Freeform Transparency

Introducing a novel fabrication technique for curved glass utilizing knitted moulds

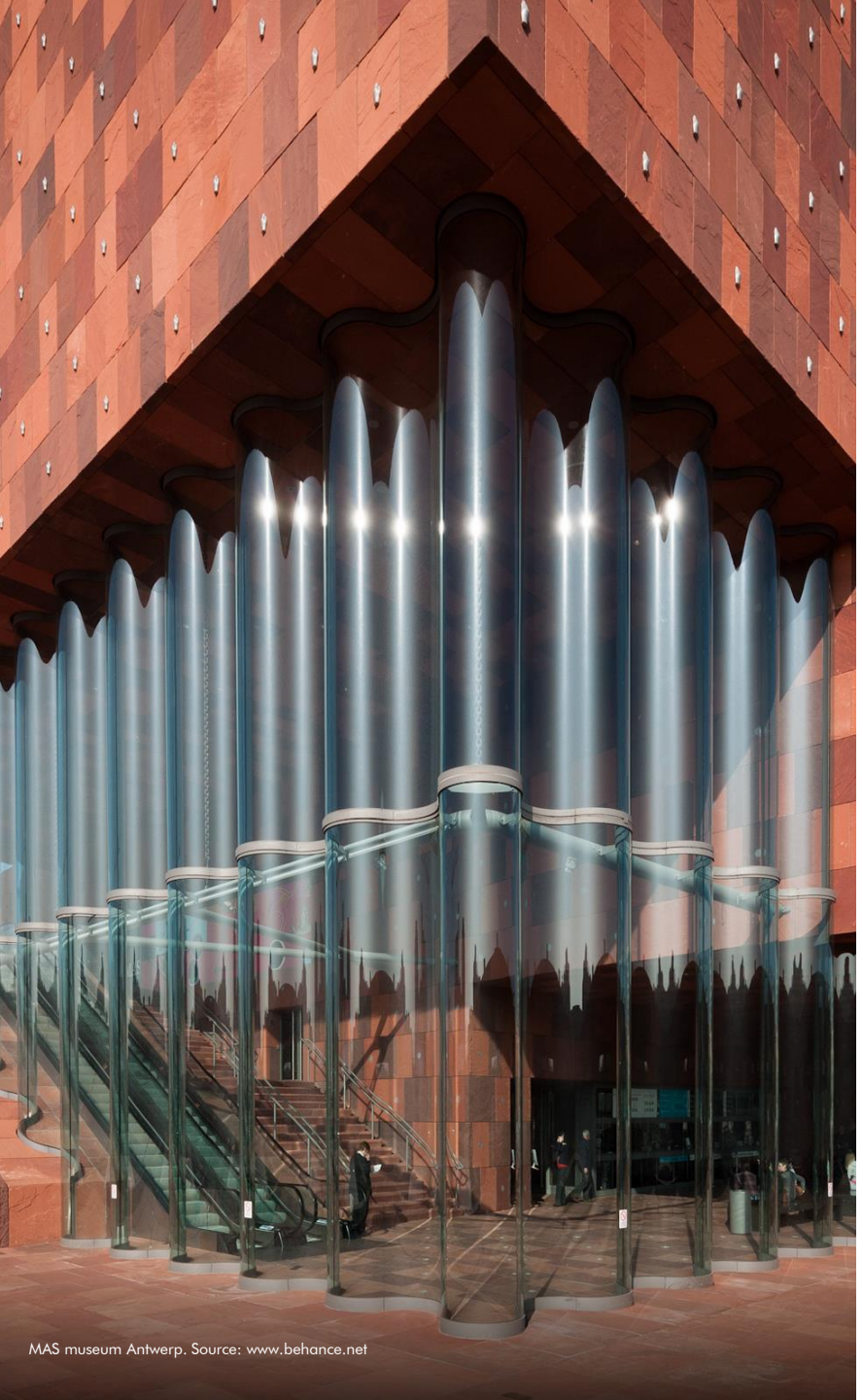
P5 presentation - 21/6/2024

Anna Konstantopoulou | 5834384

Mentors: F. Oikonomopoulou, M. Popescu

TU Delft

Apple Store 5th Avenue NYC. Source: www.bcj.com



MAS museum Antwerp. Source: www.behance.net

Nordstrom flagship store in NYC. Source: www.press.nordstrom.com

knitCandela. Source: www.worldarchitecture.org

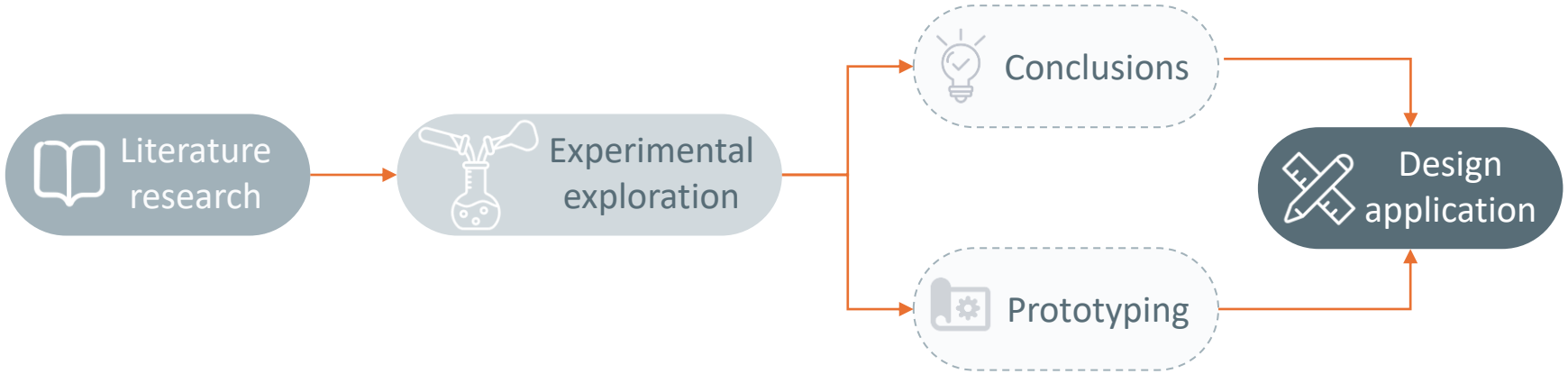
aim of this thesis

develop a novel fabrication technique that enables an easily customizable production of freeform, curved float glass components while resulting in little waste

main question

*What is the **potential** and **limitations** of utilizing **knitted basalt moulds** for the creation of customizable, freeform curved float glass components?*

METHODOLOGY



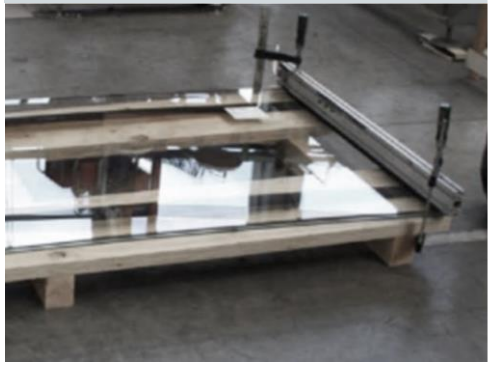
Literature research

Fabrication of curved glass geometries

Curved glass

Manipulating flat glass

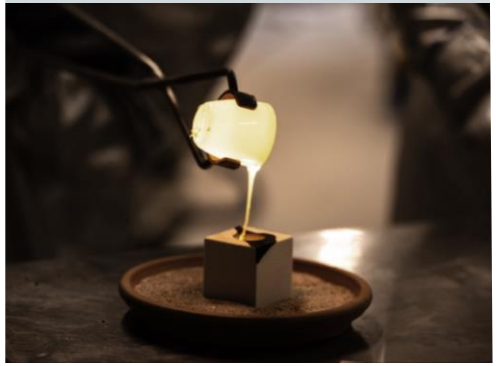
Cold bending



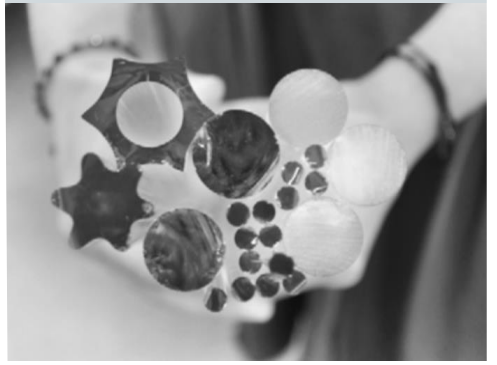
Hot bending

Melting glass

Casting



Extrusion

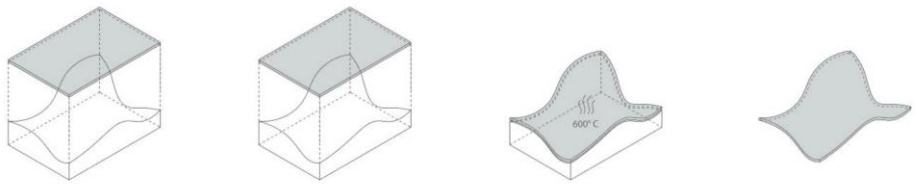


3d printing

Assess & compare

Hot bending can achieve big curvatures.

→ **slumping** seems the most promising (extreme curvatures)



a Mould fabrication **b** Heating process **c** Hot slumping process **d** Bent panel

Fabrication methods		Assessment criteria: Visual	Geometrical Freedom				Structural	
		Transparency	Possible curvature (radius)	Consistency (thickness) of glass	Scalability	Ease of customization	Redundancy	Increased strength
Casting	monolithic	-	++	+	-	+	--	--
Casting	tessellated	-	+	+	-	+	++	--
Col bending	fastening to supports	++	--	++	+	-	+	++
Col bending	warm bending	++	--	+	+	-	++	++
Hot bending	roller bending	+	+	-	+	+	+	++
Hot bending	slumping	+	++	-	+	+	+	+
Extrusion		--	--	++	--	-	-	-
3d printing		--	-	++	--	++	--	--

Symbols : ++ very + medium / positive - medium / negative -- little

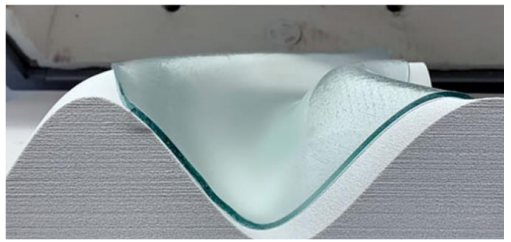
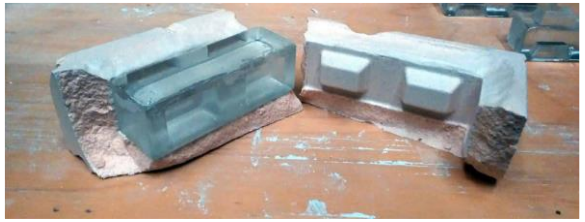
Types of moulds for curving

glass

multiple alternatives

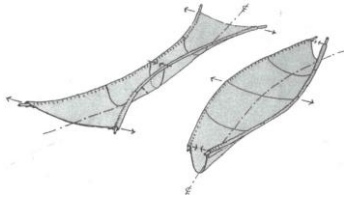







Types of moulds for curving
other materials



Flexible moulds

fabric formworks

inflatables

knitted

Assess & compare

No existing mould for glass offers at the same time

- Possibility for freeform geometry
- Big curvatures
- Easy customization

Flexible moulds for other materials

Knitted moulds

- Promising for complex geometries
- Easily customizable
- Little waste

			Assessment criteria												
			Visual			Geometrical Freedom					Fabrication limitations		Sustainability	
			Transparency	finishing quality	texture on surface	Possible curvature (radius)	Consistency (thickness) of glass	Size limitation for product	Freeform geometry production	Ease of mould customization	Need for post-processing/ coatings	Cost	Waste production	Reusability/ recyclability
Mouds for glass	Casting	permanent steel/graphite	++	++	-	++	+	-	+	-	+	++	+	+
		displosable	+	-	+	++	-	-	+	+	++	--	--	--
		3d printed sand	-	-	++	++	+	-	+	++	++	--	+	+
	Col bending (on site)	permanent steel/timber frame with clamps	++	+	-	--	++	++	--	+	--	-	-	+
	Hot bending (slumping)	steel-rod permanent	++	+	--	++	-	++	++	+	-	++	--	--
		adjustable	++	-	+	++	-	+	++	++	+	-	++	++
		3d printed sand	++	+	+	++	-	-	++	++	-	--	+	+

			Assessment criteria												
			Visual			Geometrical Freedom					Fabrication limitations		Sustainability	
			Transparency	finishing quality	texture on surface	Possible curvature (radius)	Consistency (thickness) of glass	Size limitation for product	Freeform geometry production	Ease of mould customization	Need for post-processing/ coatings	Cost	Waste production	Reusability/ recyclability
Mouds for other materials	Unconfigurable / flexible moulds	Inflatable	n/a	++	--	++	n/a	++	+	+	n/a	n/k	+	+
		Fabric formwork	n/a	++	+	++	n/a	++	++	++	n/a	n/k	+	-
		Knitted	n/a	n/k	++	++	n/a	++	++	++	n/k	--	++	-

Symbols : ++ very + medium / positive - medium / negative -- little n/a not applicable n/k not known

combination
not been tested

Experimental research

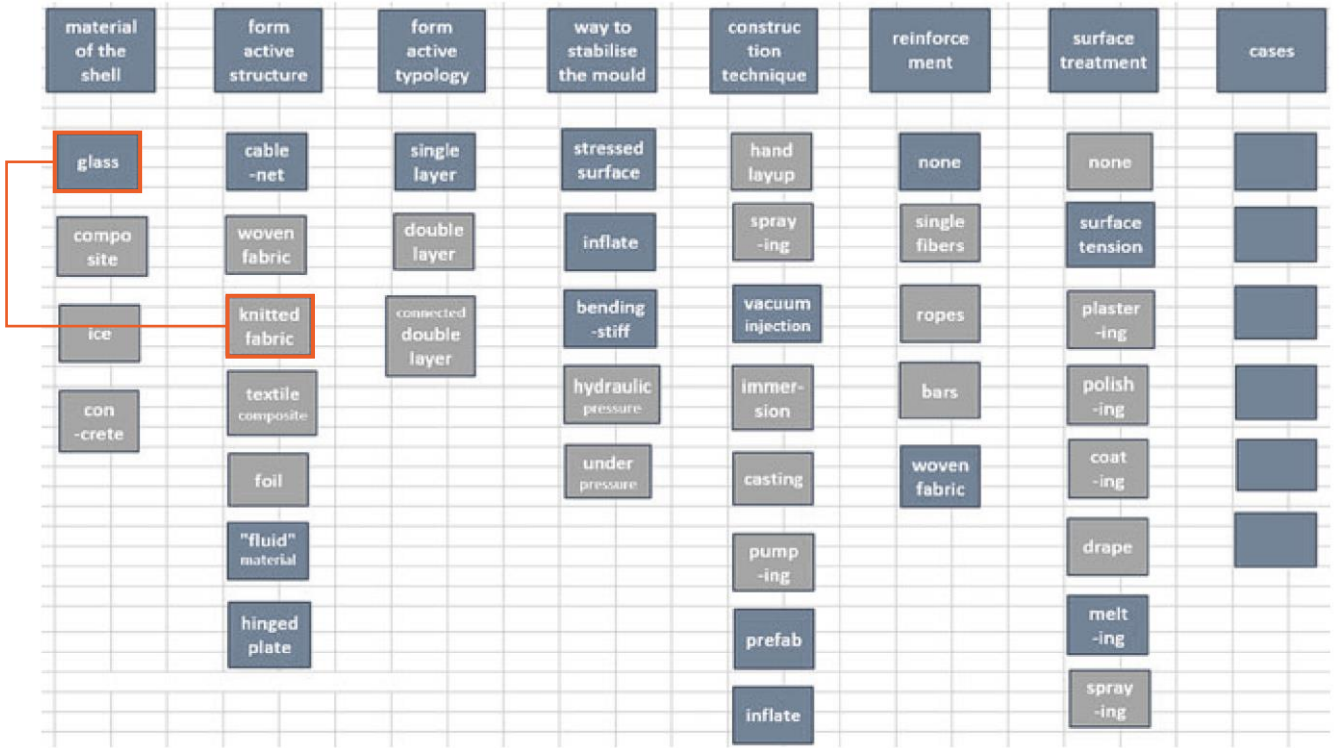


Diagram of flexibe moulding for fluid architecture with glass. Source: Pronk, 2021

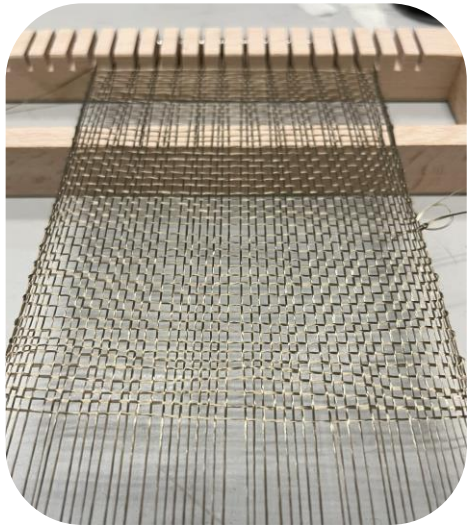
Experimental exploration

1. *Heat-resistant textile*

Moulds with Basalt fiber → **how?**

→ *Basalt yarn bobbin*

→ *Hand-weaving*



→ *CNC knitting*

why basalt?

