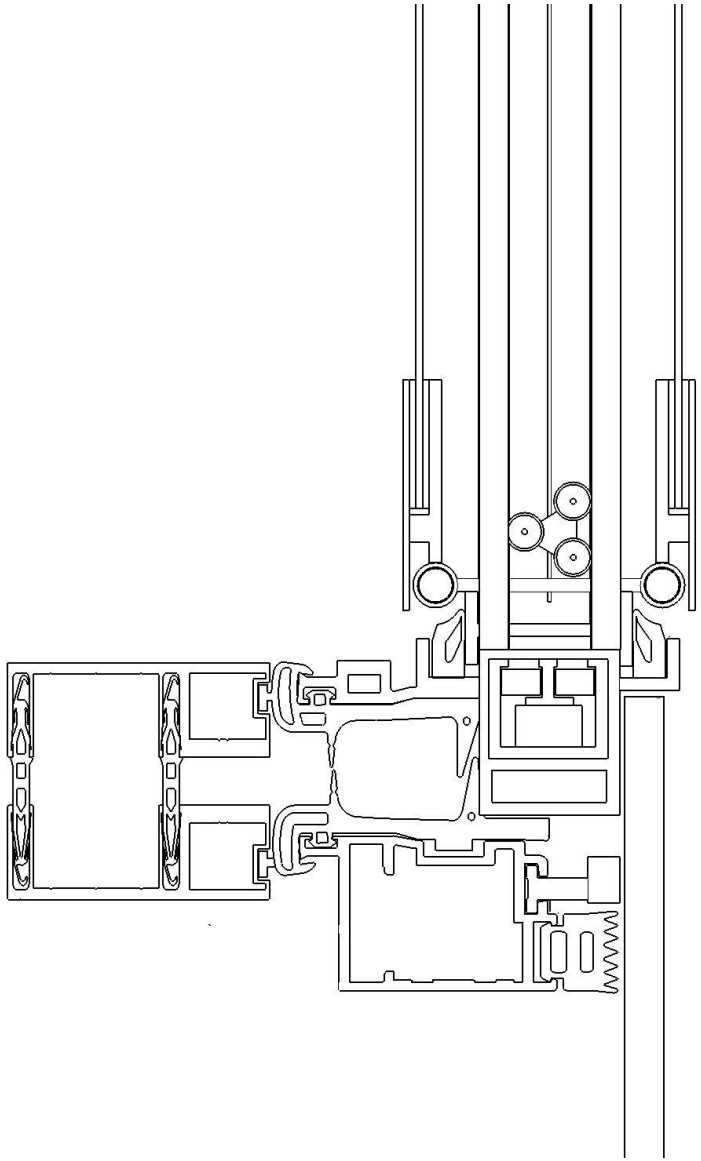
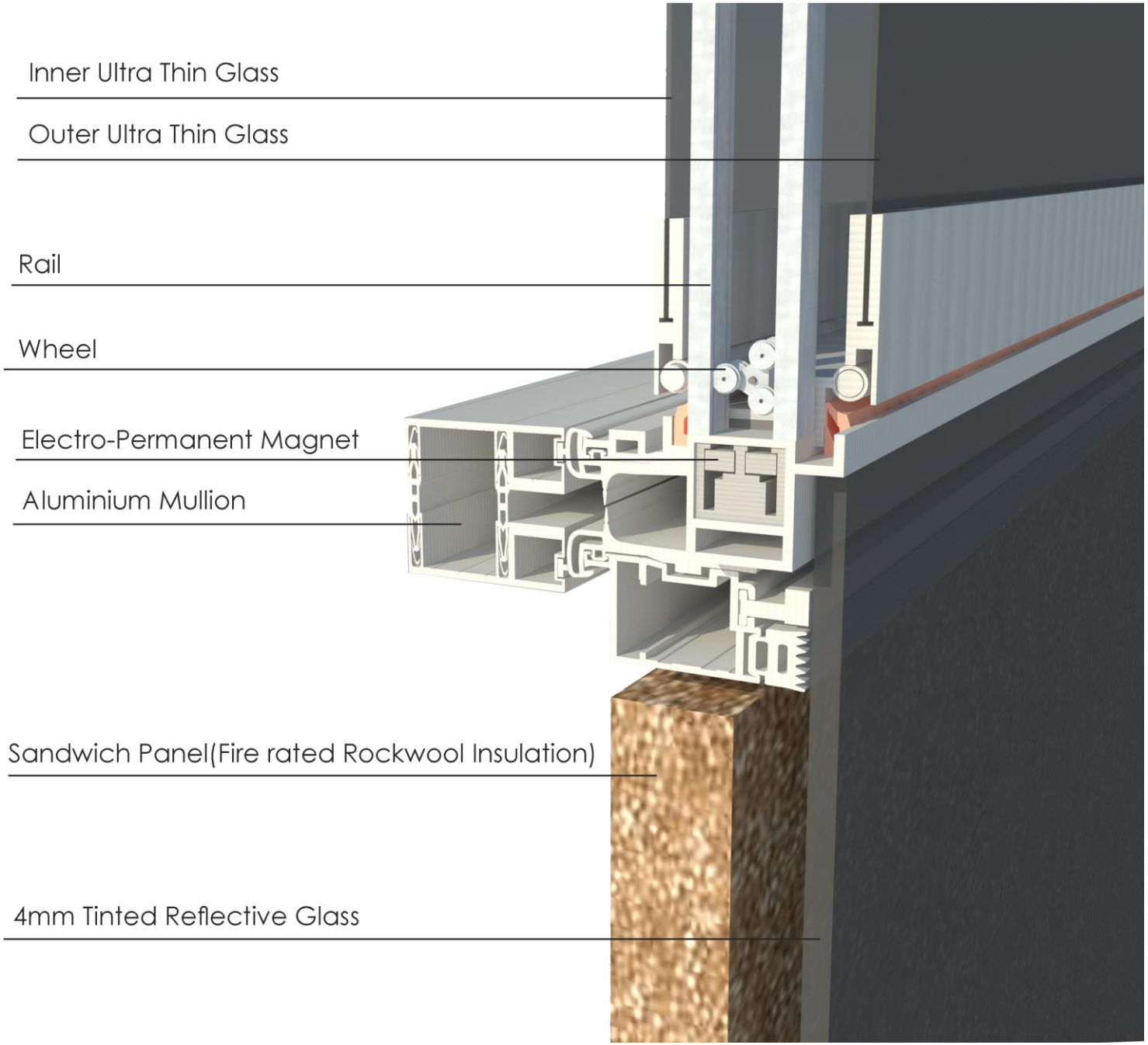
