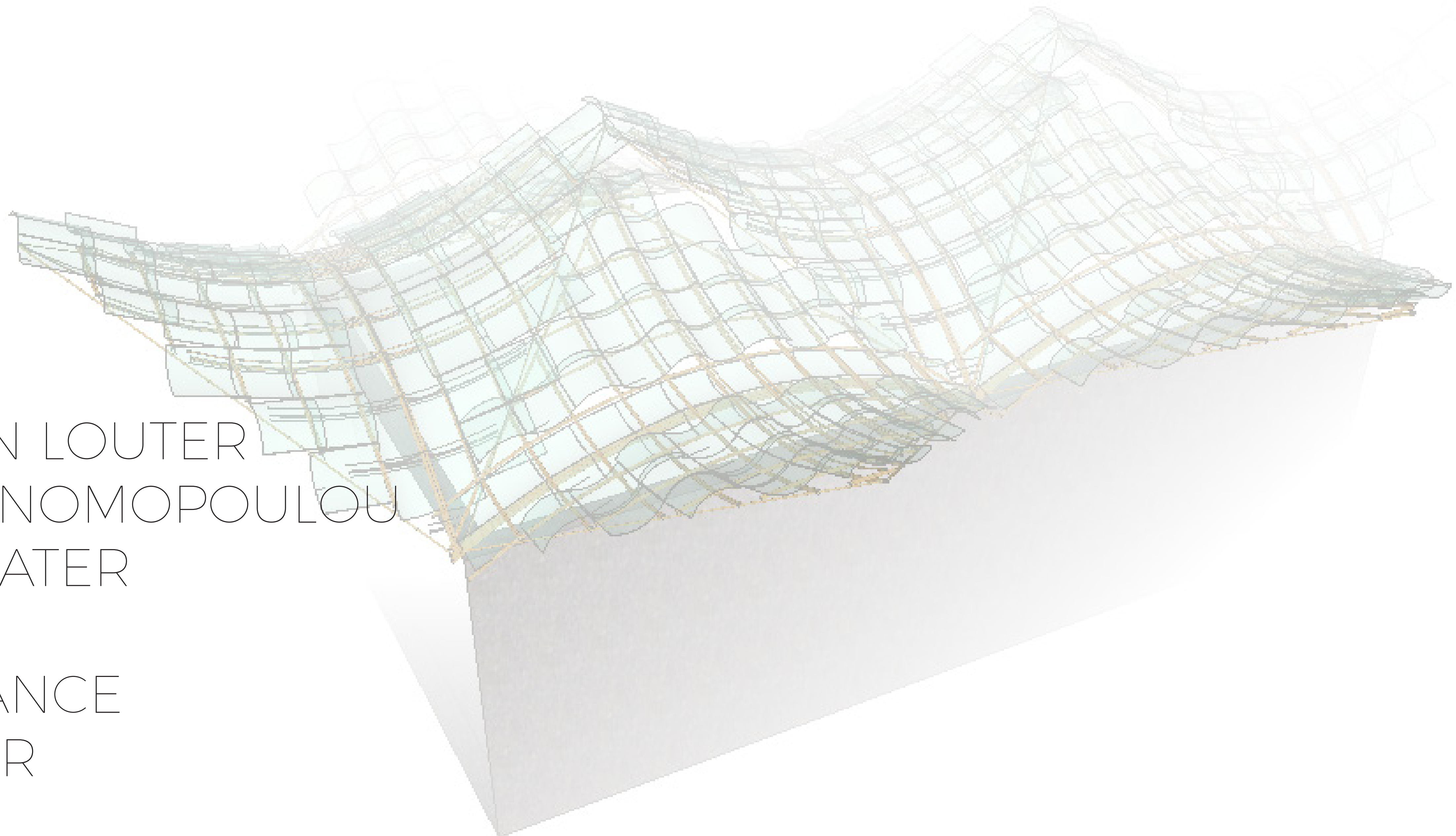
STRUCTURAL ANALYSIS OF BENDING BAMBOO AND THIN GLASS FOR GRIDSHELL

PRIYANKA GANATRA | 4409841

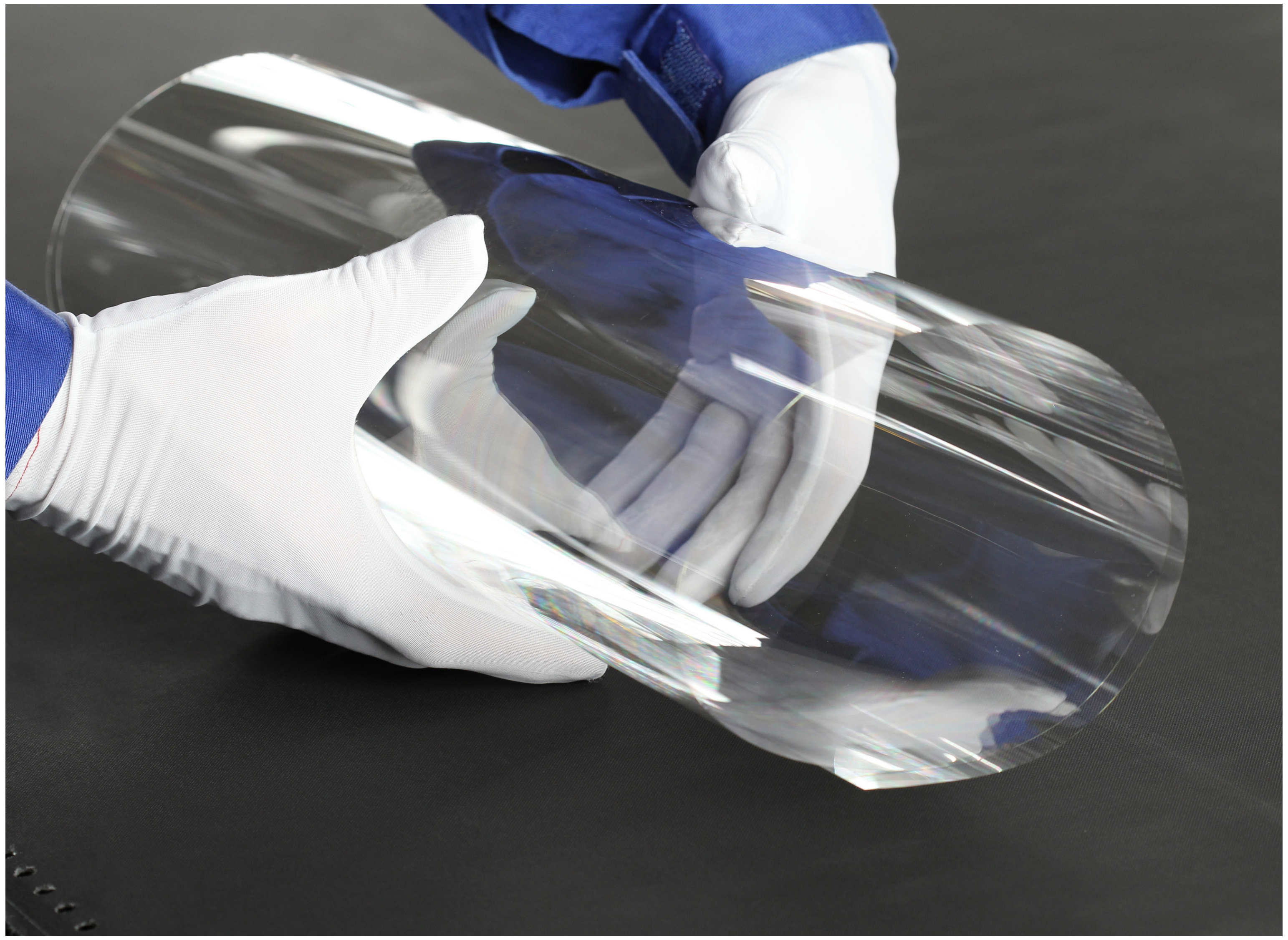


SUPERVISORS
DR.IR. CHRISTIAN LOUTER
IR. FAIDRA OIKONOMOPOULOU
IR. FRANK SCHNATER

BAMBOO GUIDANCE
DR.IR. FRED VEER

MATERIAL MATTERS

WHY BAMBOO AND THIN GLASS?



WHY BAMBOO AND THIN GLASS?

BAMBOO STRUCTURES

- STRONG
- LIGHT WEIGHT
- FLEXIBLE
- RENEWABLE

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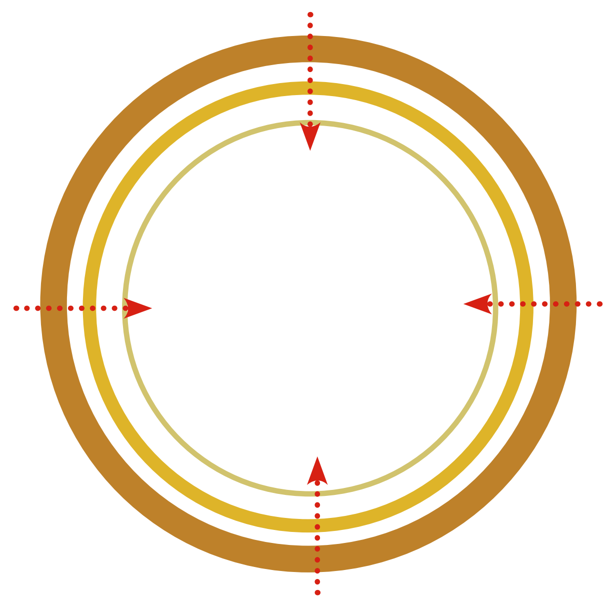
- IRREGULAR
- NO STANDARD SIZE
- VARYING STRENGTH



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PRIMITIVE JOINERY SYSTEM

- Needs to be checked and replaced periodically.

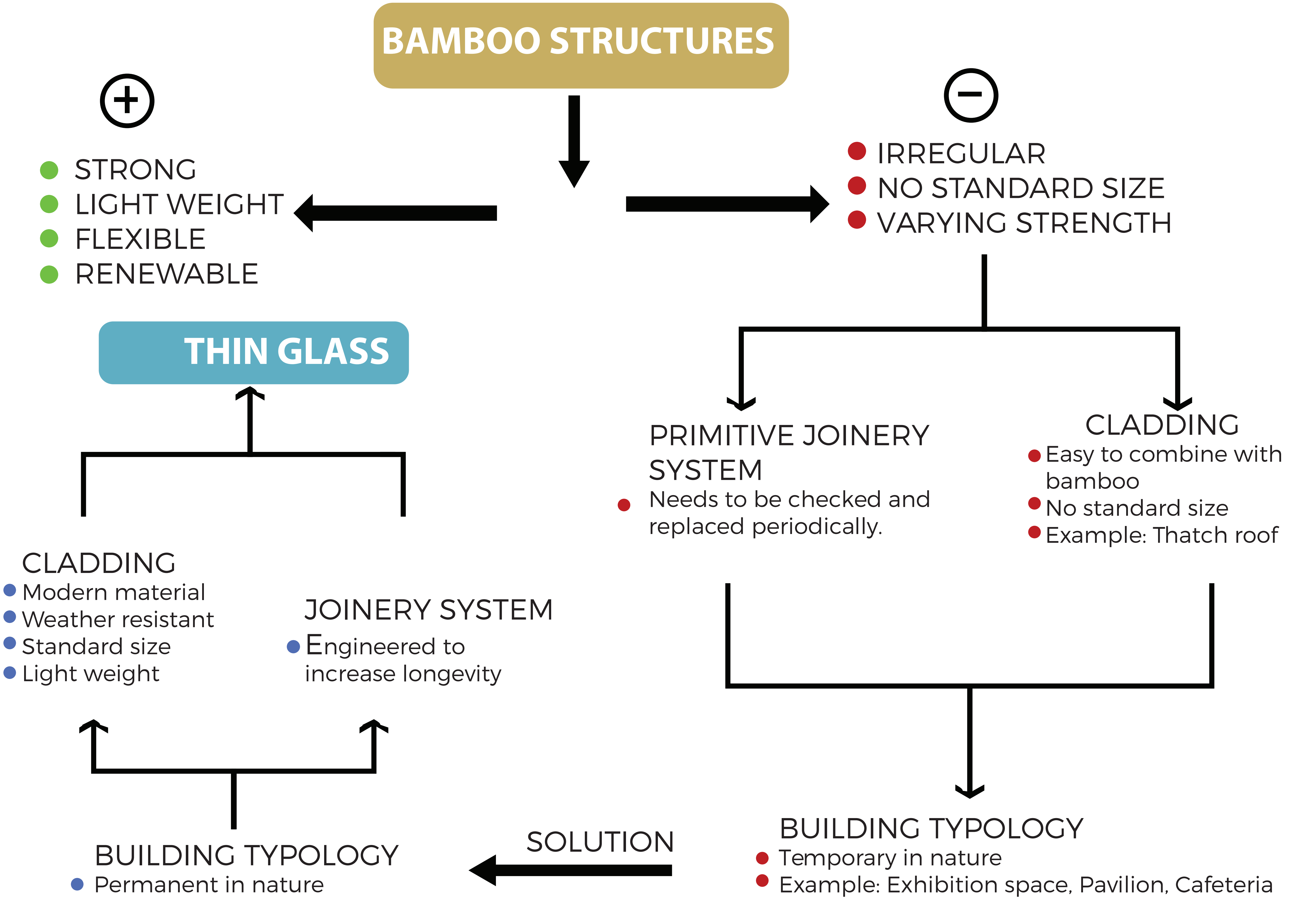
CLADDING

- Easy to combine with bamboo
- No standard size
- Example: Thatch roof

BUILDING TYPOLOGY

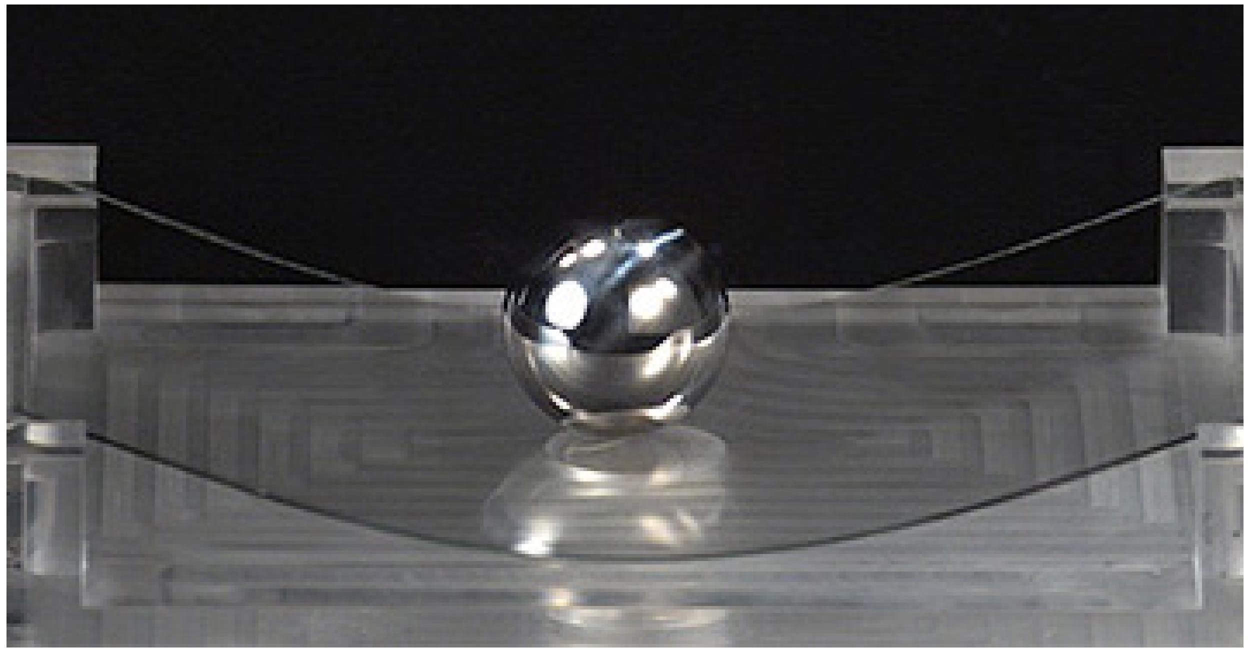
- Temporary in nature
- Example: Exhibition space, Pavilion, Cafeteria

WHY BAMBOO AND THIN GLASS?

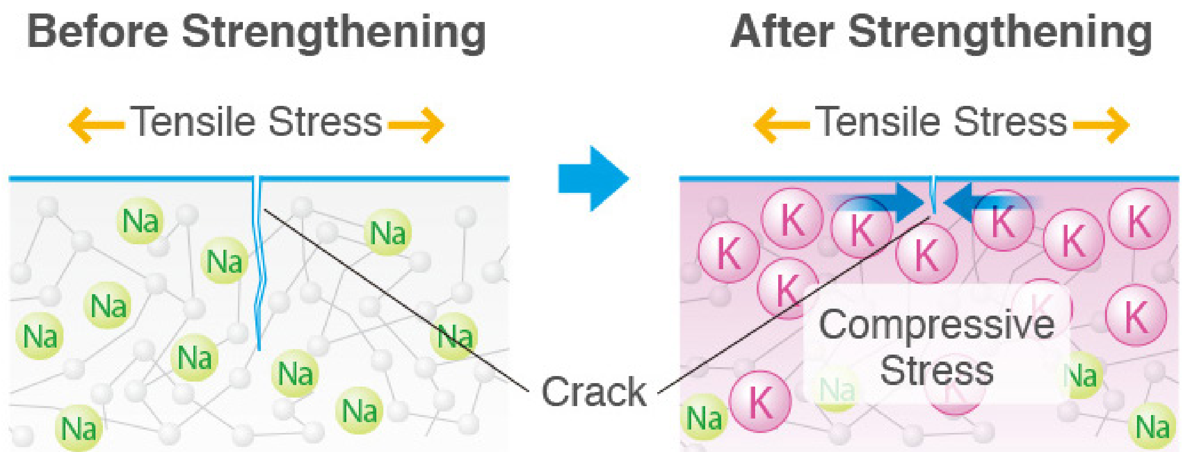


THIN GLASS

Fusion Overflow Process
ref: glasscon



Thin glass
ref: agc.com



ion exchange process
ref: agc.com

THESIS MAIN GOAL

To explore the potential and feasibility of bamboo and thin glass structure.

INTRODUCTION

PART 1: STUDYING BENDING BEHAVIOUR OF BAMBOO

PART 2: STUDYING BENDING BEHAVIOUR OF THIN GLASS

PART 3: TO DEVELOP CONNECTIONS BASED ON DRAWBACKS AND STRENGTH OF BAMBOO AND THIN GLASS

PRE-BENT BAMBOO STRUCTURES

Naman Retreat, Vo trong Ngheia

Ecological Center, 24 Architects

Community Center, Vo Trong Ngheia

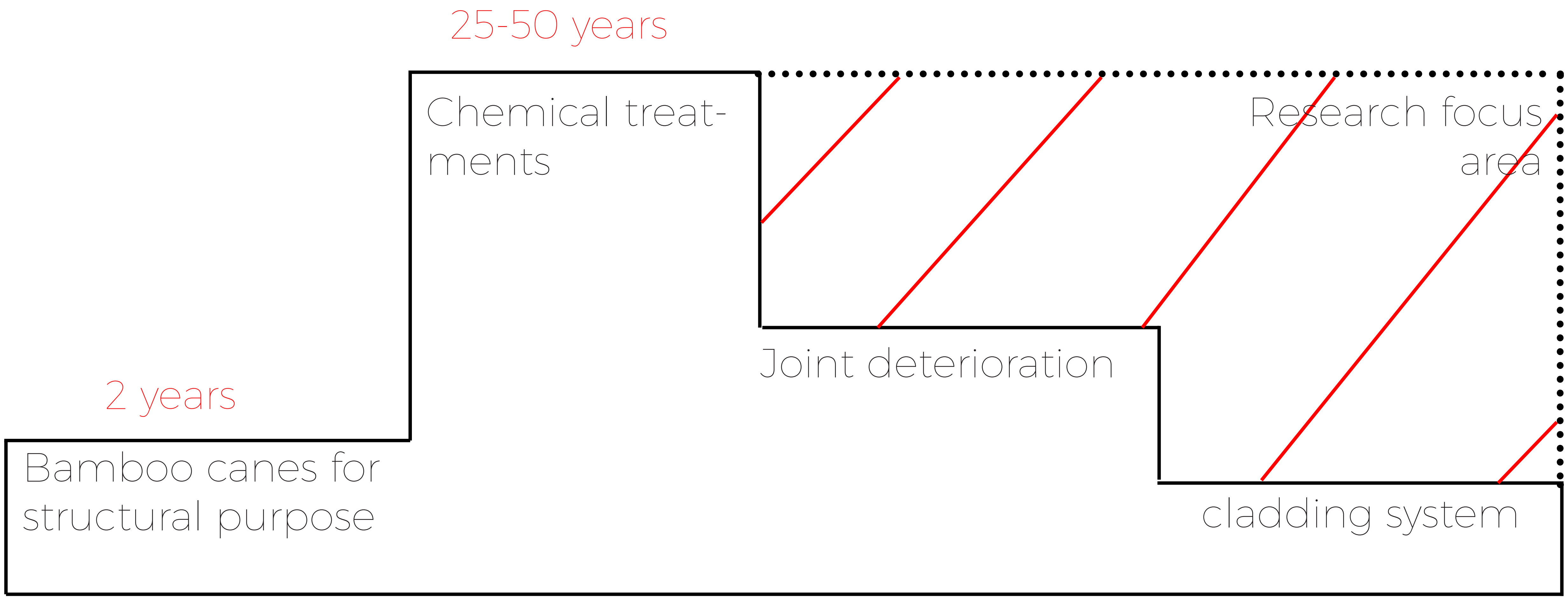
PRE-BENDING PROCESS

Steaming bamboo
ref: www.bamboocraft.net

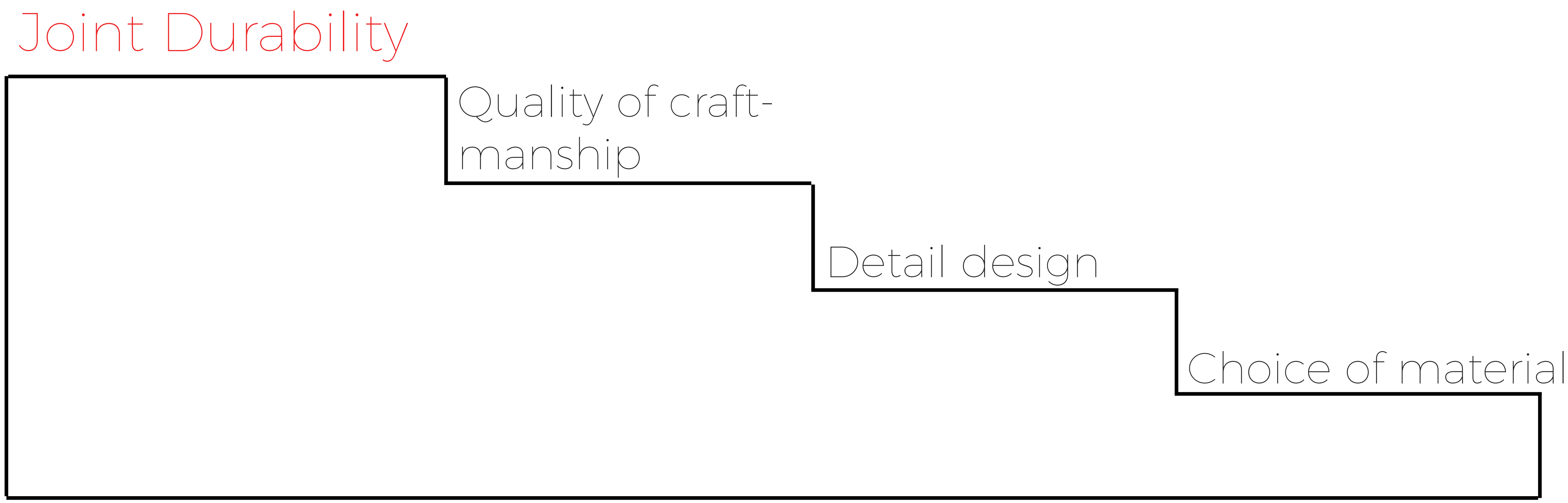
Bamboo bending form work
ref: www.bamboocraft.net

Bamboo bending grid system
ref: 24H Architects

Bolted and Lashing Connection
ref: http://constructpix.com/?attachment_id=2



Durability of bamboo structure.