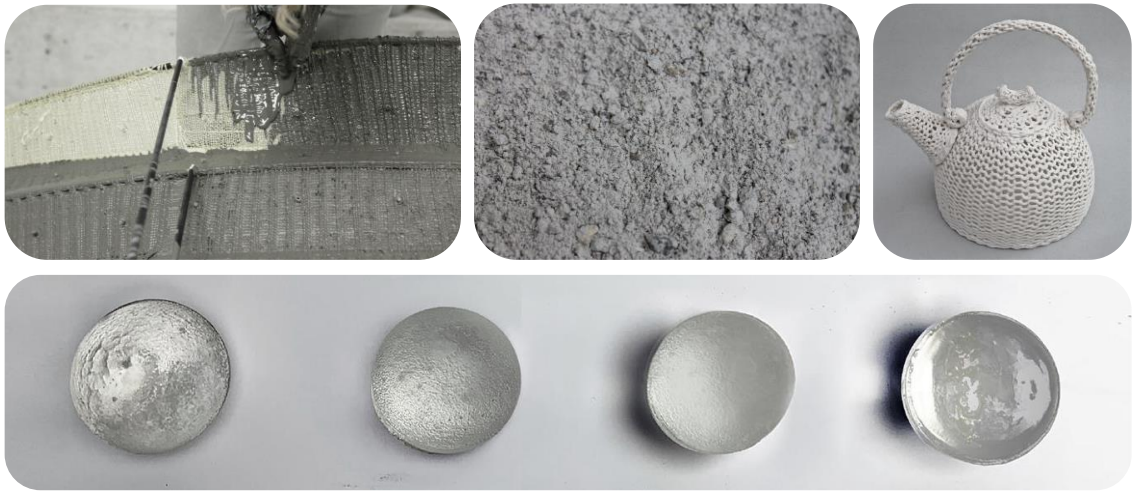
- Glass slumping temperatures: **600-800°C**
- *"**Basalt** fibre is the most environmentally friendly high temperature resistant material when it comes to both manufacturing and recycling it"*
  [Final Advanced Materials]

2. *Coatings & firing schedule*

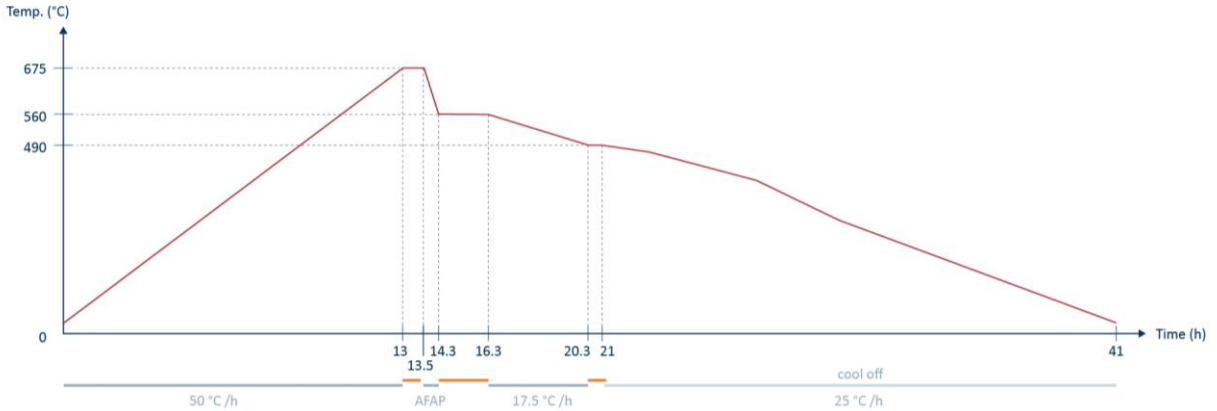
different coatings
- no coating
- cement
- porcelain
- crystalcast
- zirkofluid
- arkopal
- combinations

rigidifying shape

improving surface



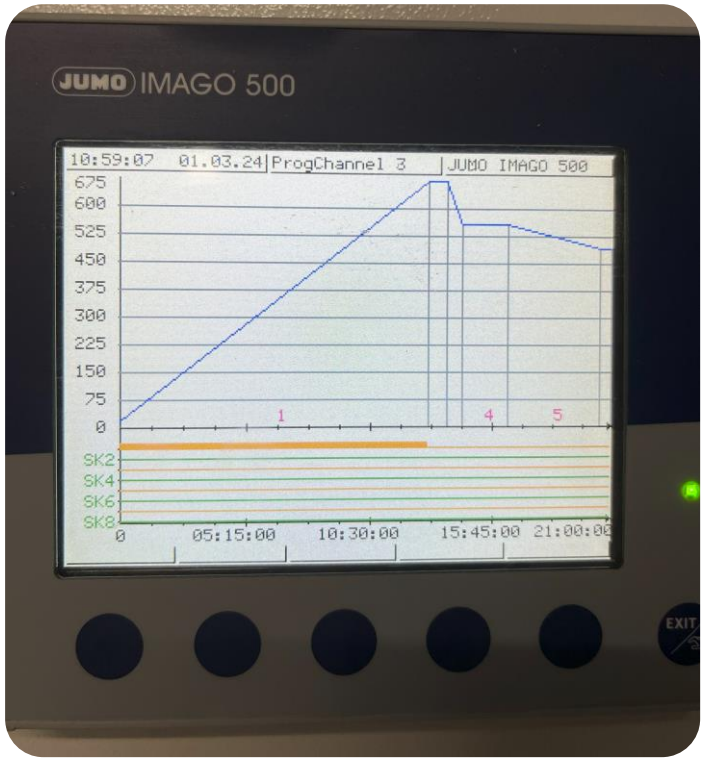
different temperatures
- 675 °C
- 800 °C



Typical set-up

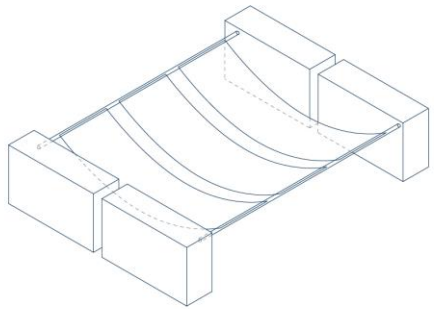
***1.** Glass oven*

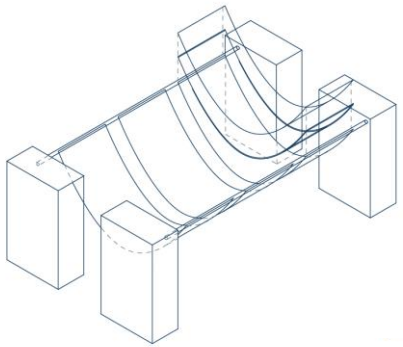
***2.** Use of bricks & stainless steel bars to set-up the basalt moulds and then place glasses on top*

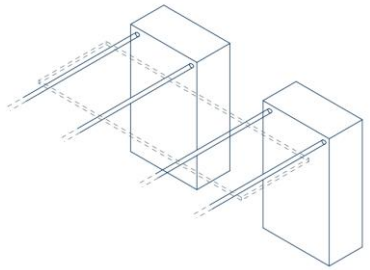


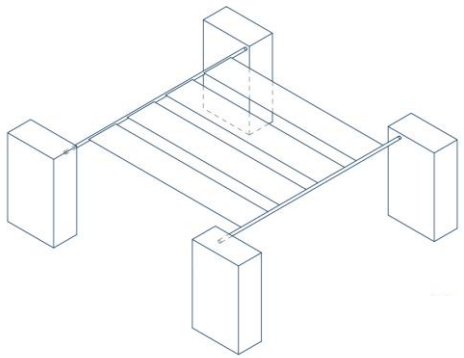
***3.** Set the oven schedule: 21 hours of firing + about 20 hours cooling time*