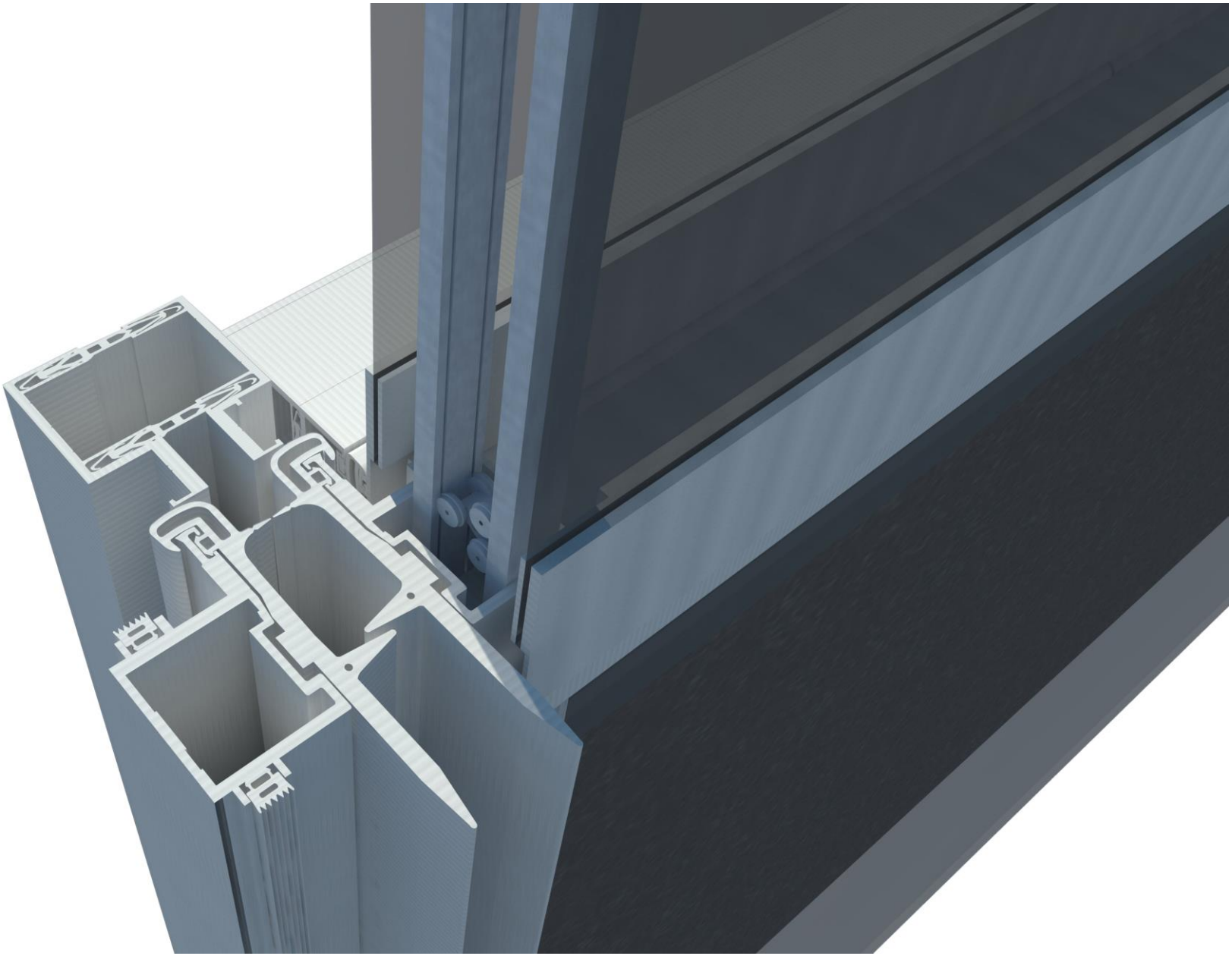
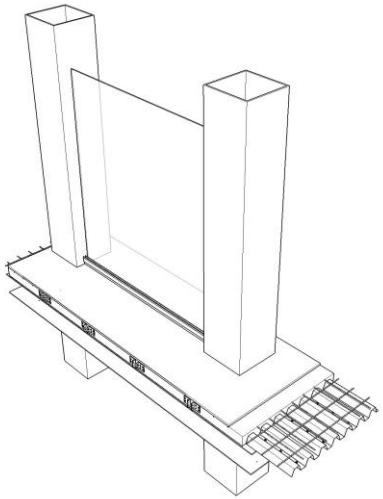


