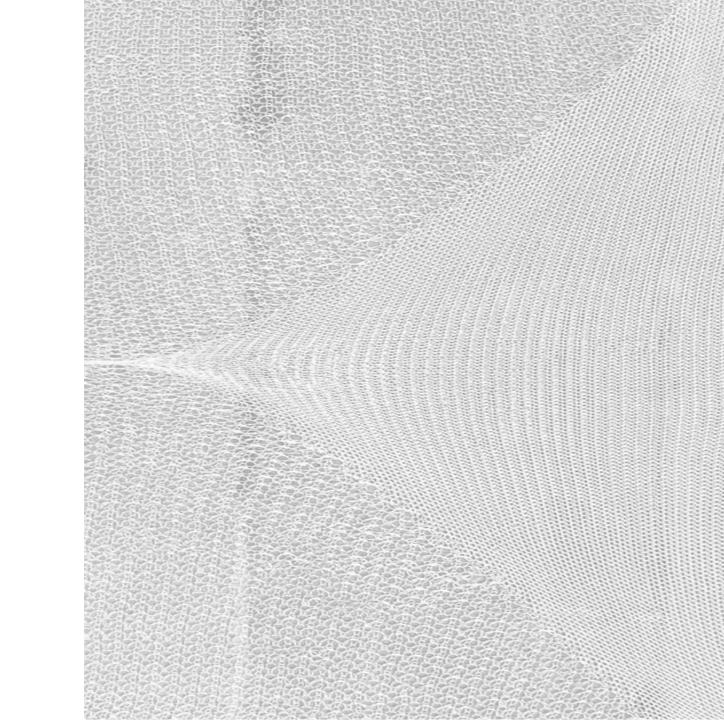
FLEXIBLE FORMWORK: A Textile-Centric Approach

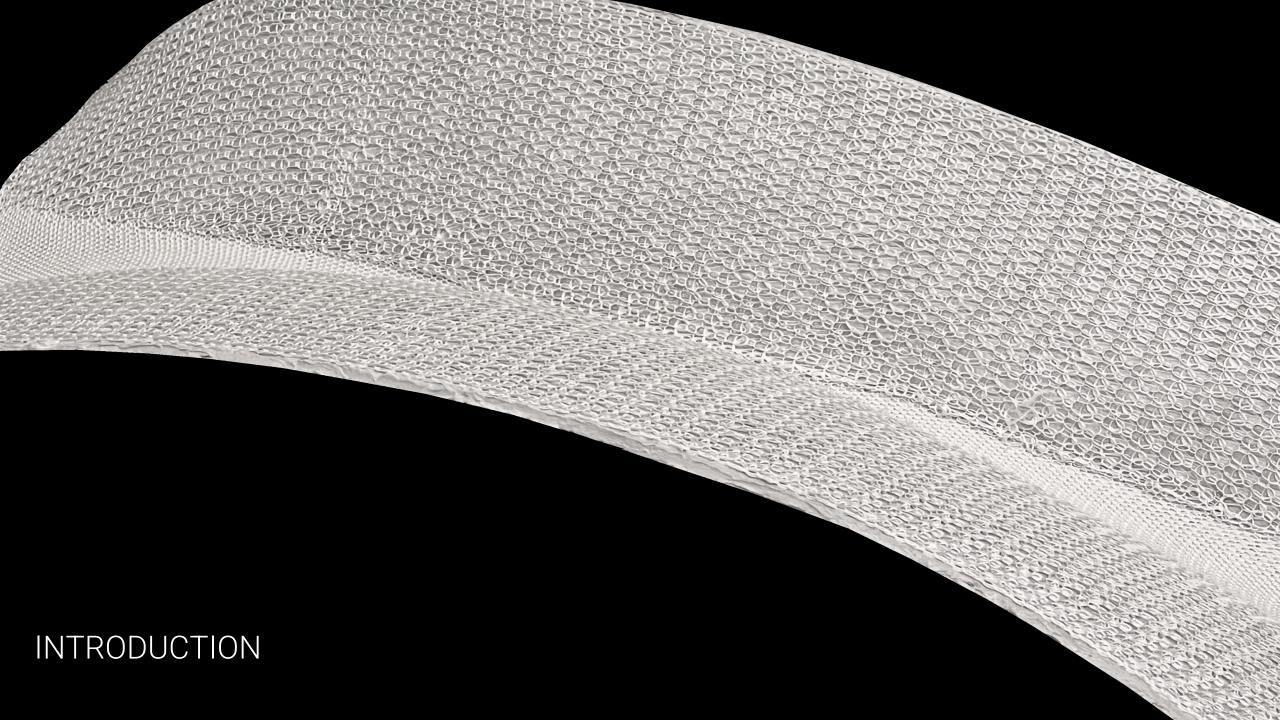
Investigating pattern influence on the deformation behavior of weft-knitted textile formworks under hydrostatic loading



PRESENTATION STRUCTURE

- INTRODUCTION
- RESEARCH
 - PHASE 1 : PATTERN REPOSITORY
 - PHASE 2 : PATTERN-SPECIFIC DEFORMATION BEHAVIOR
 - PHASE 3 : PATTERN COMBINATIONS
- IMAGINING FUTURE APPLICATIONS
- REFLECTION + FUTURE WORK







Kenzo Unno URC Wall via Mark West

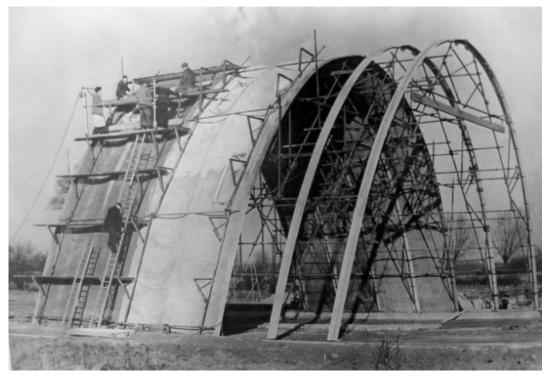


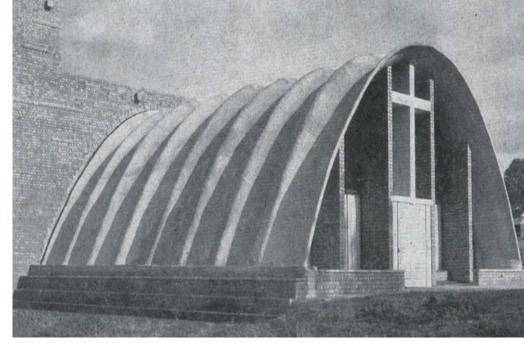
C.A.S.T / Mark West

<u>Flexible Formwork</u> is an innovative building technology that uses structural membranes (textiles) as the main formwork material in concrete molds.



C.A.S.T / Mark West

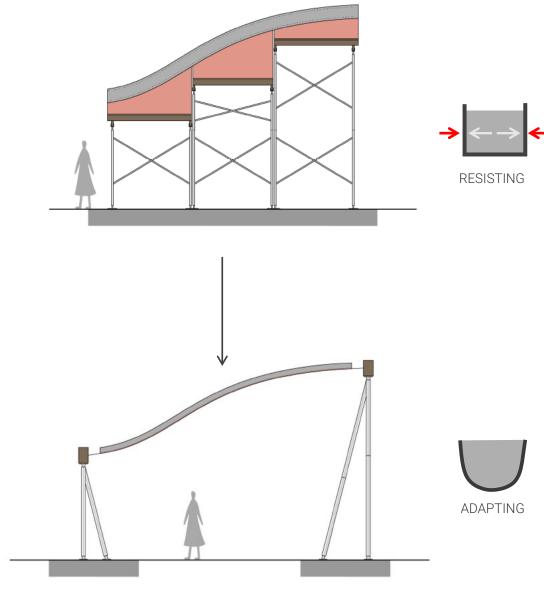




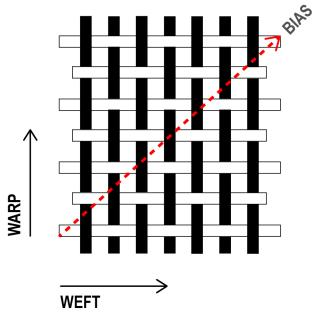
Waller & Aston, 1953 ArchiDave via Flickr



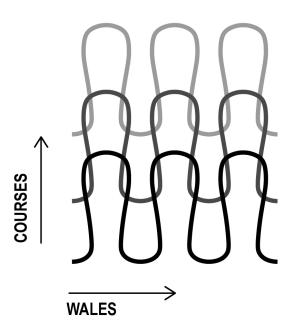
Construction of Chapel de Palmira by Felix Candela, 1958 (ArchDaily)



M.A. Popescu, 2019

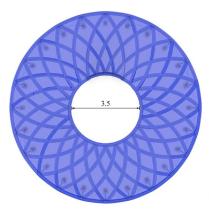












KnitNervi (Scheder-Bieschin et al., 2023)

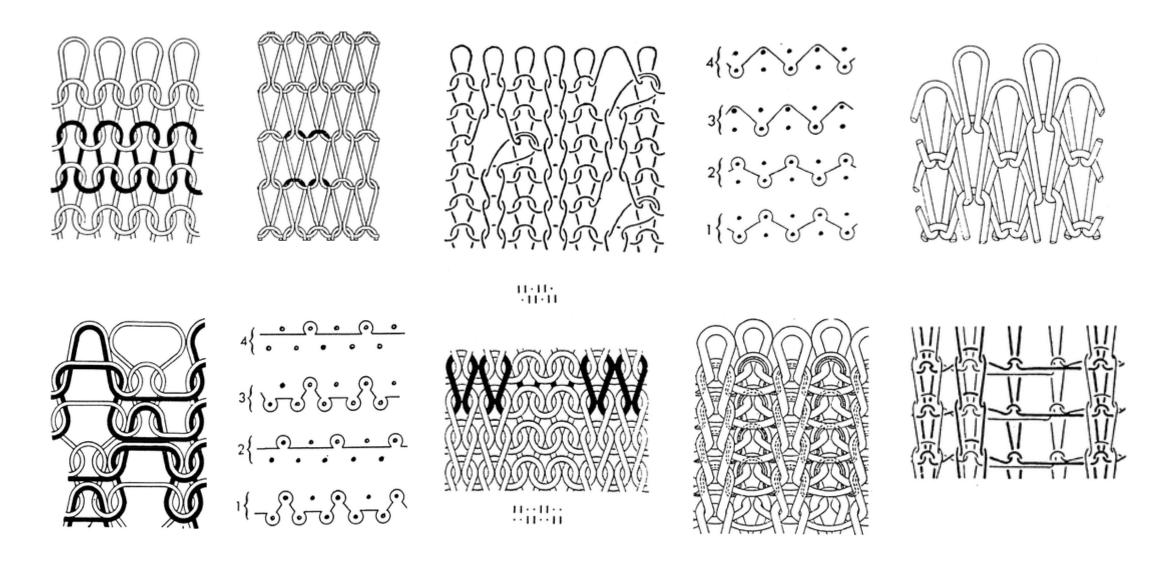
<u>CNC-knit textiles</u> are uniquely suited for creating complex or double curved geometries with flexible formwork.