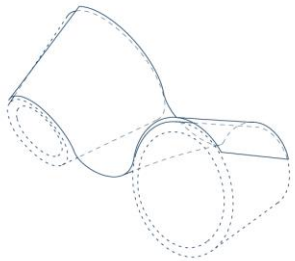
Experiments performed

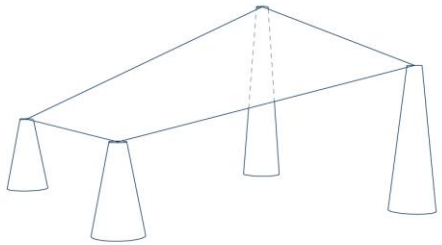


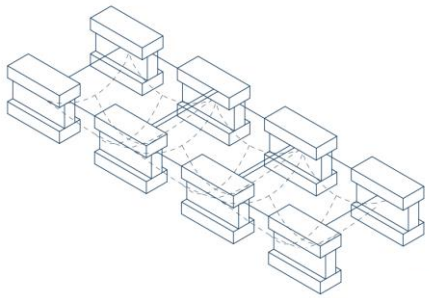


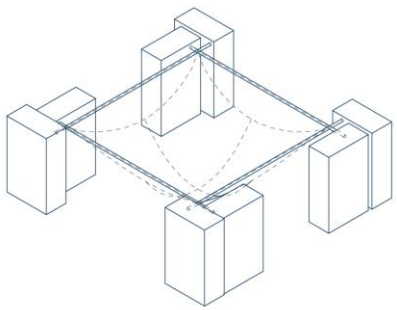


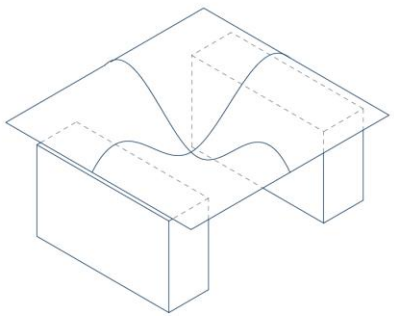






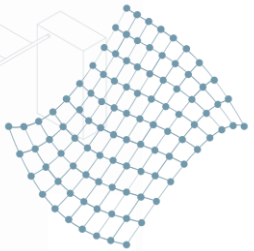






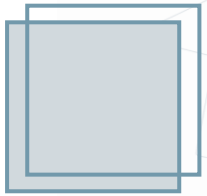
Main objectives

- geometry



- surface

- redundancy

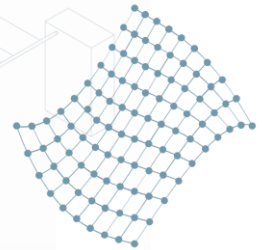


Main objectives

geometry

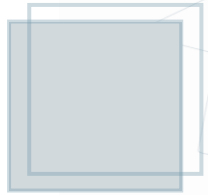
Single curved

Double curved



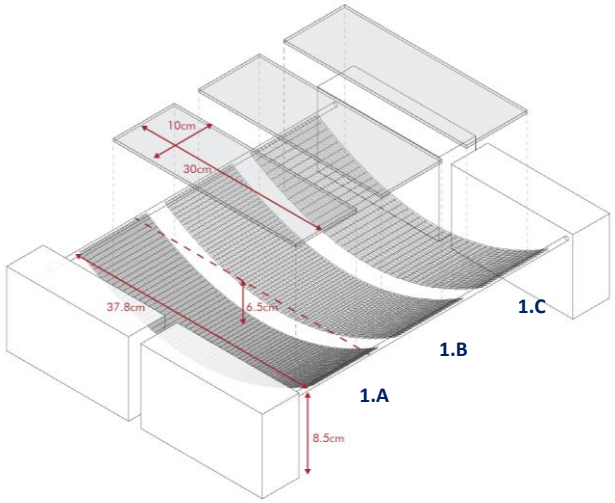
surface

redundancy



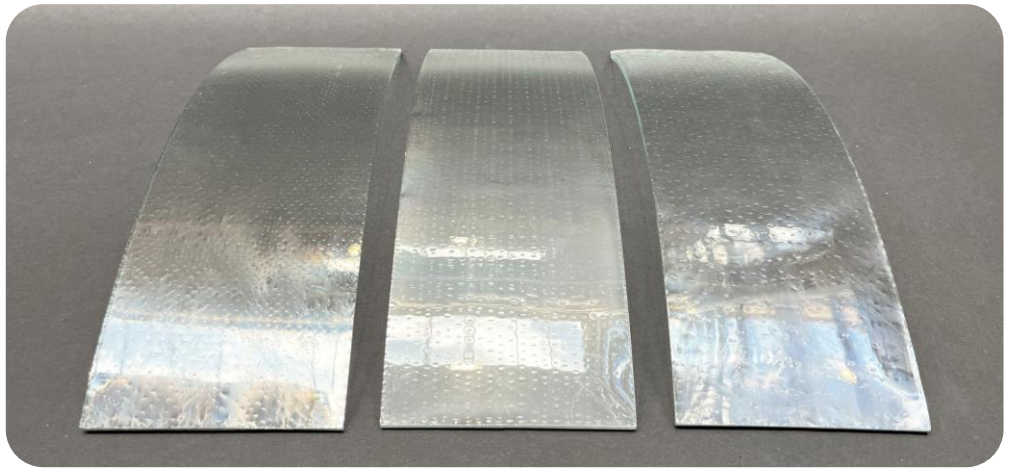
Single curved

Hand-woven moulds

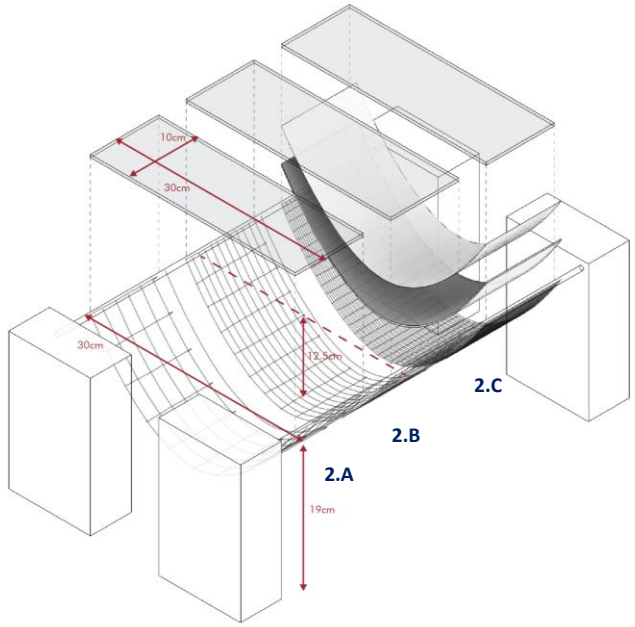


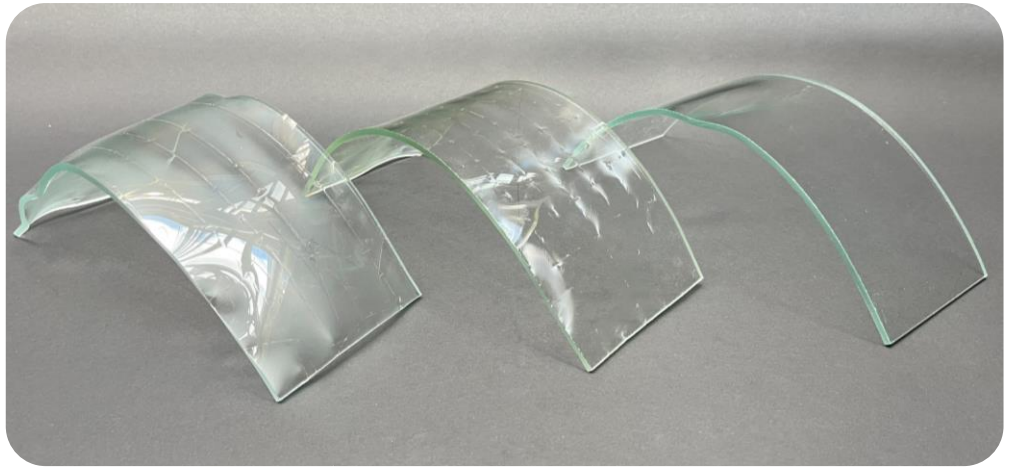
loose set-up

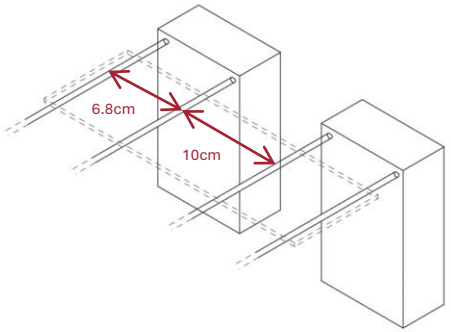
Single curved



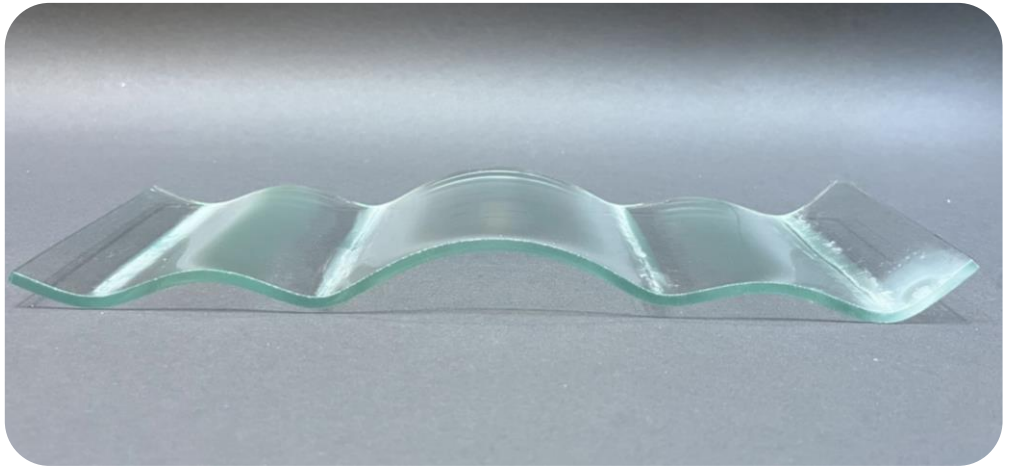
Hand-woven moulds





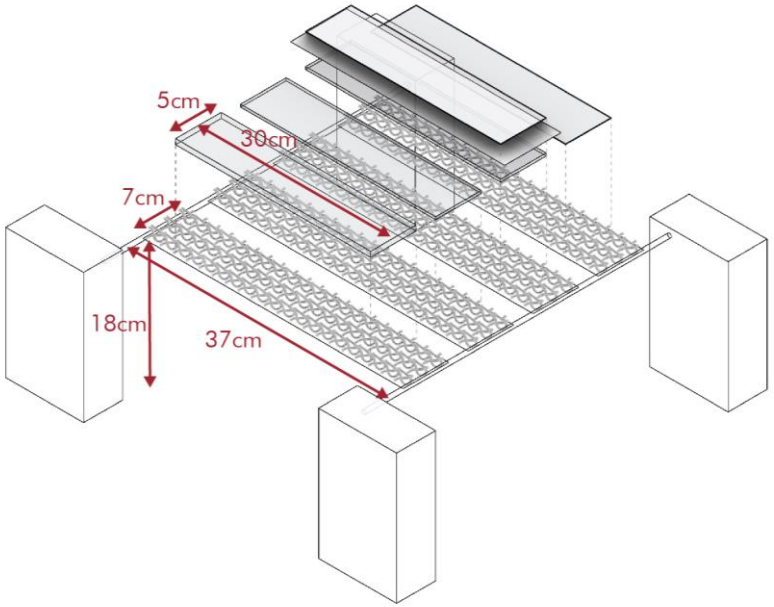


self-weight

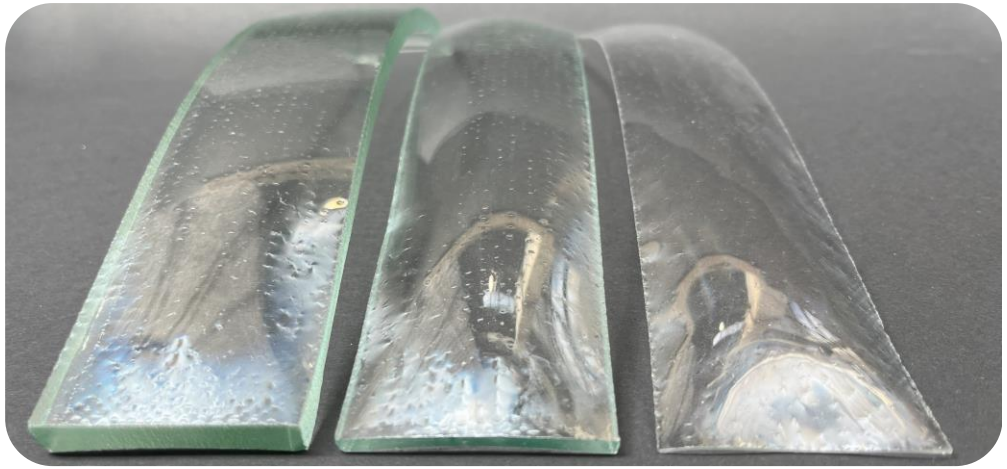


Single curved

CNC knitted moulds

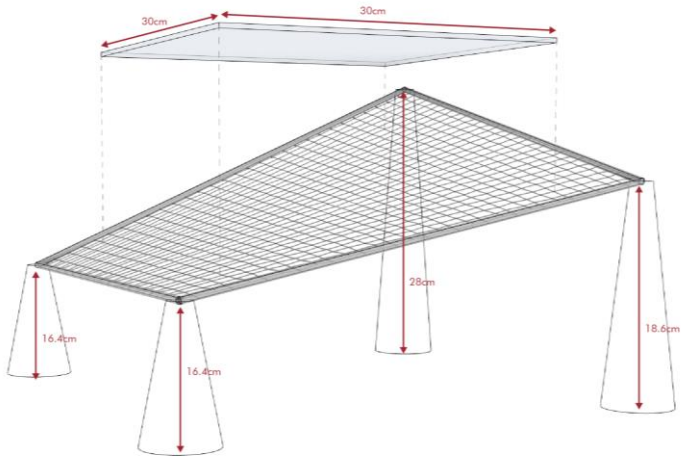


pretension



Double curved

Hand-woven mould



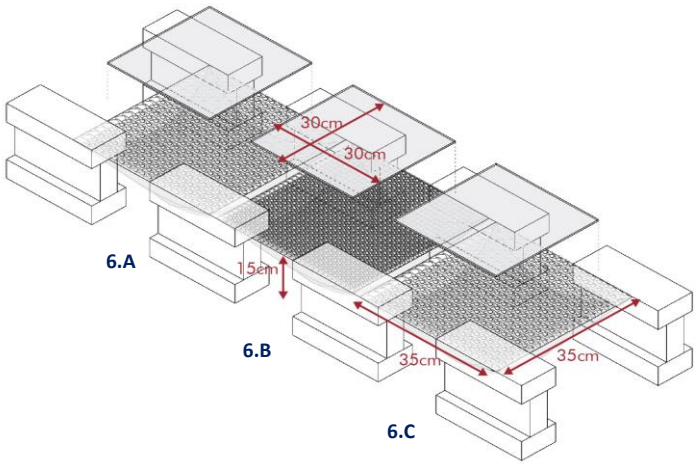
simple
double curvature

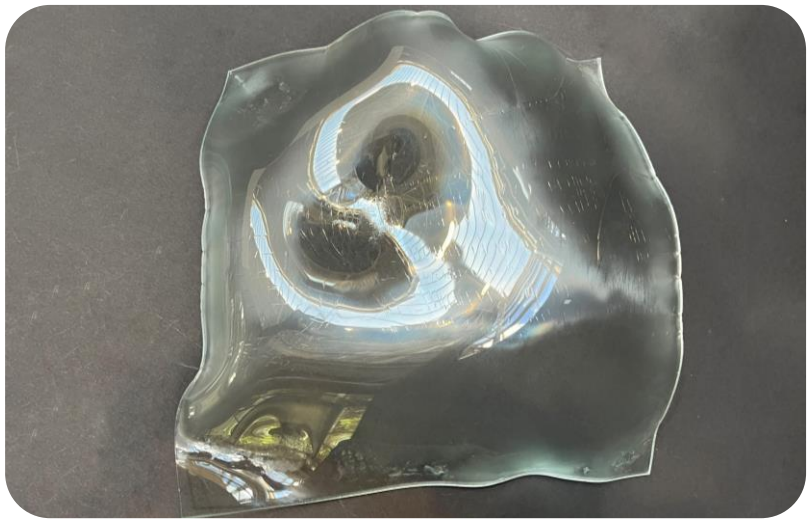
different heights

Double curved

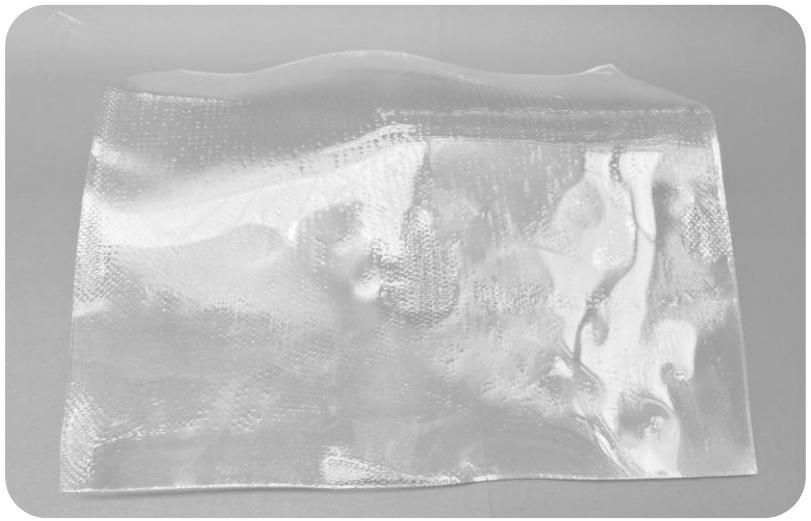
simple vault

CNC knitted moulds



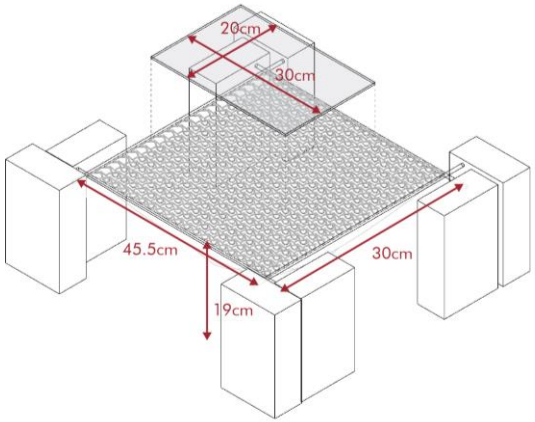


mould collapse / freeform result



mould collapse / no result

CNC knitted mould



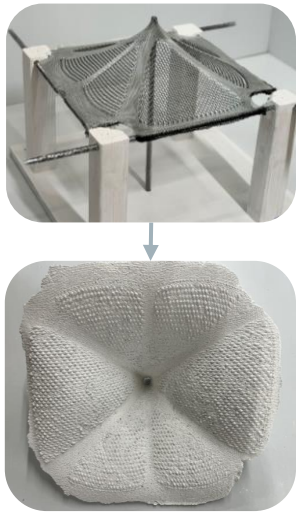
introducing multiple curvatures

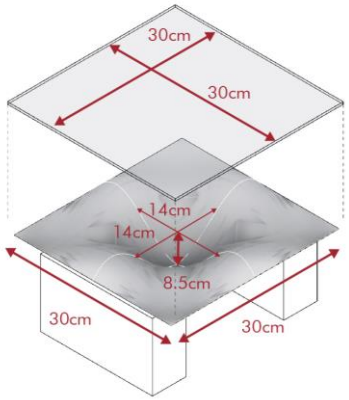
with different knit patterns

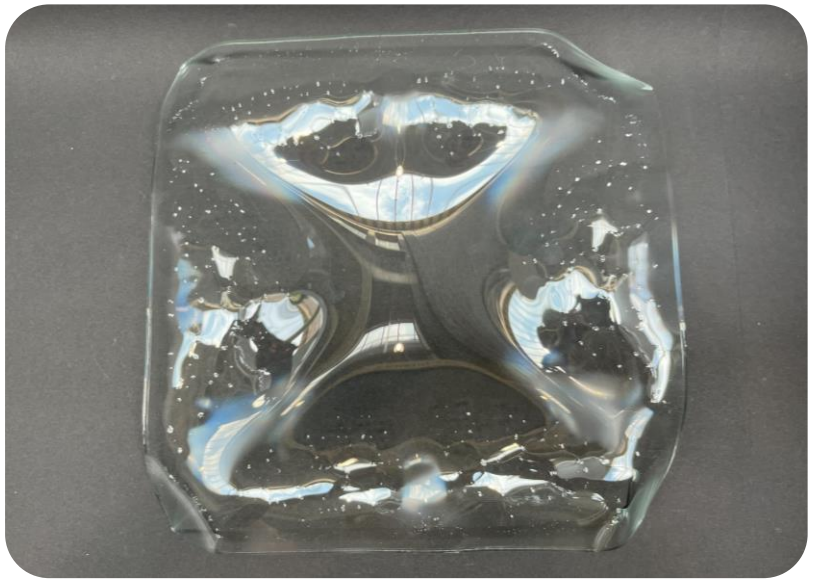
Double curved

with rigid mould

Heat-resistant cement mould







Results summary

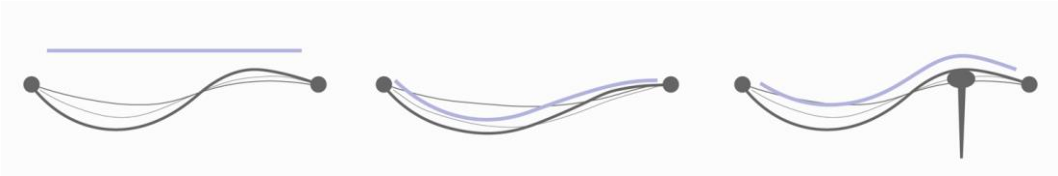
geometry

Deformation:

- limited for spans<10cm → max temperature constraints.
- Max deformation varies with glass thickness and knit pattern.

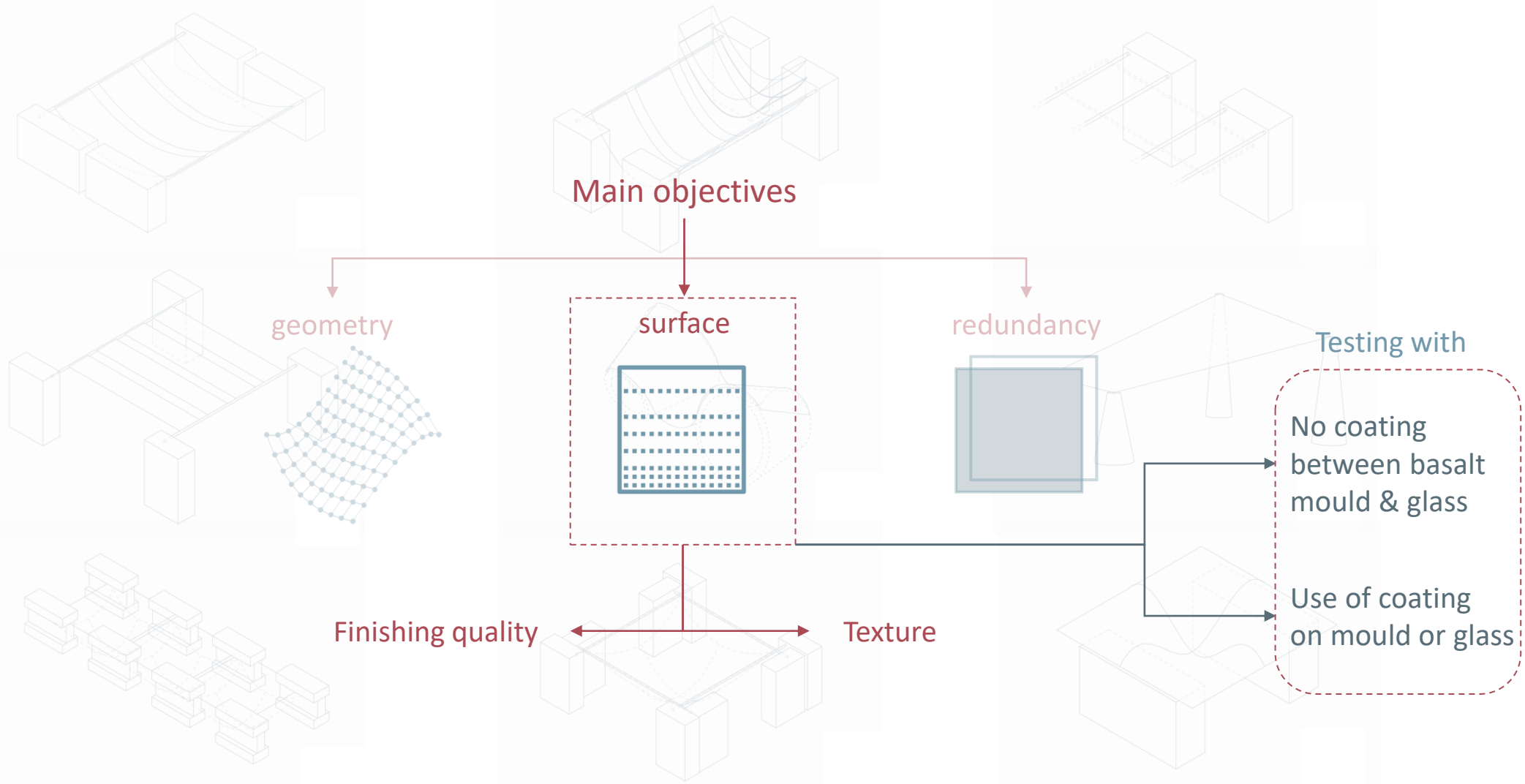
Freeform shapes:

- Change in knit pattern → can result in different curvatures.
- Change in curvature from positive/negative not possible with textile draping → only with extra supporting system.



X ✓

			experiment	glass size	glass thickness	span (a)	result
Geometry	2 supports 	hand-woven mould : loose set-up	1	10 x 30cm	4mm	single curved a > 30cm	deformation = a/5.8
			2				deformation = a/2.3
		no mould	3	10 x 30cm	4mm	single curved a = 10cm	deformation = a/4
			3			single curved a < 10cm	deformation = a/17
		knit mould : pretensioned	4	5 x 30cm	8mm	single curved a > 30cm	deformation = a/6.8
					4mm		deformation = a/8.8
					1 + 4mm		deformation = a/8.3
					1mm		deformation = a/10
		support in 2 points : mould fixed in place by coating	5	10 x 30cm	4mm	double curved a = 34cm	failed
	4 supports 	4 corners : different heights	6	30 x 30cm	4mm	double curved a = 35cm in both directions	accidental freeform - no control in geometry result
		4 corners : same heights	7	30 x 30cm	4mm	double curved a = 35cm in both directions	failed
		4 edges (knit mould)	8	20 x 30cm	4mm	double curved a1 = 30cm a2 = 45.5cm	vault geometry + extra bubble formations
		4 edges (cement mould)	9	30 x 30cm	4mm	double curved a = 30cm in both directions	multiple curvatures following the shape - middle deformation not as much as cement
					1mm		


Main objectives
geometry
surface
redundancy
Testing with
No coating between basalt mould & glass
Use of coating on mould or glass
Finishing quality
Texture

No coating

No coating

Finishing quality

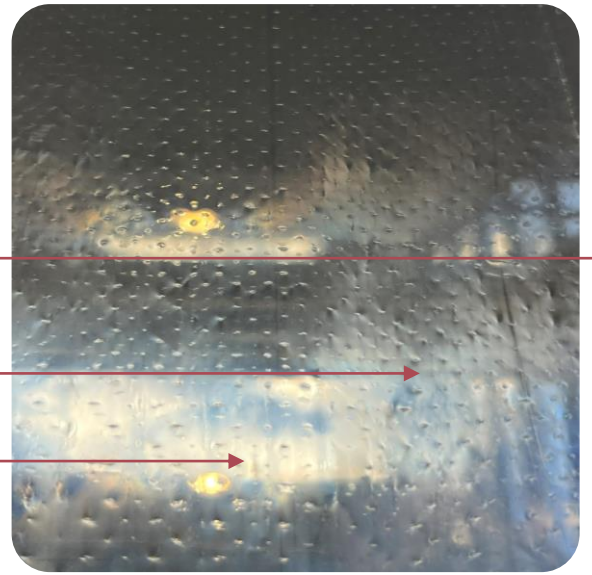
“Foggy” surface

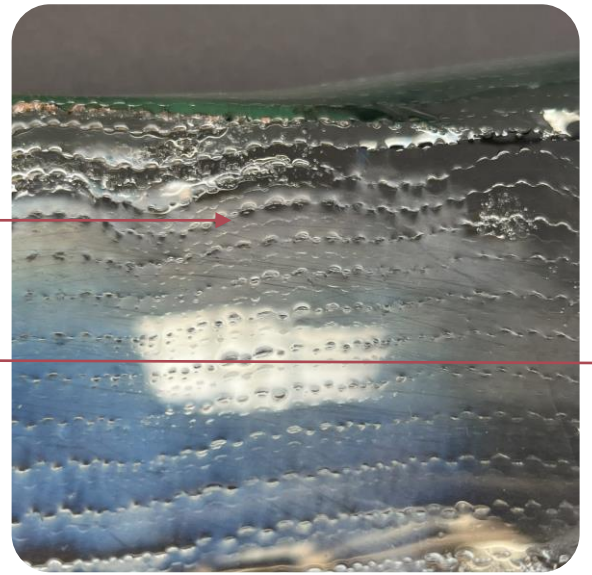
↓

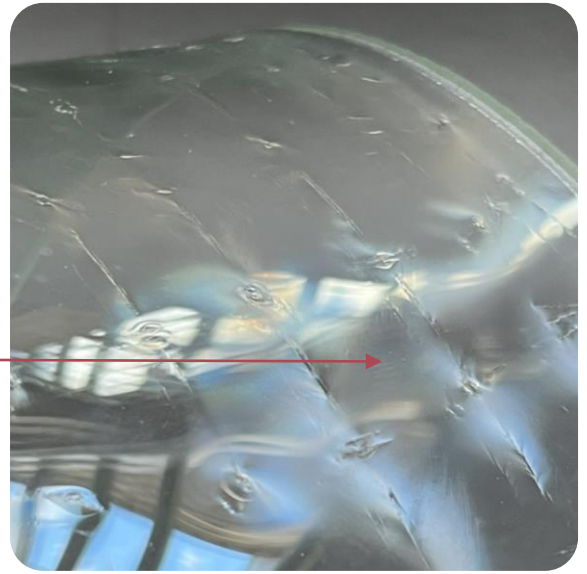
crystallization

Texture

- Following mould support point
- Fewer supports from mould → stronger imprints







No coating

Light color on surface texture

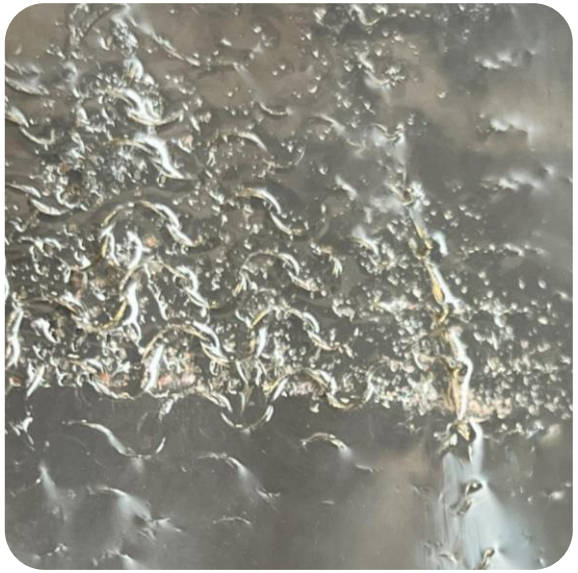
↓

Basalt inclusions

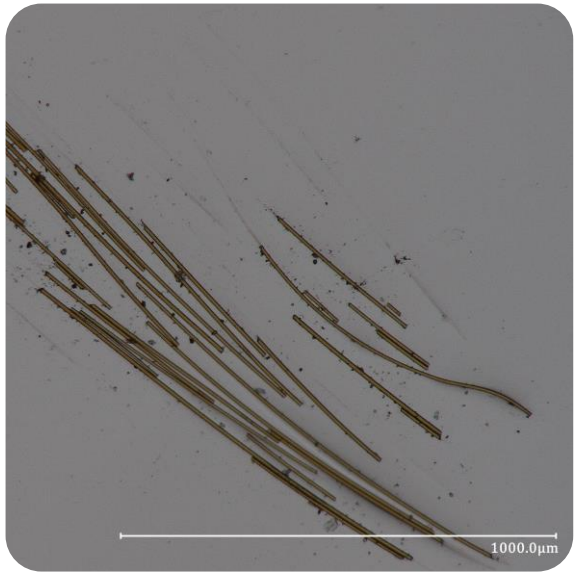
↓

Microscopic study & extra tests

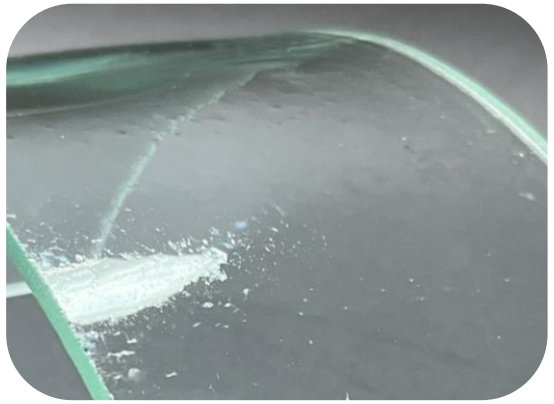
- No residual stresses in the glass
- Different material properties do not pose threat for post-breakage of glass