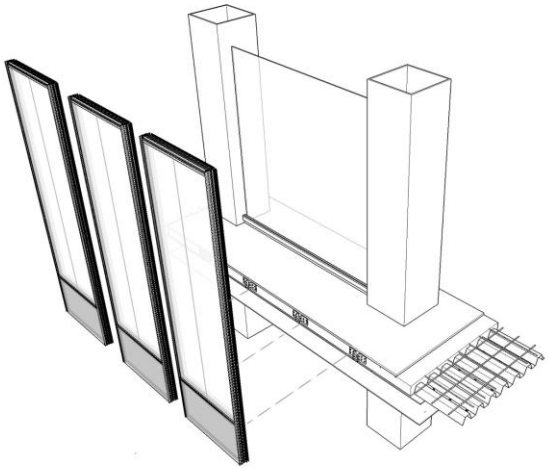


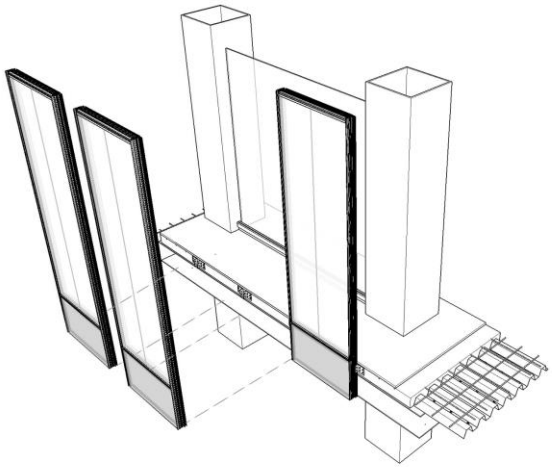

Inner Ultra Thin Glass
Outer Ultra Thin Glass
Rail
Wheel
Electro-Permanent Magnet
Aluminium Mullion
Sandwich Panel(Fire rated Rockwool Insulation)
4mm Tinted Reflective Glass

