Sustainable Design Graduation Studio_**Alkistis Krousti**_4420705

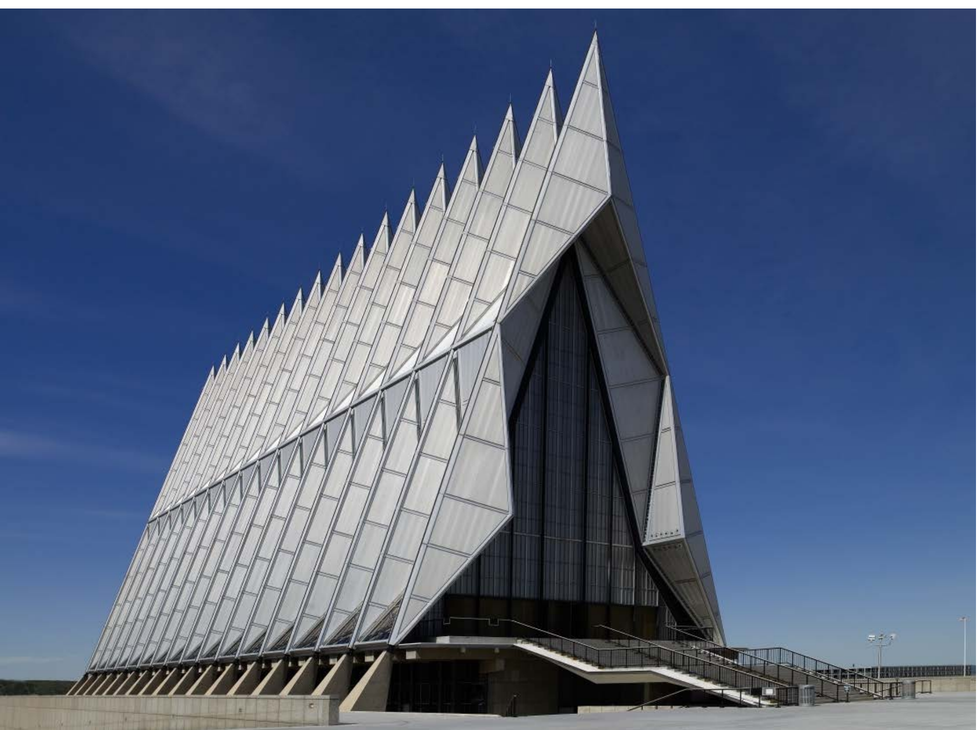
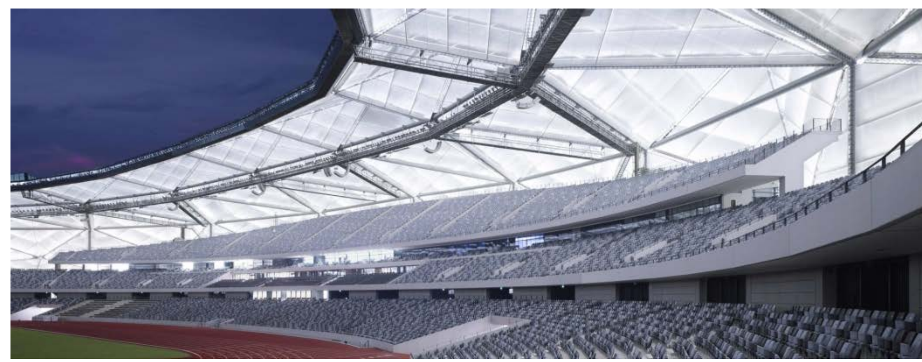
FOLDED GLASS PLATE STRUCTURES: A DEPLOYABLE ROOF SYSTEM

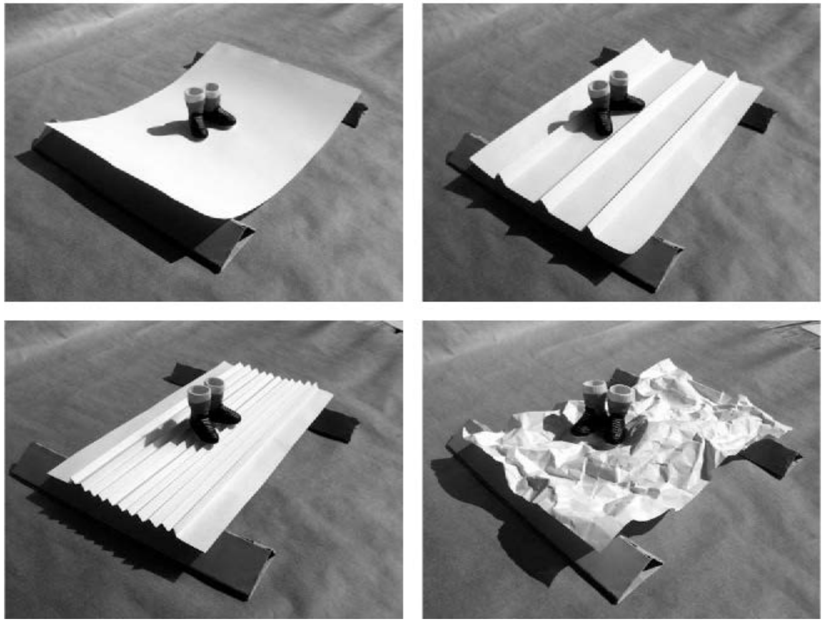
MENTORS: Ate Snijder, Peter Eigenraam, Michela Turrin



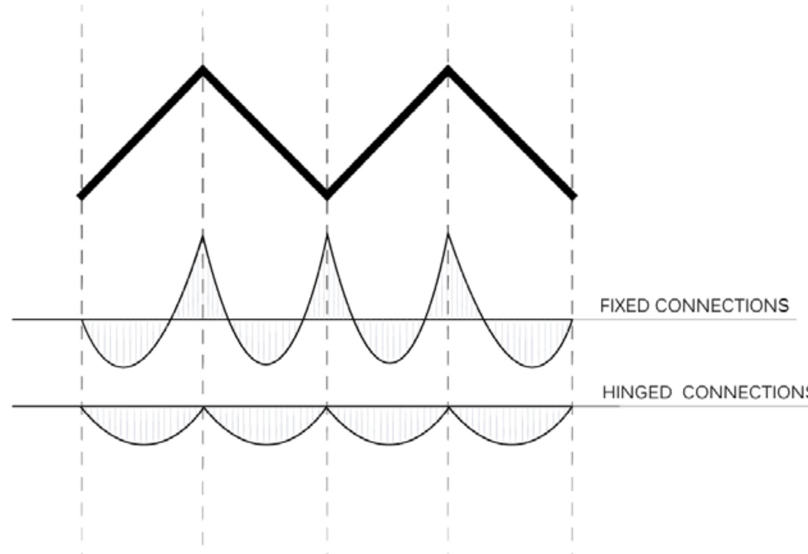




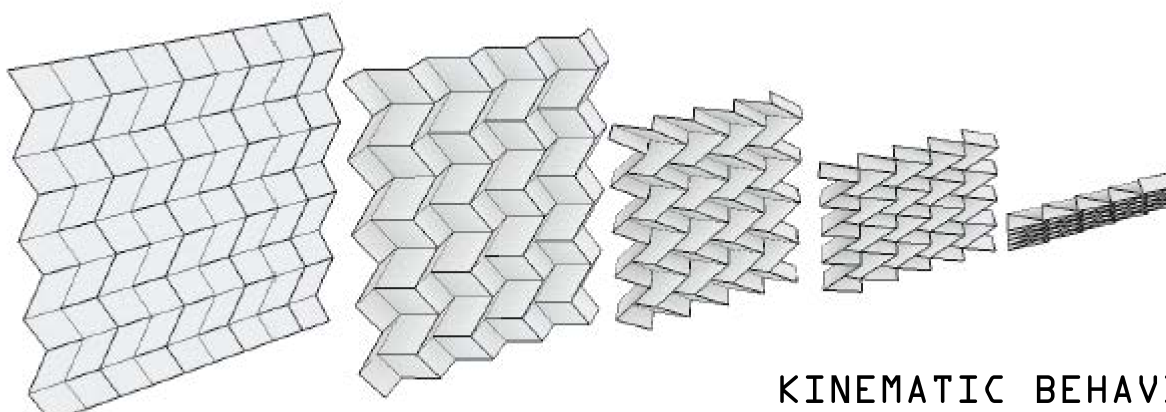



STRUCTURAL PERFORMANCE



FOLDED PLATE PROPERTIES



KINEMATIC BEHAVIOR

RESEARCH QUESTION :

To which extent can the kinematic qualities of folded geometries be combined with the structural benefits of glass plates and more specifically, how can these be applied in the case of a deployable glass roof system?

SUB-QUESTIONS

- What are the criteria for selecting a folding pattern that provides both stiffness and deployment potential?
- How do the geometrical parameters of the folding pattern affect the structural properties of the system?
- What kind of mechanism enables the specified deployment movement and what restrictions does this present for the design?
- What types of connections are required between plates and in the structure supports to ensure that the load transfer is done as expected and also to allow the necessary degree of freedom for the deployment?
- How can those connections be designed to be as invisible as possible, while providing the required tolerances and envelope properties, such as waterproofing, etc.?

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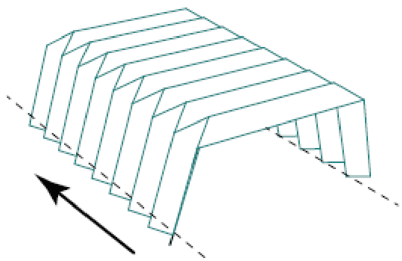
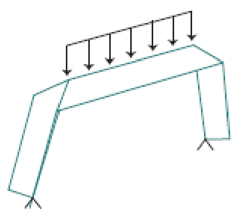
CRITERIA DEFINITION



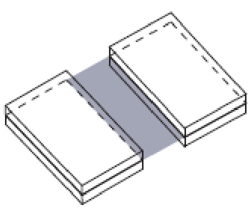
DESIGN CRITERIA

Provide natural lighting and maximum transparency
Self-supported glass plate structure (no frame)
Deployable on one side (fully adaptable)
Feasibility



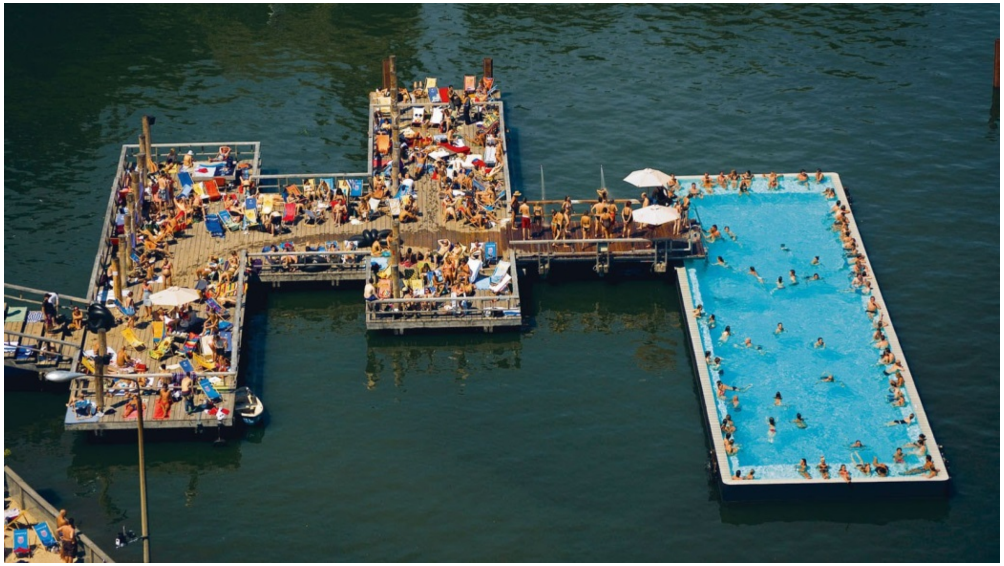
STRUCTURAL CRITERIA

Controlled element deformation + stress levels (all phases of deployment)
General shape stability (all phases of deployment)
Glass element redundancy
Damage sensitivity - Fracture mode – Safety factors



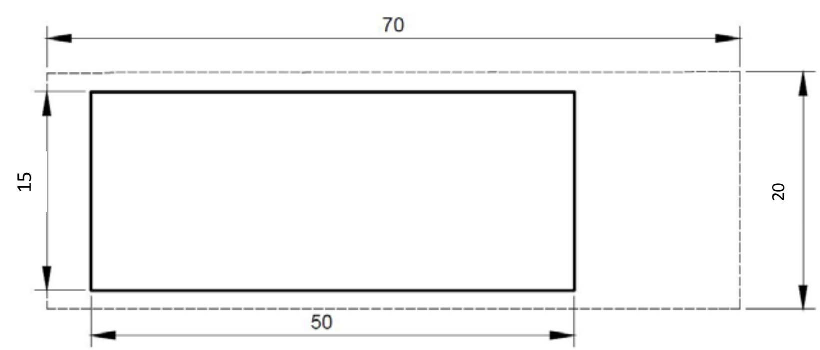
DETAILING CRITERIA

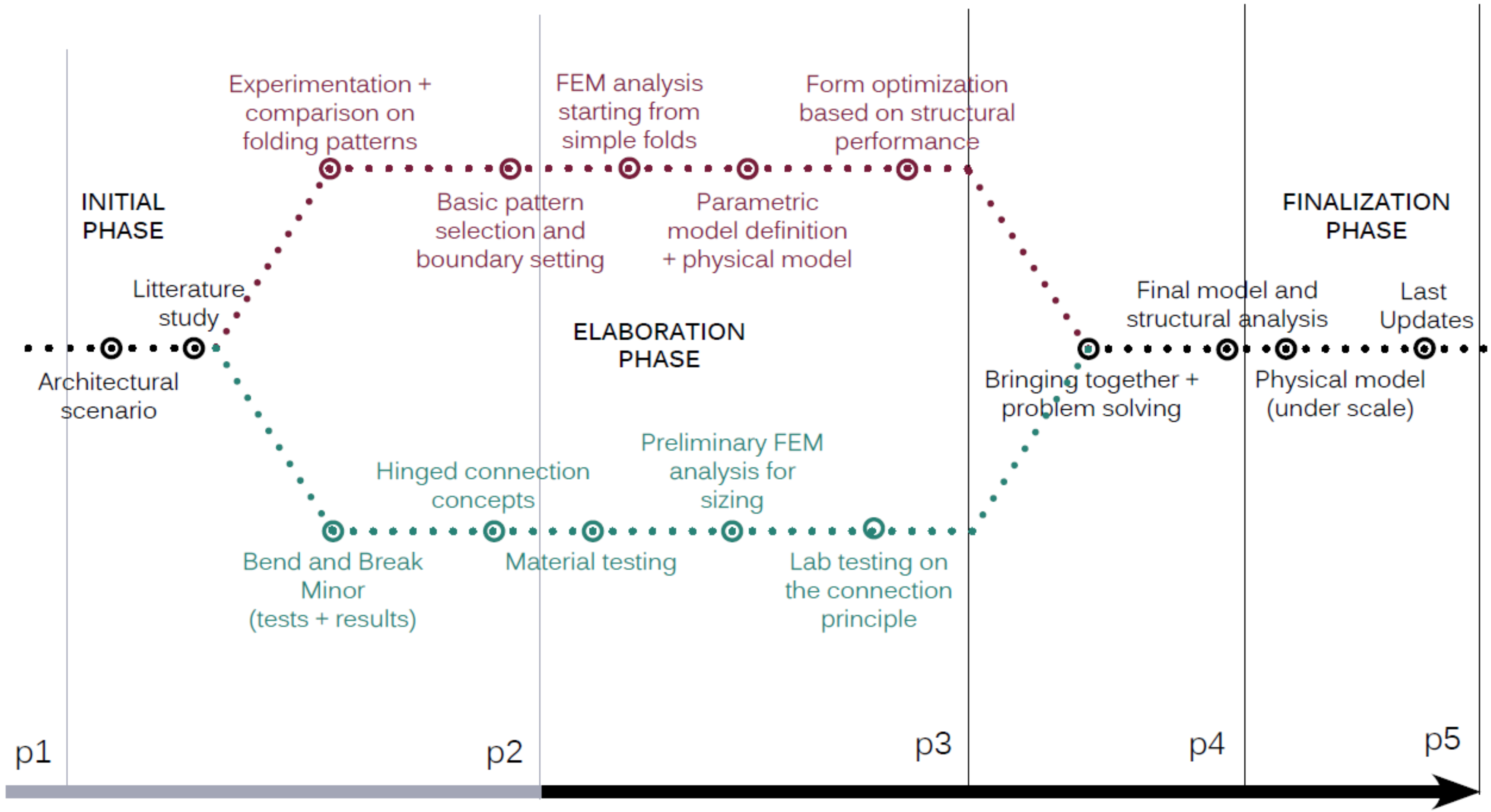
Discrete design- Invisible connection
Tolerances
Restriction of gaps- waterproofing
Repair work facilitated
BC maintained by connection detailing

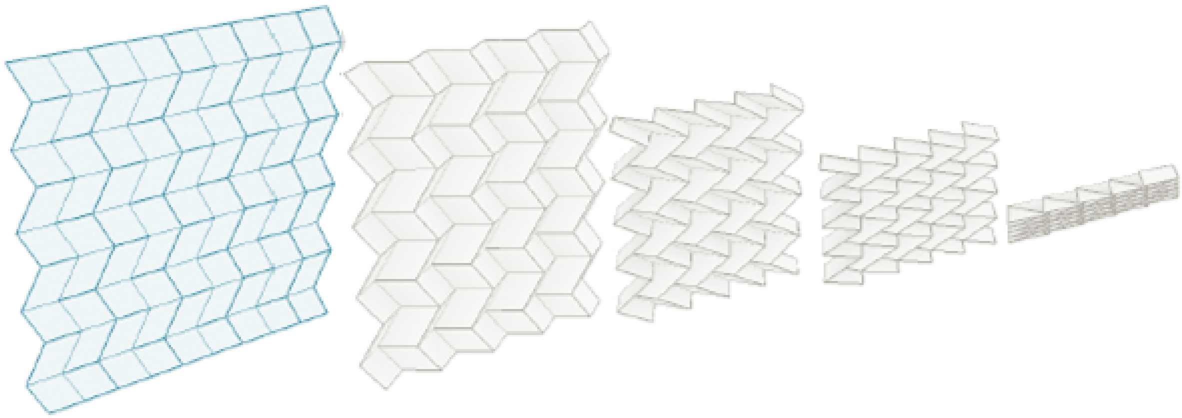


CASE STUDY

Swimming pool area :
15* 50m – Total span: 20m



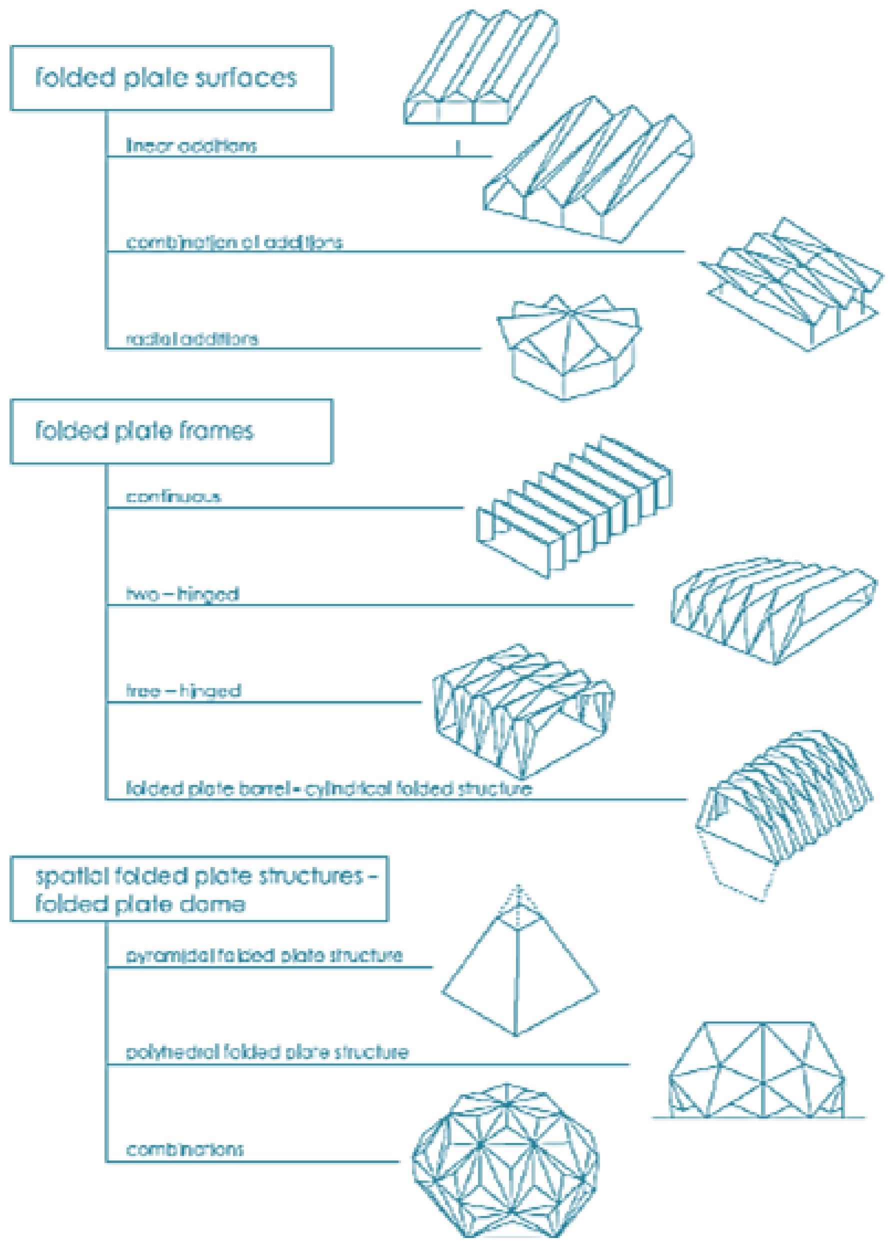

INITIAL PHASE
ELABORATION PHASE
FINALIZATION PHASE
Architectural scenario
Litterature study
Experimentation + comparison on folding patterns
Basic pattern selection and boundary setting
FEM analysis starting from simple folds
Parametric model definition + physical model
Form optimization based on structural performance
Bend and Break Minor (tests + results)
Hinged connection concepts
Material testing
Preliminary FEM analysis for sizing
Lab testing on the connection principle
Bringing together + problem solving
Final model and structural analysis
Physical model (under scale)
Last Updates
p1
p2
p3
p4
p5



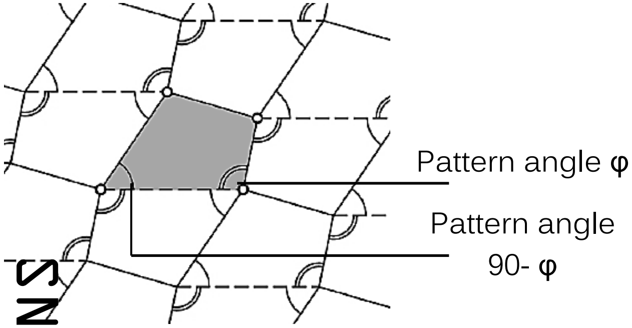
PART 1:
FOLDING PATTERN SELECTION

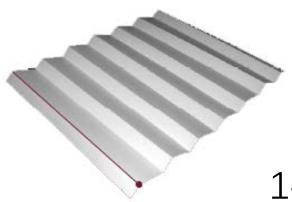
TYPES OF FOLDED PLATES

A folded plate structure is a three-dimensional structure formed out of thin plate elements arranged in a manner to form a load bearing system.
[J.Born,1954.]