Cross-polarization test

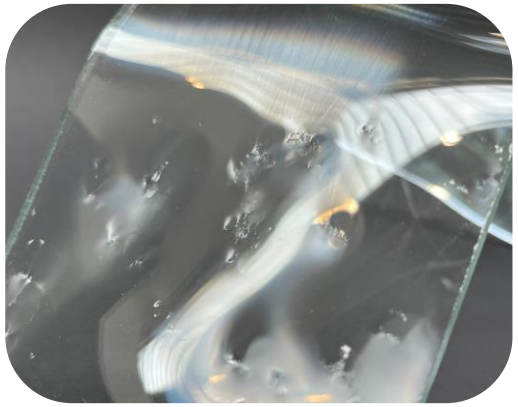


Coating

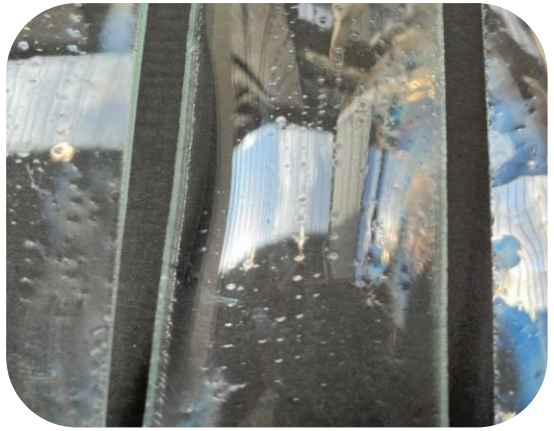


Biosoluble + thin fire paper

Cystalcast



Coating



Clearcoat Overglaze

Heat-resistant cement

Results summary

surface

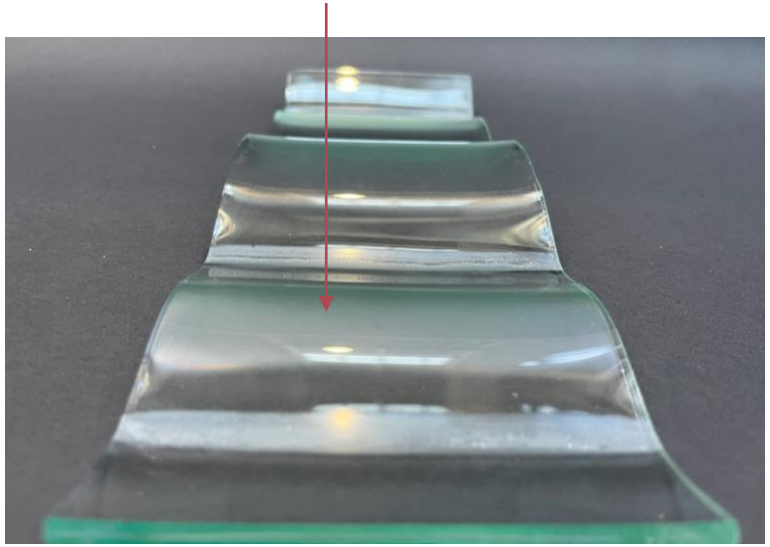
No Coating:

- Easy de-moulding = no need for coating.
- Surface crystallization.

With Coating:

- Almost transparent surface but still not perfect.
- Best surface with rigid coatings.

No mould: shows crystallization! → **Matter of the firing schedule**



				experiment	glass thickness	curvature	result
Surface	finishing quality	no coating	many contact / support points with mould	1	4mm	single curved	light crystalization + stretch marks
				7		double curved	almost completely transparent
				8		double curved	almost completely transparent
			few contact / support points with mould	2.A	4mm	single curved	great crystalization + stretch marks
				2.B		single curved	light crystalization + stretch marks
				6		double curved	great crystalization + stretch marks
				3		single curved	great crystalization
		coating	biosoluble & fire paper	2.C	4mm	single curved	almost completely transparent
			crystalcast	5	4mm	double curved	almost completely transparent
			heat-resistant cement	9	4mm	double curved	fully transparent
			devitrificati on spray	4	4mm	single curved	very light crystallization at some parts of the glass

Results summary

surface

No Coating:

- Texture imprints depending on density of mould & glass thickness.

With Coating:

- No texture from the mould itself.
- Paper layers leave light texture.
- Rigid. coatings (crystalcast & cement) leave strong imprints and inclusions of material → potential microcracks.

No use of coatings preferred

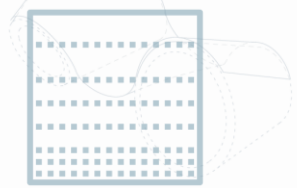
				experiment	glass thickness	curvature	result
Surface	texture	no coating	many contact / support points with mould	1	4mm	single curved	visible smaller point imprints & small inclusions of basalt fiber
				7		double curved	
			few contact / support points with mould	2.A	4mm	single curved	strong imprints & visible inclusions of basalt fiber
				2.B		single curved	
			change in supporting pattern of mould	6	4mm	double curved	strong visible support point imprints
				8		double curved	visible imprints only at edges of changing pattern (bubble edges)
		coating	biosoluble & fire paper	2.C	4mm	single curved	very light texture from biosol. paper
			crystalcast	5	4mm	double curved	visible strong imprint spots/dots like cracks
			heat-resistant cement	9	4mm	double curved	visible strong imprint spots/dots like cracks

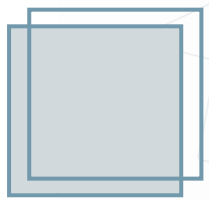
Main objectives

geometry

surface

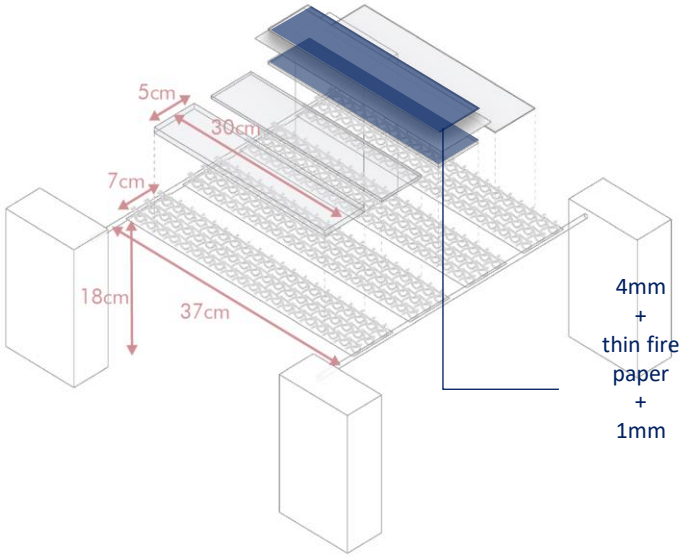
redundancy



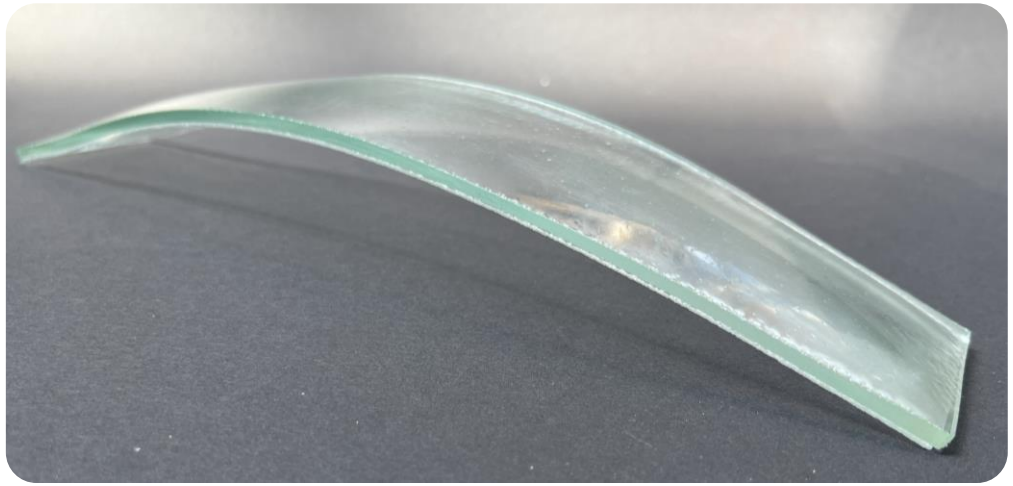


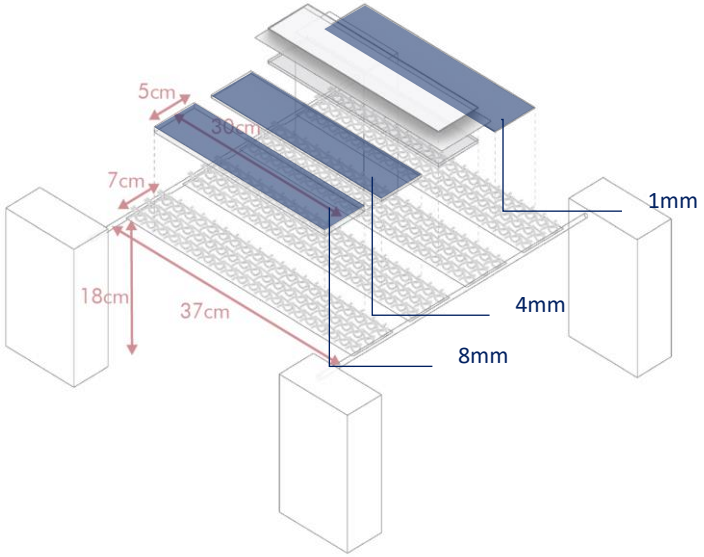
Lamination possibility

Glasses need to result in same curvature
& be able to inter-lock perfectly



Simultaneous slumping

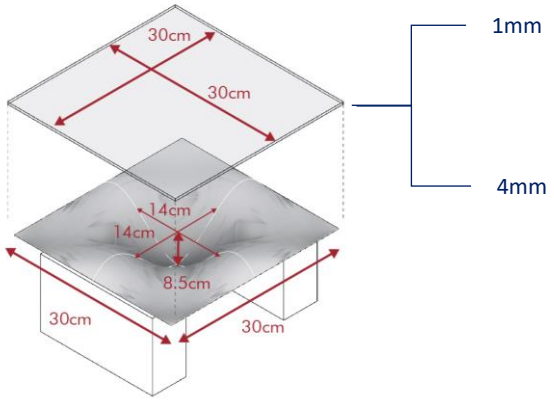


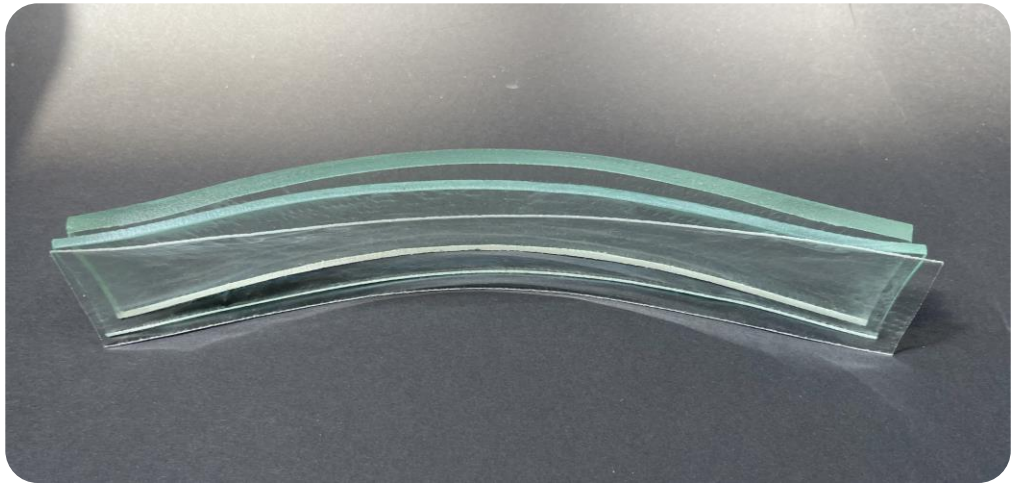


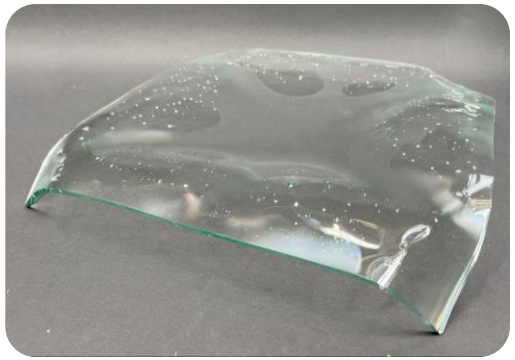
3 different glass thicknesses

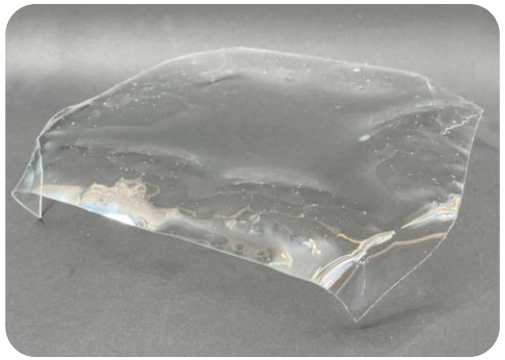
Separate slumping

2 different glass thicknesses









Results summary

redundancy

Simultaneous Slumping:

- Possible to slump two glass pieces together.
- Achieved even and exact replicate curvature.

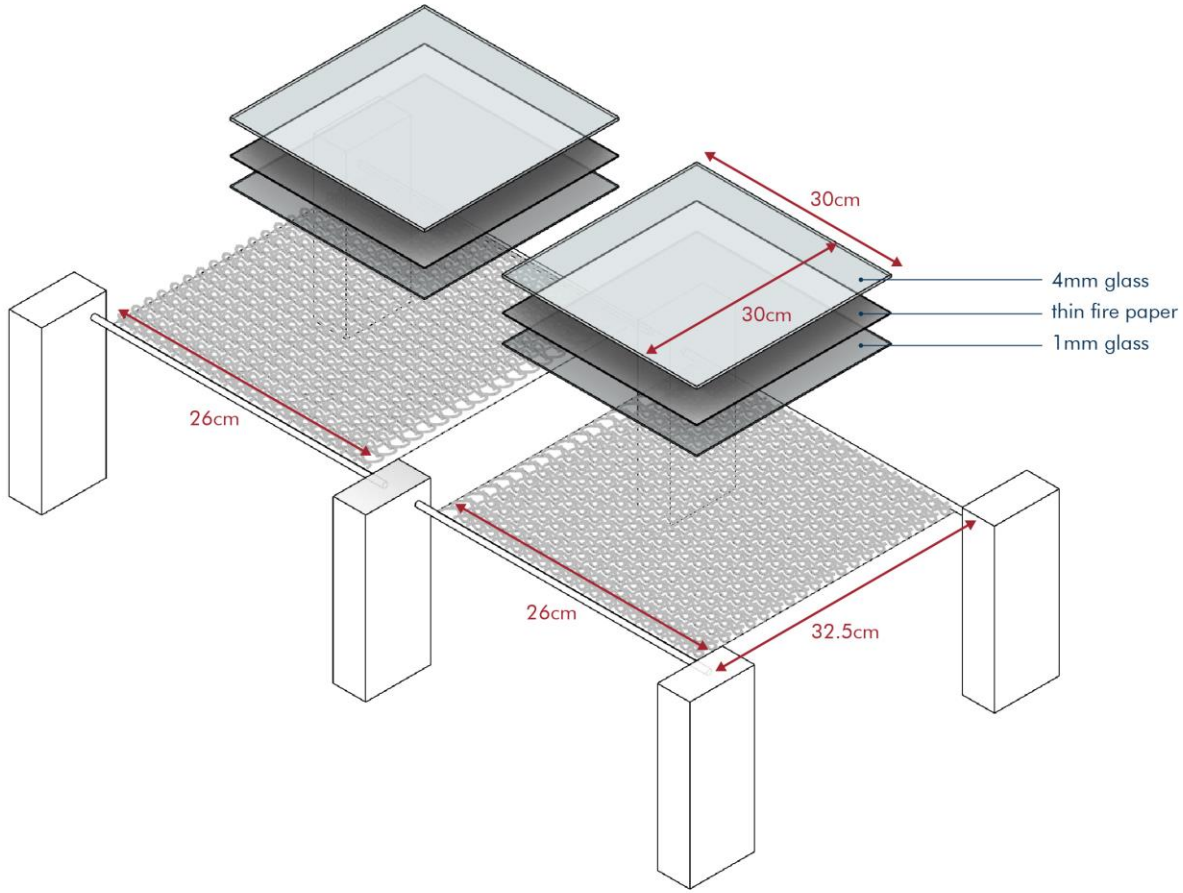
Separate Slumping:

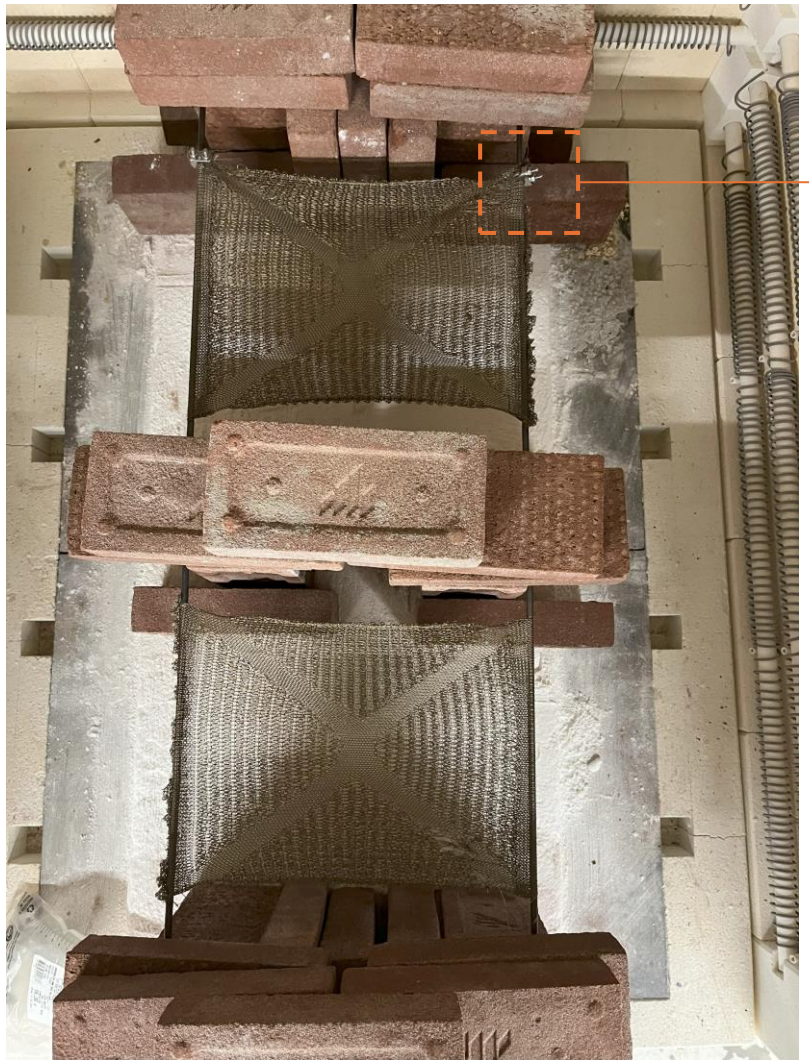
- Different curvatures under the same conditions.
- Thicker and thinner glasses did not match in curvature → different loading “pushing down” the glass (self-weight).
- Lamination of separately slumped glass pieces is not feasible → misalignment in curvature.

		experiment	glass thickness	curvature	**result**
Redundancy	simultaneous slumping 	4	4+1mm	single curved	perfectly aligned
	separate slumping 	9	4mm	double curved	not same curvature
			1mm		
		5	8mm	single curved	not same curvature
			4mm		
			1mm		

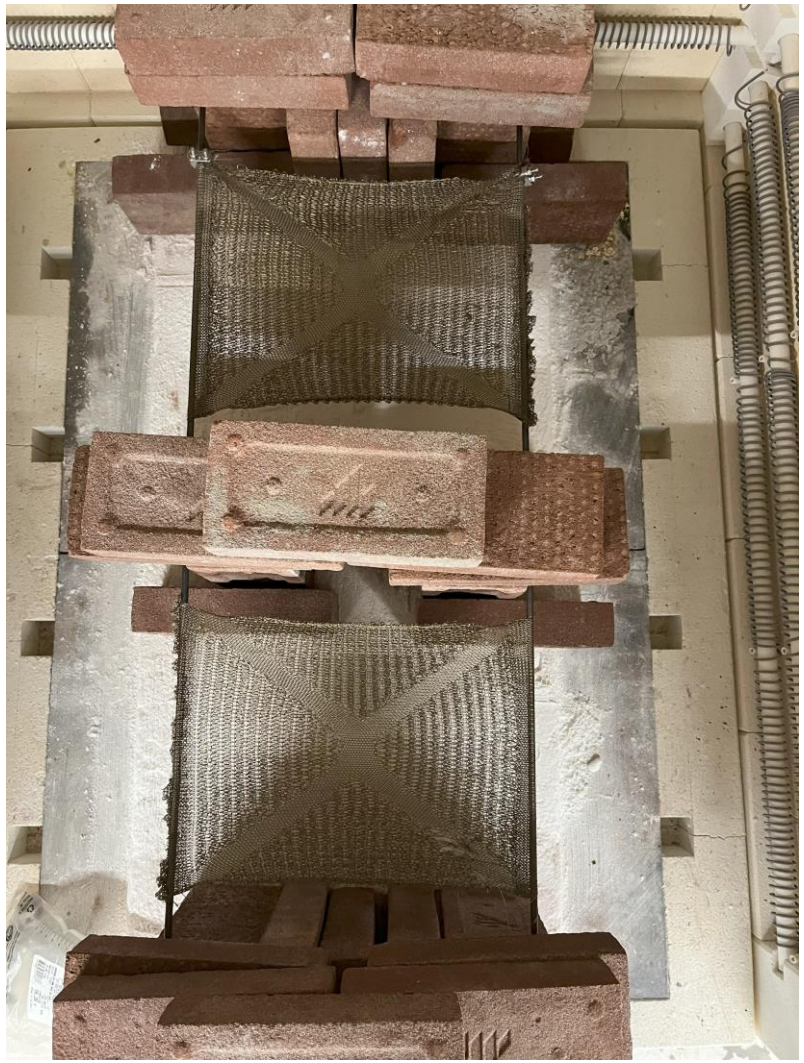
Final prototype

Aim: determine the level of control in the final achieved geometry by testing its replicability

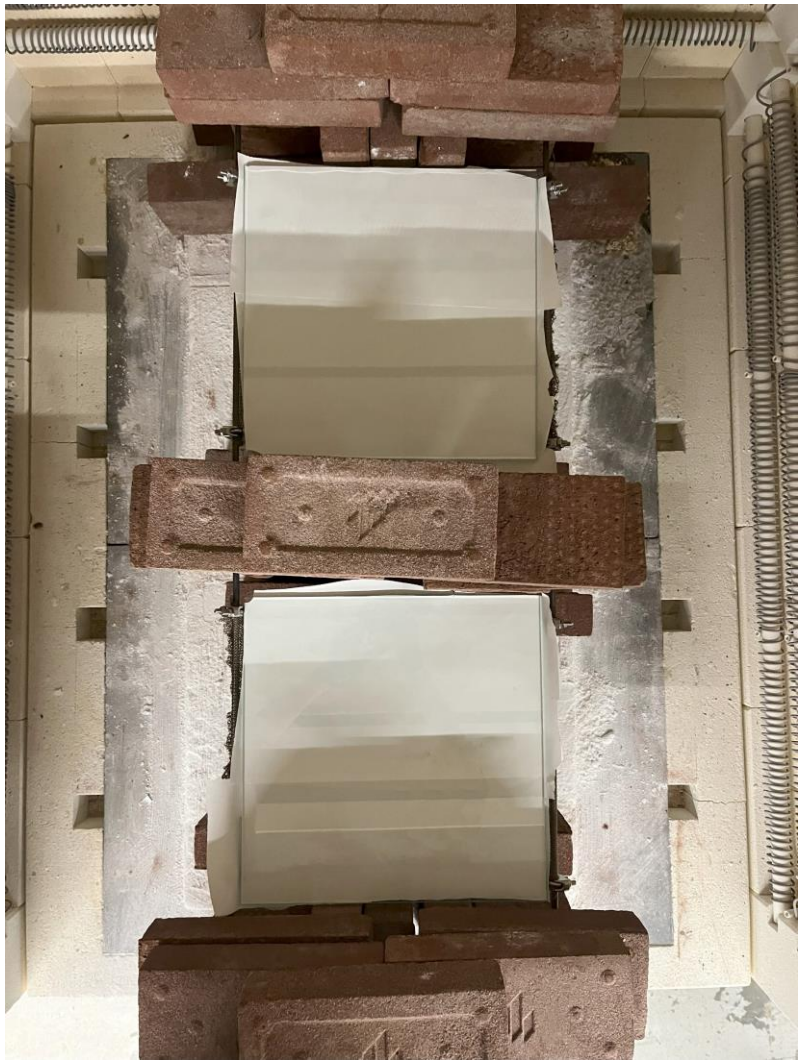




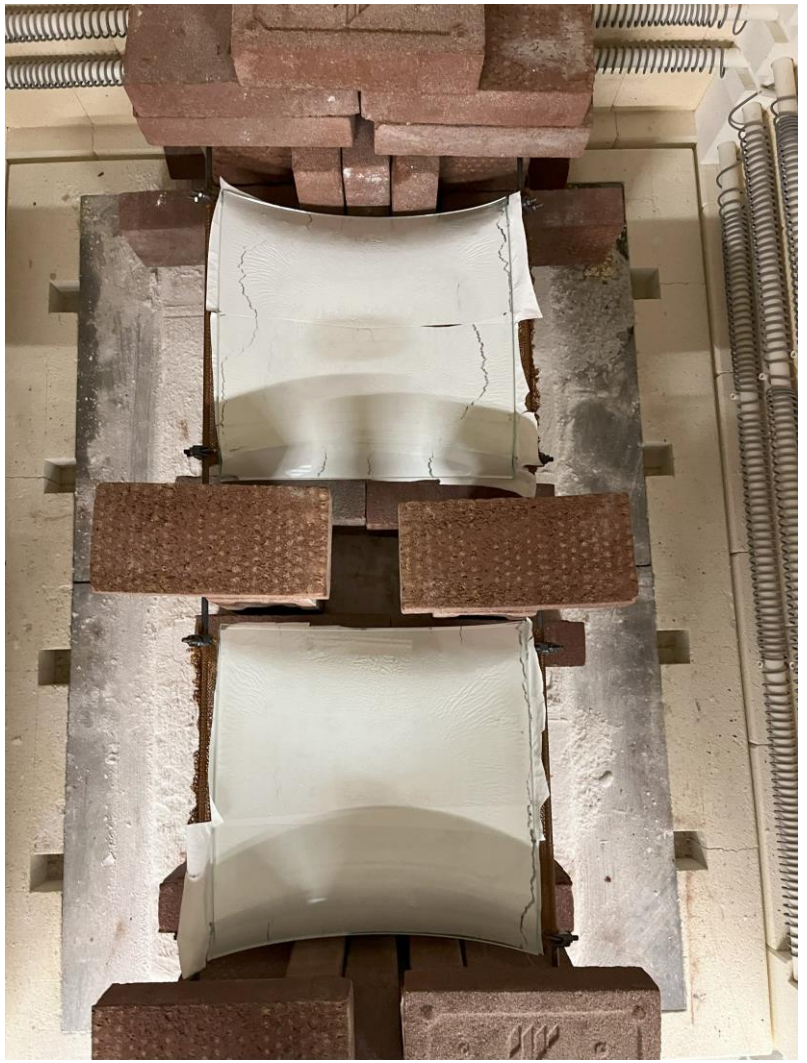
Moulds are tensioned in place on the set-up inside the oven



Moulds are tensioned in place on the set-up inside the oven



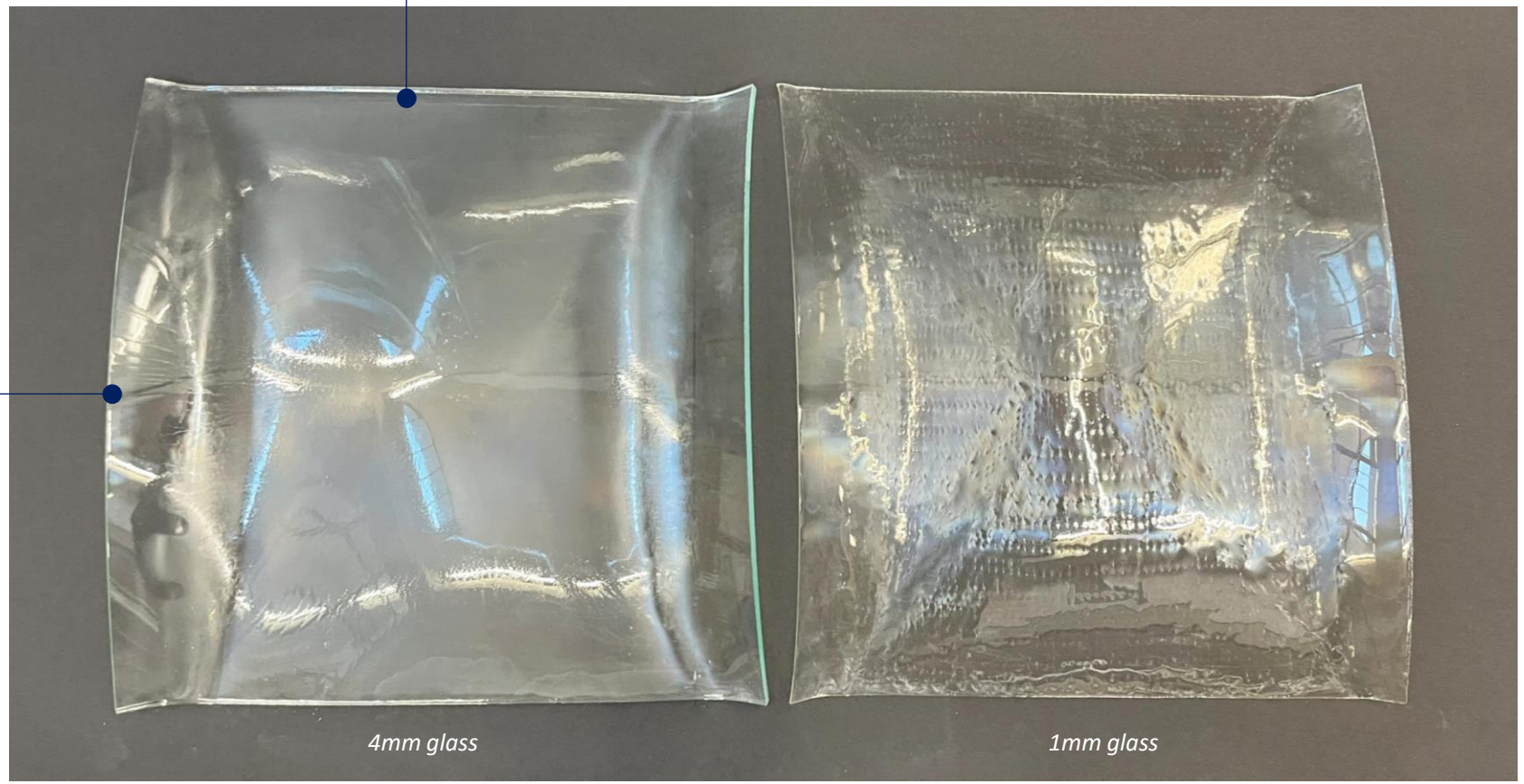
First glass placed on top of mould, then thin fire paper, then glass



After slumping at 675°C firing schedule

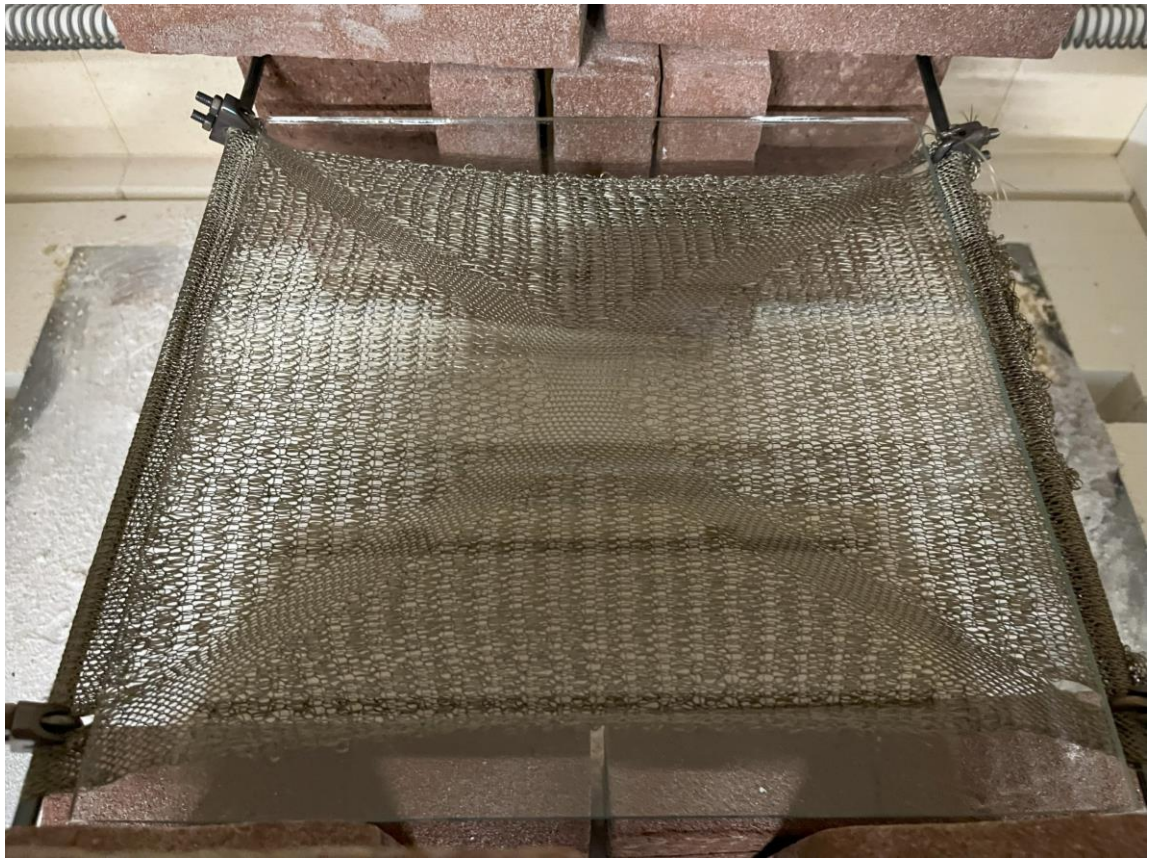
flat side along supported edges

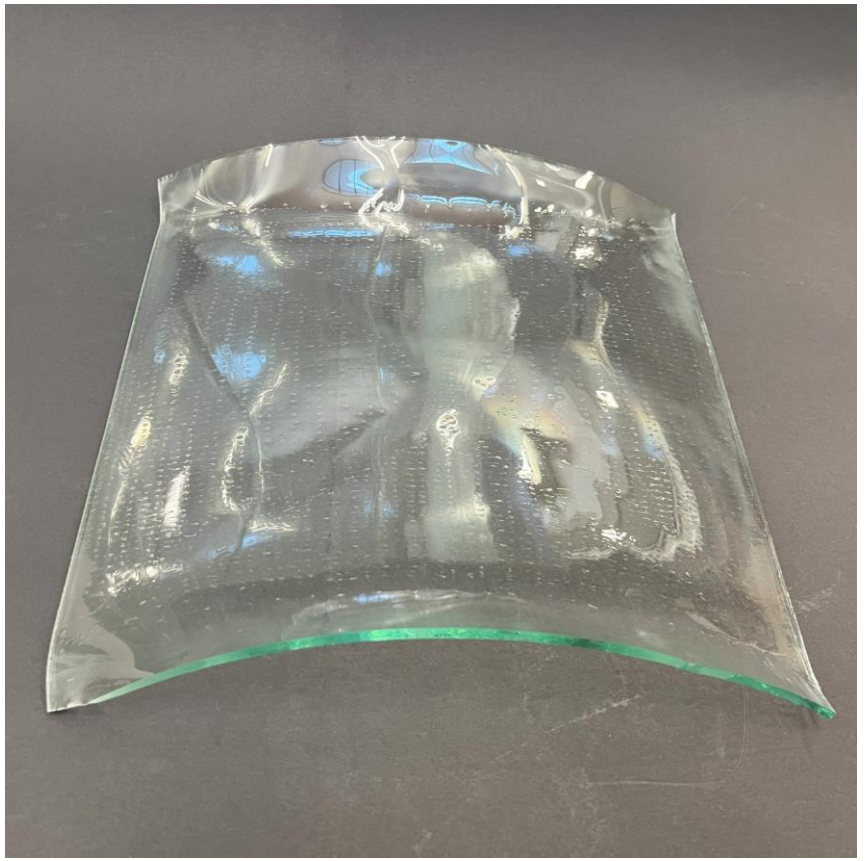
larger side curvature due to cantilevered sides