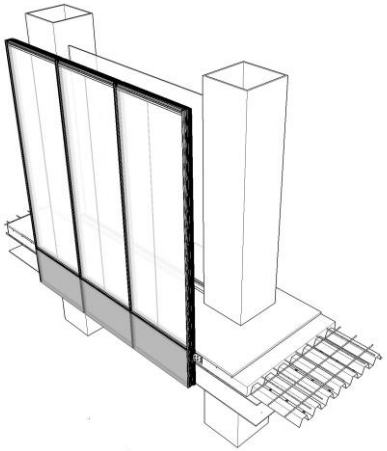


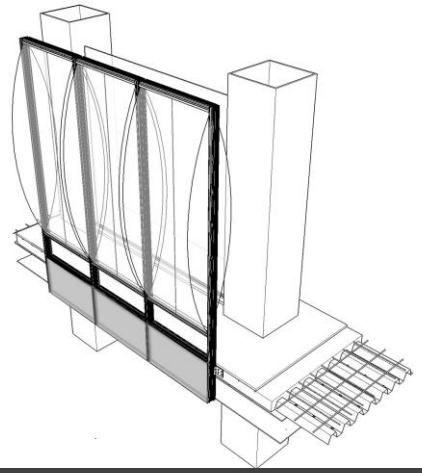
Setup

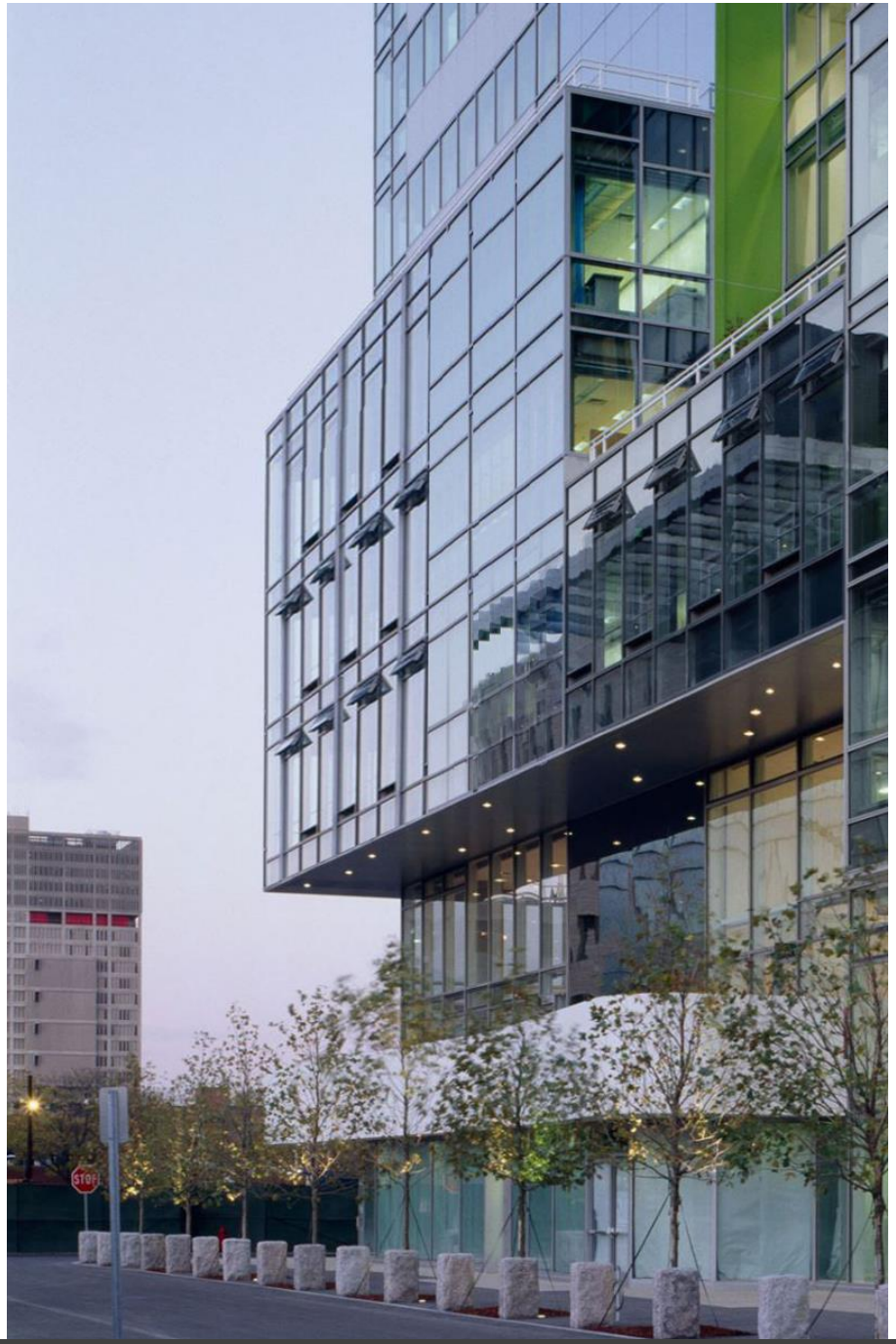


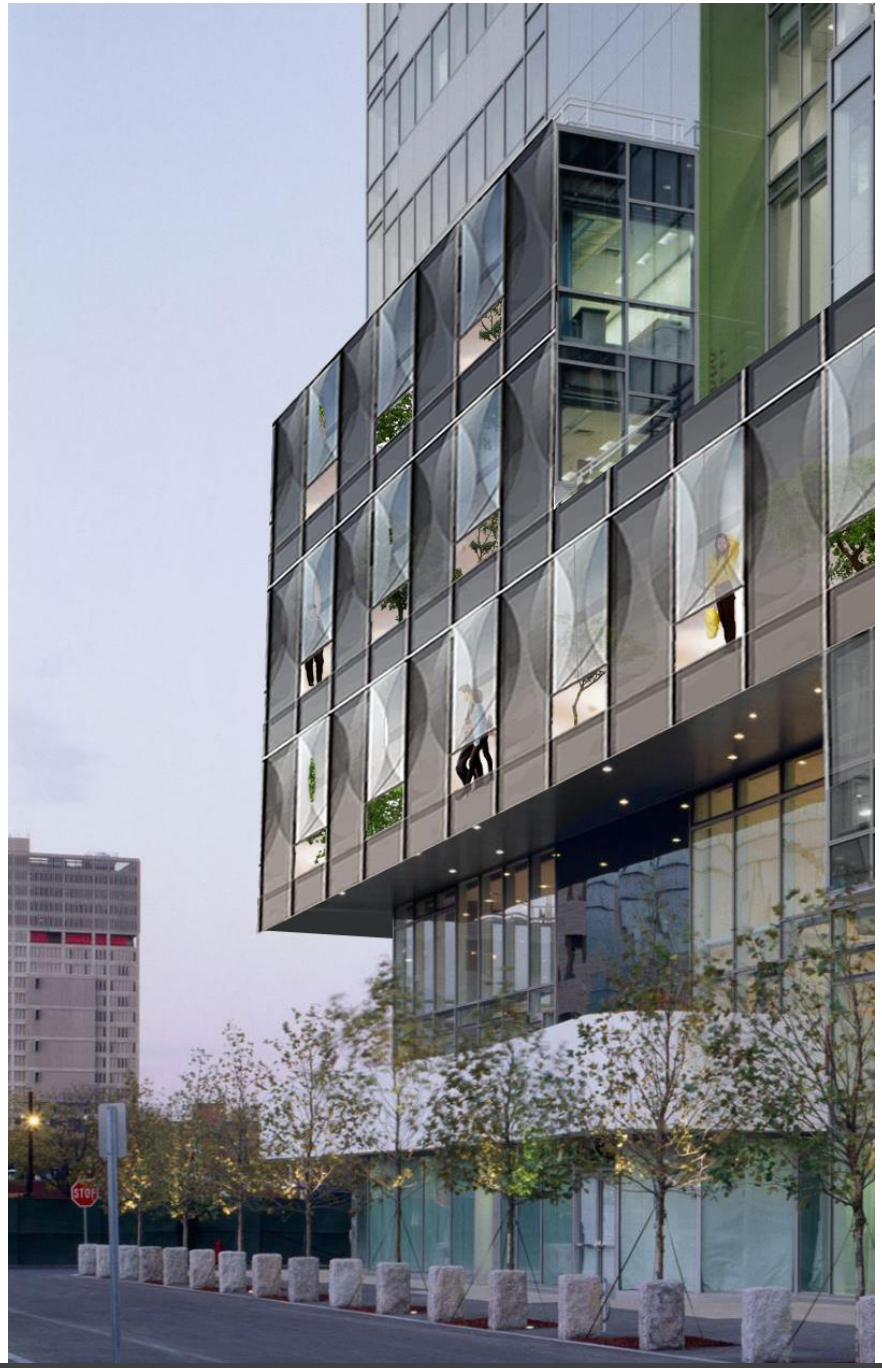









STOP


STOP

Research Structure

Literature Review

Design Exploration

Material Analysis

Practical Feasibility

Case Study

Conclusion

Conclusion

How can a thin glass skin be applied as an adaptive façade developed by smart materials?

