Pure Transparency

Designing a complete glass shelter for the temple of Apollo Epikourios at Bassae

Final Presentation

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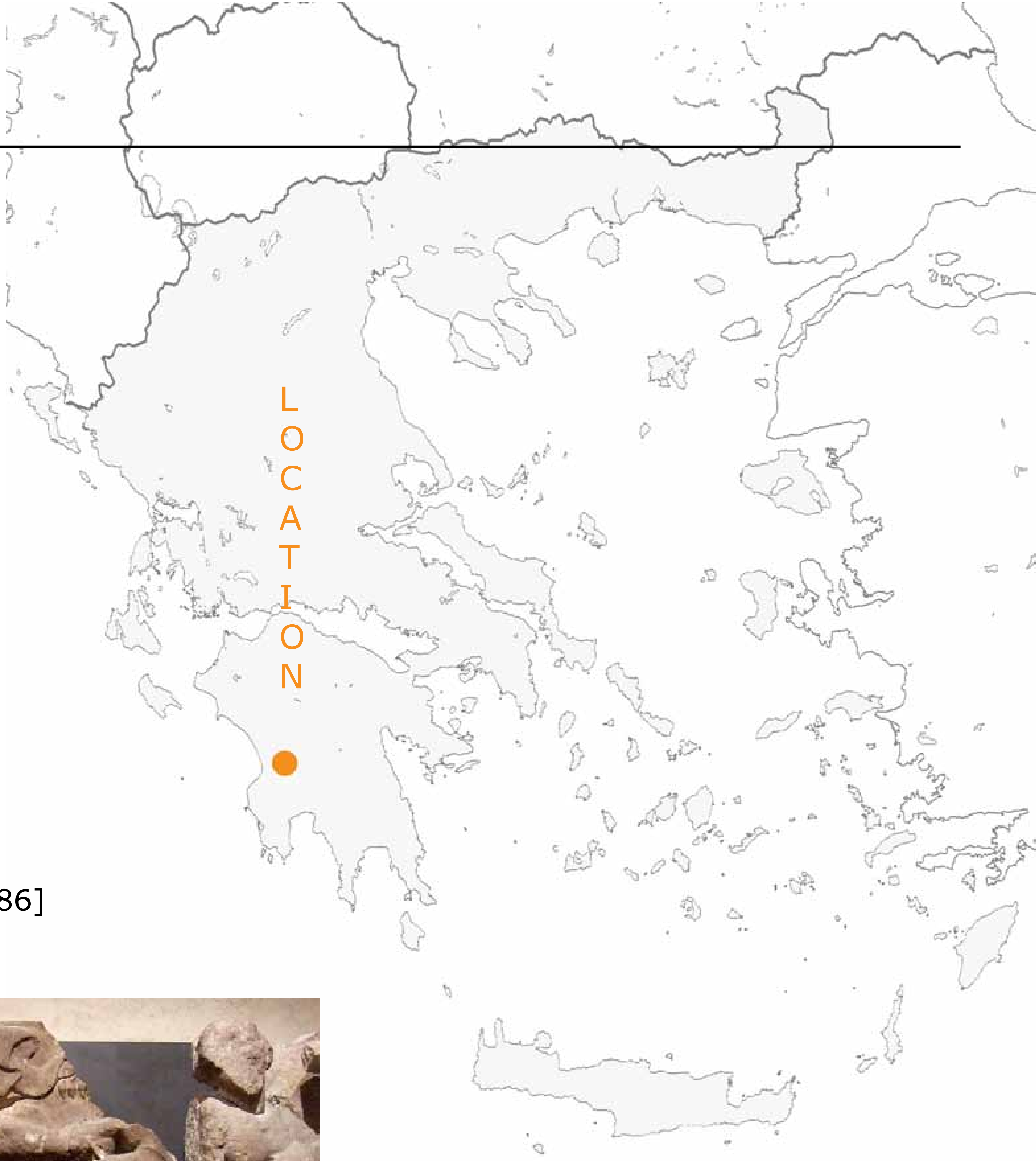
Mentors: Fred Veer   Regina Bokel

The temple

Quick Facts



Location: Bassae, Peloponesse, South Greece

Altitude: 1131 m

Date: 420-400 BC

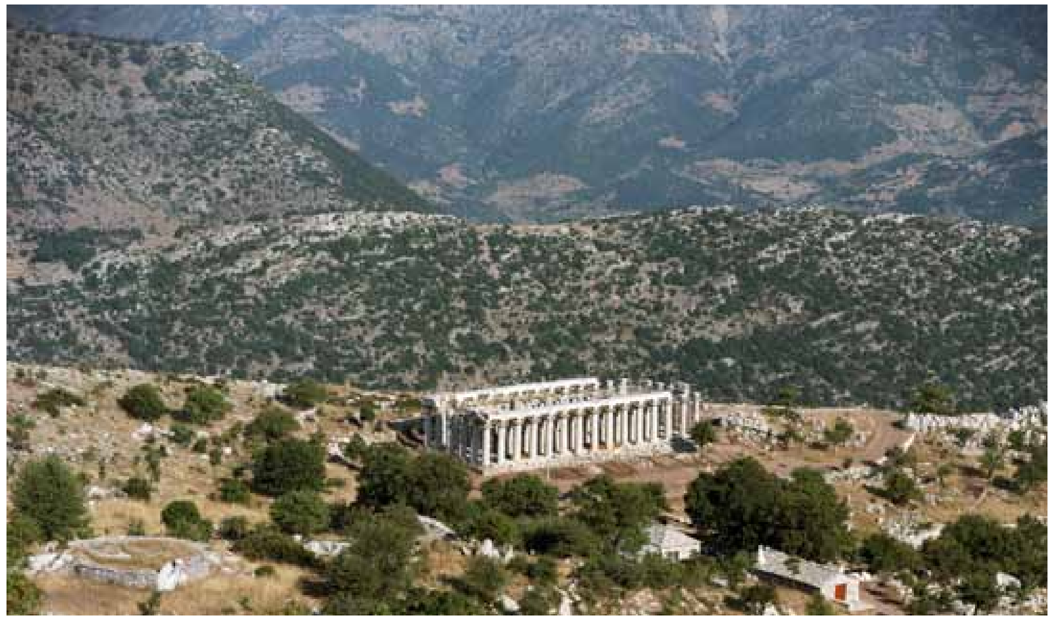
Architect: Iktinos

Type: Doric Temple

Overall dimensions: 39.9 m x 16.1 m

Material: Local Gray Limestone

The first Greek Monument to be listed as **UNESCO World Heritage** [1986]



Why?

- The harsh weather conditions together with
- The nature of the main construction material, the local gray sedimentary limestone
- The wide external temperature range
- The intense seismic activity in the area
- The human pillaging
- The foundation conditions of the temple.




Assessment of the existing solution [Canopy]

The temple is not visible from outside

Leakages on the roof allow the water to penetrete

The monument is always seen in subdued light

Objective

"Design a new shelter that protects the temple against the elements and at the same time it exhibits the monument by placing it into full view."

Objective

Requirements

Design Criteria

Materialization

Protect the temple from the elements (ice, rain) → Closed Shape

Connect the monument with its Surroundings; Make it publicly visible → **Transparency**

Minimize the temperature fluctuations → **Thermal Performance**

Closed Shape, **Transparency**, **Thermal Performance** → Minimalistic Design; Material Assessment

Material Assessment → Cladding; **Load-bearing Structure**

Cladding, **Load-bearing Structure** → **Glass**

Points of Focus

Requirements

Design Criteria

Materialization

Protect the temple from the elements (ice, rain)

Closed Shape

Connect the monument with its Surroundings

Make it publicly visible

Transparency

Minimize the temperature fluctuations

Thermal Performance

Minimalistic Design

Material Assessment

Cladding

Load-bearing Structure

Glass

Challenges

1. Architecture

Combine ancient with high-tech architecture

2. Structure

Such a large scale glass structure has **never been realized before**.

Demountable structure / Seismic Issues : Design a "moving" structure

3. Thermal Performance

Protect the temple from ice formation / Minimize the temperature fluctuations

Optimize through passive systems

4. Sustainability

Maintenance of the shelter

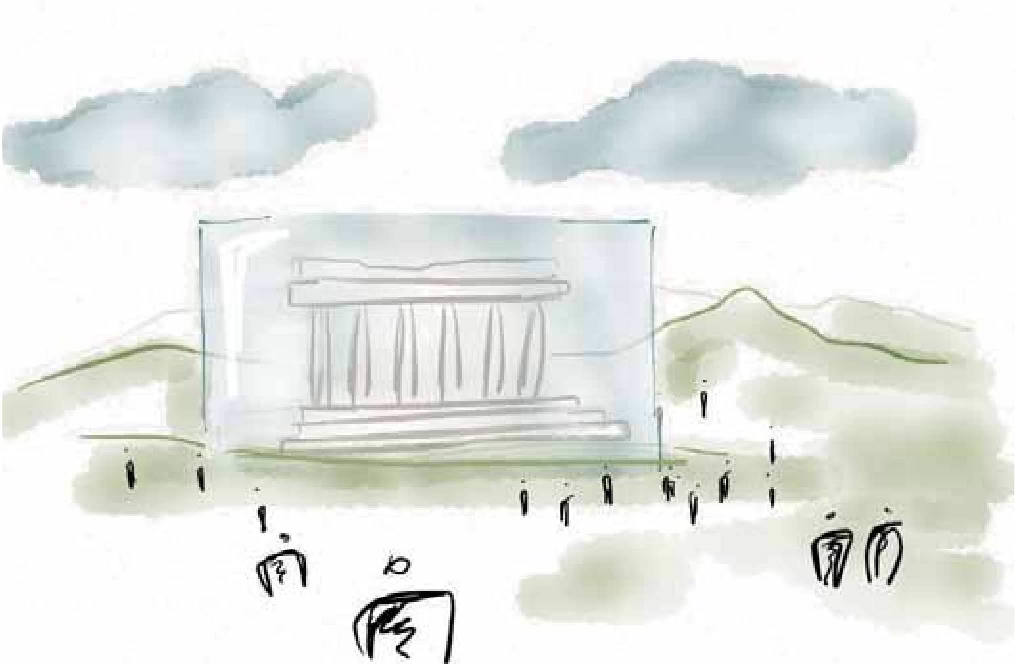
Is such a structure possible?

Architectural Design

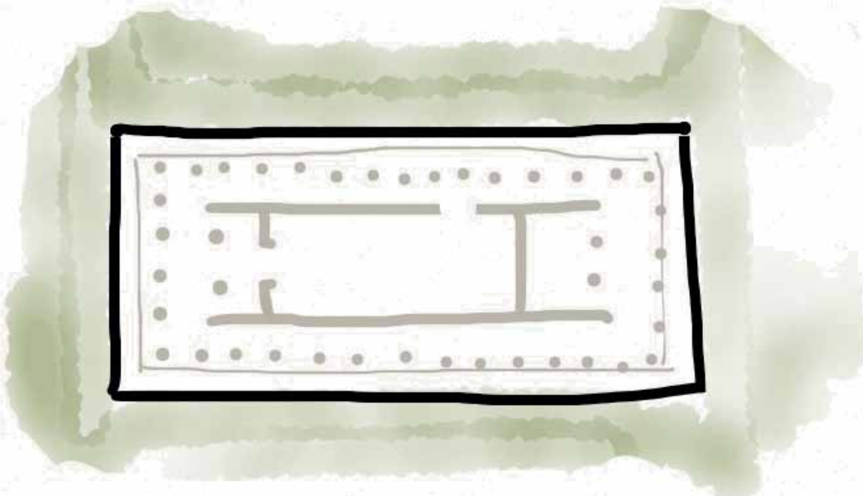
Architectural Design

Main Design Principles

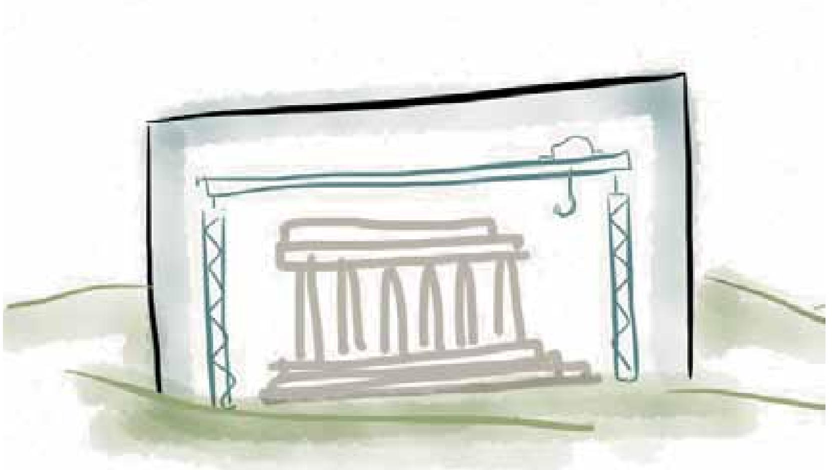
1. Maximum Transparency



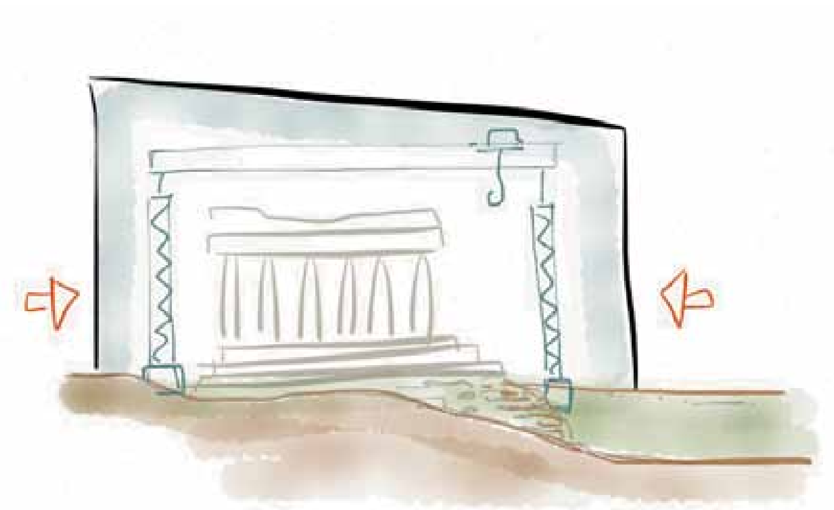
2. Proportions of the temple



3. Integration of the girder crane

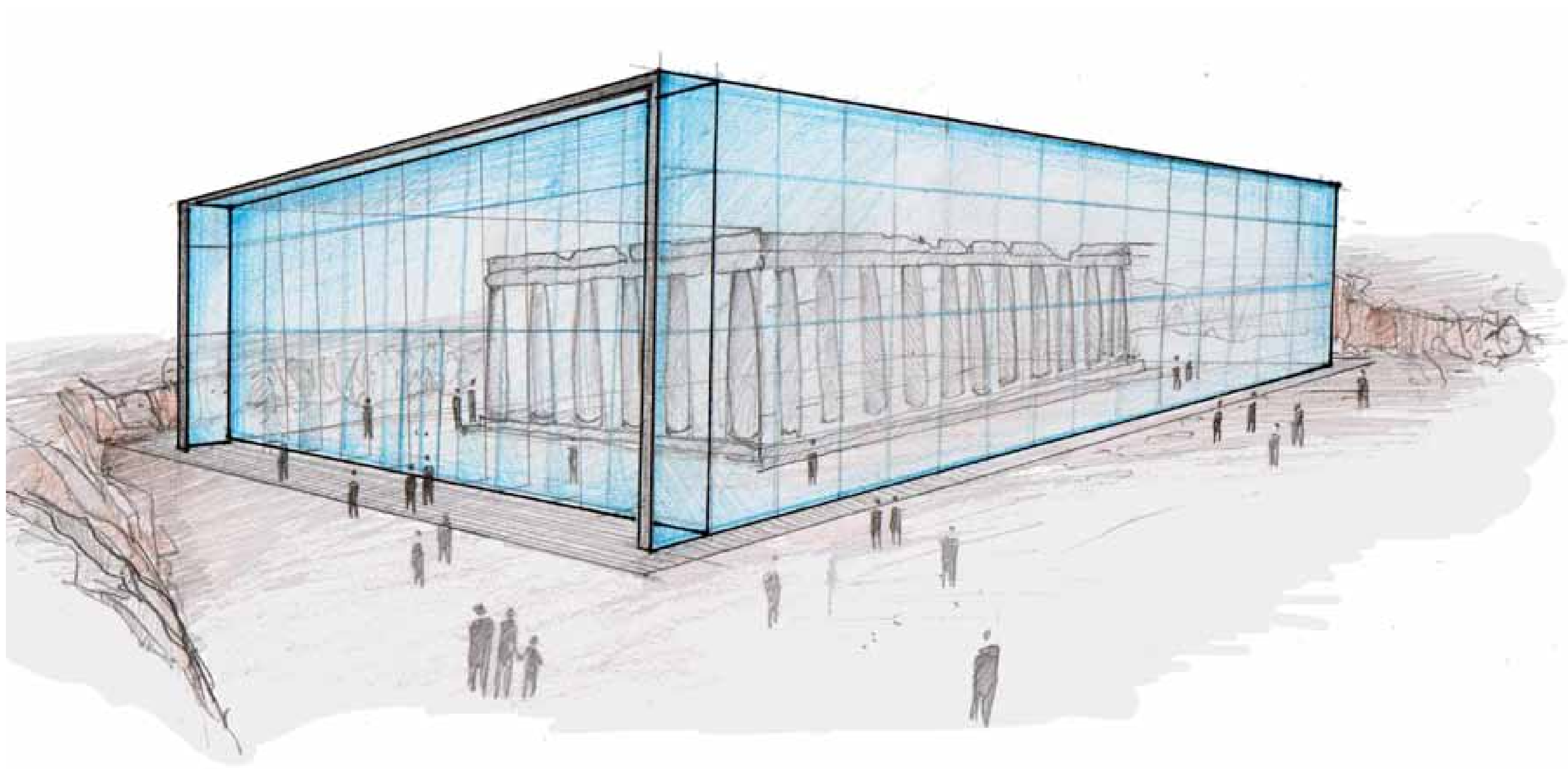


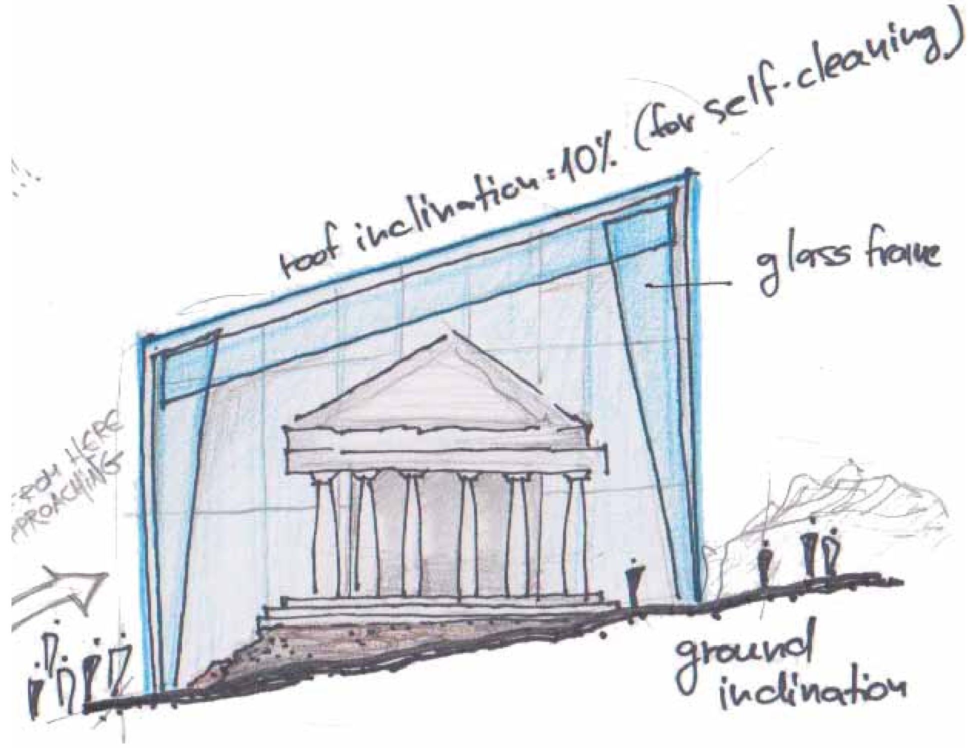
4. Foundation restrictions



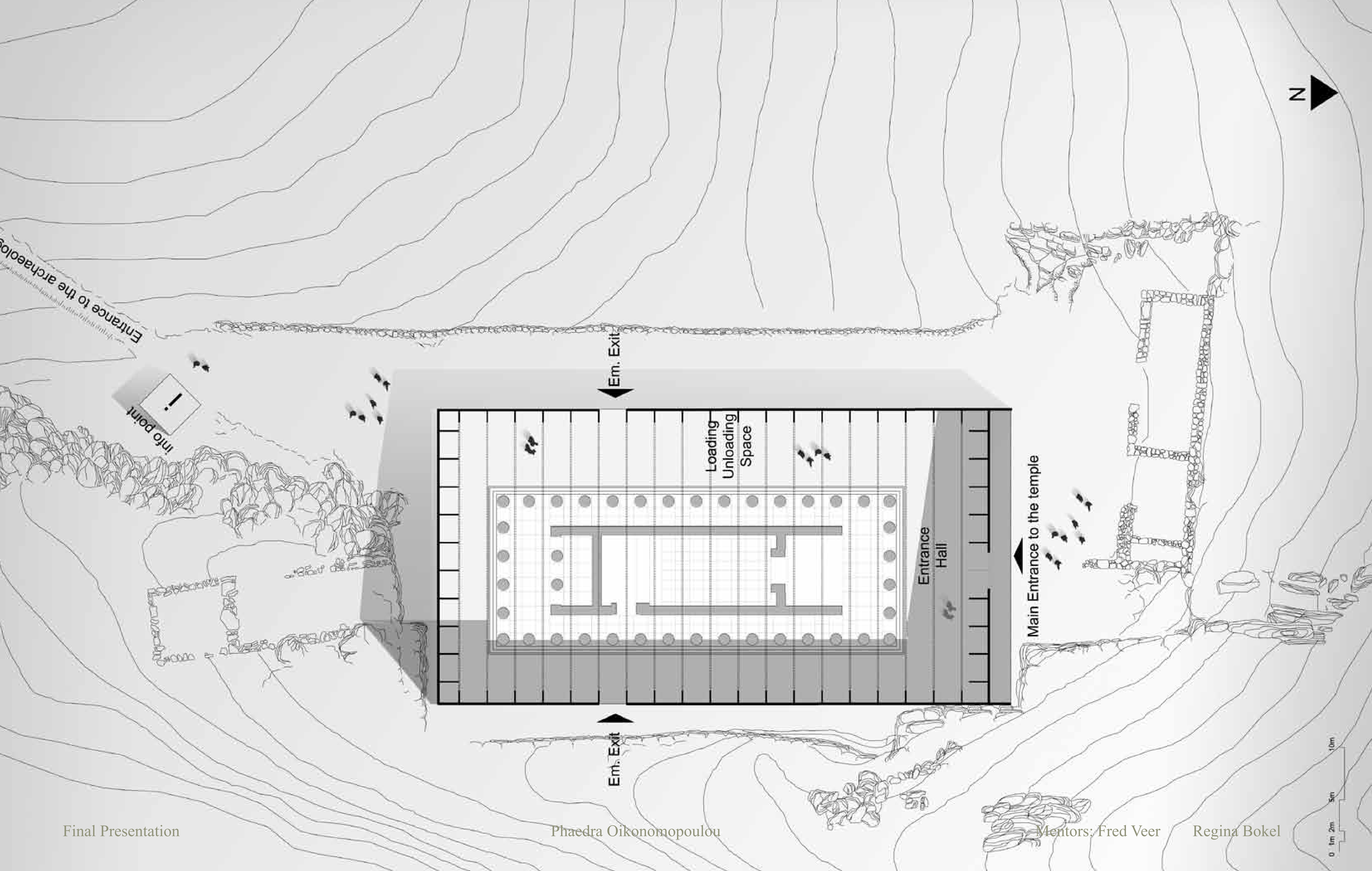
5. Sustainable Maintenance of the shelter