KnitCandela (Popescu et al., 2021)







KnitCandela (Block Research Group)

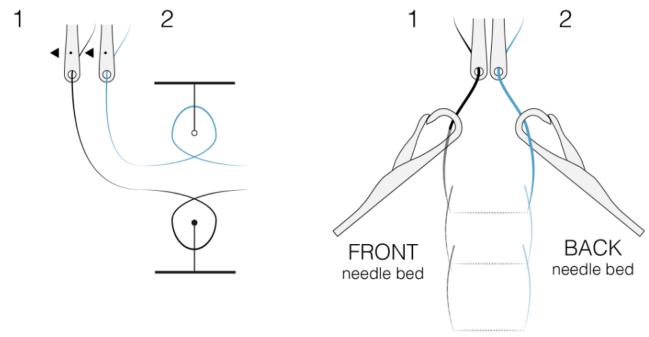


Isoropia Pavilion (Rasmus Hjortshoj - COAST)



Steiger 9 Flatbed Weft Knitting Machine at the Faculty of Civil Engineering at TU Delft





Yarn Guides and their working on the needle bed (M.A. Popescu, 2019)



Click

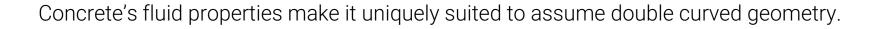
PROBLEM STATEMENT

Traditional concrete construction is polluting, wasteful, and materially intensive.

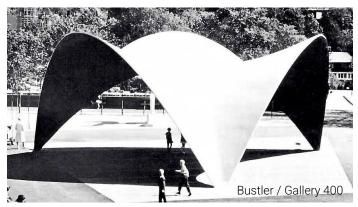


PROBLEM STATEMENT

Traditional concrete construction is polluting, wasteful, and materially intensive.

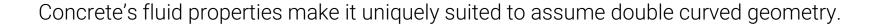






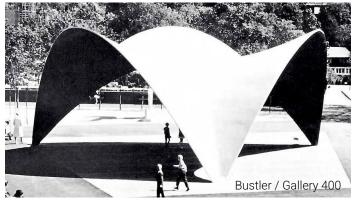
PROBLEM STATEMENT

Traditional concrete construction is polluting, wasteful, and materially intensive.



While various projects have demonstrated the potential of CNC Knit flexible formwork, more research is required to understand how different knit patterns influence flexible formwork design.







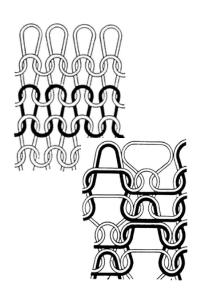
How do different knit patterns influence the deformation behavior and formal properties of cast

concrete elements?

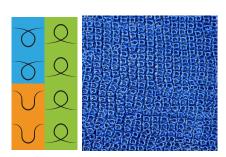
2

Can strategic pattern combination lead to the design of innovative architecture and structures?