Main purpose of using thin glass

Main purpose of making an adaptive facade

Possibilities of movement of the thin glass panel

Possible technologies for bending the thin glass

The most suitable technology for bending thin glass

Necessary force for bending thin glass in different situations

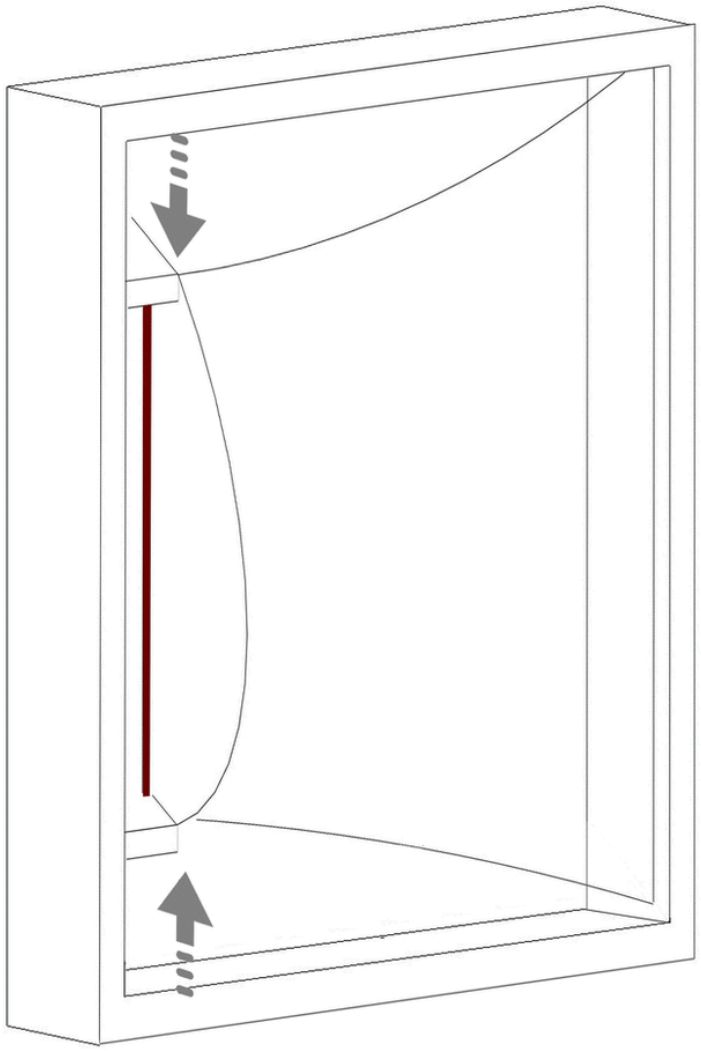
Structural performance of thin glass toward wind

Attachment of actuator to thin glass panel

Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke



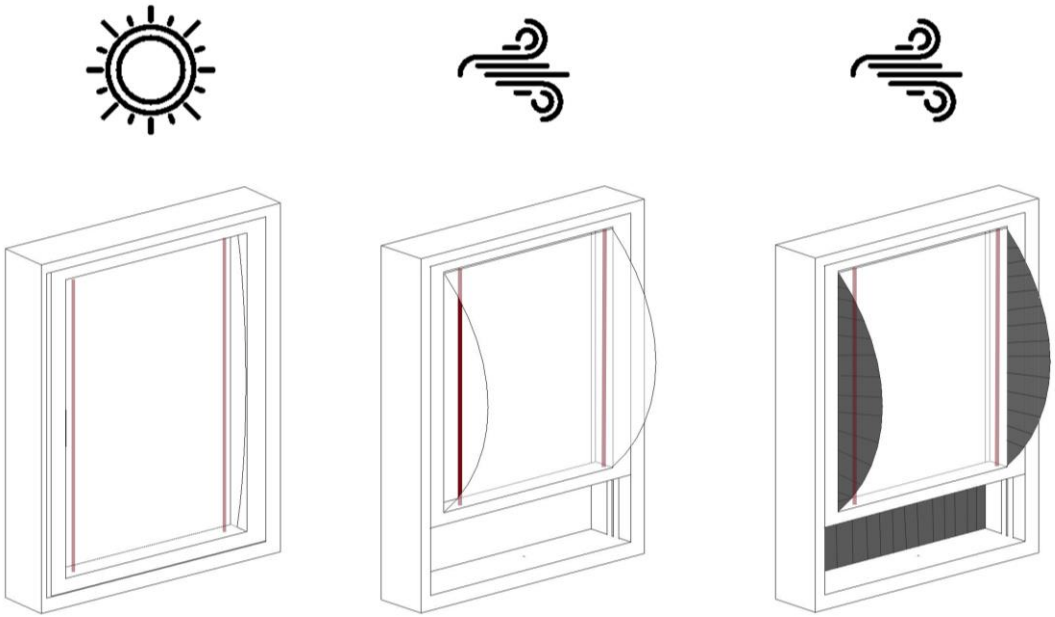
Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