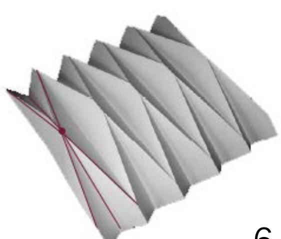
TYPES OF FOLDING PATTERNS





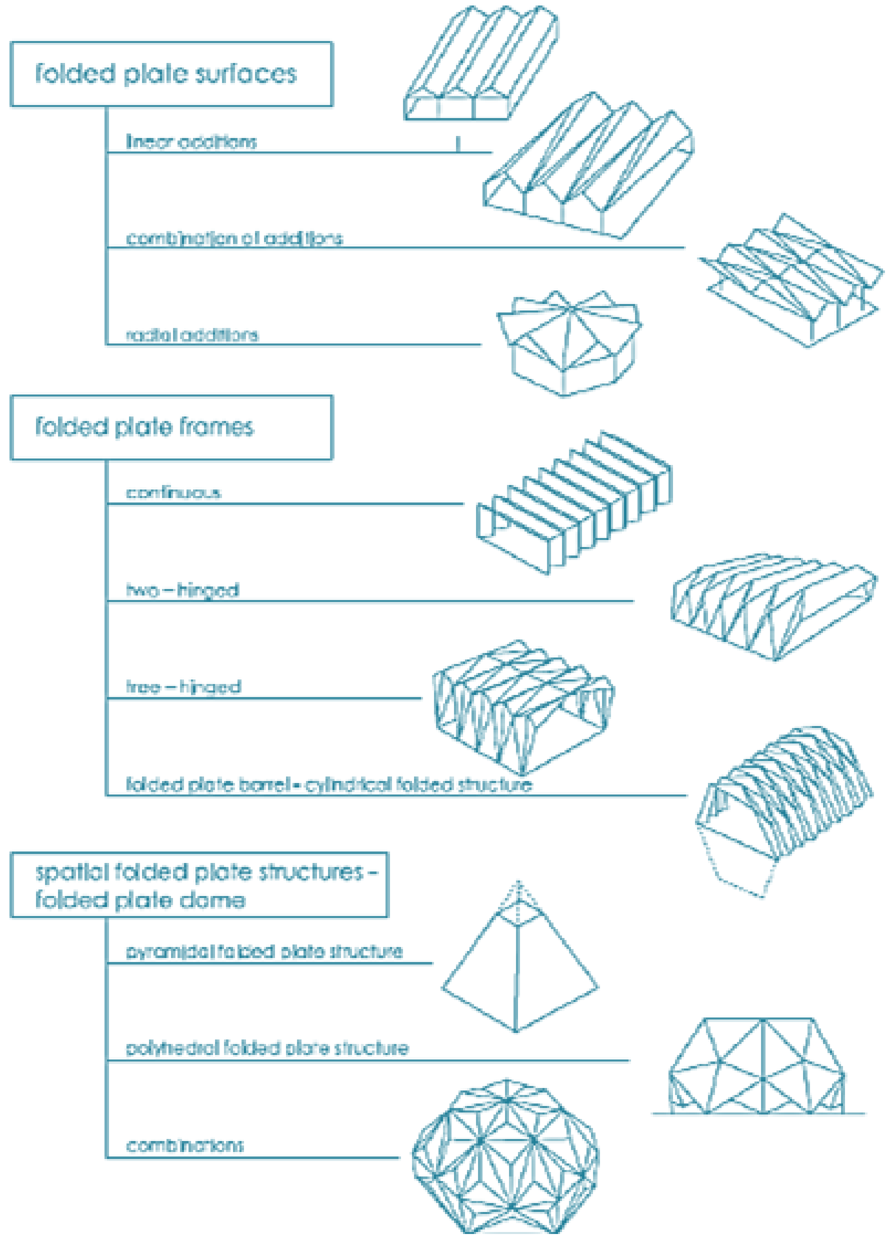
1-fold

4-fold



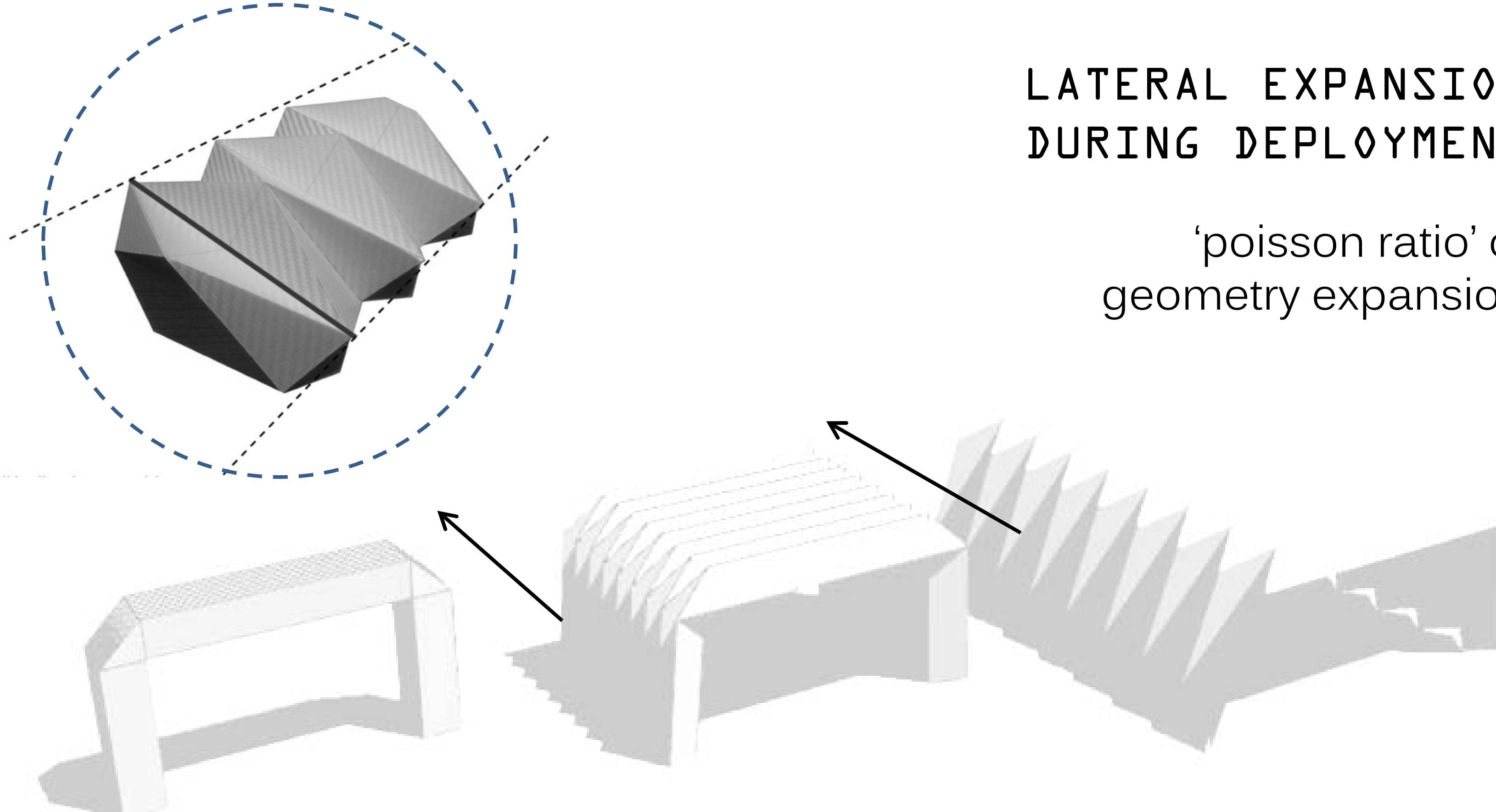
6-fold

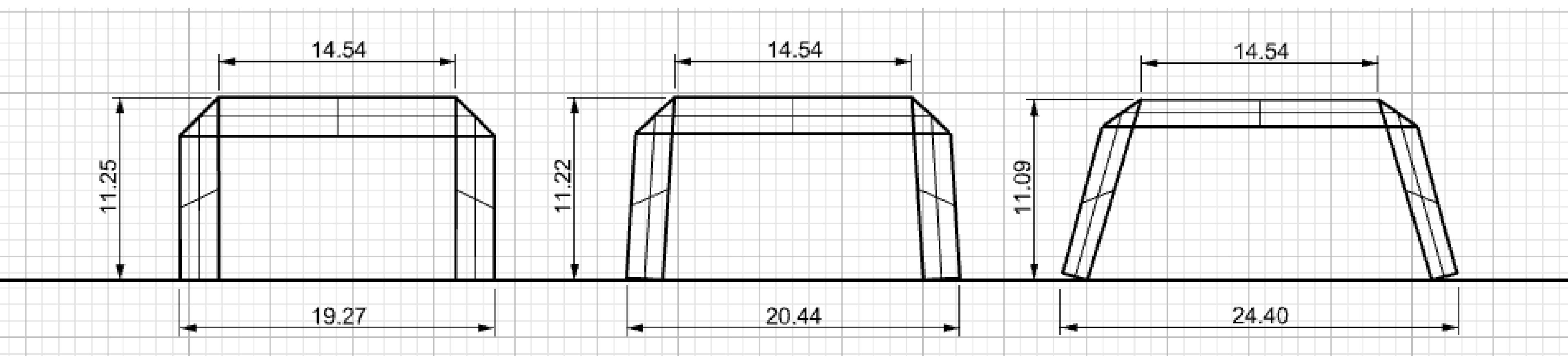
TYPES OF FOLDED PLATES



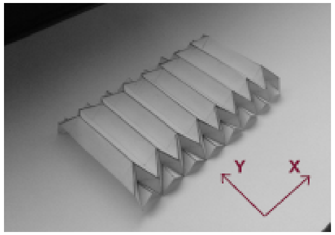
LATERAL EXPANSION DURING DEPLOYMENT

'poisson ratio' of
geometry expansion





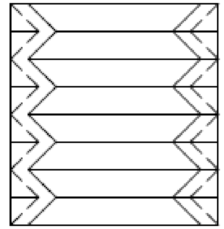
FOLDING PATTERN COMPARISON

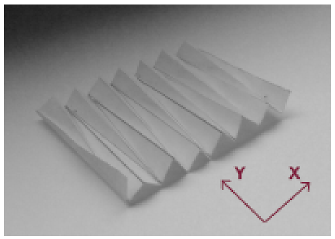


1. Simple 1-fold with hybrid endings

TYPE: planar
quadrilaterl pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is the hybrid of a simple 1-fold pattern. It can effectively span over one direction, but is prone to bending. The extra folding around the ends helps the load distribution, avoiding large stress concentration around supports.

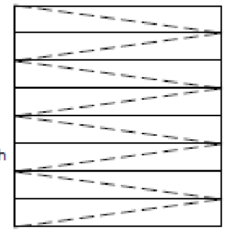


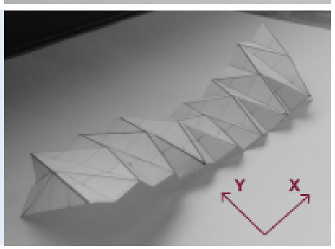


2. Triangular 1-fold

TYPE: planar
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is a triangular version of the above. Due to the triangulations, this structure copes with bending better. It has been used in architectural applications, such as the new Terminal of Pulkovo International Airport.

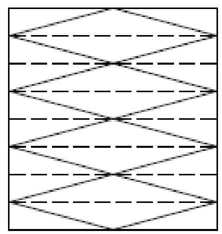


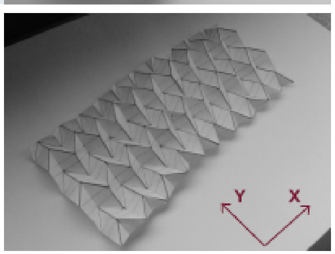


3. Diamond 6-fold (single)

TYPE: planar
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is one of the few triangular meshes with zero lateral expansion during deployment. This makes it ideal for rail systems. The triangulation of the surface also increases structural height, reduces the bending stresses.

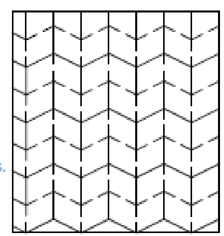


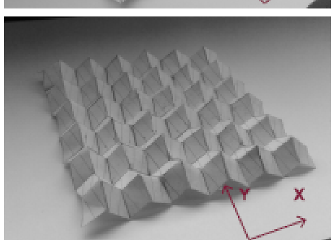


4. Miura-Ori 4-fold

TYPE: planar
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is one of the most typical examples of folding patterns for architectural applications. Such a level of tesselation of a flat surface cannot achieve stiffness in the case of hinged connections. Unstable structure.

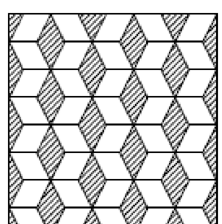


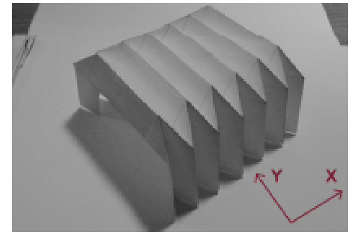


5. Eggbox 4-fold

TYPE: planar
quadrilateral pattern
non- developable - no DOF rigid motion
span direction: Y and X

This is one of the very few non-developable patterns. since it involves cutting it doesn't directly fall under the definition of origami. Much like the Miura-Ori, it looses stiffness in both span directions, when hinged connections are used.

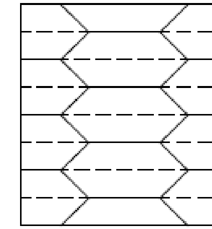


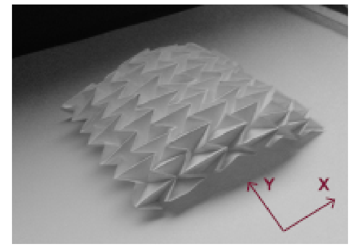


6. Simple 4-fold

TYPE: frame / tunnel
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is the simplest form of origami-frame structure. Folds across the span direction increase stiffness, replacing beams.

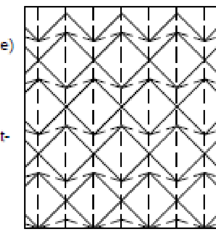


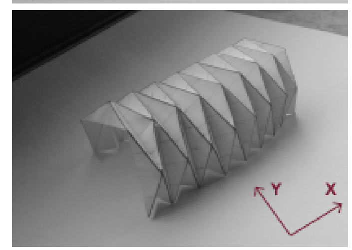


7. Butterfly 6-fold

TYPE: planar/ spatial (dep. on folding angle)
triangular pattern
developable - 2 DOF rigid motion
span direction: X, Y / retractable on Y

This is a rather complicated pattern, unsuitable for structures, as it provides very low stifness in both span directions. Performs better if applied on a curved surface but sitll unstable in combination with hinged connections.

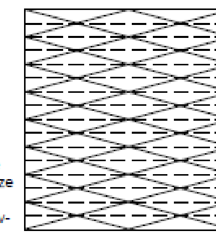


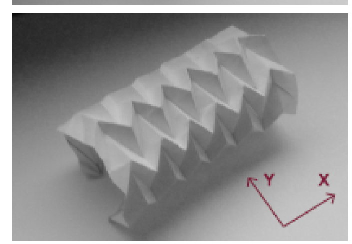


8. Diamond 6-fold

TYPE: frame / tunnel
triangular pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is a simple pattern, in which, the pattern angle determines the curvature of the final surface assumed, and the element size the coarseness of the folding. Although its shape and folding provides stifness, behavior with hinged connections is uncertain.

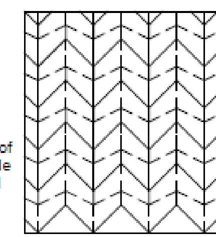


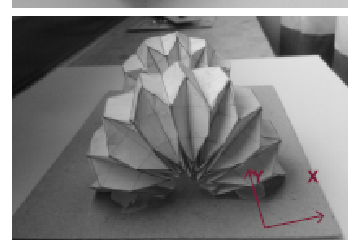


9. Miura-Ori (uneven)

TYPE: frame / tunnel
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is a version of Miura-Ori with the use of two different angles. According to the angle difference, the curvature of the final tunnel shape is altered. Presents the same structural concetn as the Diamond pattern.

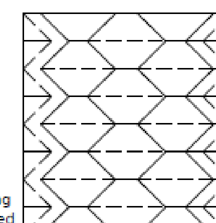




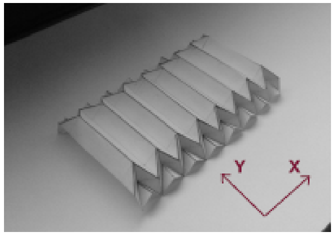
10. Hybrid Dome

TYPE: spatial
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: X,Y / retractable ar. Y axis

This pattern is producing a dome-like shape, which is rotationally retractable. Special folds are added around the two poles, to avoid gaps. Despite the interesting form, it presents reduced stifness compared to a plate shell dome.



FOLDING PATTERN COMPARISON



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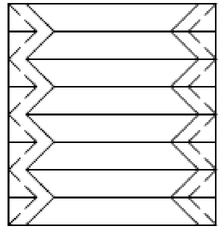

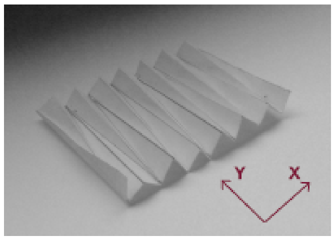

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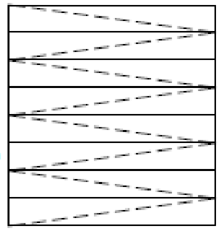

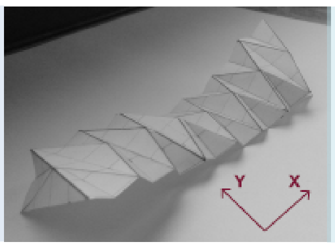

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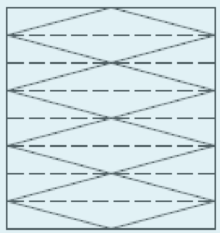

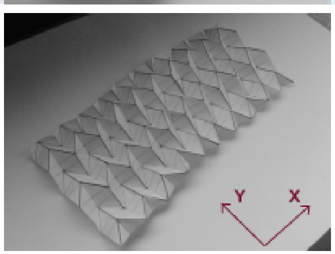

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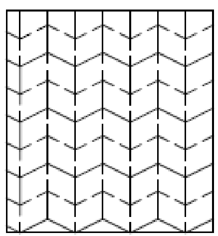

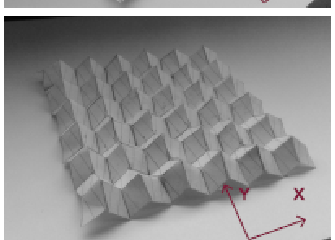

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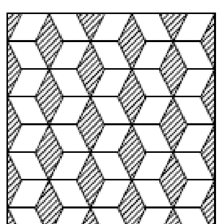

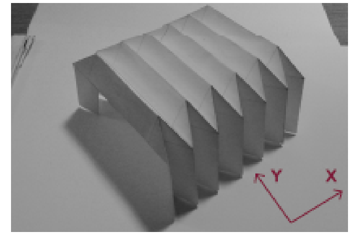

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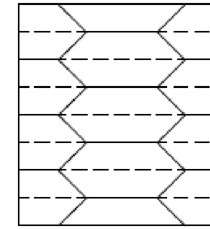

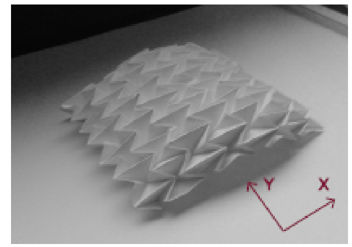

7. Butterfly 6-fold

TYPE: planar/ spatial (dep. on folding angle)
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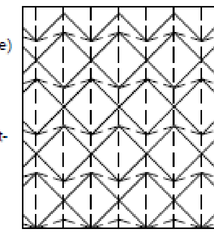

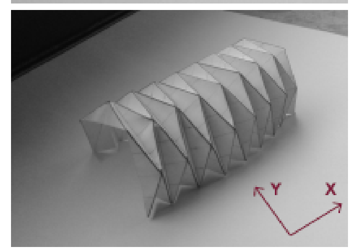

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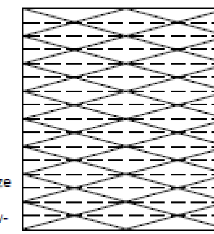
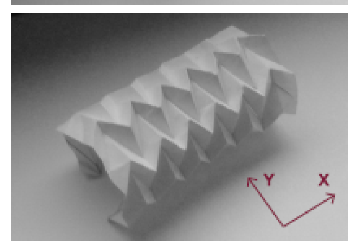
This is a simple pattern, in which, the pattern angle determines the curvature of the final surface assumed, and the element size the coarseness of the folding. Although its shape and folding provides stifness, behavior with hinged connections is uncertain.