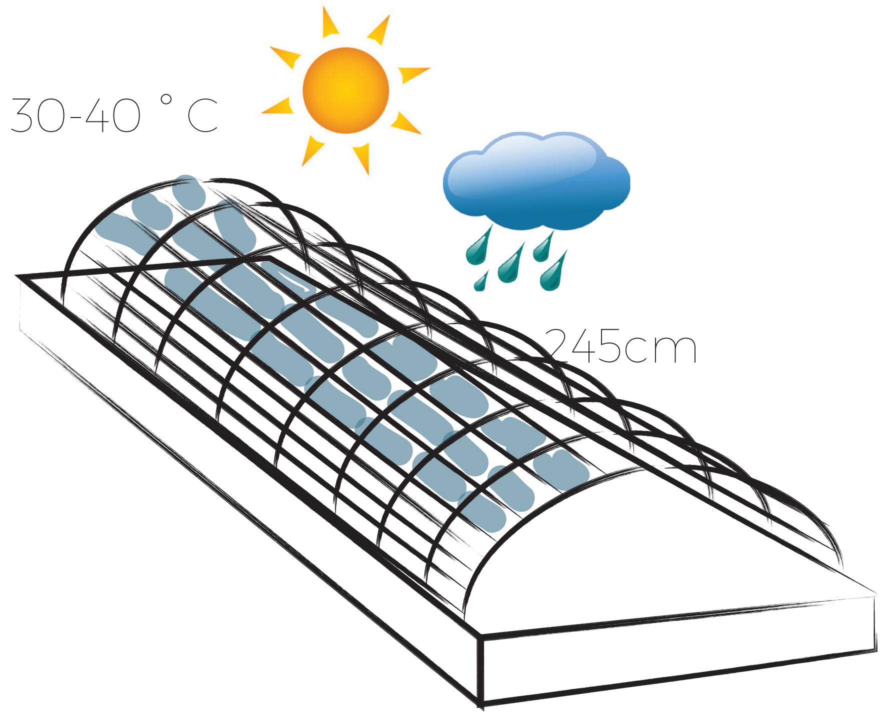
SITE

SITE _ IMPRESSION

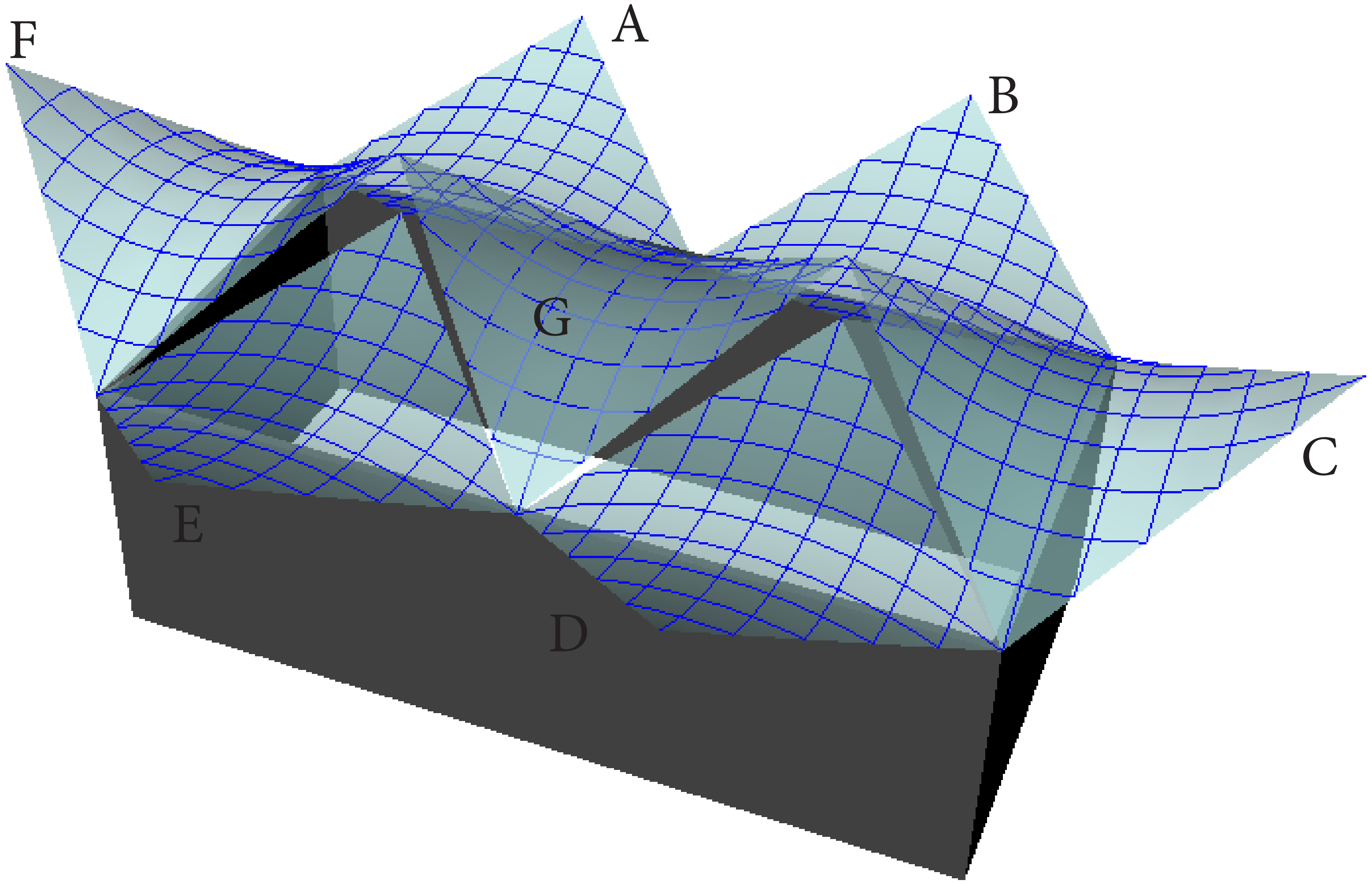
LOCATION: INDIA

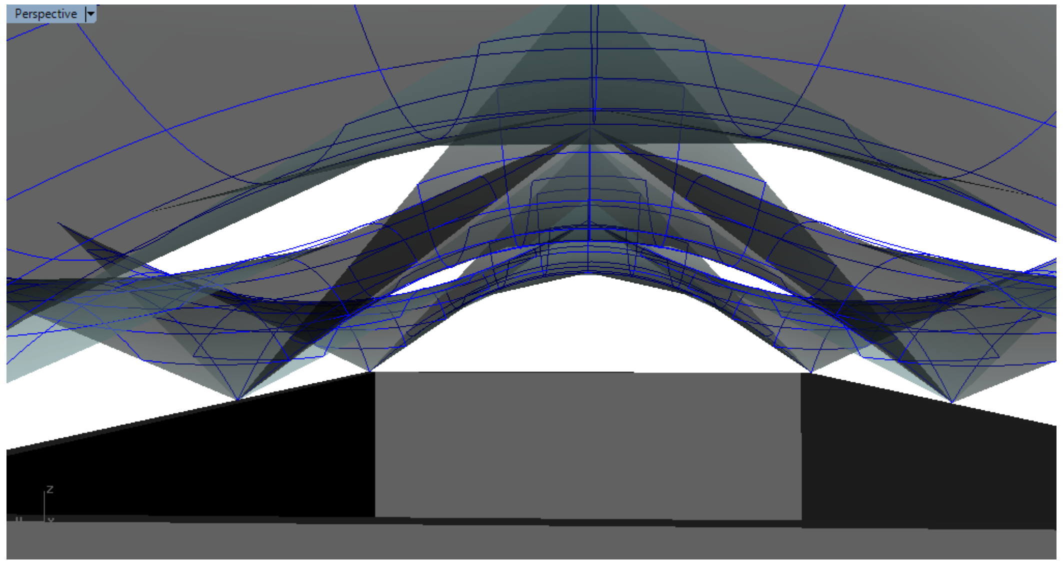
FUNCTION: WAREHOUSE

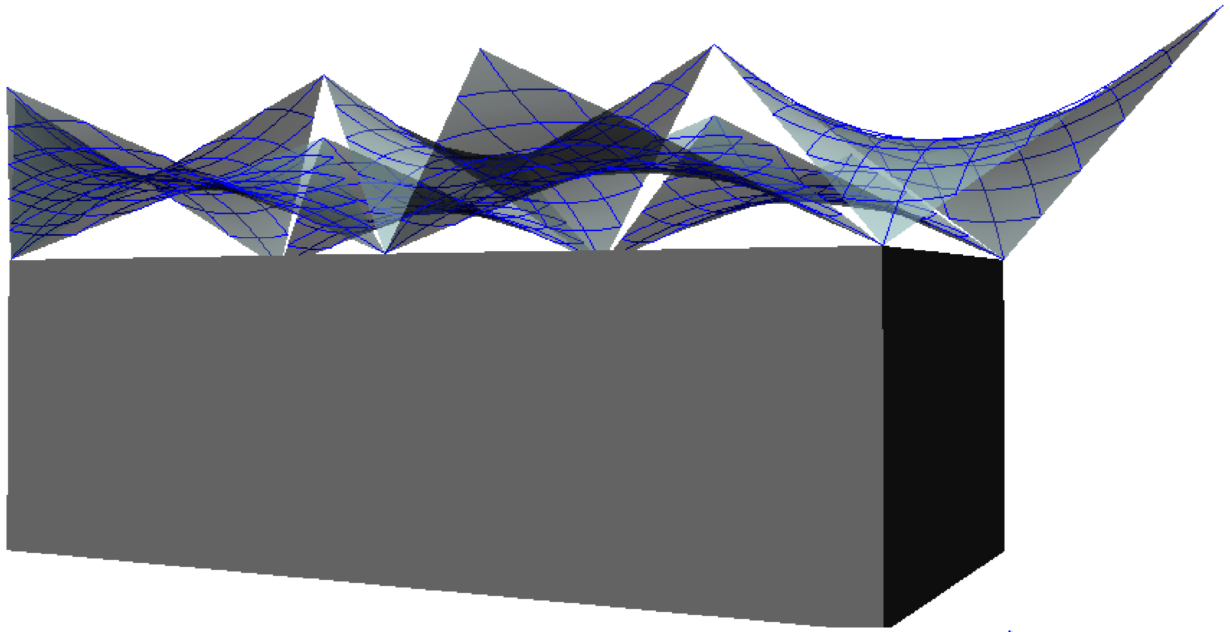
SPAN: 20x10 METERS

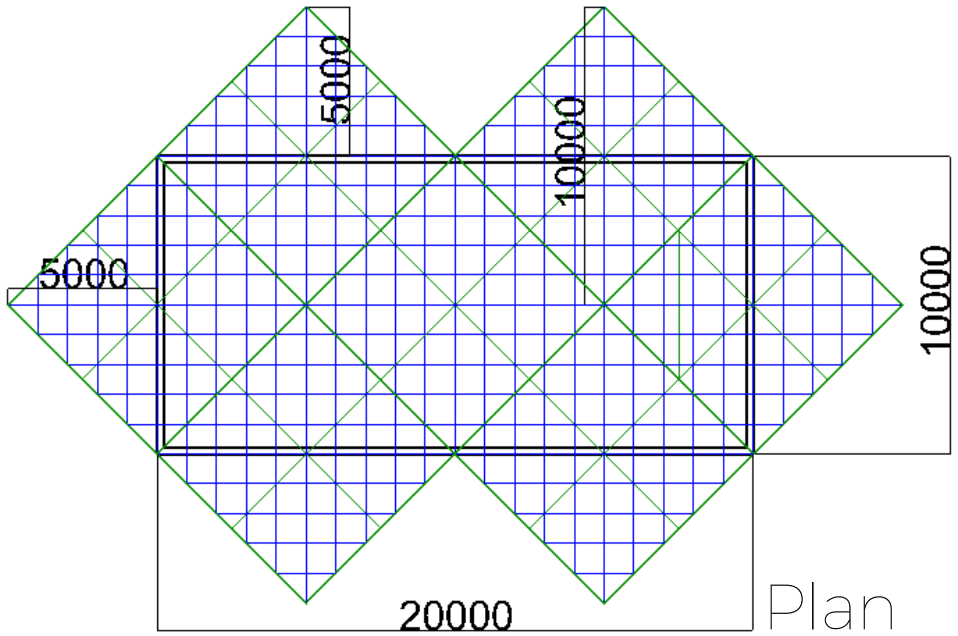


BASIC FORM

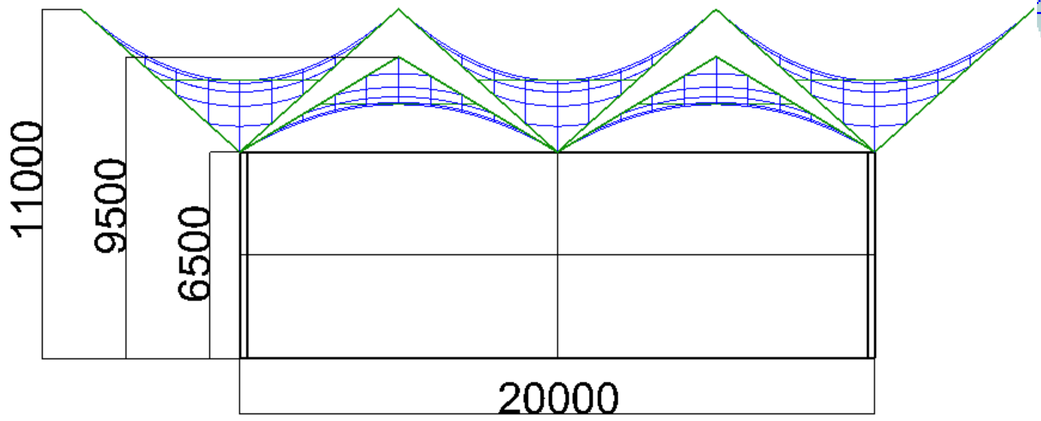




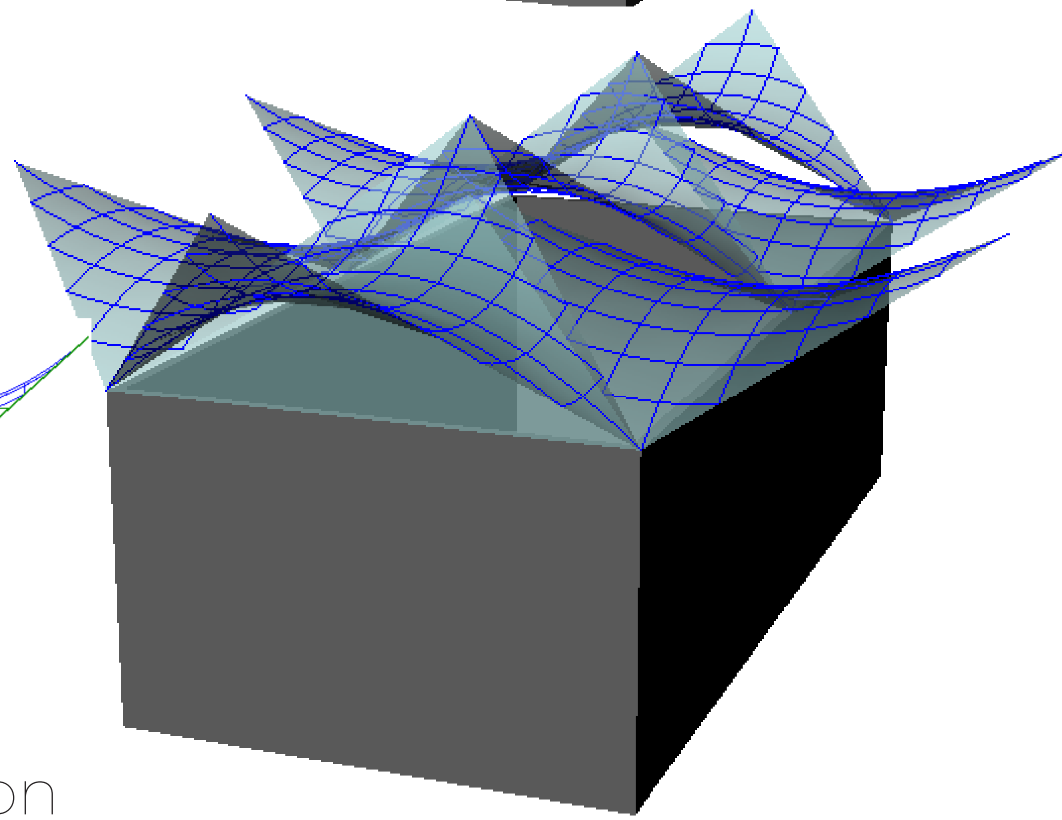




Plan



Section



BAMBOO + THIN GLASS

BENDING ANALYSIS

PRE-BENT MEMBERS

- To obtain free form geometry
- Increase stiffness of the overall structure by pre-stressing the members.

BAMBOO EXPERIMENTS

TO OPTIMIZE GEOMETRY

TO ACHIEVE MINIMUM DIFFERENCE IN BENDING

- Connections will be as planned
- Global stiffness of the structure is not decreased (membrane forces)

THIN GLASS BENT

- To obtain overlap between the panels
- Flow of water directed in a specific manner
- Increase stiffness of individual panels

THIN GLASS FEA

MAXIMUM CURVATURE/ BENDING

To determine panel size

To determine bamboo grid distance

PART 1

STUDYING BENDING BEHAVIOUR OF BAMBOO

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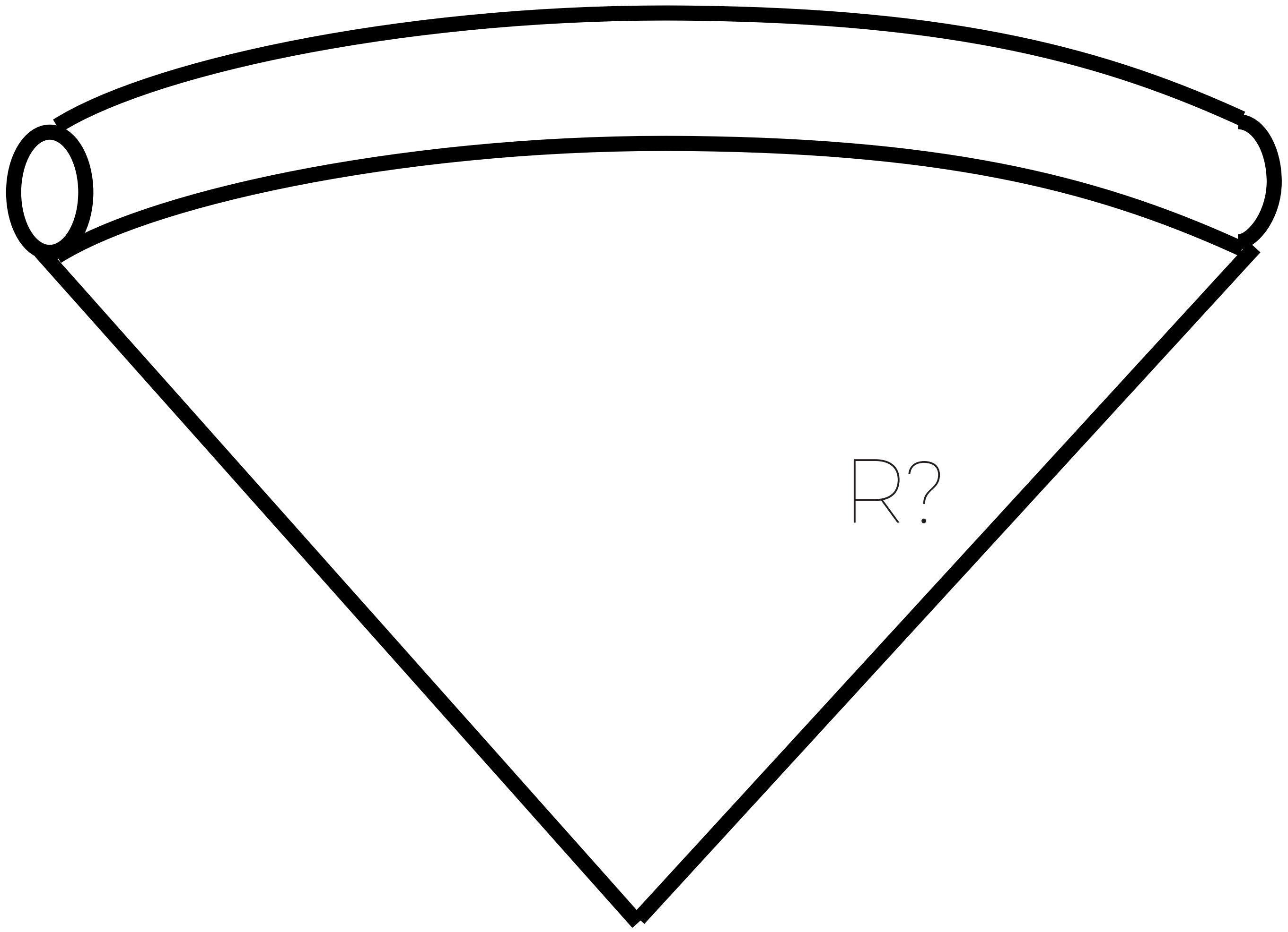
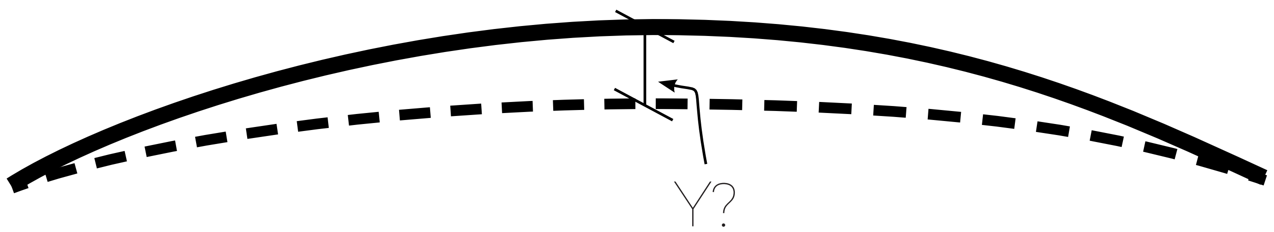
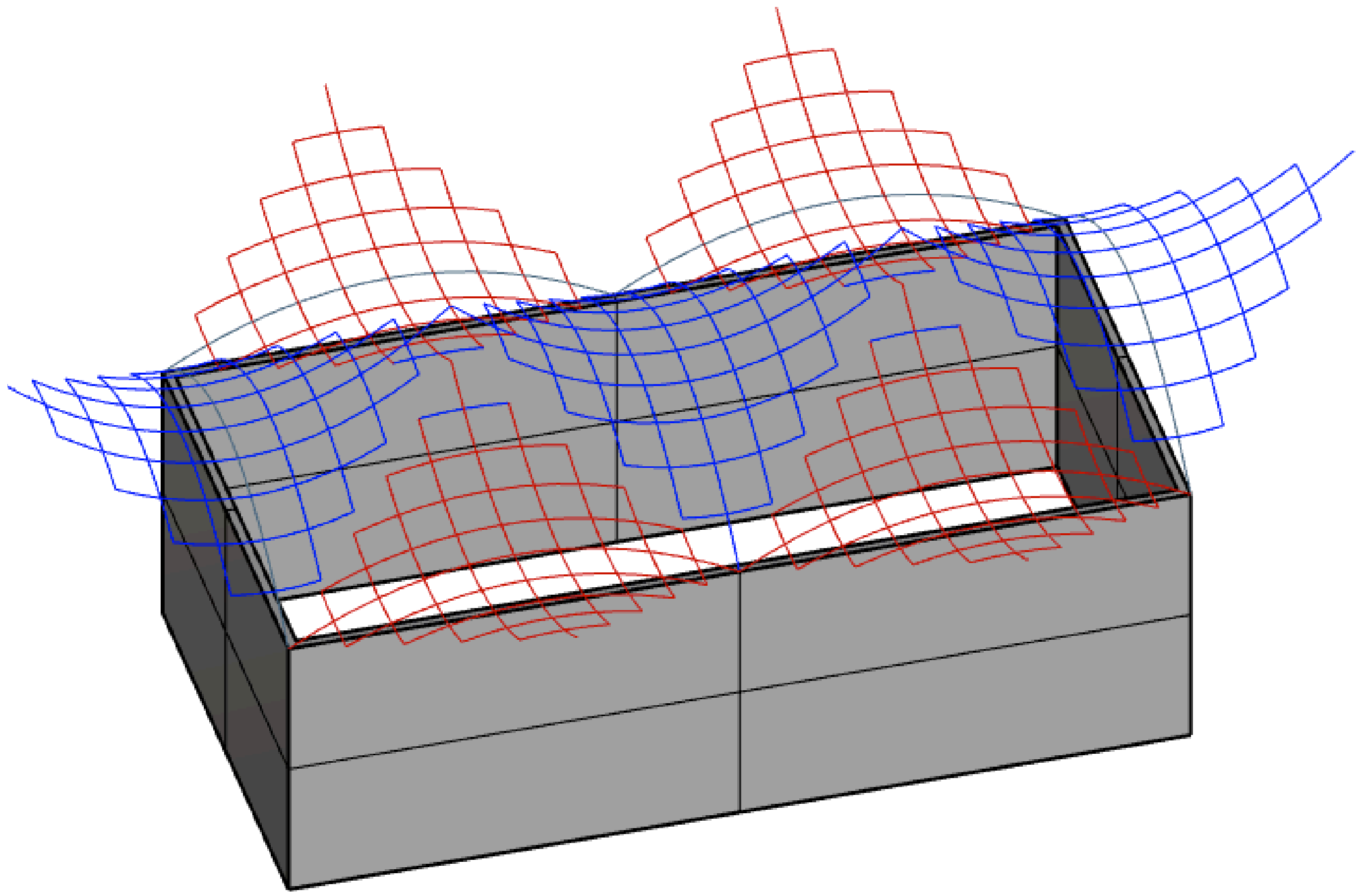
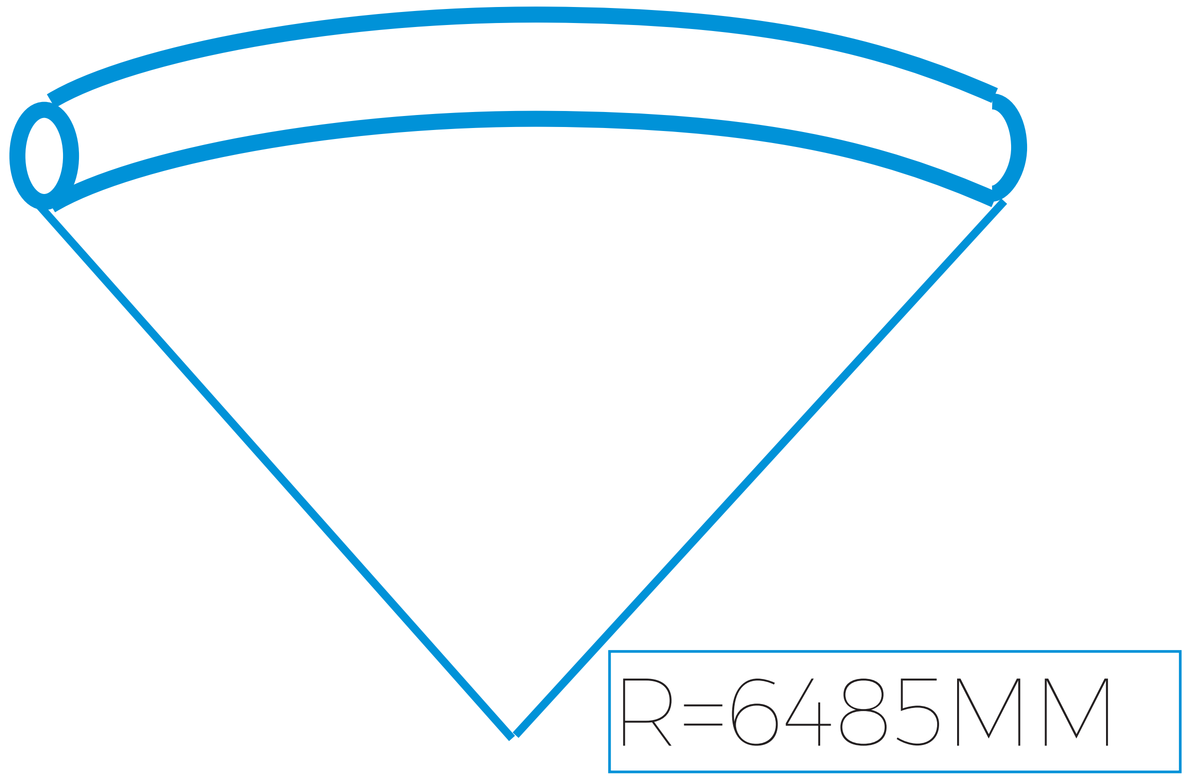
STUDYING BENDING BEHAVIOUR OF BAMBOO

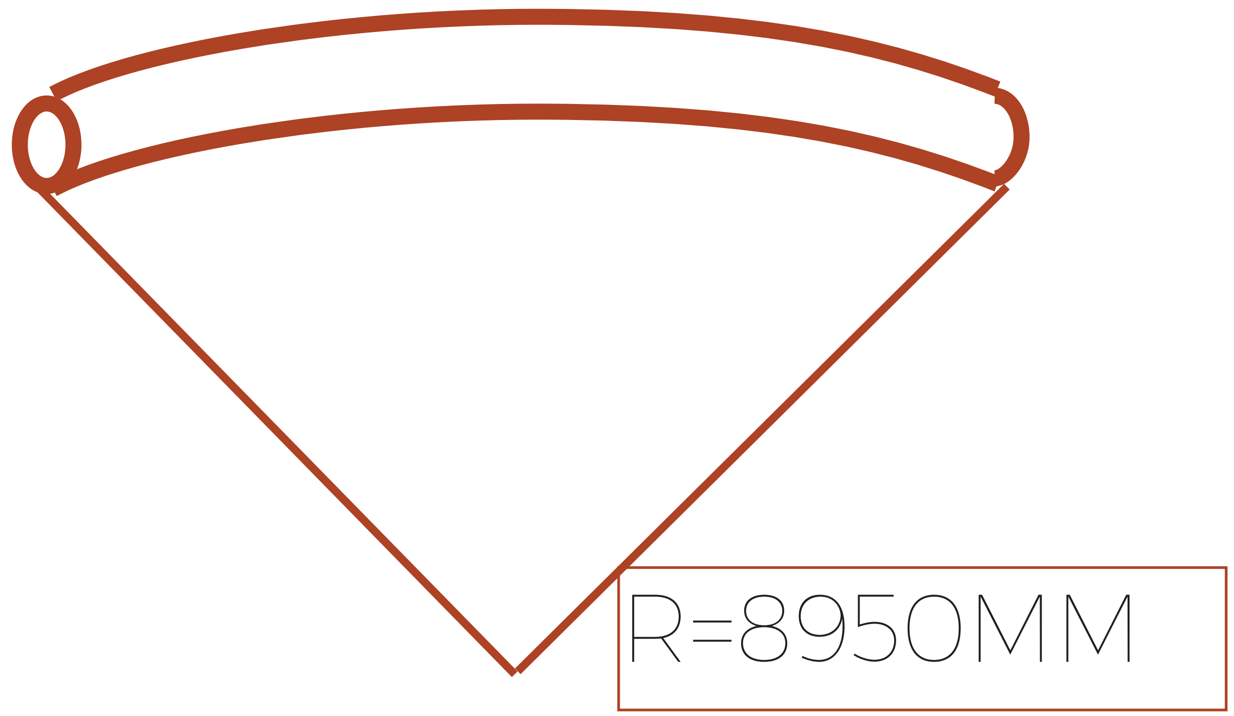




REQUIRED BAMBOO CURVATURE



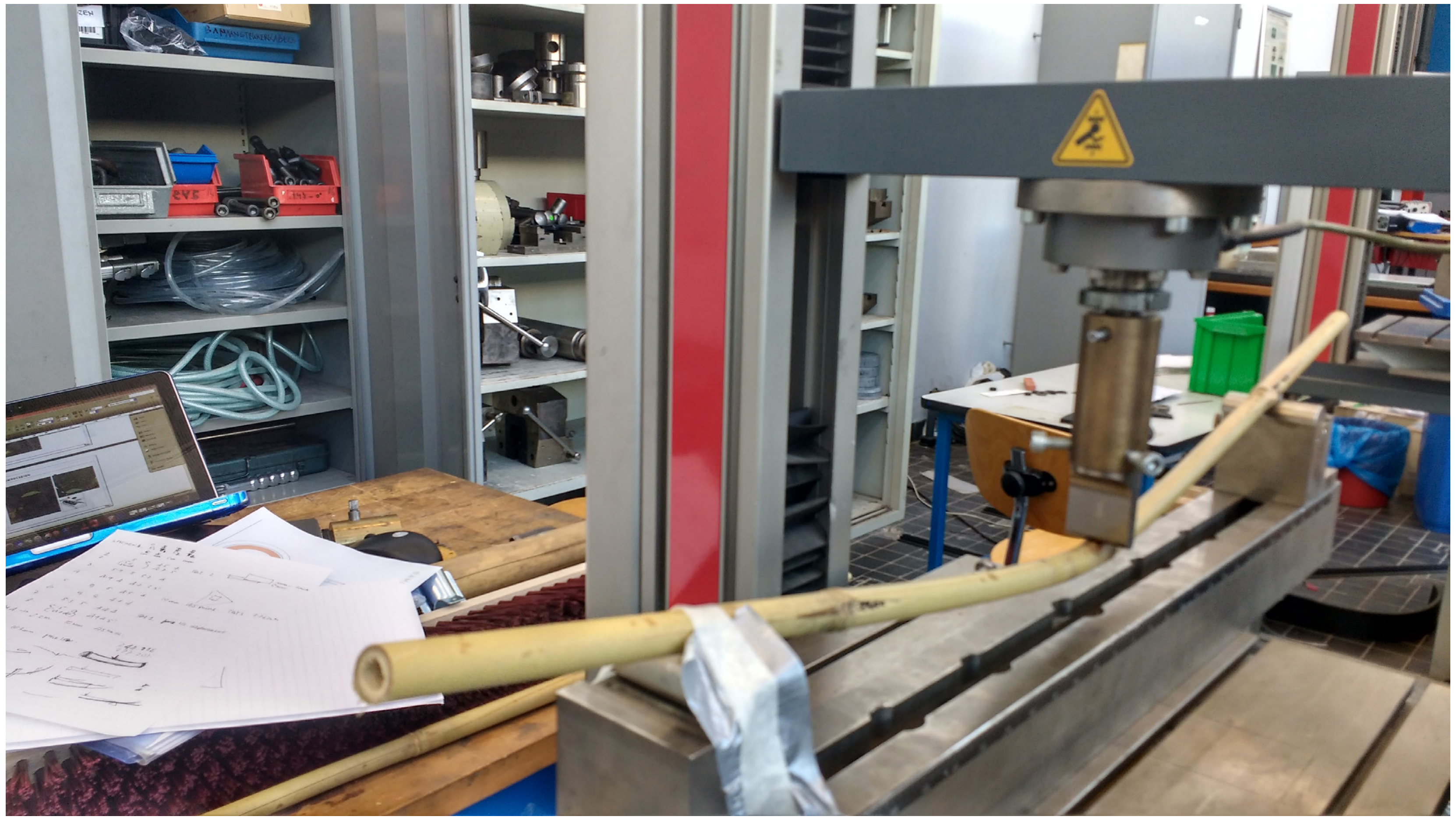




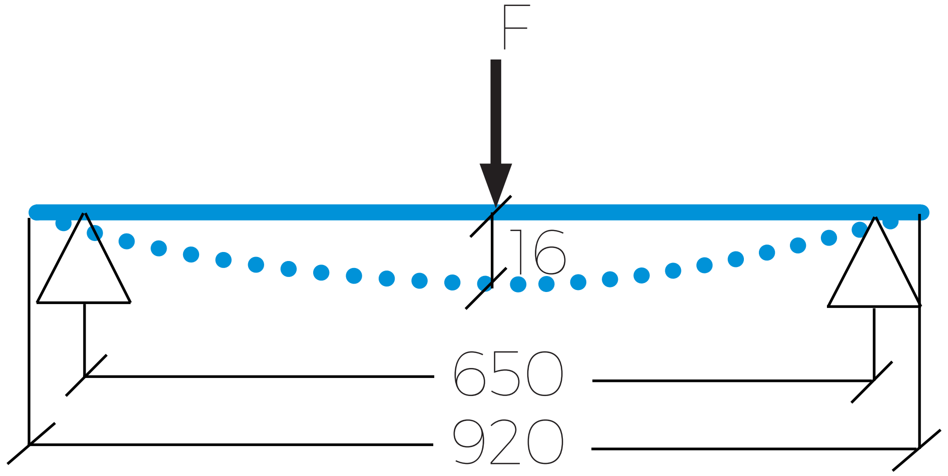
SPRING BACK DEFLECTION

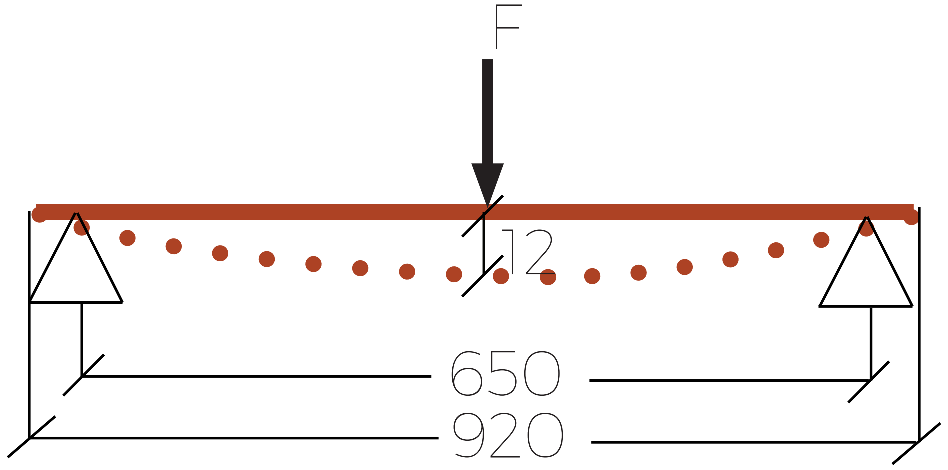
EXPERIMENT 2

Bamboo size:
Length: 920mm
Diameter:1.7-1.5cm
Soaked in water for 9 days



	Length mm	Dout mm	Thickness mm	Constant dl mm	Time mins	F_{max} N	Ffinal N	Final dL mm	Springback %
Specimen 1	920	16	4	60	30	464.76	341.86	15.61	73.9



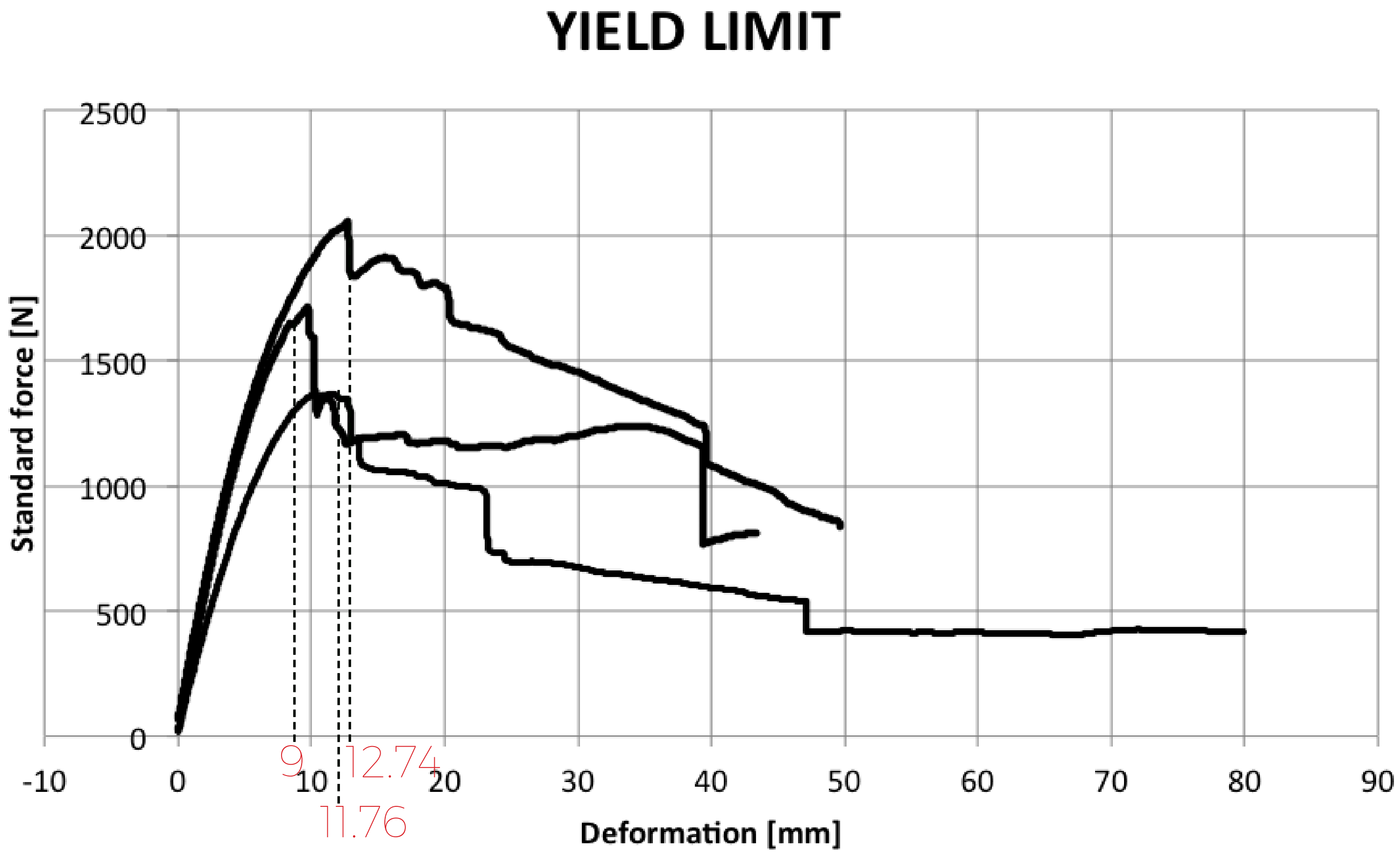


Deflection required as per design.

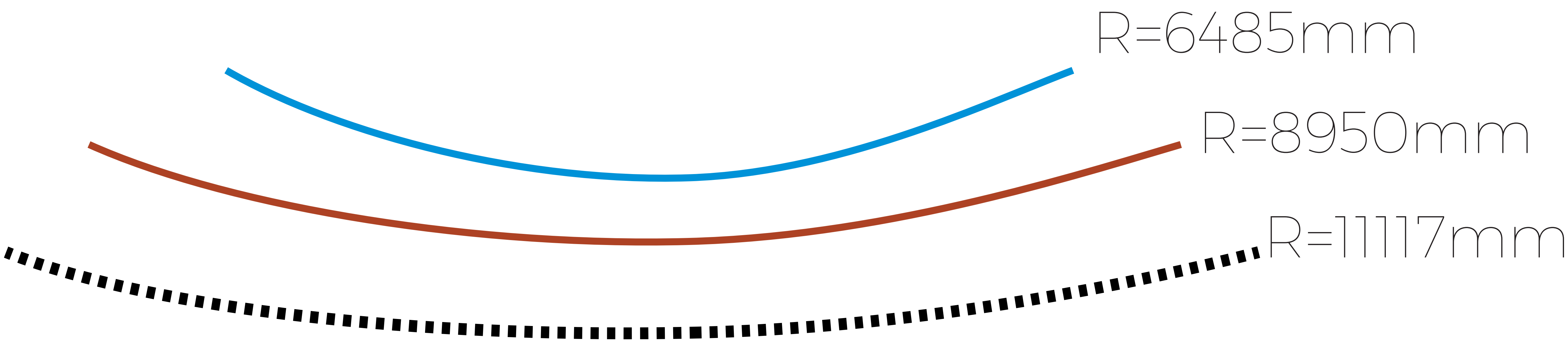
TESTING MAXIMUM CURVATURE

EXPERIMENT 2

Bamboo size:
Length: 920mm
Diameter: 5-5.5cm
Soaked in water for 4 days

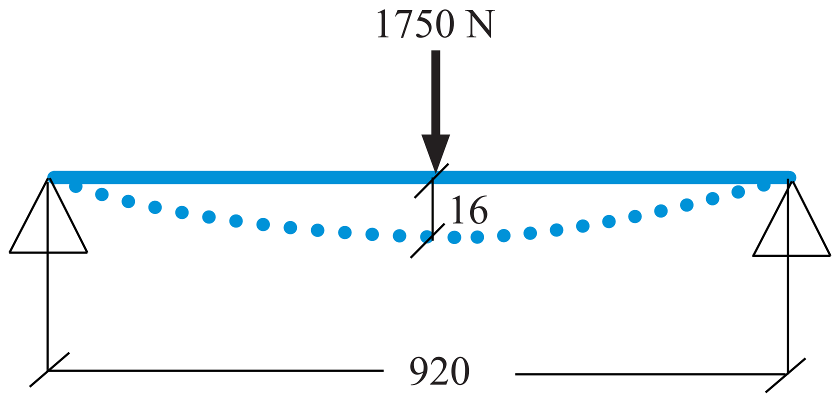


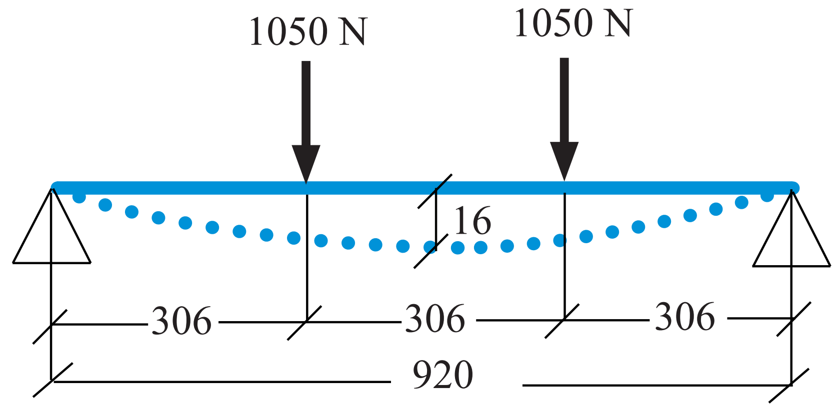
3-point bending test. Graph showing maximum deflection and yield limit.