RESEARCH METHODOLOGY OVERVIEW









Phase 1: Pattern Repository



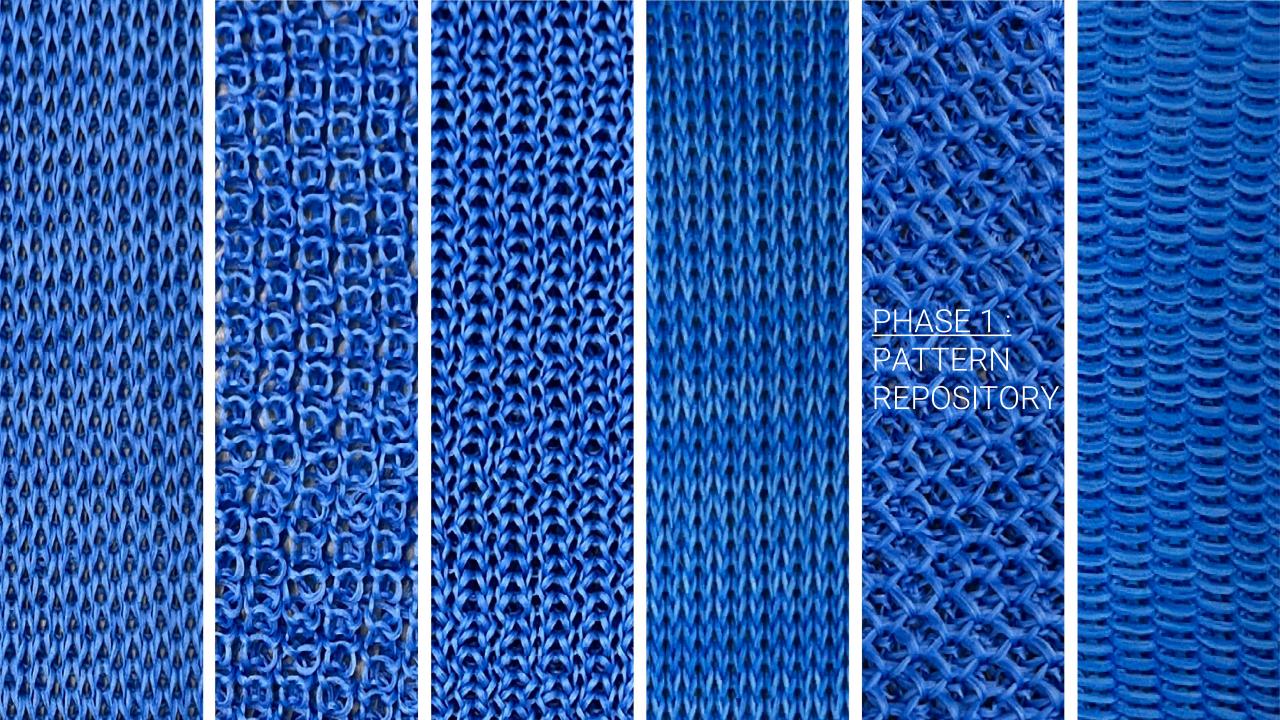


Phase 2: Deformation Behavior + Analysis

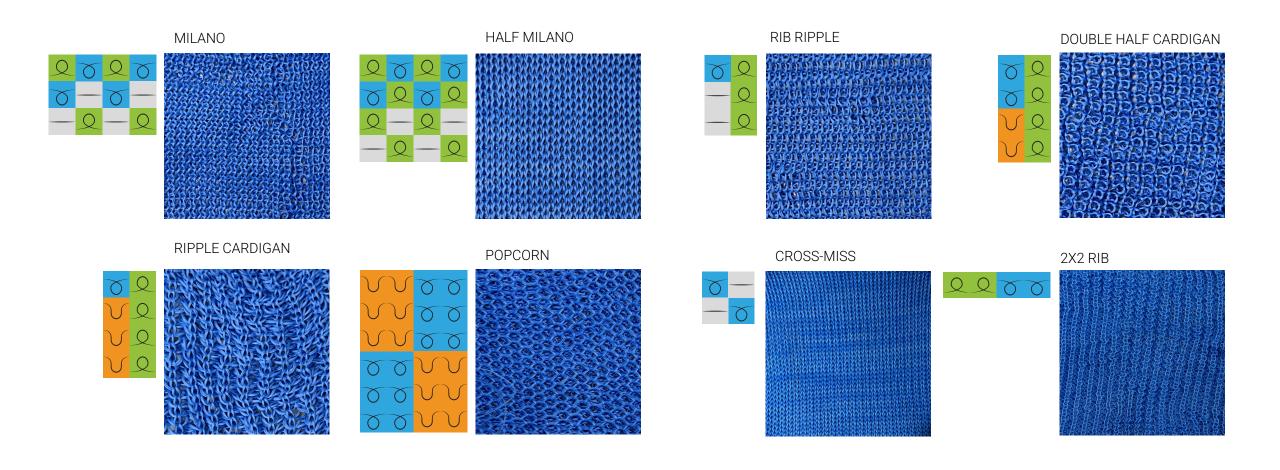


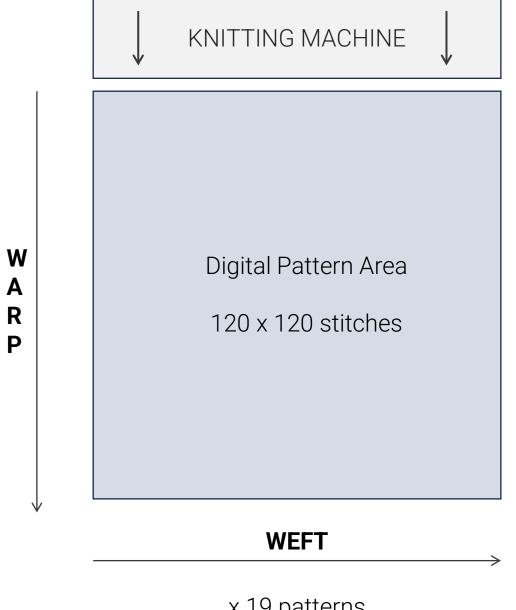


Phase 3: Pattern Combinations



REPOSITORY EXCERPT EXAMPLES

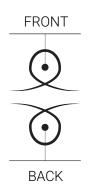


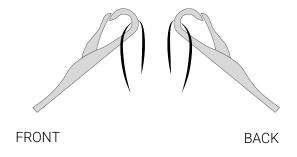


x 19 patterns

PHASE 1

2-BED SAMPLES 120x120 STITCHES







01 Milano 265mm x 135mm



03 Rib Ripple 240mm x 145 mm



05 Half Cardigan 340mm x 70mm



07 Ripple Cardigan 360mm x 85mm



02 Half Milano 300mm x 90mm



04 Double Half Cardigan 350mm x 110mm



06 2x2 Rib 180mm x 150mm



08 Cardigan 260mm x 125mm



01 Milano 240mm x 140mm



03 Rib Ripple 205mm x 160mm



05 Half Cardigan 320mm x 85mm



07 Ripple Cardigan 390mm x 85mm



02 Half Milano 250mm x 100mm



04 Double Half Cardigan 325mm x 135mm



06 2x2 Rib 180mm x 225mm



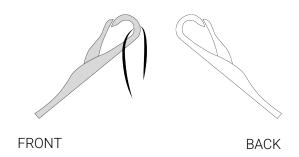
08 Cardigan 230mm x 150mm

PHASE 1

1-BED SAMPLES 120x120 STITCHES









11 Crepe 320mm x 120mm



13 Double Cross-Miss 250mm x 110mm



15 Long Tuck Stripe 390mm x 145mm



17 Polo Pique 410mm x 80mm



19 Single Cross Tuck 380mm x 125mm



21 Weft Lock 240mm x 150mm



12 Cross-Miss 250mm x 110mm



14 Double Lacoste 410mm x 70mm



16 Mock Rib 225mm x 90mm



18 Popcorn 360mm x 90mm



20 Twill Effect 380mm x 70mm



11 Crepe 340mm x 130mm



13 Double Cross-Miss 215mm x 115mm



15 Long Tuck Stripe 335mm x 120mm



17 Polo Pique 350mm x 90mm



19 Single Cross Tuck 360mm x 110mm



21 Weft Lock 220mm x 145mm



12 Cross-Miss 200mm x 135mm



14 Double Lacoste 330mm x 90mm



16 Mock Rib 180mm x 115mm



18 Popcorn 310mm x 100mm



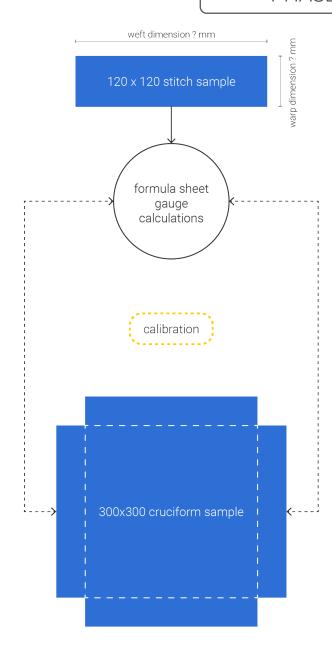
20 Twill Effect 330mm x 110mm

PATTERN REPOSITORY

GAUGE ADJUSTMENT PROCESS

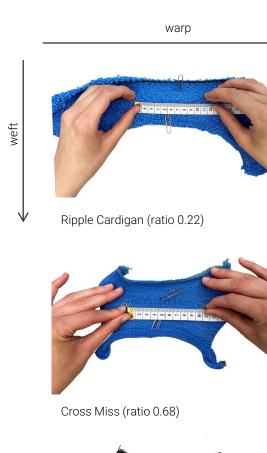
A	В	C	D	E	F	G	Н	I I	J K
				Target Width (W) mm	Target Height (H) mm	Target Tab Width (W) mm		Target Tab Height (H) mm	4 yarns polyester
				?	?	60		60	
				Square Stitch Count (Gauge)					
				120	*do not adjust				
			Pattern #	Pattern Name	Measured Width (W) mm	Measured Height (H) mm		Adjusted Stitch Count (W)	Adjusted Stitch Count (
		н	1	MILANO	240	140		#VALUE!	#VALUE!
		4							
		5	2	HALF MILANO	250	100		#VALUE!	#VALUE!
		S.							
		BEDS GROUP	3	RIB RIPPLE	205	160		#VALUE!	#VALUE!
		DS			7202			,	A.C. 10. 10. 10. 10. 10. 10. 10. 10. 10. 10
		8	4	DOUBLE HALF CARDIGAN	325	135		#VALUE!	#VALUE!
	S	7	-	HALF CARDIGAN	200	85		#VALUE!	ADJANUEL .
	□		5	HALF CARDIGAN	320	85		#VALUE!	#VALUE!
	8								
	2 NEEDLE BEDS		6	2X2 RIB	180	225		#VALUE!	#VALUE!
	=======================================	7	U	ZAZ NIU	100	223		#VALUE!	#VALUE!
	Z	5	7	RIPPLE CARDIGAN	390	85		#VALUE!	#VALUE!
		2				52			
		BEDS GROUP	8	CARDIGAN	230	150		#VALUE!	#VALUE!
		S							
		8	9	DROP STITCH					
		2 B							
			10	4x2 RIB					
			11	CREPE	340	130		#VALUE!	#VALUE!
			12	CROSS-MISS	200	135		#VALUE!	#VALUE!
			77.00		54,540,640	C.1-ao 20			
			13	DOUBLE CROSS-MISS	215	115		#VALUE!	#VALUE!
				2012151400075				The state of the s	100001051
			14	DOUBLE LACOSTE	330	90		#VALUE!	#VALUE!
	BED		15	LONG TUCK STRIPE	335	120		#VALUE!	#VALUE!
	8		15	LONG TUCK STRIPE	335	120		#VALUE!	#VALUE!
	2		16	MOCK RIB	180	115		#VALUE!	#VALUE!
	NEEDLE		10	WOCK RID	180	115		#VALUE!	#VALUE!
			17	POLO PIQUE	350	90		#VALUE!	#VALUE!
	1		1,	TOLO , IQUE	330	50		TVALUE:	#VALUE!
					310				

PHASE 1

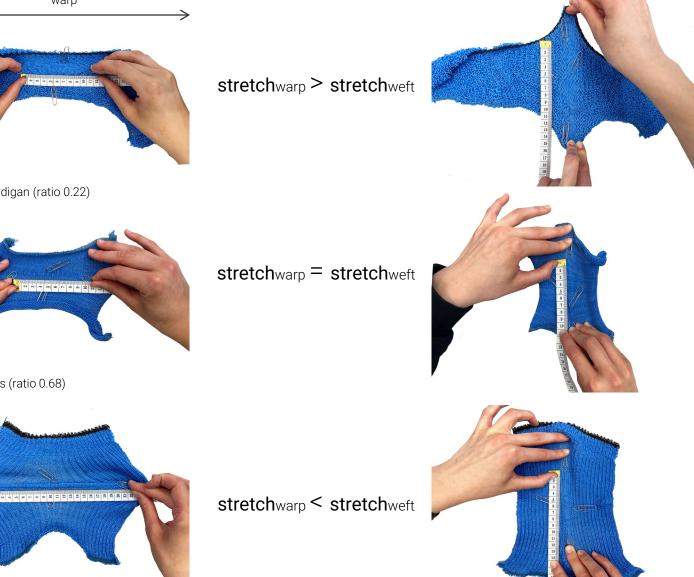




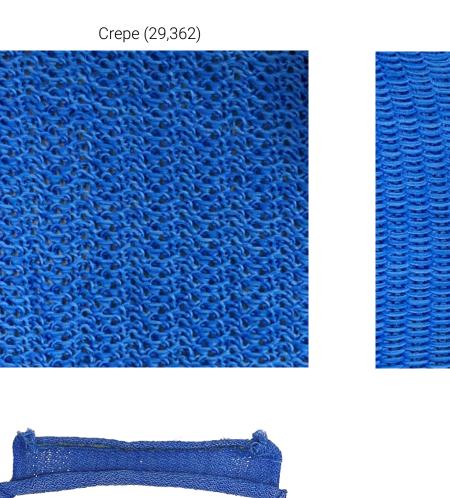
Pattern Name	Type	Weft to Warp Stitch Count (300x300mm)	Weft/Warp Ratio
Rp. Cardigan	2 Bed	92 / 424	0.22
Polo Pique	1 Bed	103 / 400	0.26
Double Lacoste	1 Bed	109 / 400	0.27
Half Cardigan	2 Bed	113 / 424	0.27
Single Cross Tuck	1 Bed	100 / 327	0.31
Popcorn	1 Bed	116 / 360	0.32
Twill Effect	1 Bed	109 / 327	0.33
Long Tuck Stripe	1 Bed	107 / 300	0.36
Crepe	1 Bed	106 / 277	0.38
Half Milano	2 Bed	144 / 360	0.40
Db.Half Cardigan	2 Bed	111 / 267	0.42
Double Cross Miss	1 Bed	167 / 313	0.54
Milano	2 Bed	150 / 257	0.58
Mock Rib	1 Bed	220 / 313	0.64
Cardigan	2 Bed	157 / 240	0.65
Weft Lock	1 Bed	164 / 248	0.66
Cross Miss	1 Bed	180 / 267	0.68
Rib Ripple	2 Bed	176 / 225	0.78
2x2 Rib	2 Bed	200 / 160	1.25