- *Overall geometry influenced by thin fire paper between glasses & density of knit patterns*

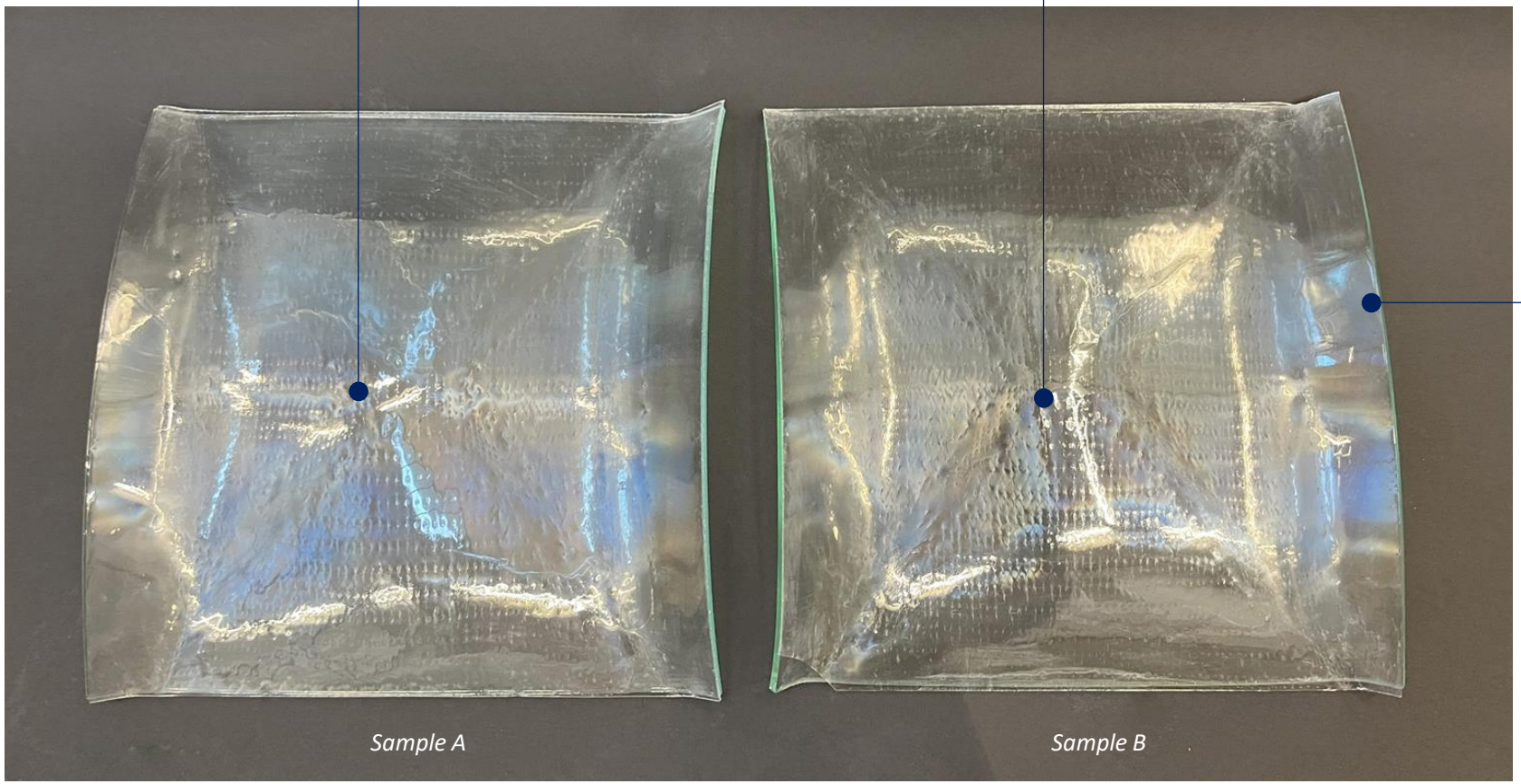
Repeating with 1 glass layer





- *Almost exact geometry replication showing minimal influence by thin fire paper in previous experiment*

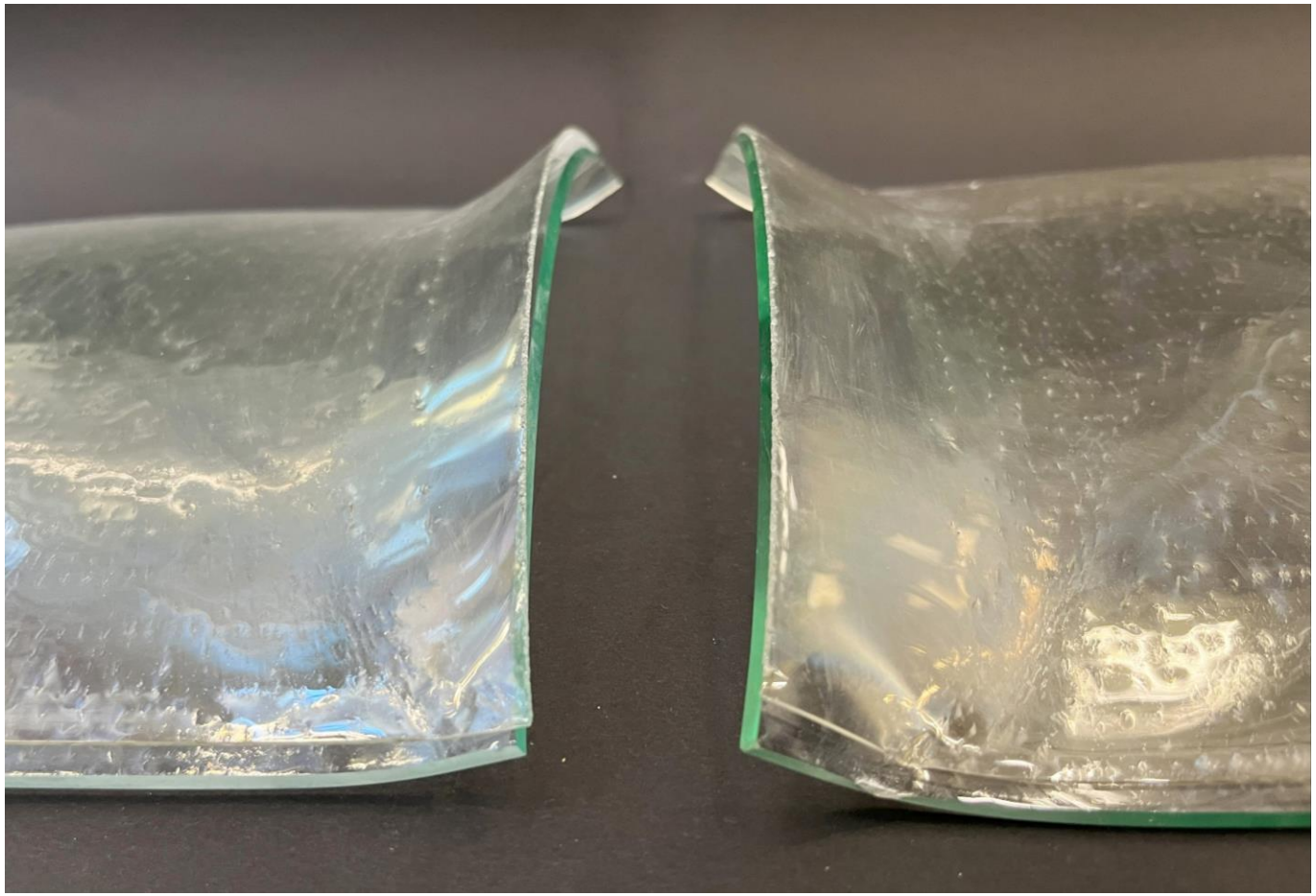
Comparing the 2 samples



- *Sample might have moved during set-up & differences between set-ups caused different deformations*
  → relatively high fabrication tolerance for this scale

Swapping the pairs

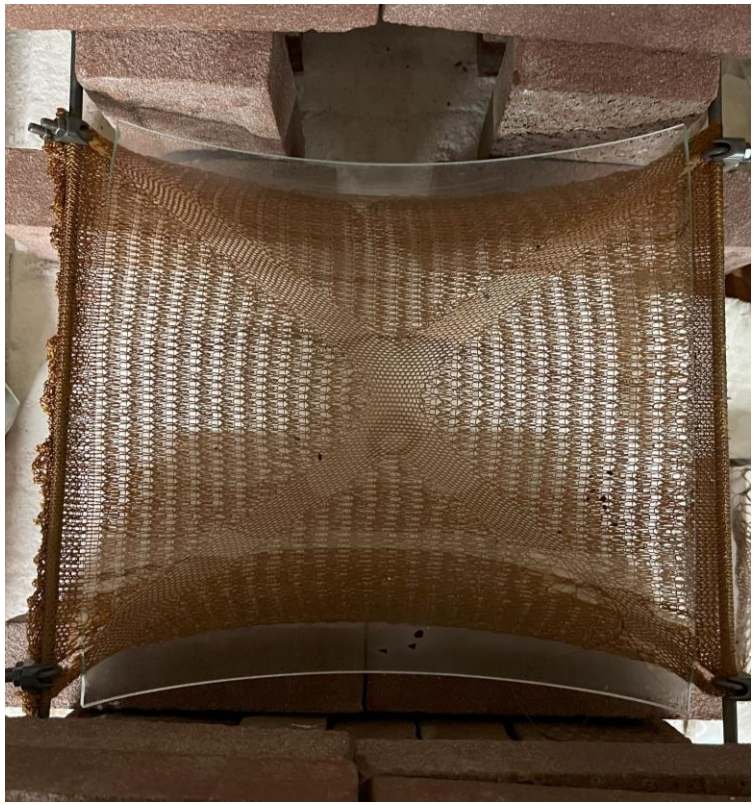
- *Clear movement during set-up*
- *Not symmetrical (cannot be swapped in any of the 2 directions)*
- *Supported sides' 'triangles' follow the same curvature*

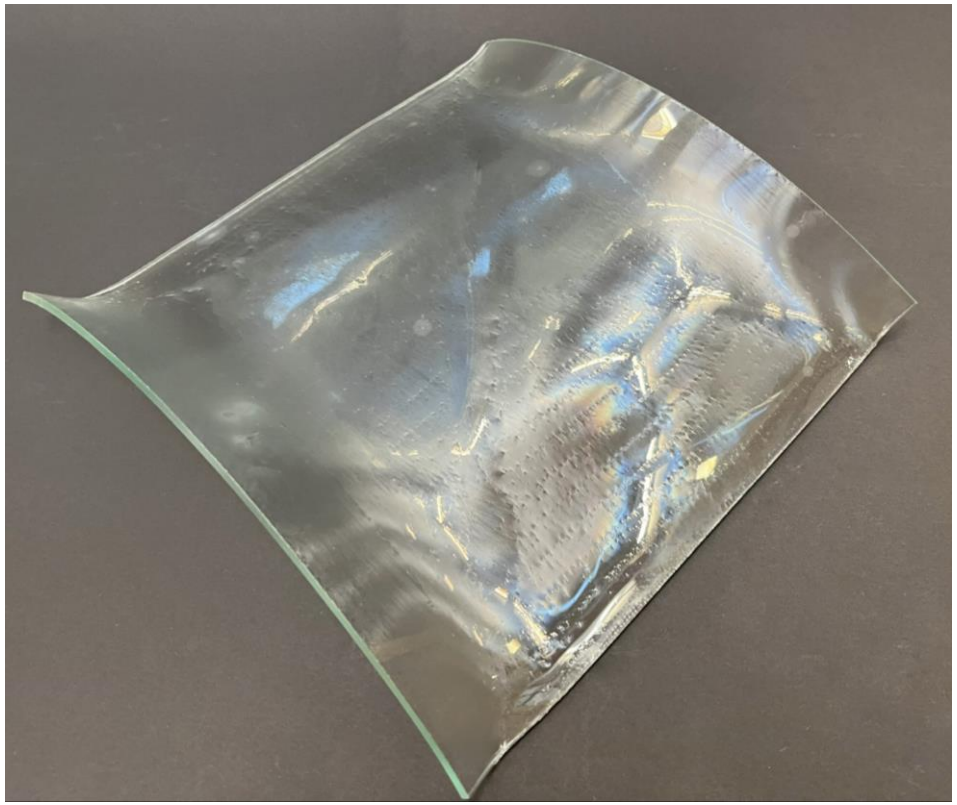


The mould after slumping

- *Basalt becomes brittle & loses large percentage of its strength*
- *Not possible to retention mould without breakage*
- *No possibility for reuse as directly loaded mould*

- *Geometry repetition with slightly bigger deformation (mould is already "stretched")*
  Mould could not be reused 2nd time



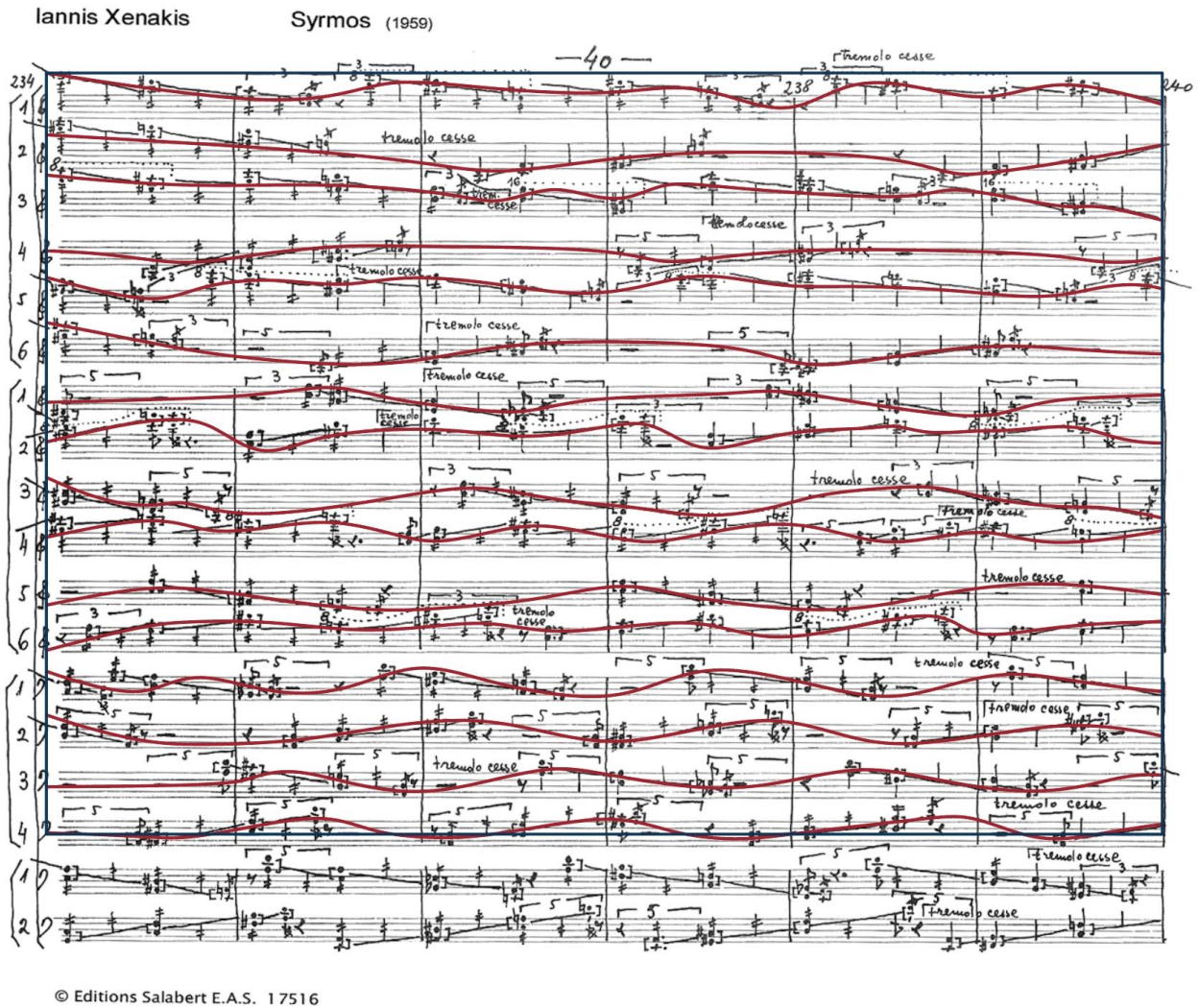


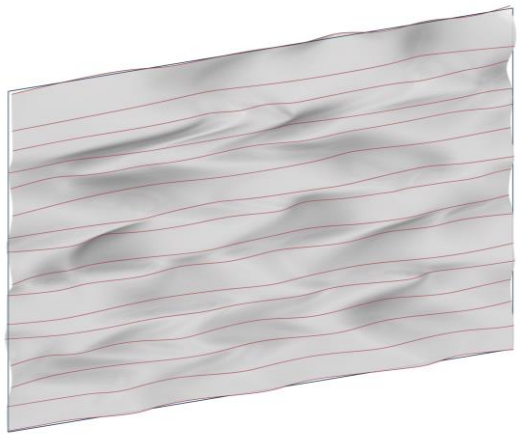
Design application

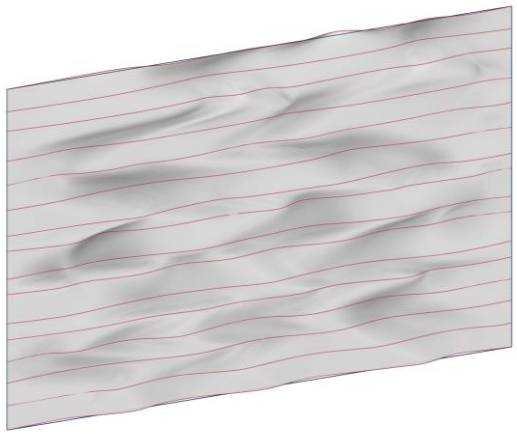
Case study

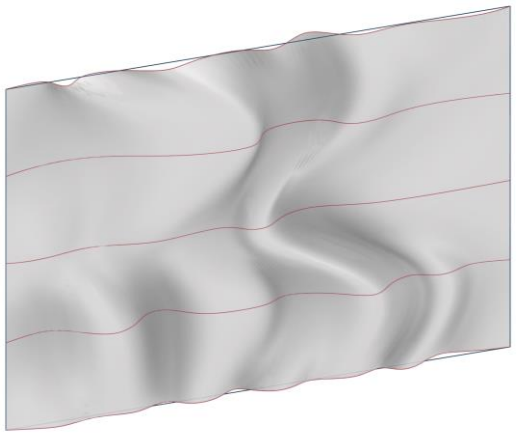
Casa da Musica, Porto

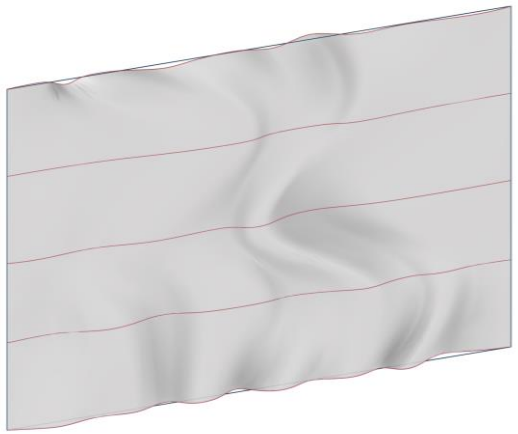
What if the façade was inspired by music?