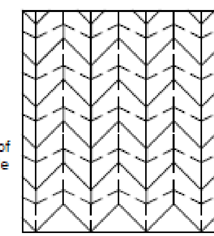


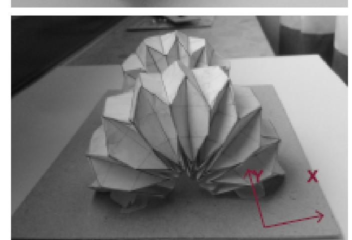


9. Miura-Ori (uneven)

TYPE: frame / tunnel
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: Y / retractable on X

This is a version of Miura-Ori with the use of two different angles. According to the angle difference, the curvature of the final tunnel shape is altered. Presents the same structural concetn as the Diamond pattern.

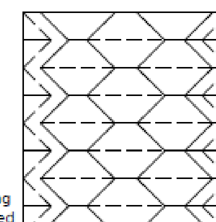


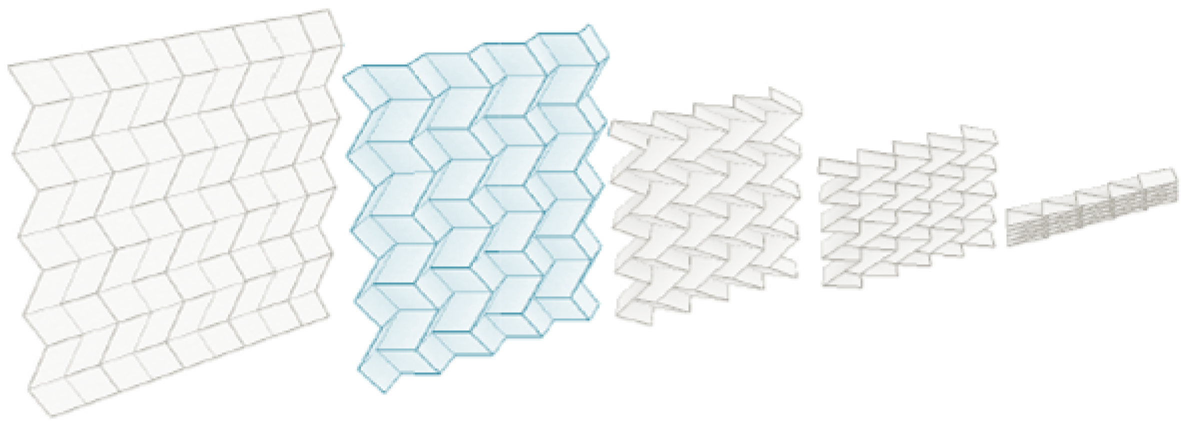


10. Hybrid Dome

TYPE: spatial
quadrilateral pattern
developable - 1 DOF rigid motion
span direction: X,Y / retractable ar. Y axis

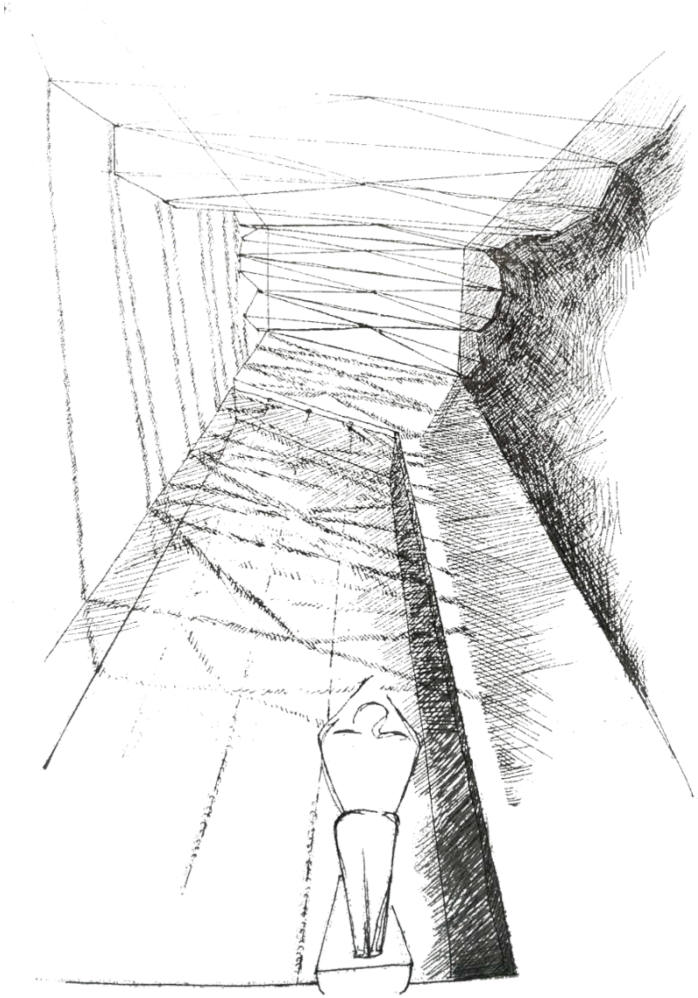
This pattern is producing a dome-like shape, which is rotationally retractable. Special folds are added around the two poles, to avoid gaps. Despite the interesting form, it presents reduced stifness compared to a plate shell dome.

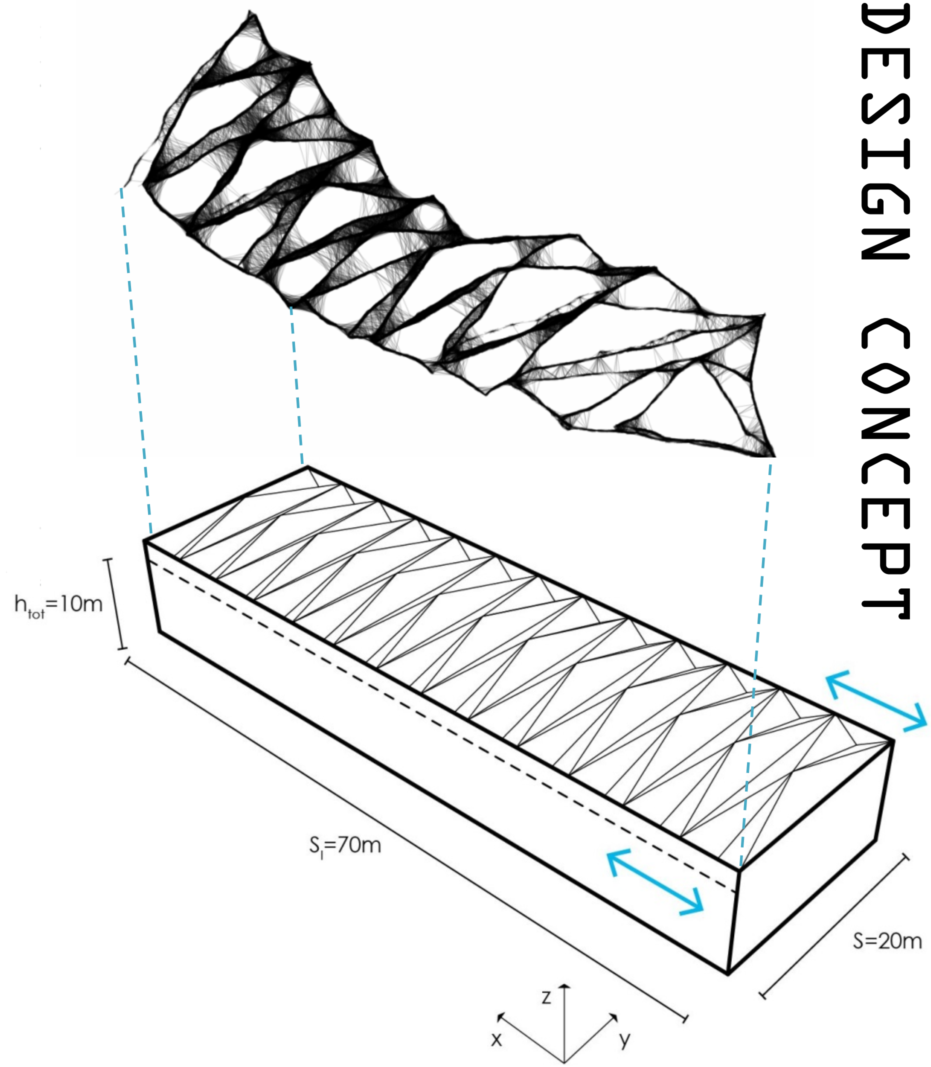


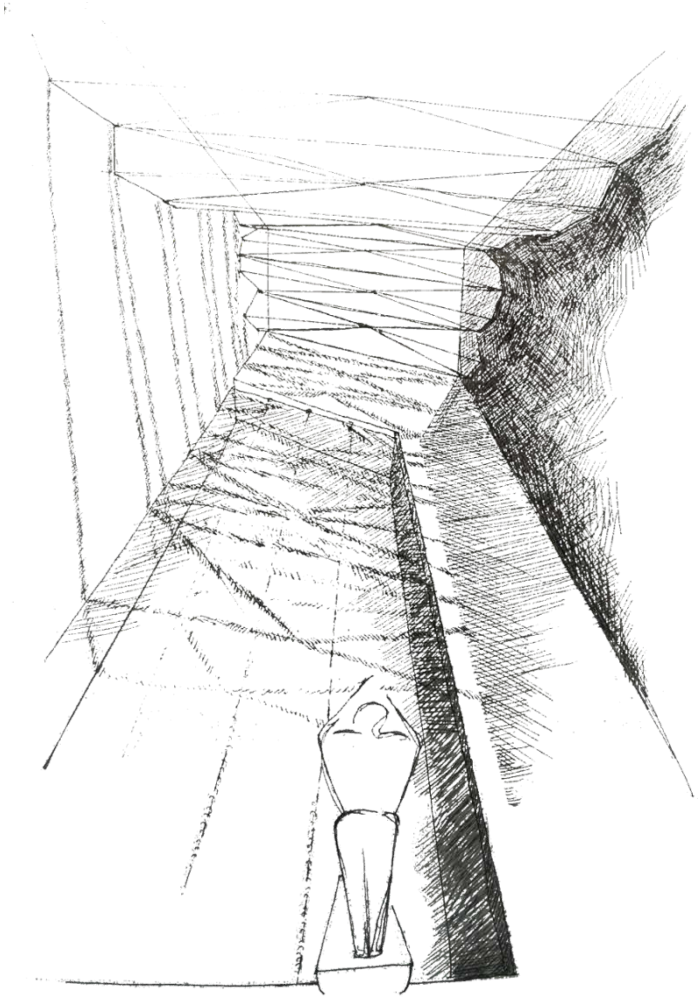


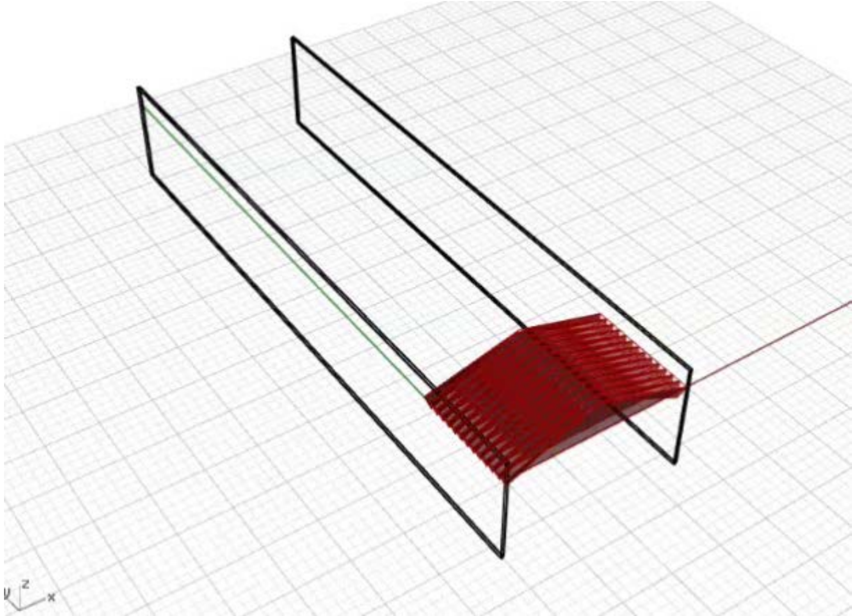
PART 2:
DESIGN DEVELOPMENT

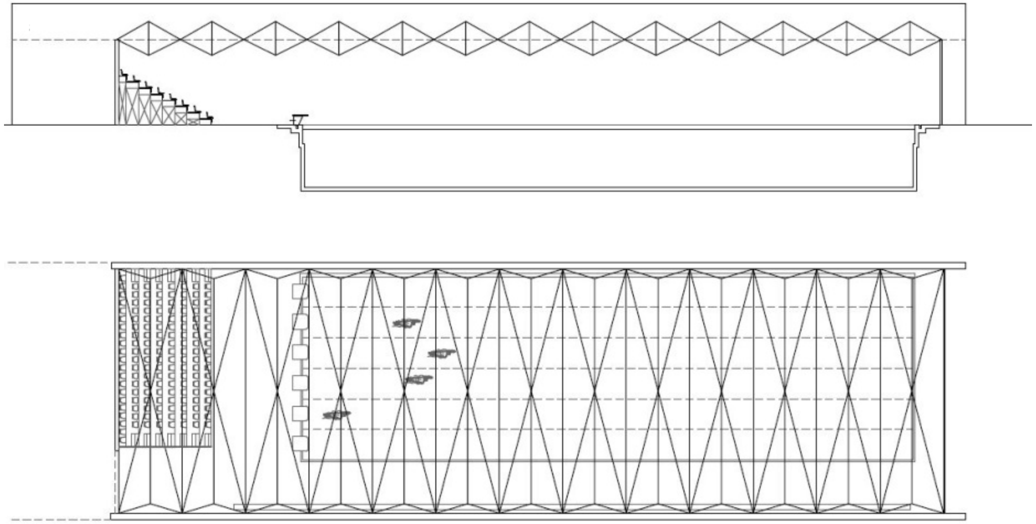
DESIGN CONCEPT



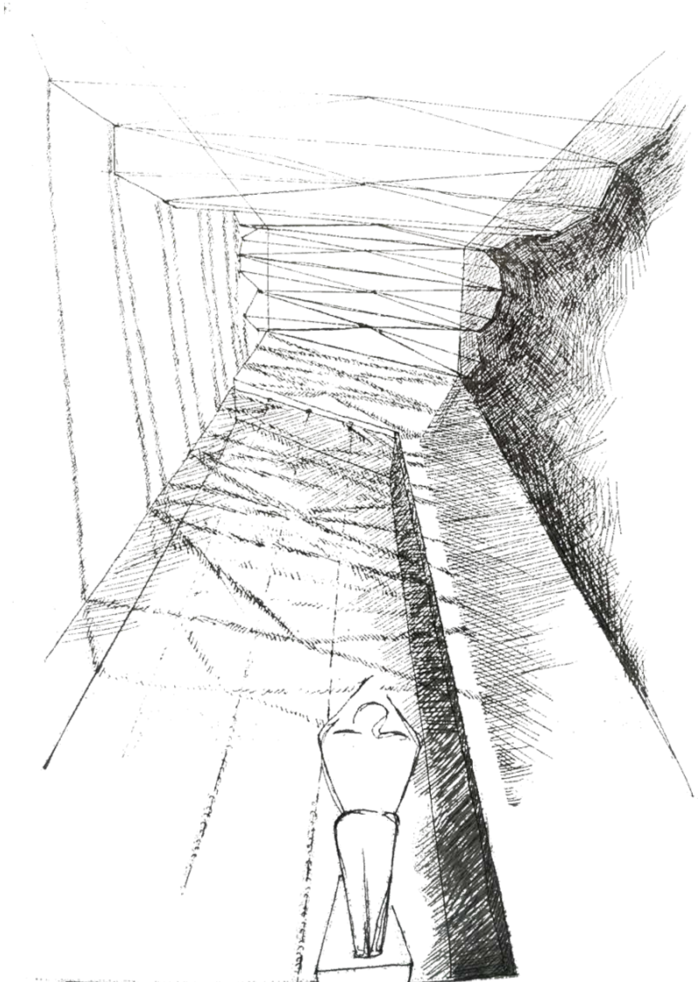


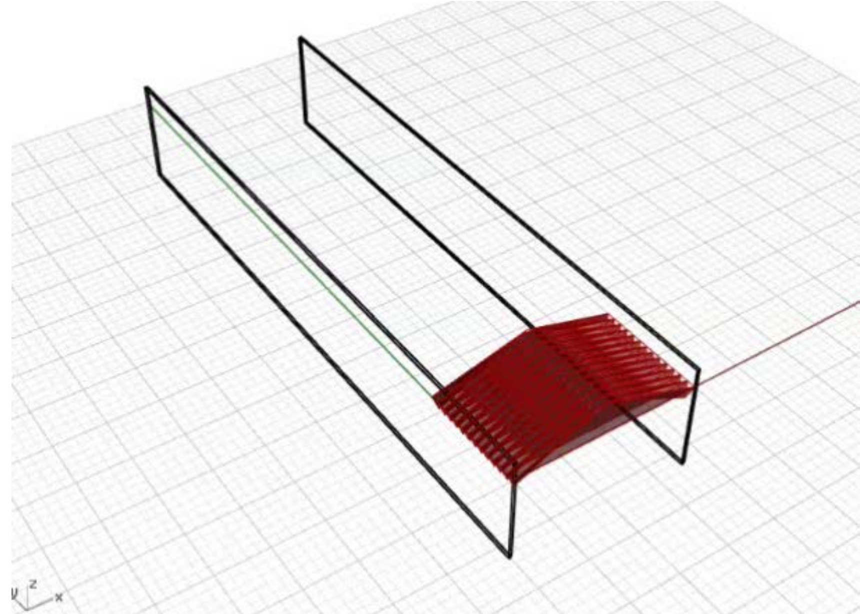


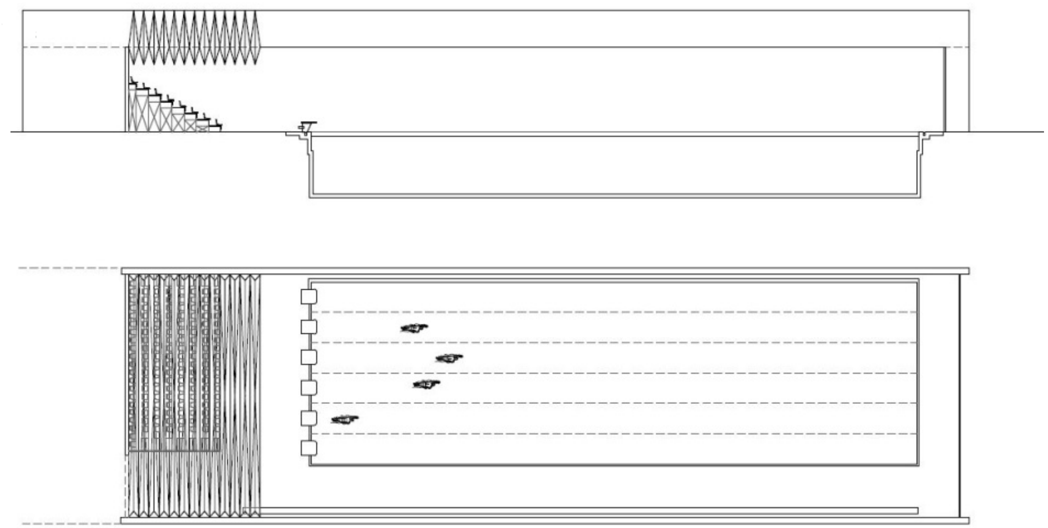




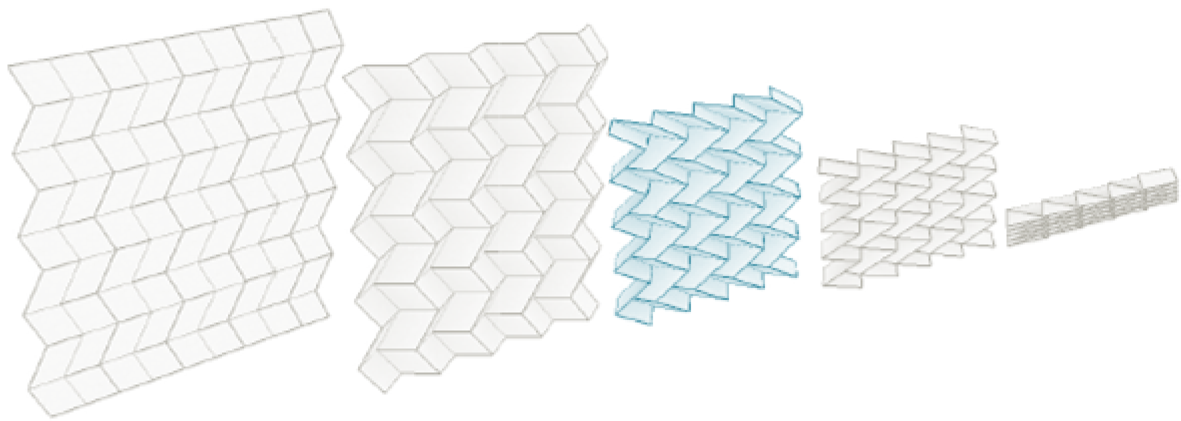
FULLY COVERED STATE







FULLY OPENED STATE



PART 3:
STRUCTURAL ANALYSIS

PARAMETER DEFINITION

GIVEN:
Span S
S=20m

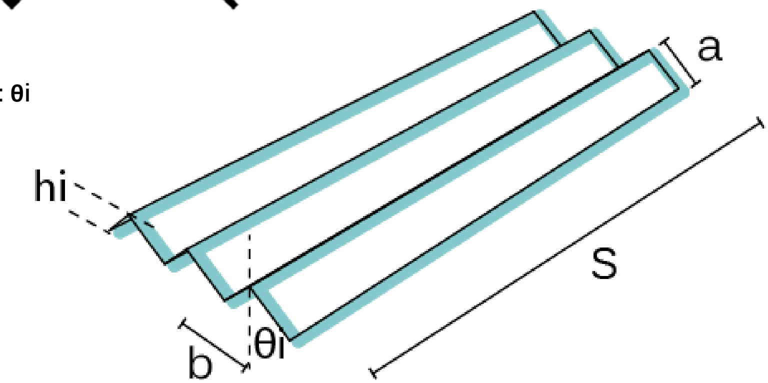
VARIABLES:
plate width: a
thickness: t

DEPENDENT VARIBALES:
fold width: b
folding angle: ϕ

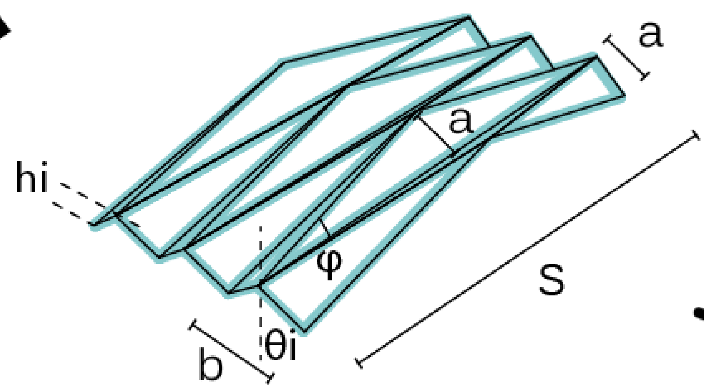
TIME-DEPENDENT:
deployment angle: θi
structural height :hi