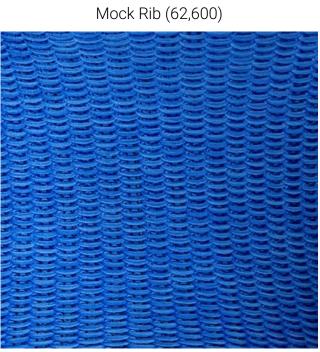






	Туре	Weft to Warp	Total Stitch Magnitude	
Pattern Name		Stitch Count (300x300mm)		
Crepe	1 Bed	105 x 277	29,362	
Db. Half Cardigan	2 Bed	111 x 267	29,637	
2x2 Rib	2 Bed	200 x 160	32,000	
Long Tuck Stripe	1 Bed	107 x 300	32,100	
Single Cross Tuck	1 Bed	100 x 327	32,700	
Twill Effect	1 Bed	109 x 327	35,643	
Cardigan	2 Bed	157x240	37,680	
Milano	2 Bed	150 x 257	38,550	
Rp. Cardigan	2 Bed	92 x 424	39,600	
Rib Ripple	2 Bed	175 x 225	39,600	
Weft Lock	1 Bed	164 x 248	40,672	
Polo Pique	1 Bed	103 x 400	41,200	
Popcorn	1 Bed	116 x 360	41,760	
Double Lacoste	1 Bed	109 x 400	43,600	
Half Cardigan	2 Bed	113 x 424	47,912	
Cross-Miss	1 Bed	180 x 267	48,000	
Half Milano	2 Bed	144 x 360	51,840	
Db. Cross Miss	1 Bed	167 x 313	52,271	
Mock Rib	1 Bed	200 x 313	62,600	







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Double Half Cardigan (29,637)





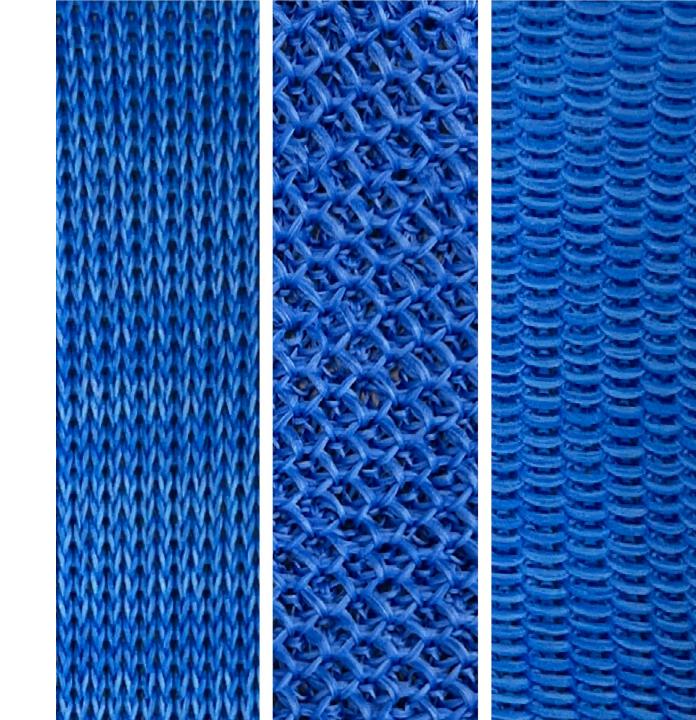
Double Cross Miss (52,271)

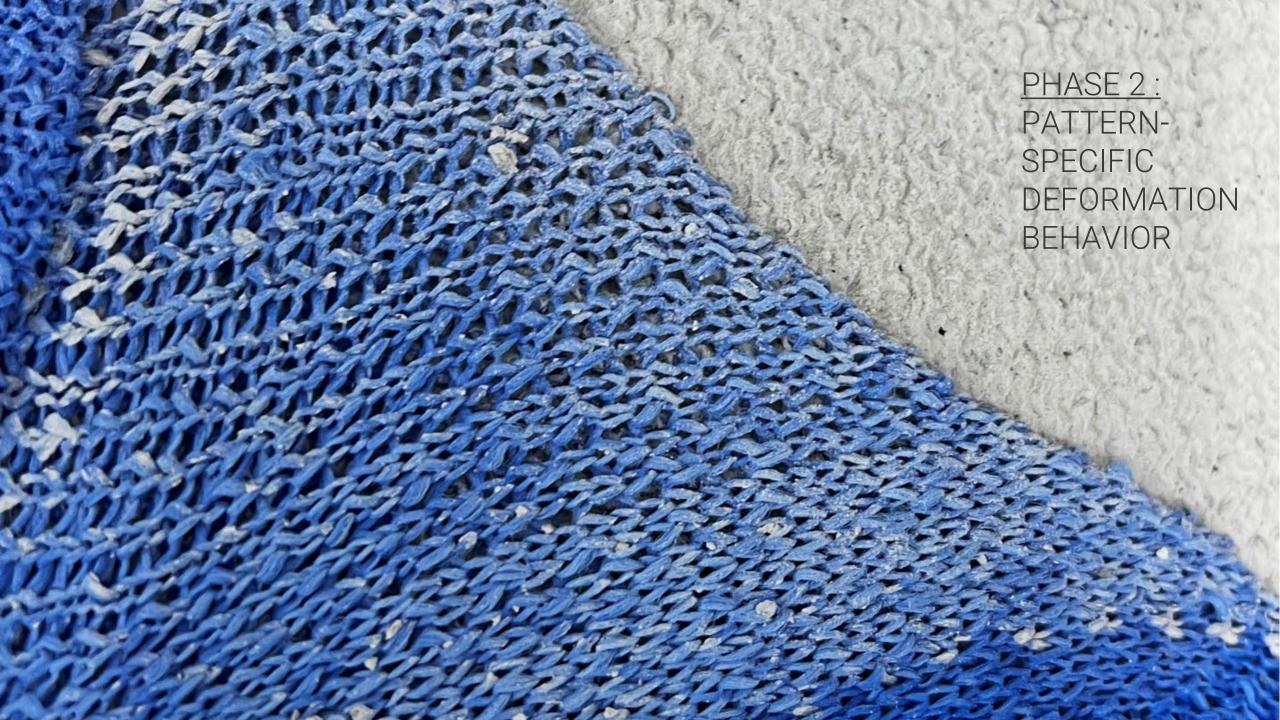




KEY FINDINGS SUMMARY PHASE 1:

- weft vs. warp stitch count is likely related to the stretching behavior of the textile
- total stitch magnitude is related to surface texture and general flexibility
- ratios and magnitudes are not consistent between yarn types, but extremes remain