Architectural Design

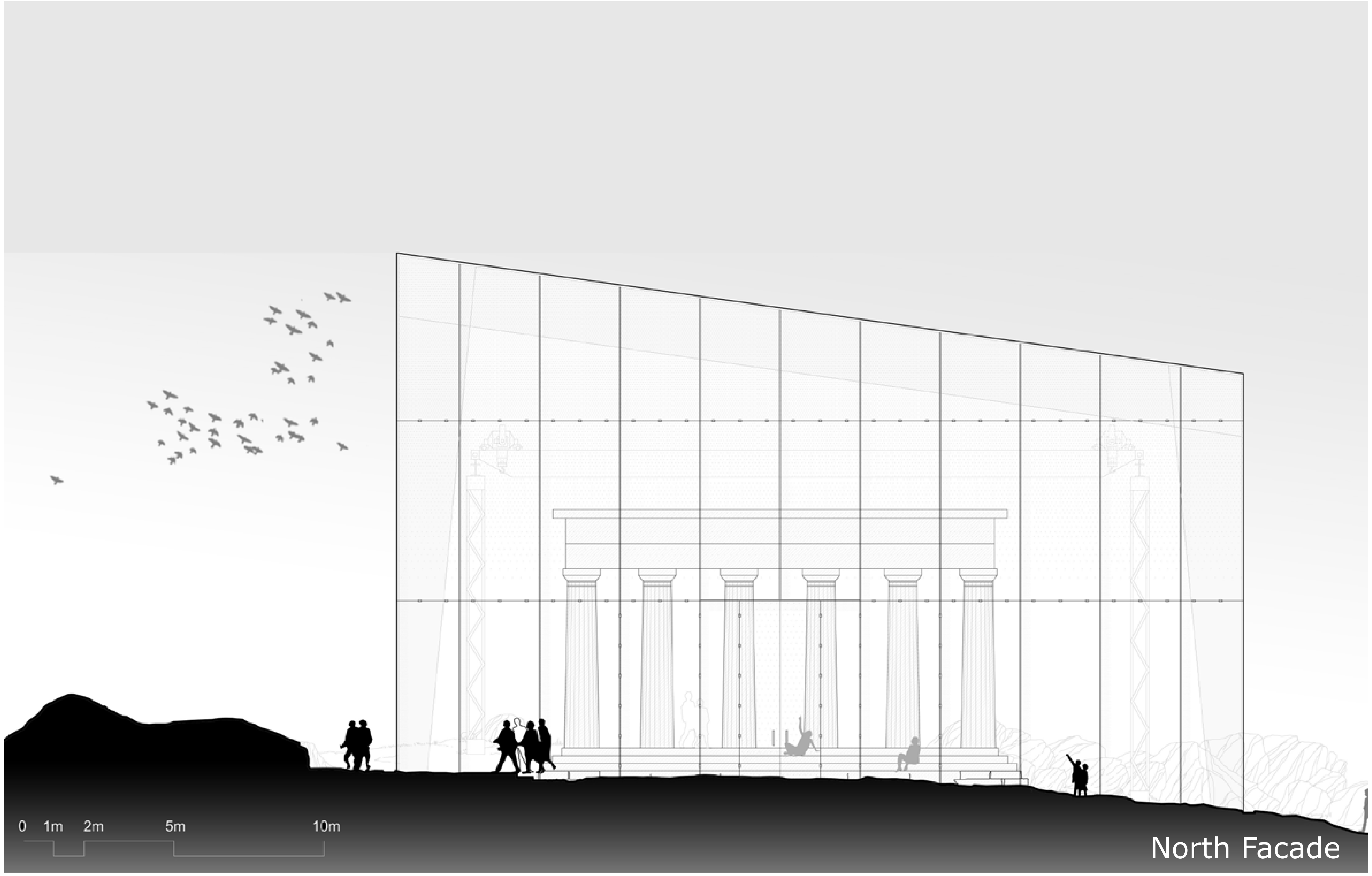




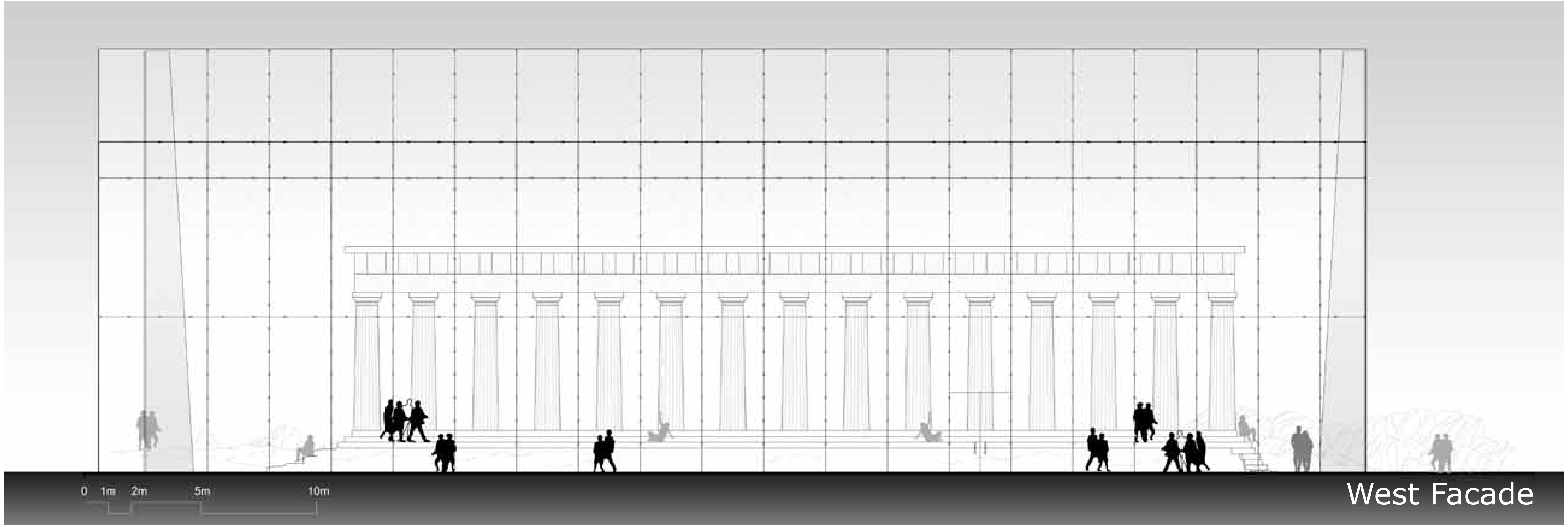
Architectural Design / Drawings

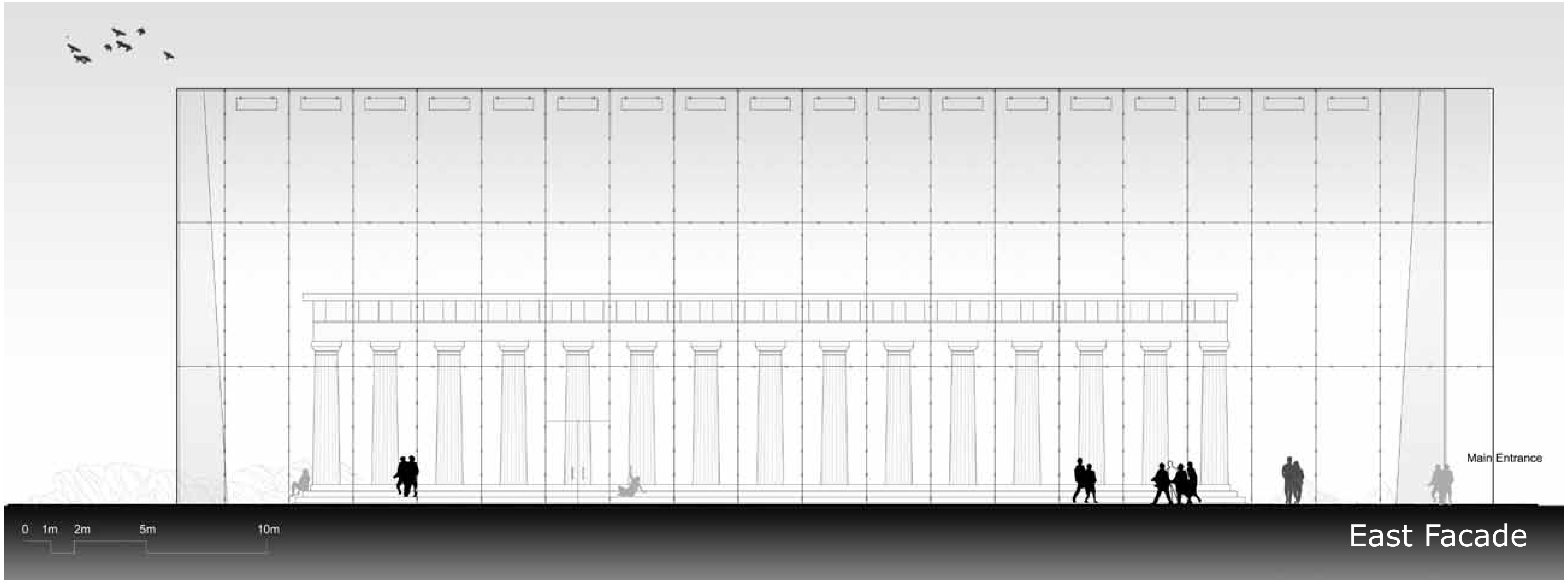


Architectural Design

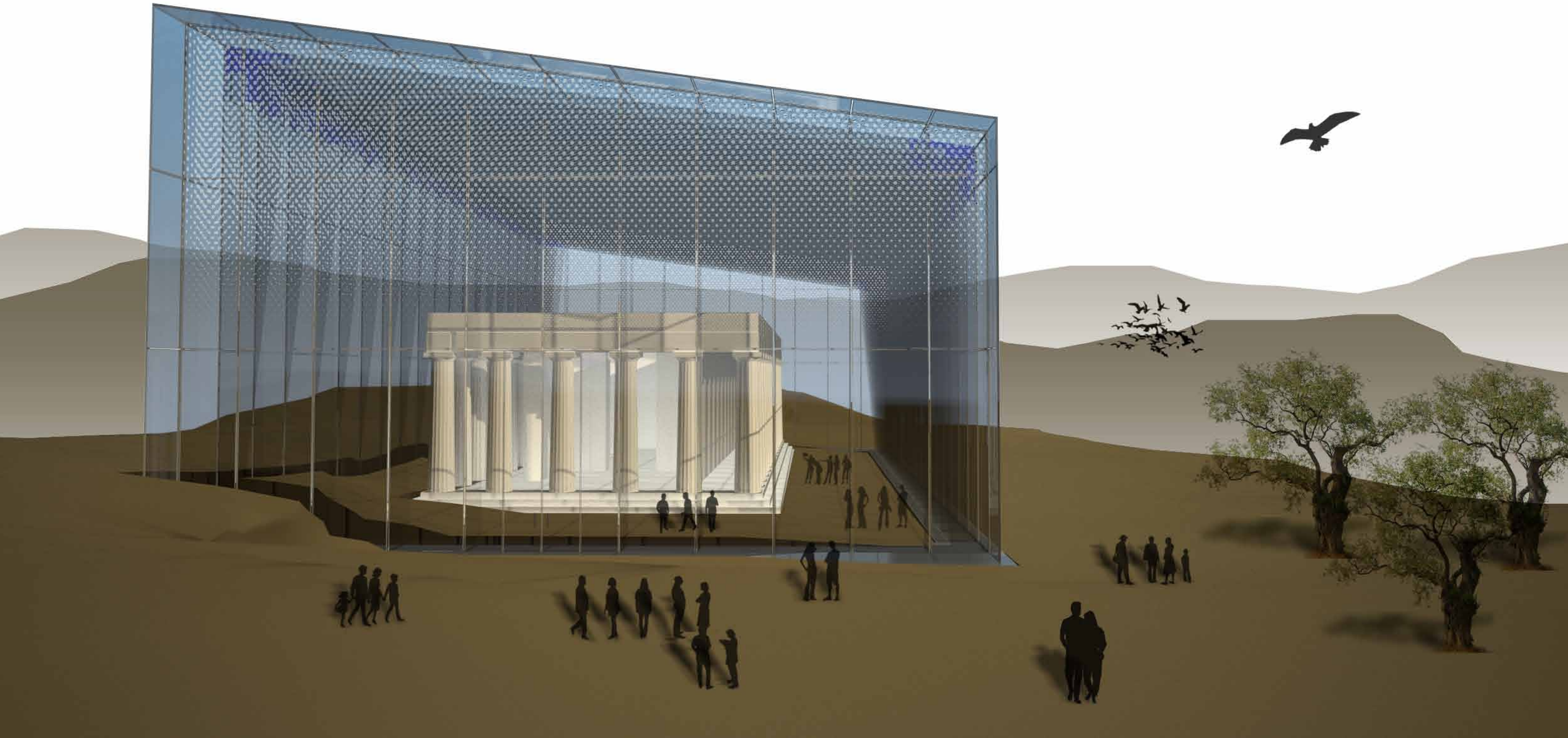


Architectural Design / Facade Division Modulus





Architectural Design / Impression



Architectural Design / Impression

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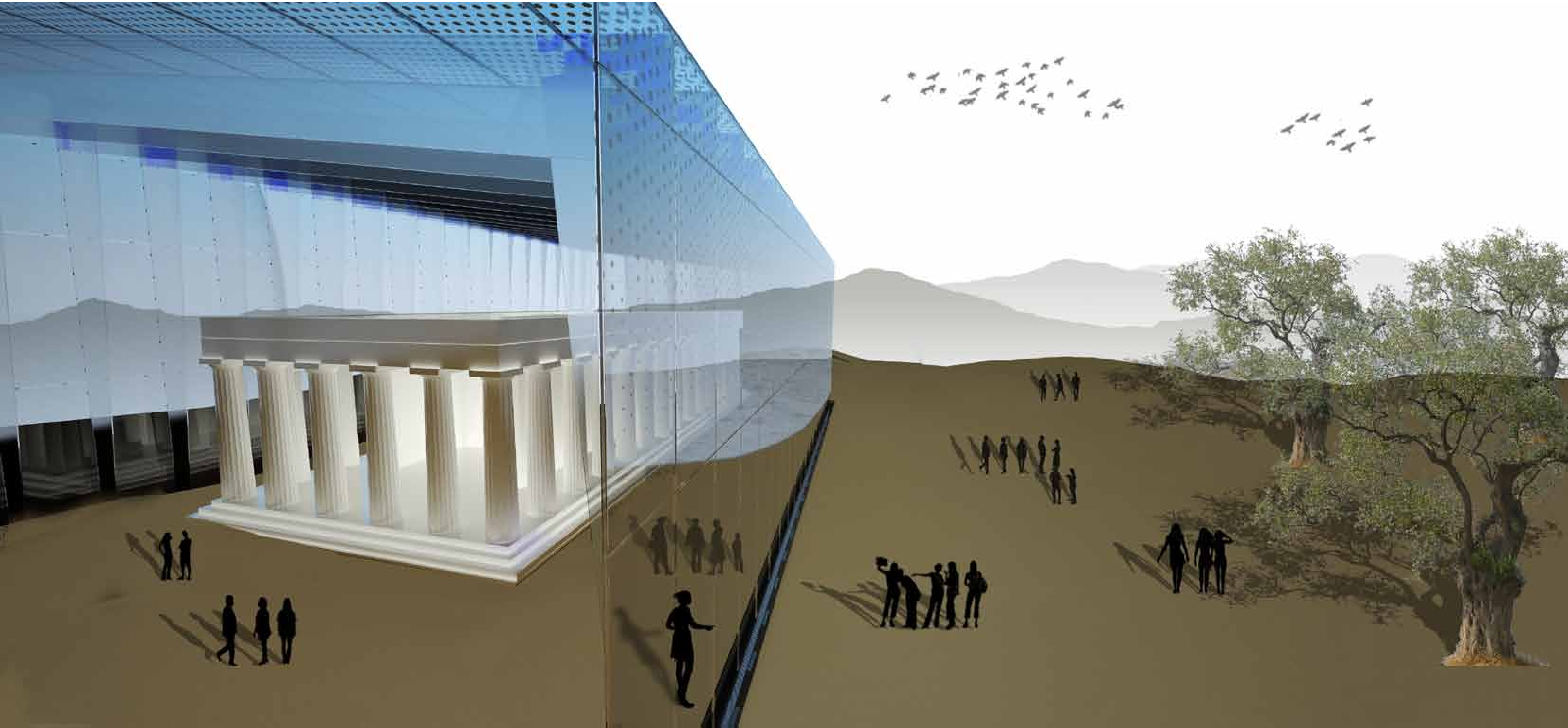


Structure

Structure / Existing Glass Structures

Gloucestershire Country House

Apple Store, 5th Avenue, NY

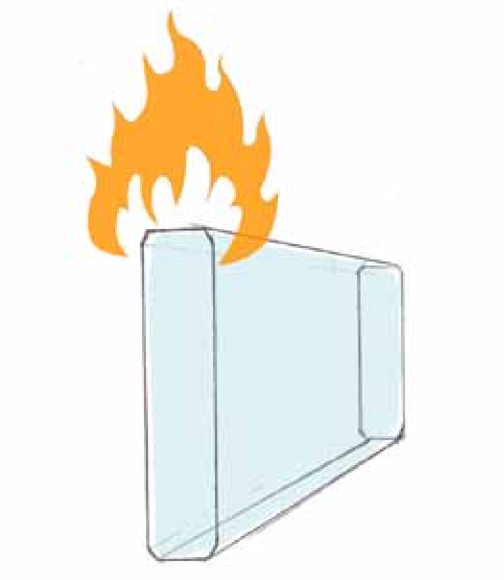
Structure / Reinforced Glass Beams

Reinforced Glass Beams

Safety Measures for turning glass into a safe structural material:

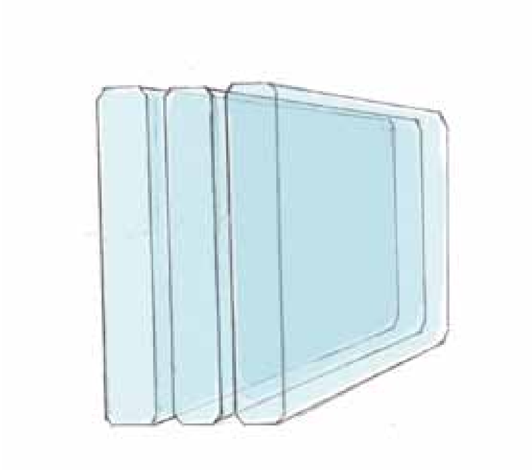
1. Tempering process

Increase of the (tensile) strength of the glass



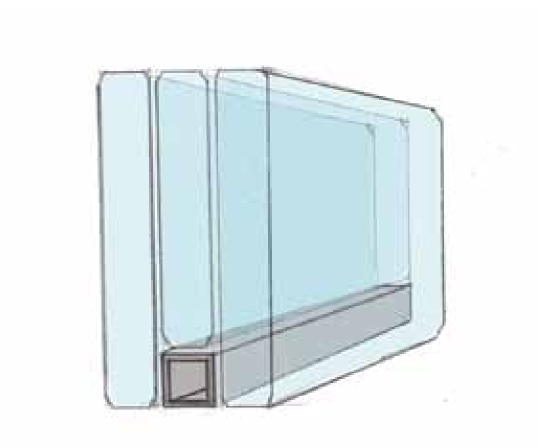
2. Over-dimensioning

of the multiple glass layers that compose one glass beam



3. Stainless steel reinforcement

bonded in the tensile zone along the edge of the glass beam.