deployment angle: θi
structural height :hi

span: s
plate width: a
fold width: b
thickness: t



PRELIMINARY
θi range
S, a



deployment angle: θi
structural height :hi

- **span: s**
plate width: a
fold width: b
thickness: t

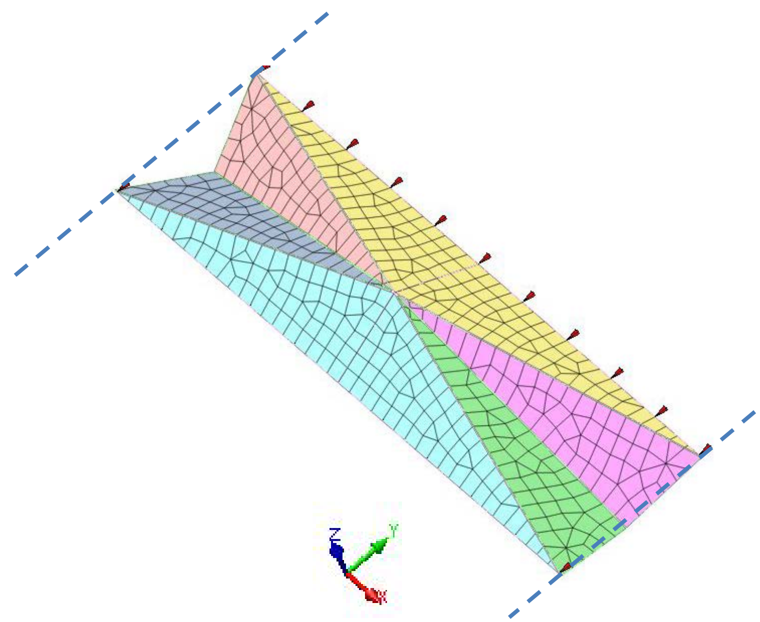
folding angle: ϕ

LOADCASES

	[KN/m2]	SAFETY FACTOR	TOTAL [KN/m2]	for hand calculation [KN/m]
Self weight	1.0591182	1.2	1.27094184	7.62565104
Live load (snow)	0.7	1.6	1.12	0.935243237
Wind suction	-0.08	2	-0.16	-0.133606177
Snow + Wind	surface load:		0.96	0.801637061
Wind load (H)	0.2	2	0.4	
	0.2	2	0.4	
	0.13	2	0.26	

SLS q=	6.87243313 [KN/m]	ULS q=	8.427288101	[KN/m]
SLS q=	6872.4331 [N/m]	**ULS q=**	**8427.288101**	[N/m]

BOUNDARY CONDITIONS



PINNED SUPPORTS: one side: translation on x / z
other side : translation on z

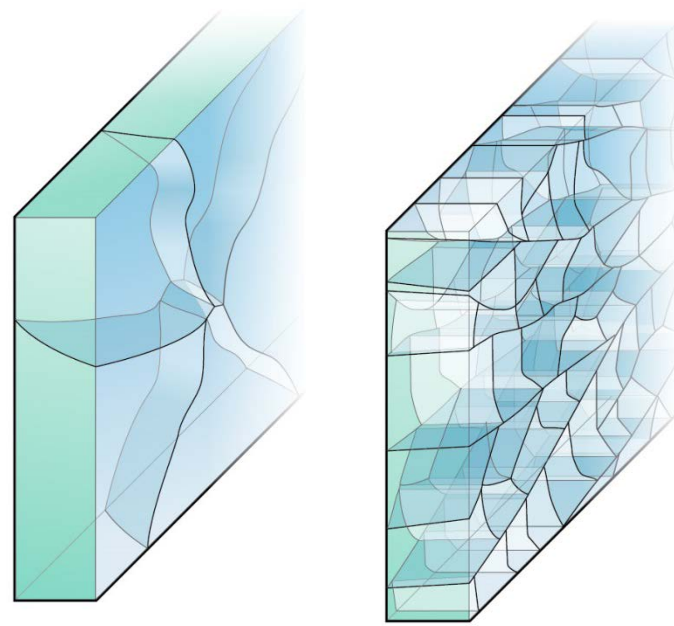
SUPPORTS ALONG LONG EDGES : translation on y

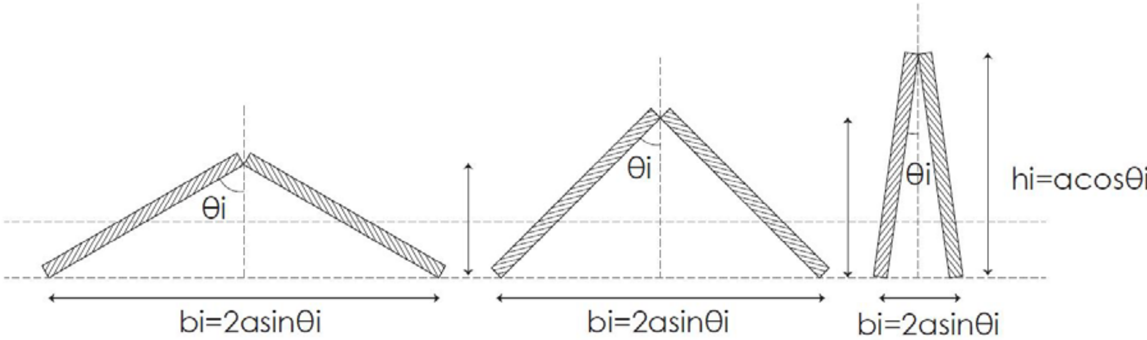
SAFETY MEASURES

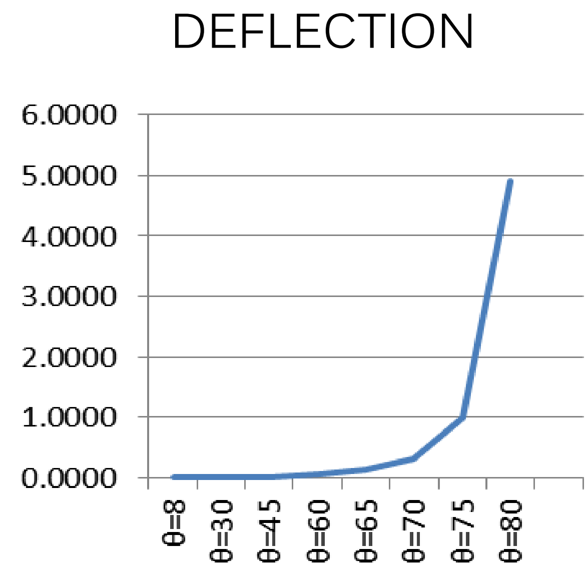
HEAT STRENGTHENED GLASS PROPERTIES	Value	Unit
Density	2400	kg/m^3
Young's modulus	67	GPa
	6,70E+07	KN/m^2
	6,70E+10	N/m^2
Tensile strength	50	Mpa
	5,00E+07	N/m^2
with safety factor (global): 1.2	**4,17E+07**	N/m^2
	1,88E+06	N/m
Yield strength	33-38	MPa
Tensile strain to failure	0.05	%
Compressive modulus	63.8-70.4	GPa
Compressive strength	390	MPa
	3,90E+08	N/m^2
Bending strength	45	Mpa
Flexural modulus	70-74	GPa
Flexural strength	40-45	MPa
Shear modulus	27-29	GPa
Bulk modulus	37-40	GPa
Poisson ratio	0.22-0.24	
Fracture toughness	1-1.3	MPa/m^2
Thermal shock resistance	up to 130	C
Permittable deflection =S/60	**0,3333**	**m**

- Material safety factor : 1.2
- Permittable stress levels / deflection
- Redundancy : extra layer of glass not included in calculations
- Use of laminated heat-strengthened glass

- Damage sensitivity, Σ: vulnerability based on probabilistic failure causes
- Relative resistance r: ratio between actions on and resistance of elements
- Redundancy : margin between damage and failure and failure and collapse
- Fracture mode: breakage and injury potential







FOLDING ANGLE θi

Moment of inertia Iy $I_y = 2t\cos\theta_i \, h_i^3 / 12$

First moment of area $S_y = t a^2 \sin\theta_i$

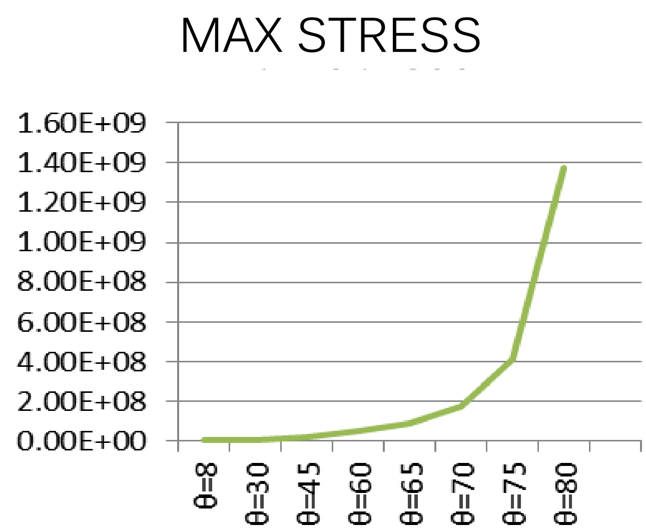
Deflection $w = 5ql^4/384EI_y$

Bending moment middle $M = ql^2 / 8$

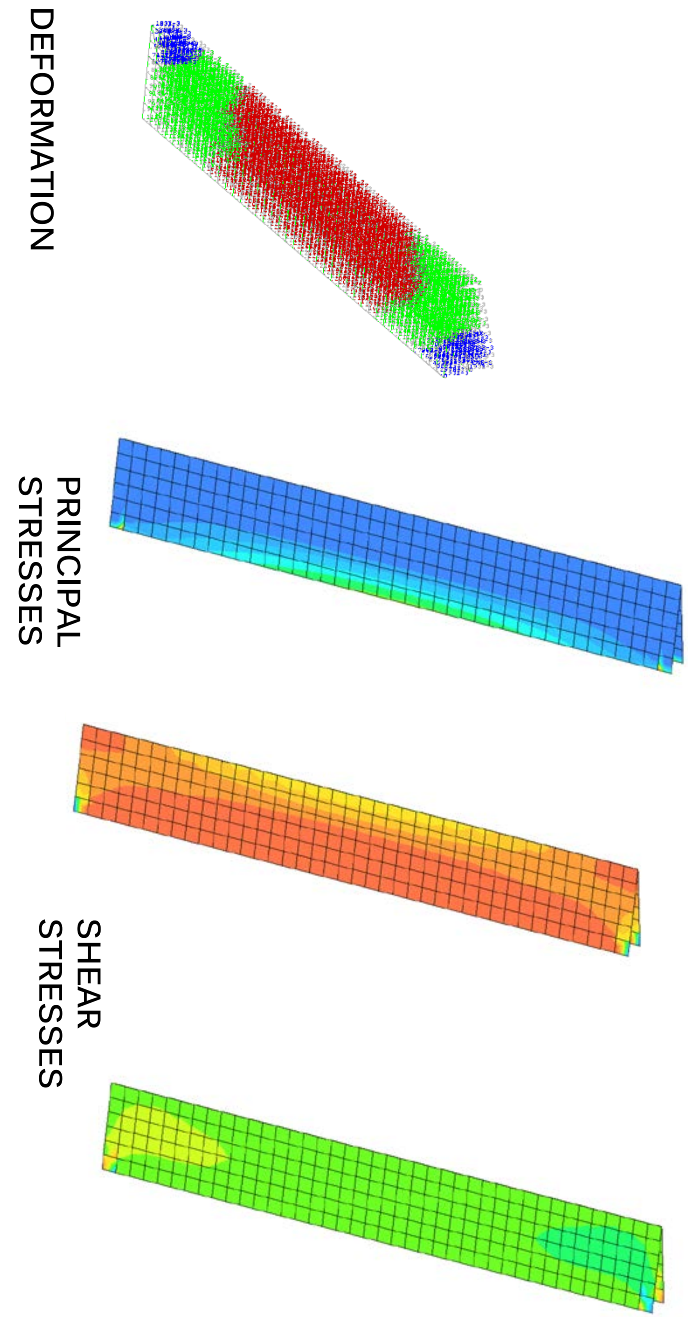
Maximum flexural stress $\sigma = Mz / I_y$

Principle Force max. $F = \sigma t$

Maximum shear stress $\tau = VQ / Ib$



SIMPLIFIED 1 - FOLD

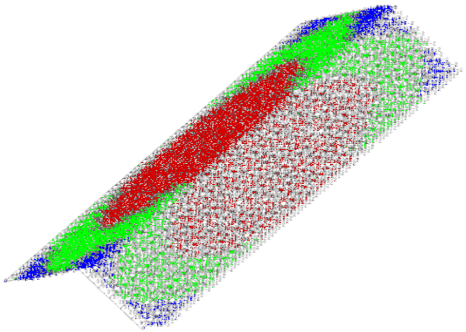


t=4*0.15
a=3m
Span 20m

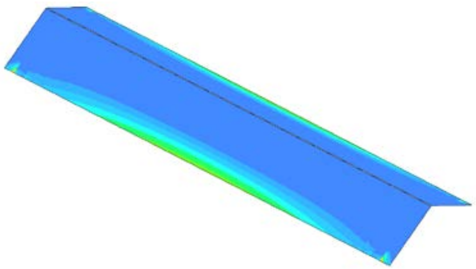
Reaction force	6,78E+04	
Deflection	0,00242	
Bending moment middle		
		PRINC.FORCE [N/m]
Maximum comress. stress	-5,44E+06	**-2,4E+05**
Maximum tensile. stress	5,04E+06	**2,27E+05**
Shear stress	1,07E+06	

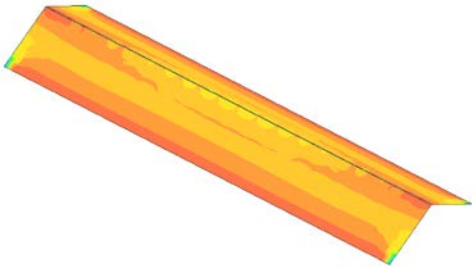
SIMPLIFIED 1 - FOLD

DEFORMATION

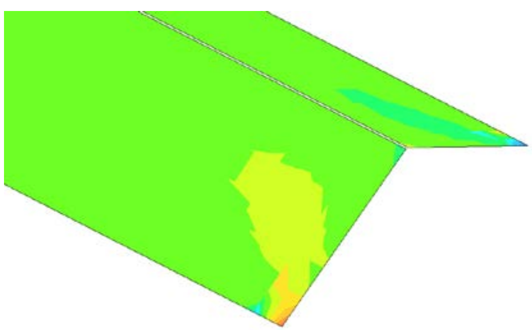


PRINCIPAL STRESSES S1



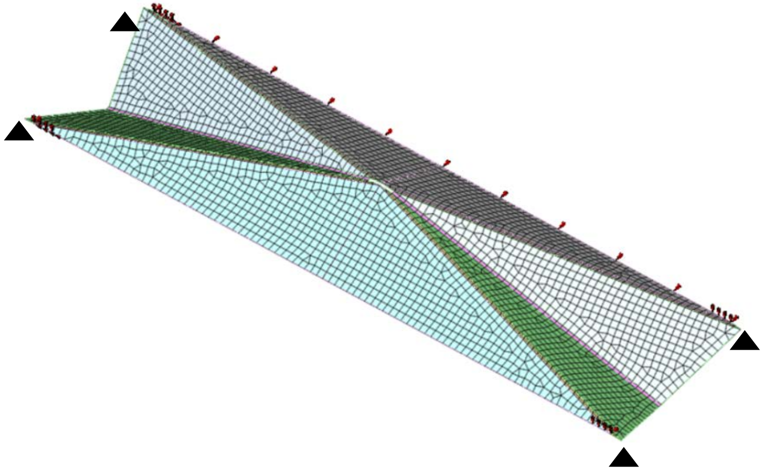


SHEAR STRESSES



t=4*0.15
a=3m
Span 20m

Reaction force	1,26E+06	
Deflection	0,0107	
Bending moment middle		
		PRINC.FORCE [N/m]
Maximum comress. stress	-1,14E+07	**-5,13E+05**
Maximum tensile. stress	9,05E+06	**4,07E+05**
Shear stress	1,95E+06	

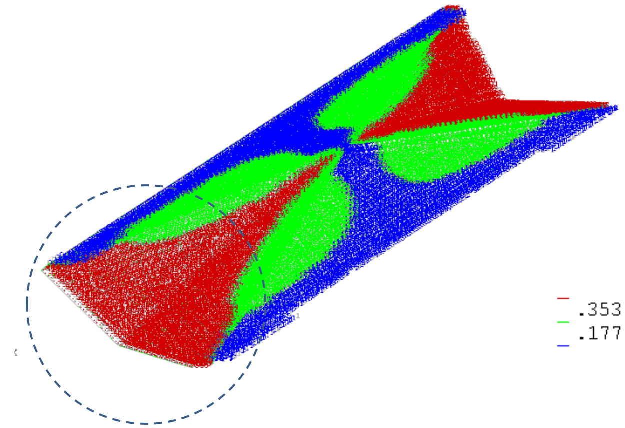


PLANAR 6-FOLD

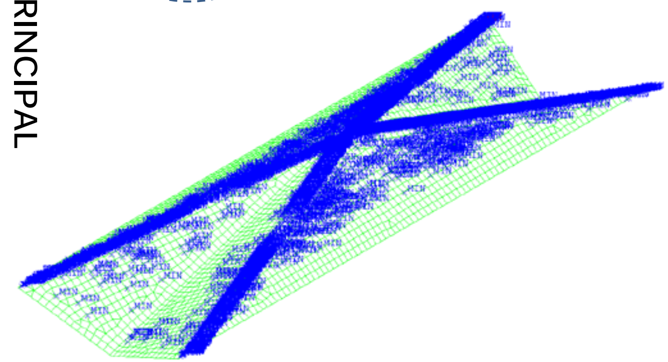
DIANA FEM CALCULATION

deployment angle	θ=60		
Reaction force	N		
Deflection	m	0.500	max
Bending moment middle	Nm		
			PRINC.FORCE [N/m]
Maximum comress. stress	N/m2	-3.59E+09	**-1.62E+08**
Maximum tensile. stress	N/m2	2.99E+09	**1.35E+08**