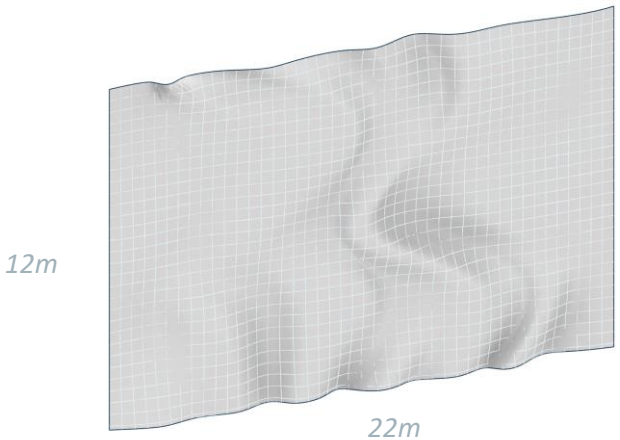






Translation of the musical curves

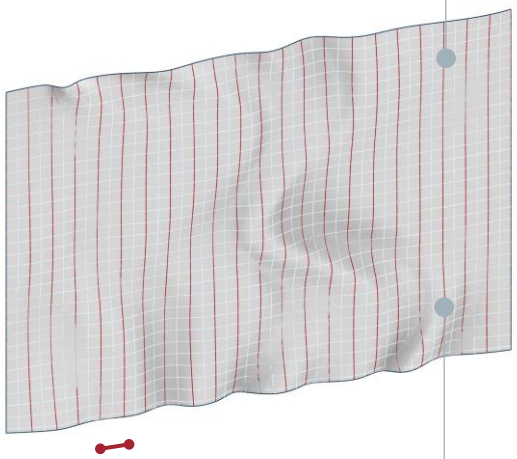
Remapping the surface giving boundaries for curvature



Divide in panels for fabrication

Division by current fabrication limitations

Division of self-supported facade

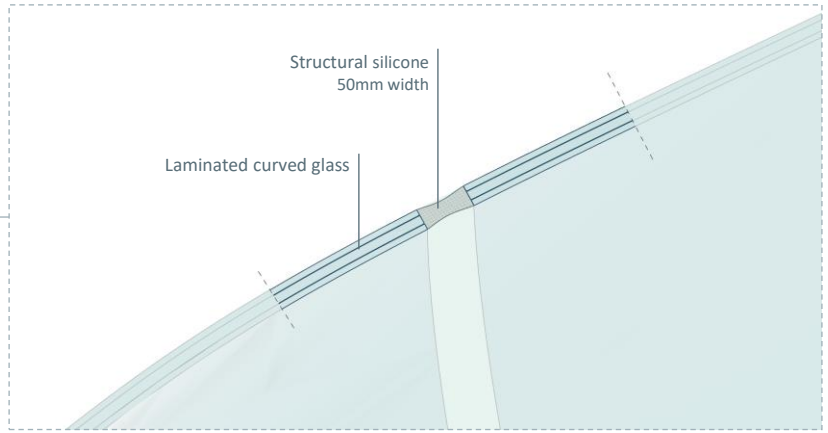


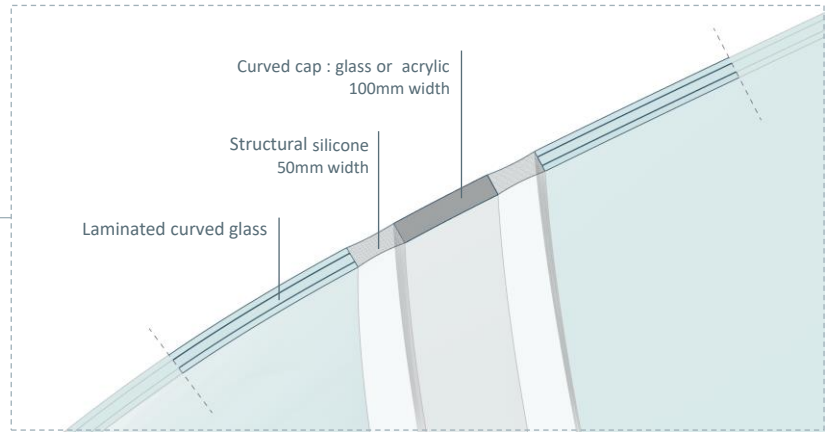
Max width produced by double-bed knitting in CNC knitting machine

small curvature difference

big curvature difference

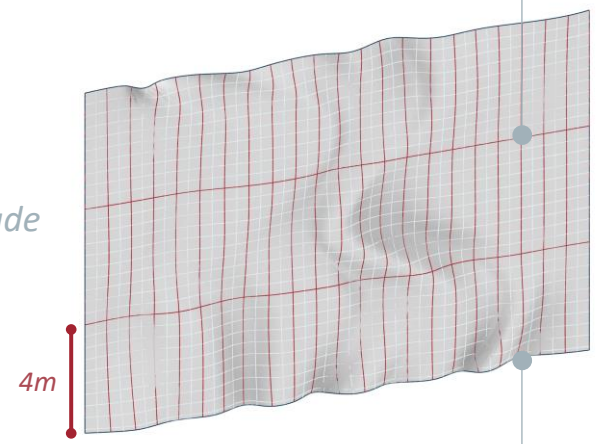
vertical connection detail



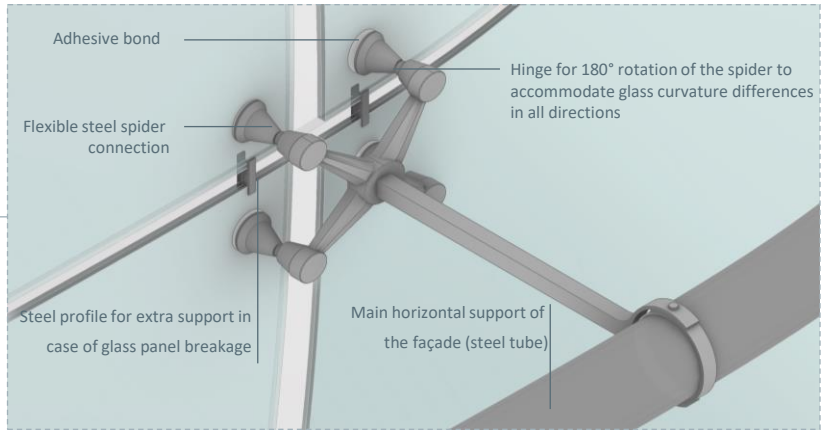


Division by current fabrication limitations

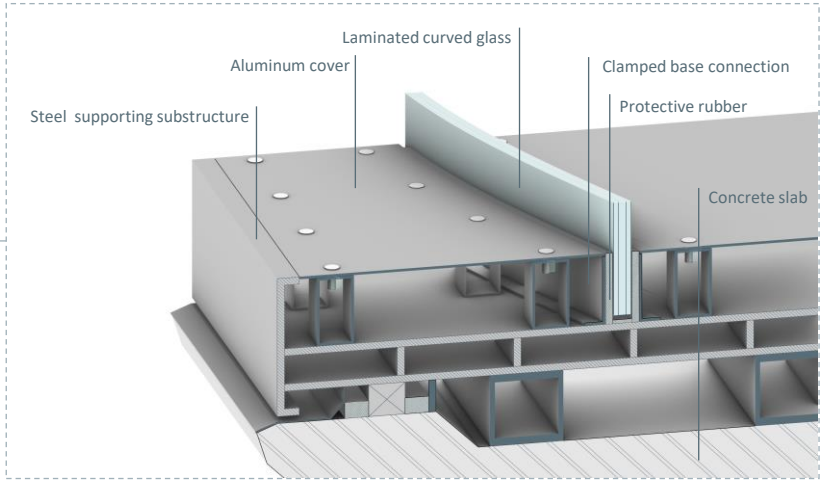
Division of non-self-supported facade

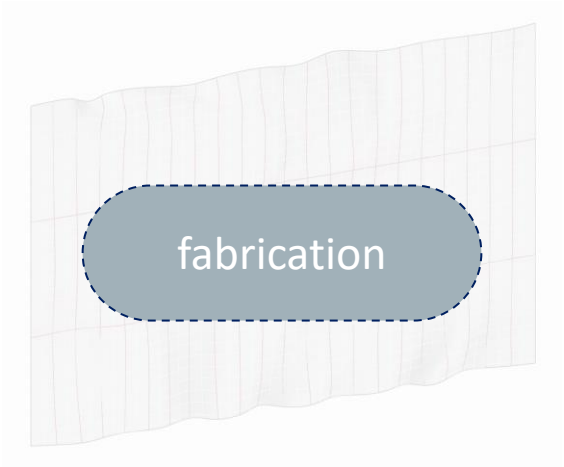


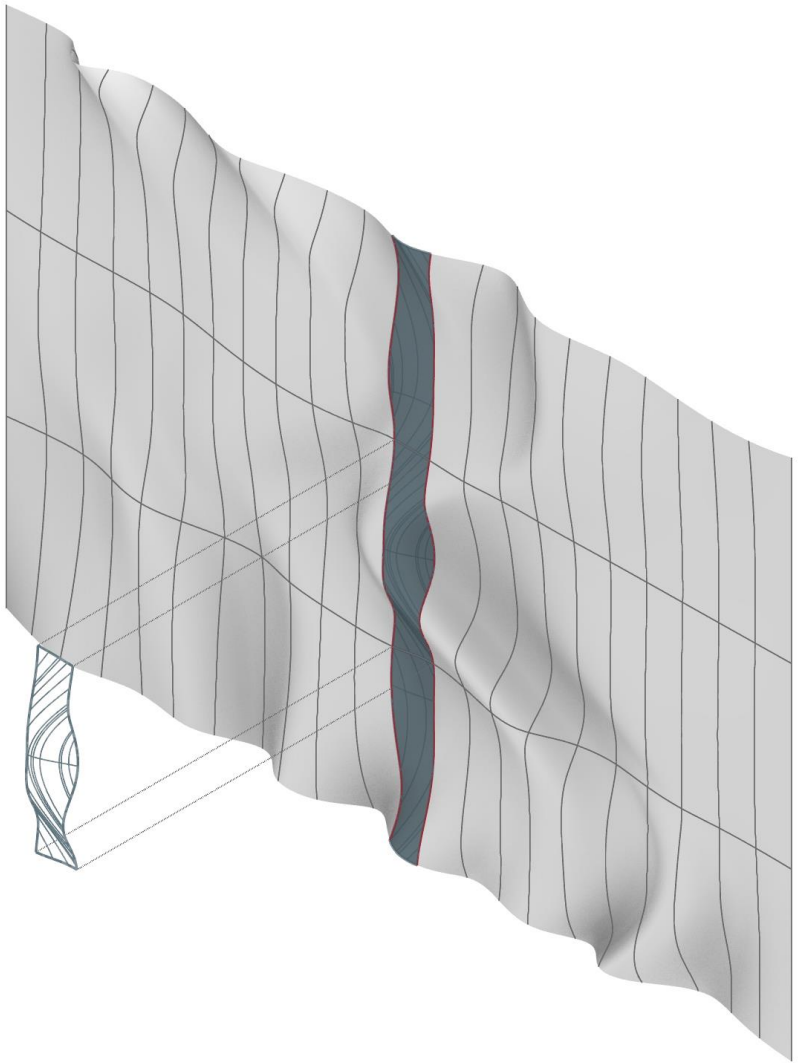
horizontal connection detail



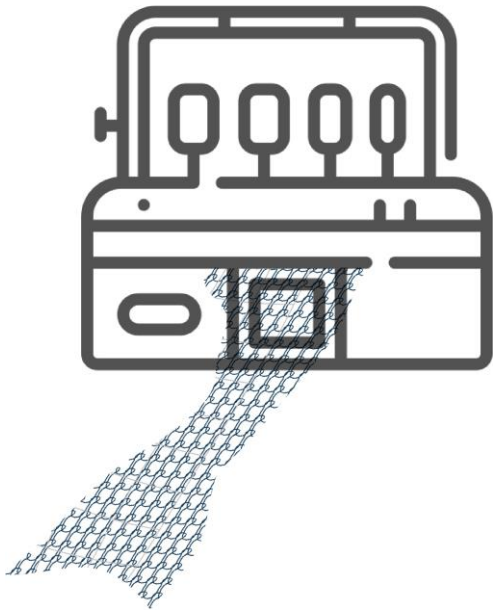
base connection detail



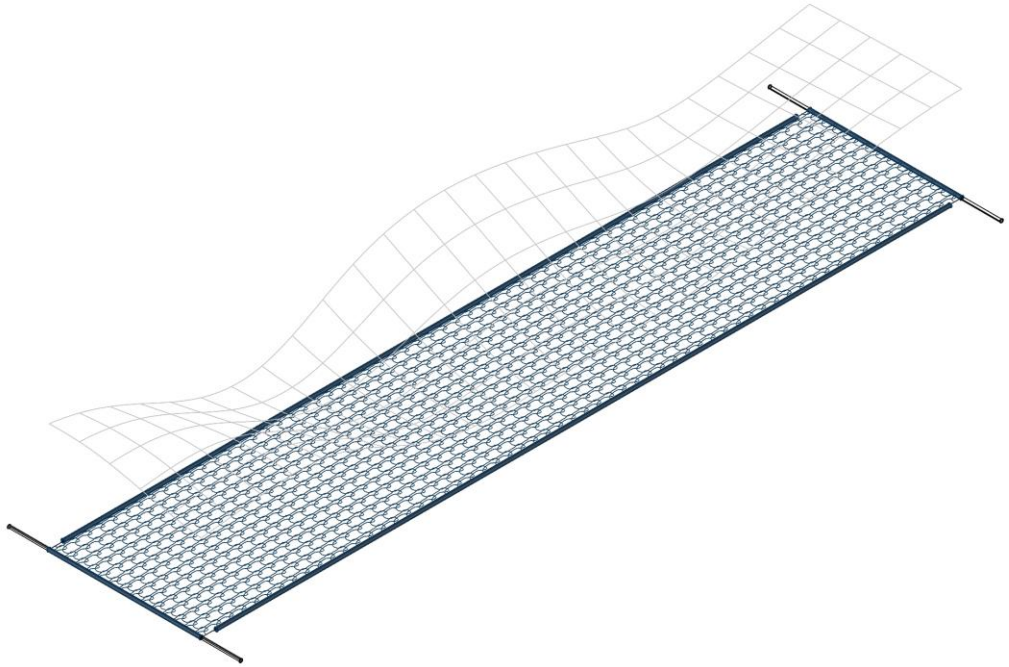

fabrication



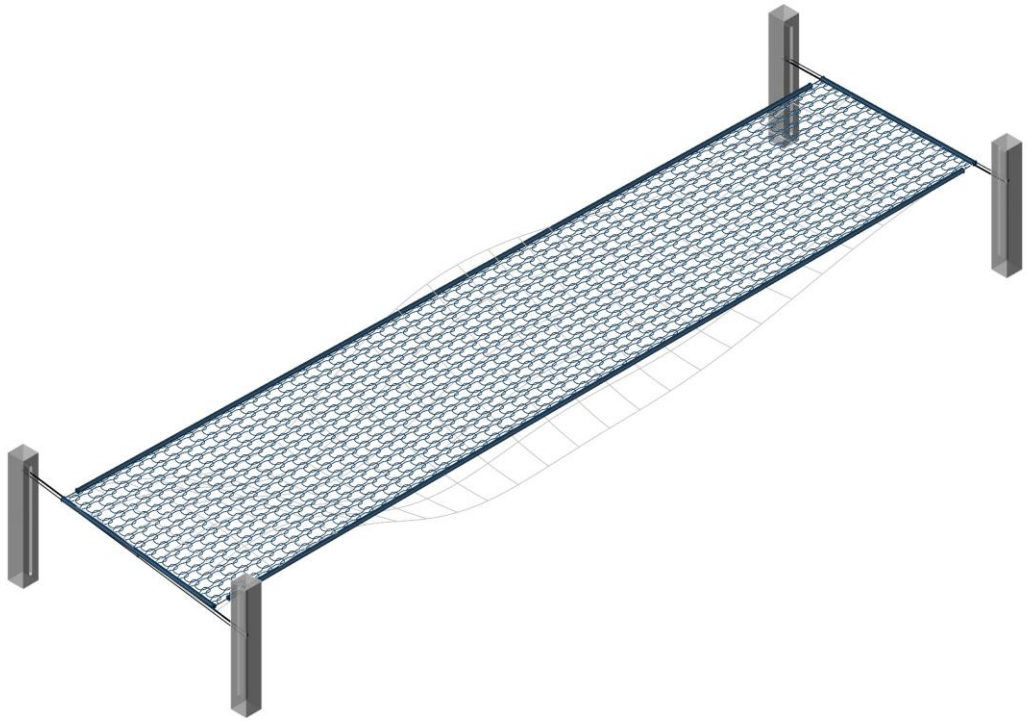
1 *Fabrication of the CNC knitted mould*