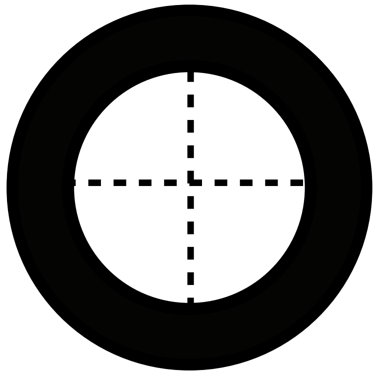
BAMBOO EXPERIMENT CONCLUSION

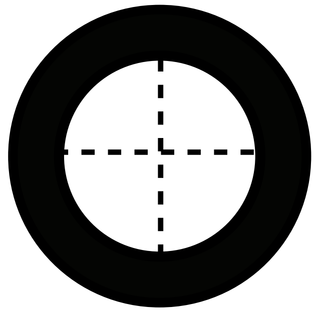
4 POINT BENDING TEST



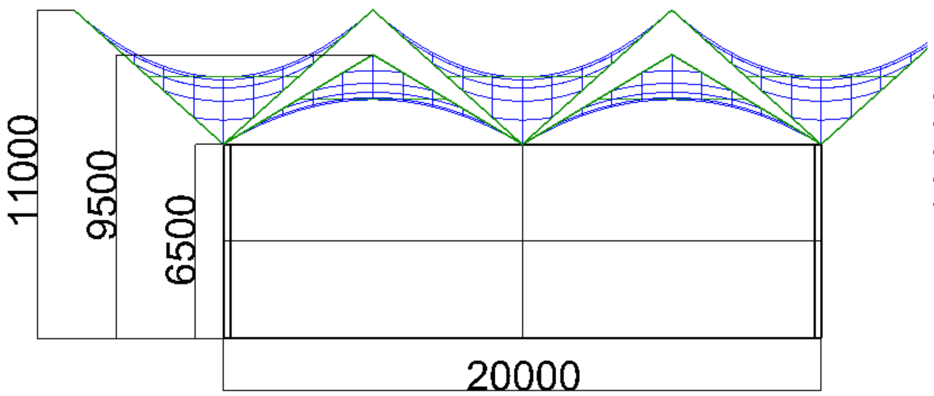


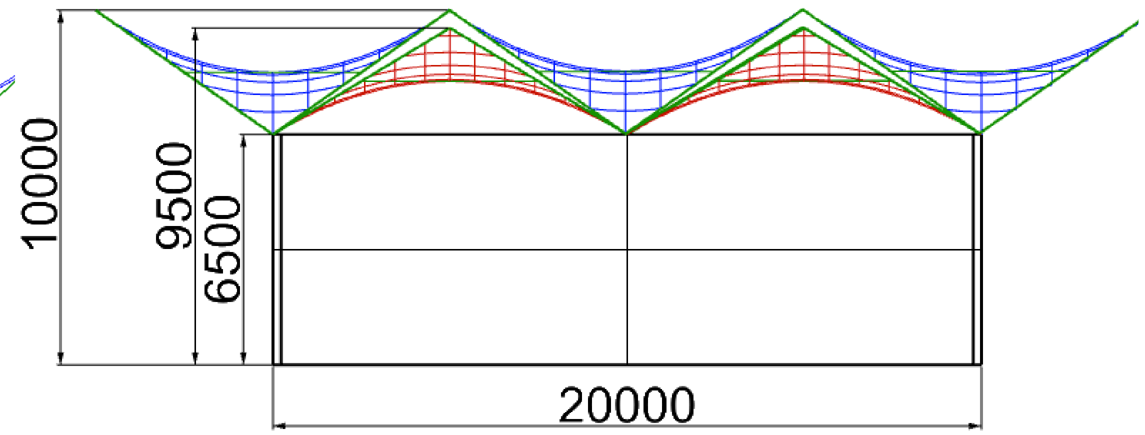
BAMBOO DIAMETER OF 4CM





INCLINATION OF THE ROOF

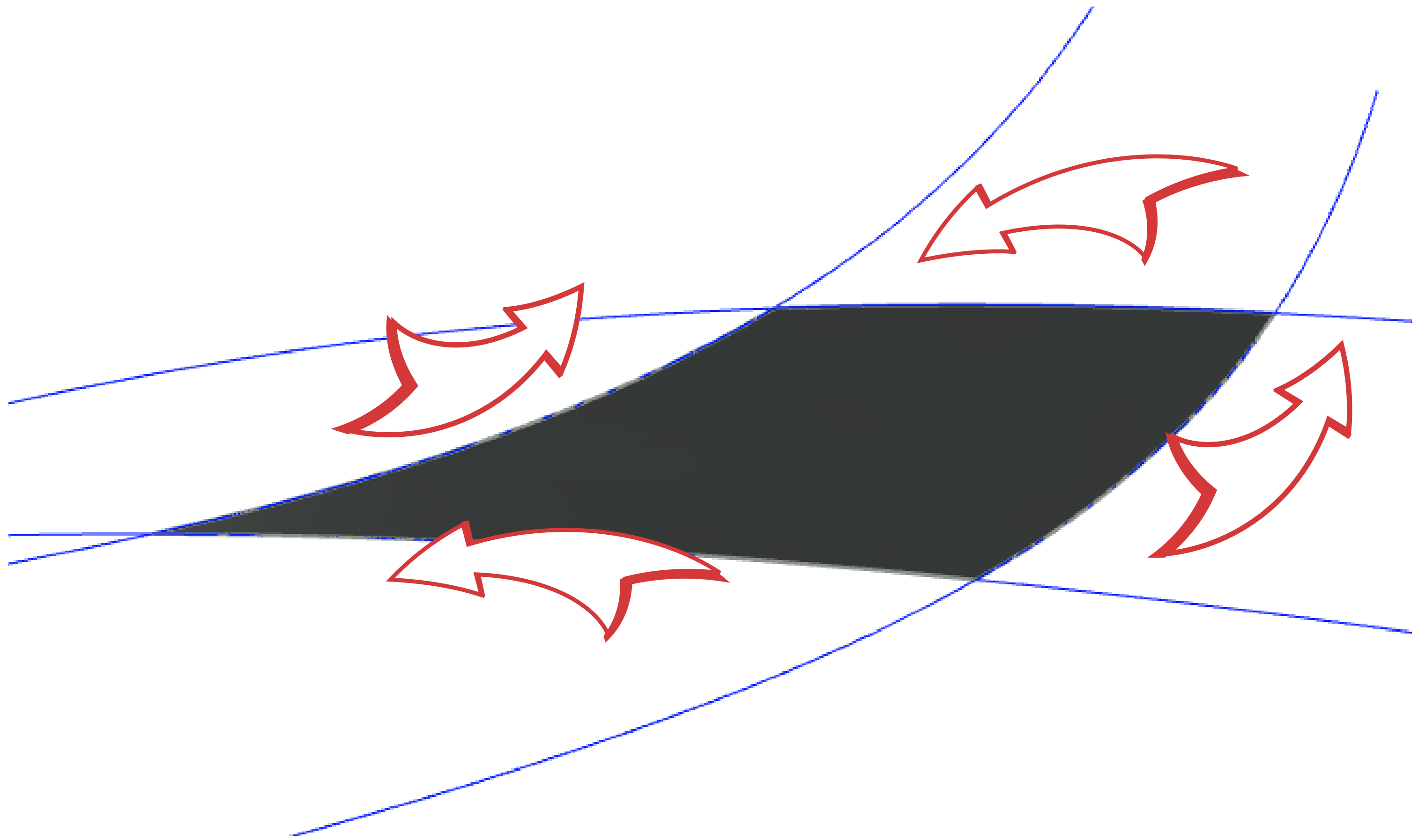




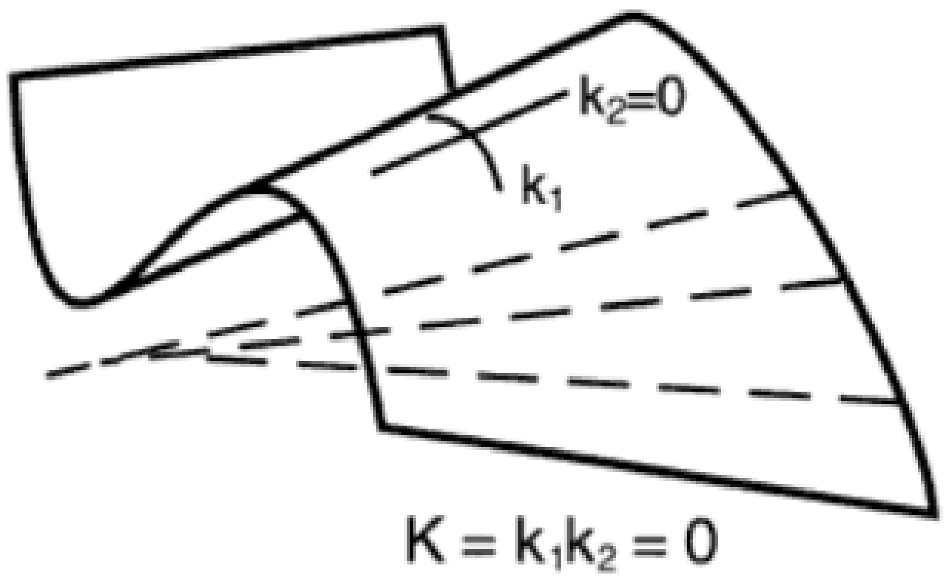
PART 2

STUDYING BENDING BEHAVIOUR OF THIN GLASS

THIN GLASS _ CLADDING SYSTEM



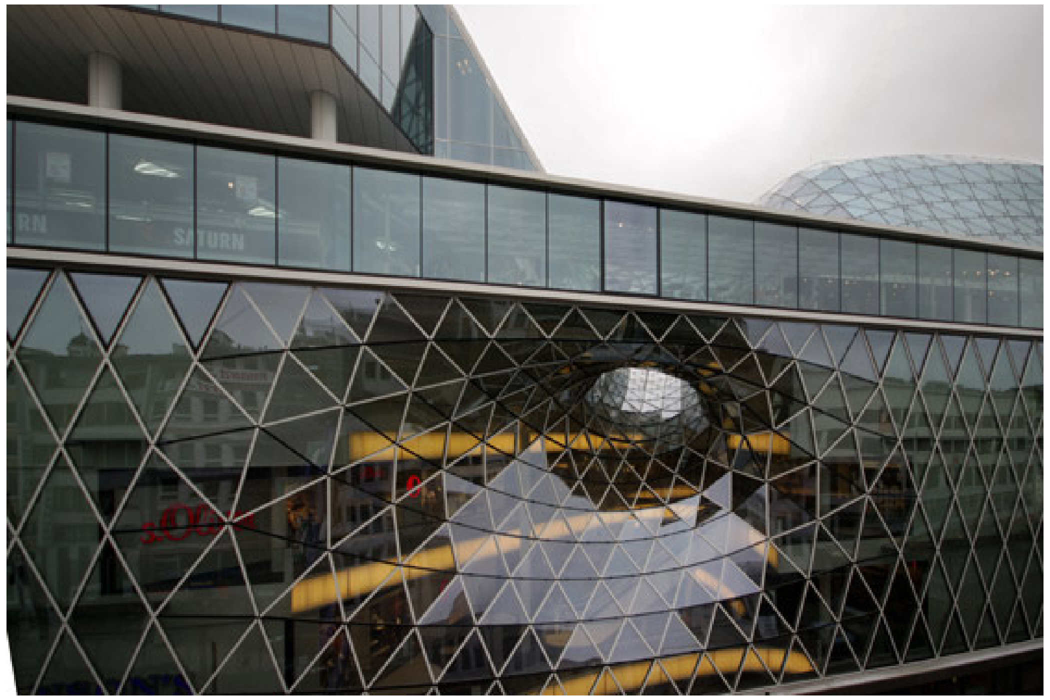
Double curved surface

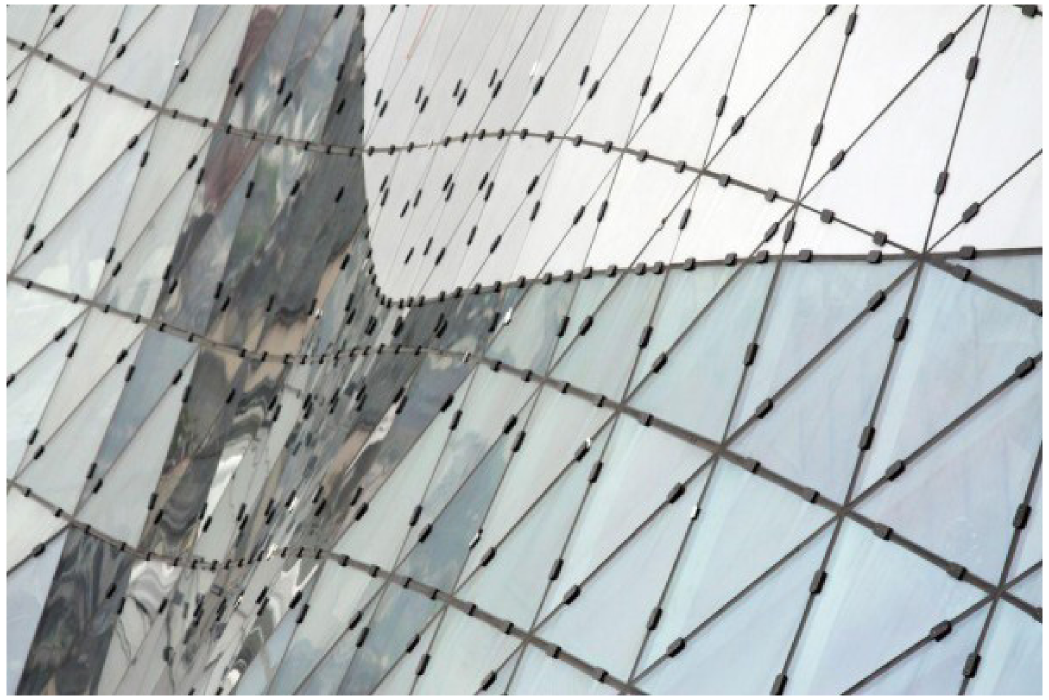


Developable surfaces

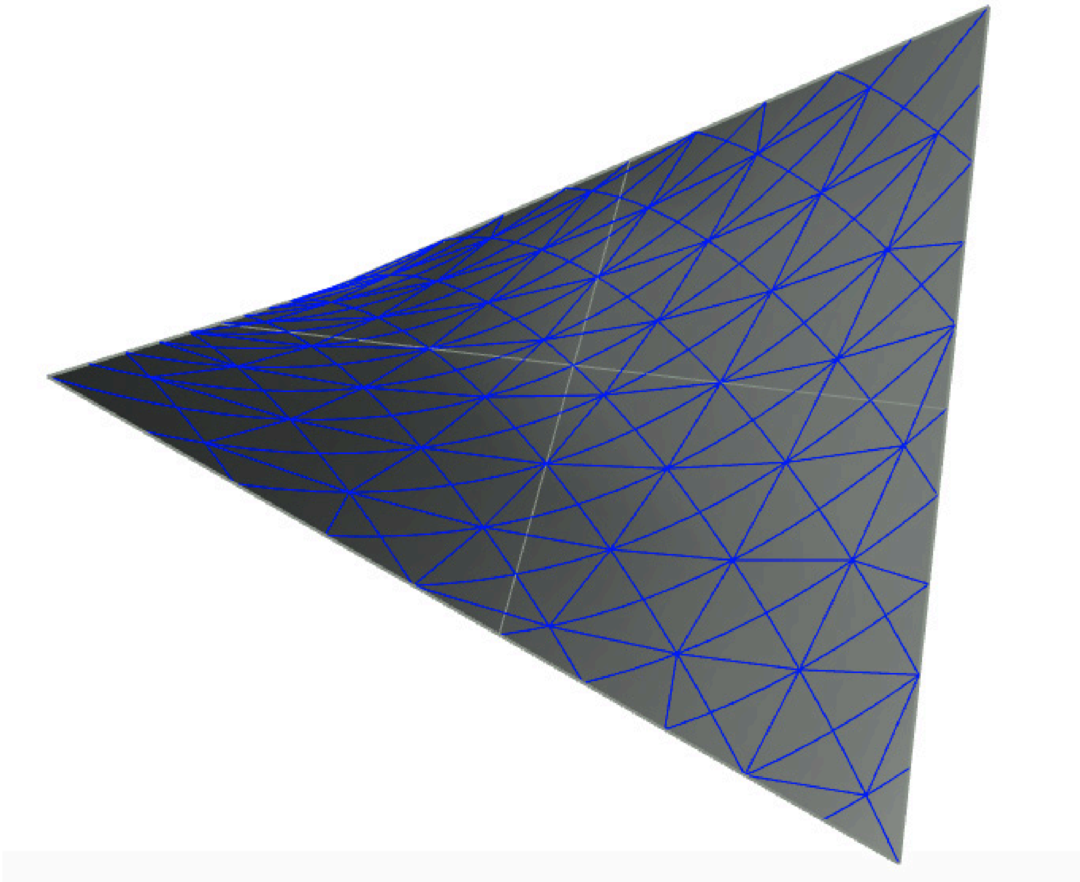
THIN GLASS _ CLADDING SYSTEM (OPTION 1)

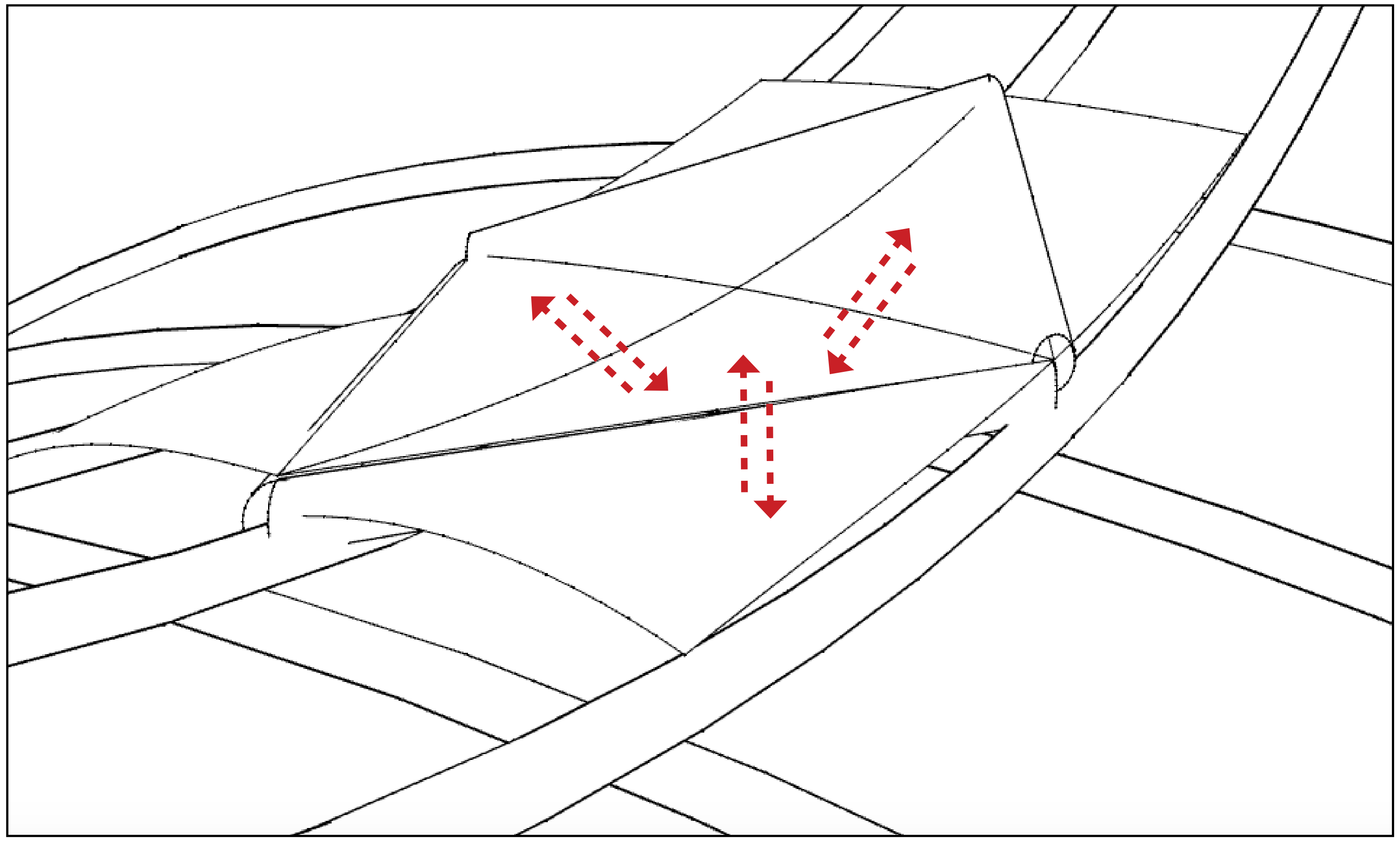
- ✗ NO ADDITIONAL MEMBERS
- ✗ CLAMPING IN ONE DIRECTION
- ✗ OVERLAP REQUIRED IN ONE OR TWO DIRECTION





MyZeil (Fuksas Studio)

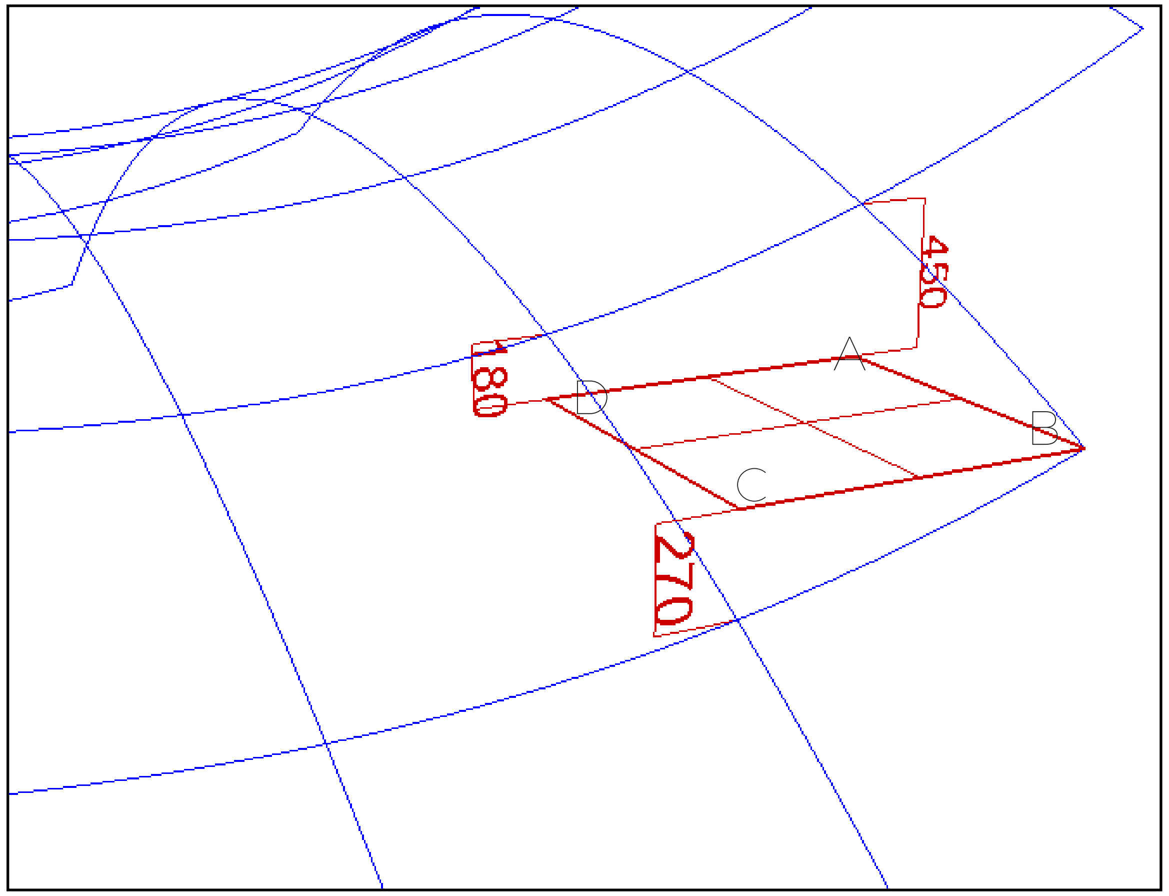


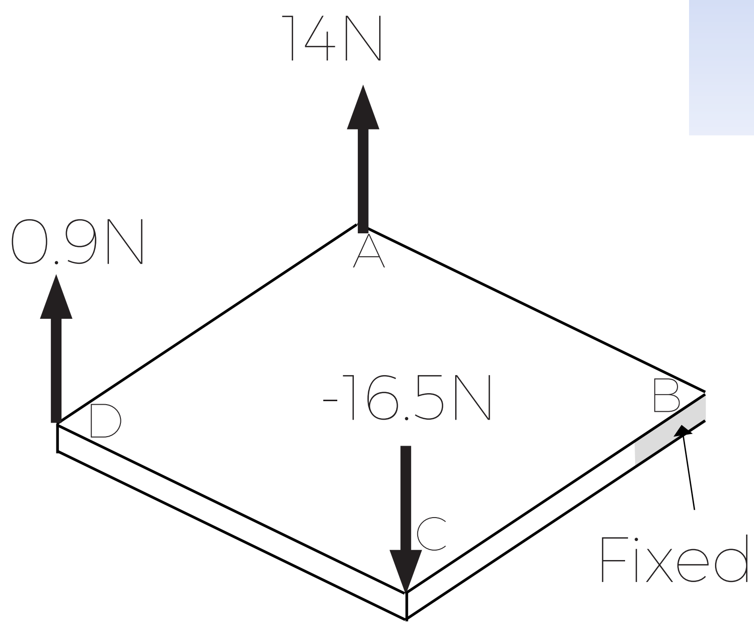


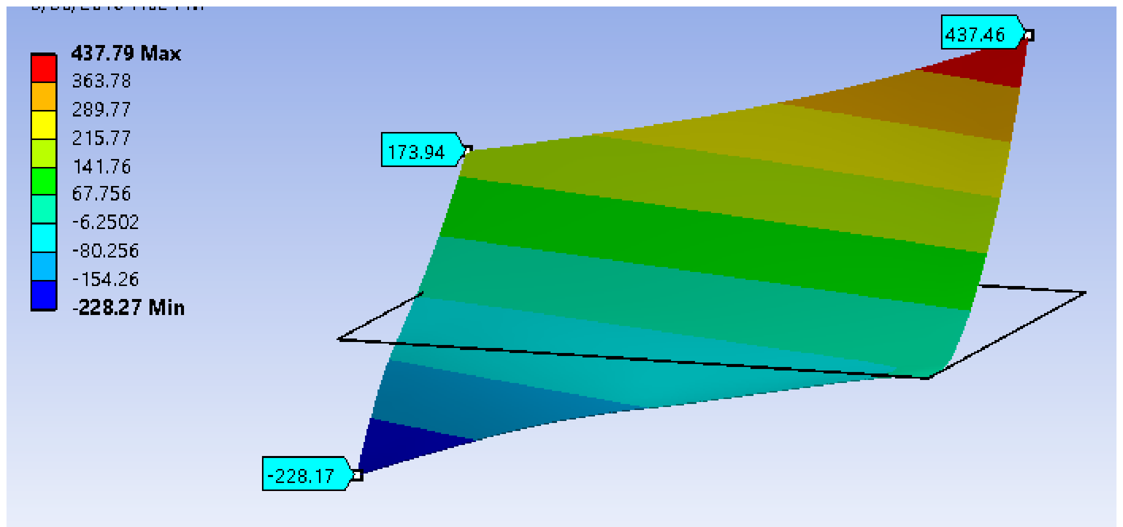
THIN GLASS _ CLADDING SYSTEM (OPTION 2)

- ✓ NO ADDITIONAL MEMBERS
- ✗ CLAMPING IN ONE DIRECTION
- ✗ OVERLAP REQUIRED IN ONE OR TWO DIRECTION

Twisted surface



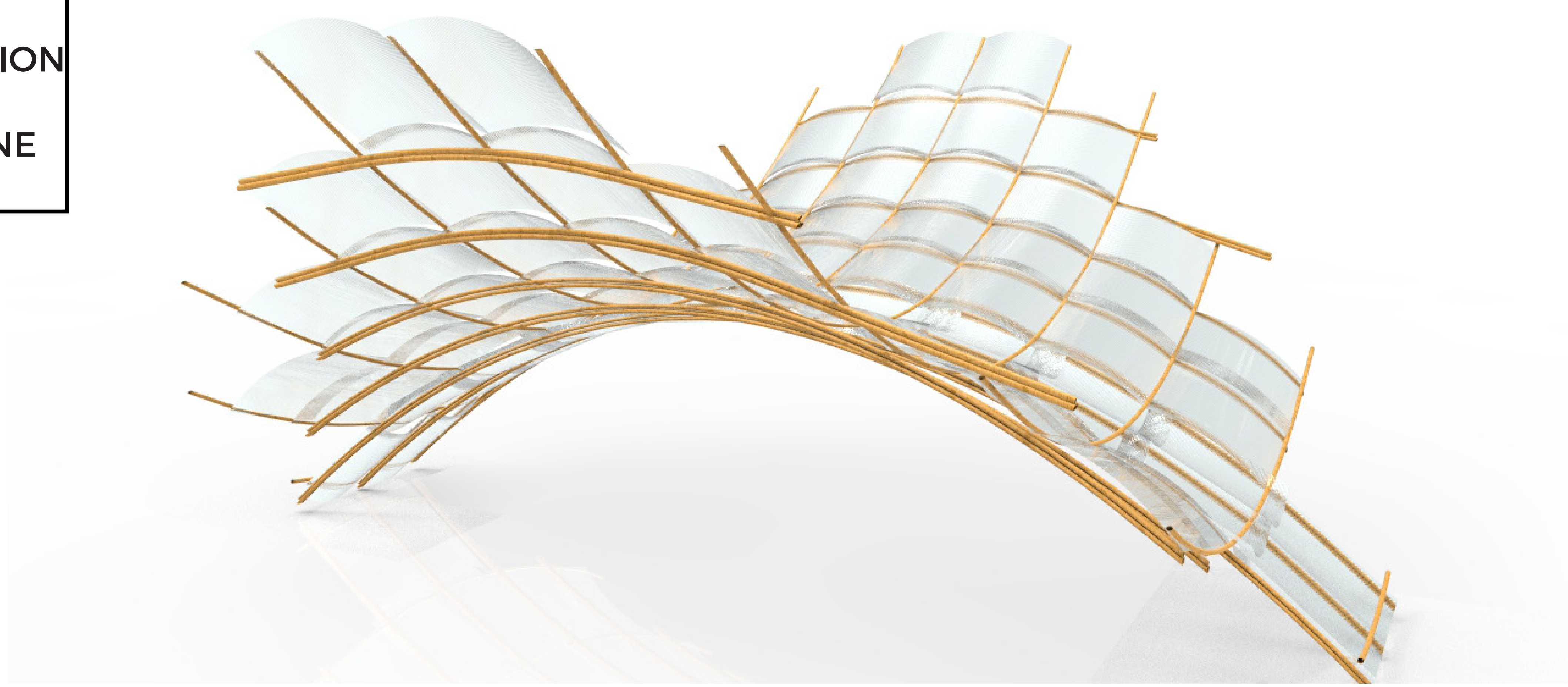


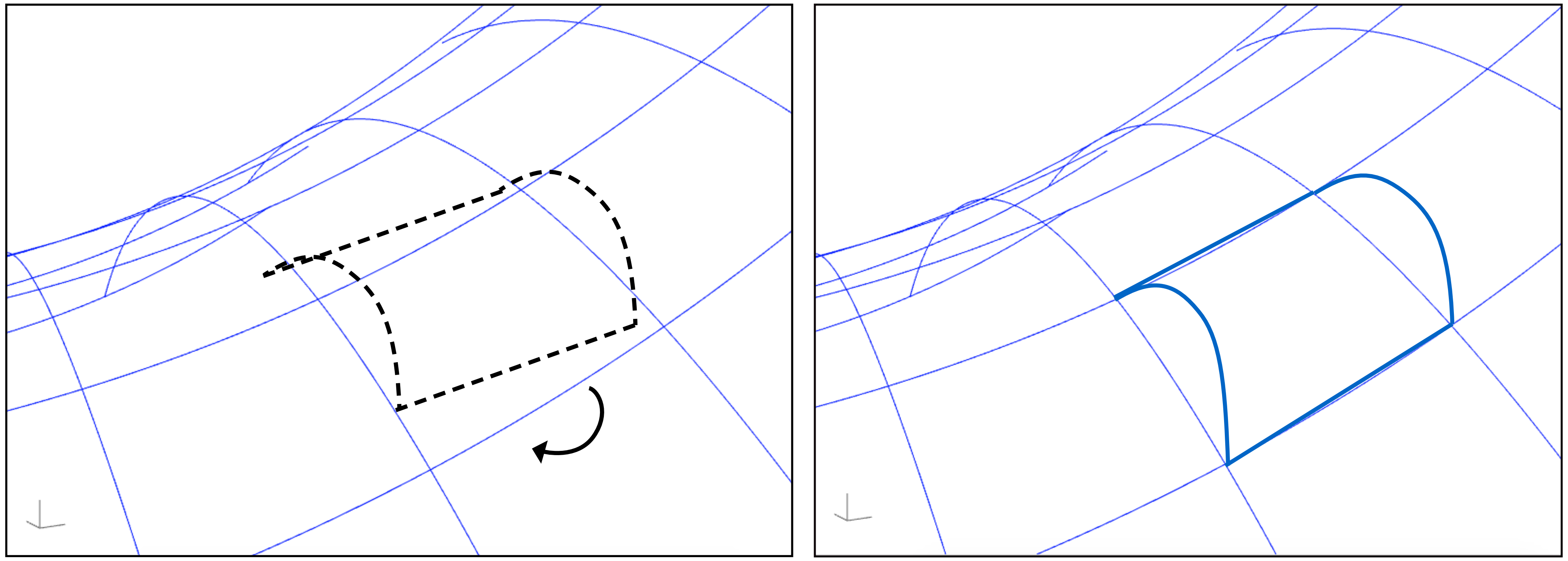


Deflection Δ_{zz}

THIN GLASS _ CLADDING SYSTEM (OPTION 3)