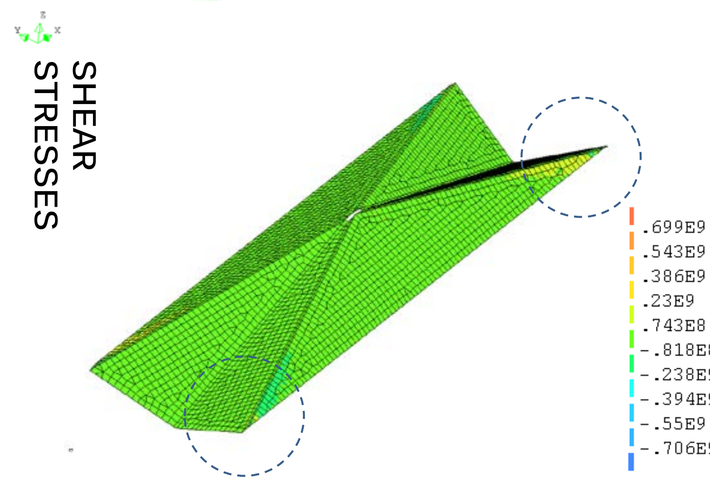
DEFORMATION

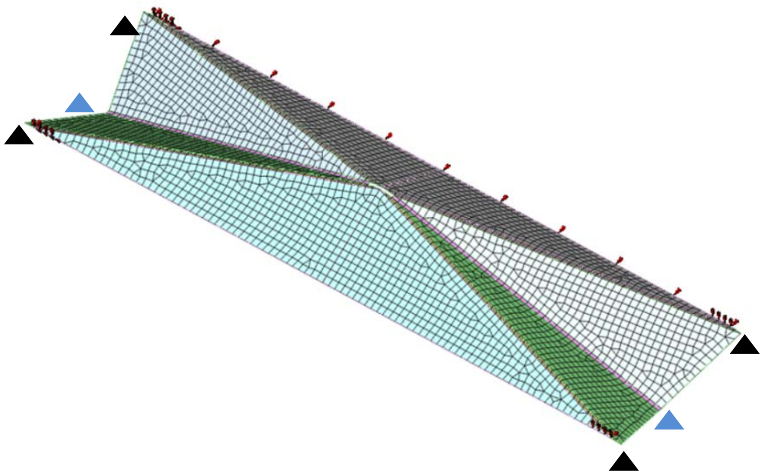


PRINCIPAL STRESSES MIN



SHEAR STRESSES

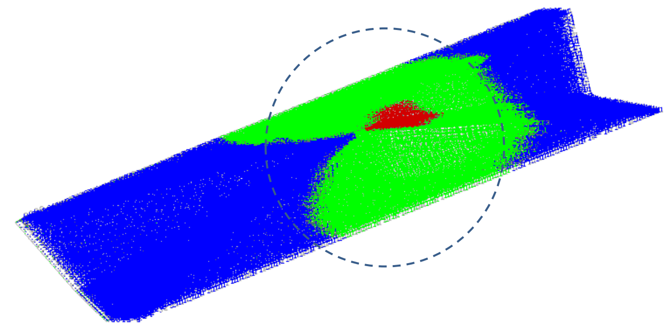




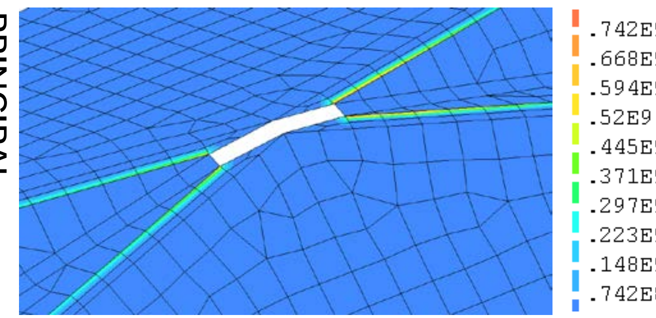
ADDITIONAL SUPPORTS

deployment angle		
Reaction force		
Deflection	0.1	at top
Bending moment middle		
		PRINC.FORCE [N/m]
Maximum comress. stress	-5.99E+08	**-2.70E+07**
Maximum tensile. stress	3.43E+07	**1.54E+06**
	1.10E+07	**4.95E+05**
Shear stress	1.96E+08	
	1.48E+07	

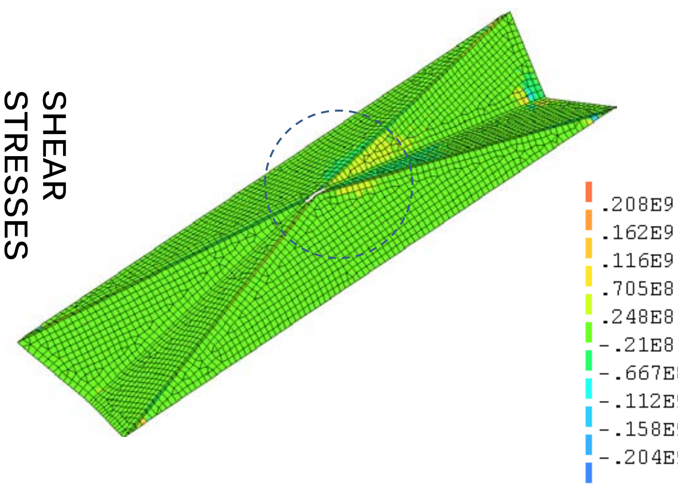
DEFORMATION

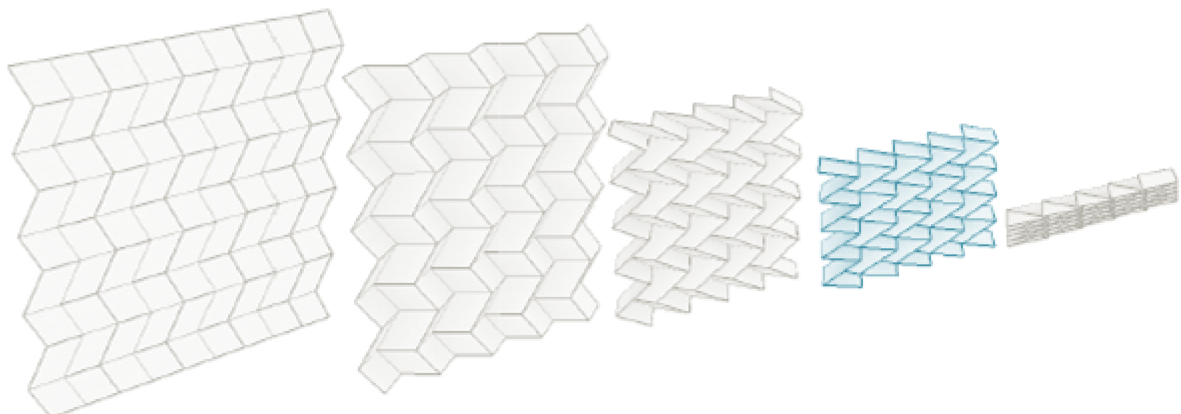


PRINCIPAL STRESSES



SHEAR STRESSES

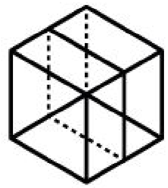




PART 4:
HINGED CONNECTION DEVELOPMENT

PANE TO PANE CONNECTION CONCEPT

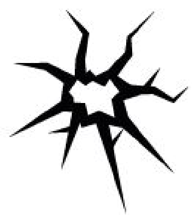
DISCRETE DESIGN

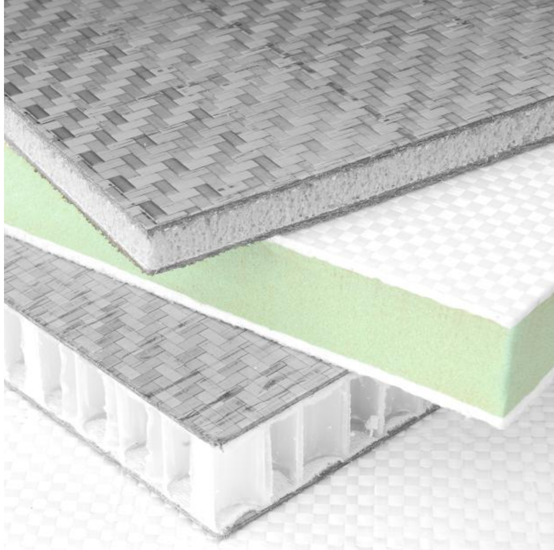


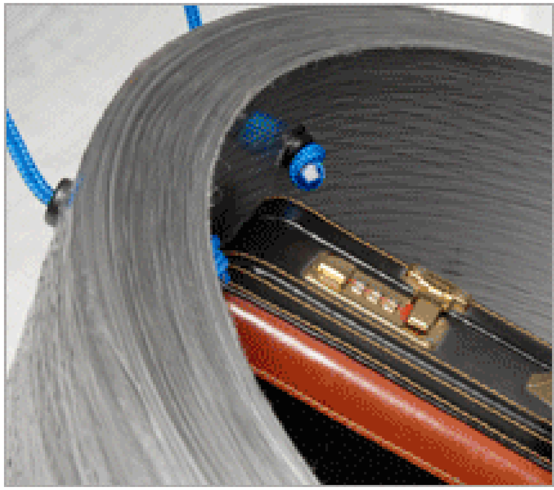
TOLERANCES

WATERPROOFING

REPAIR WORK FACILITATED



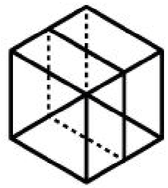




	Test method	Value	Unit
Bulk density	ASTM D792	0,78	g/cm^3
Young's modulus	ISO 527-4	5,5	GPa
Tensile strength	ISO 527-4	200	Mpa
Tensile strain to failure	ISO 527-4	9	%
Flexural modulus	ISO 178	4,5-5,5	GPa

PANE TO PANE CONNECTION CONCEPT

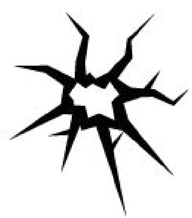
DISCRETE DESIGN

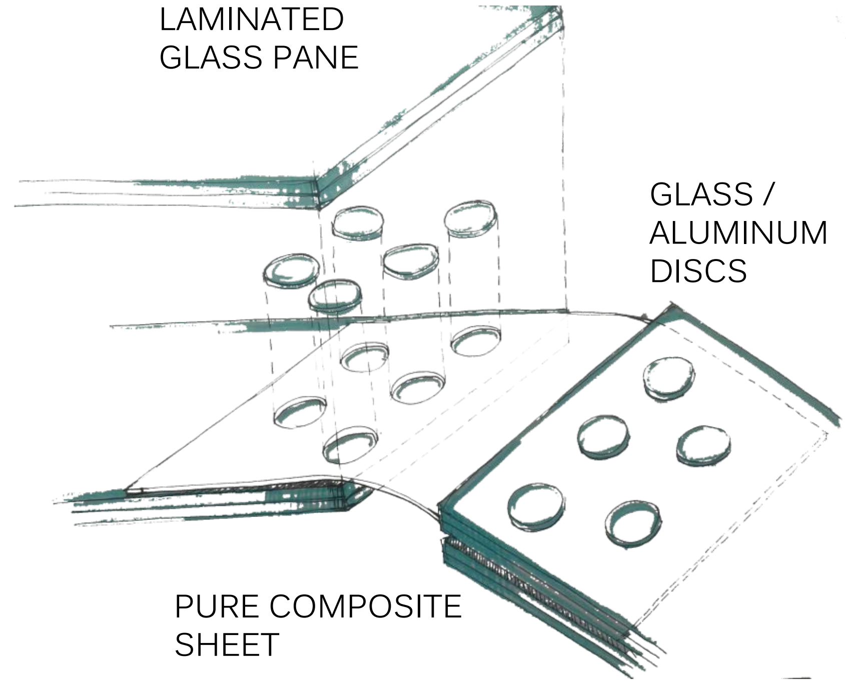


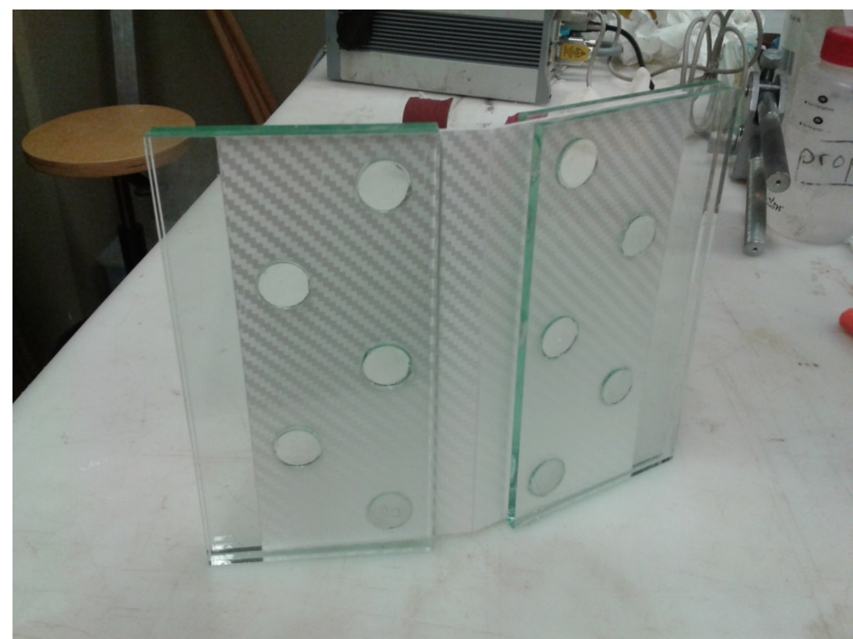
TOLERANCES

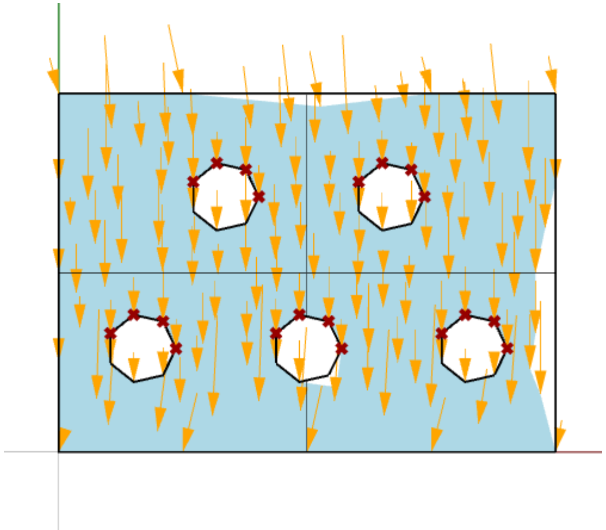
WATERPROOFING

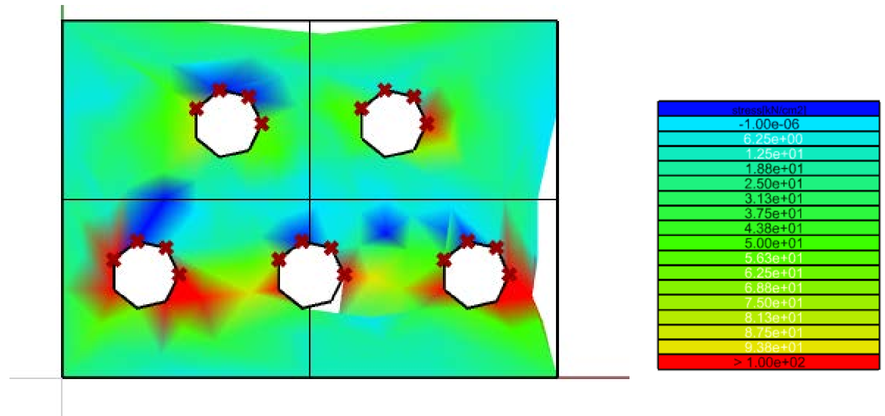
REPAIR WORK FACILITATED











CONNECTION OPTIMIZATION

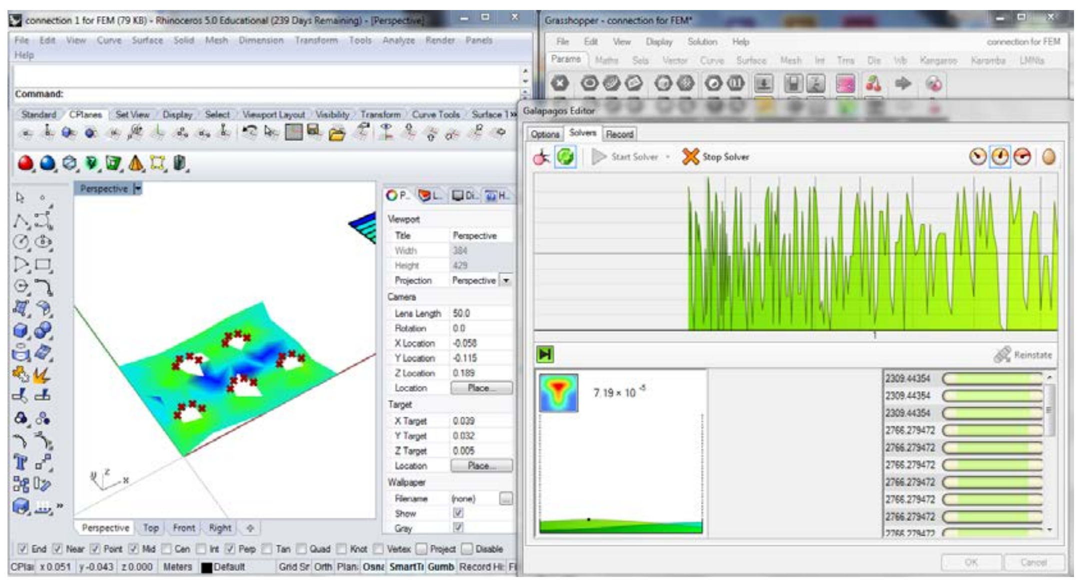
Based on steel construction regulations

Looking for adequate dimensioning of the discs

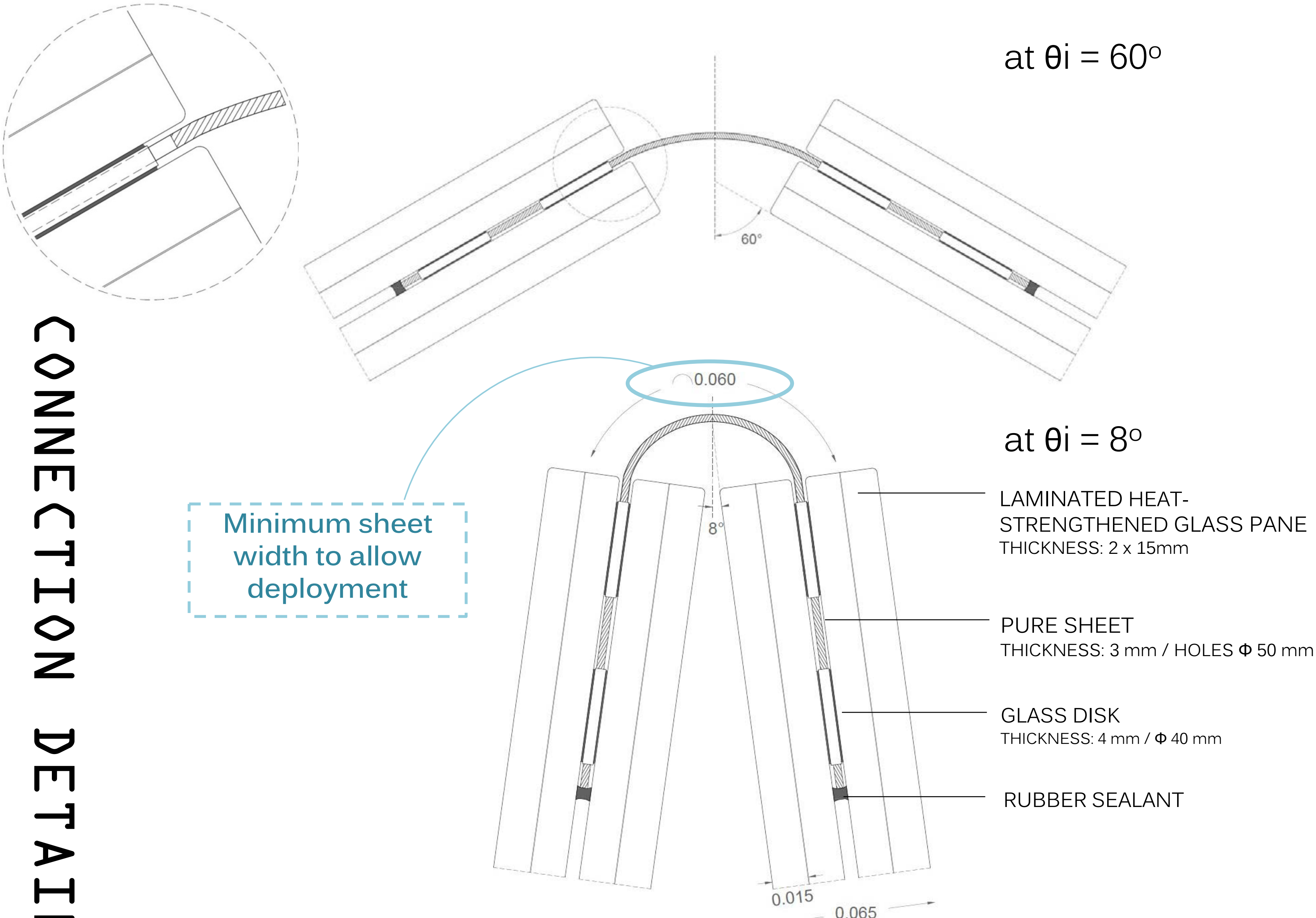
Minimalize induced Principal forces

↓

DISK DIAMETER : 20 mm



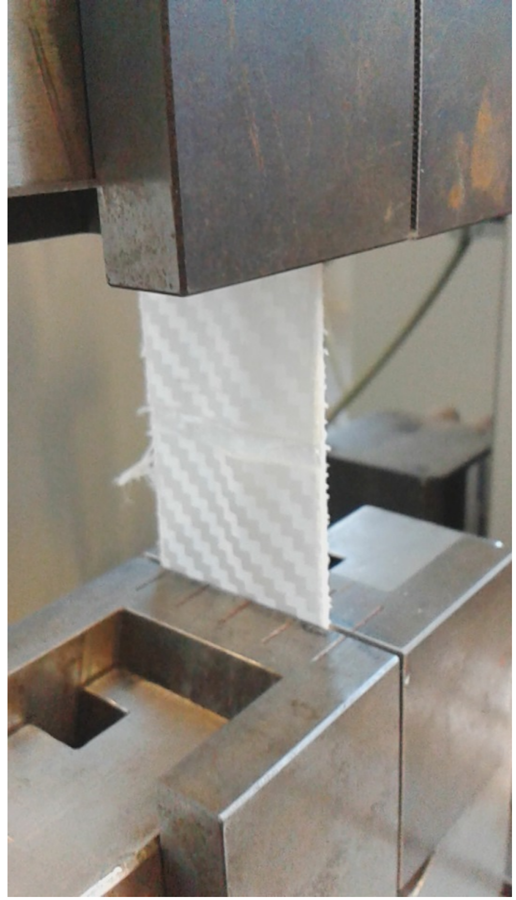
CONNECTION DETAIL

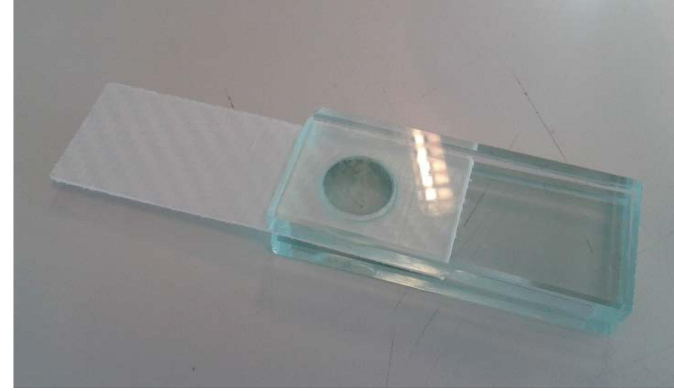


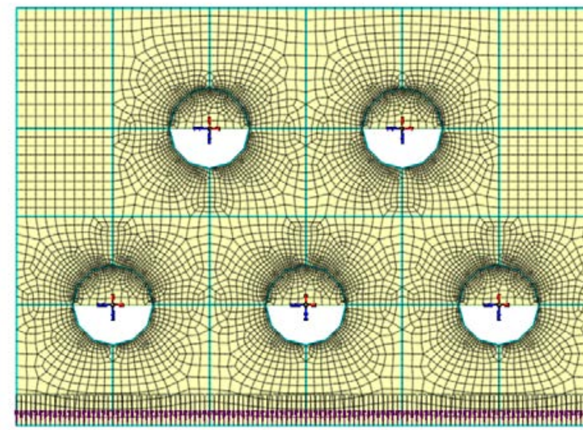
LAB TESTS

MATERIAL PROPERTIES:
- Fatigue test on PURE sheet (notched and un-notched version)