Increasing stiffness under wind

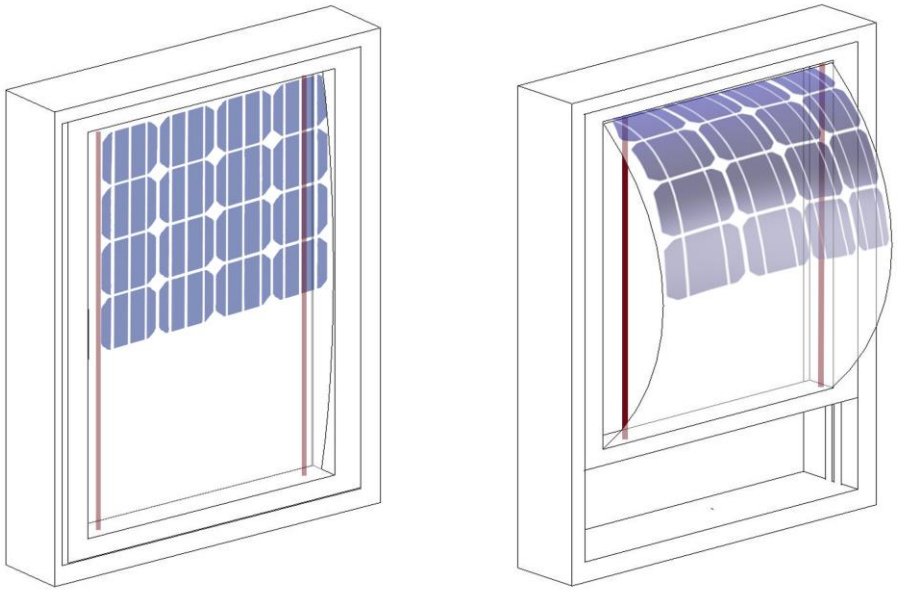


Closed Window

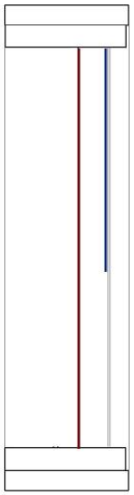
Activation of SMA
Bending the Glass
Increasing Stiffness