- NO ADDITIONAL MEMBERS
- CLAMPING IN ONE DIRECTION
- OVERLAP REQUIRED IN ONE OR TWO DIRECTION

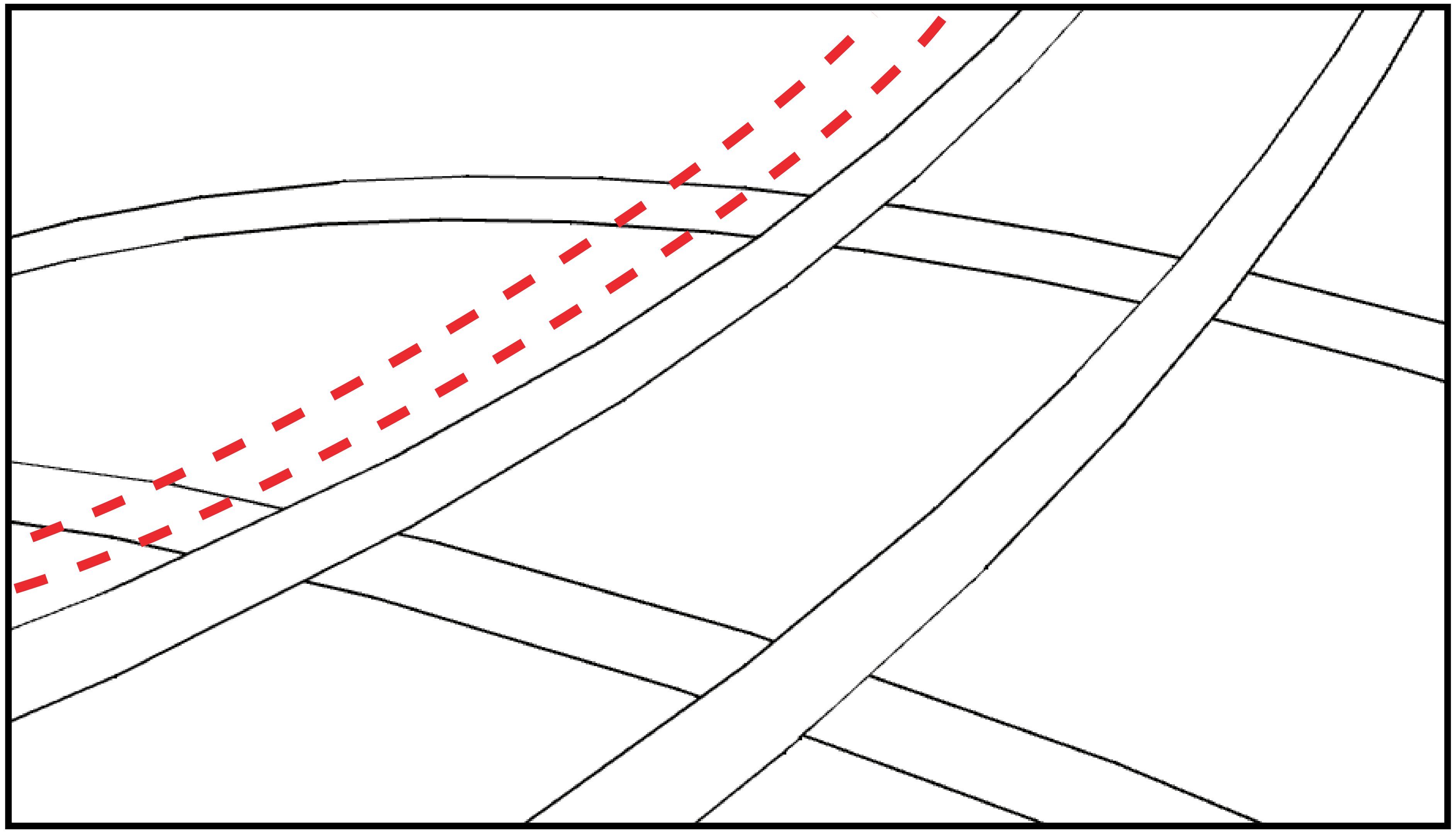




Double curved surface

PROBLEMS AND CHALLENGES

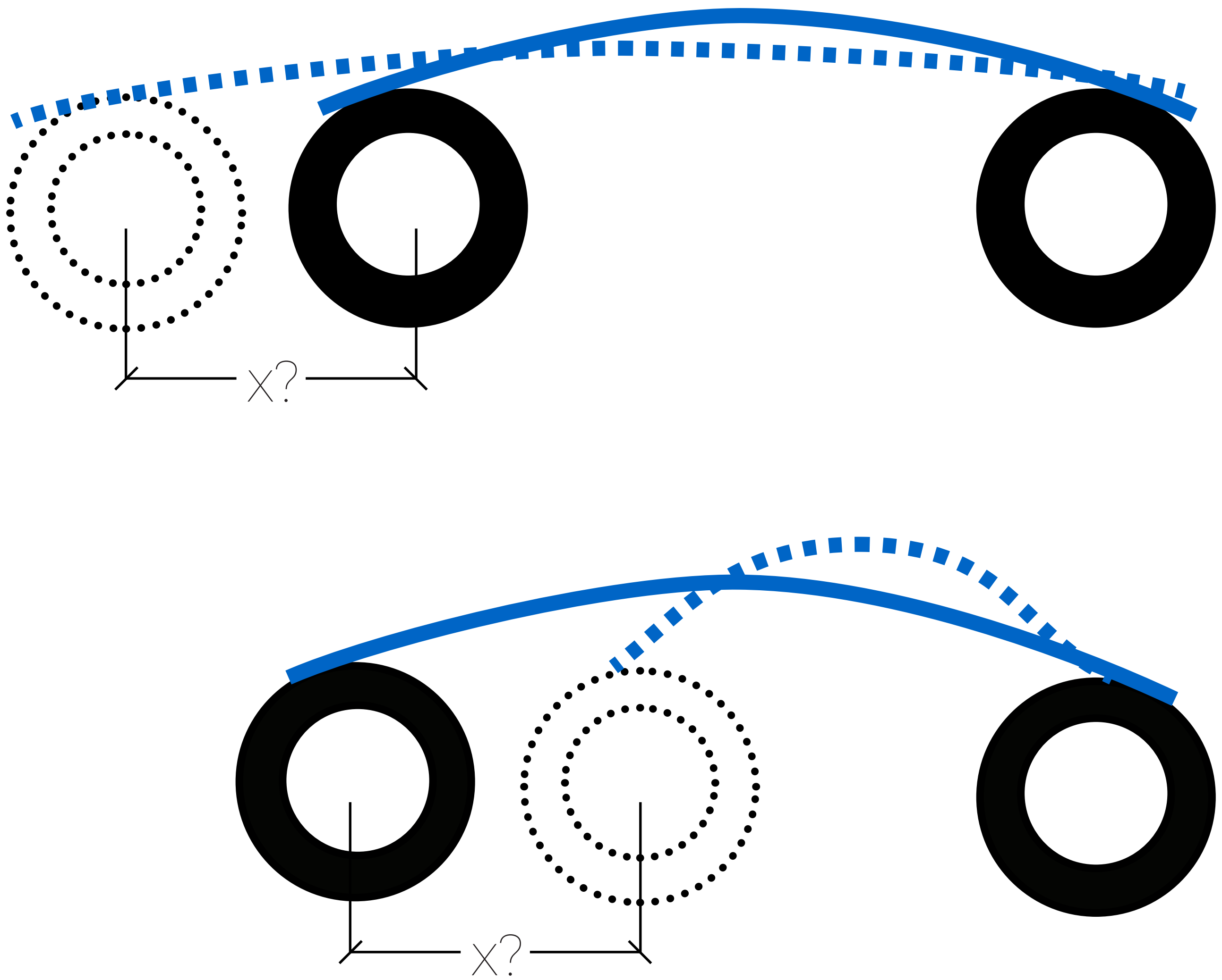
Tolerances due to:



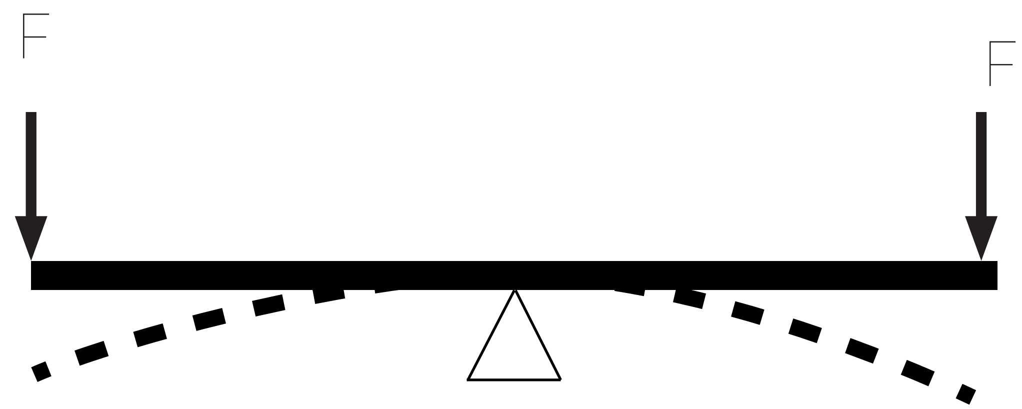
Grid difference

Cladding to accommodate tolerances.

- Cold Bending glass on site. Keeping the curvature of the glass varying to adjust the grid difference.



THIN GLASS | BENDING ANALYSIS



Thin Glass Properties:

Density: 2.48g/cm³
Young's Modulus: 74GPA
Poisson's Ratio: 0.23

PVB Properties:

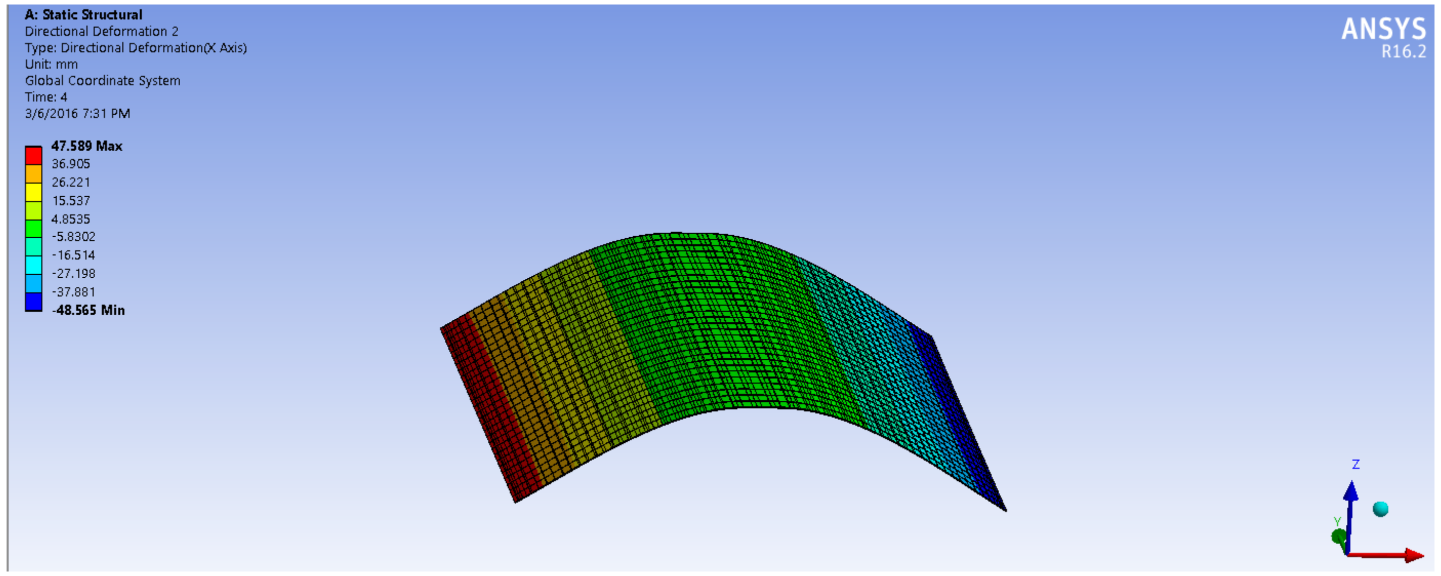
Density: 1.07g/cm³
Young's Modulus: 2.36MPA
Poisson's Ratio: 0.45
Multi-linear elasticity:

ε [-]	σ [N/mm^2]	ε [-]	σ [N/mm^2]	ε [-]	σ [N/mm^2]
0.1	0.98	1.1	17.45	2.1	73.86
0.2	1.96	1.2	20.61	2.2	82.08
0.3	2.93	1.3	24.24	2.3	90.46
0.4	3.91	1.4	28.39	2.4	99.07
0.5	5.32	1.5	33.11	2.5	108.03
0.6	7.11	1.6	38.49	2.6	117.46
0.7	8.55	1.7	44.51	2.7	127.55
0.8	10.27	1.8	51.13	2.8	138.34
0.9	12.31	1.9	58.28	2.9	149.13
1	14.69	2	65.89	3	159.30

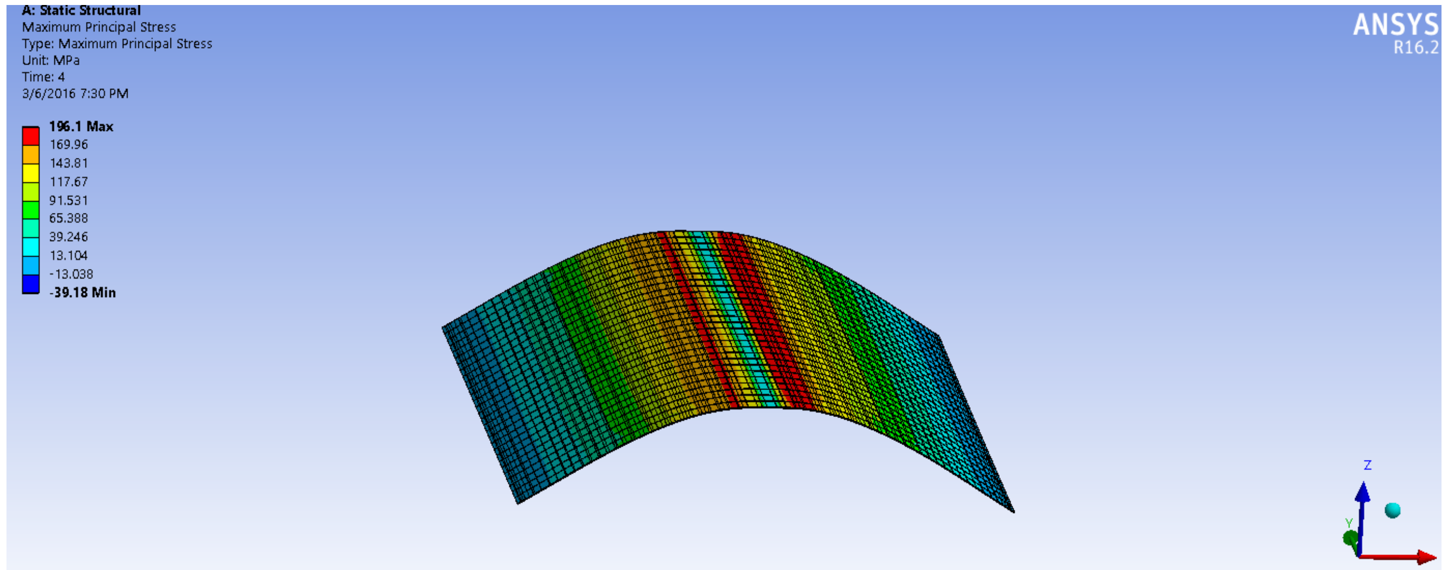
ref: Finite element analysis of laminated structural glass plates with polyvinyl butyral (PVB) interlayer.
Gergely Molnár / László Gergely Vigh / György Stocker / László Dunai