Reinforced Glass Beams

Safety Measures for turning glass into a safe structural material:

Minimize the **Probability** of complete failure

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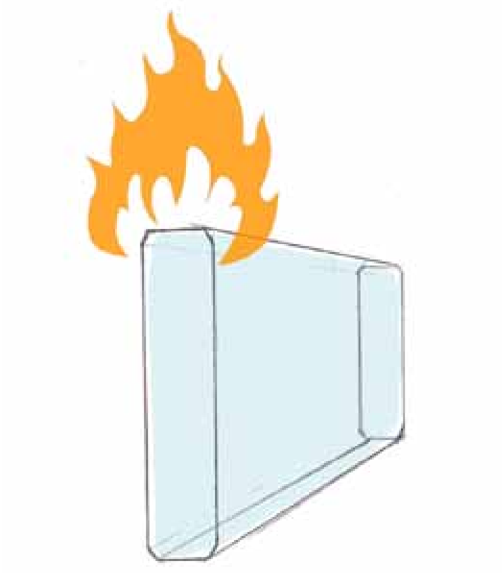

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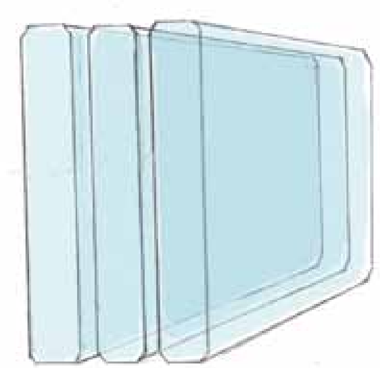
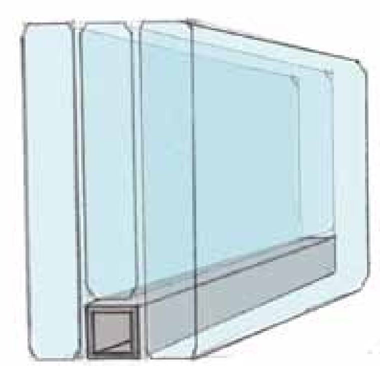


3. Stainless steel reinforcement

bonded in the tensile zone along the edge of the glass beam.



Structure / Reinforced Glass Beams

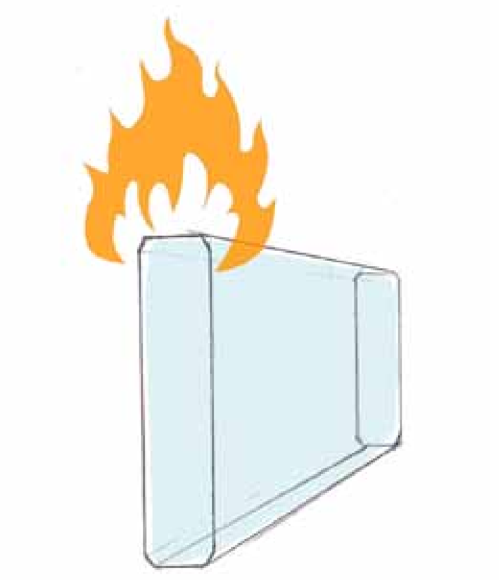
Reinforced Glass Beams

Safety Measures for turning glass into a safe structural material:

Minimizes the Consequences of complete failure

1. Tempering process

Increase of the (tensile) strength of the glass



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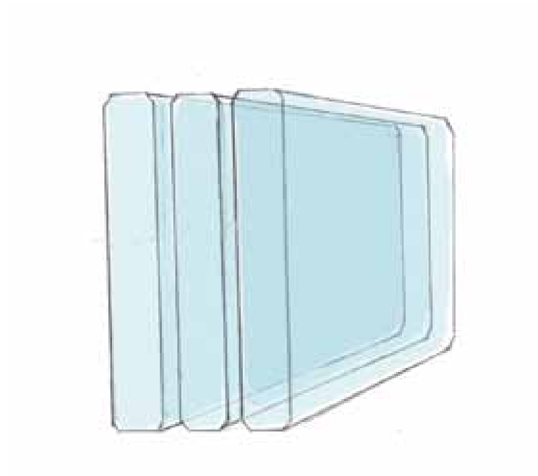

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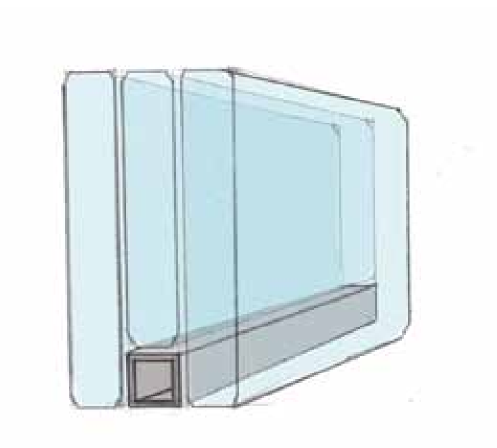

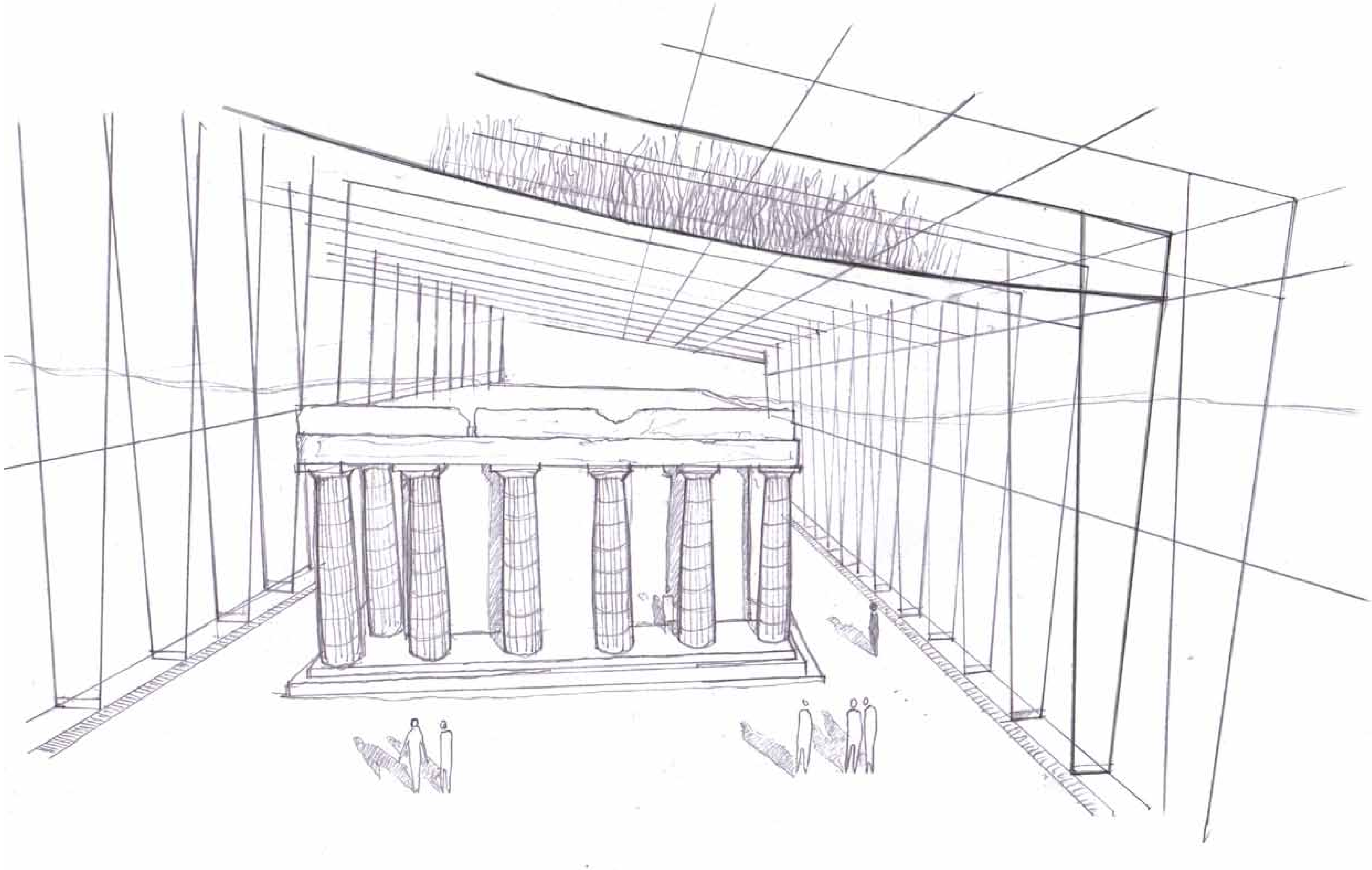

Structure / Reinforced Glass Beams

Reinforced Glass Beams are a Composite Structure of: **Structural Glass** + **Adhesive Interlayer** + **Steel Reinforcement**

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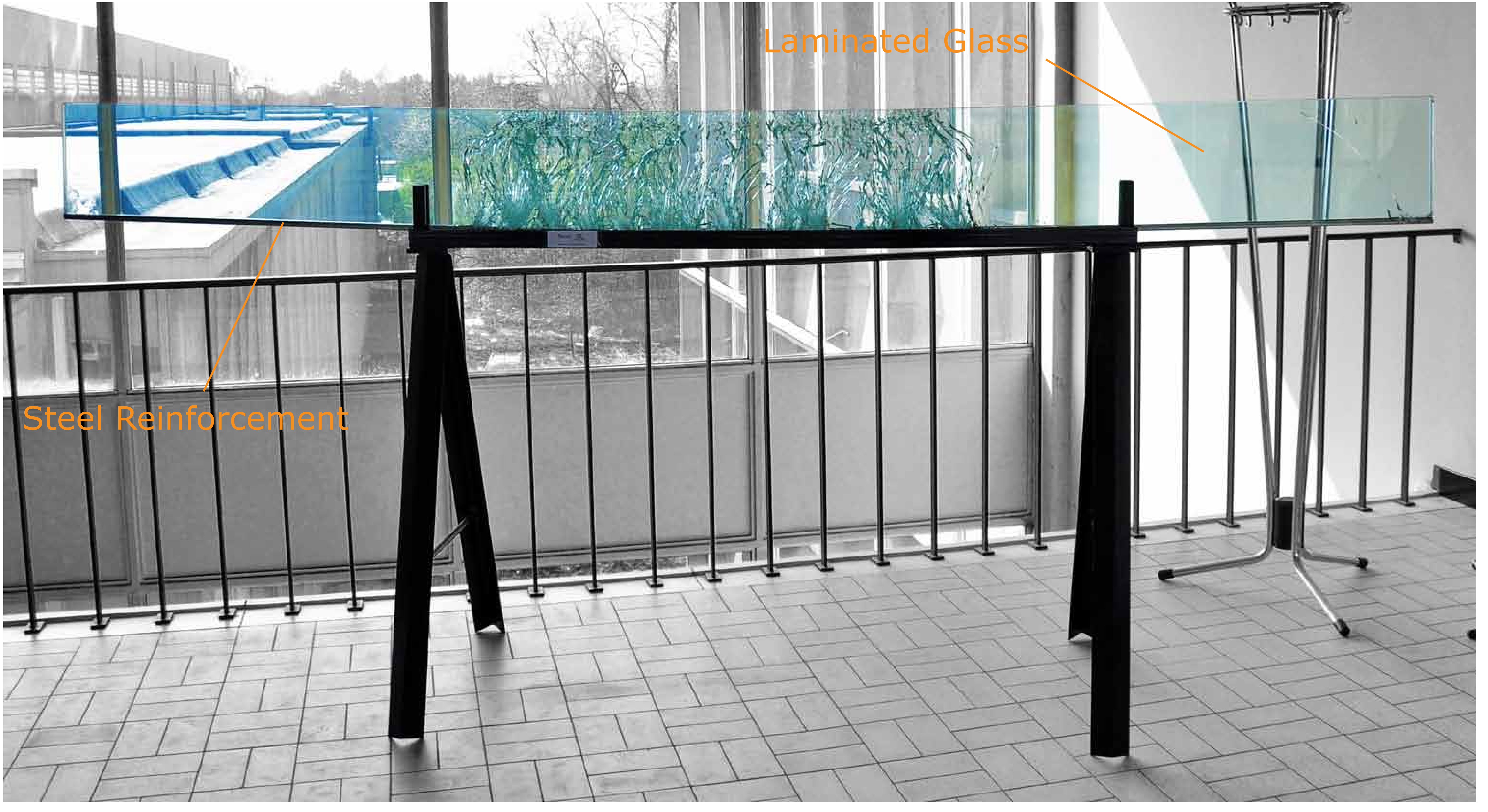
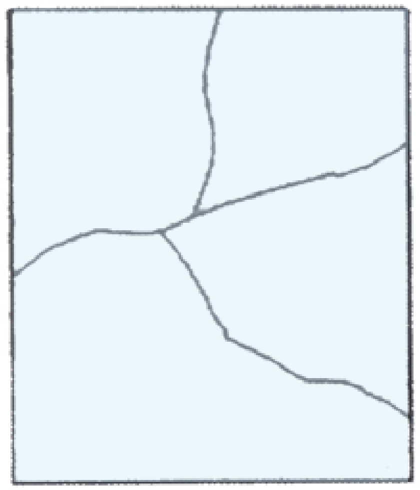
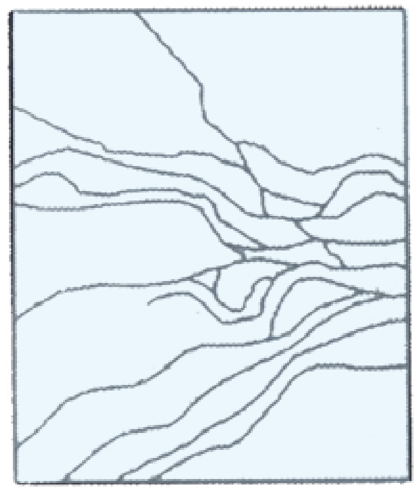
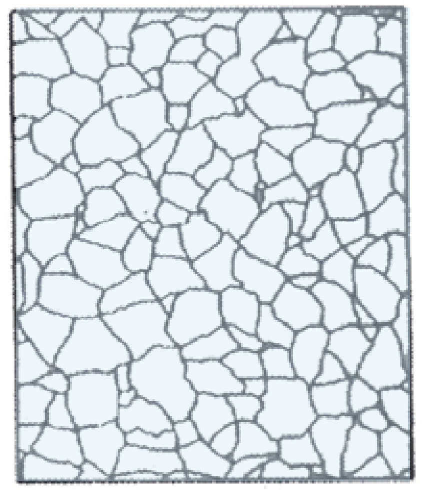


Structure / Reinforced Glass Beams / **Structural Glass**

Choice of Glass: **Heat - Strengthened**

Terminology	Annealed Glass	**Heat strengthened Glass**	Fully tempered Glass
Fracture Pattern			
Prestress Level	None	**Medium**	High
Characteristic tensile bending strength	45 MPa	**70 MPa**	110 MPa

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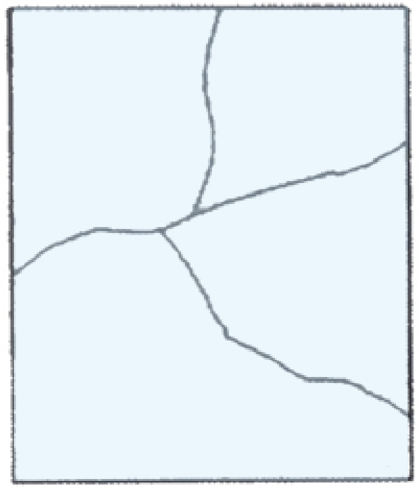
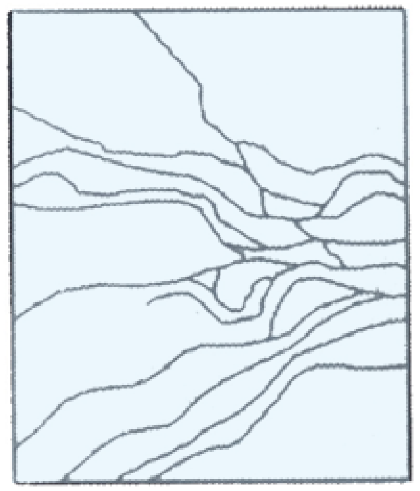
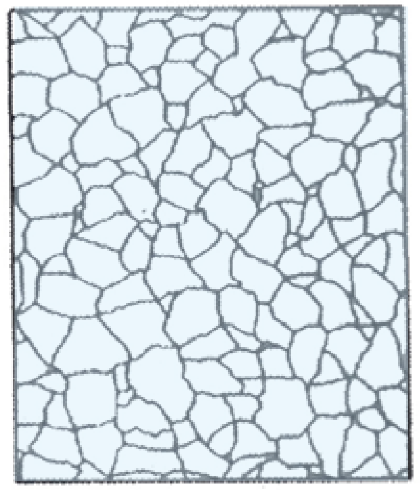
Fracture Pattern			
Prestress Level	None	**Medium**	High
Characteristic tensile bending strength	45 MPa	**70 MPa**	110 MPa

Structure / Reinforced Glass Beams / **Adhesive Interlayer**

Choice of (foil) Interlayer: **SGP** (Du Pont's Sentry Glass)

- The adhesive Interlayer:

keeps the glass fragments together in case of glass fracture

allows for an enhanced post-breakage behavior

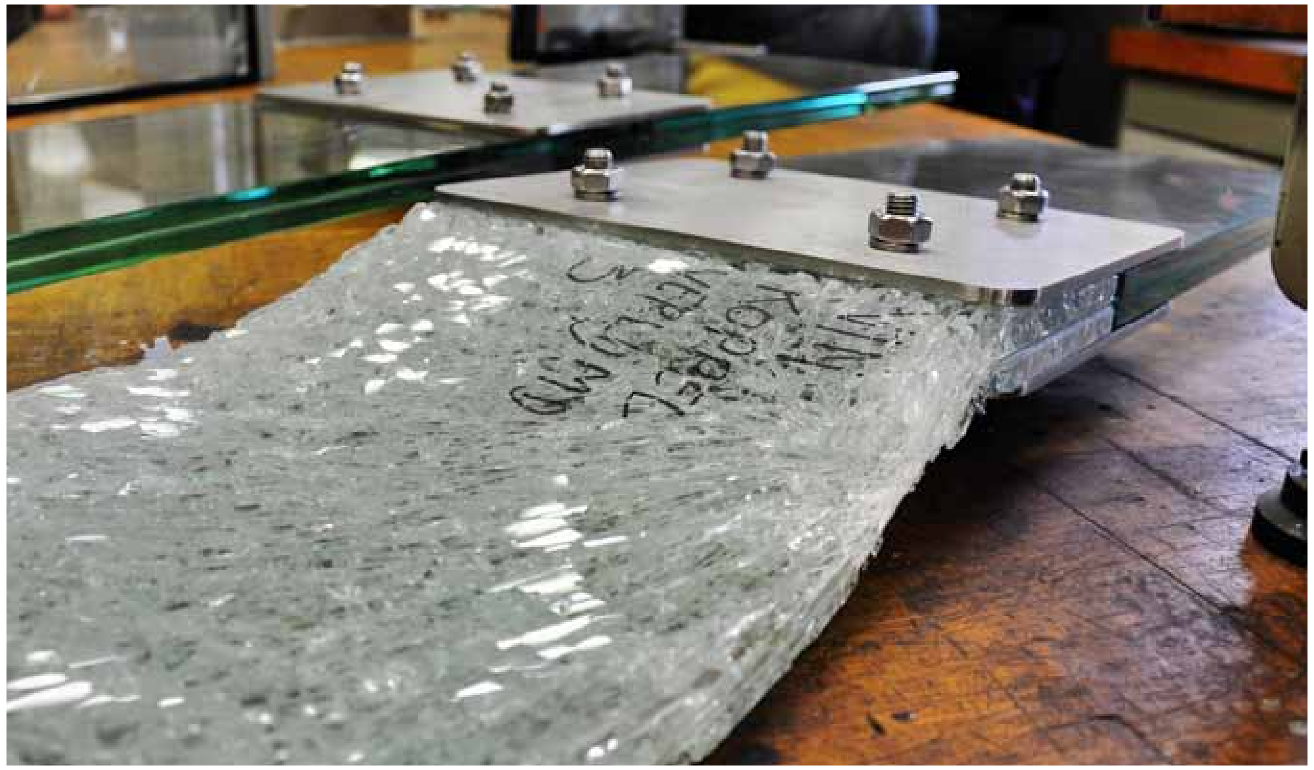
- For structural glass two common interlayers: PVB and SGP

- **SGP** compared to PVB:

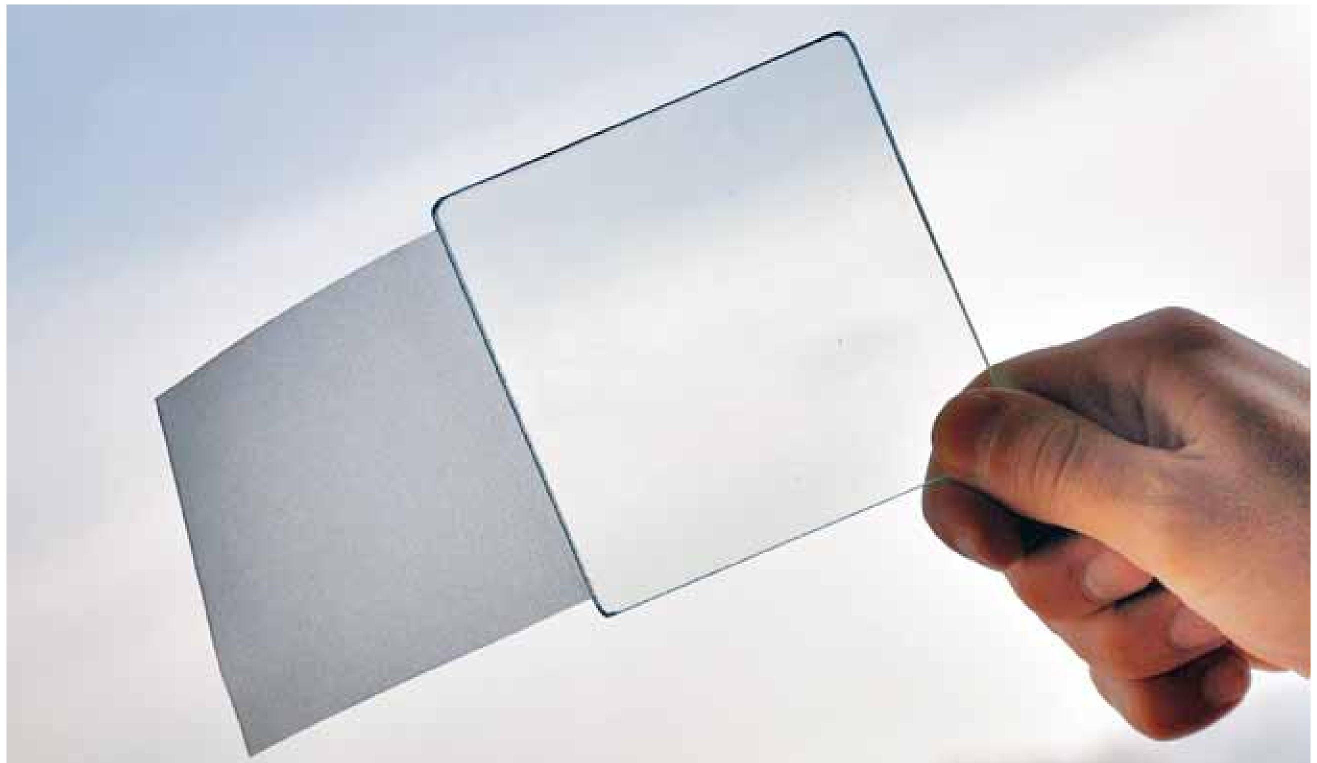
has 5 times higher tear strength

makes the laminated component 100 times more rigid

easily conforms to dimensional inaccuracies



Post-breakge behavior of laminated fully tempered glass: the fragments remain attached to the adhesive layer [TU Ghent]



PVB Interlayer: Before lamination, it has a rough surface (left side). When tempered for laminating, it becomes fully transparent (right side).