CONNECTION PROPERTIES:
- Pull-out test on PURE sheet – glass disc connection principle (different sheet thicknesses)



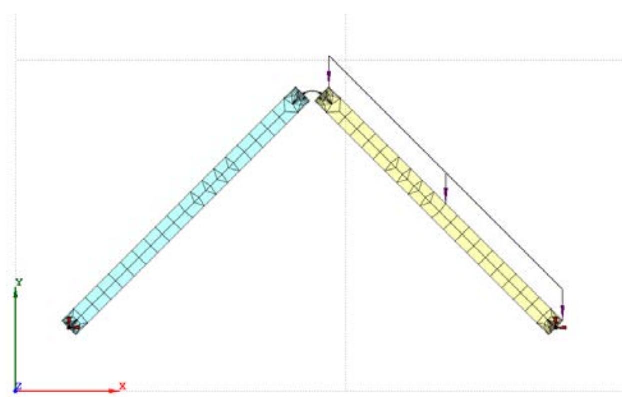




FEM TESTS

CONNECTION PROPERTIES:
- Pull-out test on PURE sheet – glass disc connection principle (different sheet thicknesses)

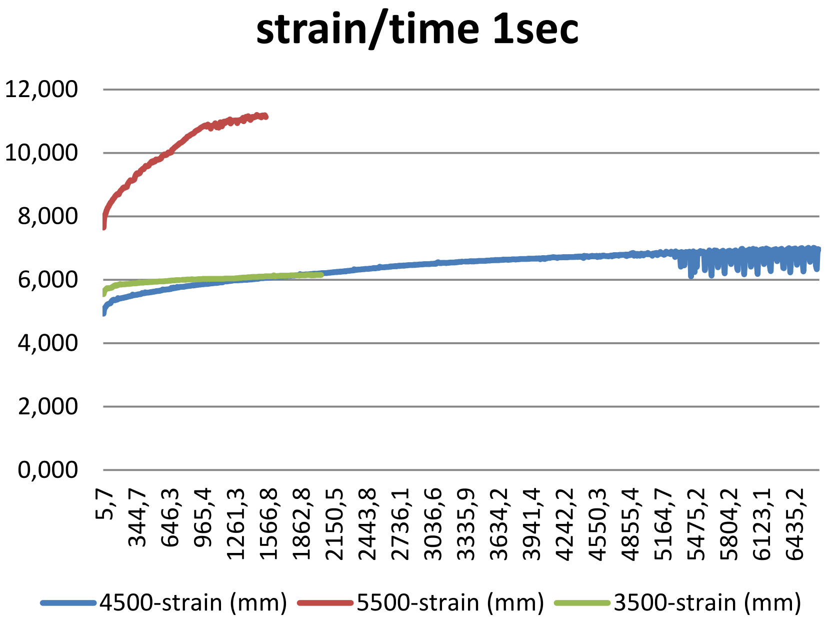
- Deformation upon out-of-plane compression (different loadcase scenarios)



FATIGUE TEST

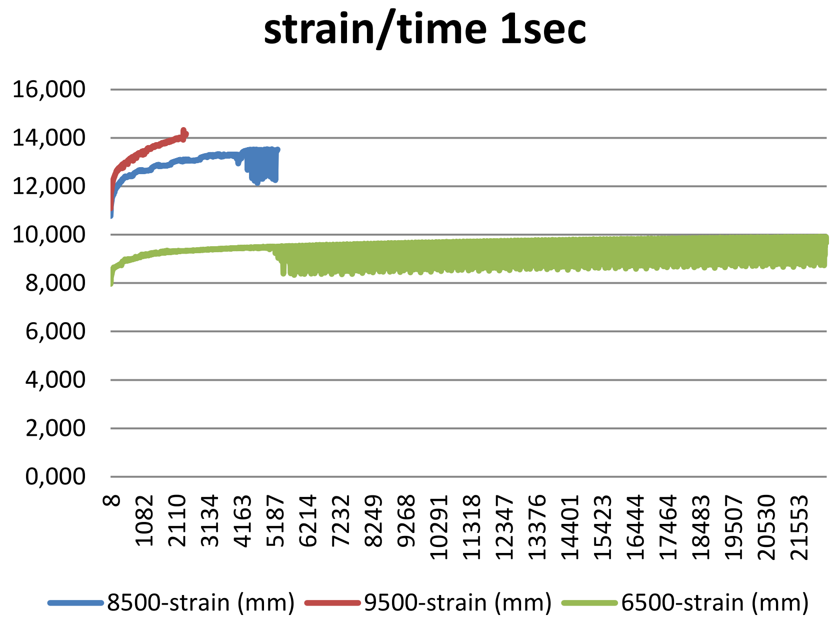
NOTCHED

MAXIMUM STRAIN
h0 [mm] : 92,5



UNNOTCHED

MAXIMUM STRAIN
h0 [mm] : 91,960



1.5 mm PURE sheet UN-NOTCHED : 90 MPa

PULL-OUT TEST

36.73 MPa 1.

73.62 MPa 2.

22 Mpa
Shear strength
Glass/glass adhesion

SINGLE 1.5mm /1 DISK

Specimen	Description	Standard travel mm	Standard force N
1	glass breakage around disks - PURE deformed	**8.954**	**2354**
2	PURE deformed + failure	**11.539**	**2557**
3	glass breakage- glue did not fail	**9.344**	**2129**
4	glue failure	**11.081**	**2497**

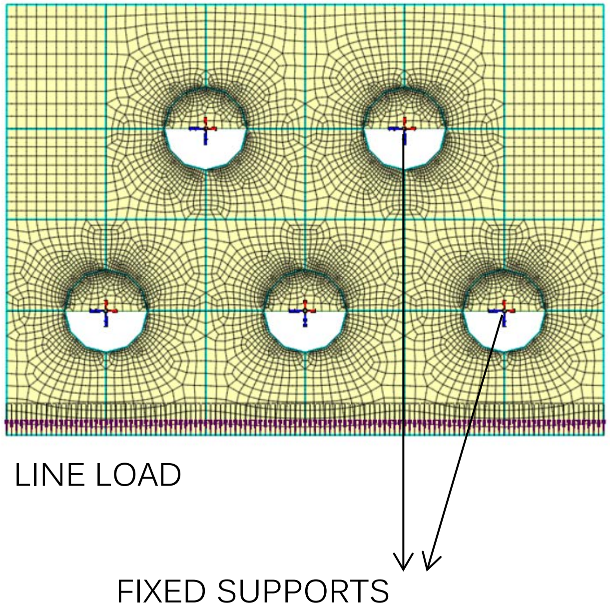
Average force 2384 N

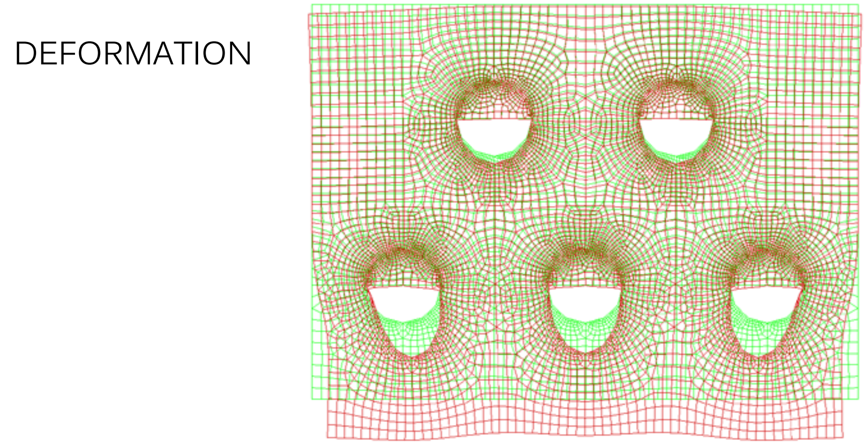
DOUBLE 1.5mm /2 DISK

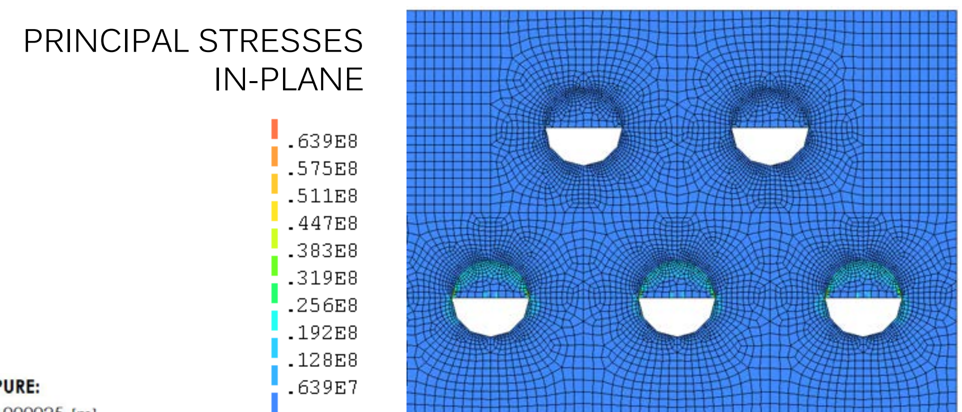
Specimen	Description	Standard travel mm	Standard force N
5	glue failure+ glass disk breakage(between disks and with plate)	**8.228**	**3955**
6	glue failure disk/pane-small PURE deformation	**14.239**	**4913**
7	glue failure disk/pane-small PURE deformation-glass breakage (disk)	**7.670**	**4132**
(dif. pat)8	glue failure disk/pane-small PURE deformation-glass breakage (disk)	**10.744**	**4207**

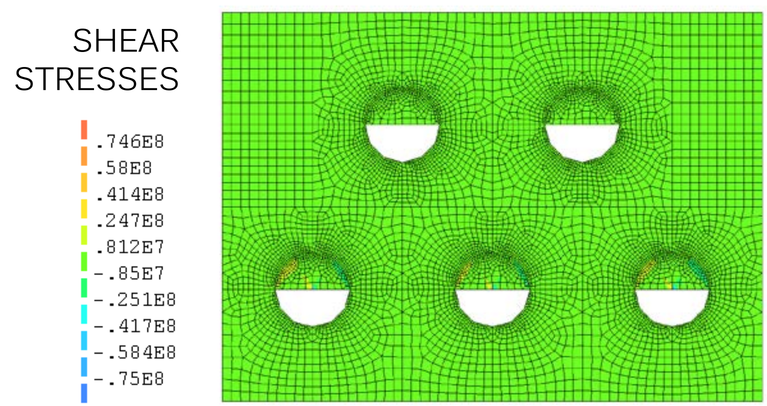
Average force 4417 N

PULL-OUT TEST - FEM









DISK DIAMETER : 20 mm

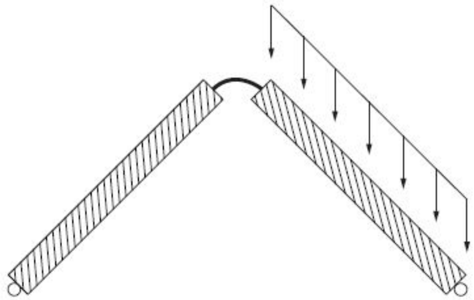
		1.5mm PURE:	3mm PURE:	5mm PURE:
displacement	general	0.00008 [m]	0.00004 [m]	0.000025 [m]
	around the holes	0.00007 [m]	0.000036 [m]	0.000022 [m]
prinicipal stress max		3.76E+07 [N/m2]	1.88E+07 [N/m2]	1.13E+07 [N/m2]
	around the holes	37.60 [Mpa]	18.80 [Mpa]	11.30 [Mpa]
	on the edge	5.24E+06 [N/m2]	2.61E+06 [N/m2]	1.57E+06 [N/m2]
		5.24 [Mpa]	2.61 [Mpa]	1.57 [Mpa]
principal force max		**5.64E+04 [N/m]**	**5.64E+04 [N/m]**	**5.65E+04 [N/m]**

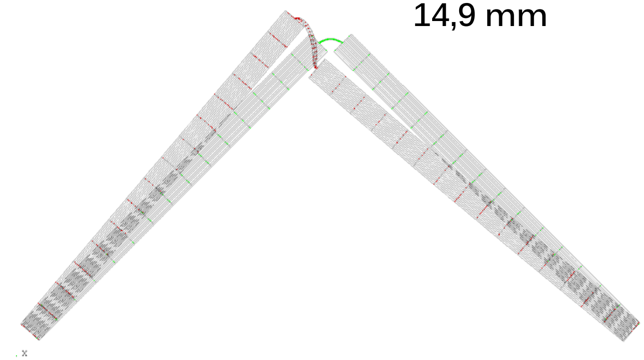
DISK DIAMETER : 40 mm

		0mm diameter 3mm PURE:
displacement	general	0.00007 [m]
	around the holes	0.000057 [m]
prinicipal stress max		7.03E+07 [N/m2]
	around the holes	70.30 [Mpa]
	on the edge	2.59E+06 [N/m2]
		2.59 [Mpa]
principal force max		**6.12E+06 [N/m]**