THIN GLASS | BENDING ANALYSIS

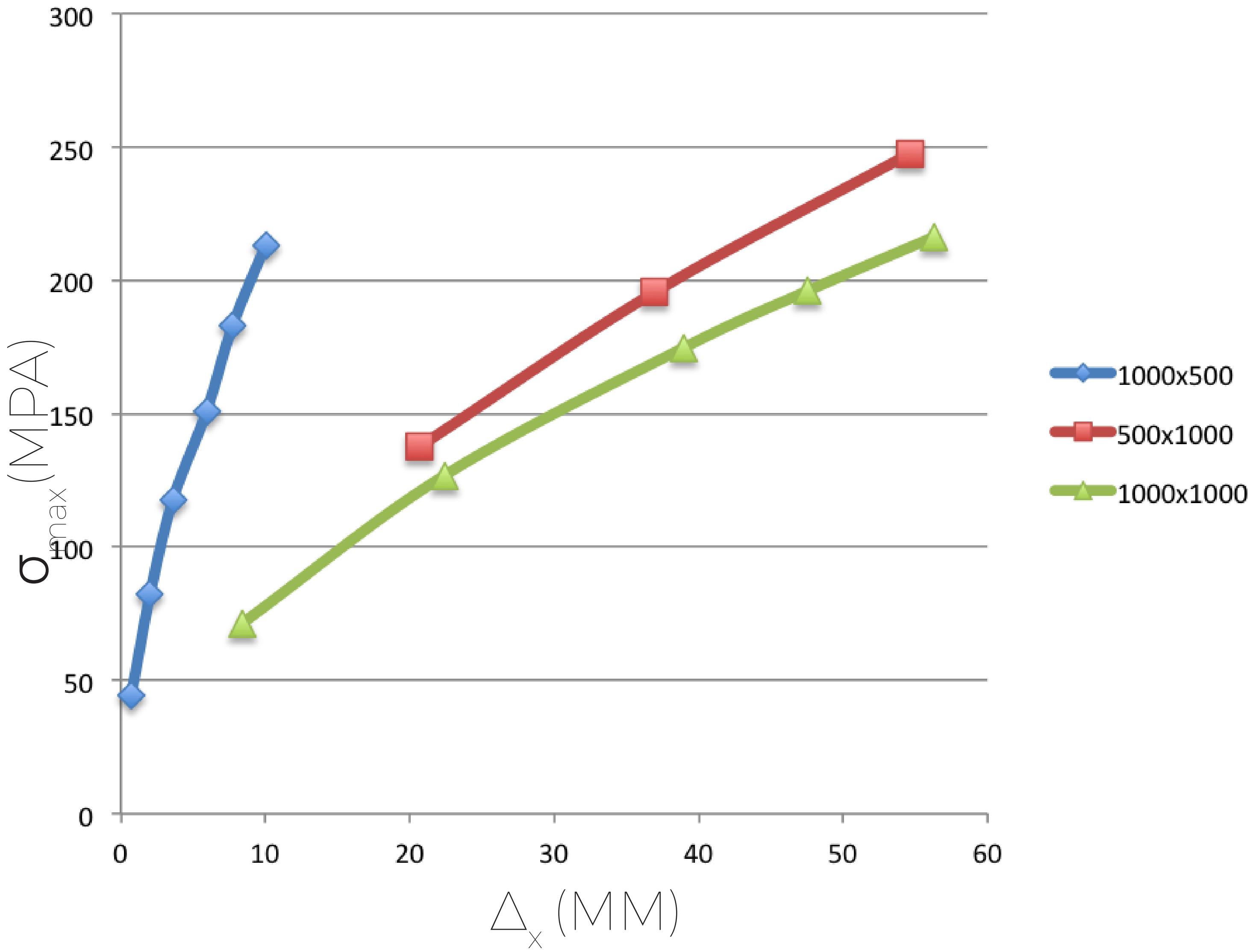
PANEL SIZE



Δ_x = 47.58 MM

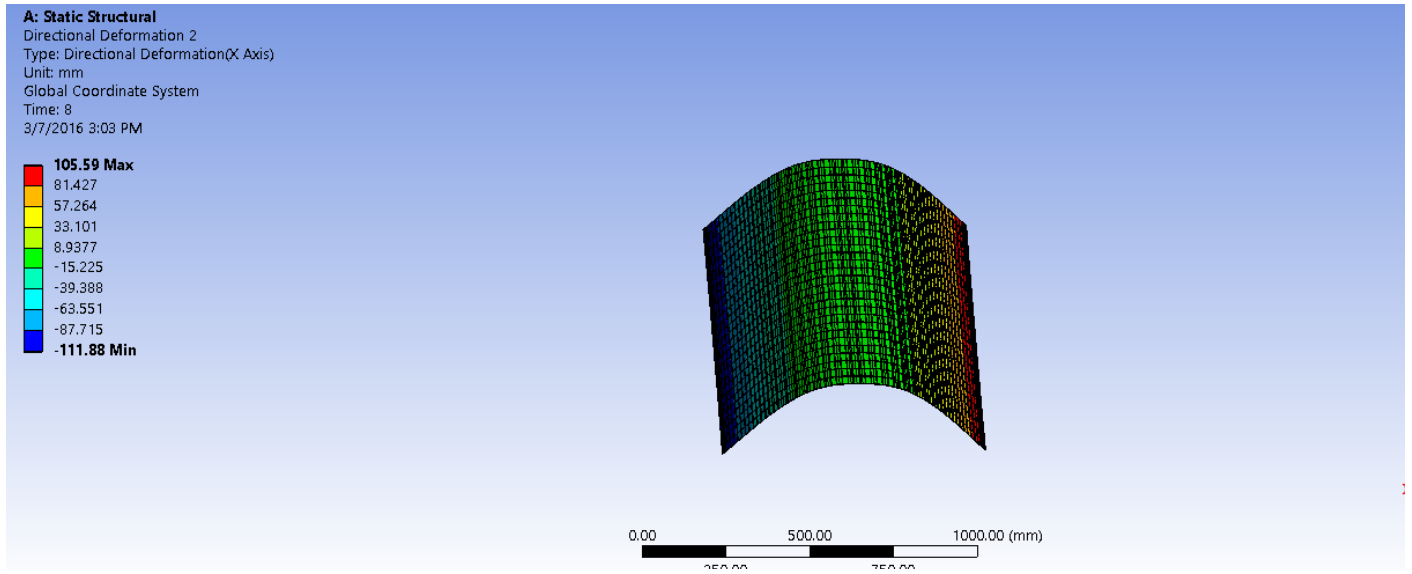


σ_{max} = 196 MPa

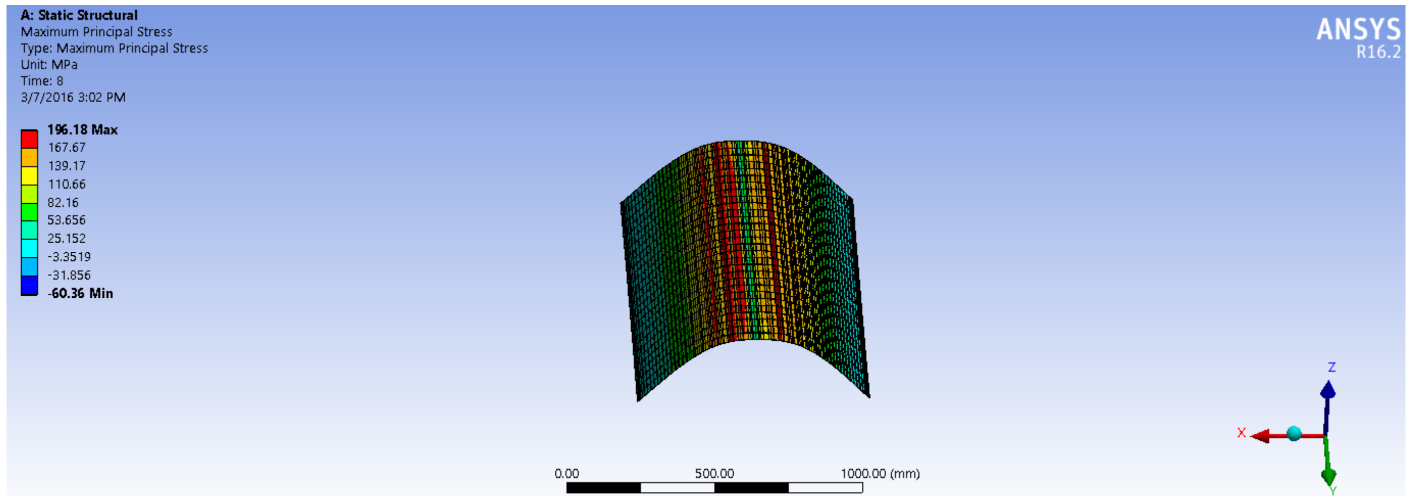


THIN GLASS | BENDING ANALYSIS

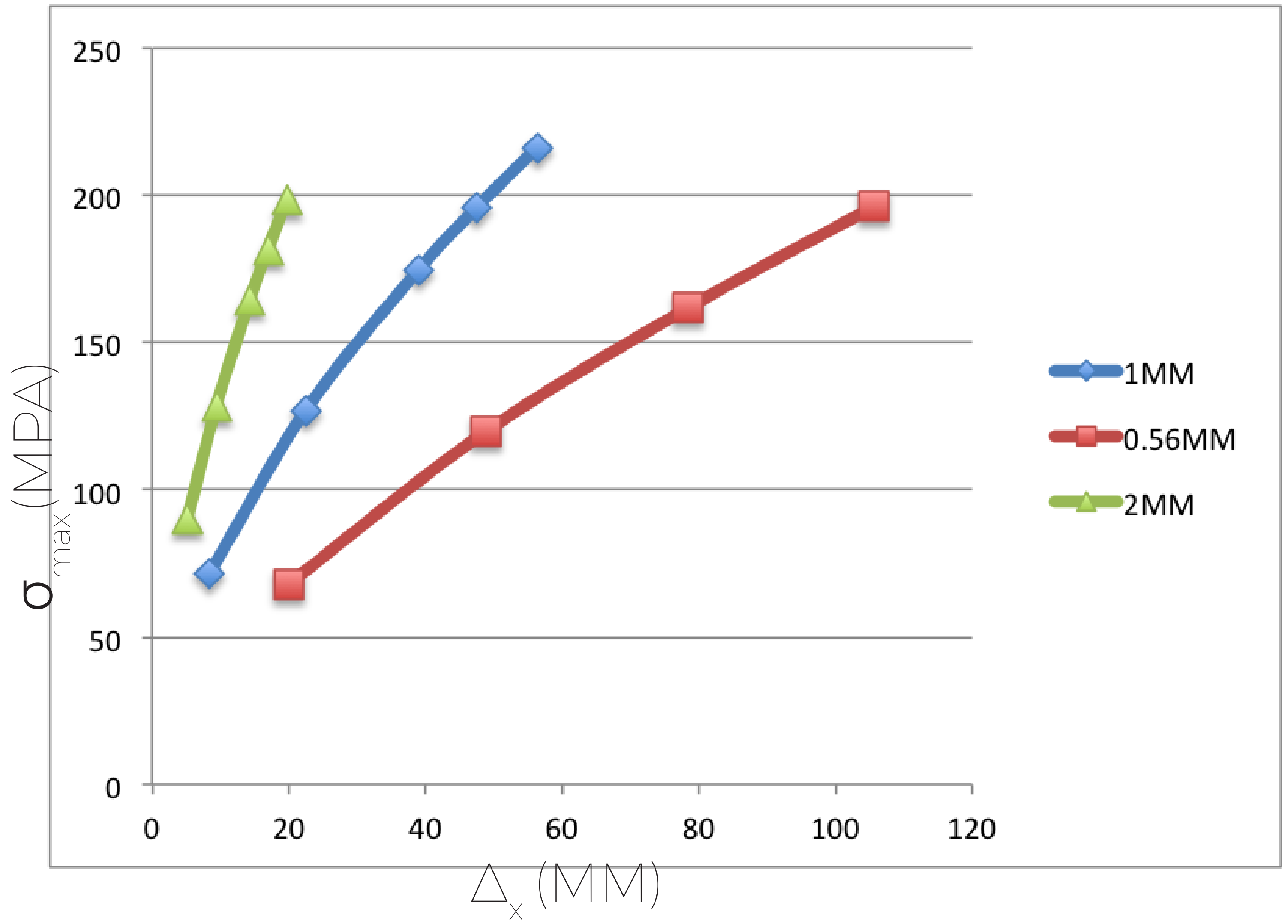
GLASS THICKNESS



Δ_x = 47.58MM

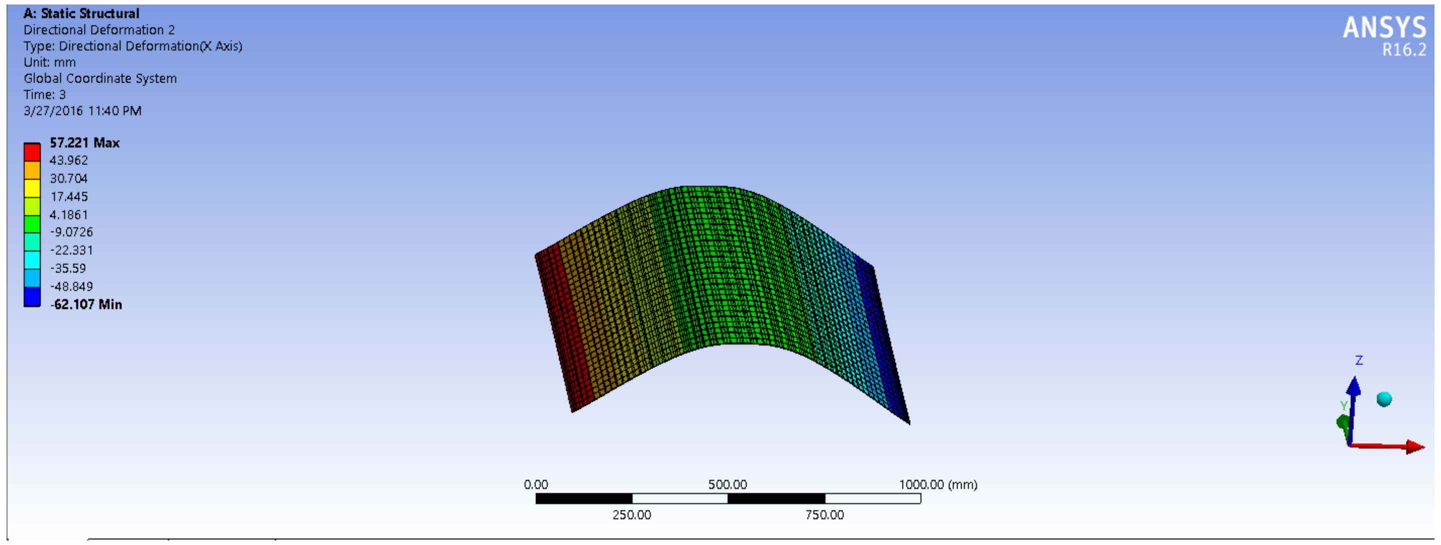


σ_{max} = 196MPA

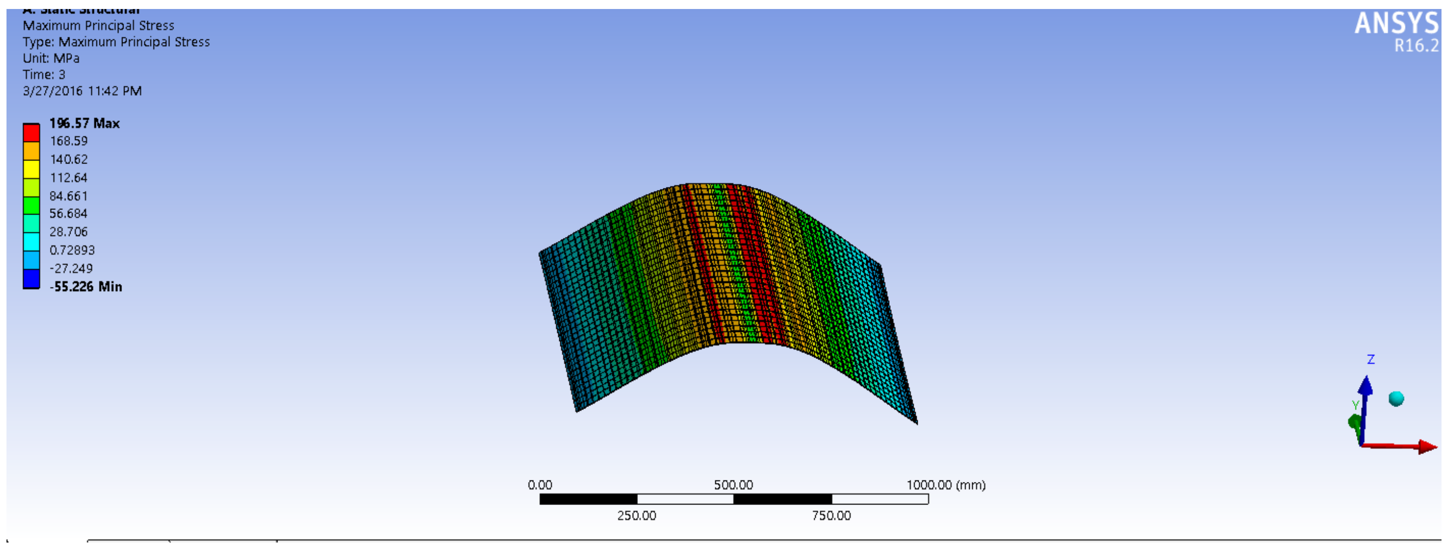


THIN GLASS | BENDING ANALYSIS

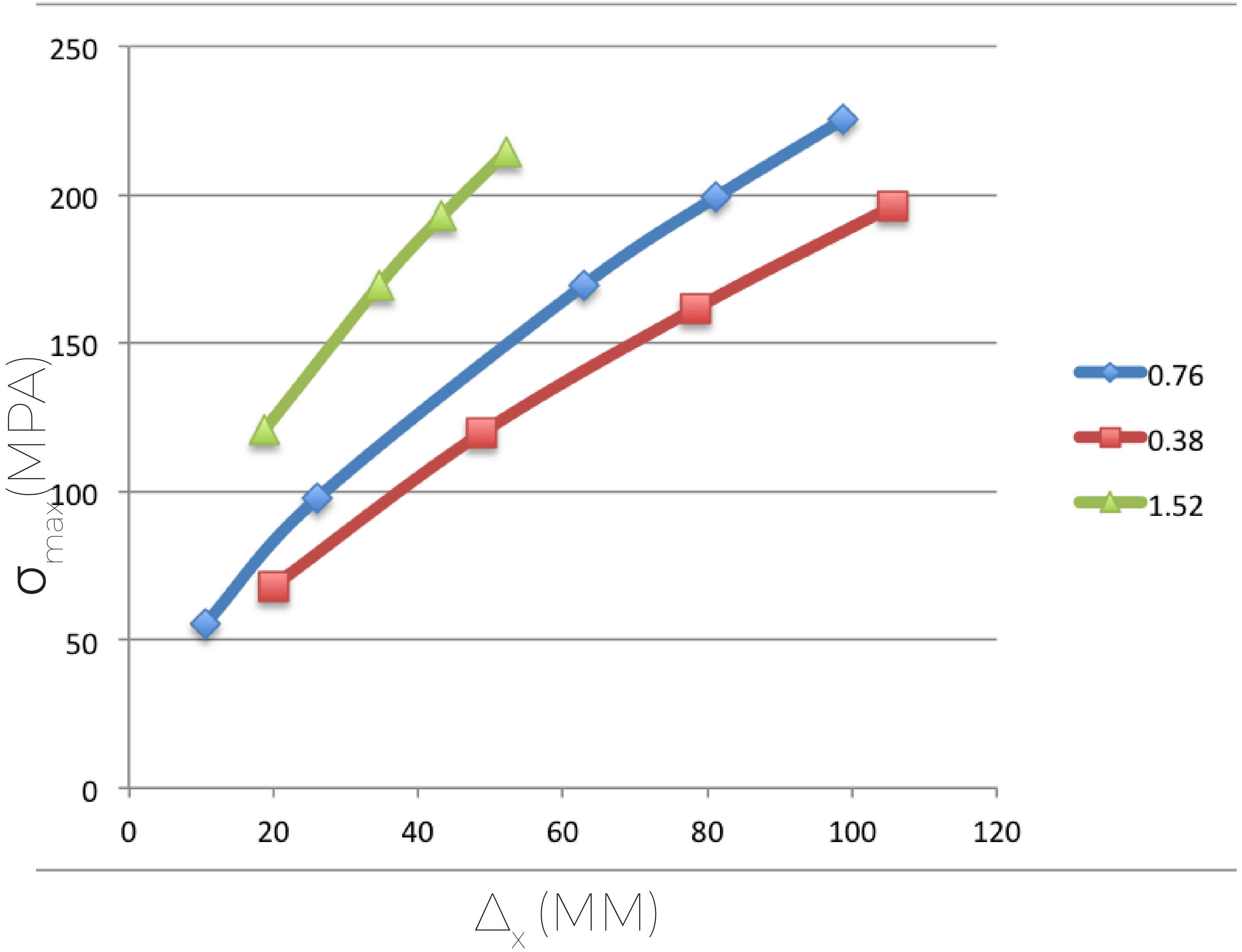
PVB THICKNESS



Δ_x = 57.22mm



σ_{max} = 196.57MPa



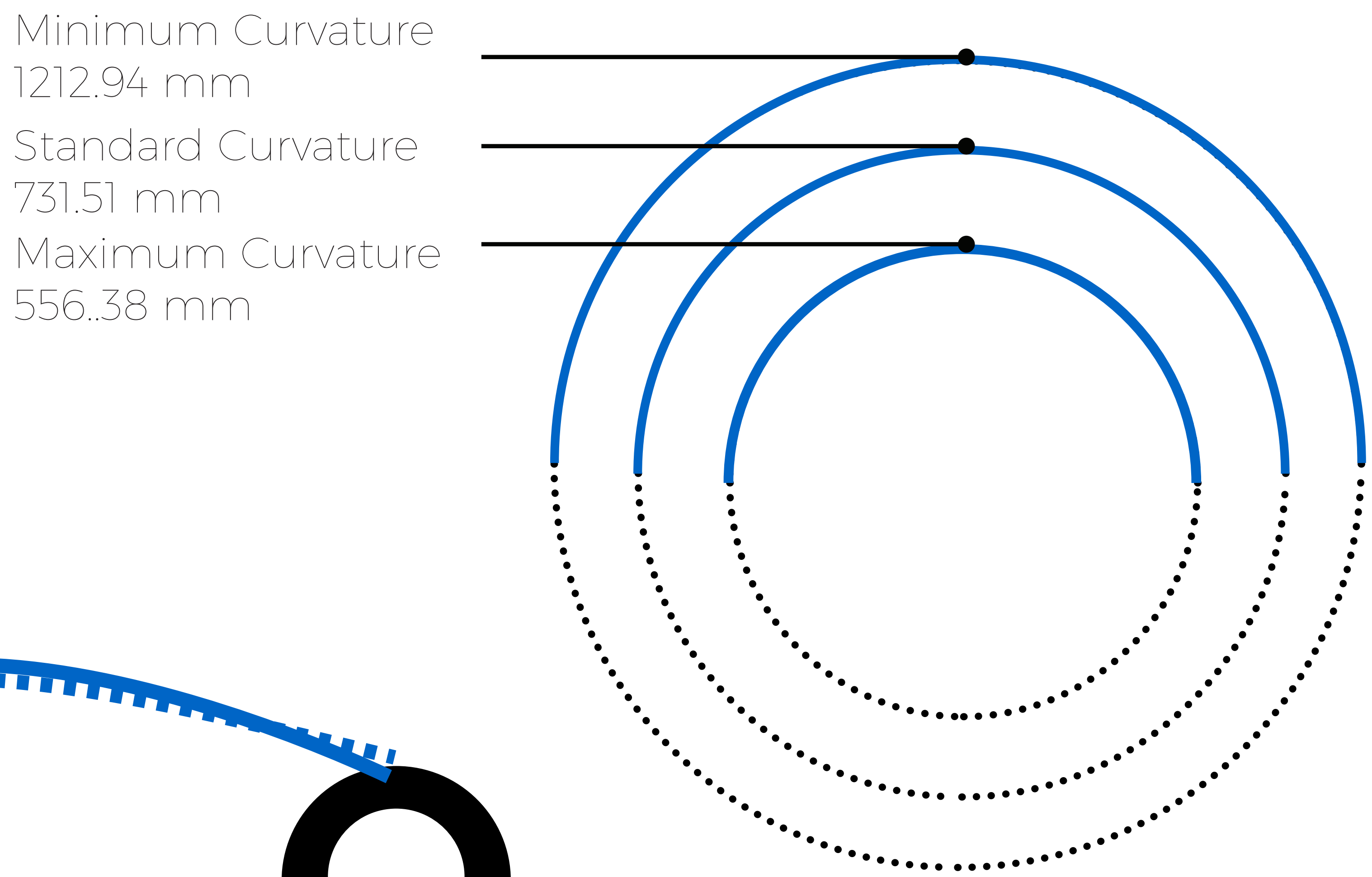
THIN GLASS BENDING CONCLUSION

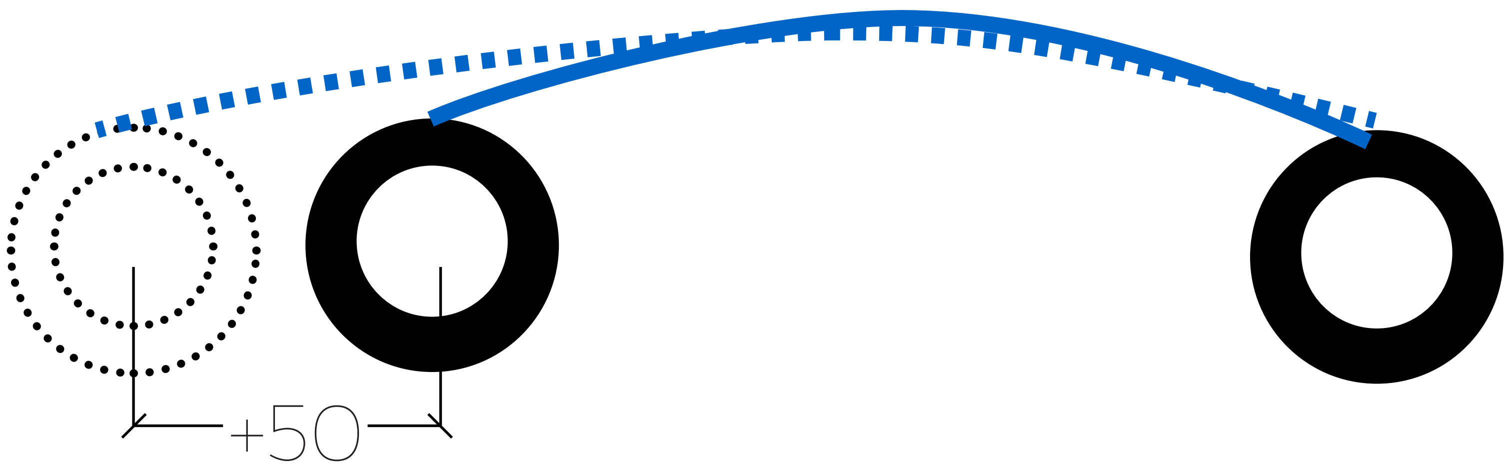
Glass Panel

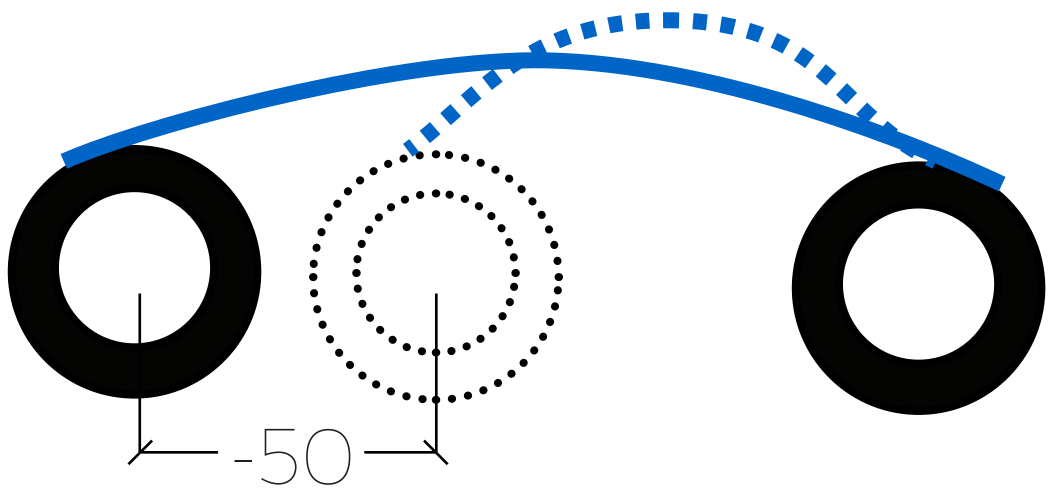
Size: 1000x1000mm

Glass thickness: 0.56mm

PVB thickness: 1.14mm







PART 3

TO DEVELOP CONNECTIONS BASED ON DRAWBACKS AND STRENGTH OF BAMBOO AND THIN GLASS

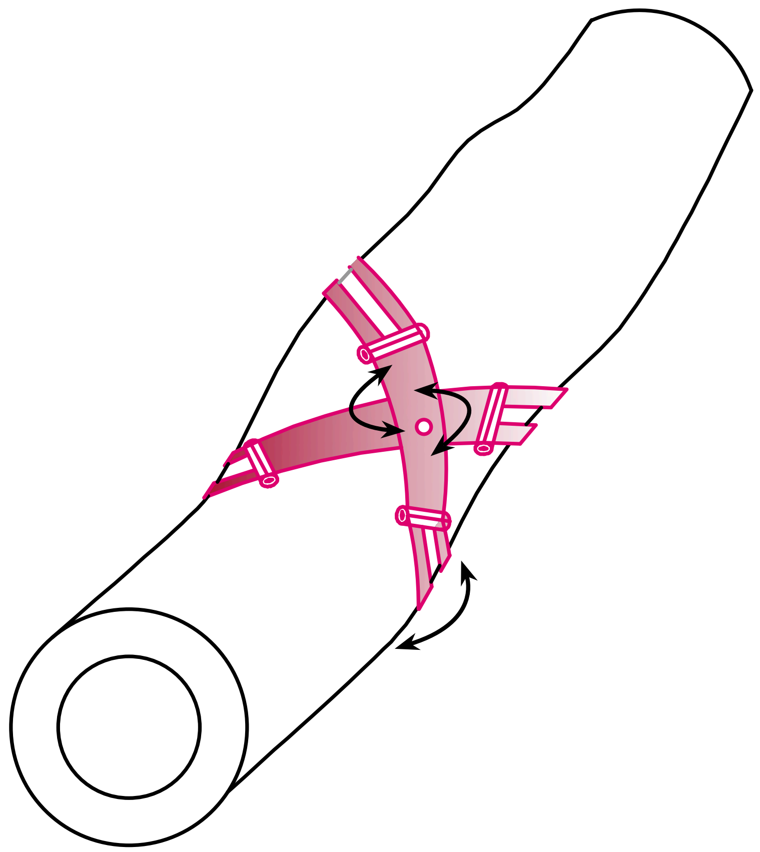
CONNECTION CRITERIA

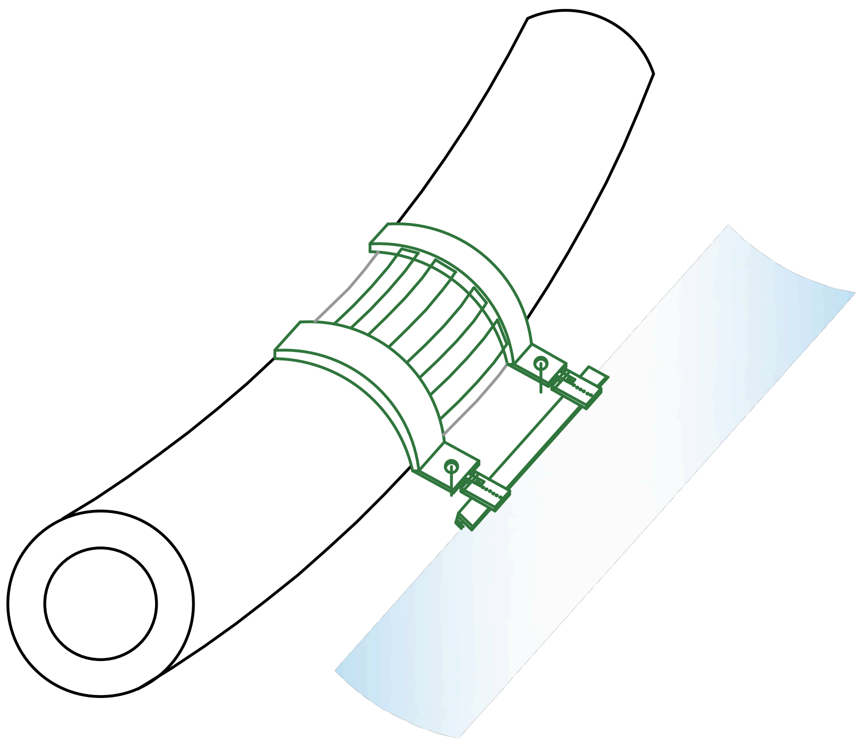
Bamboo connection
using hemp rope
ref: (Jaap Overal)

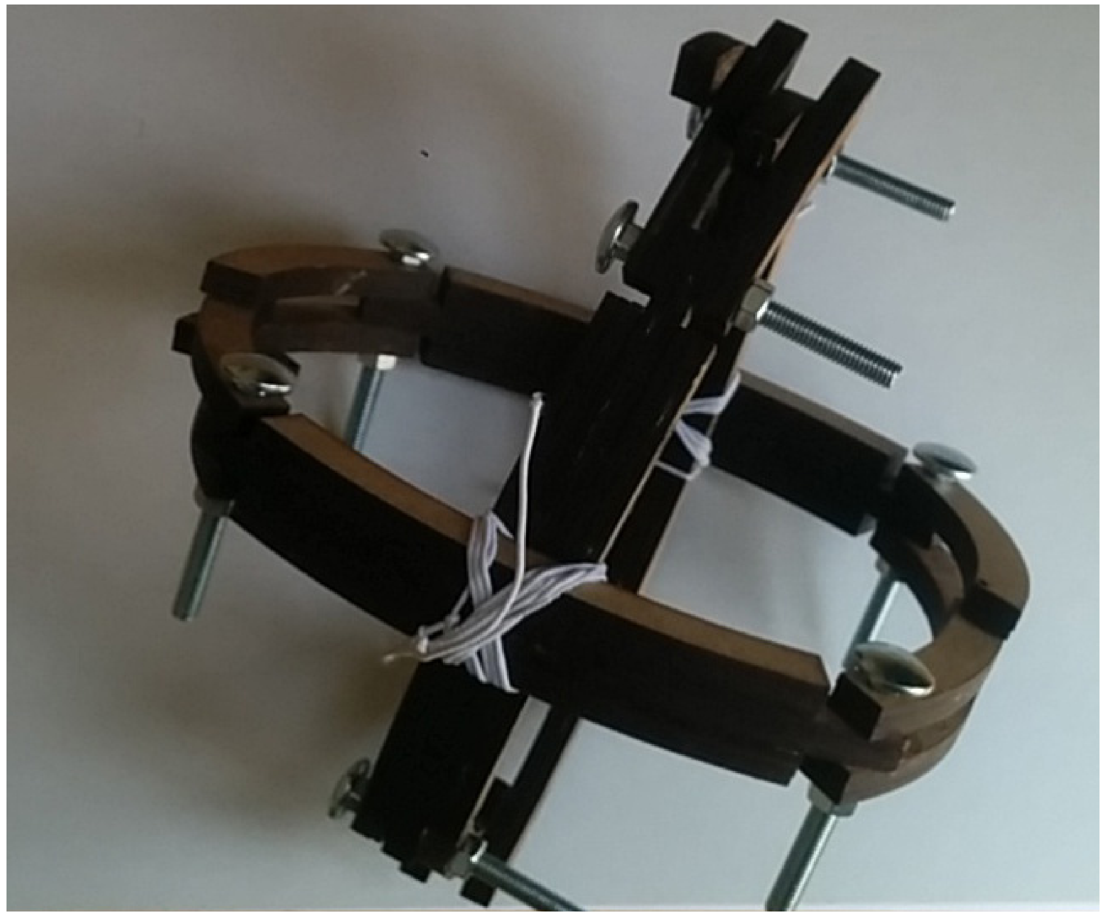
Bamboo connection using bolts
ref: (Chris Davies)

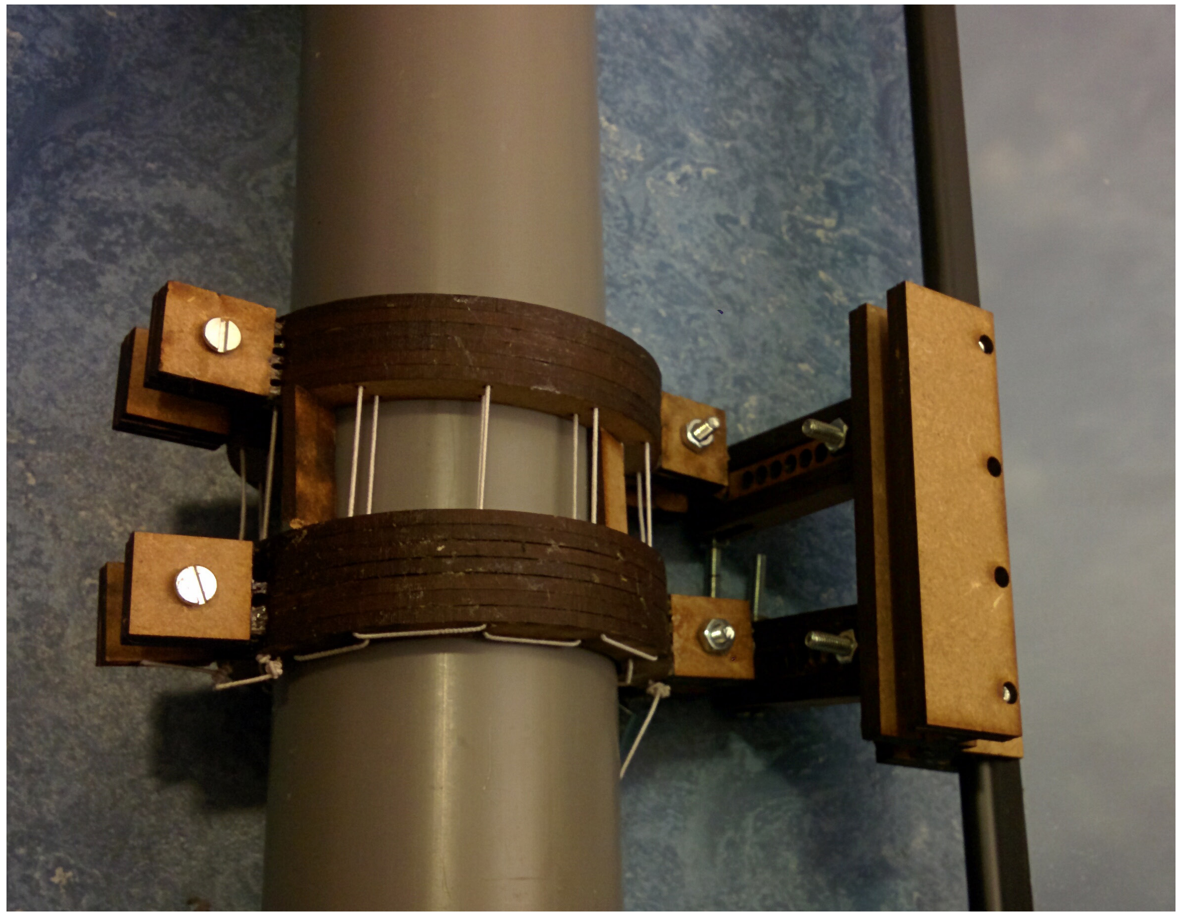
Bamboo connection using composite rope
ref: (Jaap Overal)

MECHANICAL FIXTURES









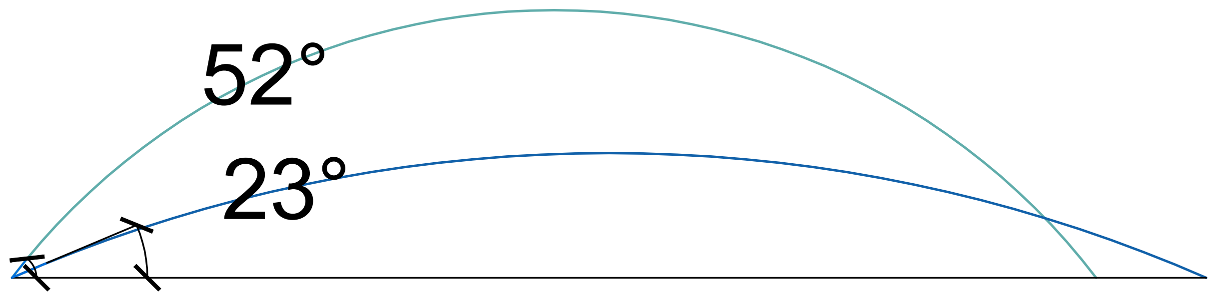
CONNECTION CRITERIA

WATEPROOF / WATER TIGHT
- Overlaping panels (both directions)
- Water tight joints

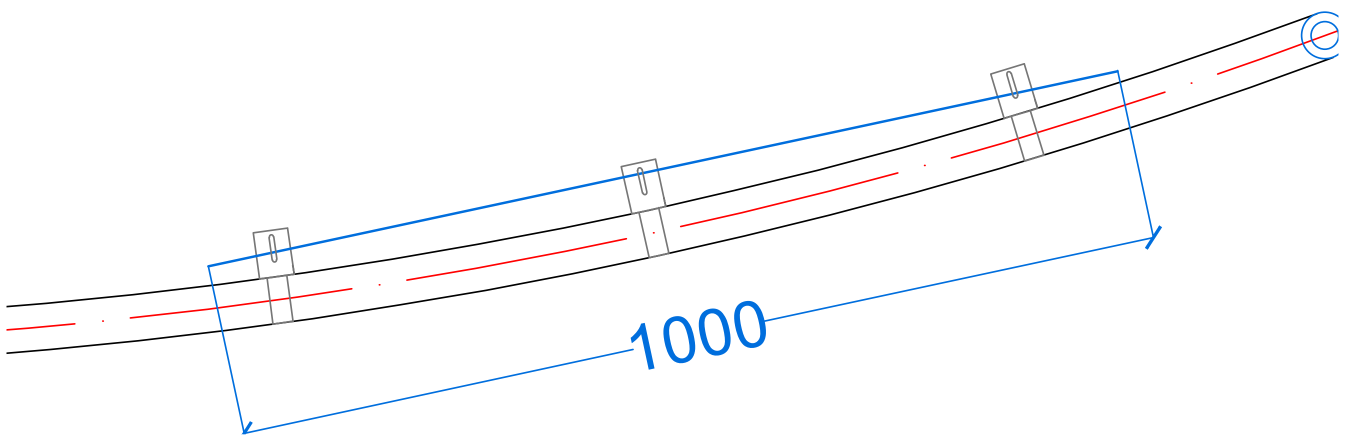
TOLERANCE
- Varying bamboo grid distance

DEGREE OF FREEDOM.
- Allow glass to extend or bend.
- Vertical movement of glass clamps required.

CLAMPING ONLY IN ONE DIRECTION (TWO PARALLEL SIDES)
- To reduce labour, cost and avoid complexities.

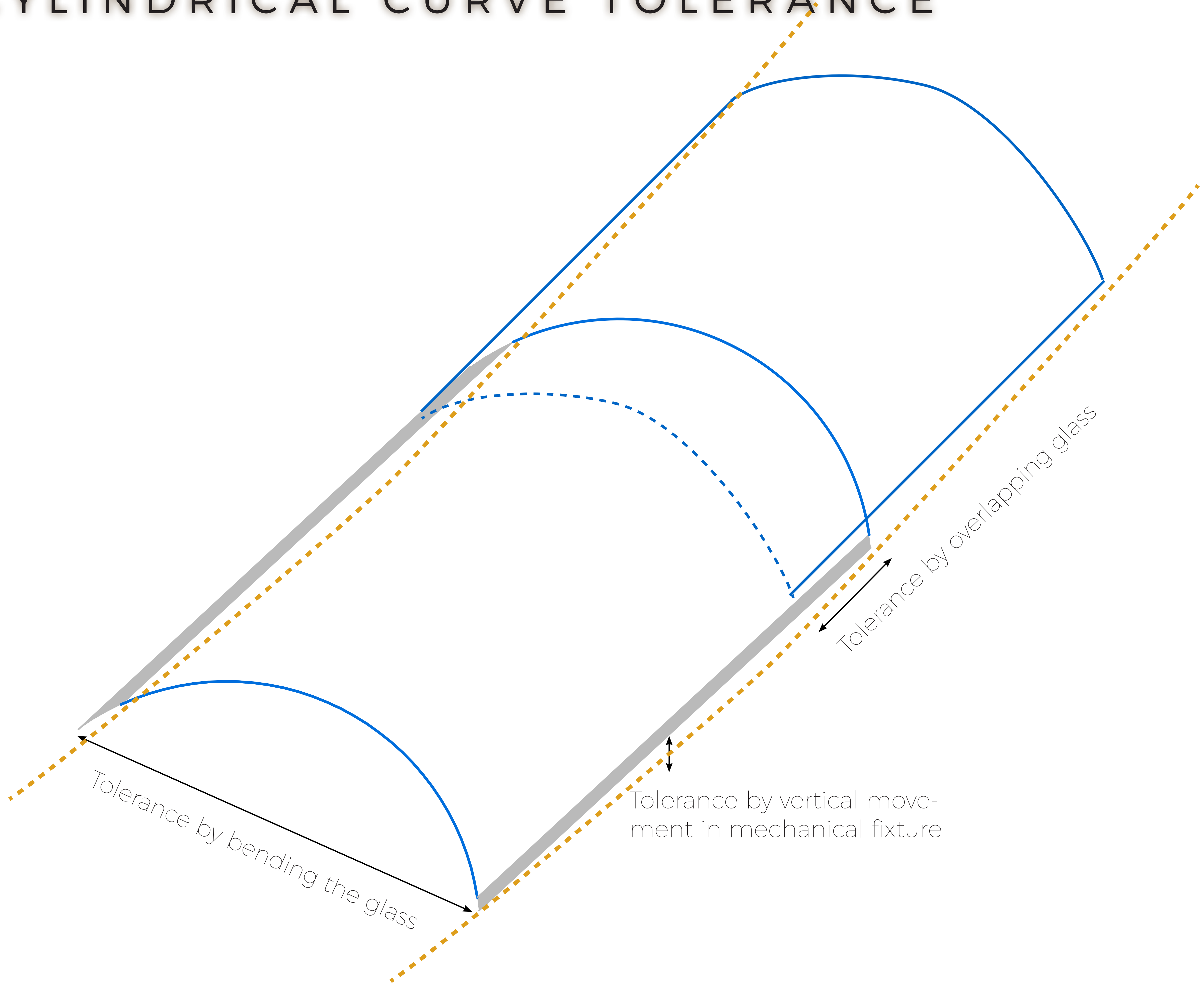


Maximum and minimum curvature of thin glass



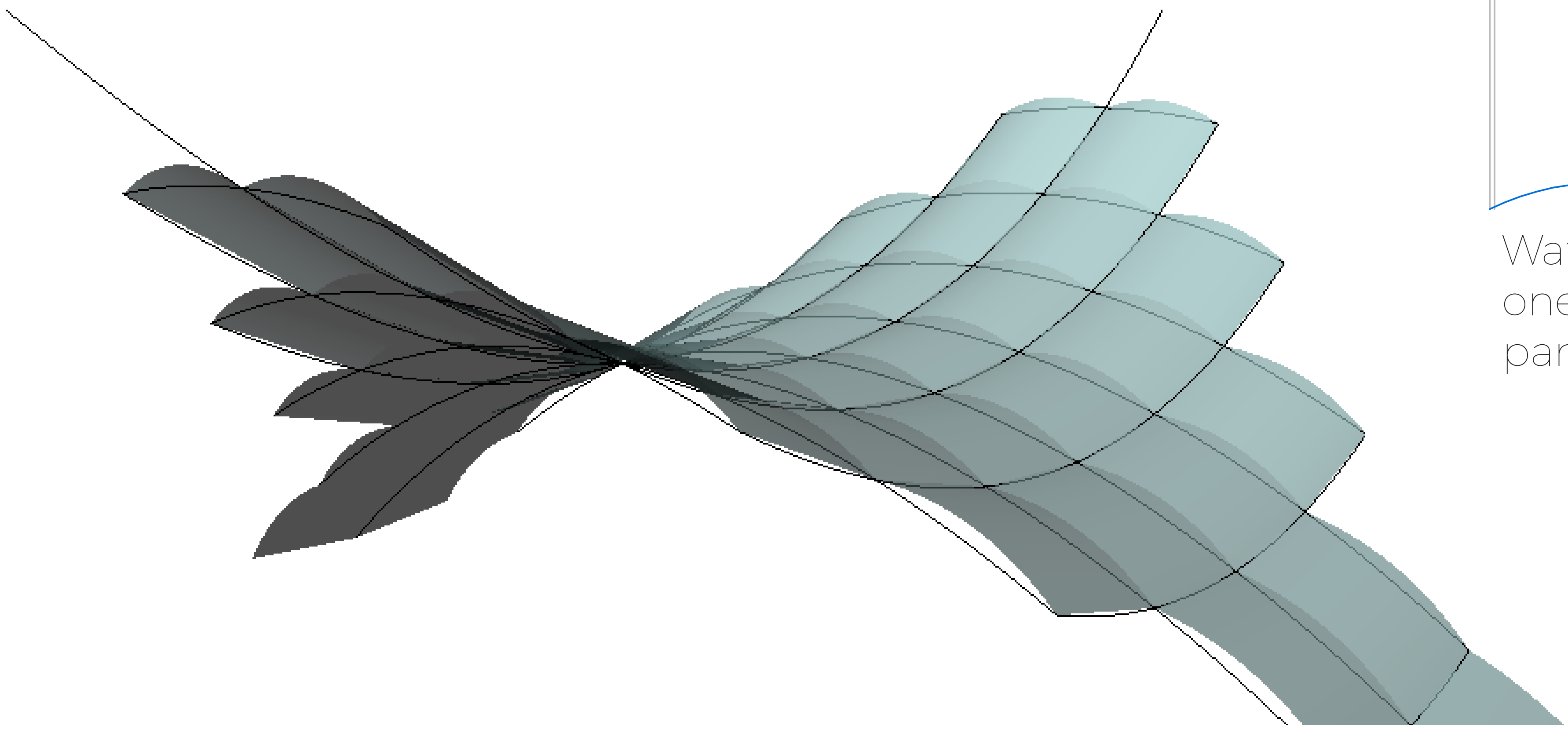
Glass panel attached at different levels

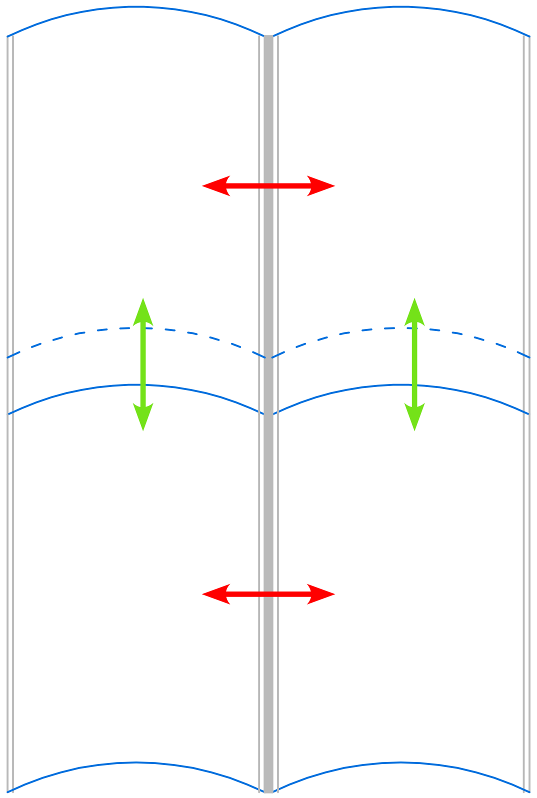
CYLINDRICAL CURVE TOLERANCE



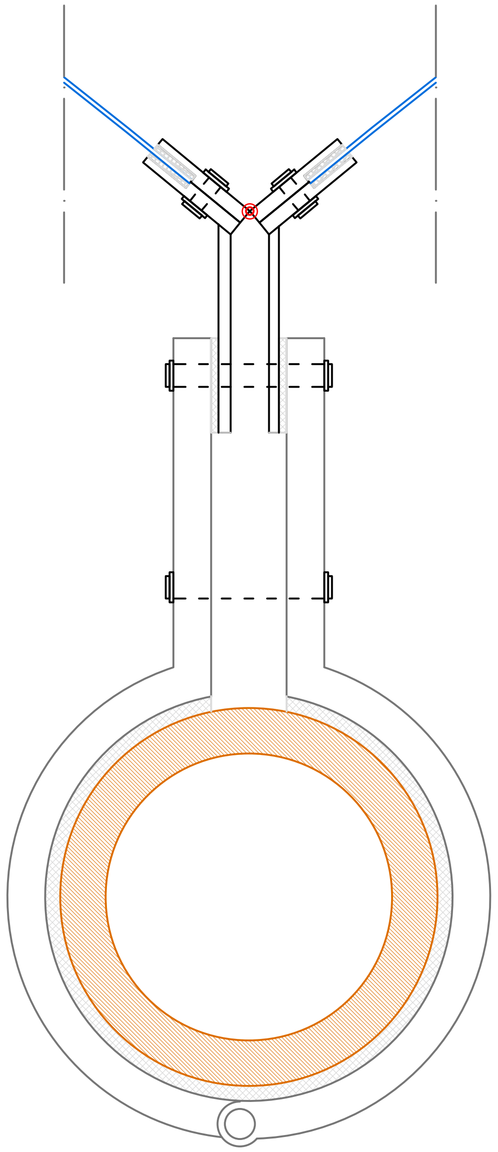
CYLINDRICAL CURVE (OPTION 1)

- ✗ WATER PROOF
- ✓ TOLERANCE
- ✓ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION

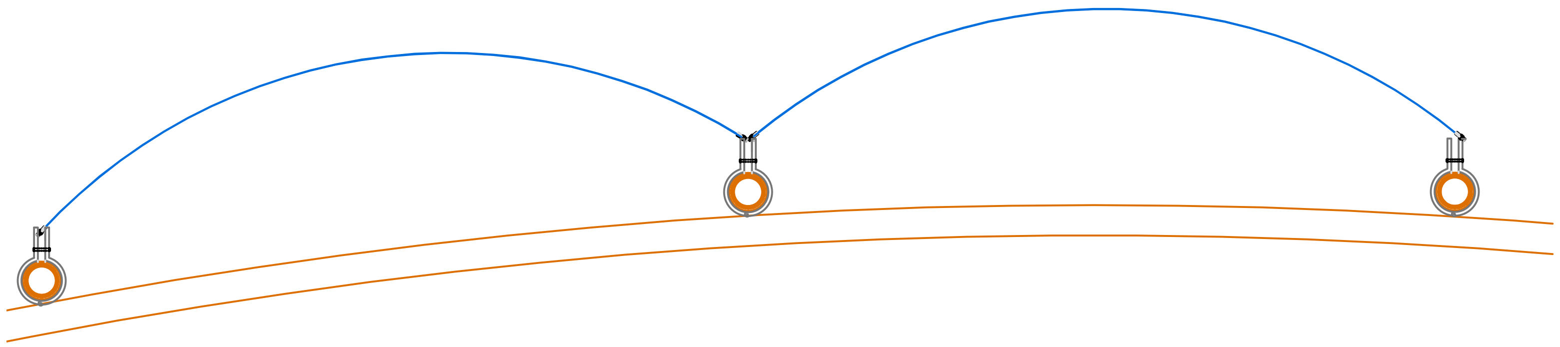




Waterproofing only in one direction, where panels overlap.