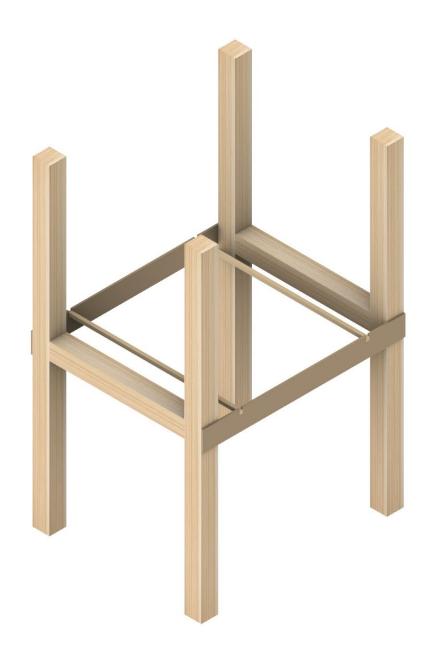




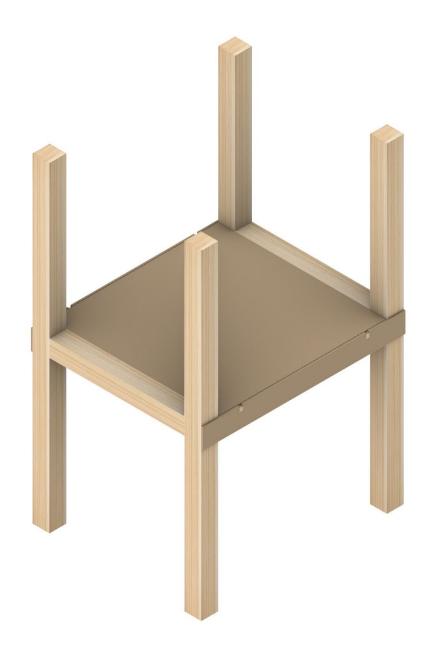


low deformation high deformation

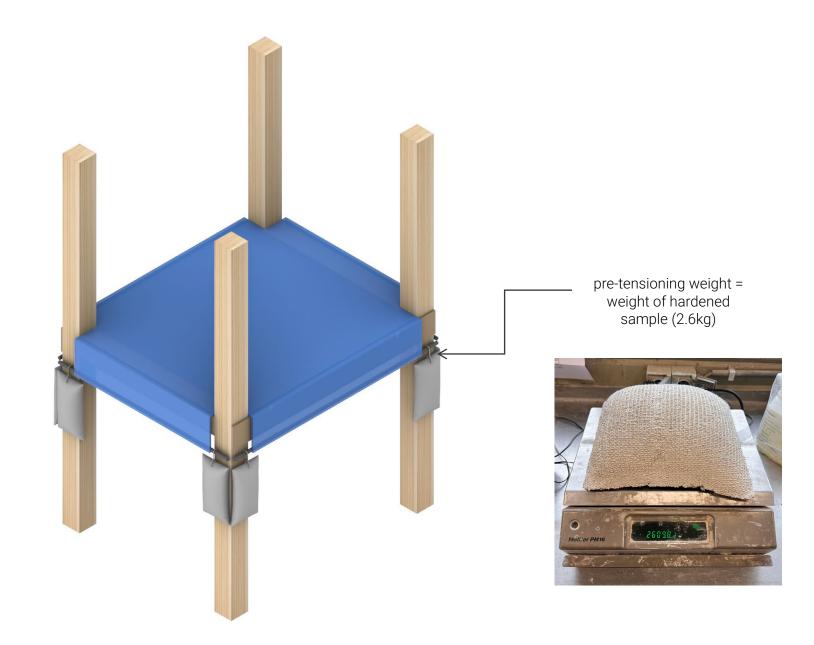




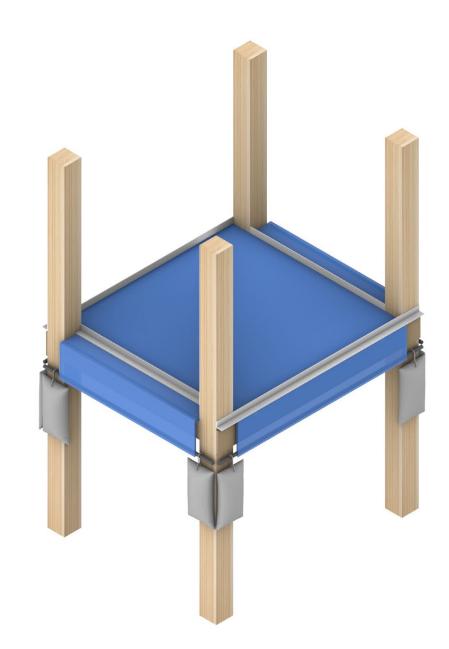








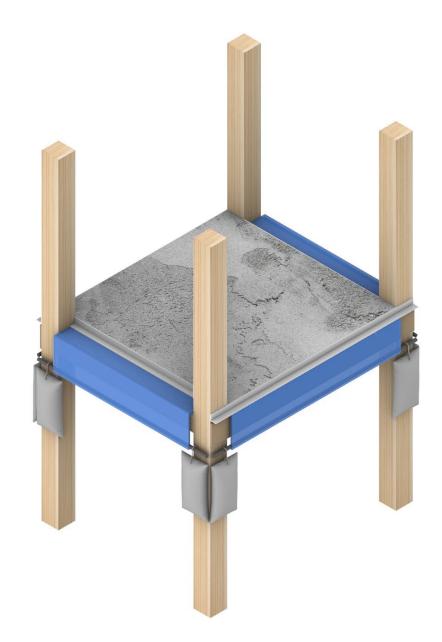




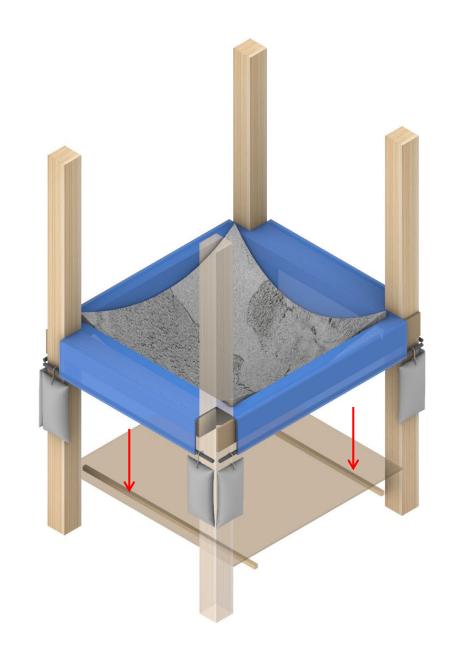
















METHODOLOGY | CASTING EXPERIMENTS







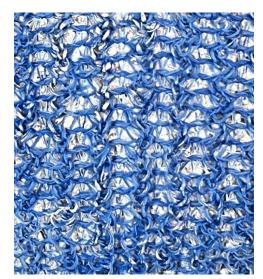
low deformation high deformation

UNDERSTANDING REUSE POTENTIAL

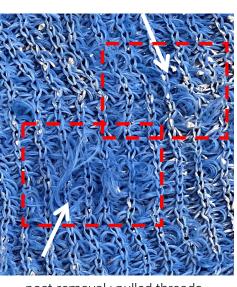


Click Here for Video

Ripple Cardigan Removal approx. 01:00



pre-removal

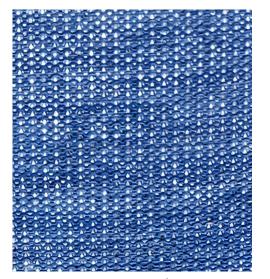


post-removal: pulled threads



Click Here for Video

Cross-Miss Removal approx. 00:20

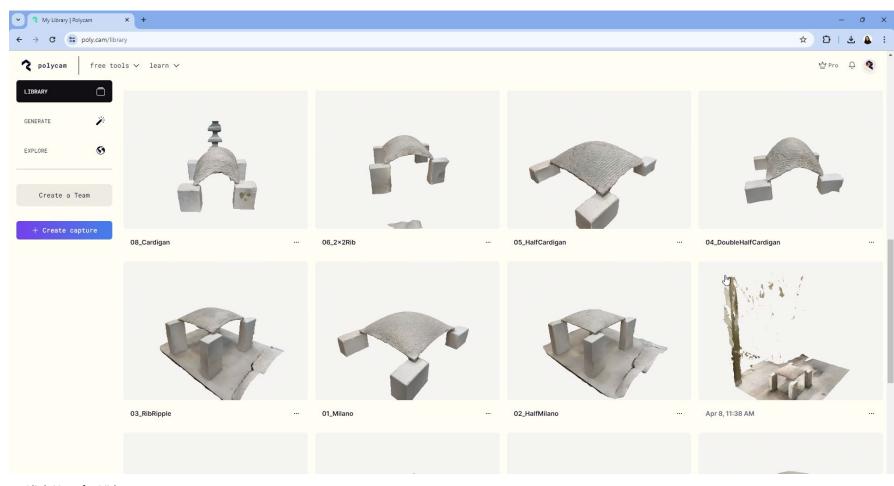


pre-removal

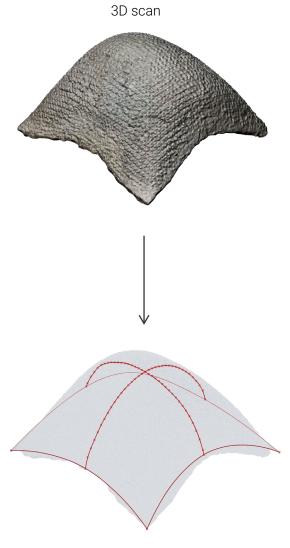


post-removal: no damage

METHODOLOGY | CURVATURE EXTRACTION WITH 3D SCANNING + GRASSHOPPER

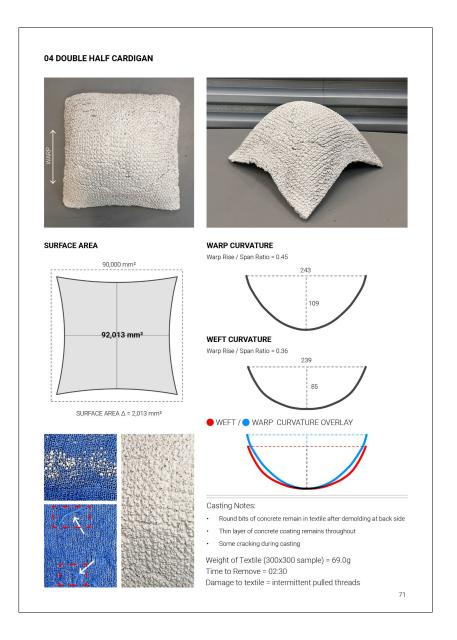


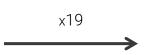
Click Here for Video



approximated curvature from GH

METHODOLOGY | CURVATURE ANALYSIS



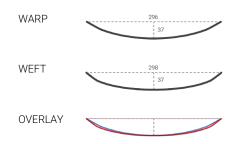


Pattern	Max Rise (mm)	Warp Ratio (rise/span)	Weft Ratio (rise/span)	Srf Area (mm²)	Warp Curve	Weft Curve	Warp/Weft Overlay
(12) CROSS- MISS	37 (warp)	0.13	0.12	95,317			
(20) TWILL EFFECT	40 (warp)	0.14	0.13	92,966			
(13) DOUBLE CROSS-MISS	43 (warp)	0.15	0.13	95,874			
(2) HALF MILANO	45 (warp)	0.16	0.15	95,840			
(21) WEFT LOCK	54 (warp)	0.18	0.17	96,818			
(11) CREPE	55 (warp)	0.19	0.18	99,092			
(14) DOUBLE LACOSTE	56 (warp)	0.19	0.17	98,605			
(3) RIB RIPPLE	57 (warp)	0.20	0.17	94,173			
(16) MOCK RIB	57 (warp)	0.20	0.18	97,255			
(15) LONG TUCK STRIPE	60 (warp)	0.21	0.18	95,834			
(19) SINGLE CROSS TUCK	60 (warp)	0.22	0.20	95,764			
(1) MILANO	64 (warp)	0.22	0.21	97,419			
(17) POLO PIQUE	66 (warp)	0.24	0.22	96,650			
(5) HALF CARDIGAN	70 (warp)	0.25	0.22	96,291			
(6) 2X2 RIB	83 (*weft)	0.22	0.31	95,323			
(18) POPCORN	86 (warp)	0.31	0.29	98,672			
(7) RIPPLE CARDIGAN	97	0.38	0.38	98,826			
(8) CARDIGAN	99 (warp)	0.45	0.27	89,473			
(4) DBL. HALF CARDIGAN	109 (warp)	0.45	0.36	94,927			