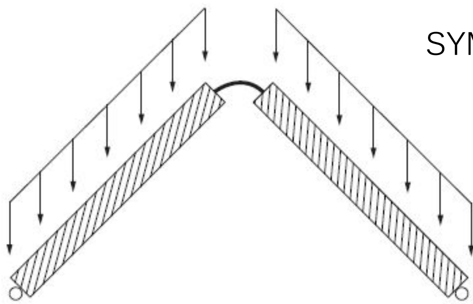
OUT-OF PLANE COMPRESSION

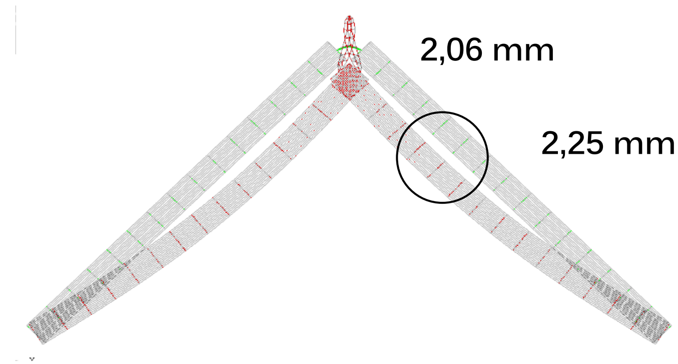
SCENARIO 1:
ASYMMERTICAL LOAD



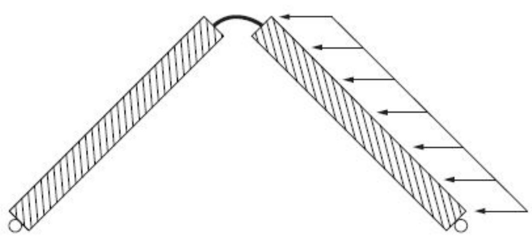


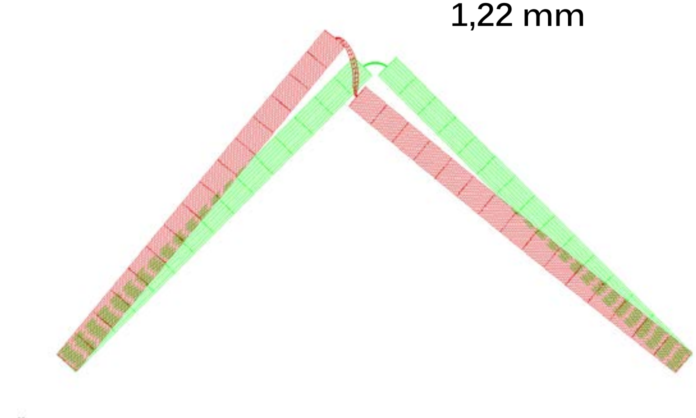
SCENARIO 2:
SYMMETRICAL LOAD

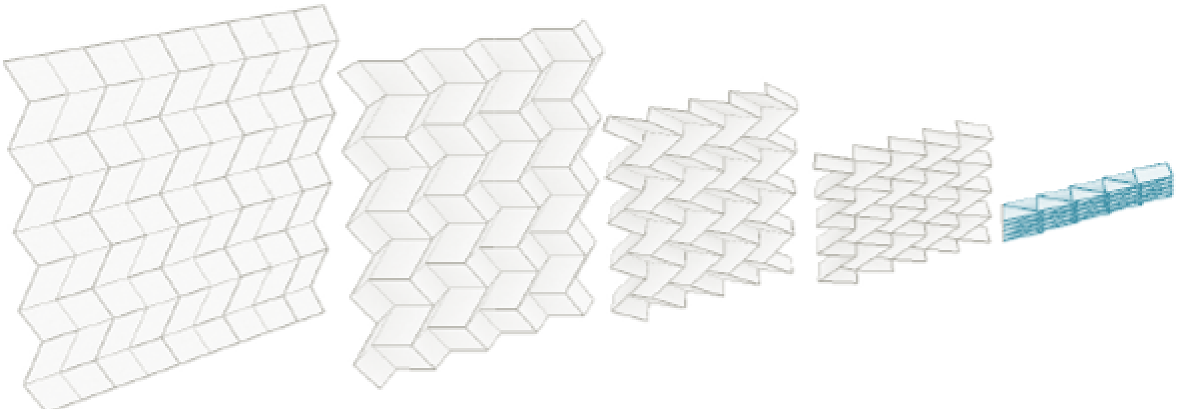




SCENARIO 3:
WIND LOAD



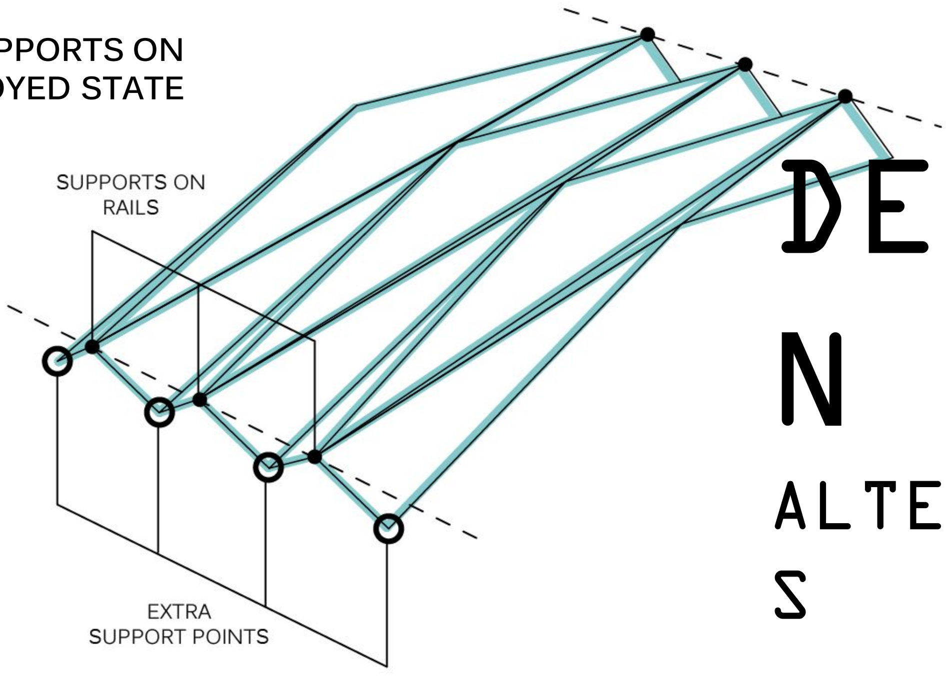




PART 5:
FINALISATION

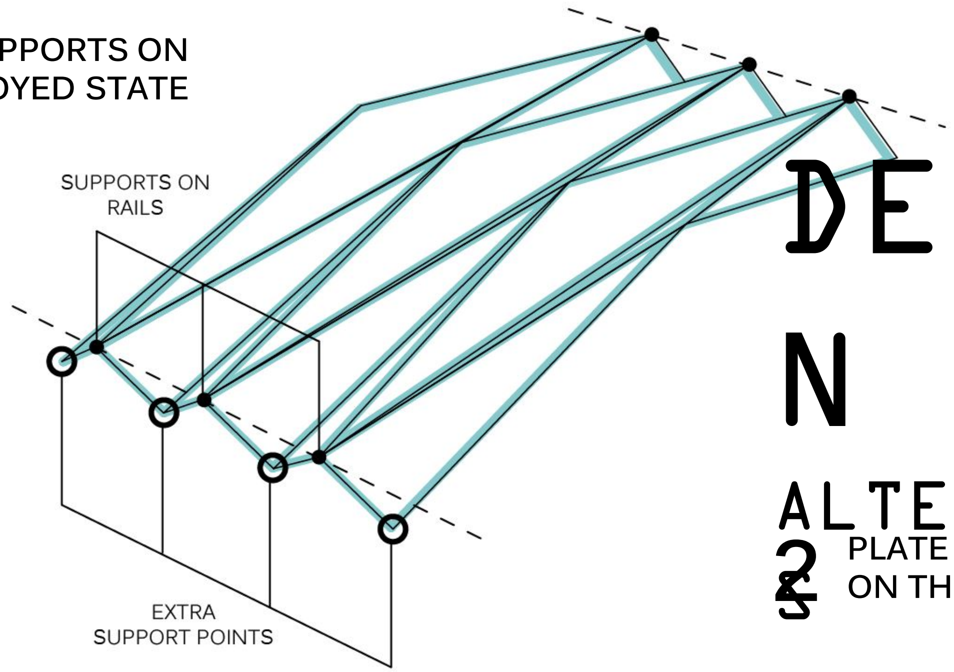
DESIG N ALTERATION S

1 EXTRA SUPPORTS ON THE DEPLOYED STATE

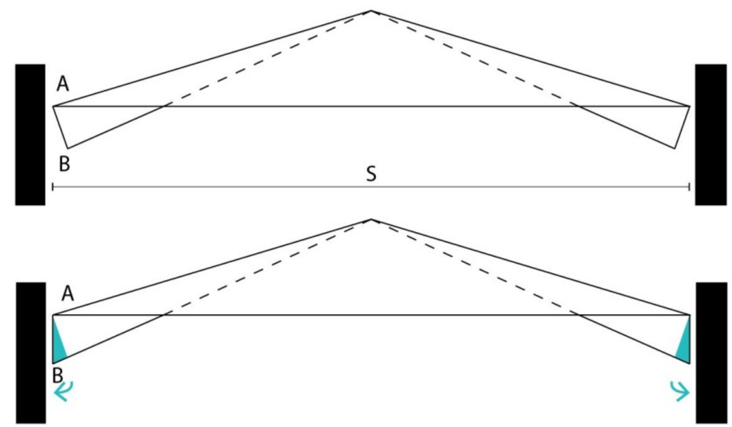


DESIGN ALTERATIONS

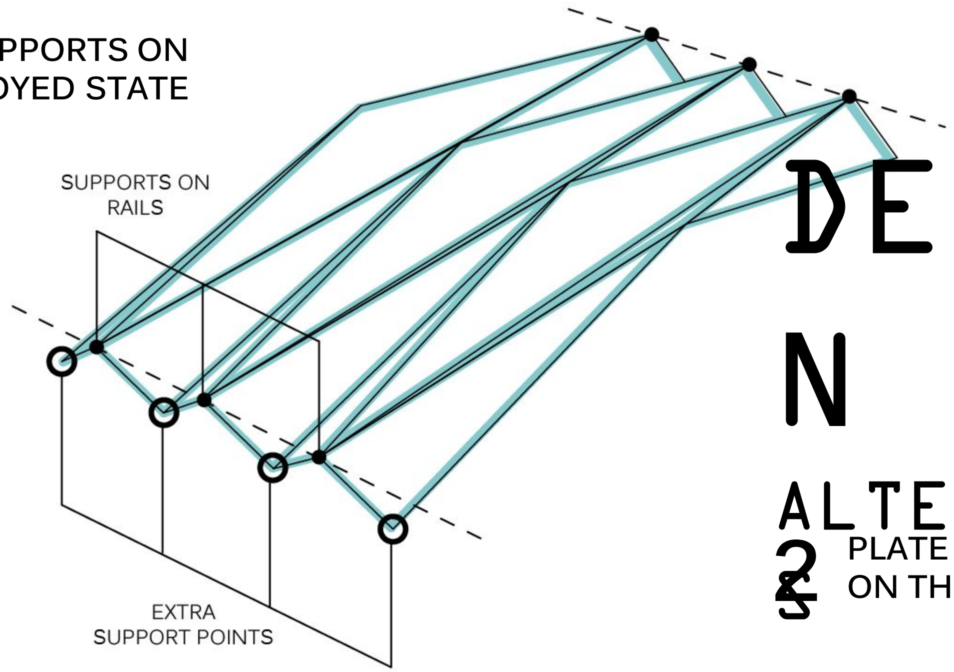
1 EXTRA SUPPORTS ON THE DEPLOYED STATE



2 PLATE EXPANSON ON THE SIDES



1 EXTRA SUPPORTS ON THE DEPLOYED STATE



DESIGN ALTERATIONS

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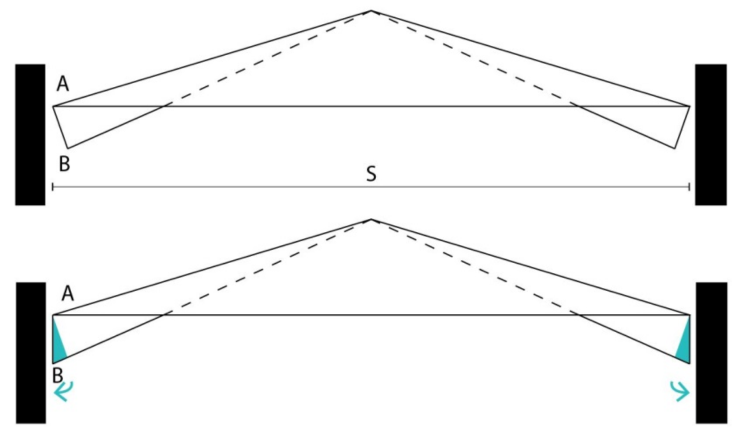
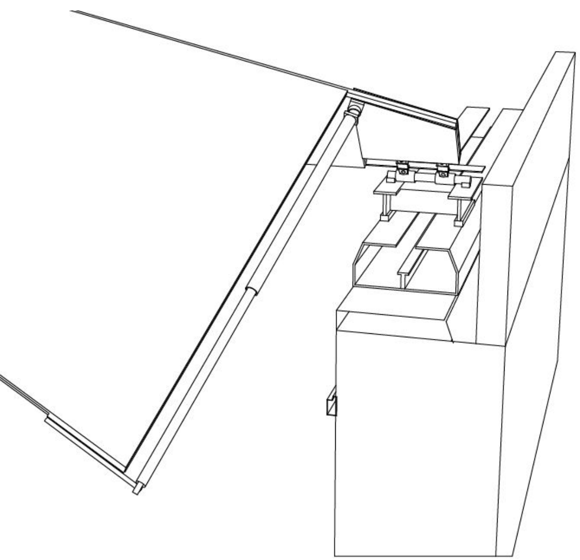
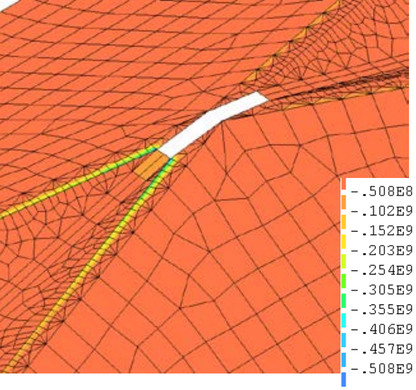
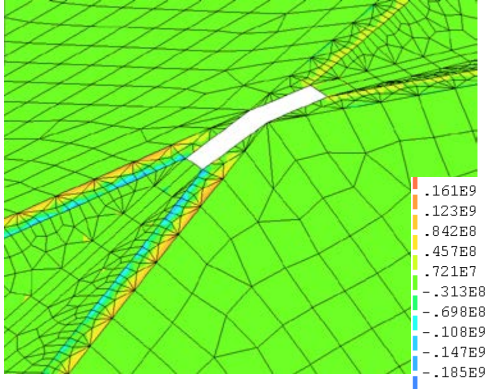


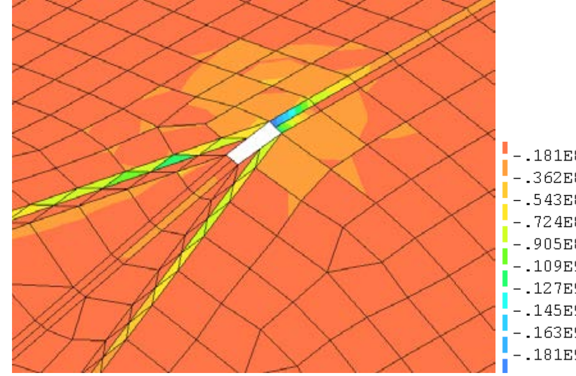


3

HYDRAULIC SYSTEM TO CONTROL DEFORMATIONS DURING DEPLOYMENT

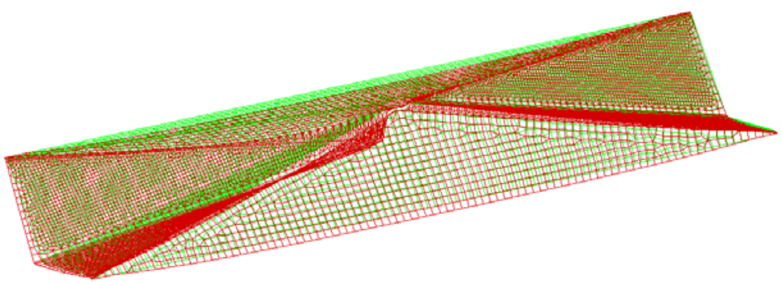


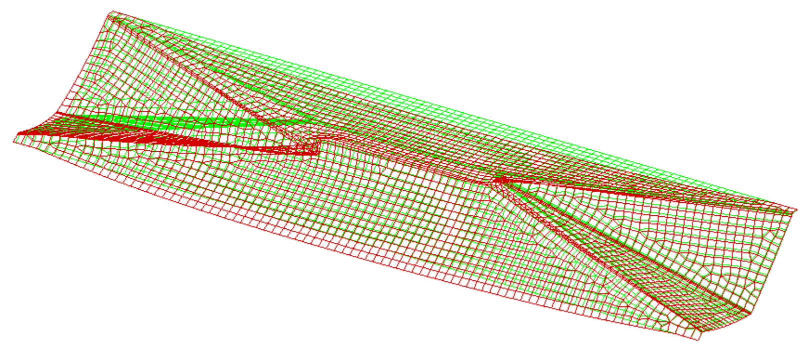




BEFOR
E

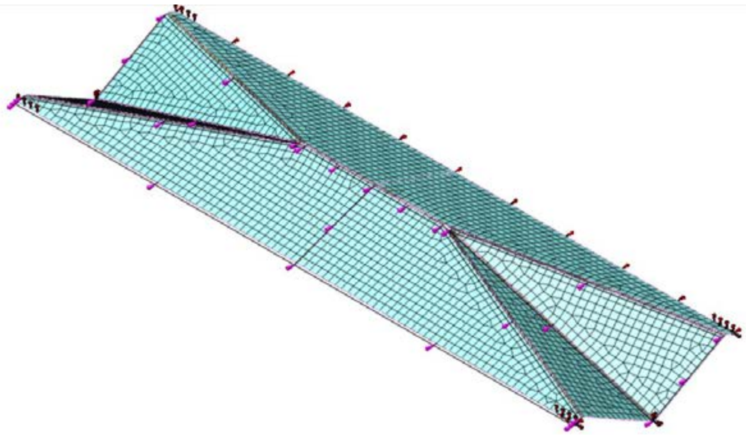
AFTER

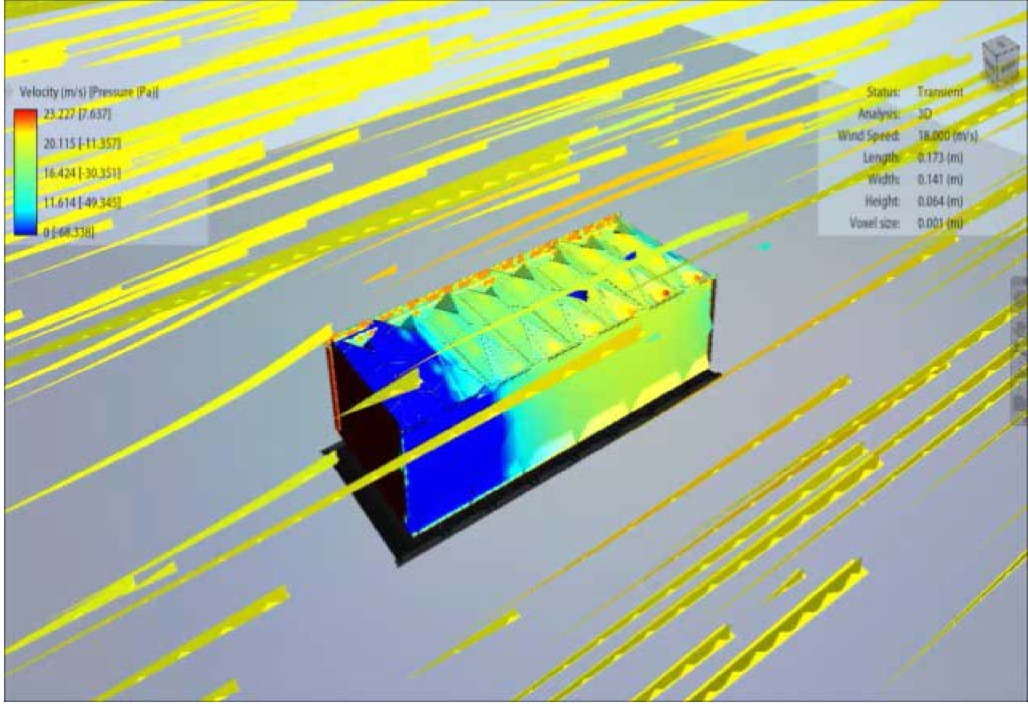




deployment angle	θ=60			
Reaction force	N			
Deflection	m	0.1	at top	
Bending moment middle	Nm			
			PRINC.FORCE [N/m]	
Maximum comress. stress	N/m2	-5.99E+08	**-2.70E+07**	
Maximum tensile. stress	N/m2	3.43E+07	**1.54E+06**	close to the edges
		1.10E+07	**4.95E+05**	mid edge on themain panels
Shear stress	N/m2	1.96E+08		peaks at the top
		1.48E+07		

2.83E+05	at supports	
2.83E+03	at the edges	NOT EVENLY DISTRIBUTED ALONG EDGE
0.04	at top	
	[Mpa]	**PRINC.FORCE [N/m]**
-1.38E+07	-13.8	**-6.21E+05**
1.28E+07	12.8	**5.76E+05** at the mid bottom
1.79E+08	179	**8.06E+06** at the connection on top
3.82E+07	38.2	at the connection at the top
-4.54E+07	-45.4	around suports

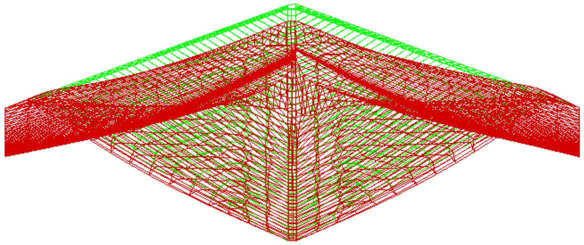




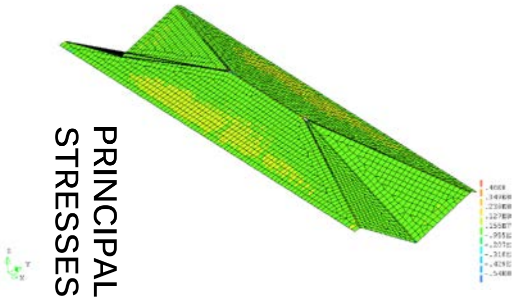
CHAMFERED 6FOLD VERSION		WIND LOAD	(WIND LOAD+SELFWEIGHT)	
deployment angle		θ=60		
Reaction force	N			
Deflection	m	0.030	AT TOP	
Bending moment middle	Nm			
				PRINC.FORCE [N/m]
Maximum comress. stress	N/m2	-6.80E+07		-3.06E+06
Maximum tensile. stress	N/m2	1.30E+08		5.85E+06
Shear stress	N/m2	2.97E+07		