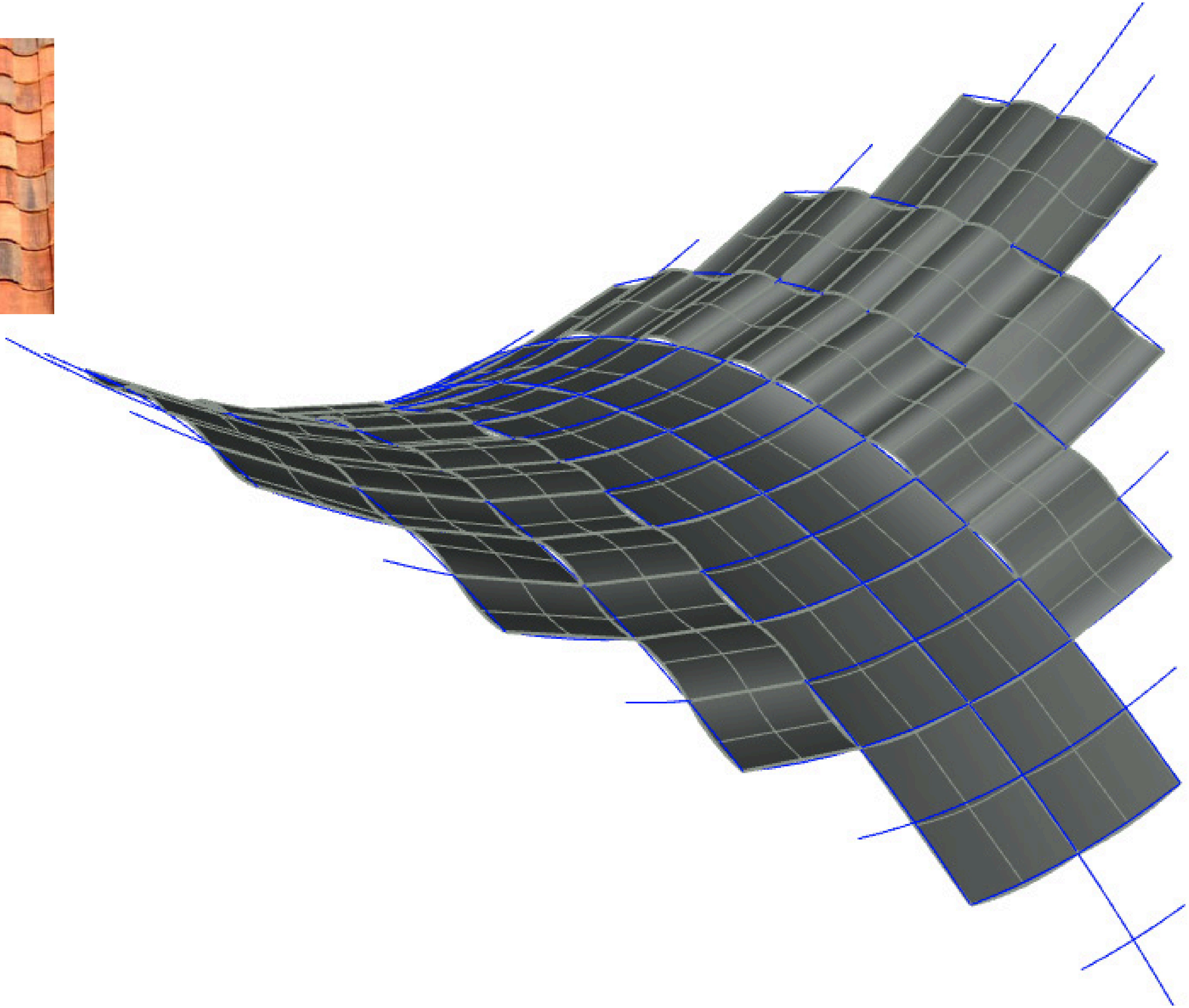
Detail 1:1- Glass clamps hinged or welded together.



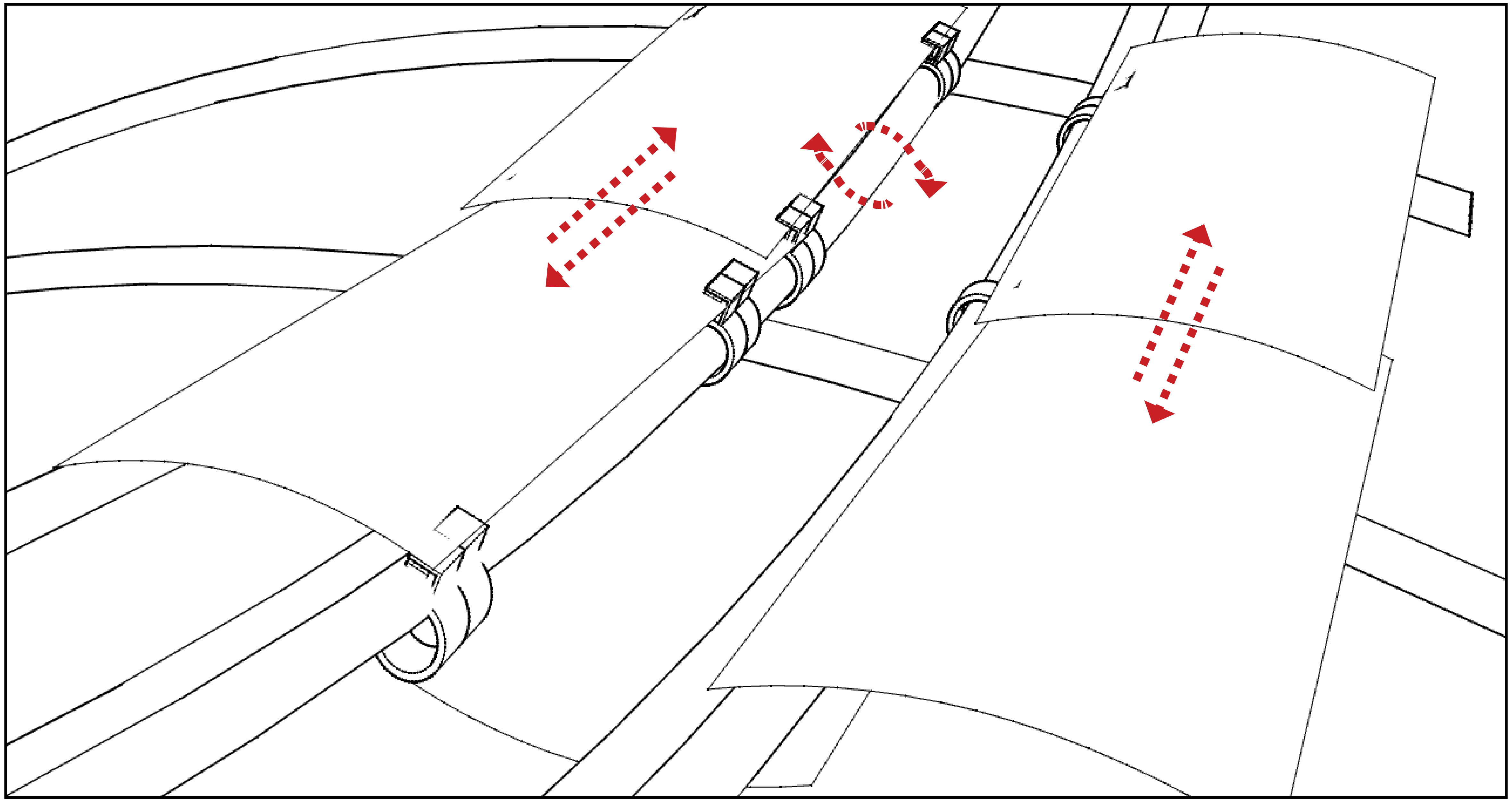
Section 1:10

CYLINDRICAL CURVE (OPTION 2)

Roman clay tiles



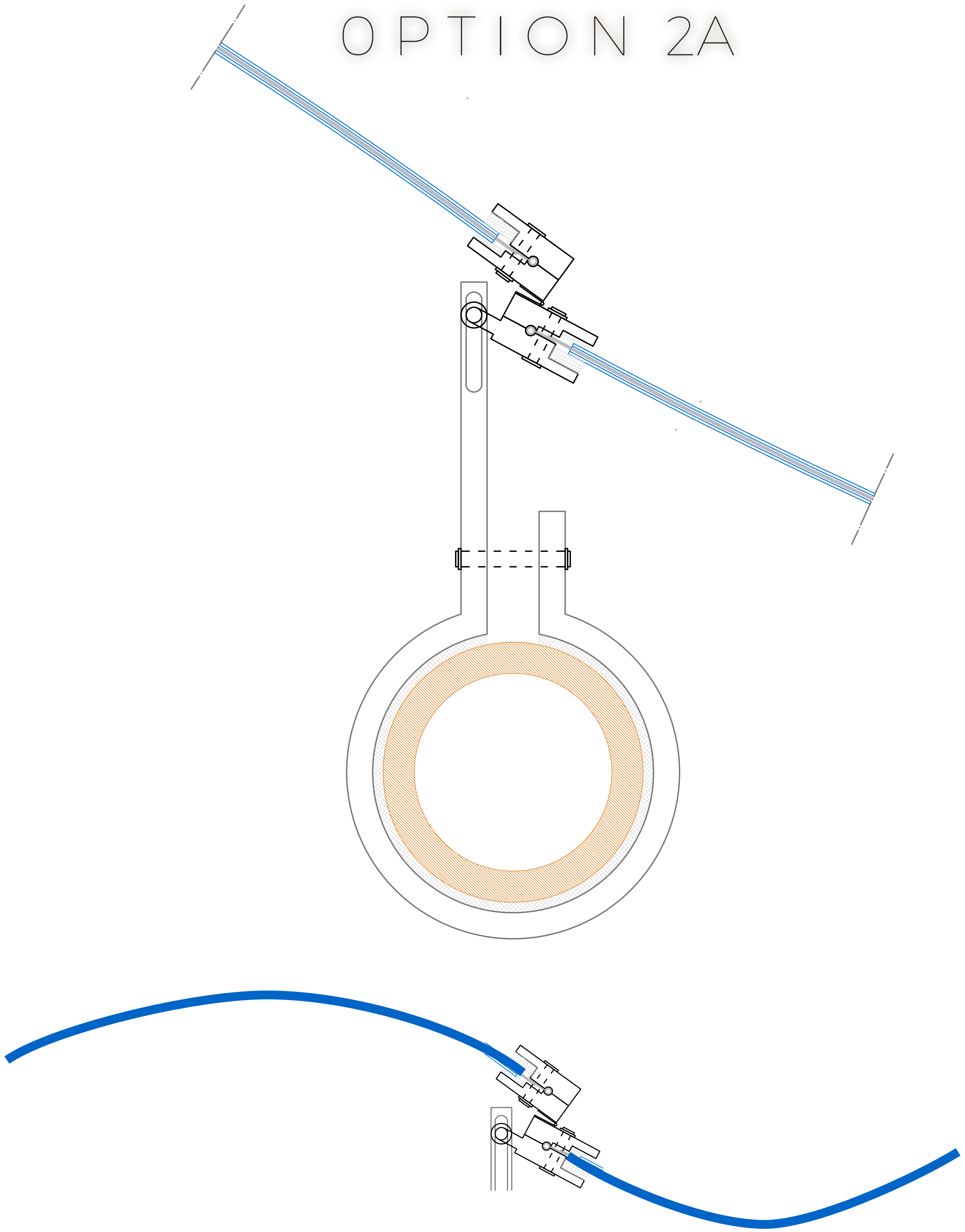
CYLINDRICAL CURVE (OPTION 4)



Panels overlapped in both directions.

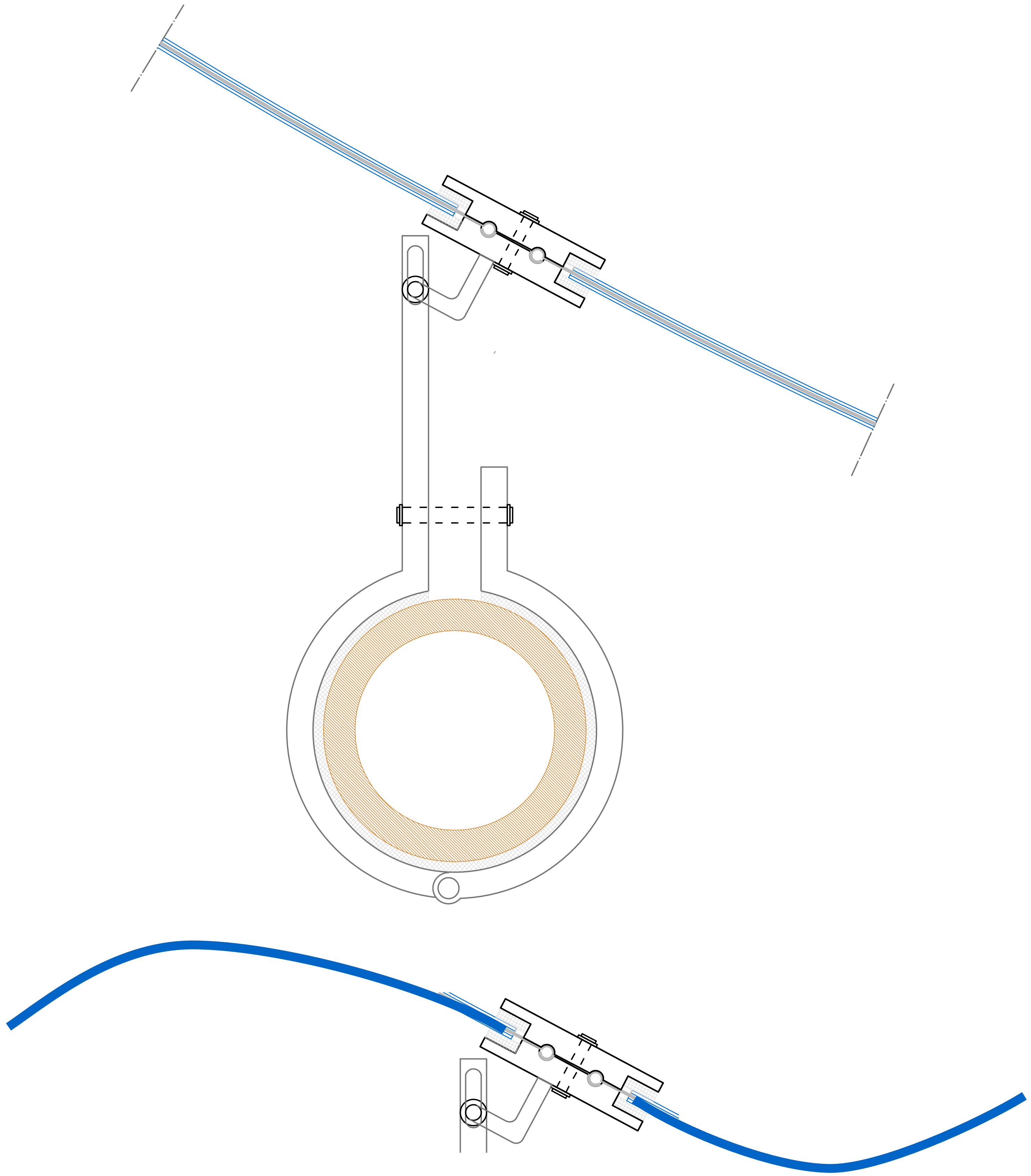
CYLINDRICAL CURVE

OPTION 2A



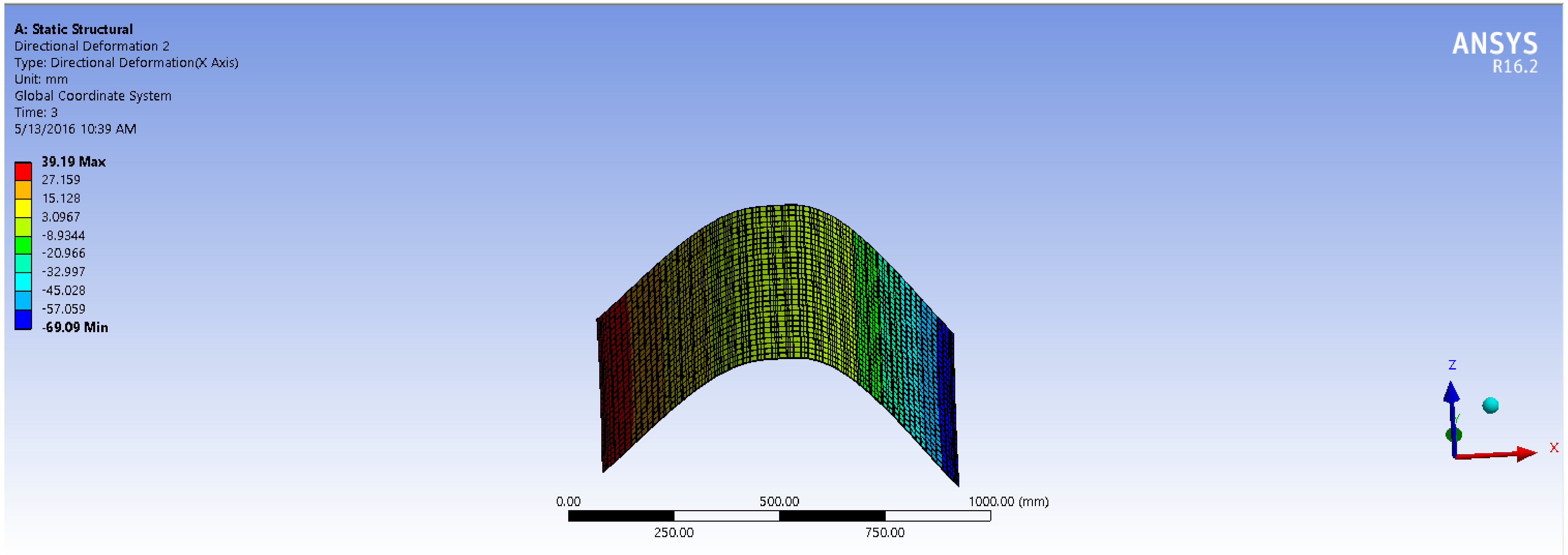
Glass Clamps Hinged to adjust glass curvature

OPTION 2B

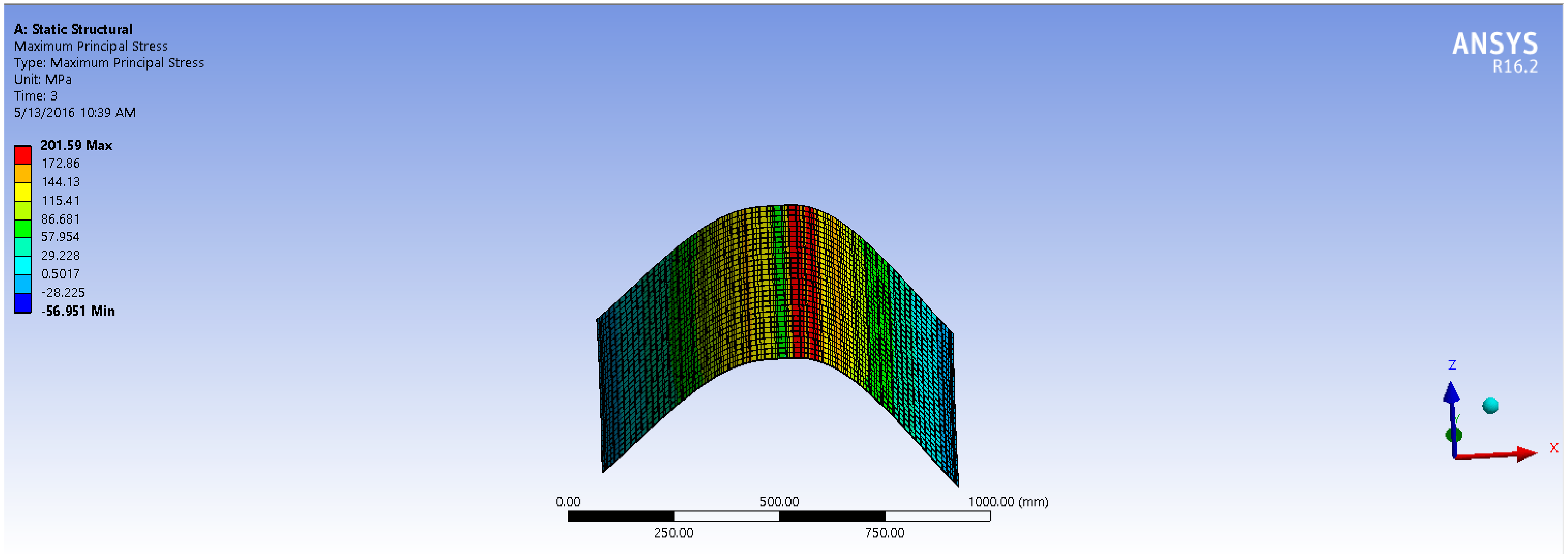


Glass Clamps fixed, glass curvature asymmetrical

THIN GLASS ASYMMETRICAL CURVATURE



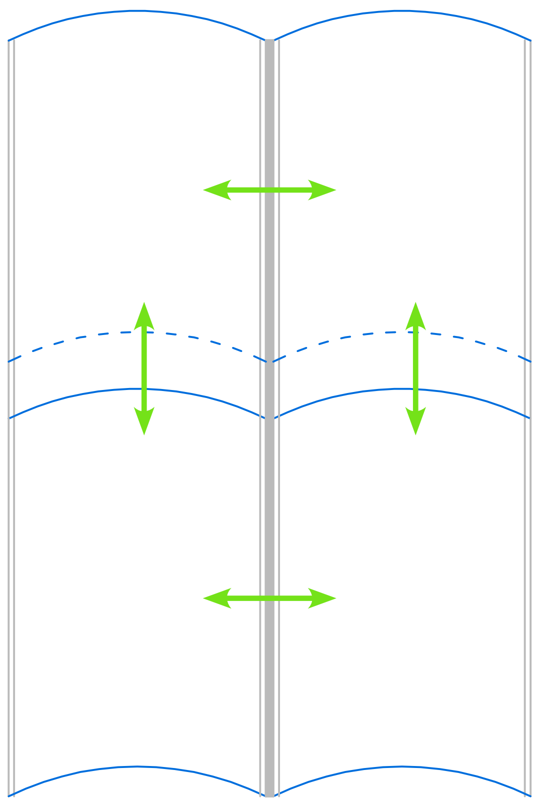
$\Delta_x = 39.19MM$ $\Delta_x = -69.09MM$



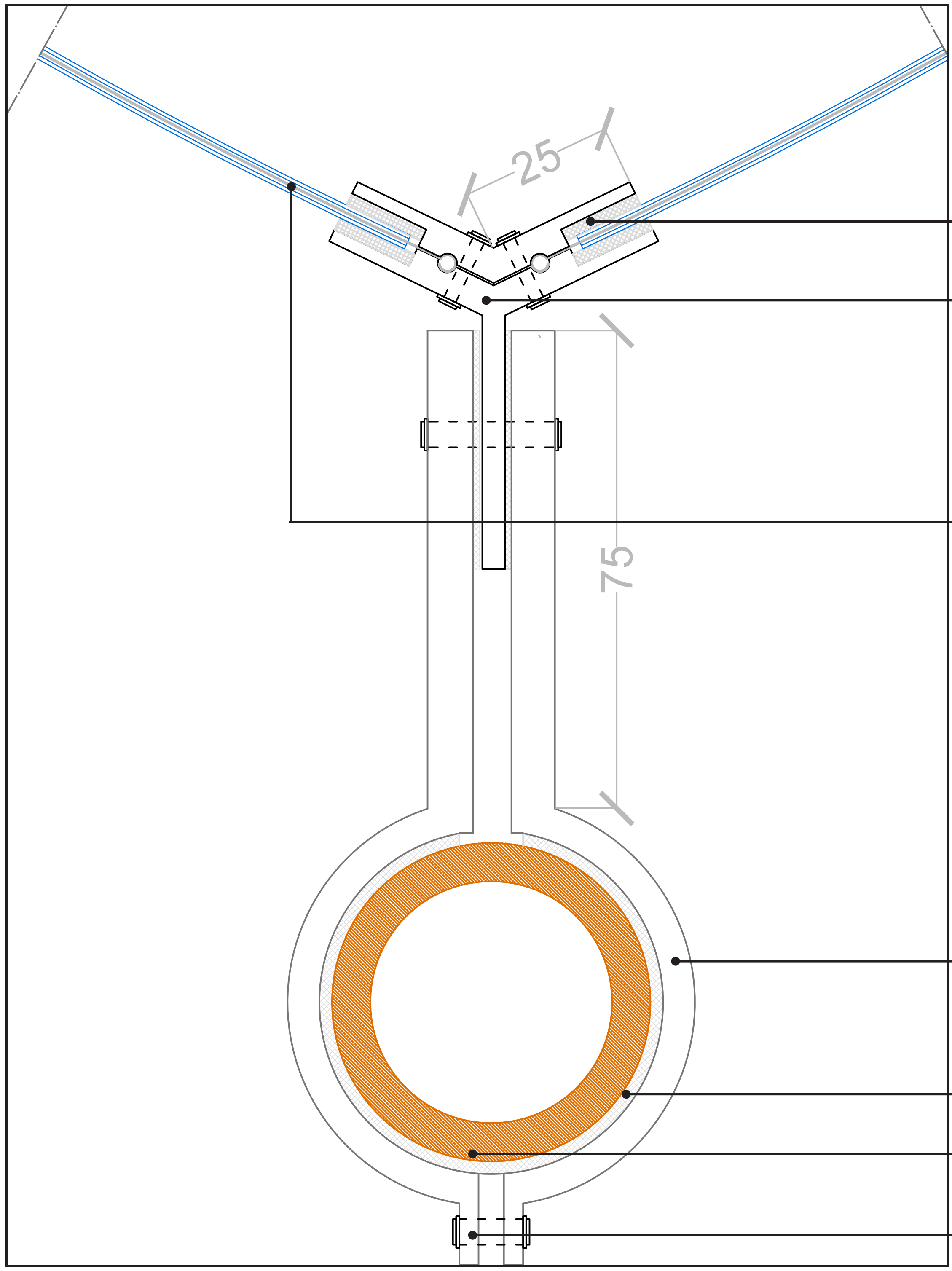
$\sigma_{max} = 201.50$ MPa

CYLINDRICAL CURVE (OPTION 3)

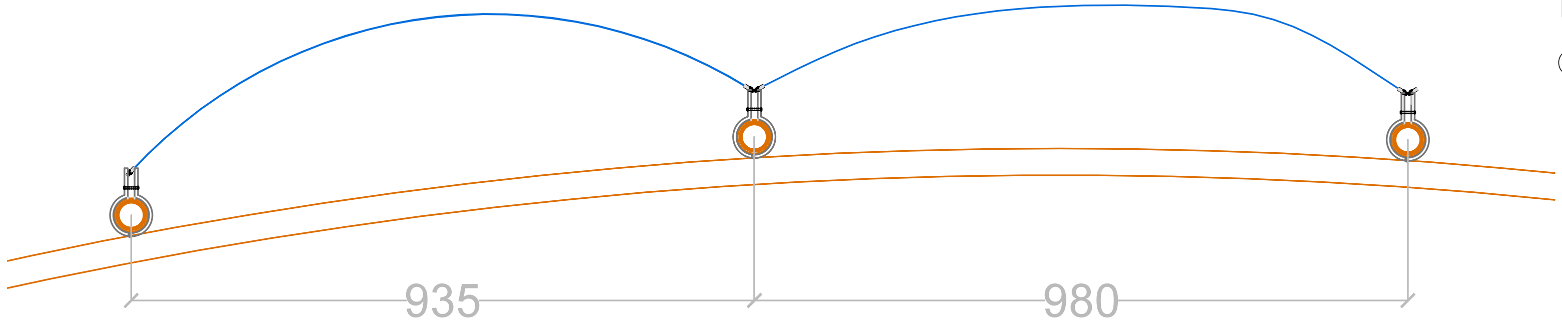
- ✓ WATER PROOF
- ✓ TOLERANCE
- ✓ DEGREE OF FREEDOM.
- ✓ CLAMPING ONLY IN ONE DIRECTION



Waterproofing on both direction, one side glass overlap, other side water tight mechanical fixture.

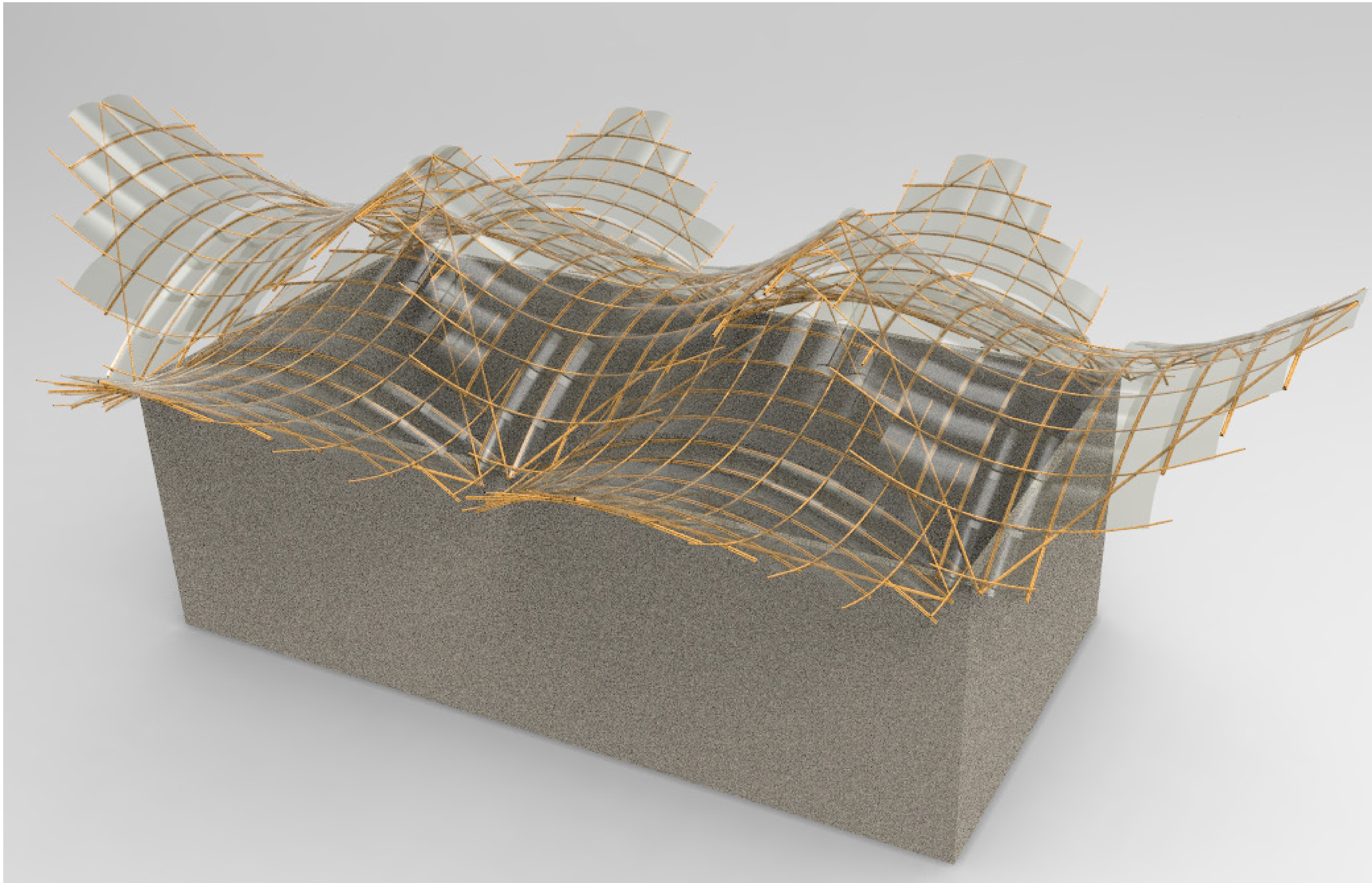


Detail 1:1- Both glass clamps form one single component.