METHODOLOGY | CURVATURE ANALYSIS

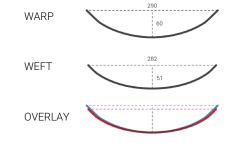


12 CROSS MISS



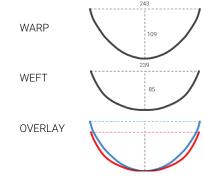


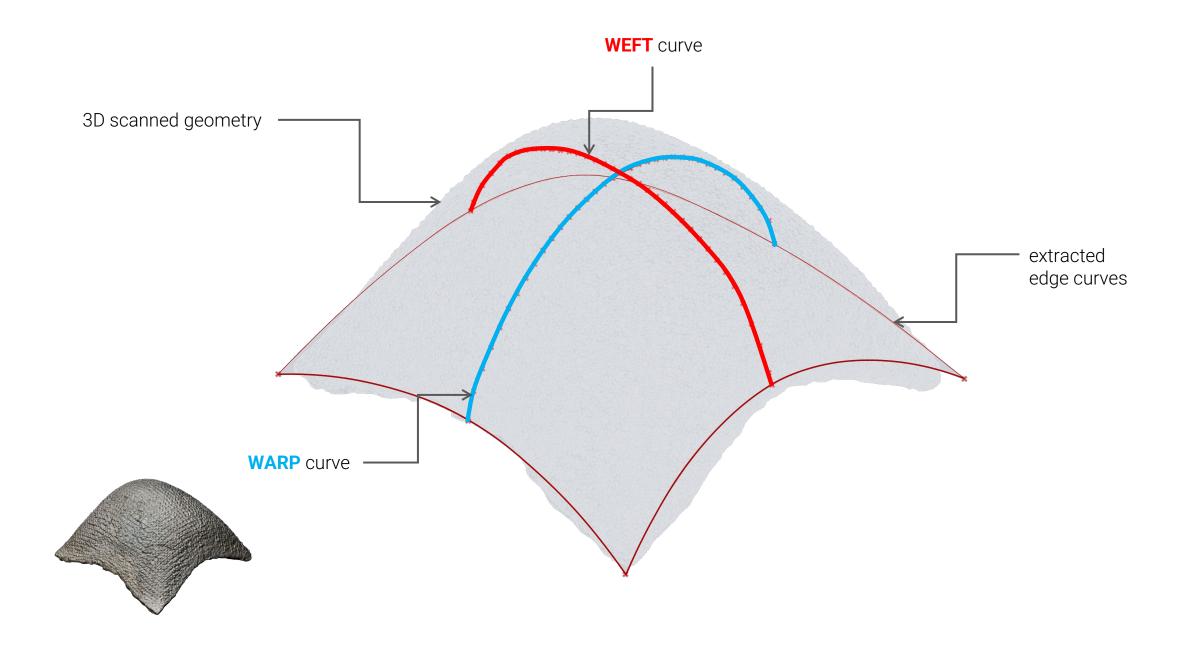
15 SINGLE CROSS TUCK



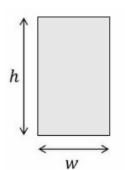


04 DOUBLE HALF CARDIGAN



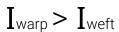


General Trend : Rise to Span Ratio

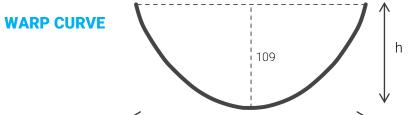


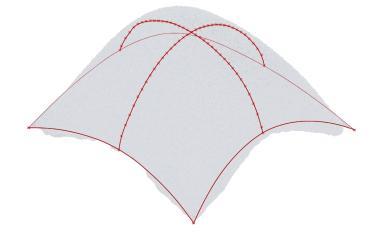
$$I_y = \frac{wh^3}{12}$$

$$I_z = \frac{hw^3}{12}$$

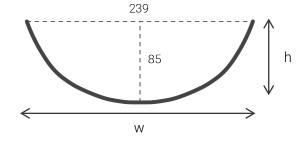


243

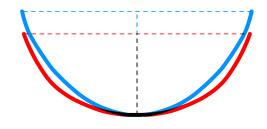










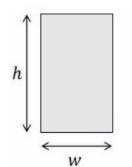


stretchwarp > stretchweft



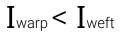


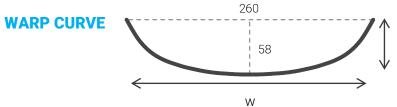
2x2 Rib: Exception 1

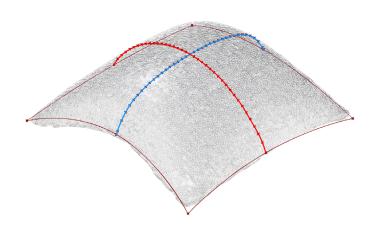


$$I_y = \frac{wh^3}{12}$$

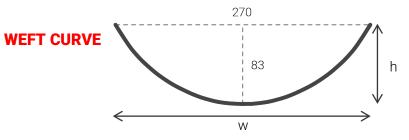
$$I_z = \frac{hw^3}{12}$$

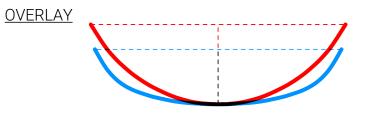






06 2x2 RIB (single exception)



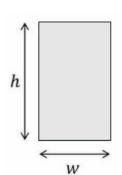


stretchwarp < stretchweft</pre>



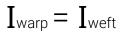


Ripple Cardigan: Exception 2

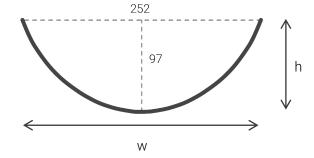


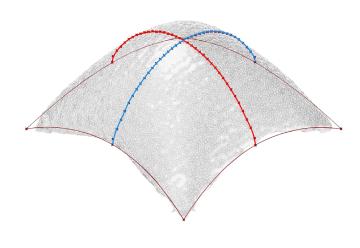
$$I_y = \frac{wh^3}{12}$$

$$I_z = \frac{hw^3}{12}$$



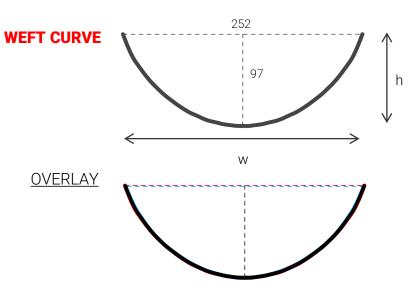
WARP CURVE





07 RIPPLE CARDIGAN (single exception)

OVERLAY

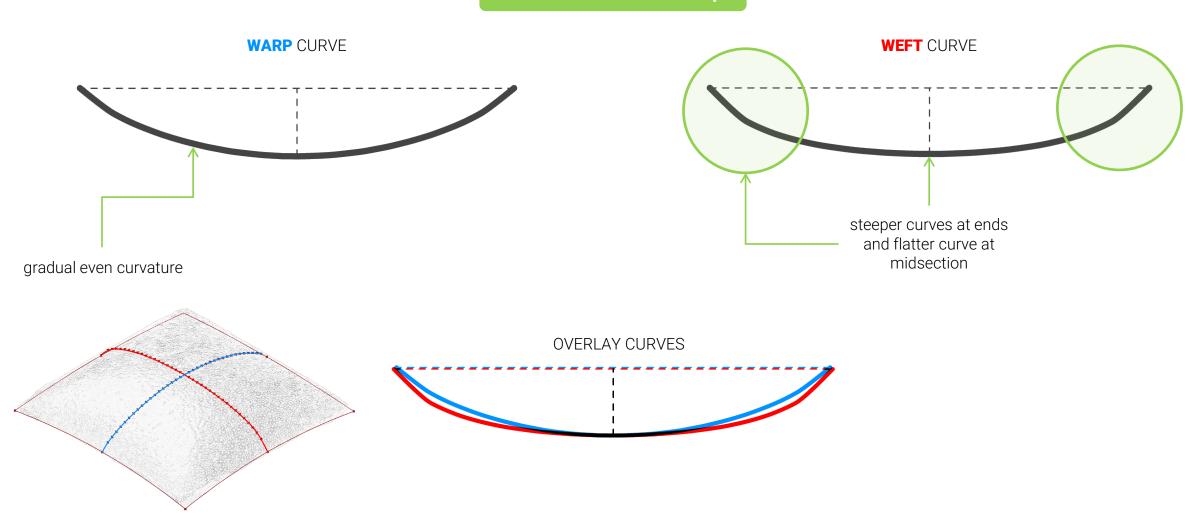


stretchwarp > stretchweft





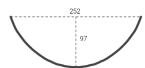
General Trend : Curve Shape

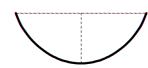


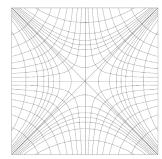
02 HALF MILANO (representative example)