Structure / Main Idea

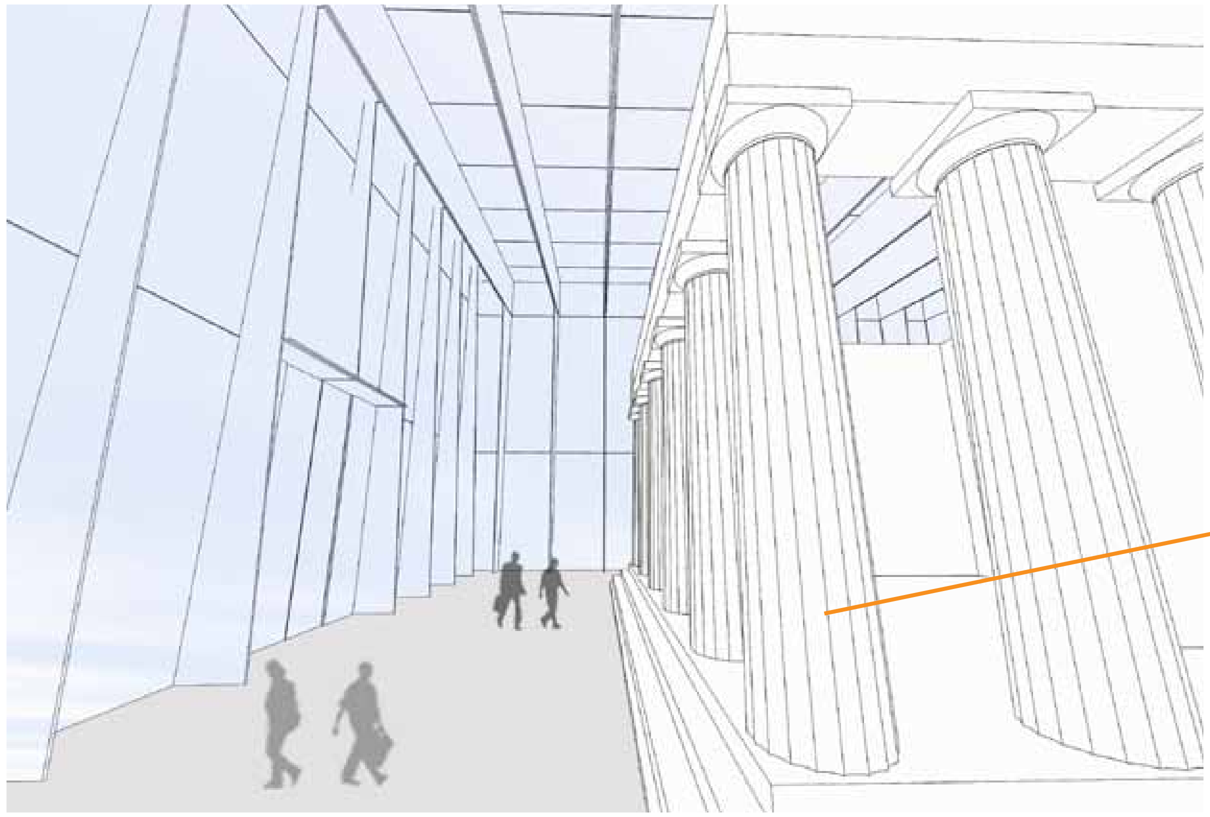
Monolithic Structural Behavior: **Rib reinforced structure**

Structure / Structural Elements

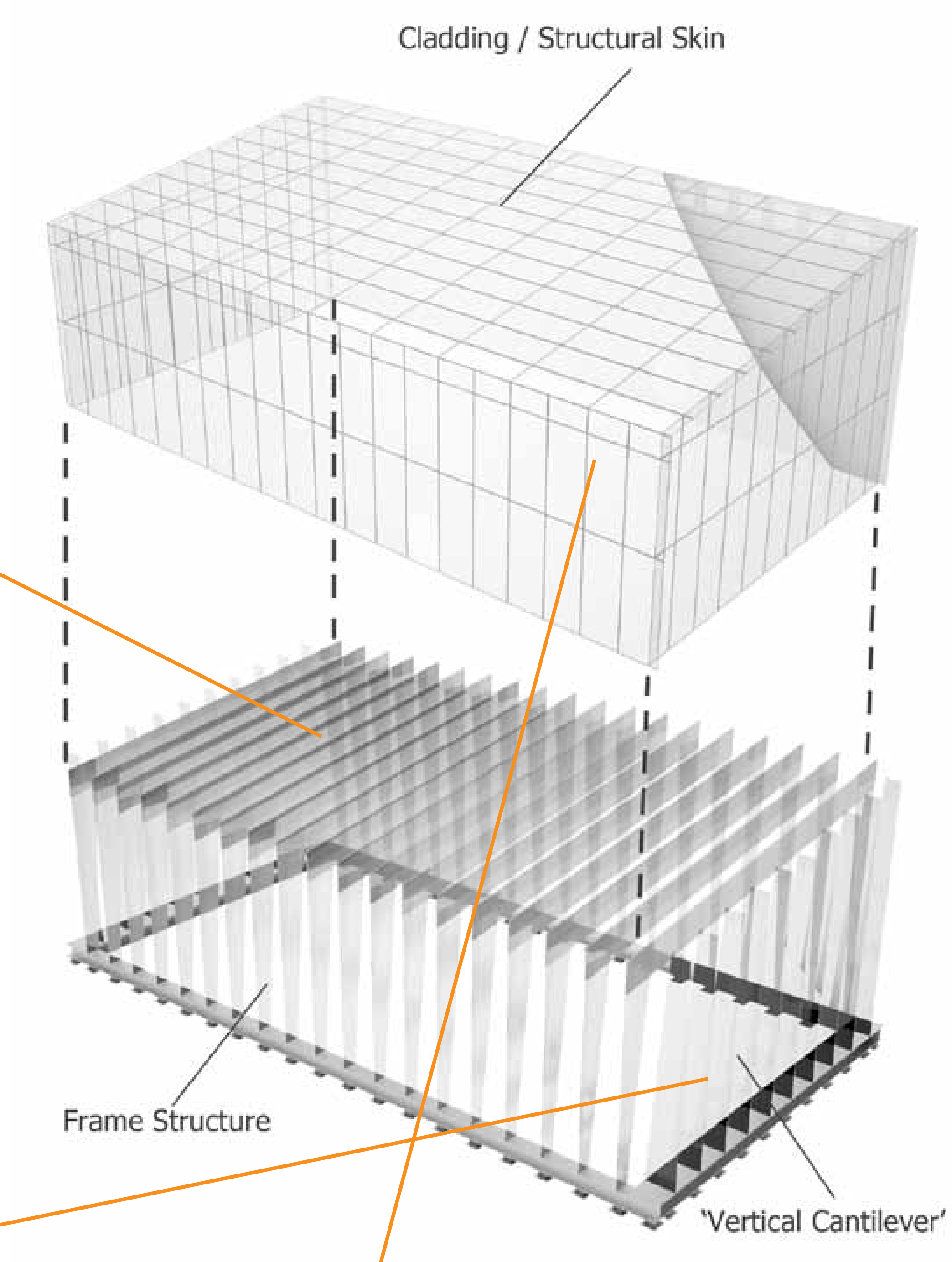
1. Frame Structure

Consists of 19 glass frames tied together through the structural skin

2. Short Facades



The columns shape here is inverted to counteract the wind load.



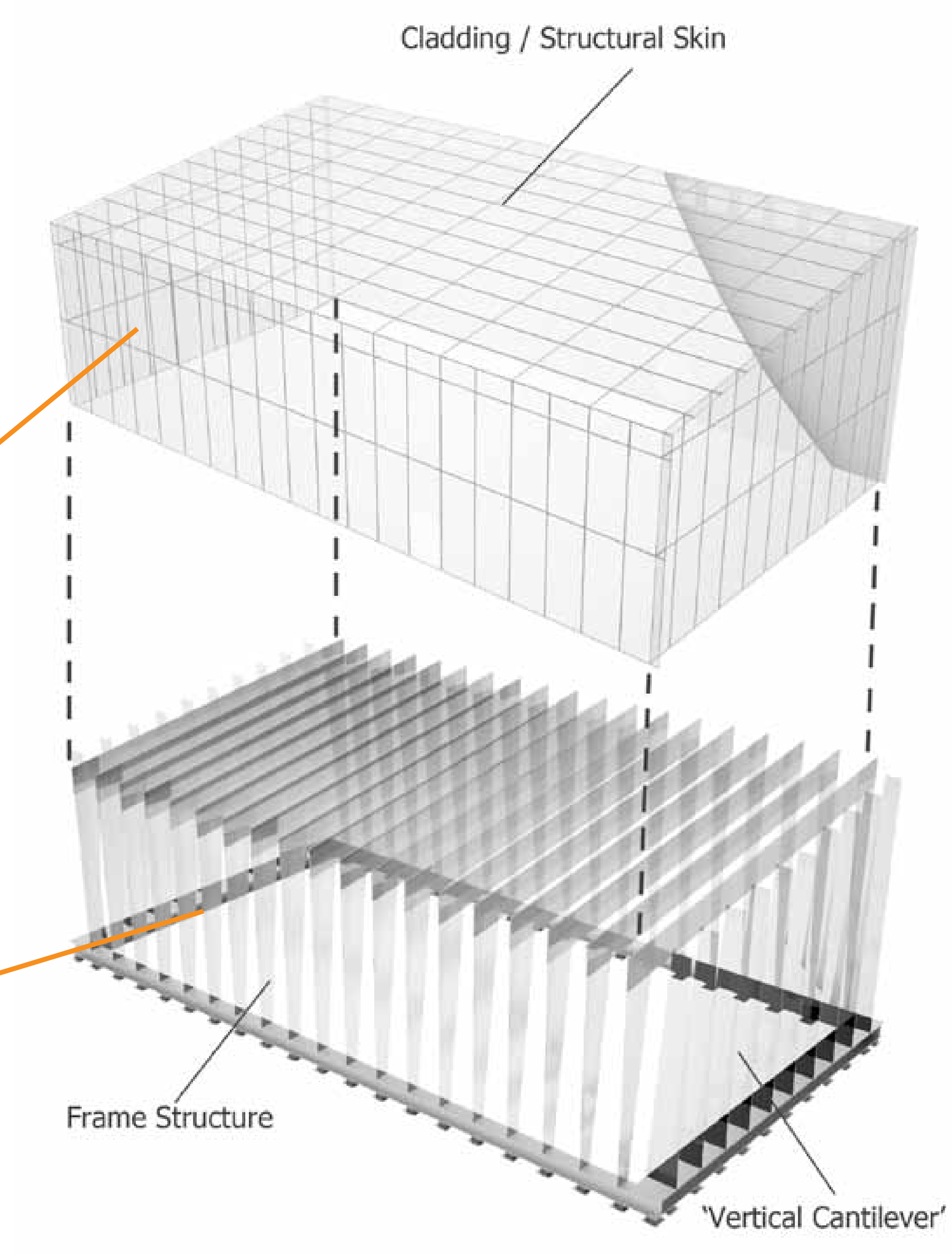
3. Structural Skin

The glass panes of the cladding **function as a structural skin that ties the structure together.** These glass panes can be used as:
1. load-bearing elements for vertical loads
2. bracing elements

Structure / From the air to the ground!

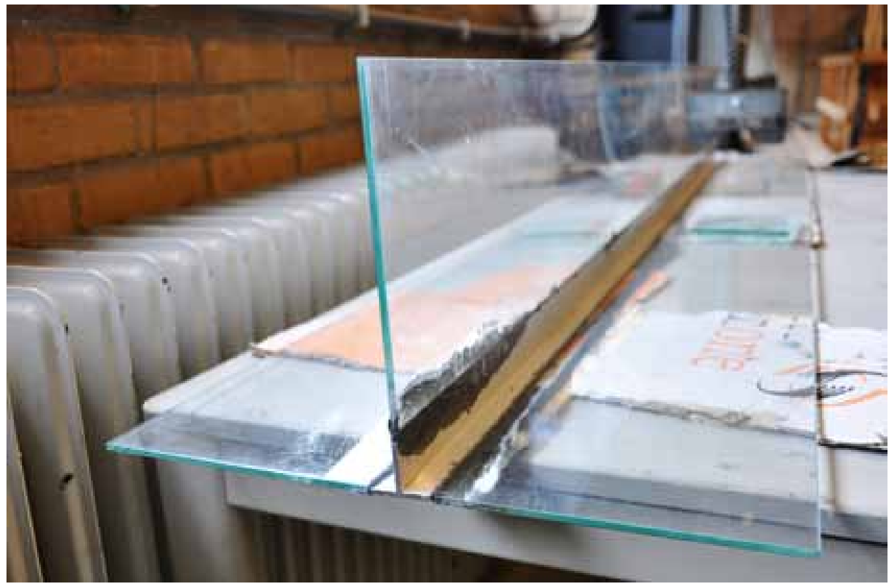
"Skin"

"Ribs"



The shelter's structure follows the same principles as the fuselage structure of airplanes in Aerospace Engineering: A frame structure tied together through the structural skin.

Structure / Buckling Resistance / Laboratory Testing



Specimens: 1000 mm height, 4 mm thick

Test report

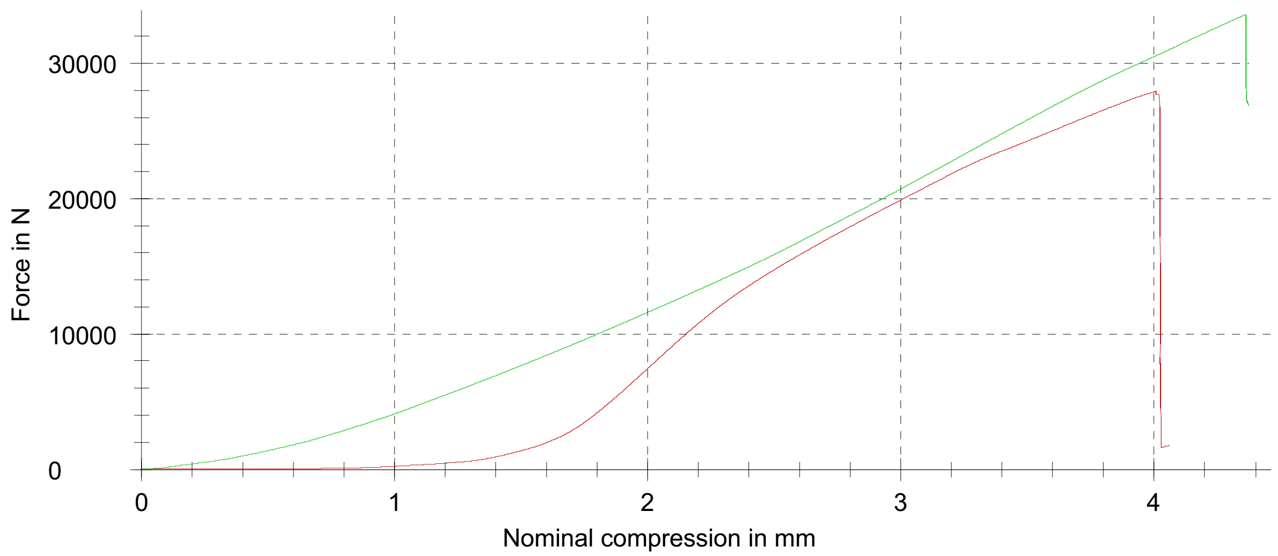
Customer	:	Specimen type	:
Job no.	:	Pre-treatment	:
Test standard	:	Tester	:
Type and designation of	:	Notes...	:
Material	:	Machine data	:
Specimen removal	:		

Pre-load : 5 N
Test speed : 1 mm/min

Test results:

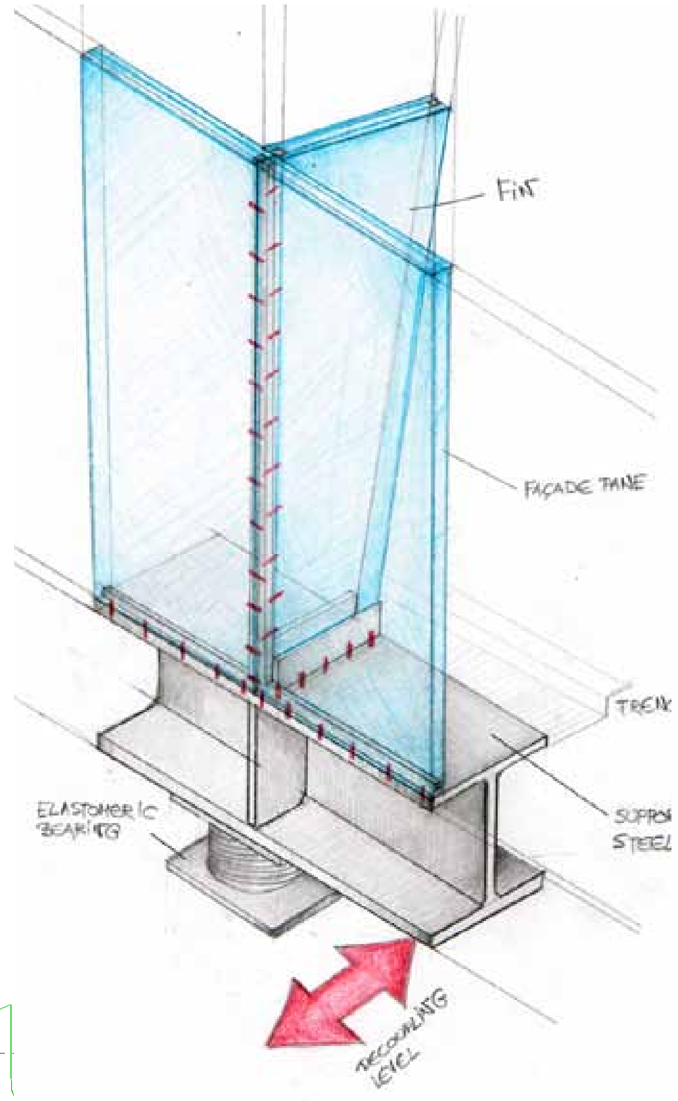
Nr	σ_M MPa	ε_M %	d_0 mm	A_0 mm²	Specimen no.
1.1	43,0	16,0	28,75	649,18	1
†1.2	-	-	28,75	-	2
†1.3	-	-	28,75	-	3
1.4	51,8	17,4	28,75	649,18	4

Series graph:



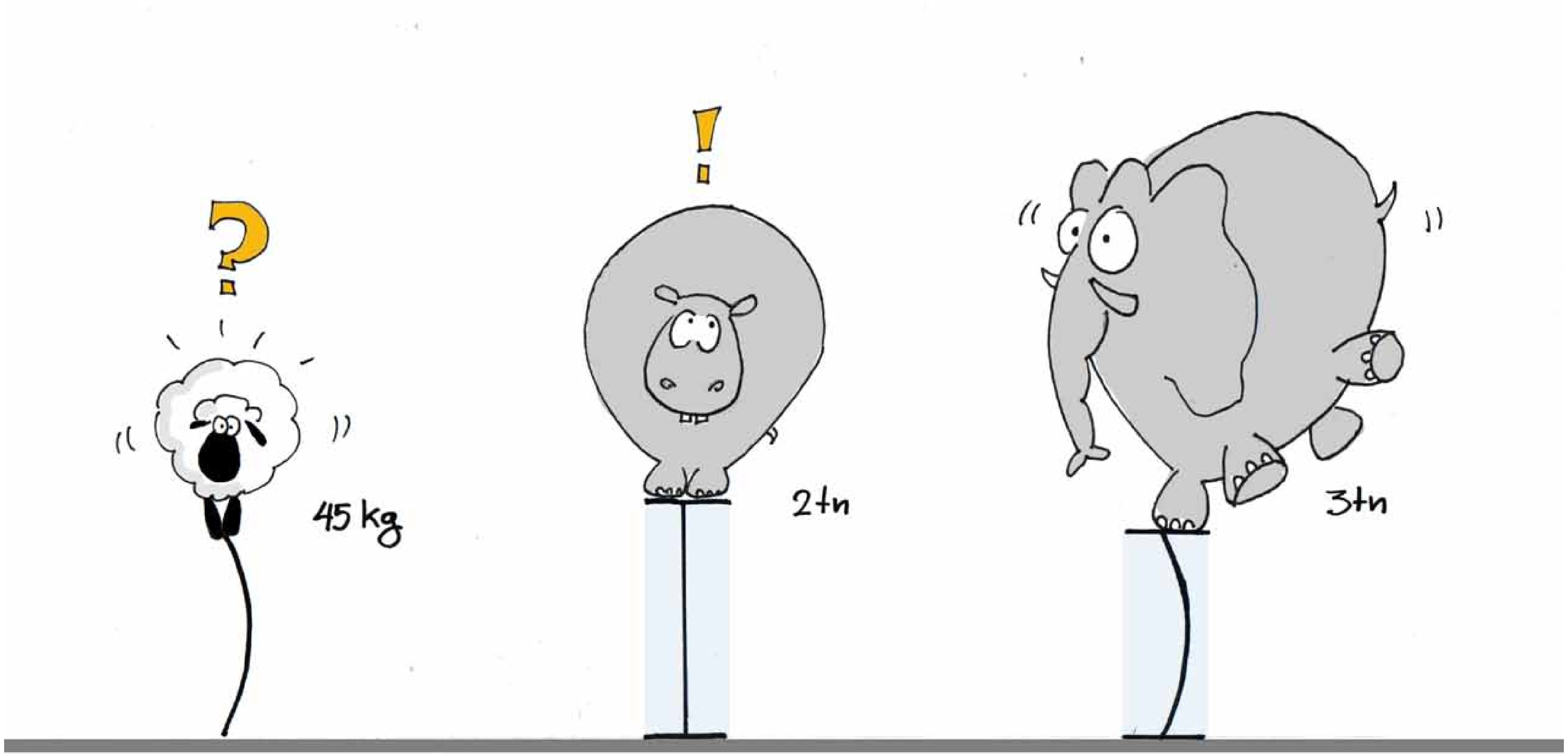
Statistics:

Series n = 2	σ_M MPa	ε_M %	d_0 mm	A_0 mm²
$\bar{x}$	47,4	16,7	28,75	649,18
s	6,17	1,0	0,000	0,00
ν	13,02	6,01	0,00	0,00



Structure / Buckling Resistance

Buckling Test Results

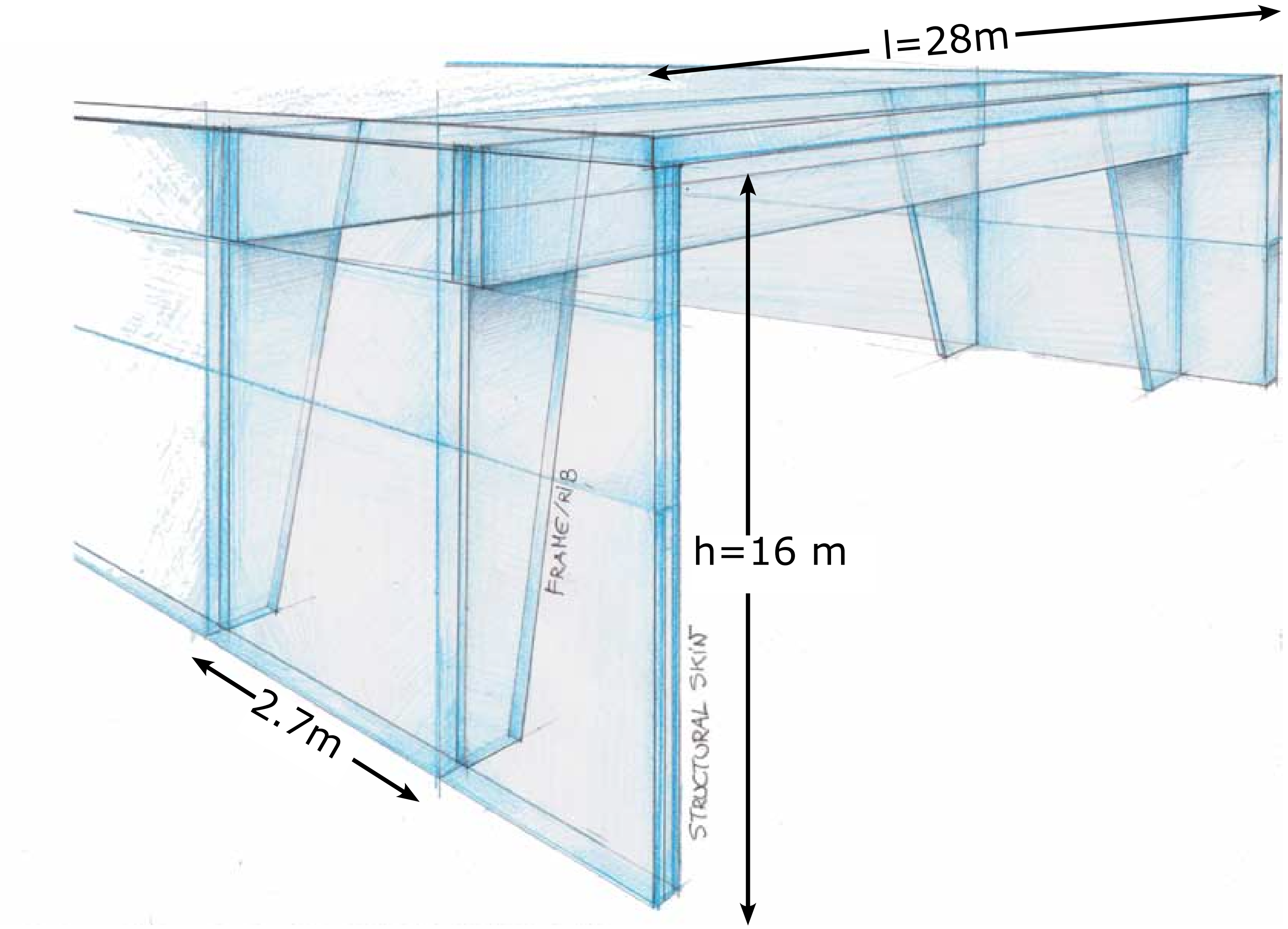


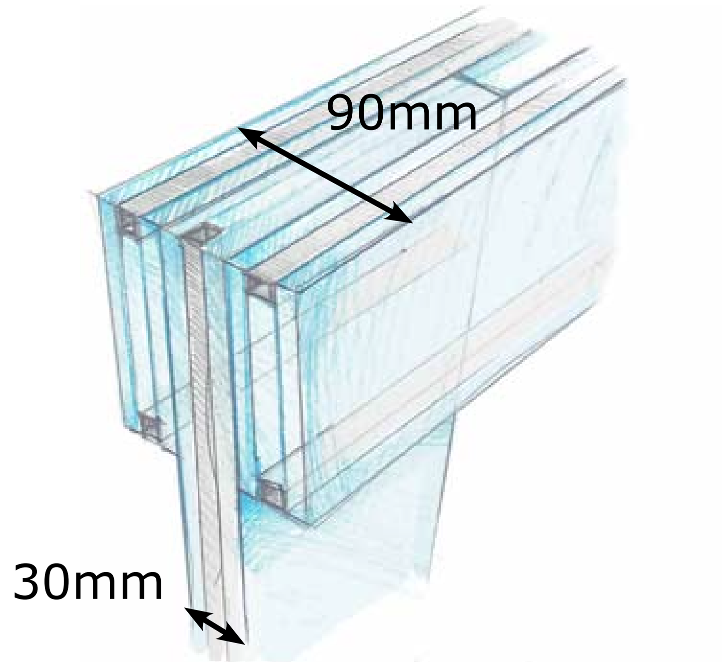
Plain 4 mm glass

T-profile 4 mm
Load: 2 tn, no buckling

T-profile 4 mm
Critical Load: 3 tn

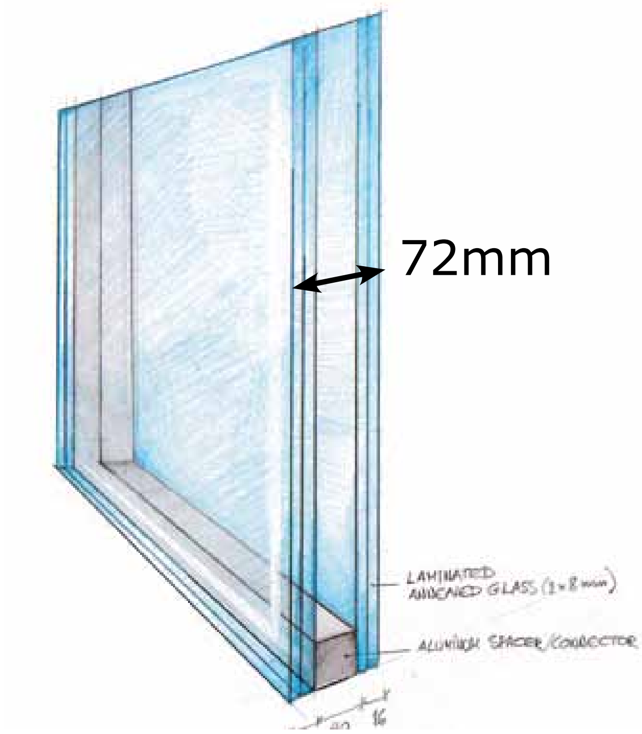
Structure / Dimensioning of the Structural Members





1. Main load-bearing structure

glass beams and fins [d = 3x10 mm = 30 mm]



Frame

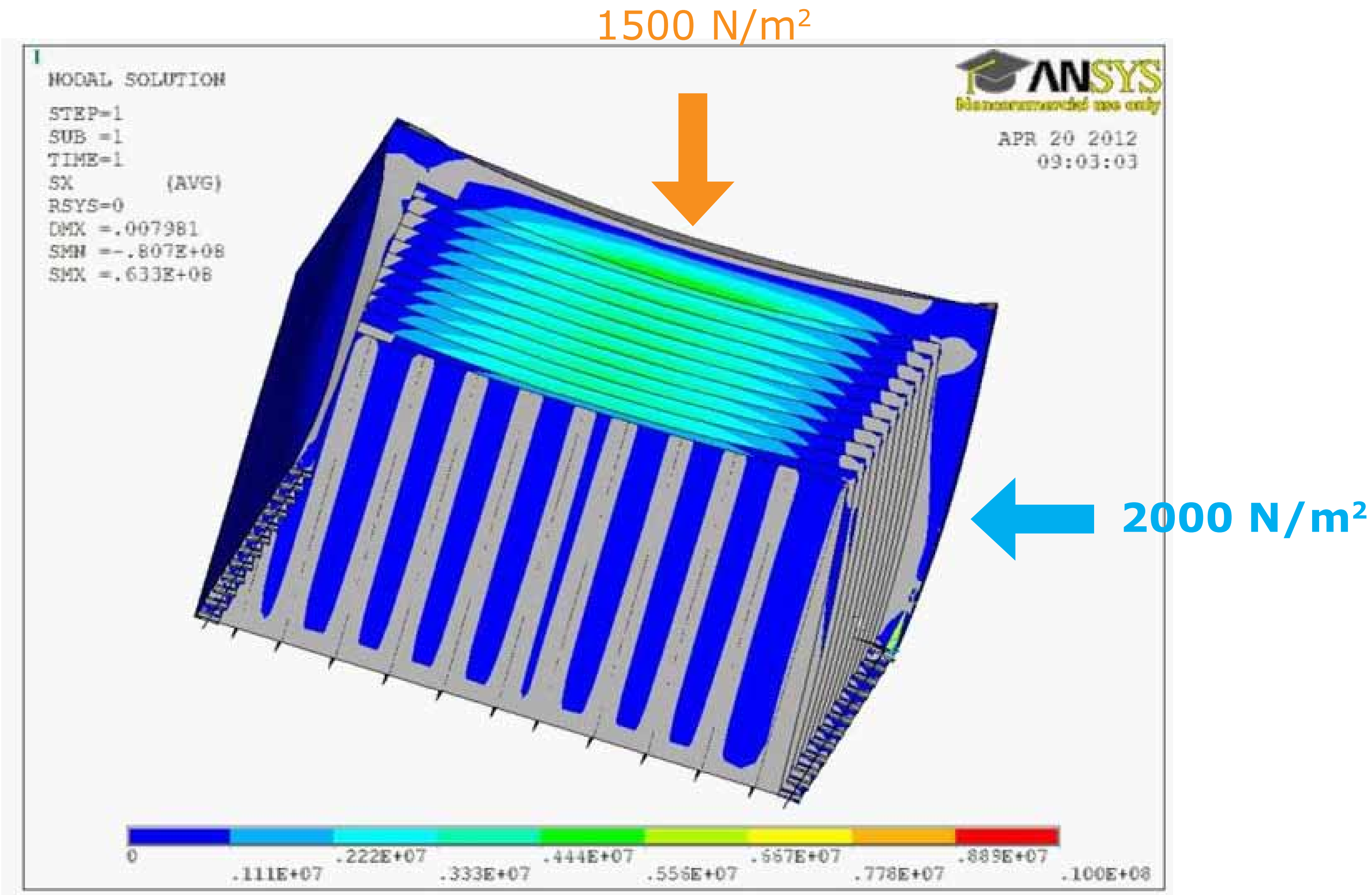
formed by two glass columns supporting a twin reinforced glass beam interlocked to the columns at both ends.

2. Structural skin

Facade and roof glass panes
[d = 2x8mm +40 mm air + 2x8mm = 72 mm]

Structure / Calculations

Validating the whole structure under static and variable loads.



Location	Direction in Model	Peak Stresses	Allowed Max. Strength (FoS=4)
Beam	x	8 MPa (tension)	10 MPa (tension)
Column (fin)	y	12 MPa (compression)	17 MPa (compression)
Plate	Stress Intensity	4 MPa (tension)	10 MPa (tension)

Structure / Key connections

The structure will function as a mechanical whole ONLY if the joints allow it.

The joints should be:

1. Strong but of negligible size [minimal intrusive]
2. Demountable [dry connection]
3. Allow for tolerances during the assembly process.
4. Avoid drilling of glass

Structure / Key connections

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The joints should be:

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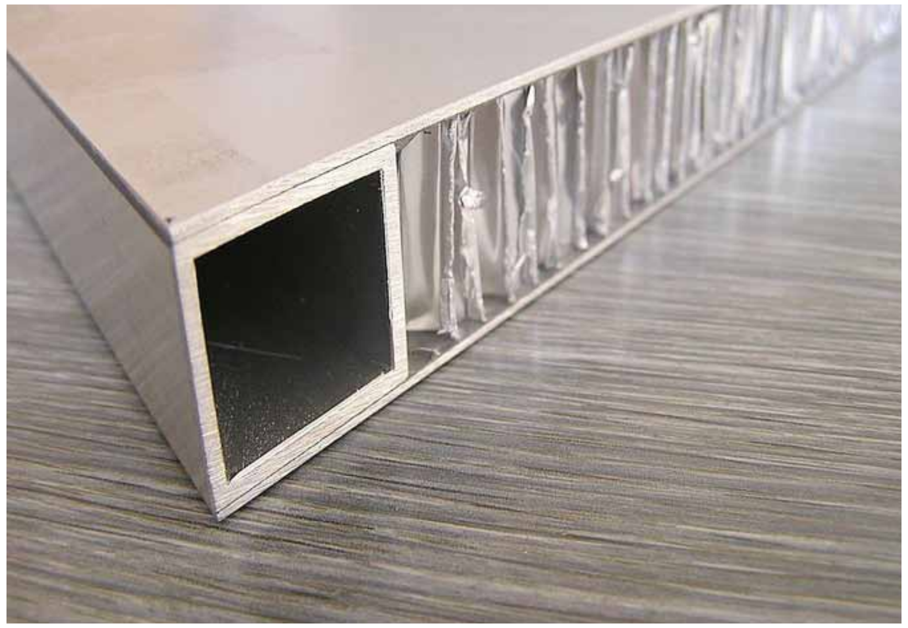
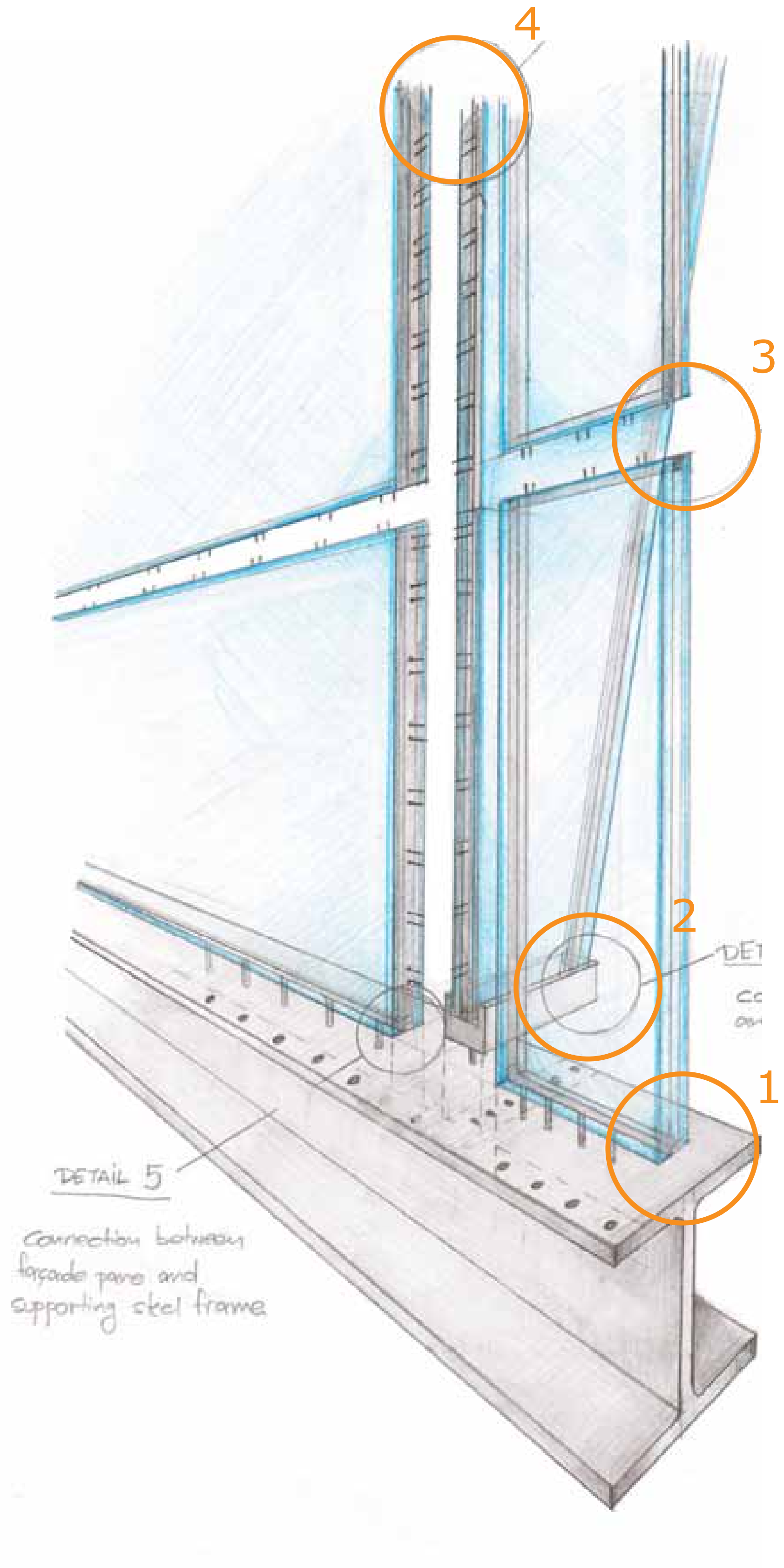
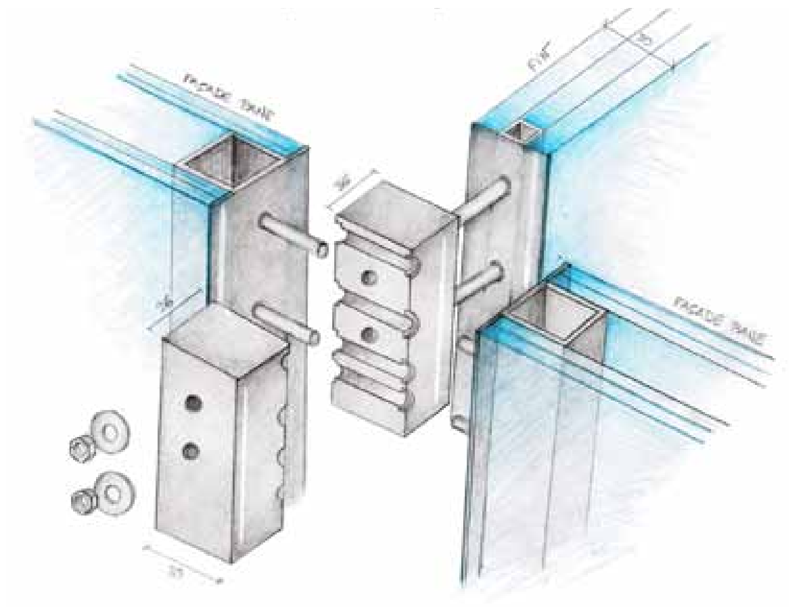
Take advantage of the **reinforcement**:
use it as a **connector.**



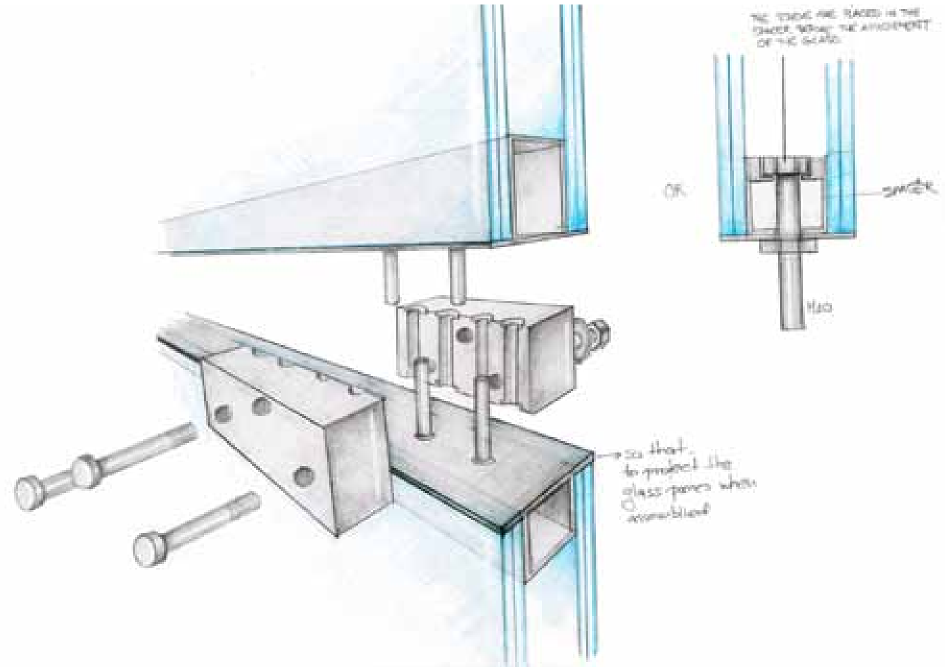
Composite material applied in aerospace enginnering