Section 1:10

CYLINDRICAL CURVE (OPTION 3)



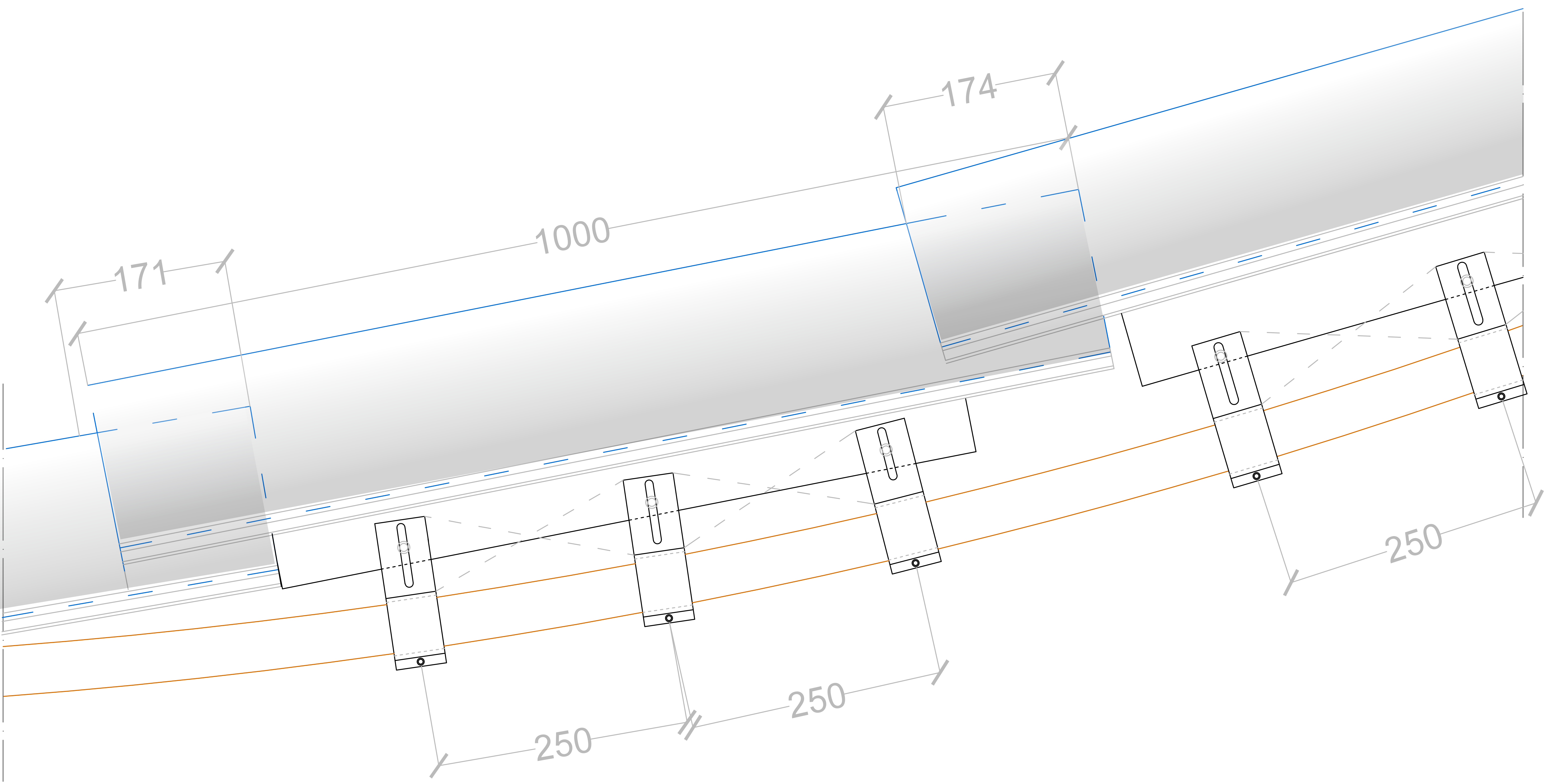
BAMBOO AND THIN GLASS JOINT ASSEMBLY

bamboo clamps fixed

connecting glass clamps to bamboo

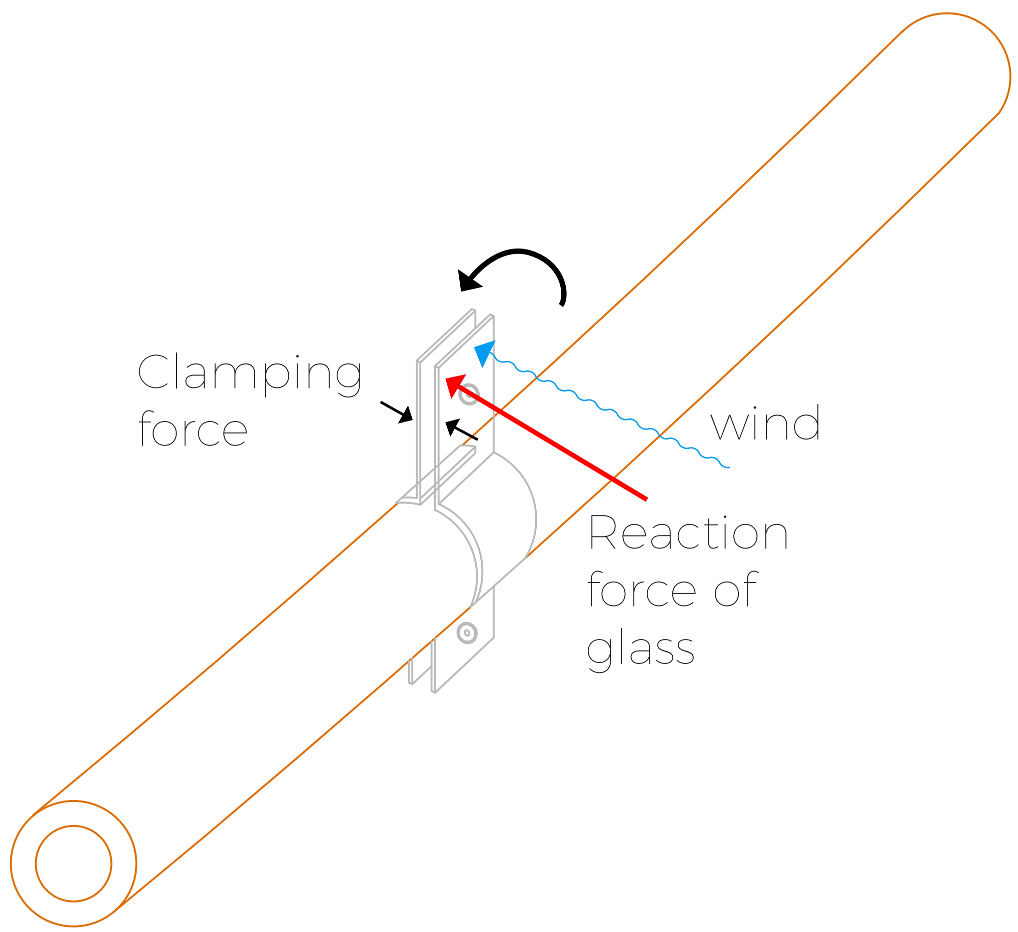
clamps bolted after placing glass in between.

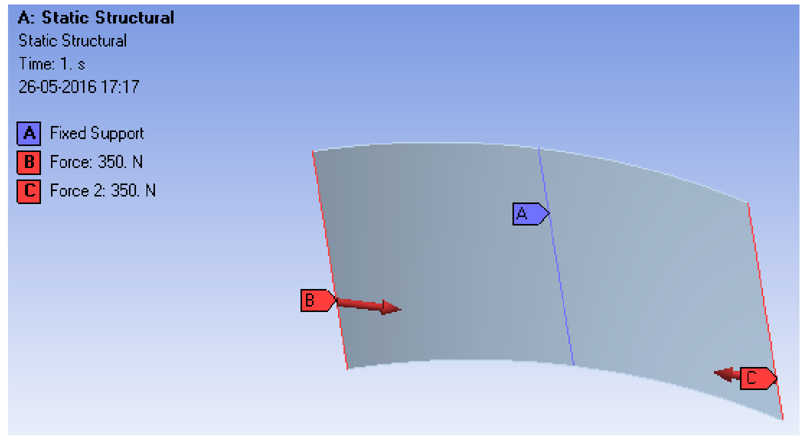
JOINT EVALUATION



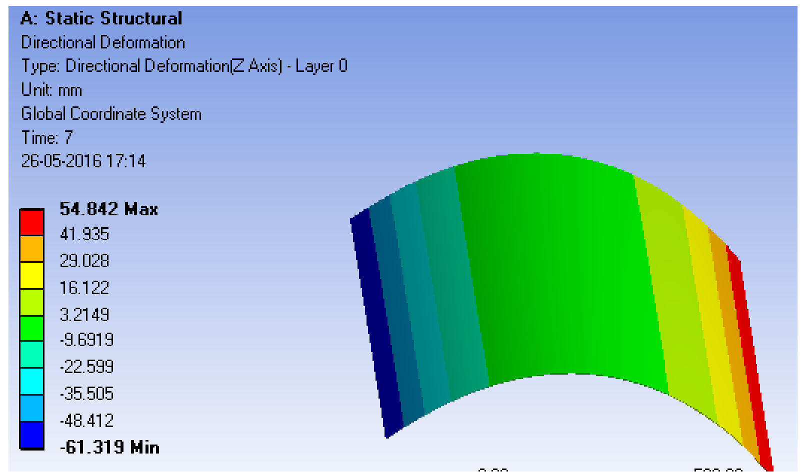
Section 1:5

JOINT EVALUATION

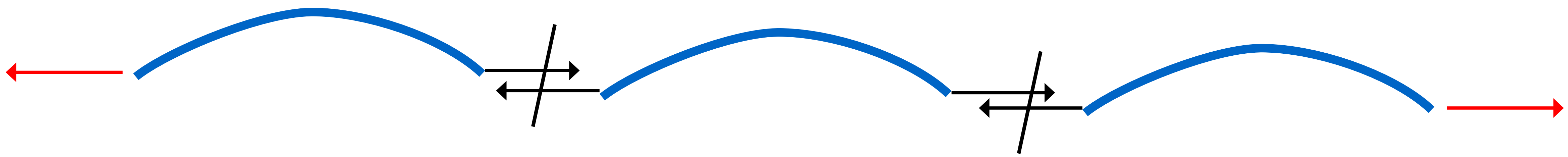




Boundary conditions to determine reaction forces



$\Delta_x = 54.84$ $\Delta_x = -61.31$



Reaction force of last panel is considered. Reaction forces of in between panels will negate each other.

Applied moment

wind torque τ_w + glass torque $\tau_g = [F_w + (F_g/3)].R$

36.26 N.m

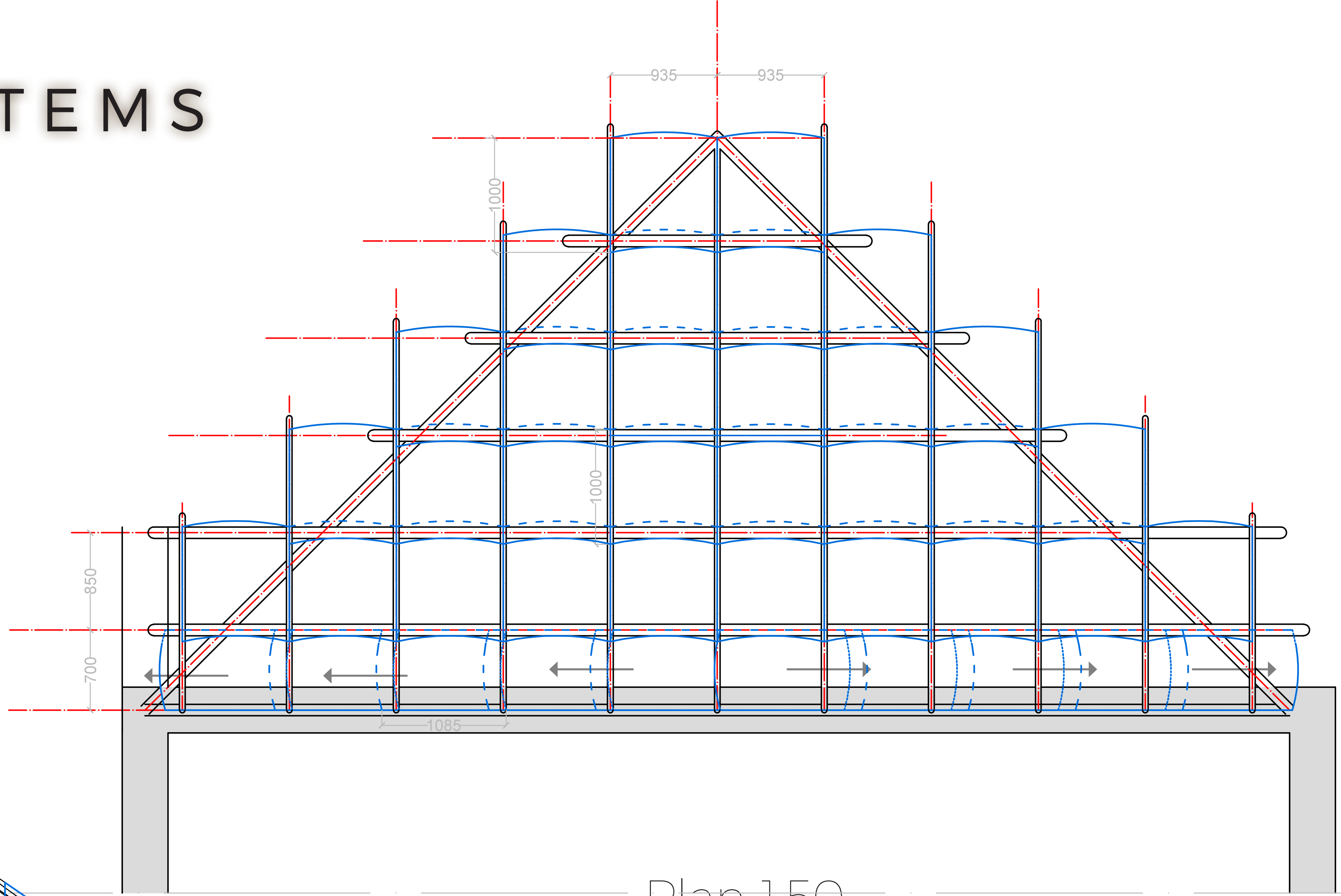
$<$

Resisting moment

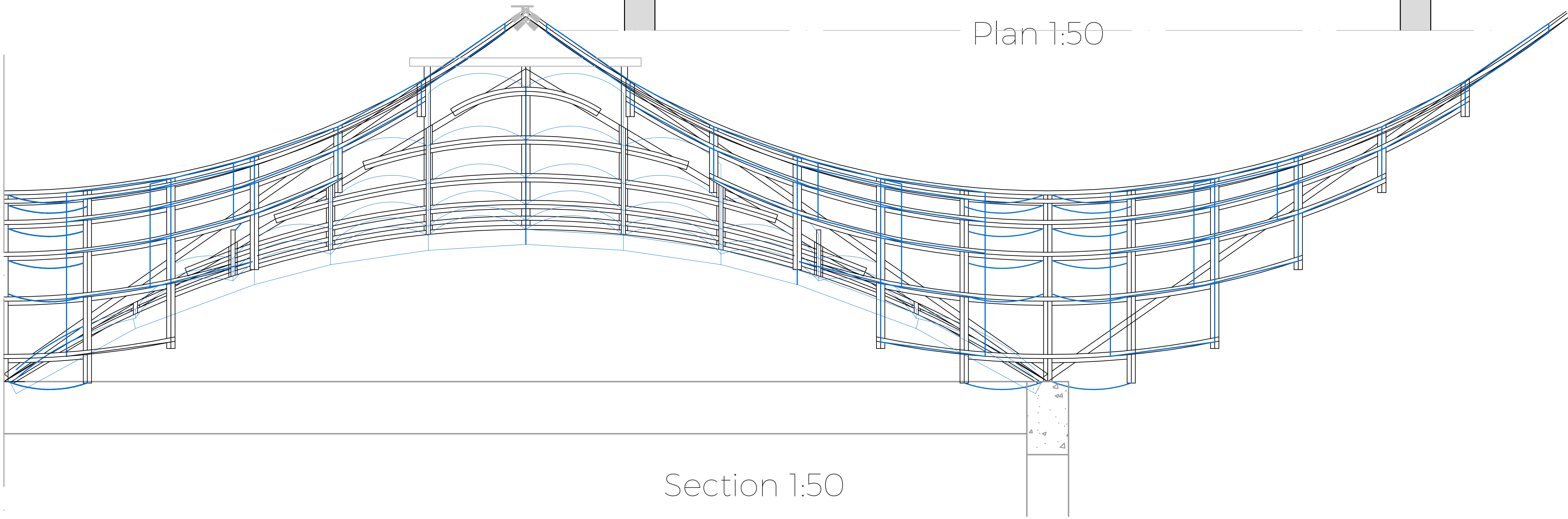
frictional torque $\tau_f = F_c.R.\mu$

63.36 N.m

CONNECTION SYSTEMS



Plan 1:50



Section 1:50

TU Delft Delft University of Technology

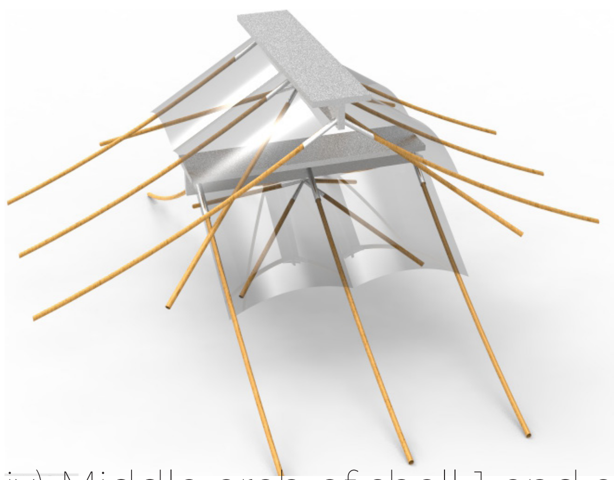
SECONDARY CONNECTIONS

Bamboo sliced and tapered using aluminium ring
ref: (Val, 2011)