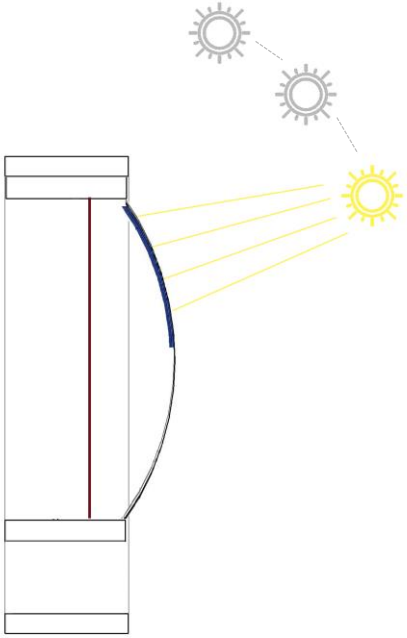
Integration with
elastic fabric

Adaptive Solar facade

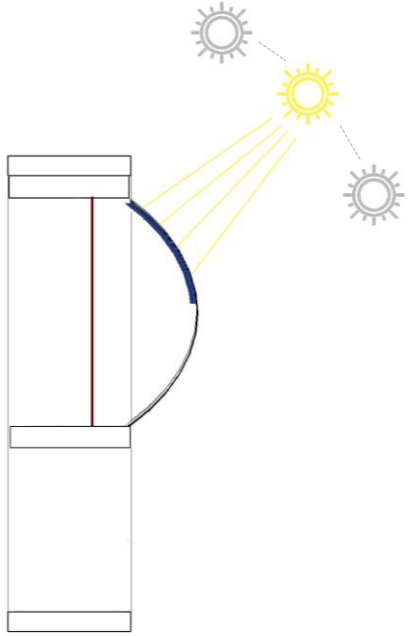


Adaptive Solar facade

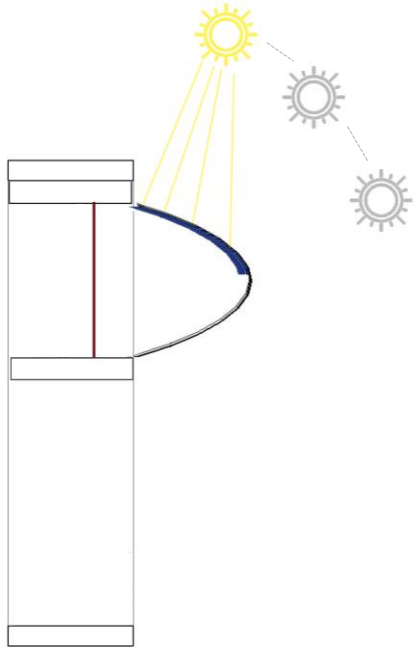




14° angle
Winter

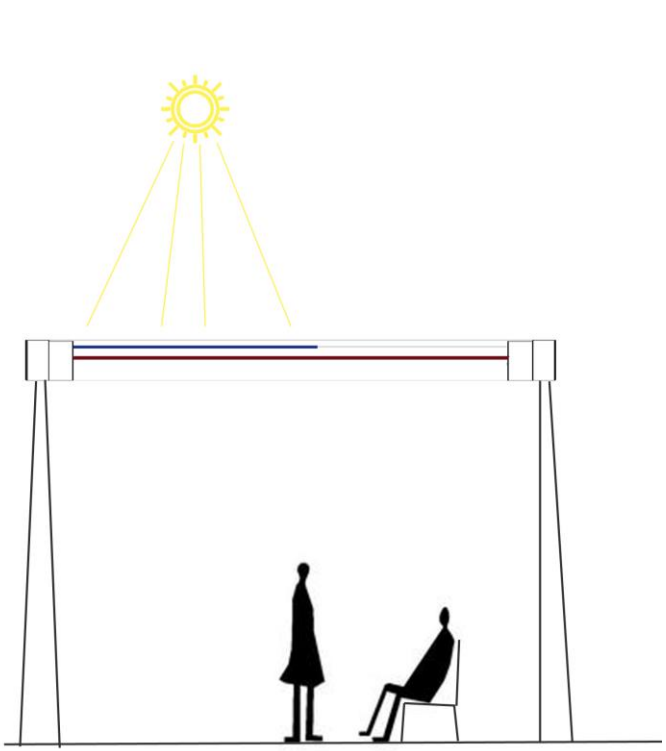


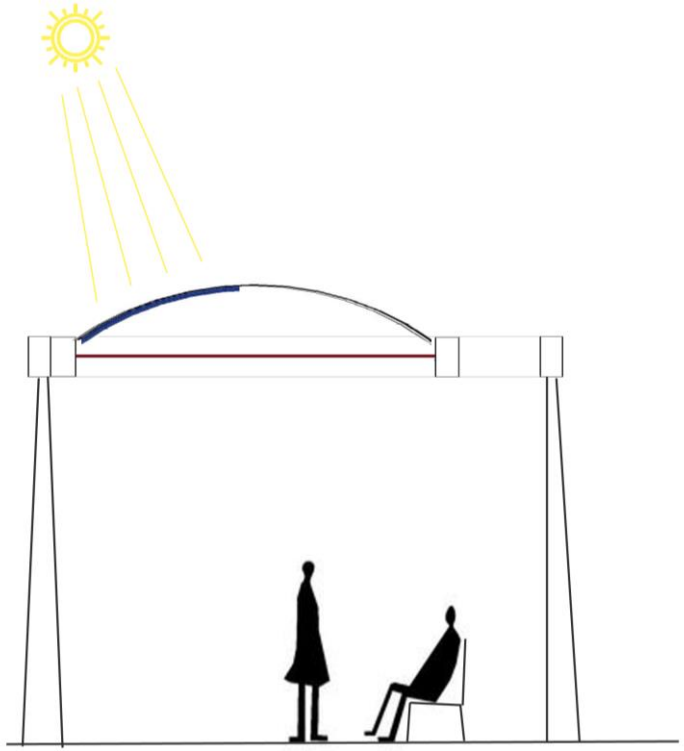
38° angle
Spring/Autumn



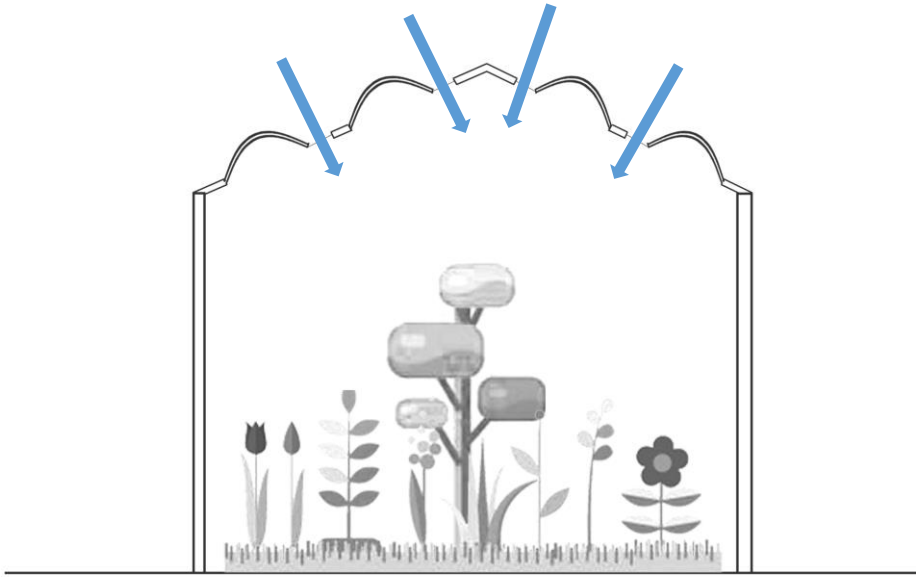
62° angle
Summer

Adaptive Solar Canopy





Auto Vent Greenhouse



Conclusion

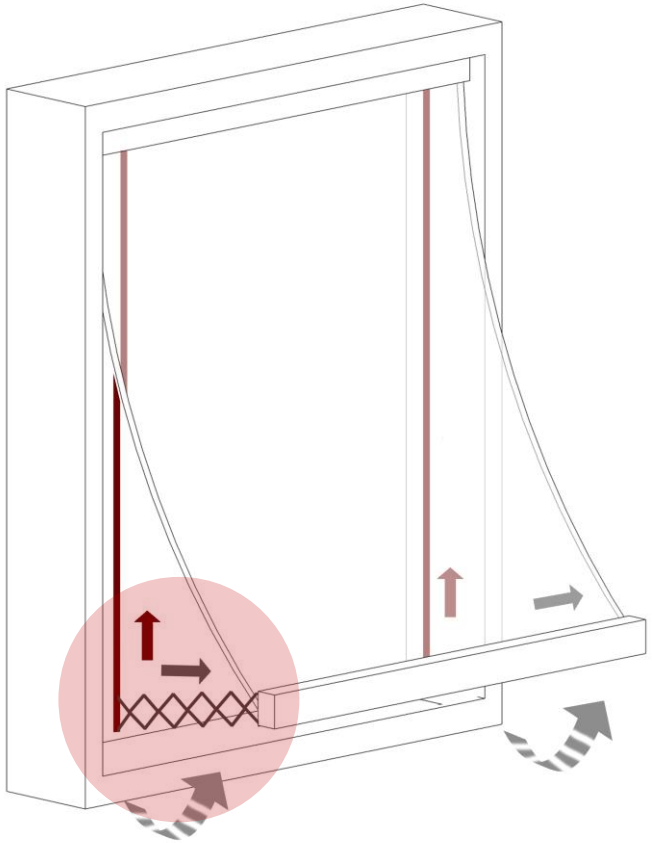
Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