Structure / Demountable key connections

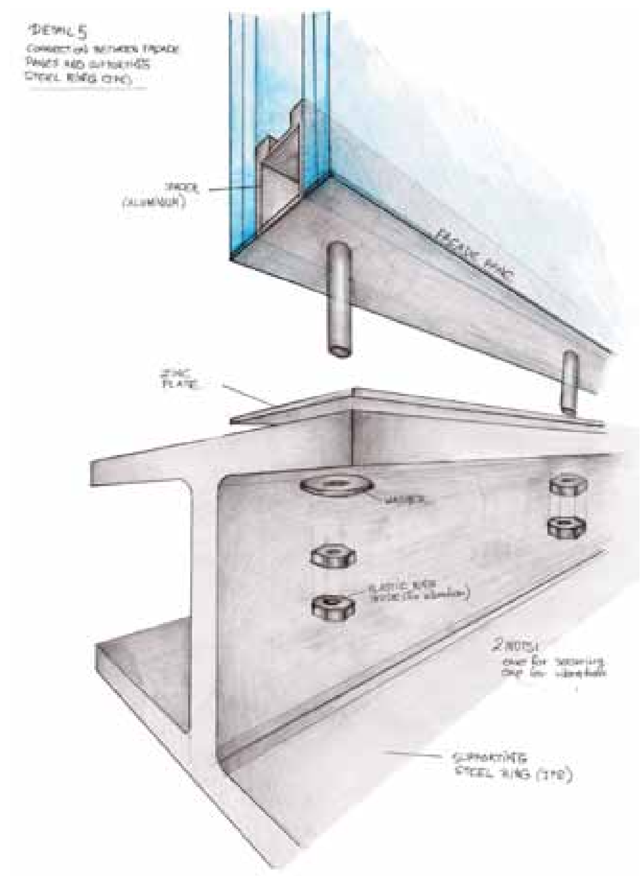




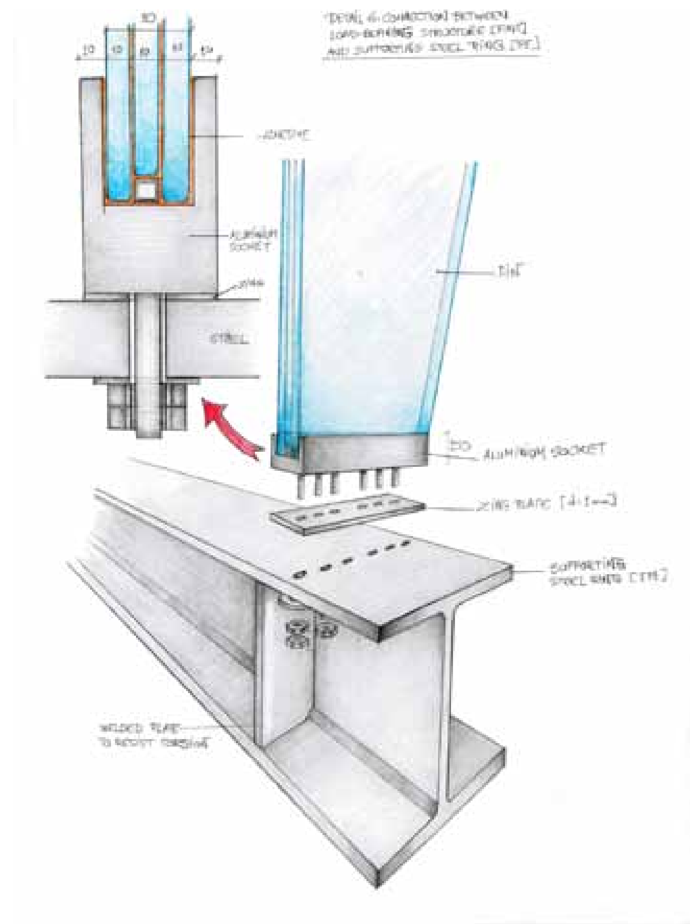
Detail 4: Connection between fin and glass panes



Detail 3: Vertical connection between glass panes



Detail 1: Connection between glass pane and supporting steel beam



Detail 2: Connection between fin and supporting steel beam

Structure / Earthquake

Measures against Earthquakes

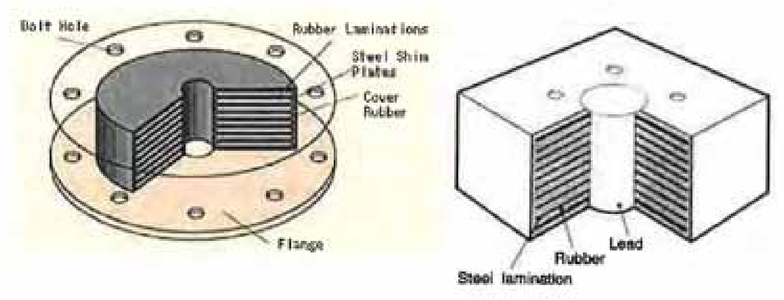
~~1. Increase the strength of the building~~ } ~~over-dimensioning: very heavy and expensive structure~~

2. Follow damage resistant principles } Post - breakage ductile behavior

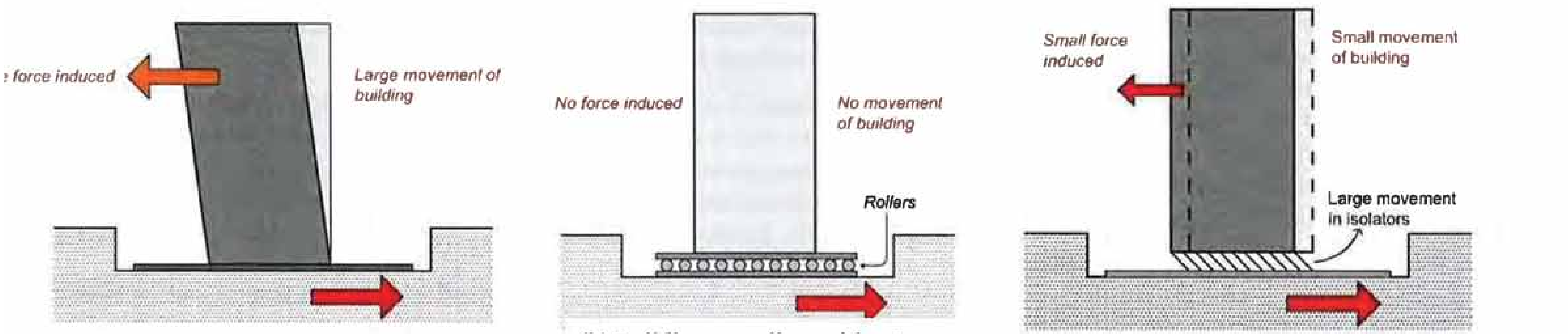
(laminated heat-strengthened glass has the highest level of fallout resistance)

3. Alter the building's characteristics externally } Base - Isolation (elastomeric bearings)

Lead Extrusion Dampers (LED)



(a) Laminated rubber bearing (b) Lead rubber bearing

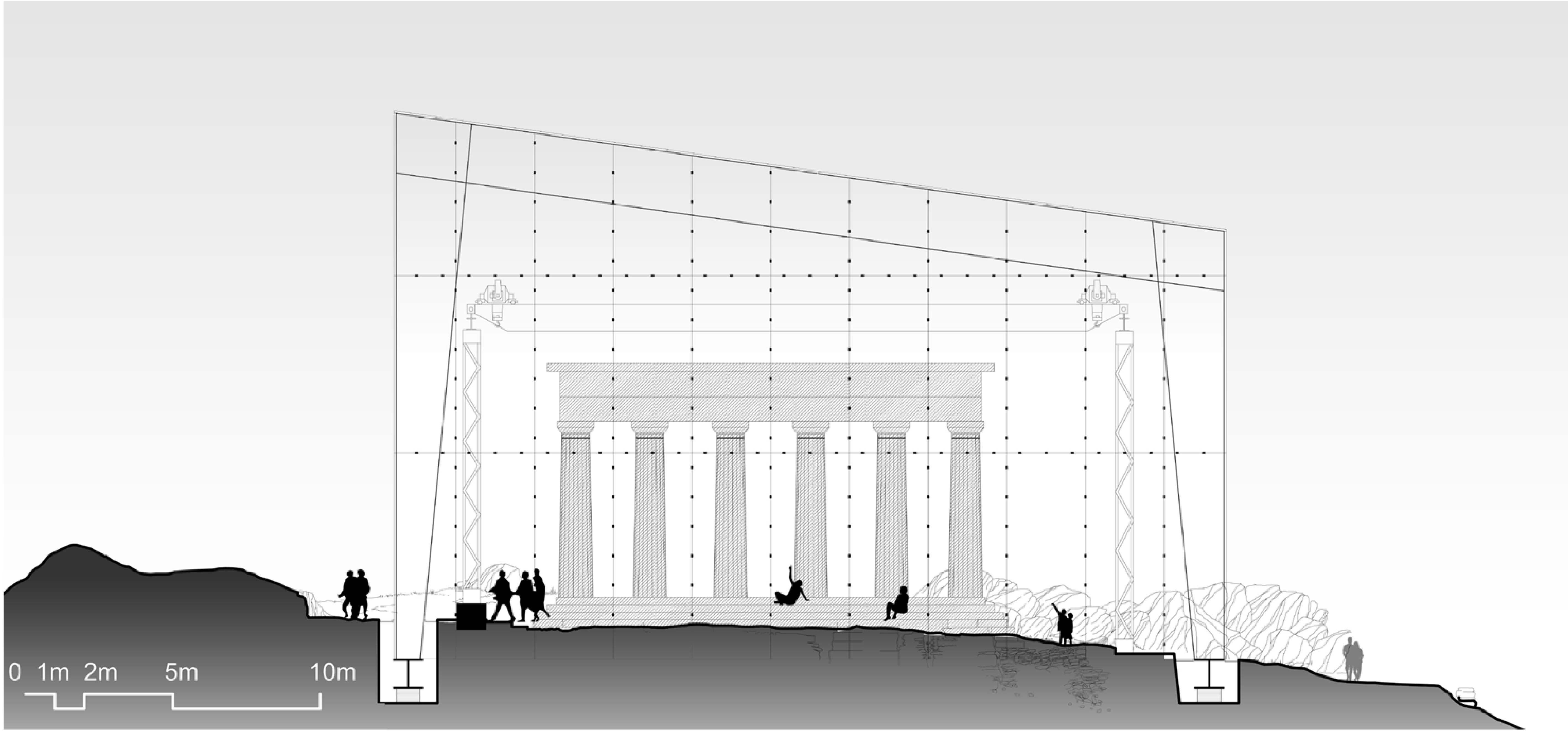


(a) Building resting directly on ground

(b) Building on rollers without any friction

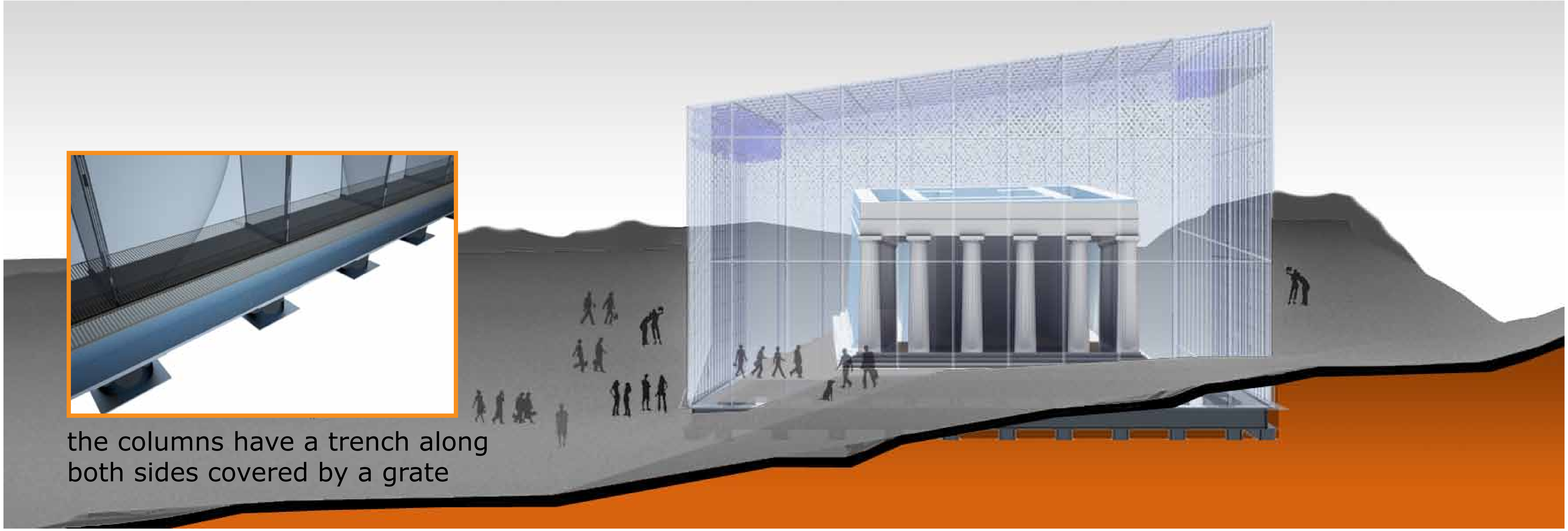
(c) Building base isolated with lead- rubber bearing.

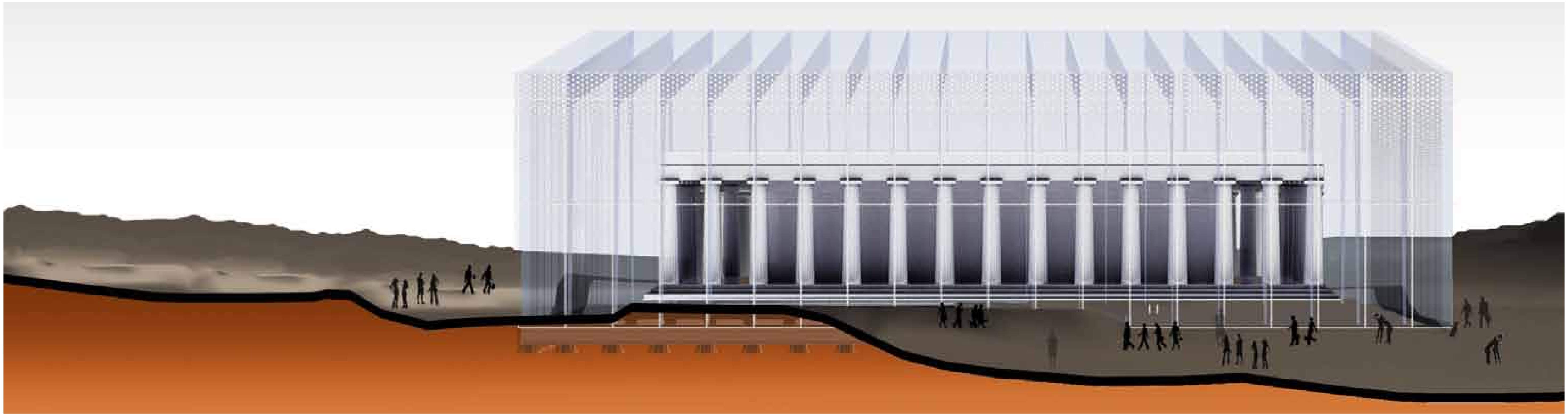
Structure / Earthquake



The foundation should be leveled, so that the upper structure functions as a rigid box.

Structure / Earthquake





Structure / Conclusions

1. The proposed all glass structure **can be realized**
2. The **slender dimensions** of the elements are possible **if the cladding is part of the load bearing structure.**
3. Due to the monolithic behavior the structure can **withstand buckling.**
4. **Joints** are needed that visually do not obstruct, allow force transfer and provide structural safety.

Thermal Performance

Thermal Performance

Aim: Minimize the overall energy demand required to obtain thermal comfort through passive strategies

- material assessment
- passive systems (e.g. natural ventilation)

Thermal Performance

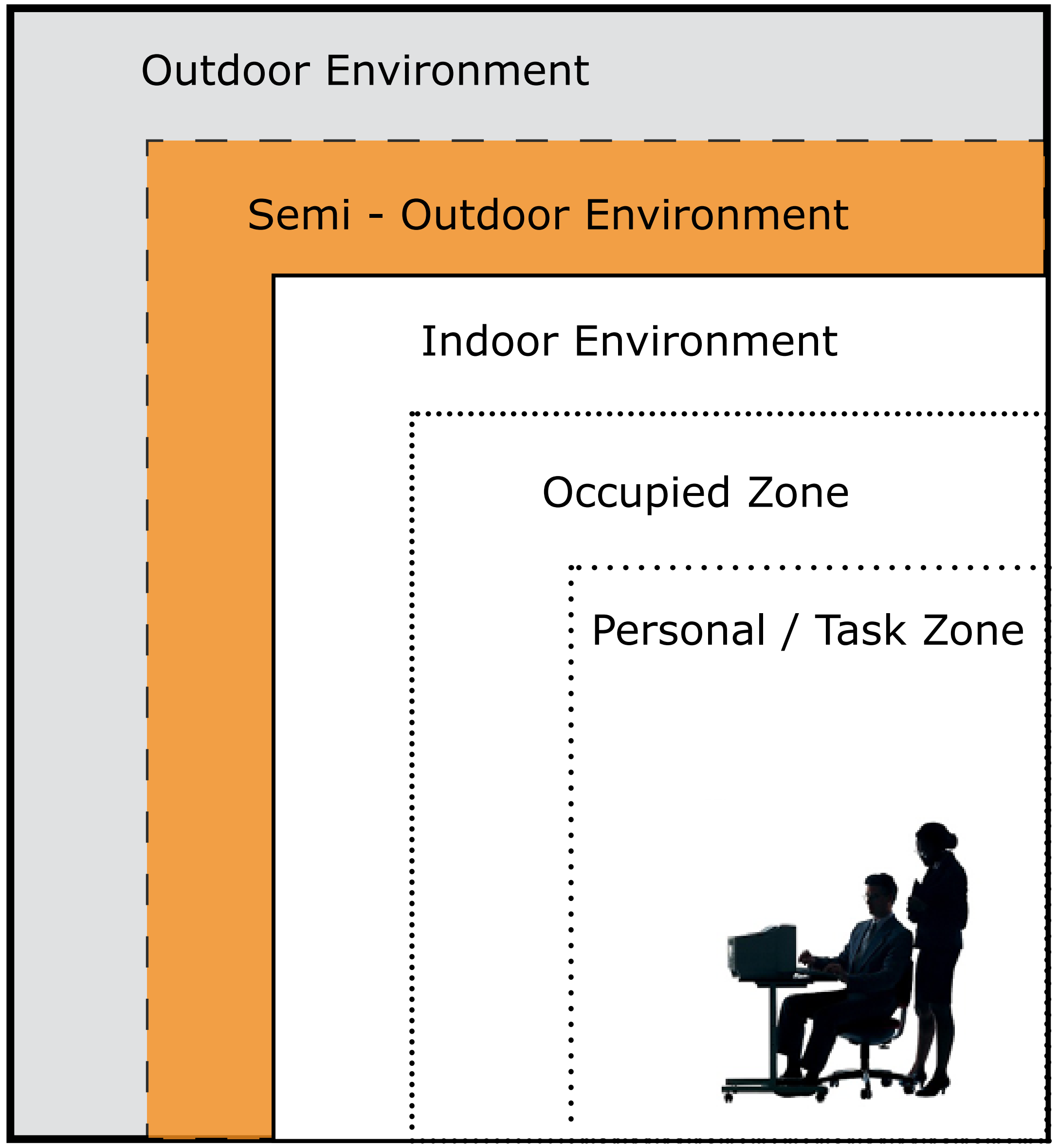
[Space Definition] : Semi-Outdoor Space

A space whose conditions are between indoor and outdoor location,which, however, can moderate the effects of the outdoor conditions.

In semi-outdoor spaces the occupants tend to tolerate a much **wider temperature range** than the ones determined based on the standard thermal comfort models.