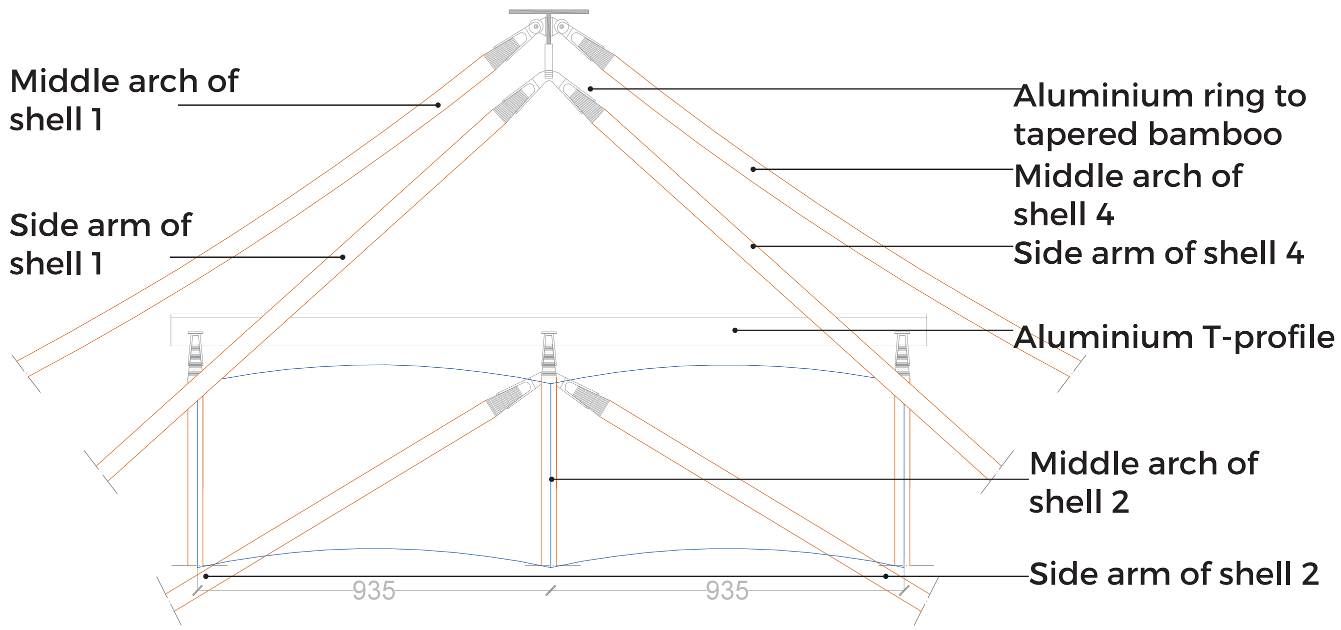
i) Side arms of shell 2 and shell 4

ii) Middle arch of shell 2 and shell 4

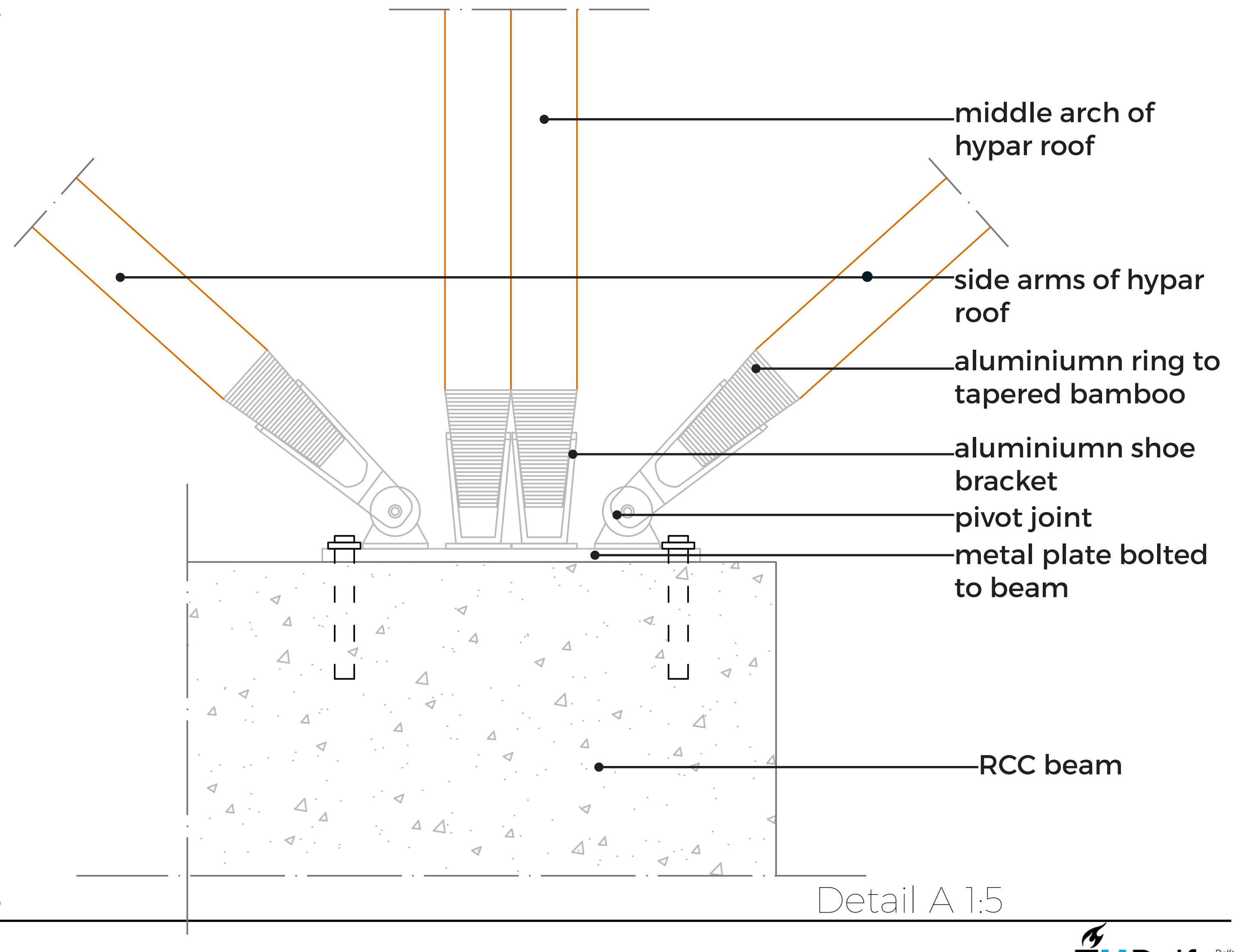
iii) Side arms of shell 1 and shell 3



iv) Middle arch of shell 1 and shell 3

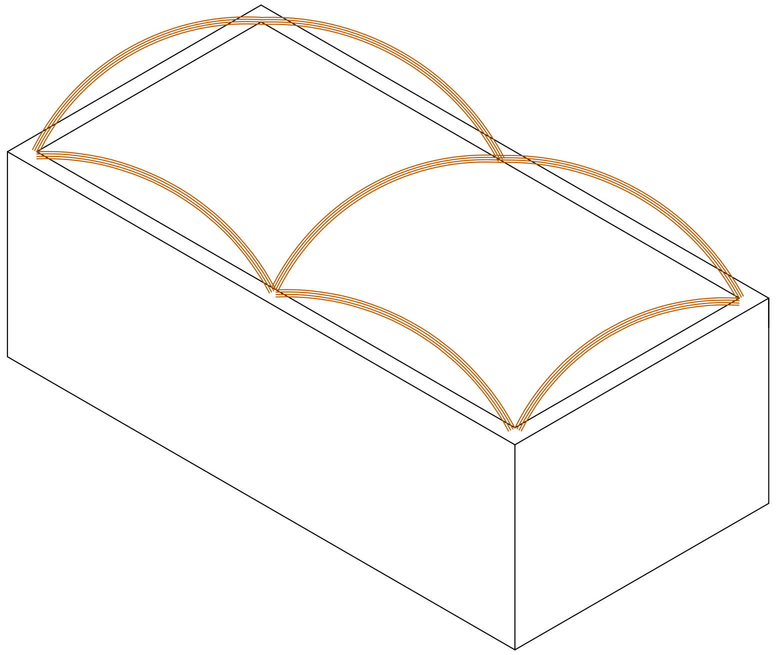


Detail B 1:20

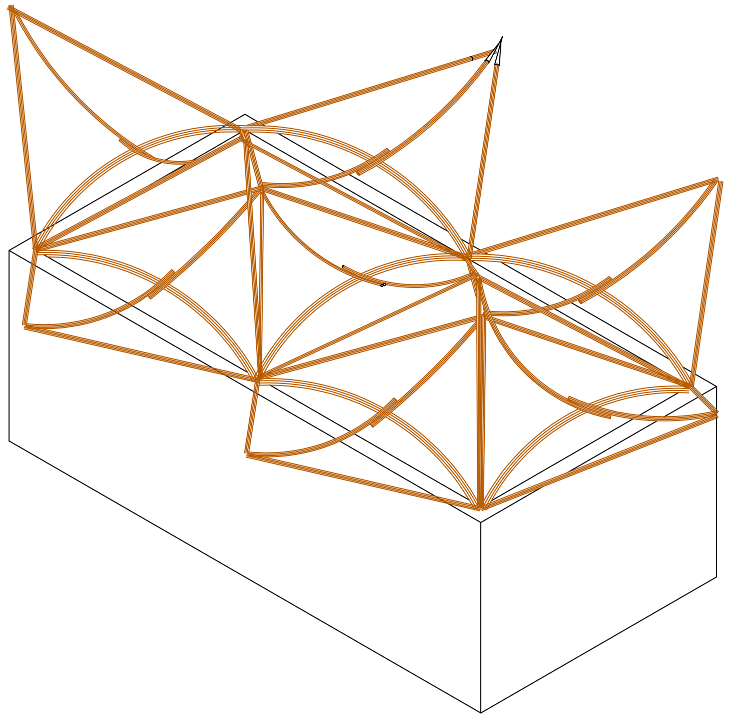


Detail A 1:5

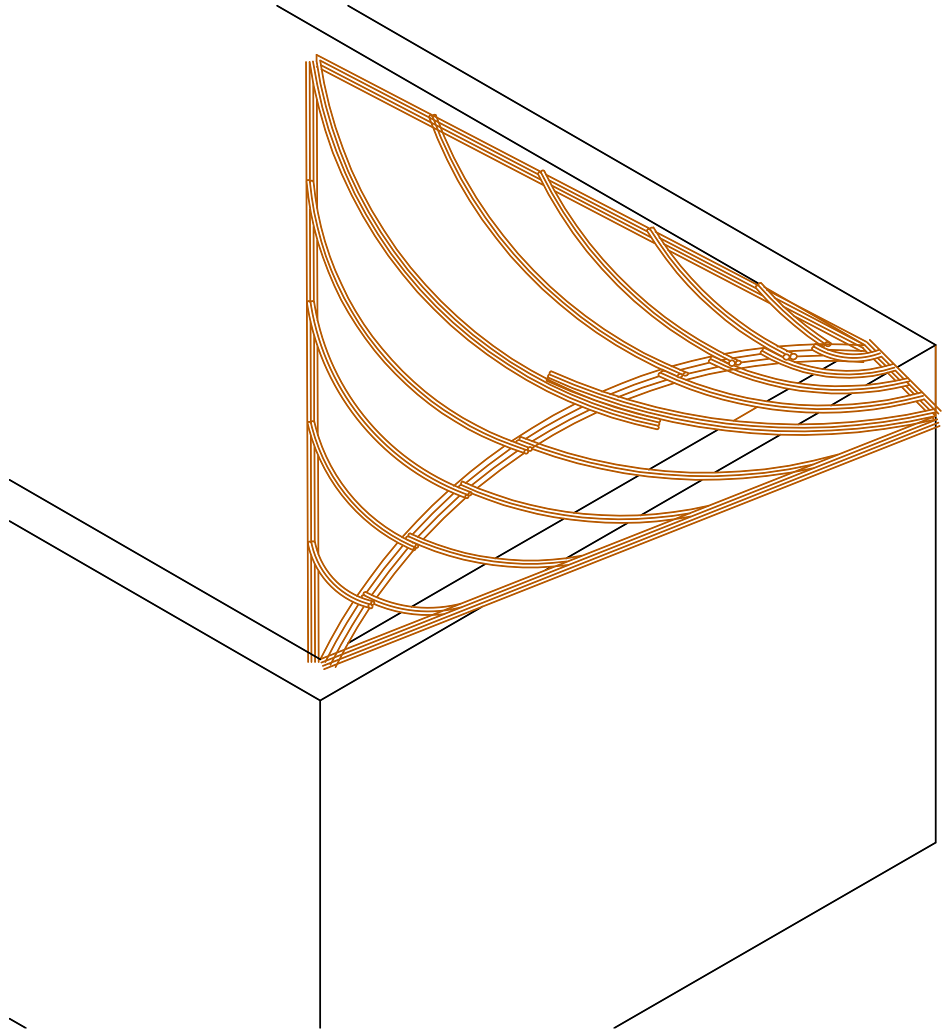
ASSEMBLY SEQUENCE



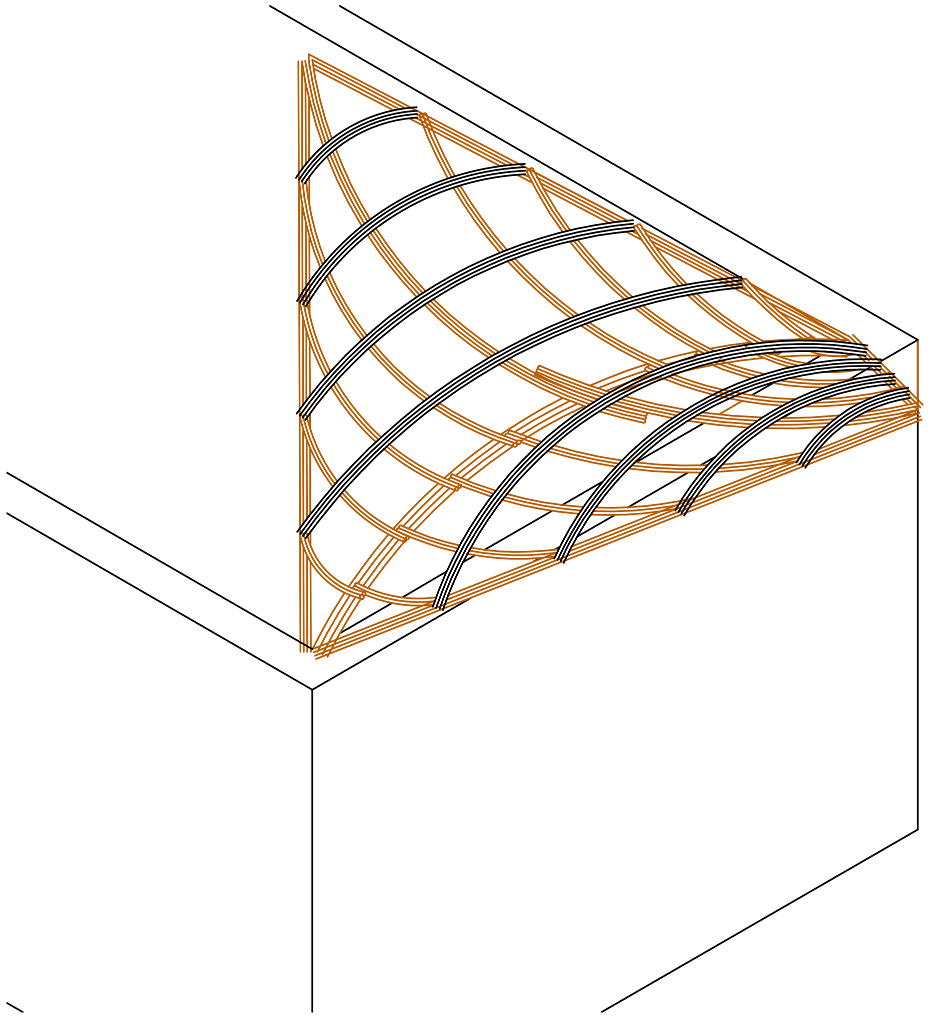
MIDDLE ARCH



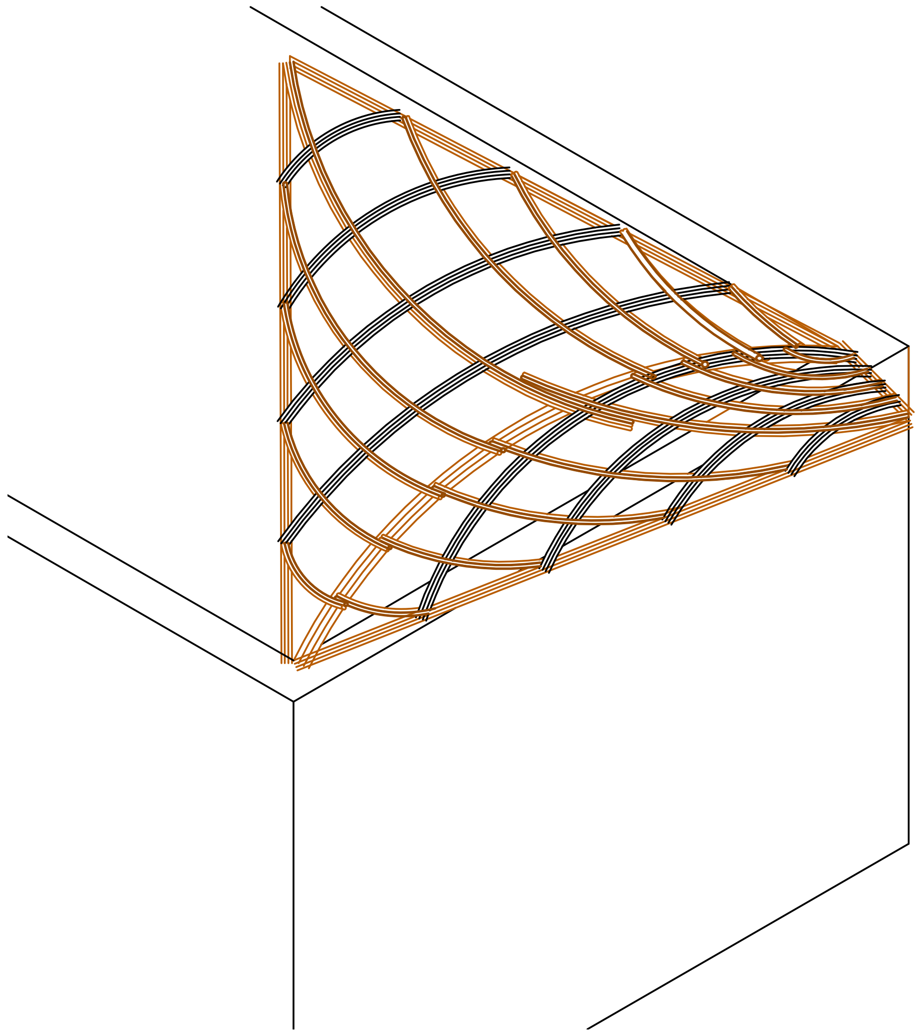
SIDE ARMS



LAYER 4

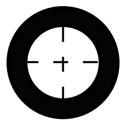


LAYER 5

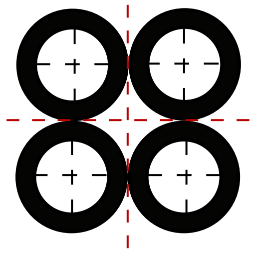


LAYER 6

BAMBOO ROOF BUCKLING ANALYSIS



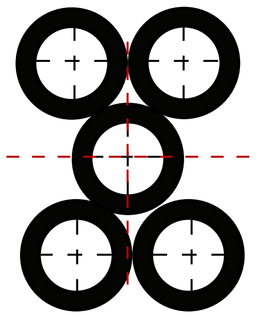
LAYER 6 - 1 STEM OF DIA 4CM



LAYER 5 - 4 STEM OF DIA 4CM

Total force (layer6+self-weight+wind+snow) = 369.69N/m

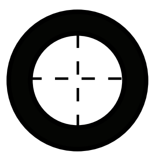
Critical load = 93.39N/m



LAYER 4 - 5 STEM OF DIA 4CM

Total force (layer6+layer5+self-weight+wind+snow) = 477.93N/m

Critical load = 118.83N/m

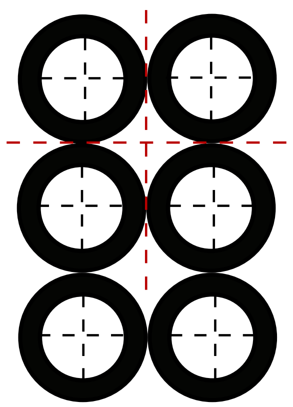


SIDE ARMS - 1 STEM OF DIA 6CM

Total force

(layer6+layer5+layer4+self-weight+wind+snow) = 579.73N/m

Critical load = 597.84N/m

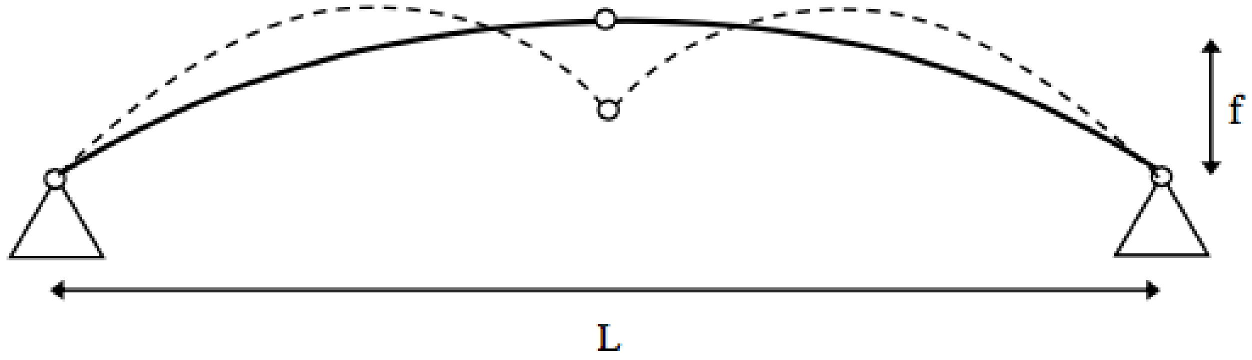


MIDDLE ARCH - 6 STEM OF DIA 6CM

Total force

(layer6+layer5+layer4+self-weight+wind+snow) = 2175.19N/m

Critical load = 375.23N/m



First in-plane buckling mode of 3 hinged parabolic arch

ref: (Bjorn Andersson and Gustaf Larsson.)

Critical load under uniform loading :

(Timoshenko and Gere, 1961)

$$q_{cr} = \gamma_4 \frac{EI}{L^3}$$

where,

EI - bending stiffness of the arch.

L - span

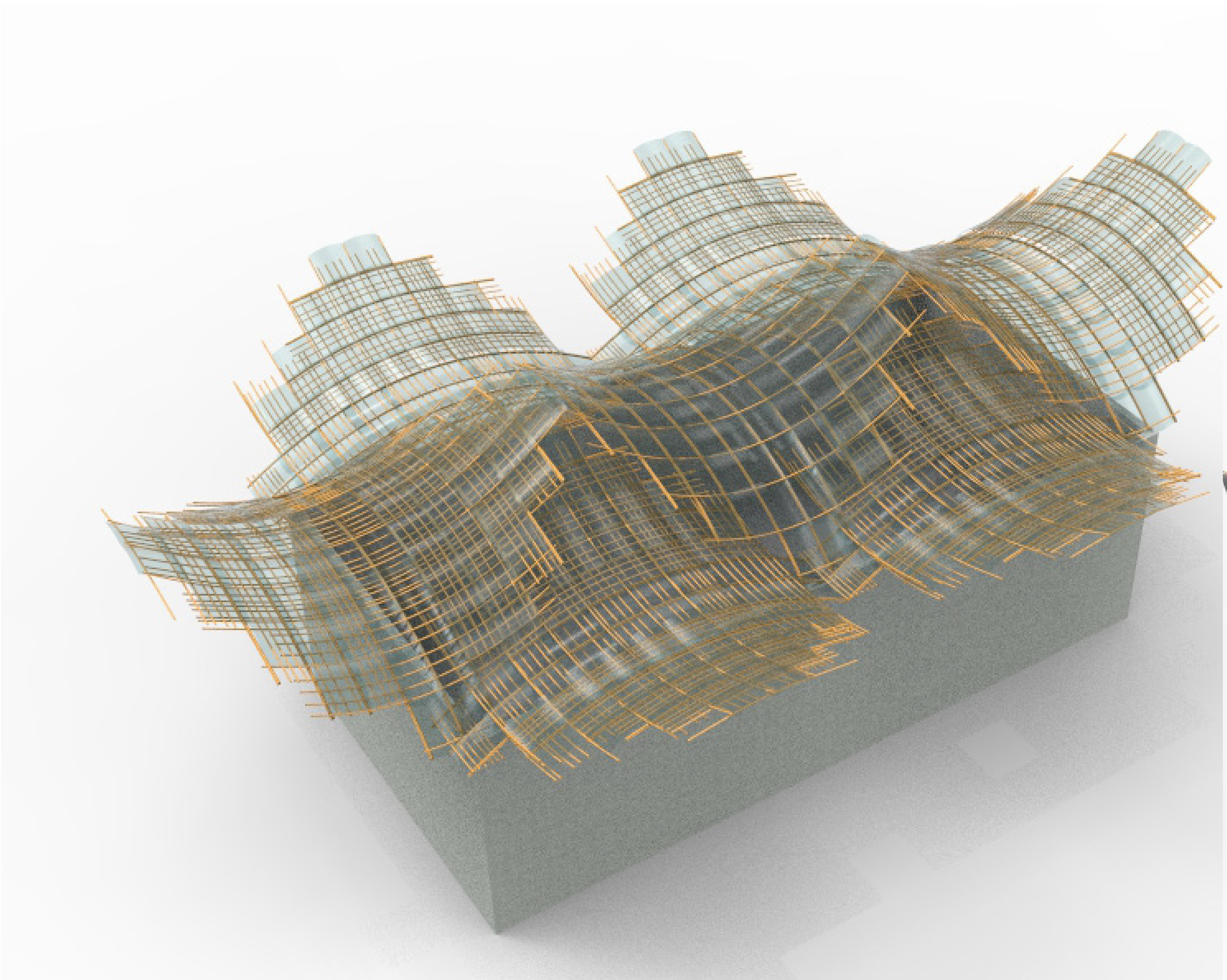
ϒ- numerical factor depending on ratio f/L and no. of hinge connections.

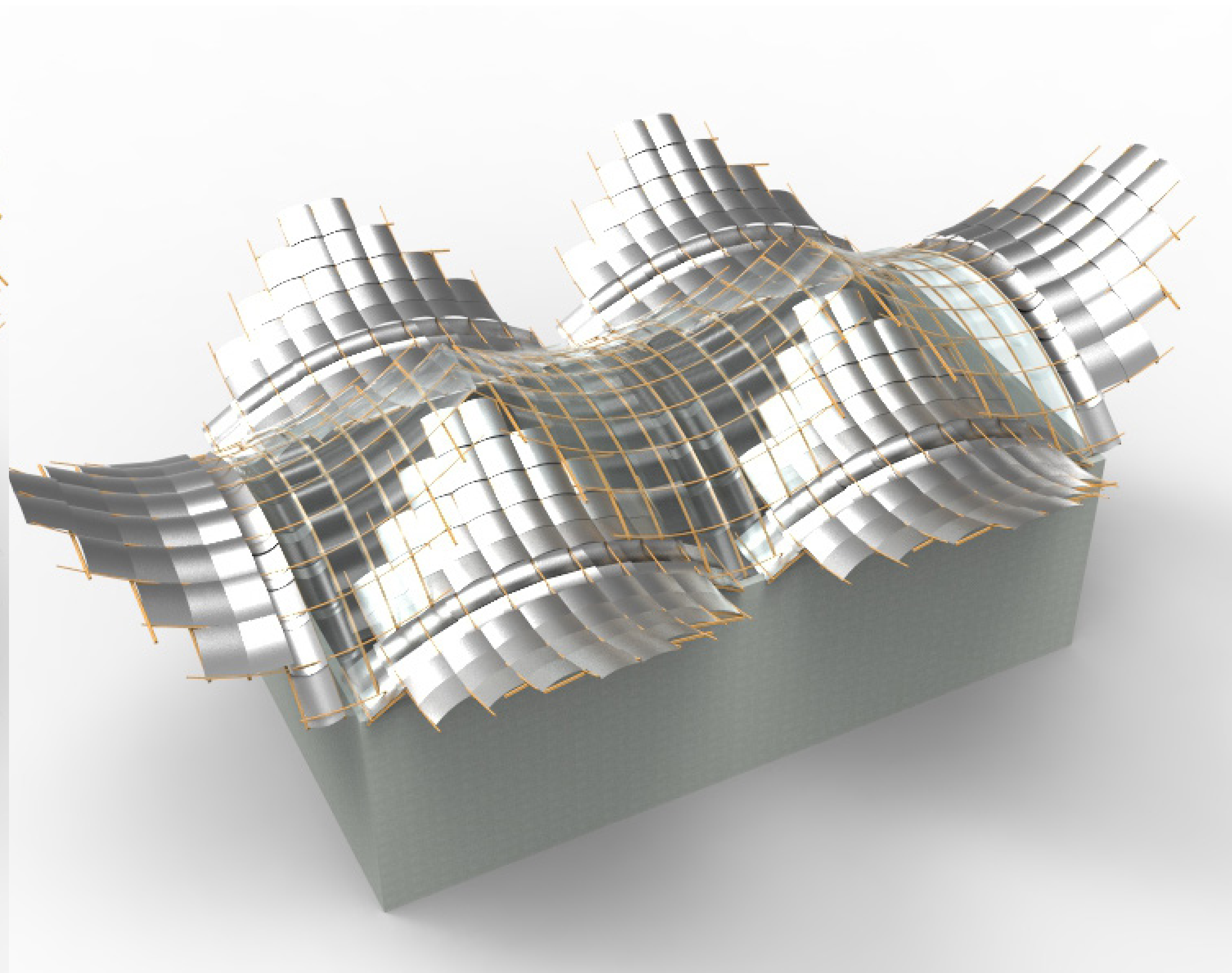
REFLECTION

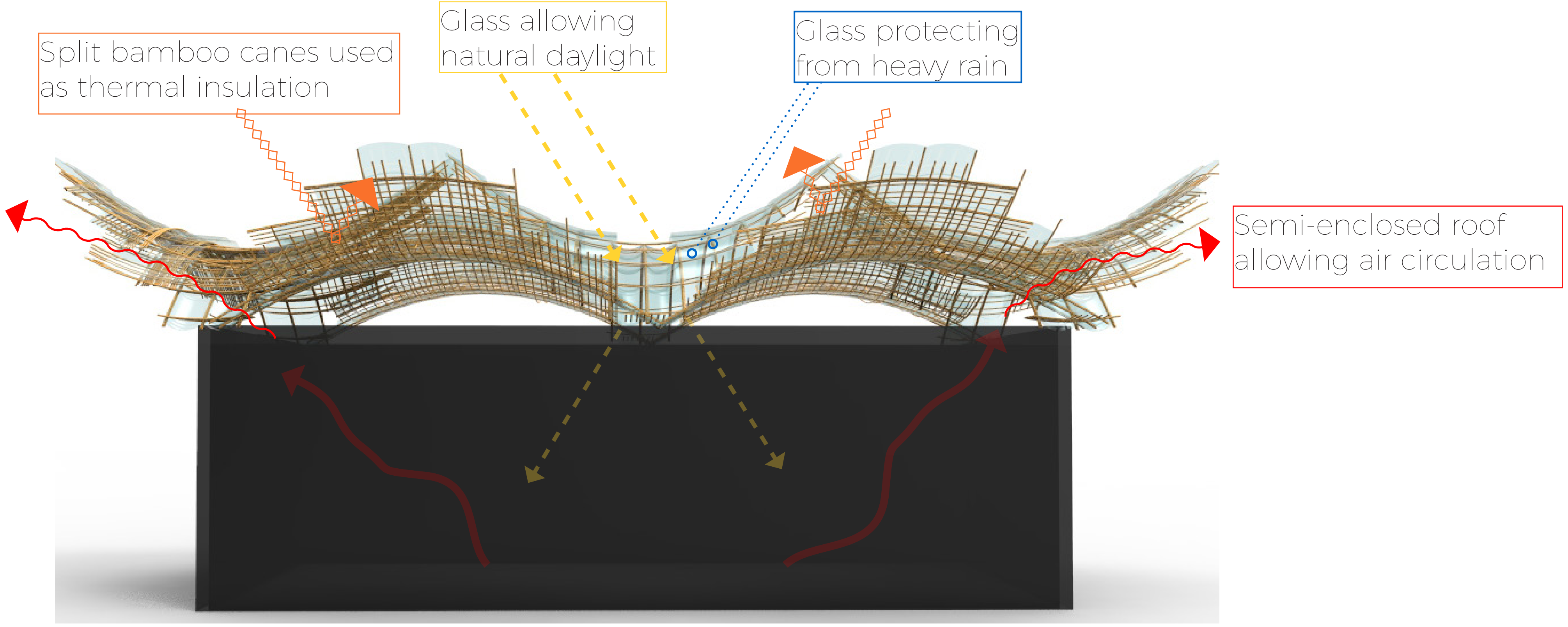
BAMBOO + THIN GLASS CONSTRUCTION
FOR TROPICAL CLIMATIC CONDITIONS

- DURABLE
  - Choice of material for cladding
  - Choice of material for connections
  - Connection detail
- THIN GLASS overcoming drawbacks of bamboo in terms of construction
- BAMBOO is natural and local material.
- LIGHT WEIGHT STRUCTURE
- ORGANIC FREE FORM GEOMETRY
- WATERPROOF SYSTEM
- ALLOWING NATURAL DAYLIGHT
- ONE STANDARD MODULE
  Same size module repeated throughout the structure.

- ACCURACY
  More accuracy required while constructing main bamboo structure.
- CAREFUL PLANNING
  Detailing and understanding limitations of both the materials at design stage.
- THIN GLASS is expensive and needs to be imported.
- EXCESS THERMAL GAIN
  Due to glass cladding
- NOT AIRTIGHT
- MIGHT REQUIRE 3RD MATERIAL
  - ALUMINIUM, TIMBER PANELS

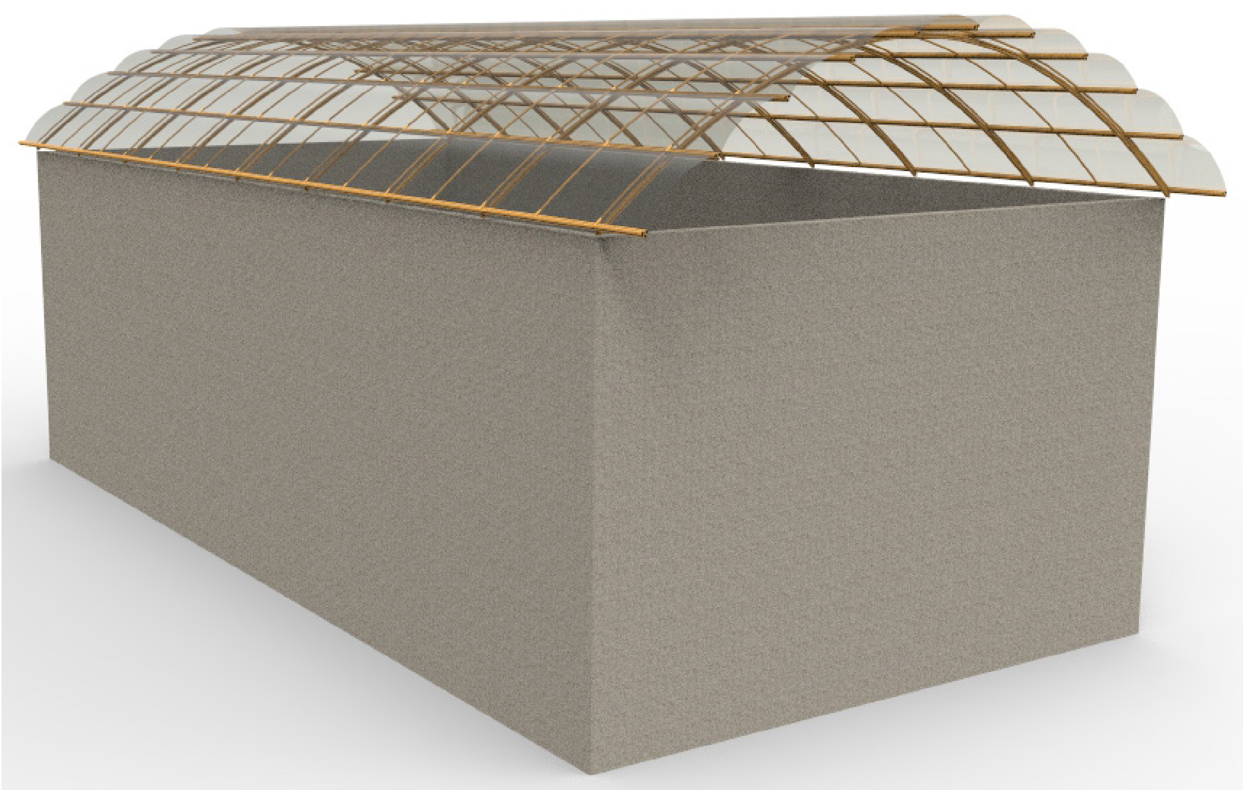


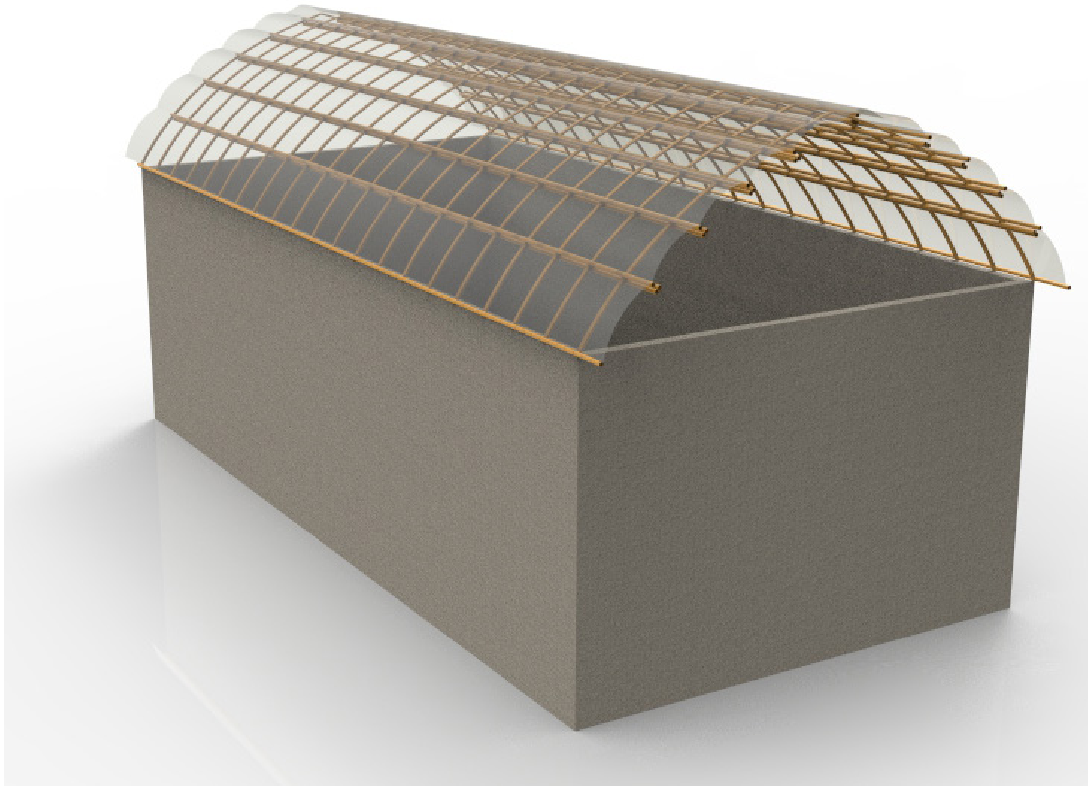


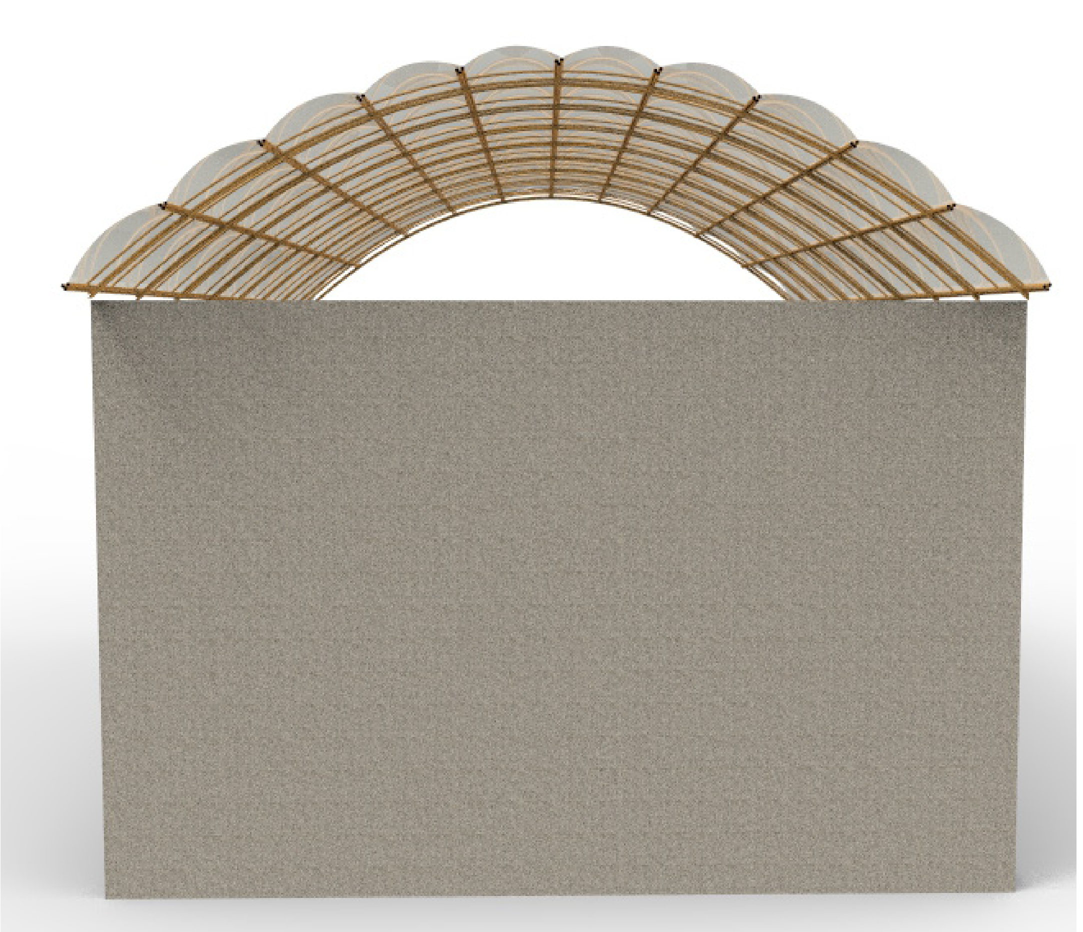


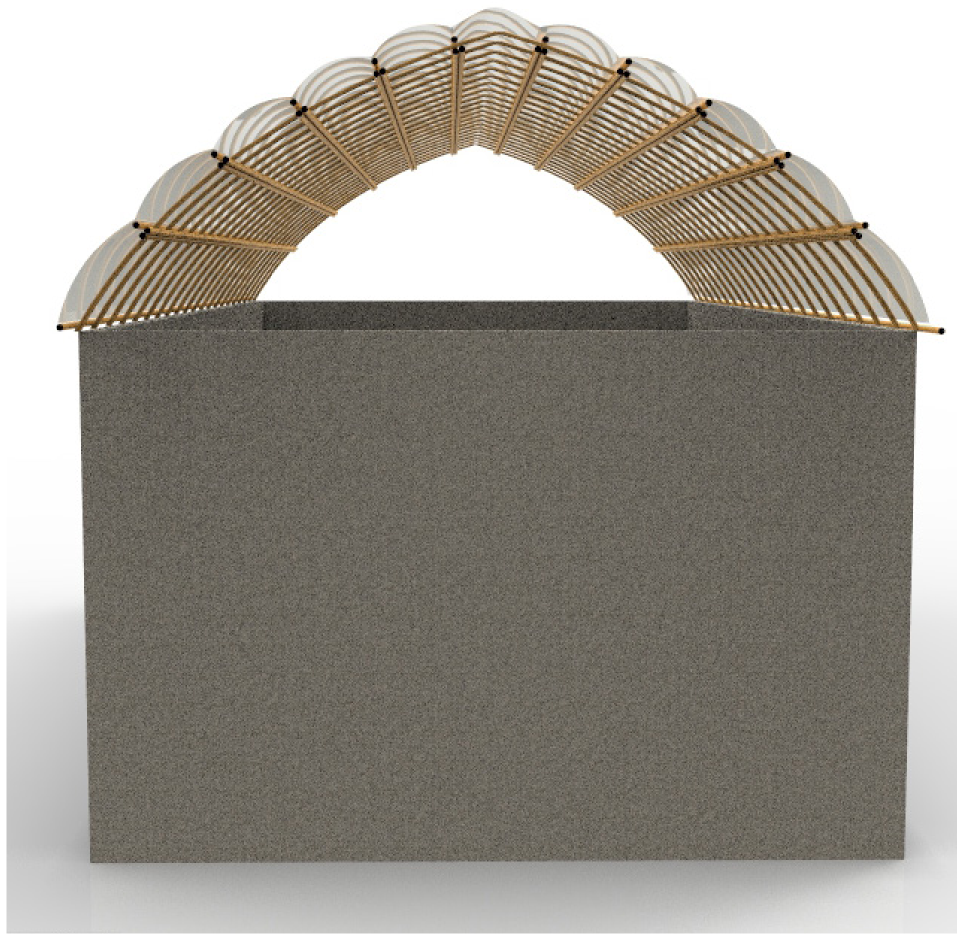
Split bamboo canes used as thermal insulation
Glass allowing natural daylight
Glass protecting from heavy rain
Semi-enclosed roof allowing air circulation

ALTERNATIVES










thank you!

	THIN GLASS	POLYCARBONATE	ALUMINIUM	TENSILE FABRIC PTFE(TEFLON)	THATCH HEMP
STRENGTH	200 MPa	70 MPa	120 MPa	25 MPa	200 MPa
WEIGHT	2.48 g/cm^3	1.15 g/cm^3	2.65 g/cm^3	2 g/cm^3	1.48 g/cm^3
TRANSLUSCENCE	TRANSPARENT	TRANSPARENT	OPAQUE	TRANSPARENT	OPAQUE
FLEXIBILITY	COLD BENDING	MOLDED	COLD BENDING	STRETCHED	BUNDLES
TEXTURE	REGULAR	REGULAR	REGULAR	REGULAR	IRREGULAR
HARDNESS	595 HV	6 HV	36 HV	6 HV	
ACOUSTICS					
ODOUR		HIGH TEMPERATURE		HIGH TEMPERATURE	
FIRE RESISTANT	NON FLAMMABLE	SELF EXTINGUISHING	NON FLAMMABLE	NON FLAMMABLE	FLAMMABLE
THERMAL RESISTANT	1 m.C/W	5 m.C/W	0.00435 m.C/W	4 m.C/W	5 m.C/W
WEATHER RESISTANT					
SCRATCH RESISTANT					
CHEMICAL RESISTANT					
RENEWABLE					
RECYCLABLE					

BAMBOO STRUCTURES CLADDING

Panyaden School - 24H Architects

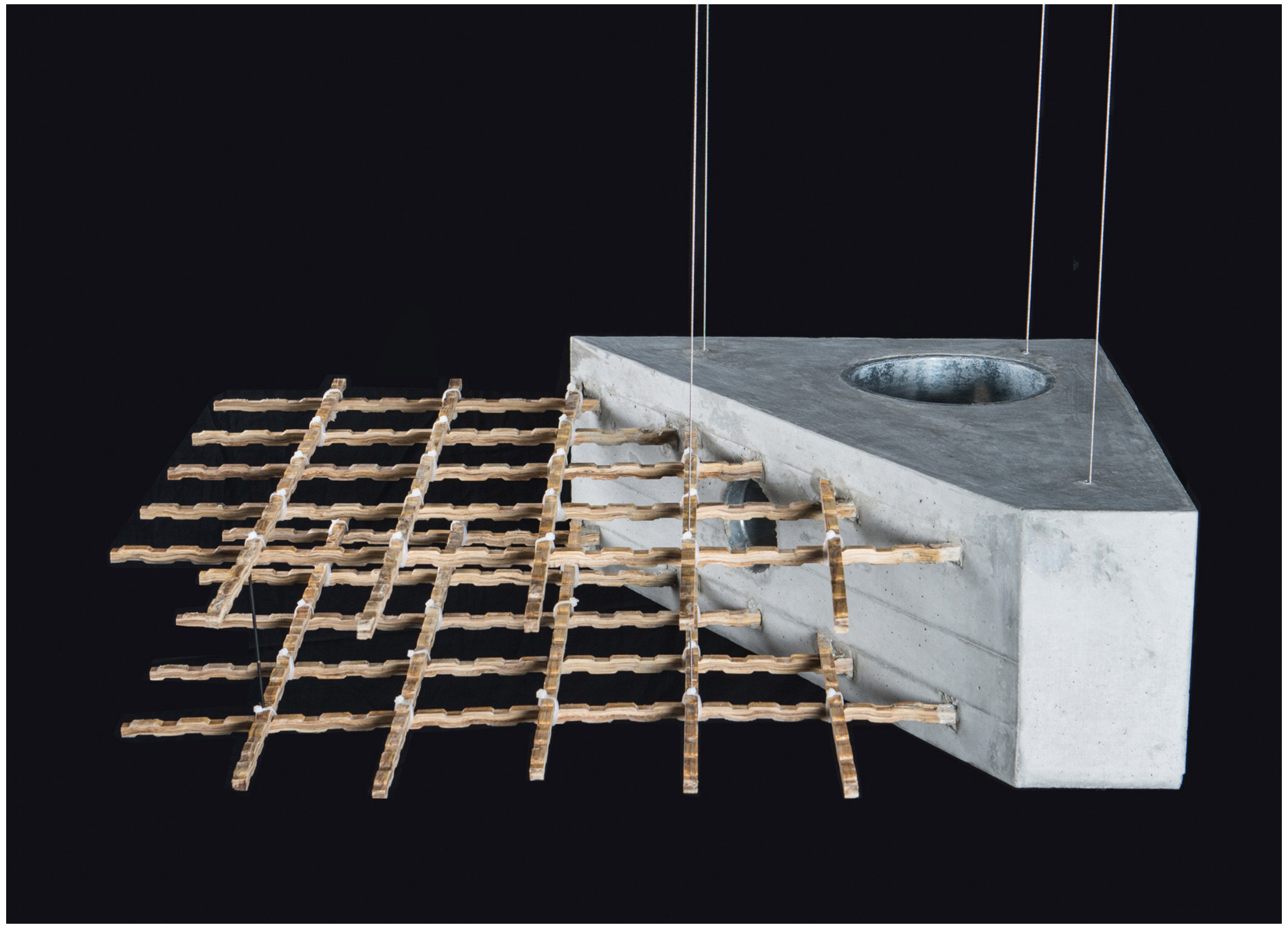
Community Center, Vo Trong Ngheia

Bamboo and thatch roof connection

Polycarbonate roofing

BAMBOO - ALTERNATE MATERIAL

Steel Reinforced Concrete



Bamboo Reinforced Concrete - Future Cities laboratory, Singapore