WIND LOAD EFFECT

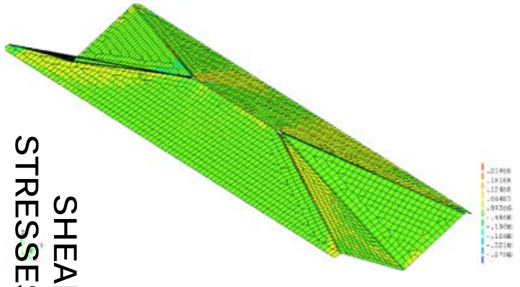
DEFORMATION



PRINCIPAL STRESSES



SHEAR STRESSES

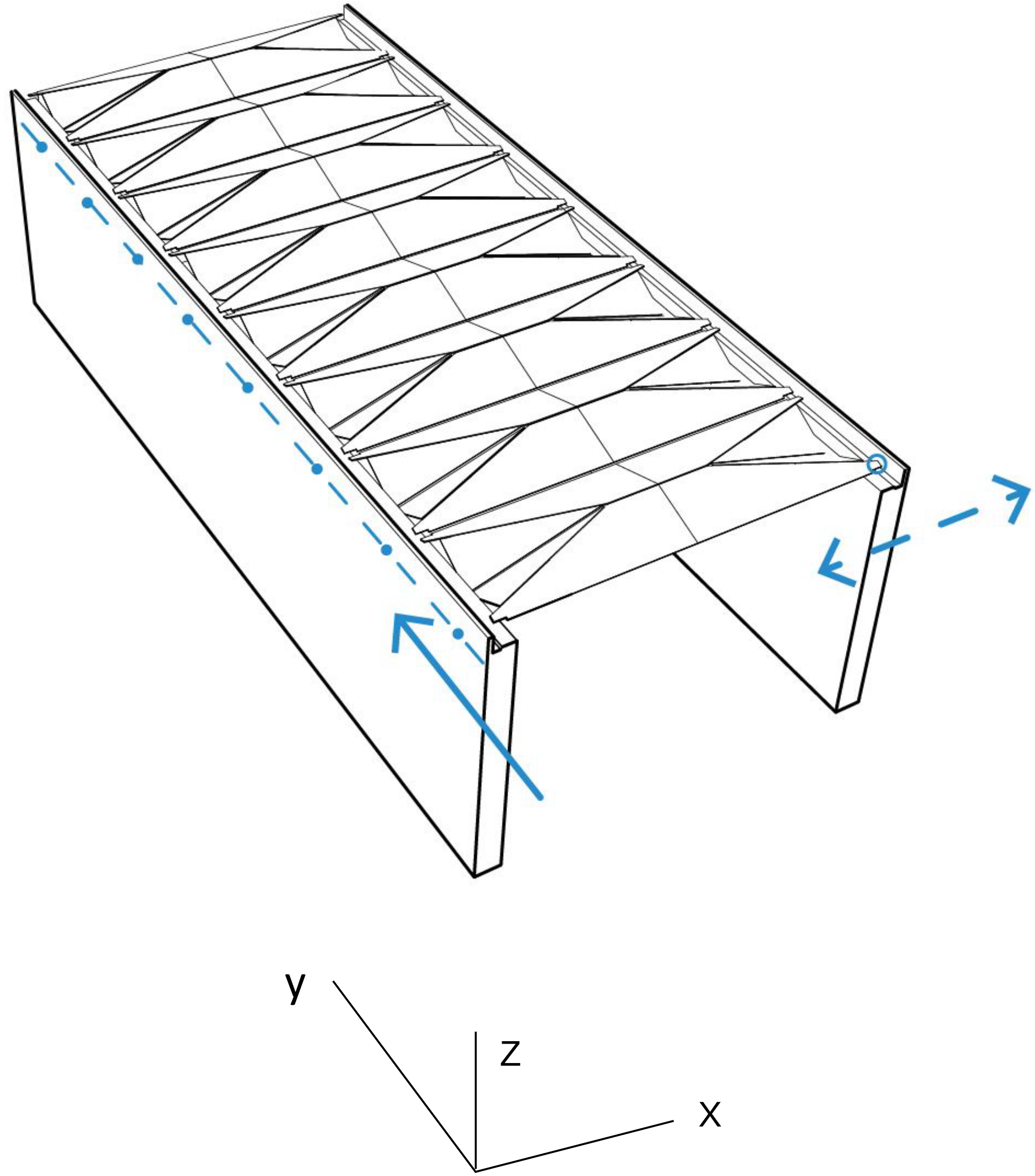


KINEMATIC SYSTEM

1. Translation on y-axis allowed during folding process and hindranced at the enclosed state.

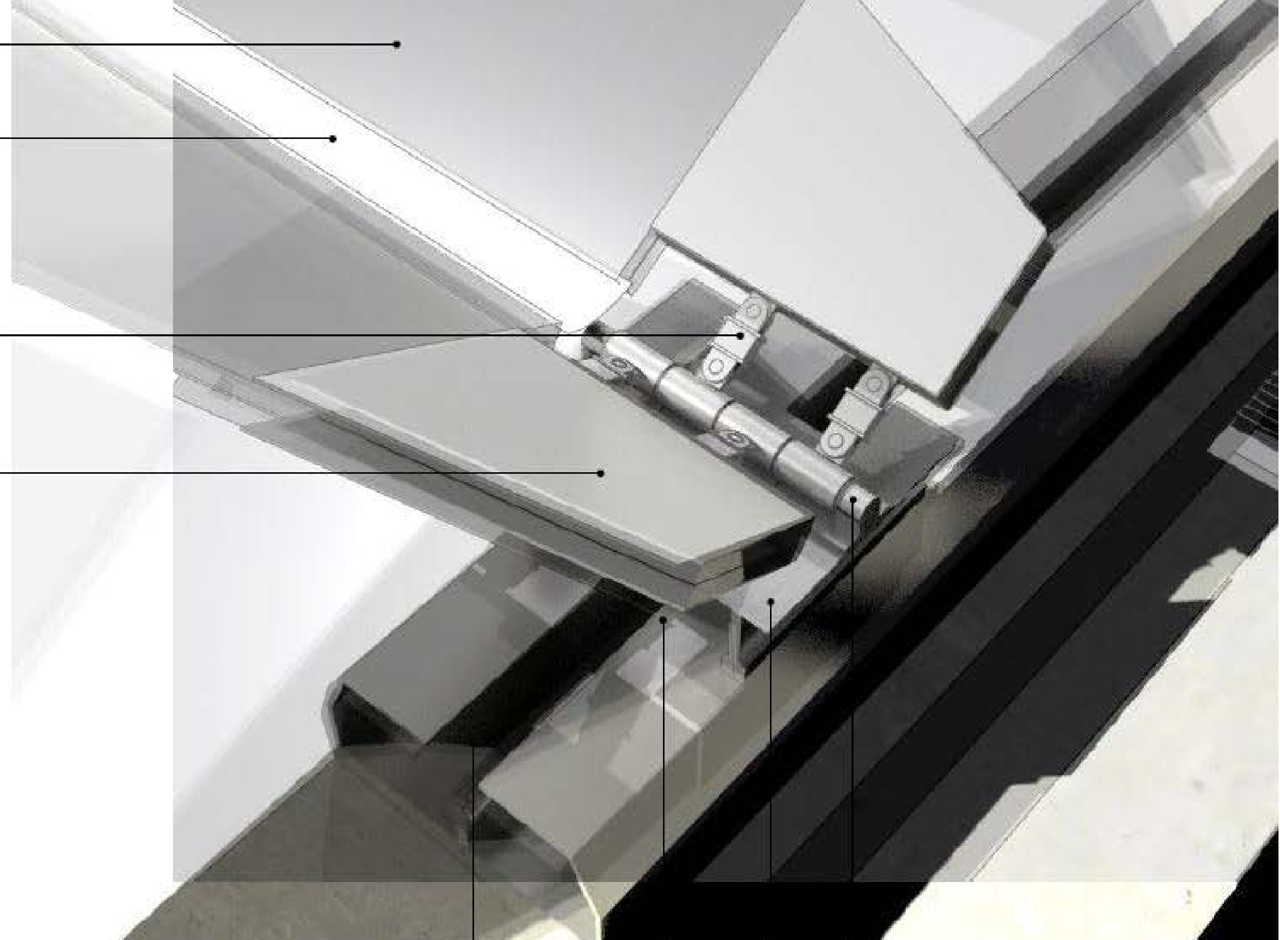
2. Tolerances on x-axis to avoid moments caused by the induced deflection.

3. Increasing the area of support as much as possible to avoid stress concentration

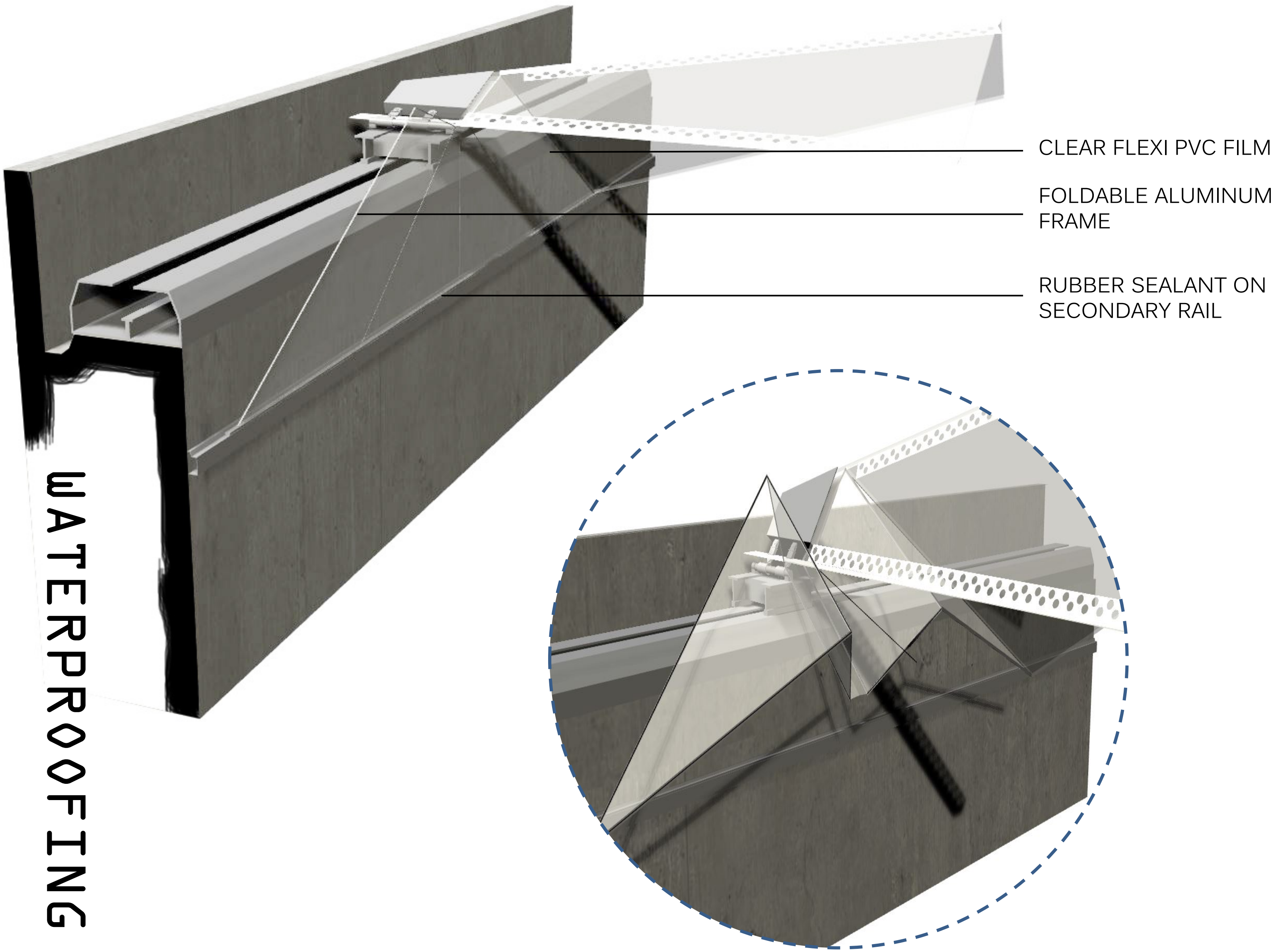


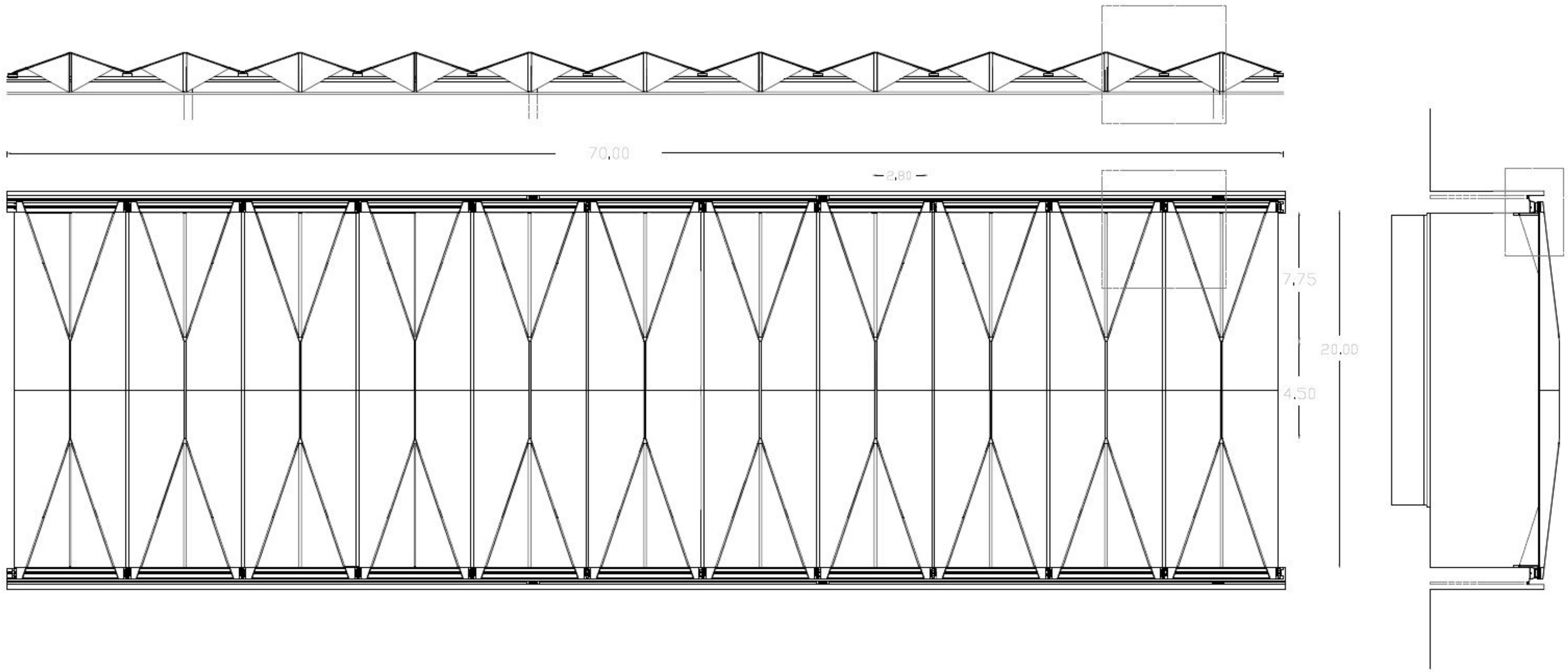
KINEMATIC SYSTEM

TRACTION DRIVE SYSTEM

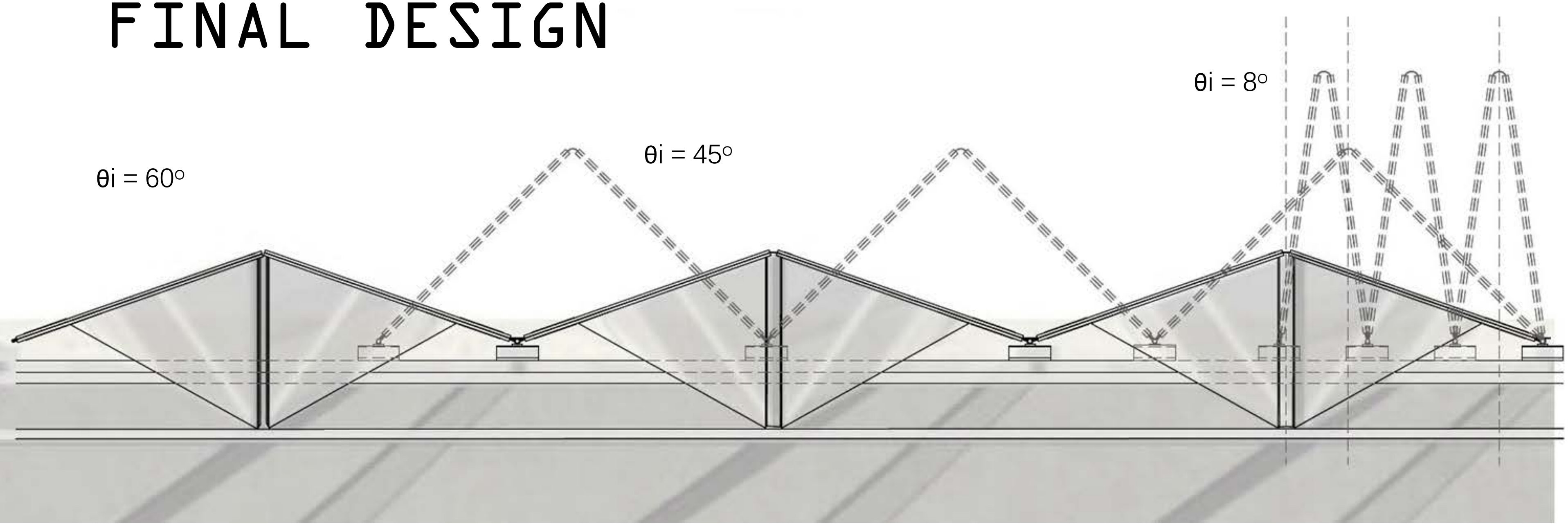


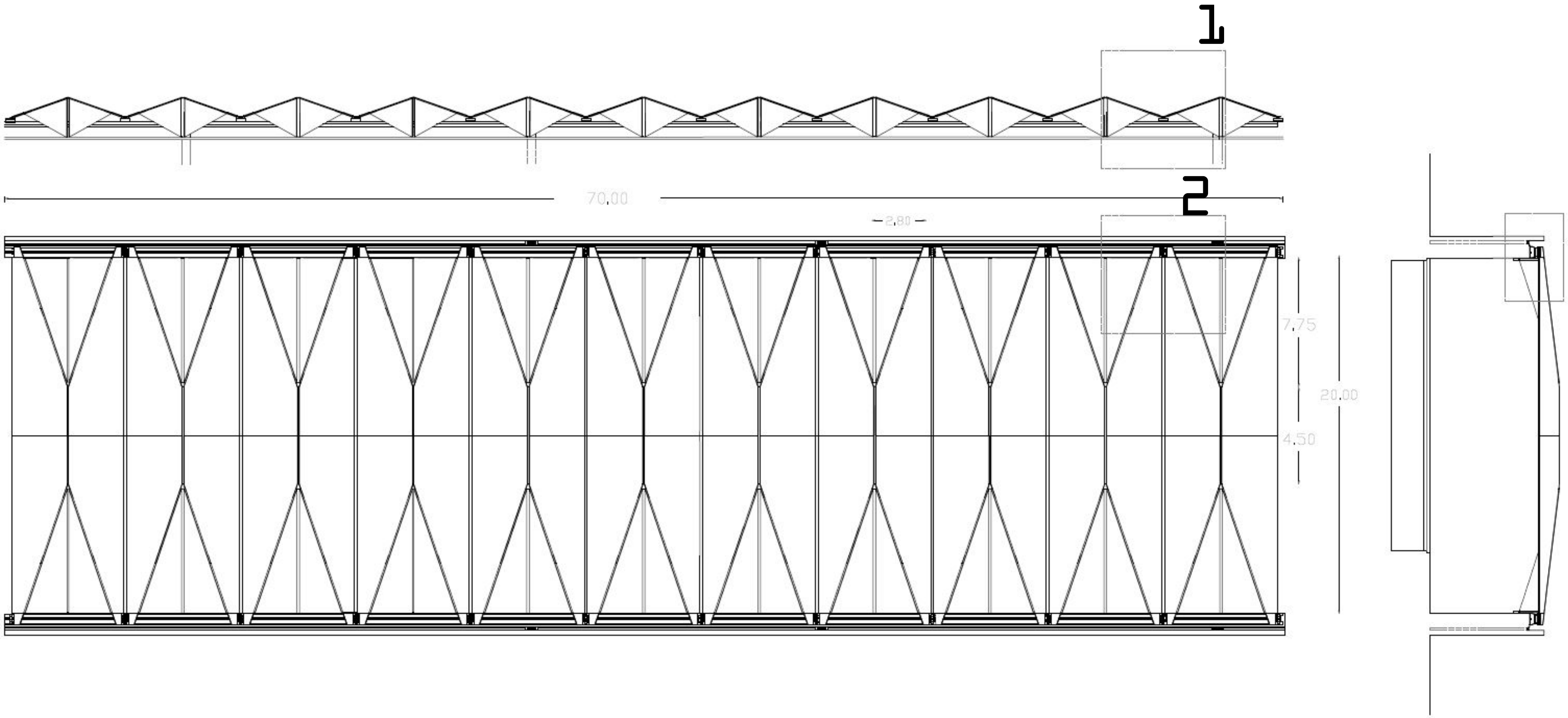
WATERPROOFING



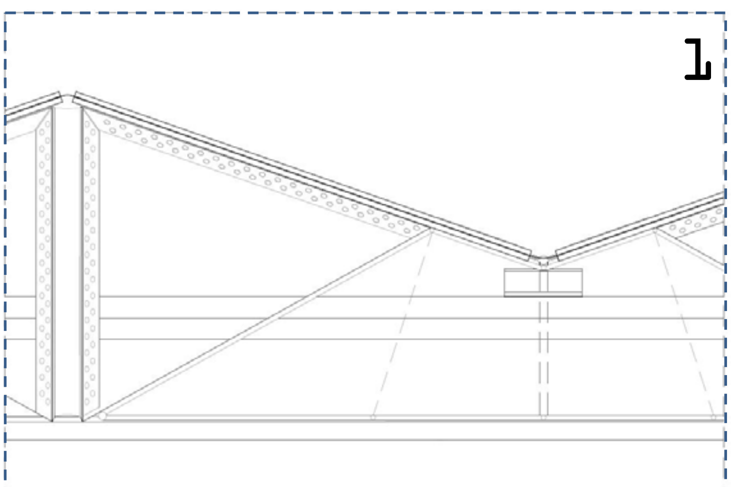


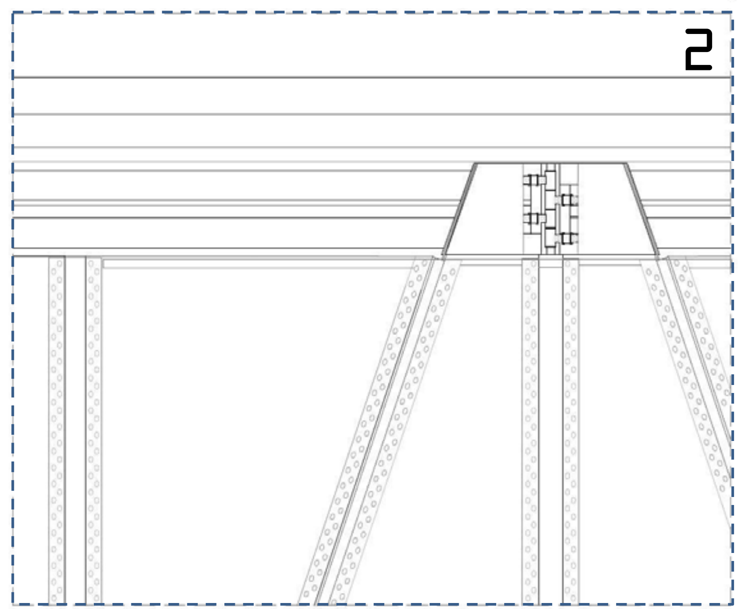
FINAL DESIGN

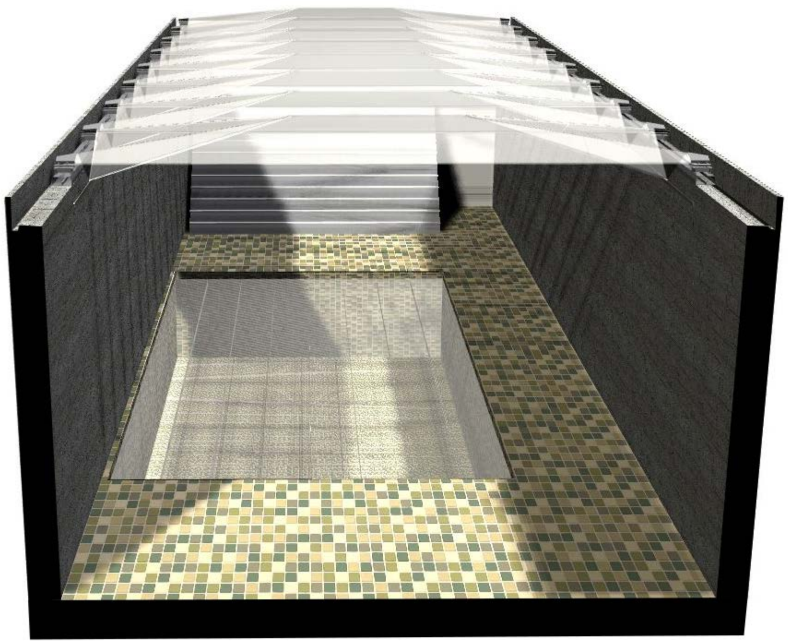




FINAL DESIGN







CRITERIA EVALUATION

DESIGN CRITERIA
Provide natural lighting and maximum transparency
Self-supported glass plate structure (no frame)
Deployable on one side (fully adaptable)
Feasibility

STRUCTURAL CRITERIA
Controlled element deformation + stress levels (all phases of deployment)
General shape stability (all phases of deployment)
Glass element redundancy
Damage sensitivity - Fracture mode – Safety factors

DETAILING CRITERIA
Discrete design- Invisible connection
Tolerances
Restriction of gaps- waterproofing
Repair work facilitated
BC maintained by connection detailing


THANK YOU