Semi-Outdoor Space can be divided into 4 main categories:

1. Canopy / Buffer
2. Tempered Buffer
3. Partial Comfort
4. Full comfort



Layers of thermal environment surrounding a man [Nakano, 2003]

Thermal Performance / Semi-Outdoor Space

Atrium Type	Performance Level	Application	Comfort Criteria			
			UK		Japan	
			Winter	Summer	Winter	Summer
Canopy Buffer	Openess of outdoor setting reguired. Avoid rain for activity within.	Links between buildings Covered courtyard Covered shopping center	Ambient Air Temperature - or 5 °C + due to solar gain	Ambient Temperature / Peak air T = 30-35 °C	May range from outdoor level to indoor level due to concept	
Tempered Buffer	Semi-outdooor environment for pleasure	Passage, Agora	Air temperature heated to 10 °C in occupancy zone	As above	approx. 18 °C	28 °C - outdoor
Partial Comfort	Winter air conditioned. Shelter, shade, heating. Summer natural and or/ mechanical ventilation.	Glazed Links Entrances Meeting halls	Air temperature heated to 19 °C in occupancy zone	As above (peak air T= 30-35 °C)	18-22 °C	26-28 °C
Full Comfort	Normal Indoor Comfort Condition.	Lobby Exhibition Space Enclosed shopping areas Meeting Space	19 °C Minimum	max. 25 °C	22 °C	26 °C

Thermal Performance / Defining the Requirements

Comfort Zone for **occupancy hours**

[Space Definition]
Semi-Outdoor Space

[Type of Semi-Outdoor Space]
Partial Comfort

[Target Interior Temperature]
10-30 ^{o}C
[margins]

Comfort Zone
[during occupancy hours]

10-30 ^{o}C
[margins]

Temperature range for **non - occupancy hours**

[Problem Definition]
Avoid Frost
Minimize temperature fluctuations

[margins]
5 -30 ^{o}C

Thermal Performance / Passive Strategies

Passive Strategies

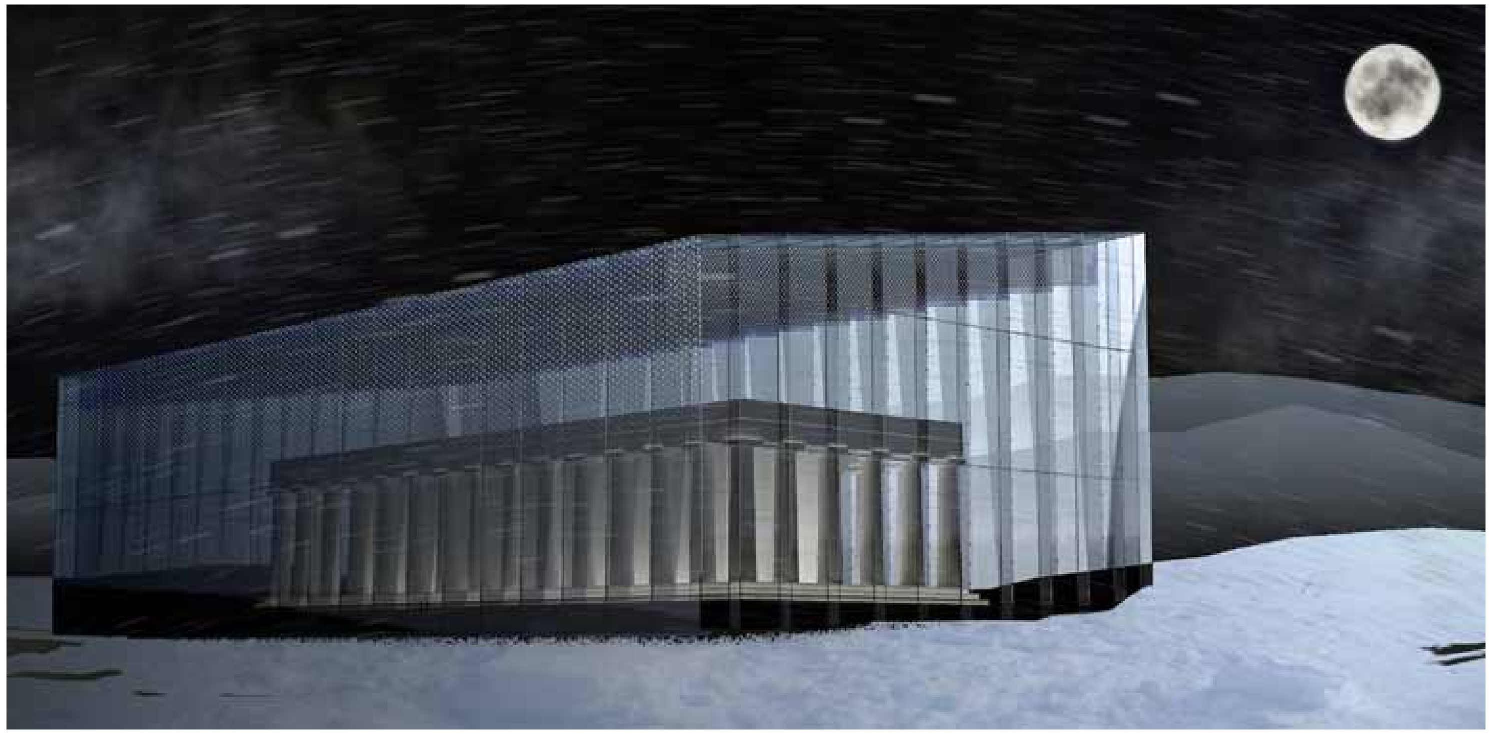
- Aim is to minimize the overall energy demand to achieve thermal comfort through passive systems.

- Passive strategies focus on minimizing the risk of overheating.

[Summer]

Risk of overheating during daytime

90 days



[Winter]

Risk of temperatures fall below 0 during night

20-30 nights

Passive strategies

1. Utilize the **thermal mass** of the temple [limestone]
2. Natural Ventilation [solar chimney effect, earth ducts]
3. Coating Assessment [light transmission, U-value, reflectivity]
4. Shading [fritting]

ENERGY DEMAND

- heating, cooling, lighting
  - Environment: reduced energy
  - Owner: reduced cost
- Occupants: thermal comfort, visual comfort

Thermal Performance / Passive Strategies

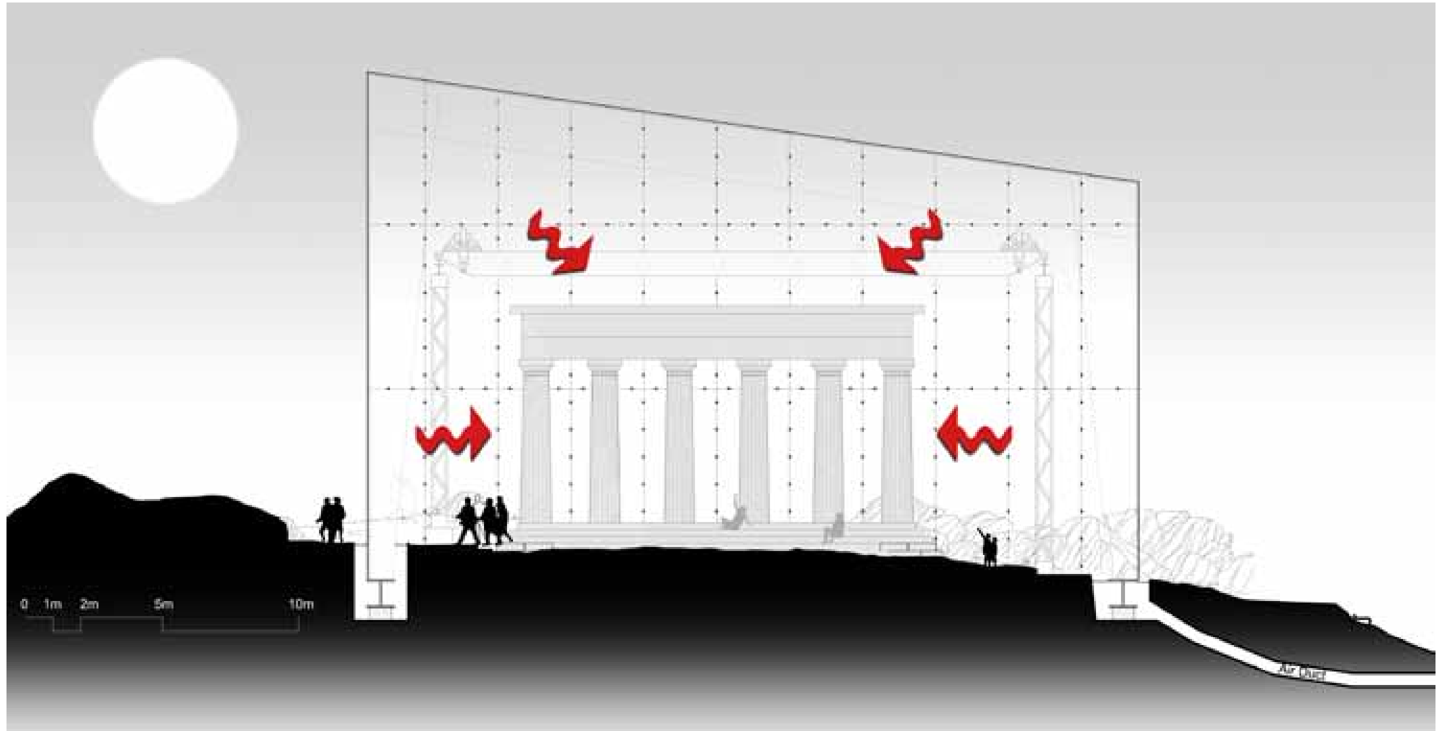
1. Thermal mass : Take advantage of the thermal mass of the temple

- Thermal mass is the ability of building materials to absorb heat, store it, and at a later time release it

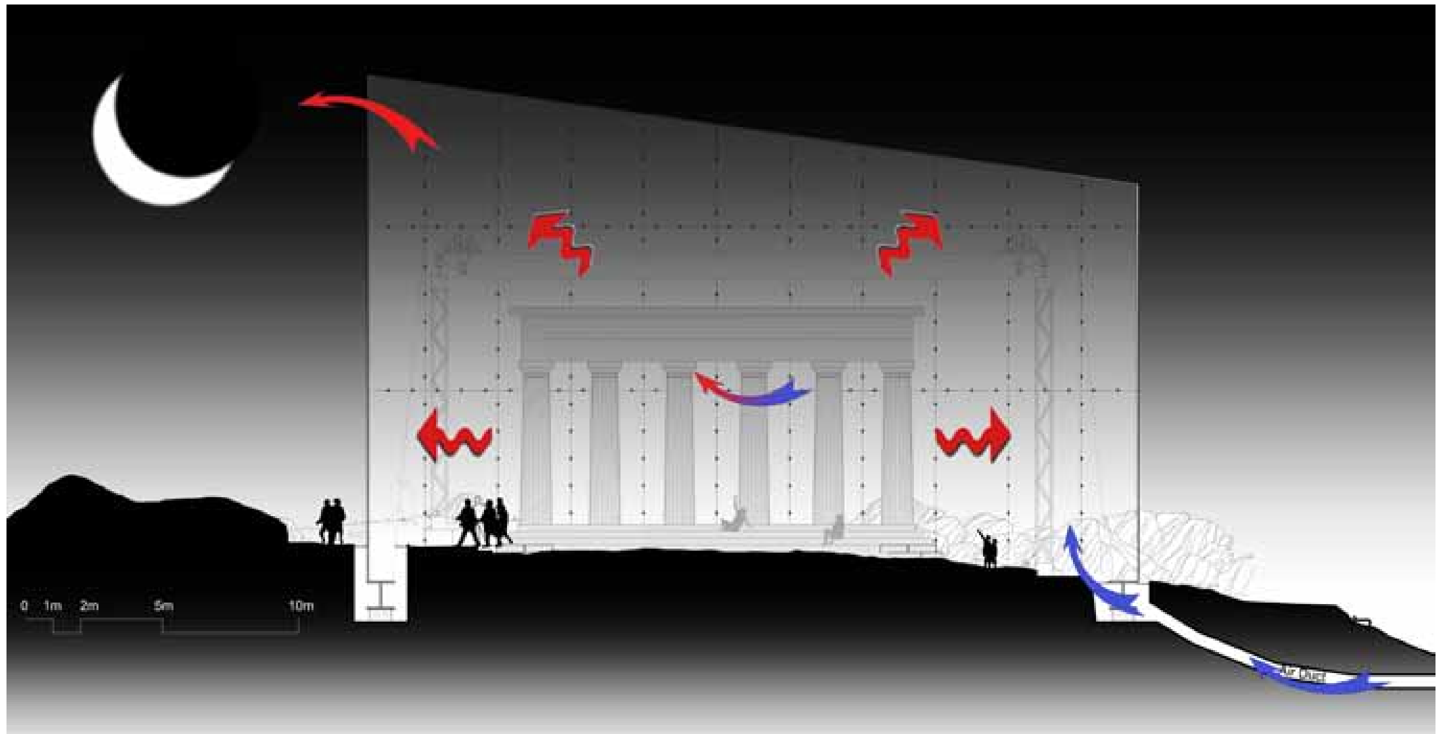
- It reduces the fluctuations in temperatures

- It decreases the peak temperatures due to thermal inertia

- The surface of the **thermal mass of the temple [limestone]** was estimated to be approx. **2500 m².**



[Summer Period] During the day, the temple absorbs and stores heat from the hot air inside the shelter.



[Summer Period] At night, ventilation cools the shelter by releasing the heat absorbed in the limestone.

Thermal Performance / Passive Strategies

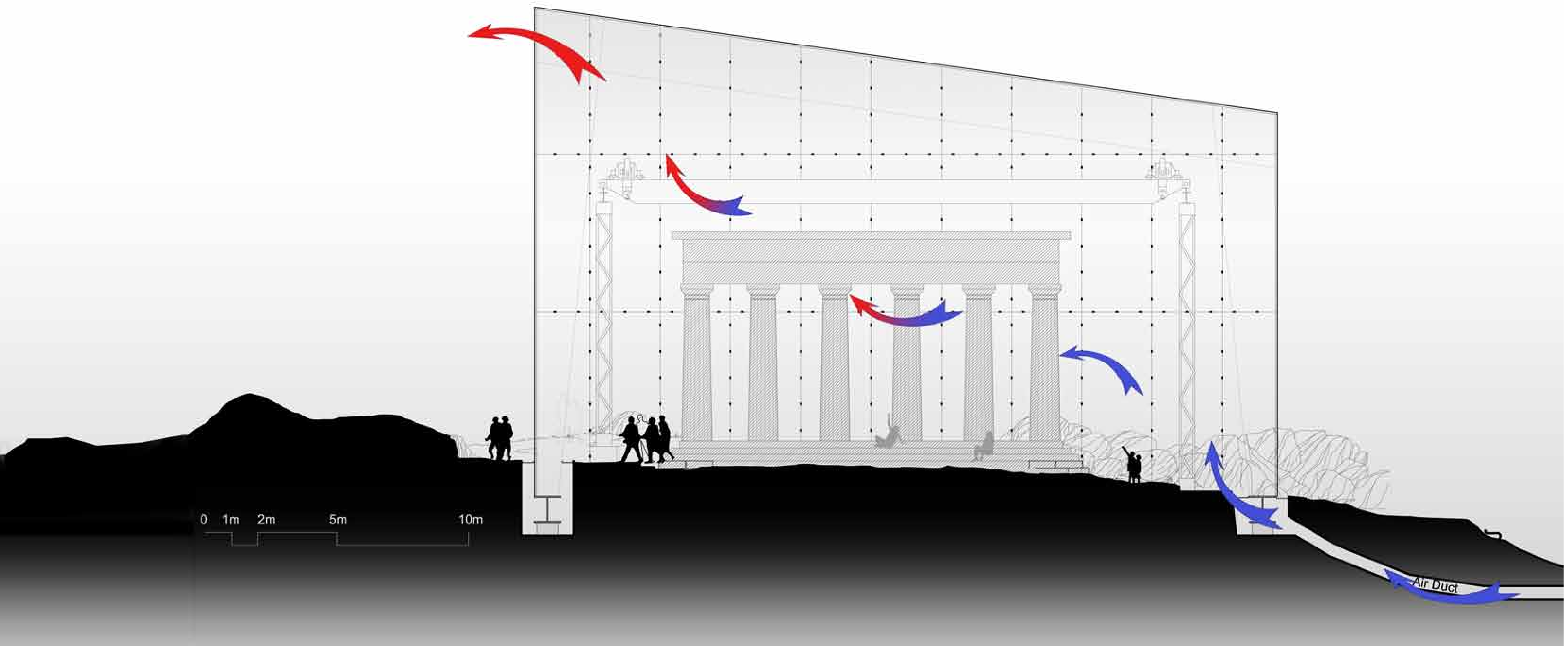
2. Natural Ventilation

- Stack ventilation [Solar Chimney effect]

Cool air is pulled in from the bottom of the west facade and hot air is pushed out from openings at the top of the east facade

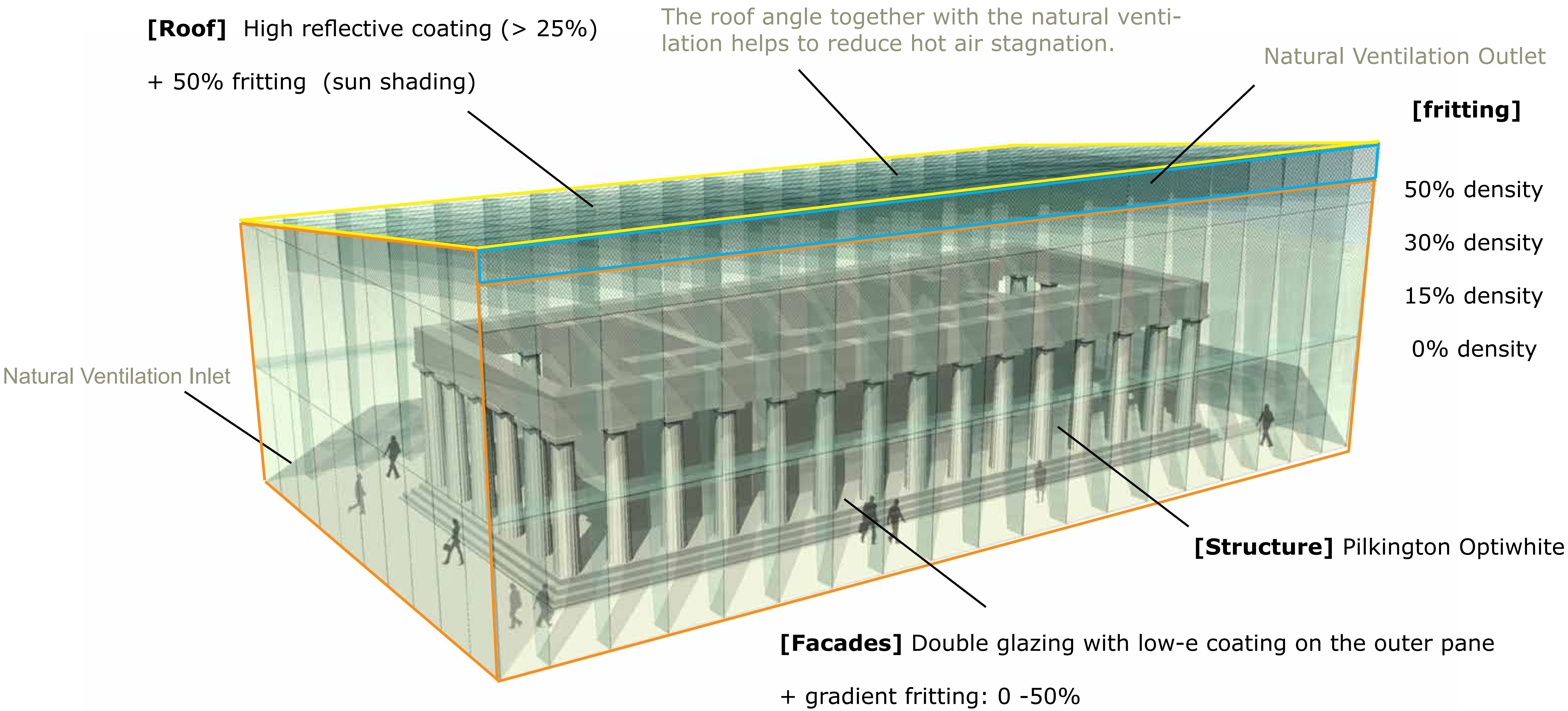
- Earth ducts

During winter outdoor air is preheated through heat exchange with soil and during summer it is cooled down through the same principle.