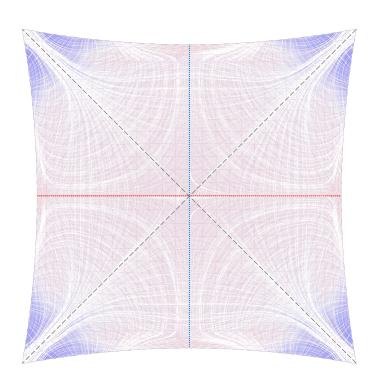
07 RIPPLE CARDIGAN







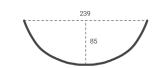


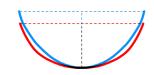


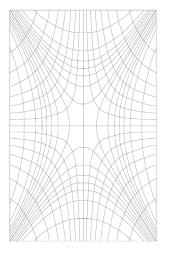
equal warp and weft curves

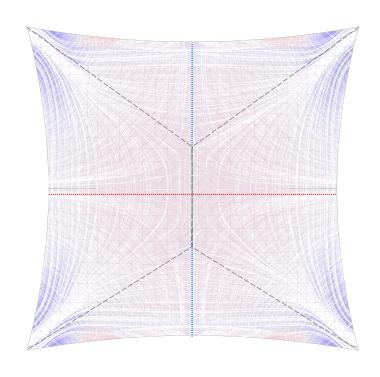
04 DOUBLE HALF CARDIGAN











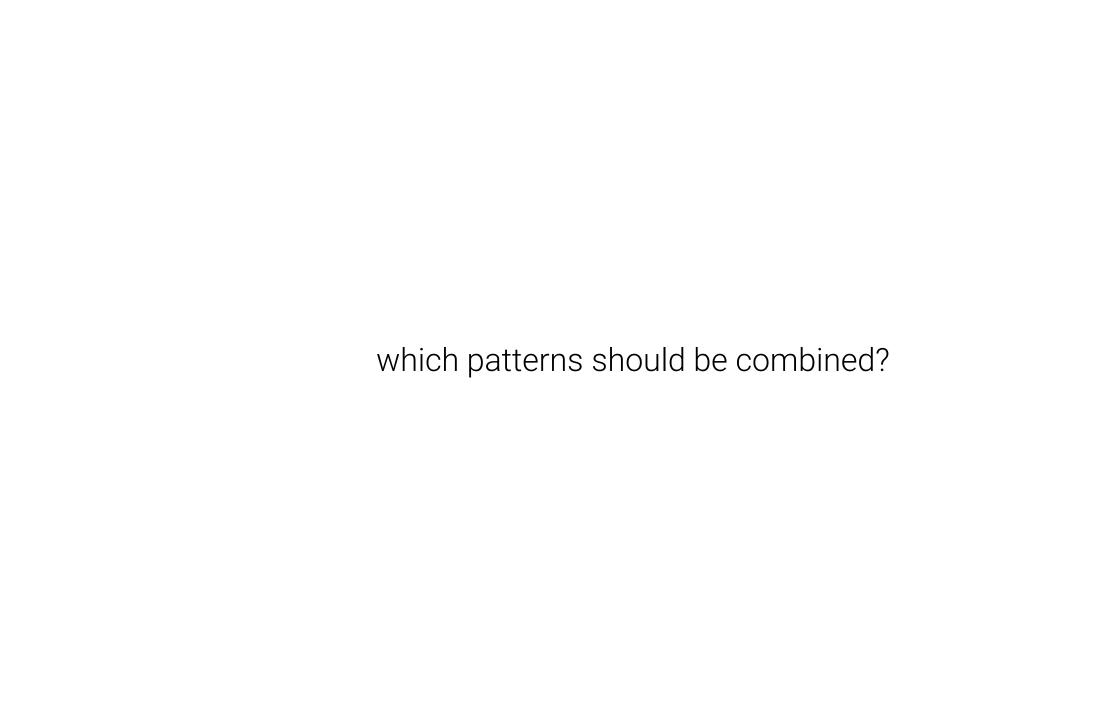
different warp and weft curve lengths

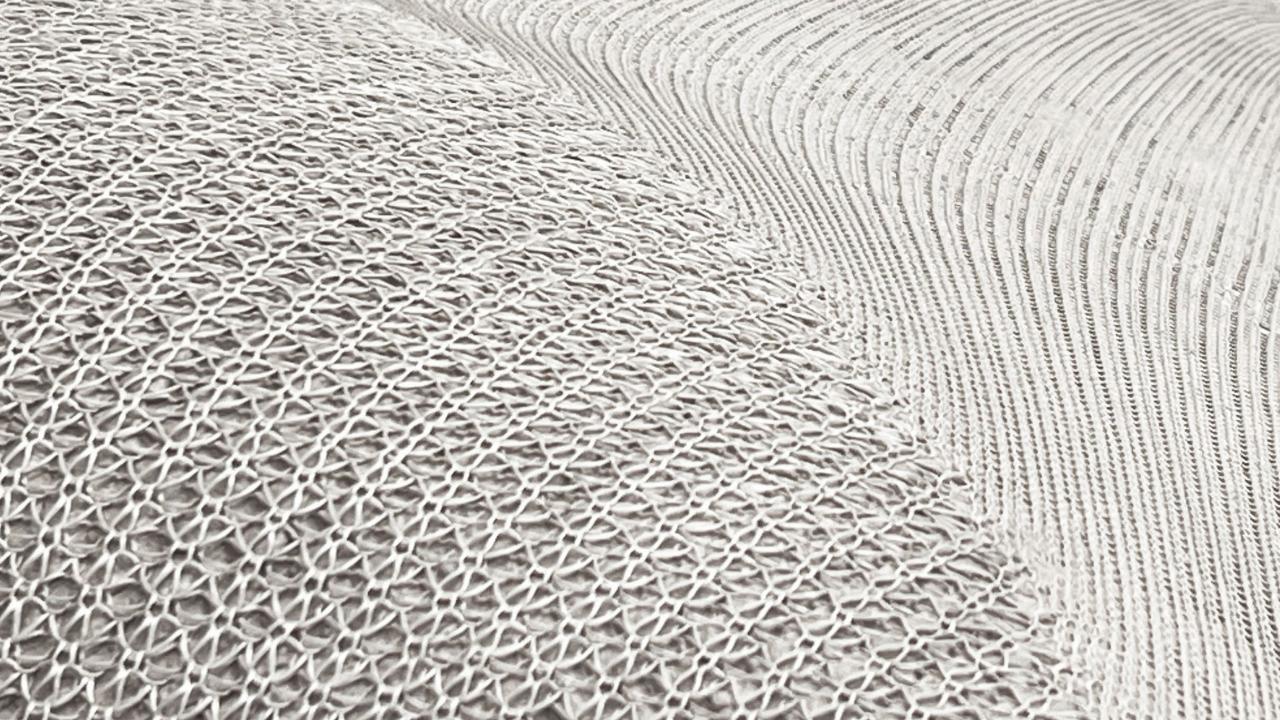
KEY FINDINGS SUMMARY PHASE 2:

- Pattern choice will likely influence the structural behavior of the cast form
- Cast forms might have different structural behavior in the warp vs. weft direction
- Controlling deformation manually is almost impossible
- Different patterns show distinct deformation behavior

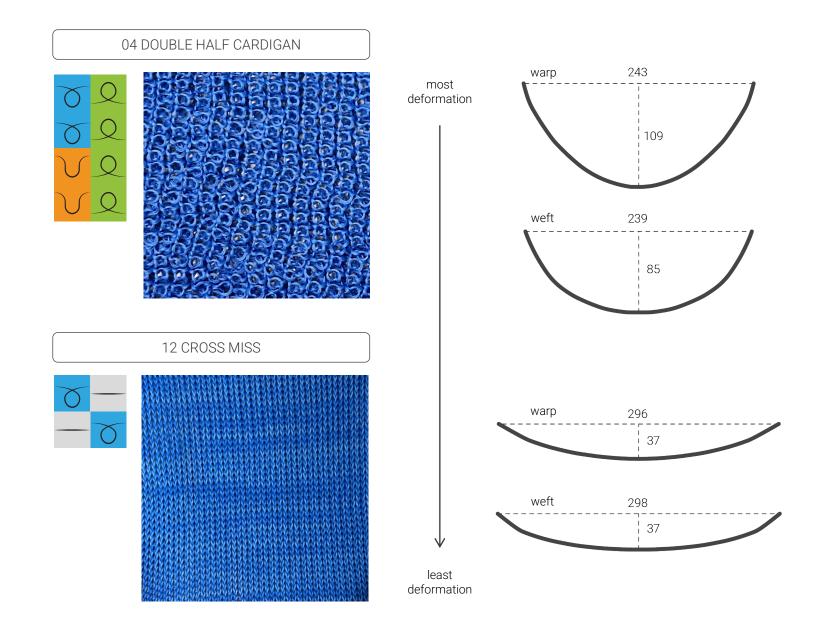








METHODOLOGY | CHOOSING PATTERNS TO COMBINE



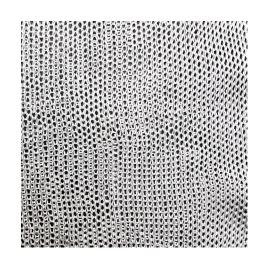
04 DOUBLE HALF CARDIGAN O Q Q Q



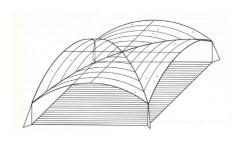
recycled PET yarn

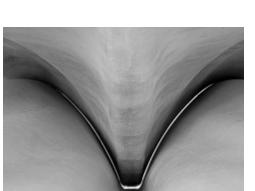


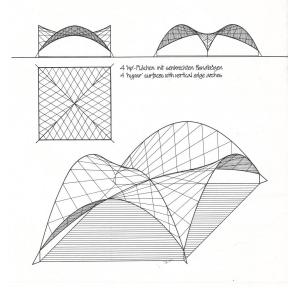




what kinds of forms can be made by combining patterns?





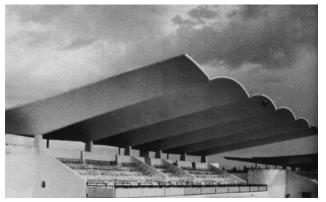


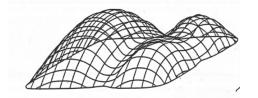






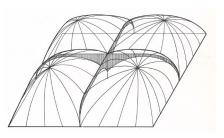
what kinds of forms can be made by combining patterns?