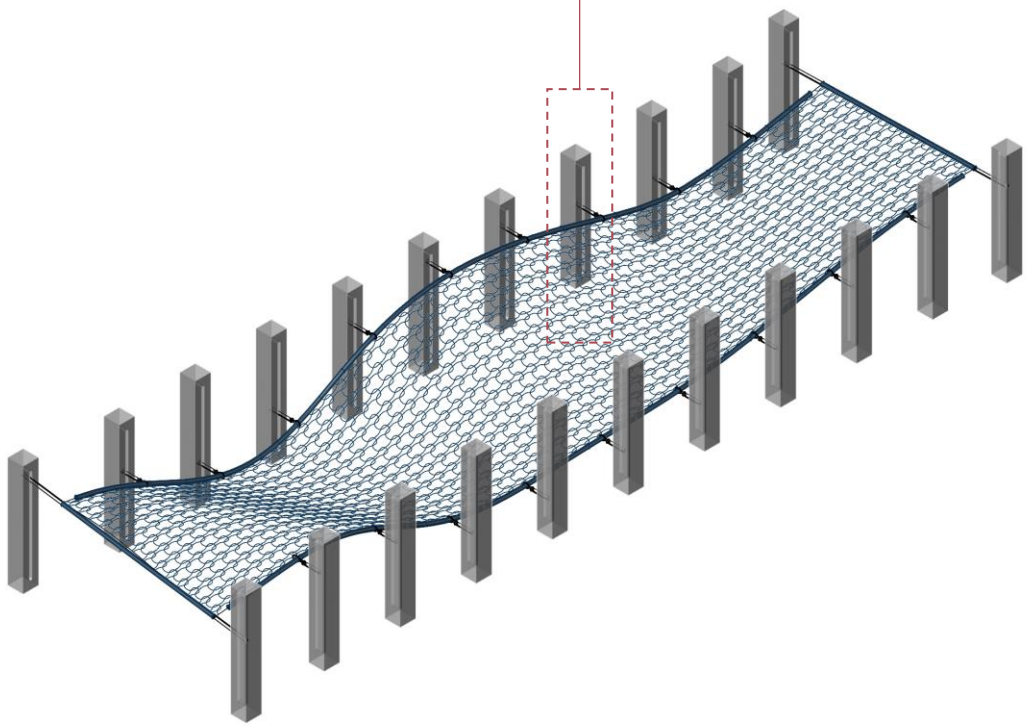
2 *Add steel rods at the short sides' channels*

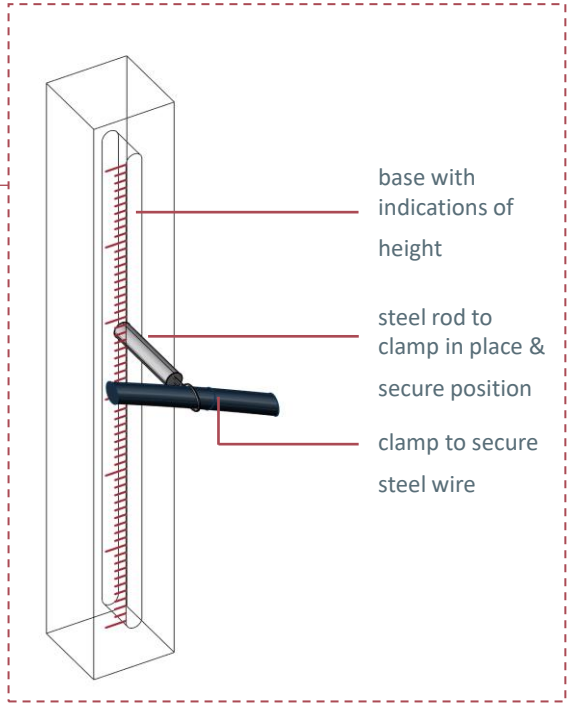


3 *Place the rods at the correct heights, secure the position & tension the textile*

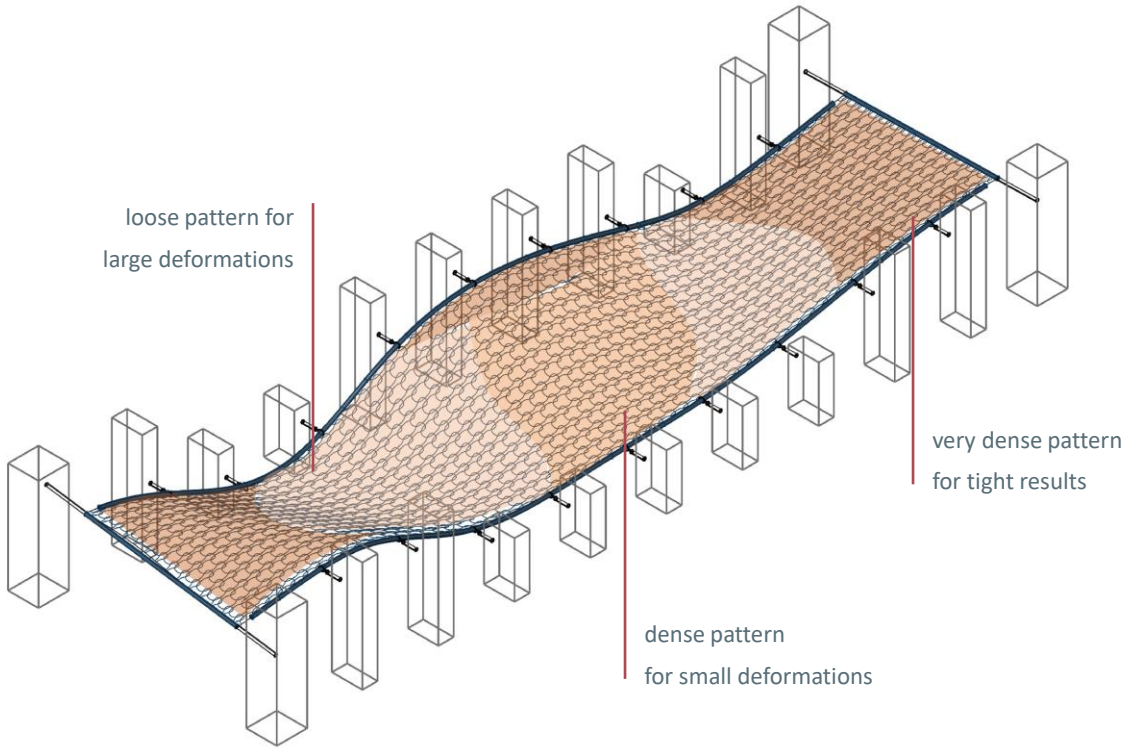


4 *Add steel wires to the long side channels, secure & tension them in place*

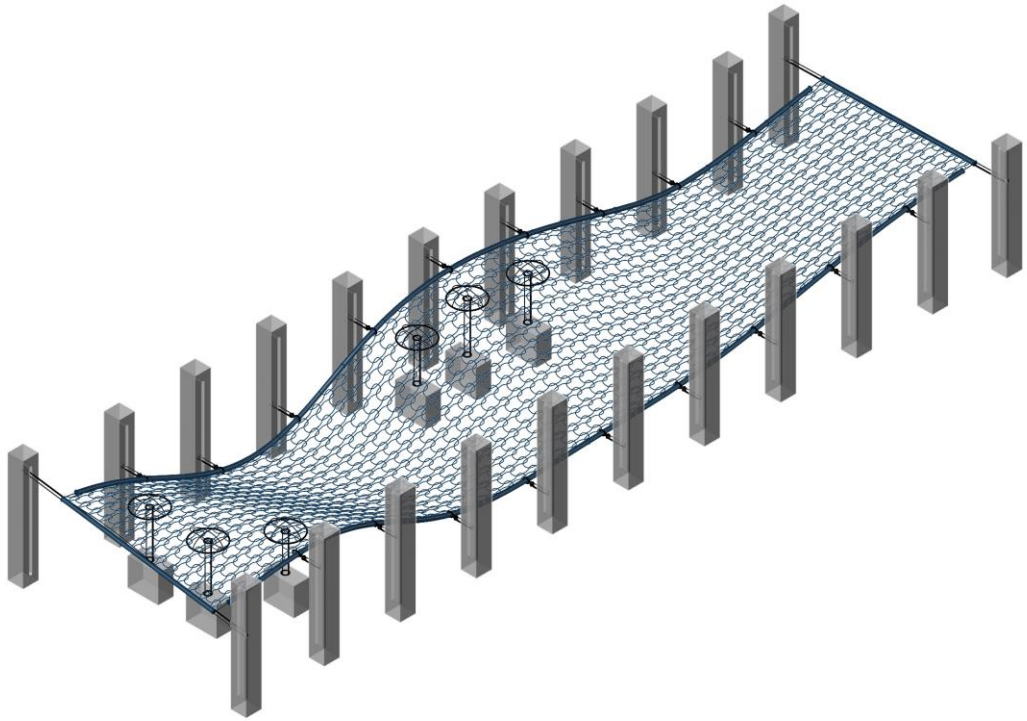




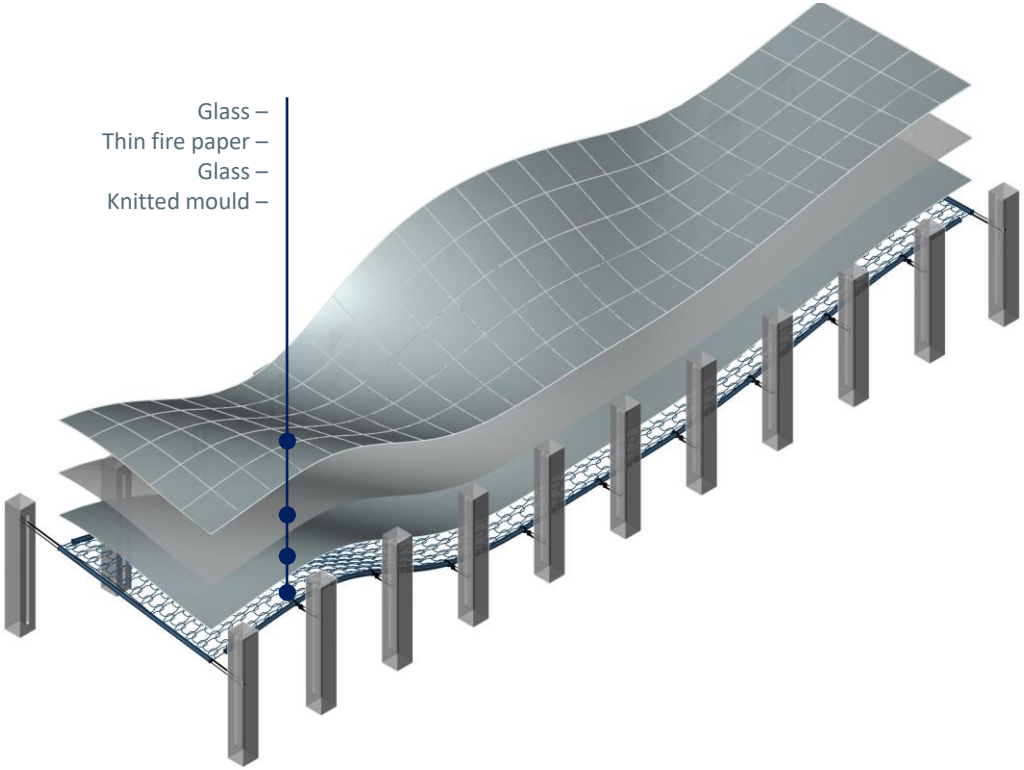
The knit pattern is considered to allow for more or less deformation



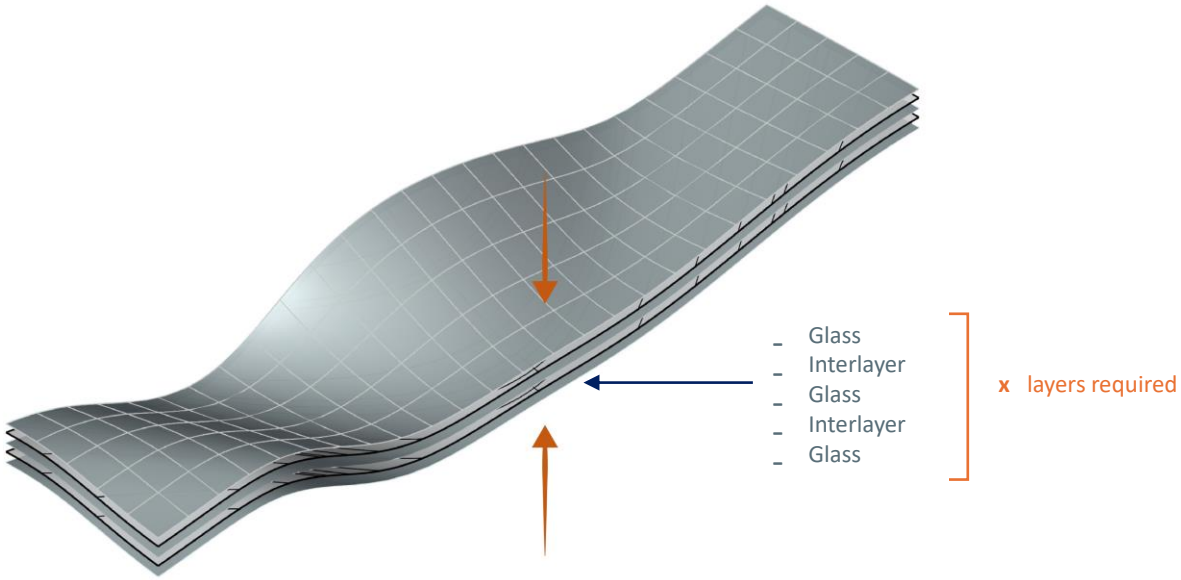
5 *Add extra “mushroom” supports underneath the textile to ensure textile staying up despite glass weight*



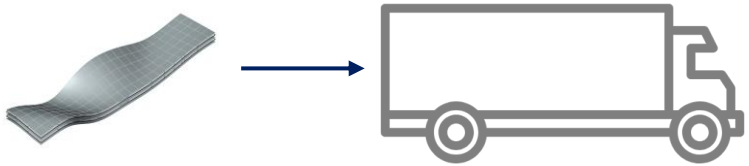
6 *Simultaneous glass slumping*



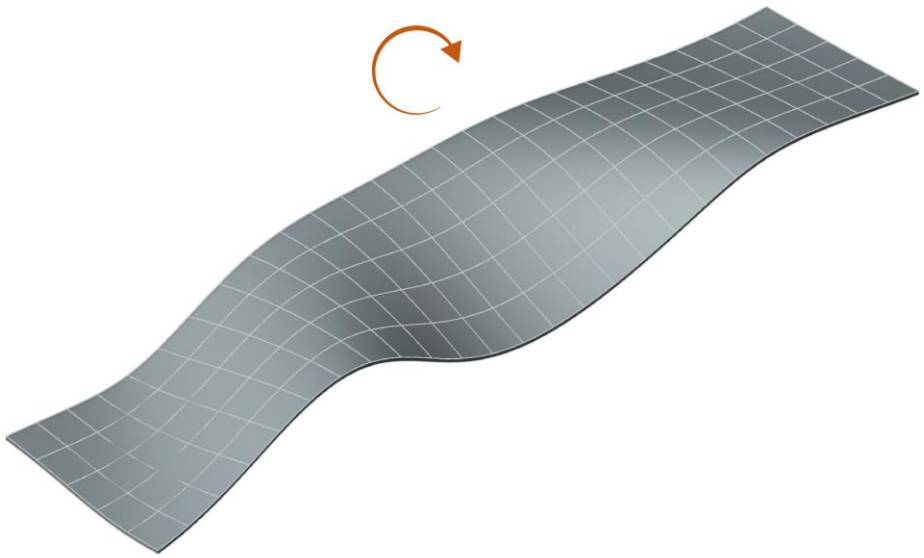
7 *Glass lamination & possible chemical tempering of panes*



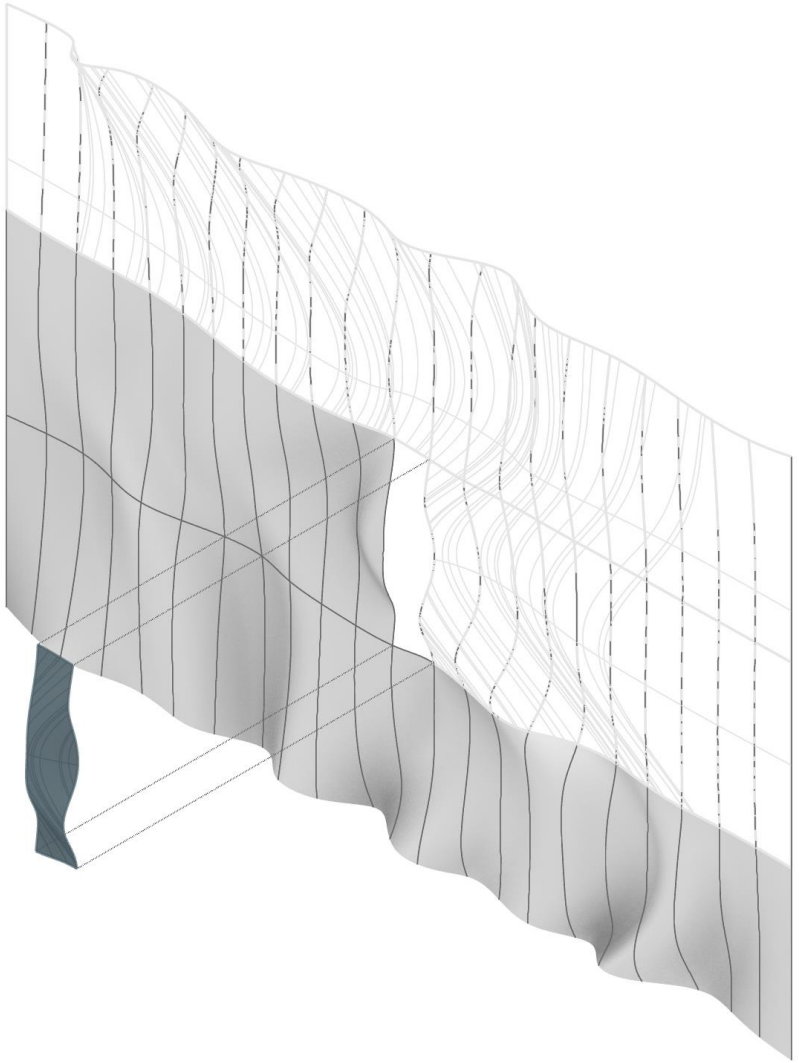
8 *Transport to site*



9 *Flip glass in its correct position*



10 *Place on facade & connect with other panels & supporting substructure*



Vision for application

Conclusions

*What is the **potential** and **limitations** of utilizing **knitted basalt moulds** for the creation of customizable, freeform curved float glass components?*

mould

- Basalt moulds are feasible and promising solution for curving glass
- Lightweight textile moulds
- Easy & high **customization** of mould with **little waste**

glass

- Can offer high geometrical accuracy & possibility for repetition
- Lamination possibility for safety
- Introducing texture on surface

limitations

- Knit density influences geometry
- Change in curvature not possible without extra elements
- Basalt moulds cannot be used multiple times

Future research

FEM simulations to compare experimental results to designed geometry

Experiment with **extreme geometries**

Experiment with **different knitting patterns** to understand the **different deformations** possible (as done for concrete in thesis of Flieger, 2024) & calculation of necessary **pretension of mould**

optimizing the **finishing surface quality** results

Mechanical testing

testing of different fibers for multiple reuses of mould

reuse and recycling strategy for the basalt mould


thank you