Thermal Performance / Material Assessment

3. Coating Assessment



Thermal Performance / Material Assessment

		Light		Solar Energy				Shading Coefficient			U value
Application	Type of Glass	Transmittance	Reflectance	Direct Transmittance	Reflectance	Absorptance	Total Transmittance	Short Wavelength	Long Wavelength	Total	W/m2K
Glass beams Facades and Roof's Inner pane	**Optifloat Clear** 8 mm	0.88	0.08	0.76	0.07	0.17	0.80	0.87	0.05	0.92	5.7
Facades' outer pane	**Optitherm S3** based on 4mm outer pane with inner pane: 4mm Optifloat Clear and 16mm argon filled cavity	0.80	0.13	0,54	0.26	0.20	0.61	0.62	0.08	0.70	1.1
Roof's outer pane	**Suncool Silver 50/30** based on 6mm outer pane with inner pane: 4mm Optifloat Clear and 16mm argon filled cavity	0.50	0.39	0.29	0.43	0.28	0.31	0.33	0.03	0.36	1.0
Glass fins	**Optiwhite** (heat-strengthened) 10mm	0.91	0.08	0.88	0.08	0.04	0.89	-	-	-	5.6

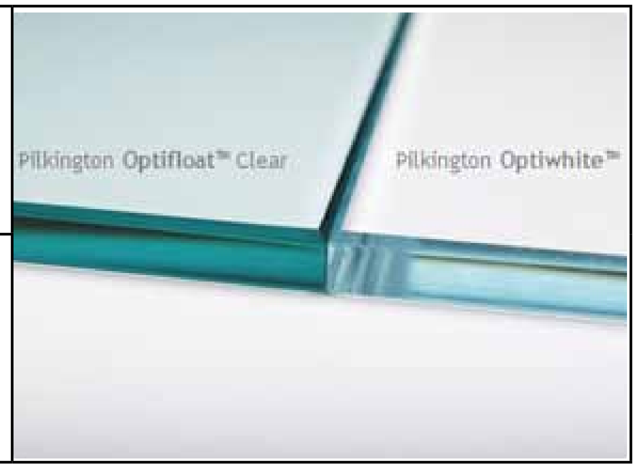
Thermal Performance / Material Assessment

Cladding > Thermal Comfort and Max. Transparency

	Outer Pane	Cavity	Inner Pane	Fritting	SHGC / Total Solar Transmis-sion	Direct Solar Transmis-sion	Light Transmis-sion	U-value (W/m2K)
Roof	Pilkington Suncool HP Silver 50/30 16mm	Air 40 mm	Pilkington Optifloat Clear 16mm	50%	0,30	0,255	0,48	1,71
Facades	Pilkington Optitherm 16mm	Air 40 mm	Pilkington Optifloat Clear 16mm	0 - 50% (gradient)	0,52	0,44	0,74	1,76

Structure > Strength and Max. Transparency

	Glass Pre-stress Level	Tensile Strength	Glass Type	Thickness	Adhesive	Reinforce-ment
Structure	Heat-Strengthened	70 MPa	Pilkington Optiwhite	3 x 10 mm (30mm)	SGP	Steel



Thermal Performance / Material Assessment

Thermal Performance / Fritting

4. Shading [Fritting]

- reduces significantly the solar gain

- reduces glare

- enhances diffuse light (good for anaglyphs and monuments)

For the shelter:

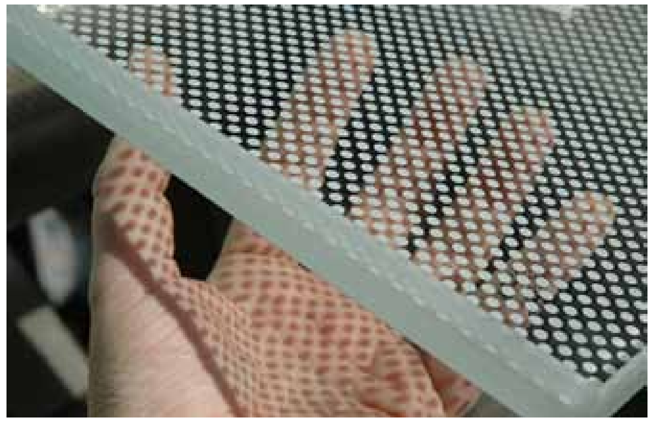
[Gradient fritting]

It starts from 0% and increases to 50% at the top of the facades and the roof.
This is achieved by increasing the diameter of the dots.
Through a gradient fritting a better blending into the environment is achieved.
Example with gradient fritting: New Acropolis Museum, Athens, Tsumi

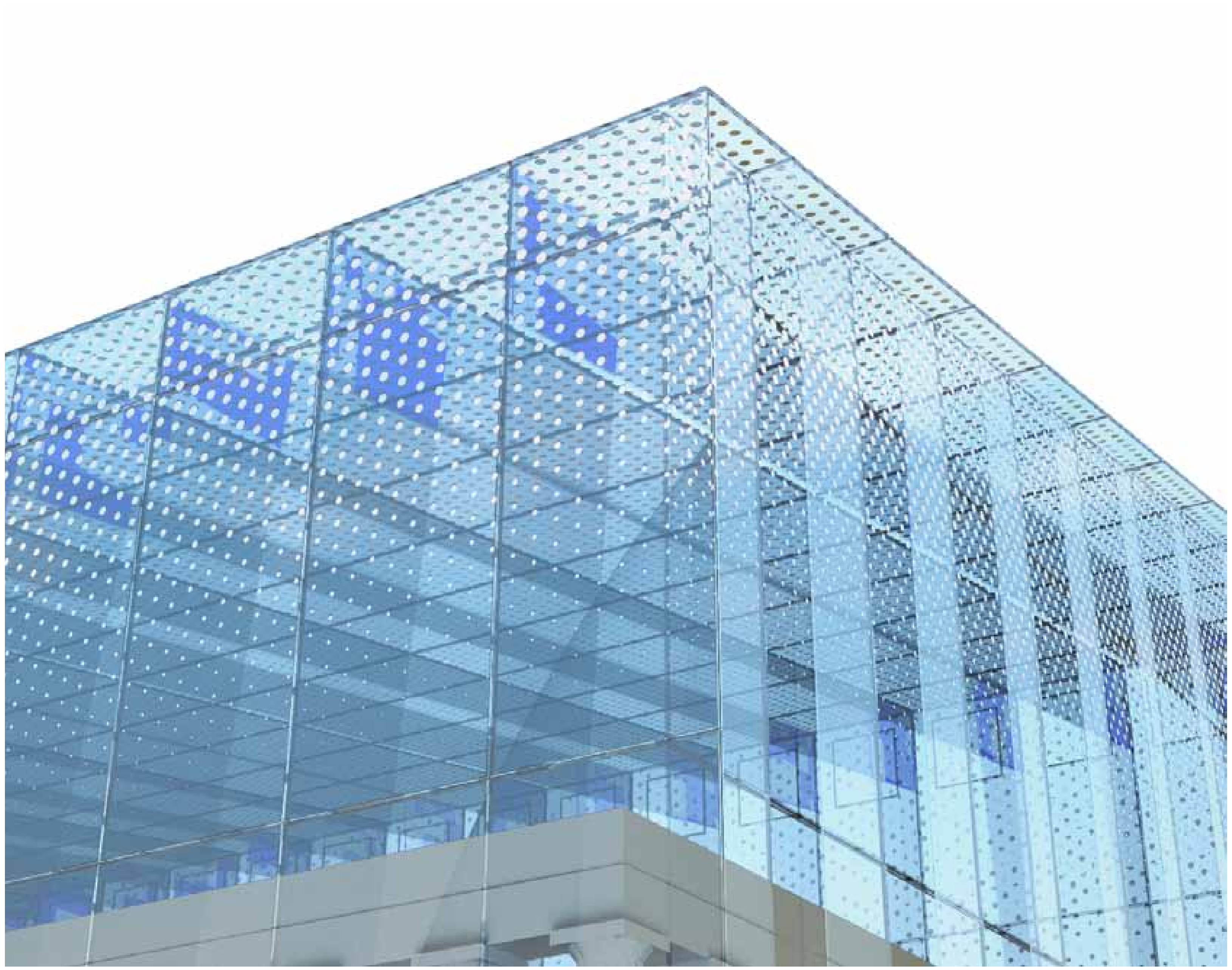
[White dots pattern]

The pattern mast be simple, so that it will not create any complicated shadows that can distort the image of the monument. Therefore dots were chosen as the most appropriate solution.

The dots are white, so that they can reflect the light and not absorb it, overheating like this the glass surface.

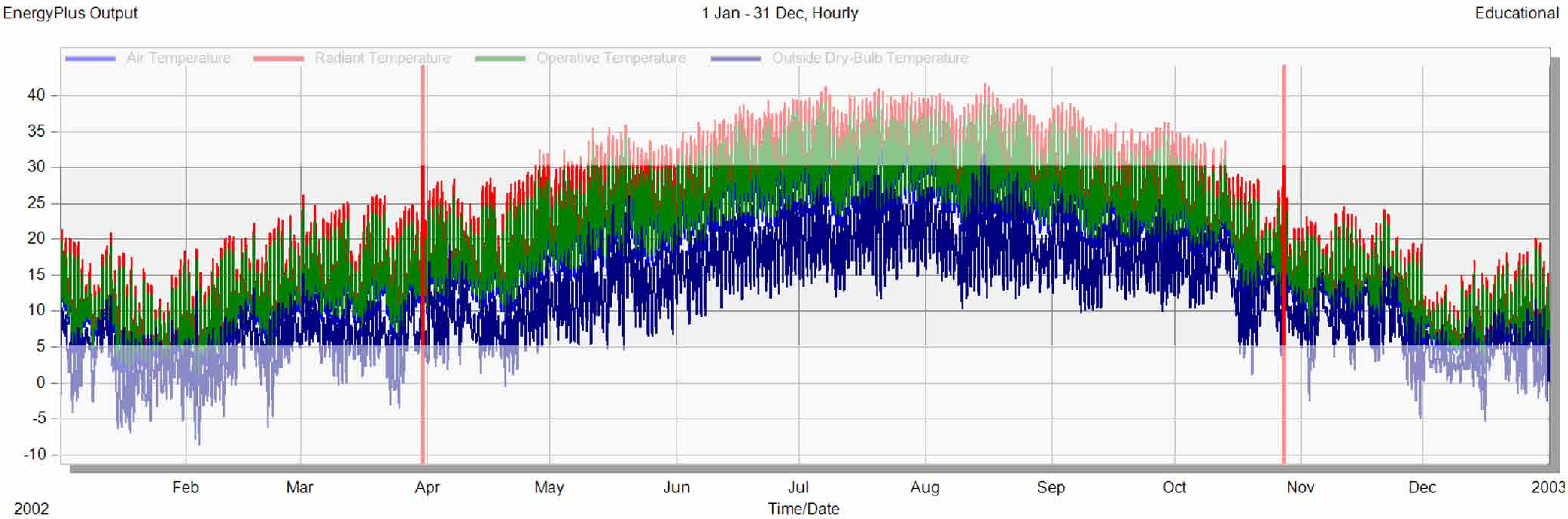


Thermal Performance / Fritting



Thermal Performance / Passive Systems contribution

Passive systems only / Annual Hourly Simulation



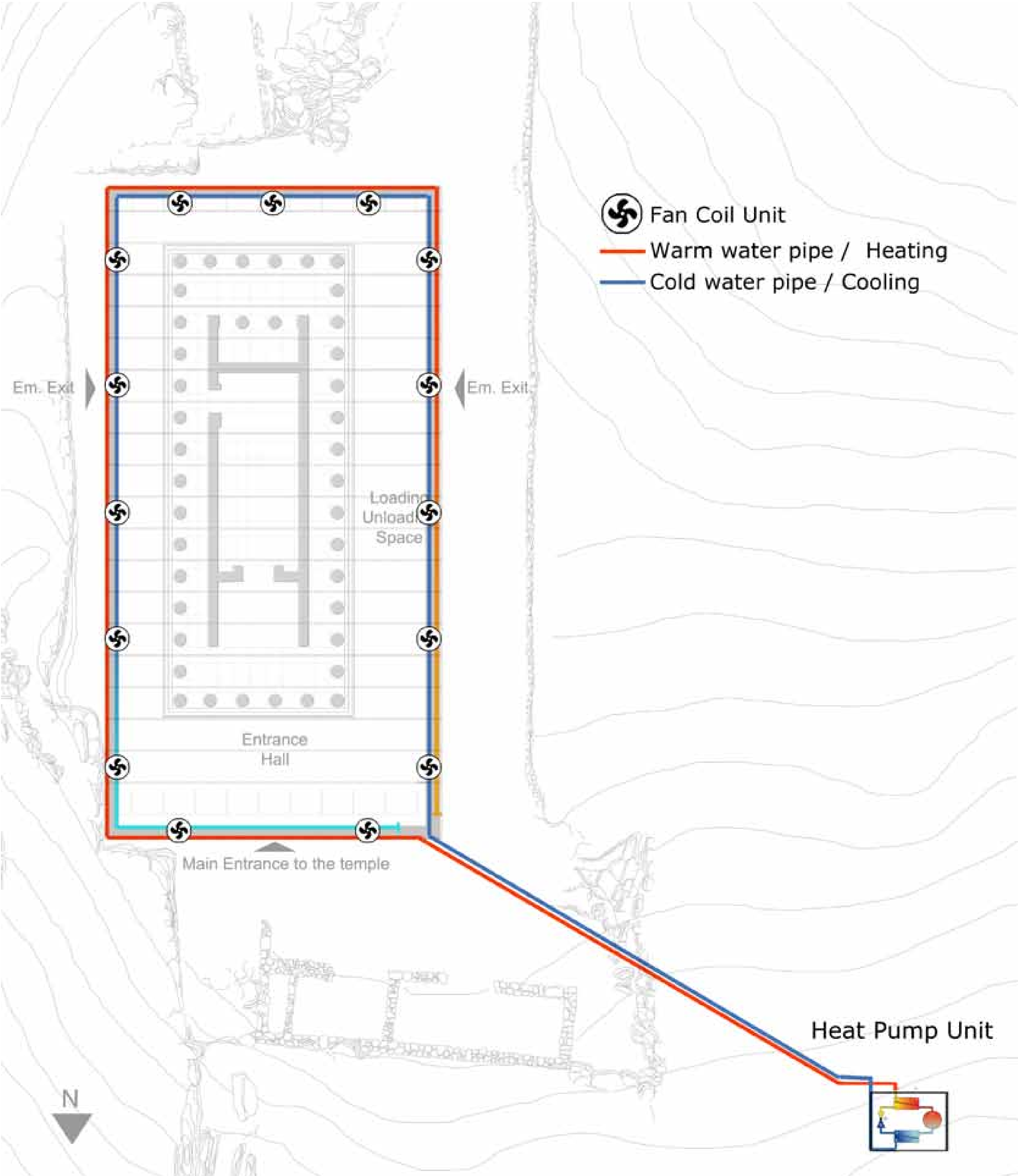
- Max. Air Temperature = 37.3 °C / **Max. Operative Temperture: 39.4 °C**

- The **operative temperature never falls below 0 °C** [Min. Operative Temperature = 1.2 °C]

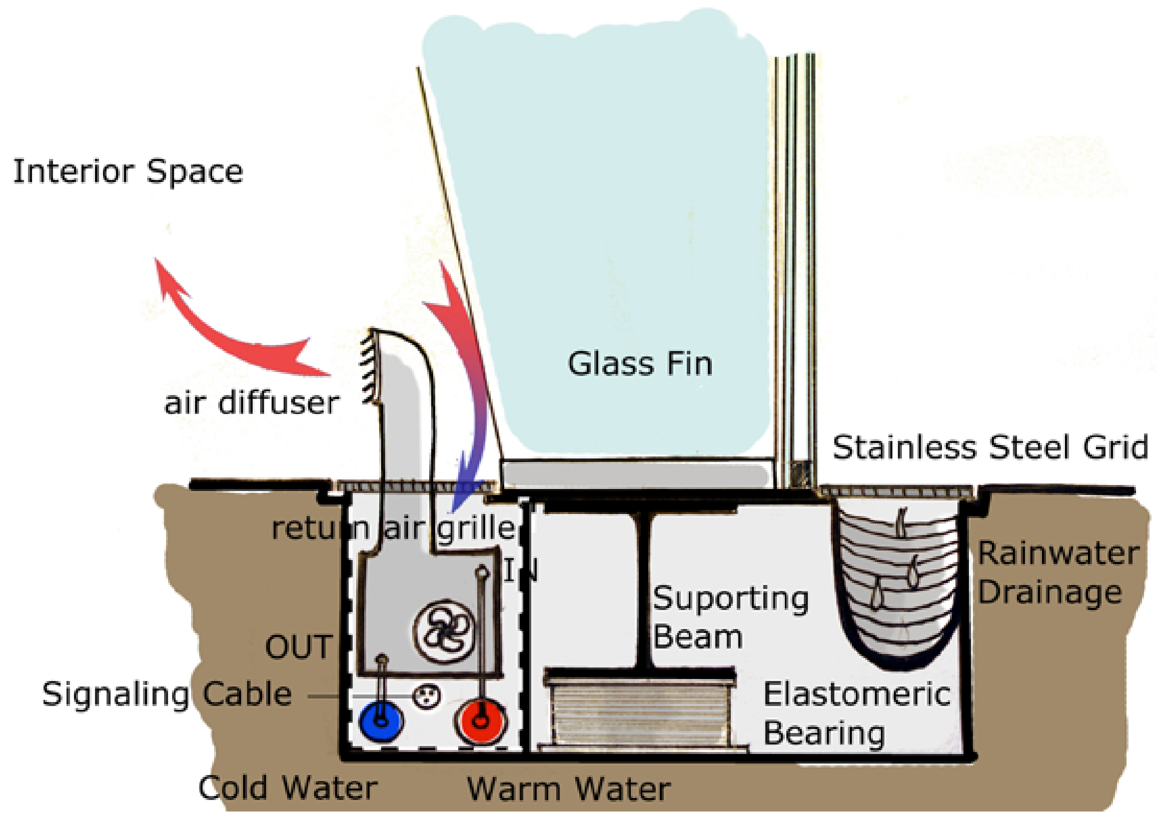
- The temple is **fully protected from frost**

- A supplementary mechanical unit is needed to always provide thermal comfort conditions for the visitors

Thermal Performance / Mechanical Supplementary Unit

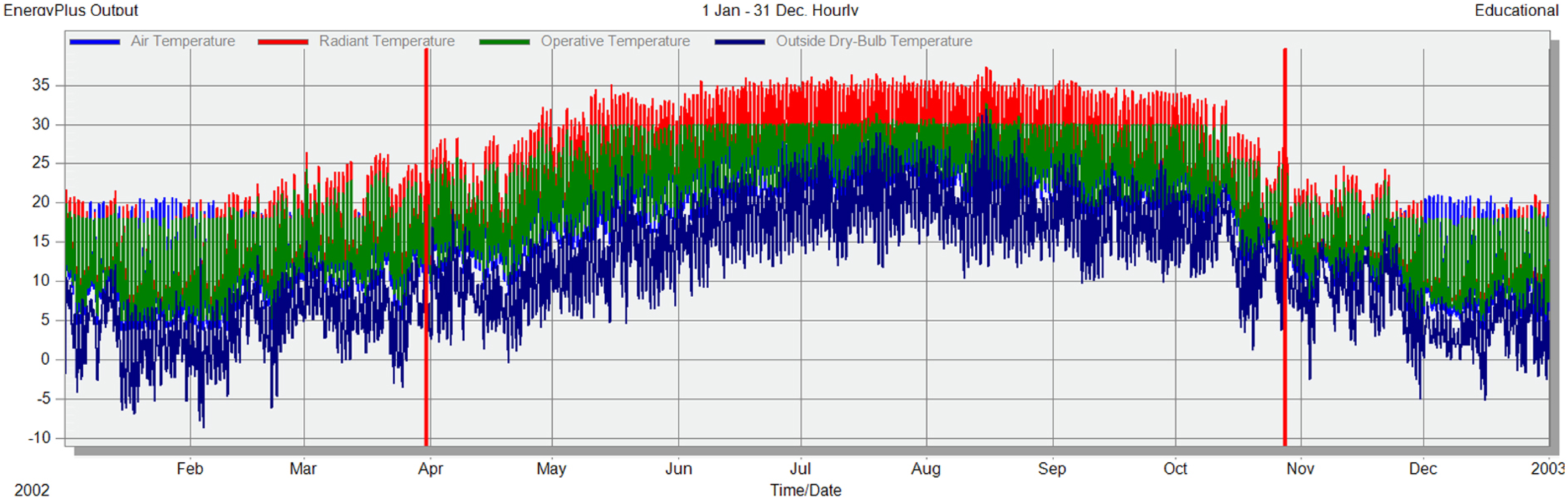


Heat pump + fan coils



Thermal Performance / Mechanical Supplementary Unit

Passive + mechanical systems / Annual Hourly Simulation

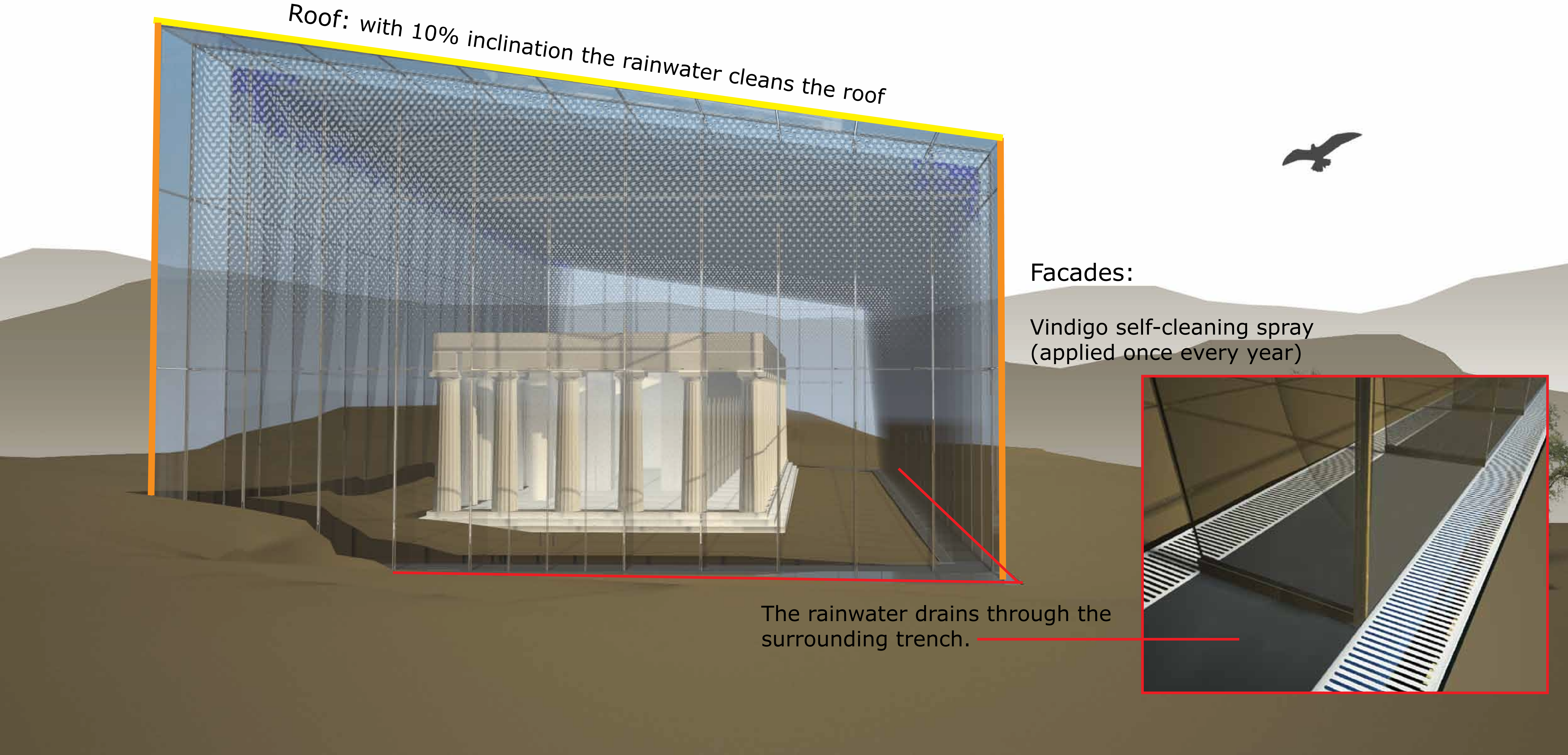


- The supplementary energy demand can be covered by a **75 kW** heat pump.

- However, only **17.3 %** of the round year time needs the activation of the heat pump.

- Significantly smaller fluctuations: **5-30 °C** instead of -9 - 37 °C

Sustainability / Self-cleaning ability of glass



Conclusions

[Architecture]

The glass structure **minimally distorts** the view of the monument

[Structure]

Glass structure of **uncommon slenderness**

↓

Cladding is part of the structural scheme

↓

Monolithic structural behaviour

↓

Joints are of great importance

[Thermal Performance]

The temple is **protected from frost** through the use of **passive measures only**

With a low energy consumption: a comfortable space for visitors is achieved

the temperature fluctuations are reduced

Large transparent enclosures for monuments that need to be protected are **possible**!!!!

Thank you!