Integration with other actuator systems

Scissor Mechanism



Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

Integration with other actuator systems

Two-way SMA

Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

Integration with other actuator systems

Two-way SMA

Activation of Flexinol by solar radiation

Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

Integration with other actuator systems

Two-way SMA

Activation of Flexinol by solar radiation

Single skin laminated glass

Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

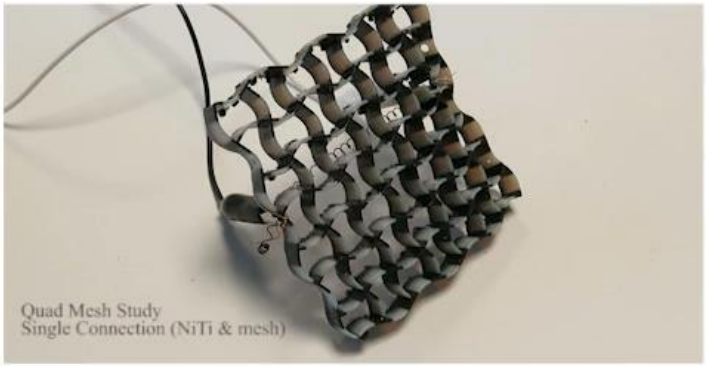
Integration with other actuator systems

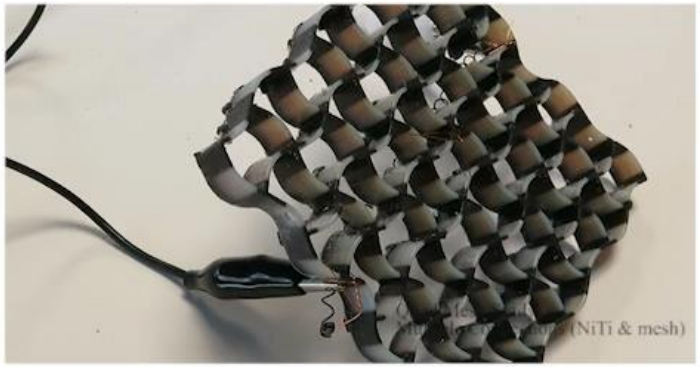
Two-way SMA

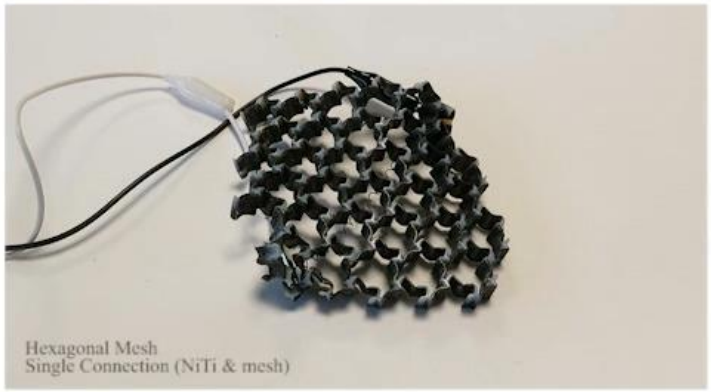
Activation of Flexinol by solar radiation

Single skin laminated glass

3d printing of Shape Memory Alloy







NiTi Wire
Mandrel Size 2.4mm
Wire Diameter: 0.020"
Pitch: 0.5 mm

Conclusion

Recommendations for further development

Further consideration for Flexinol attachment and stroke

Different application for the system

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Two-way SMA

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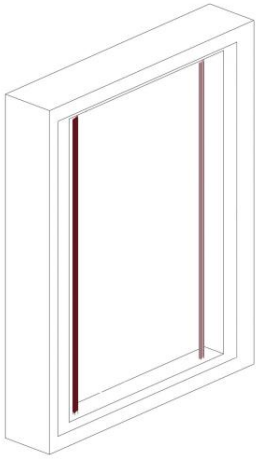
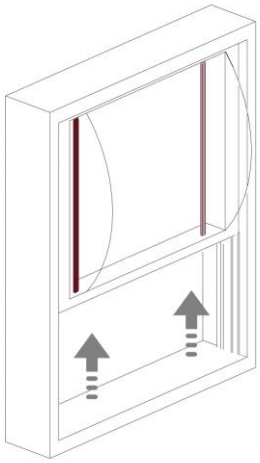
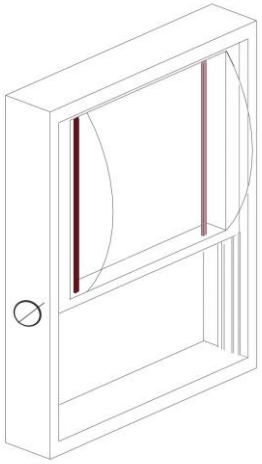
Electricity Reduction



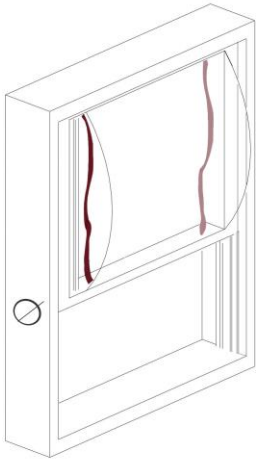
Closed Window



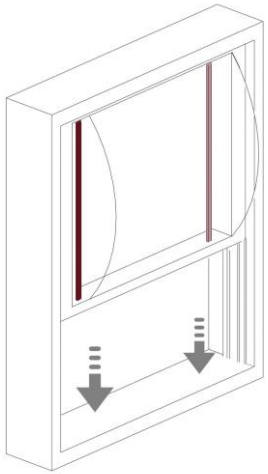
SMA Activation



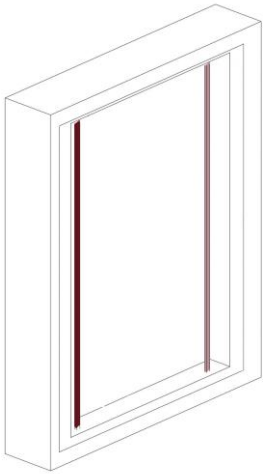
Locking Window



Turning off Electricity



SMA Activation



Closing Window

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Cost reduction

Thank You