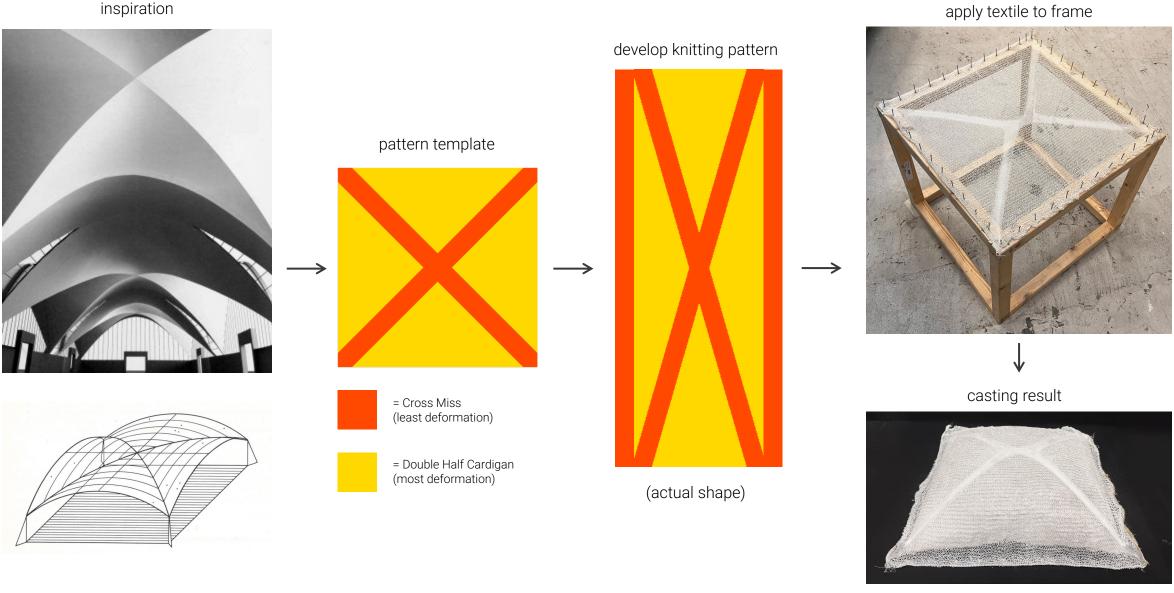




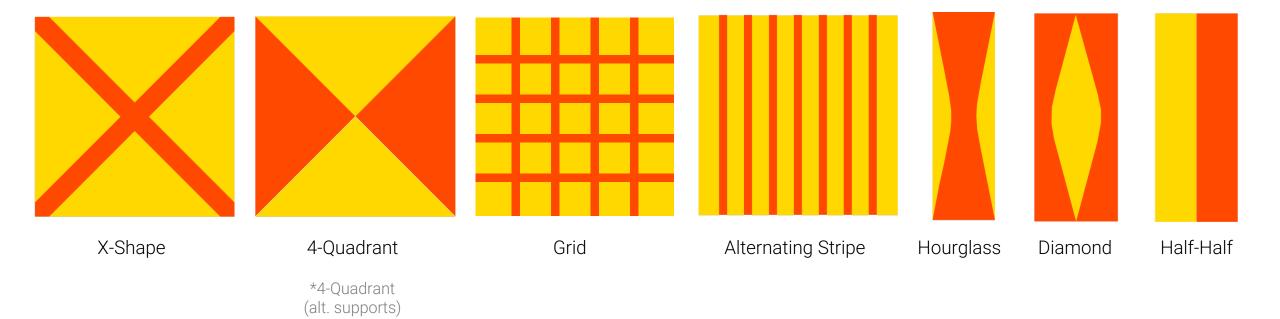


COMBINATION PROCESS

inspiration

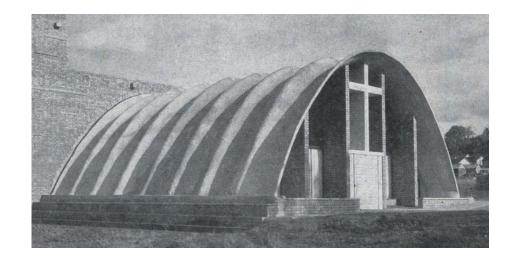


PATTERN TEMPLATES





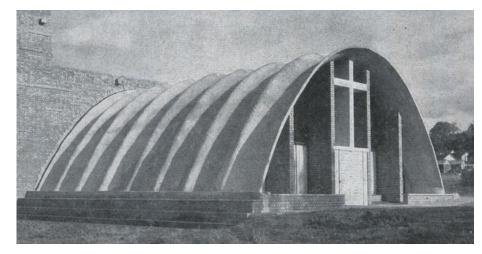
alt-stripe







alt-stripe





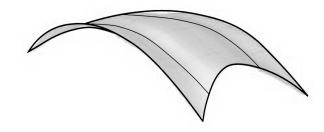








Bruhl Sports Center, 1982 | Structurae



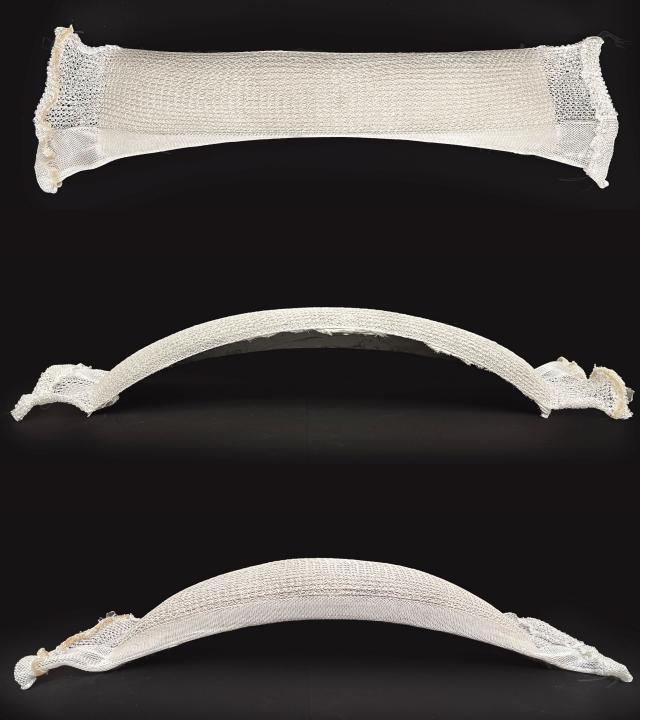


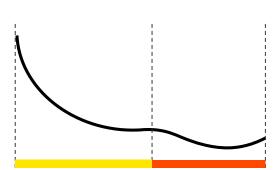




Bruhl Sports Center, 1982 | Structurae

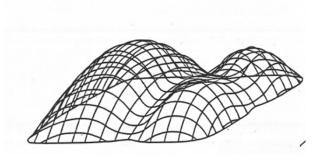








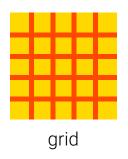


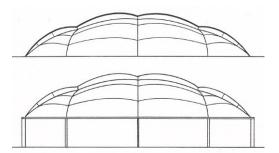


Tragsysteme, Heino Engel 1967

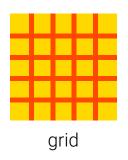


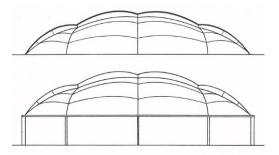






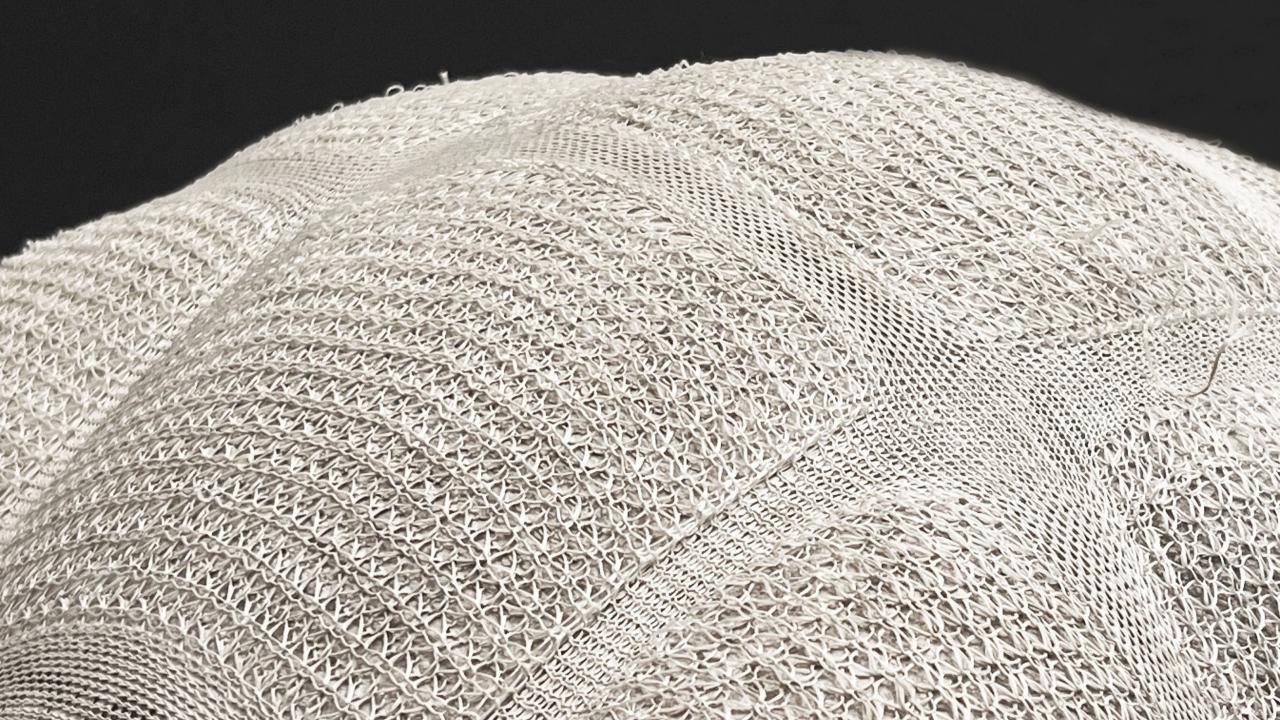




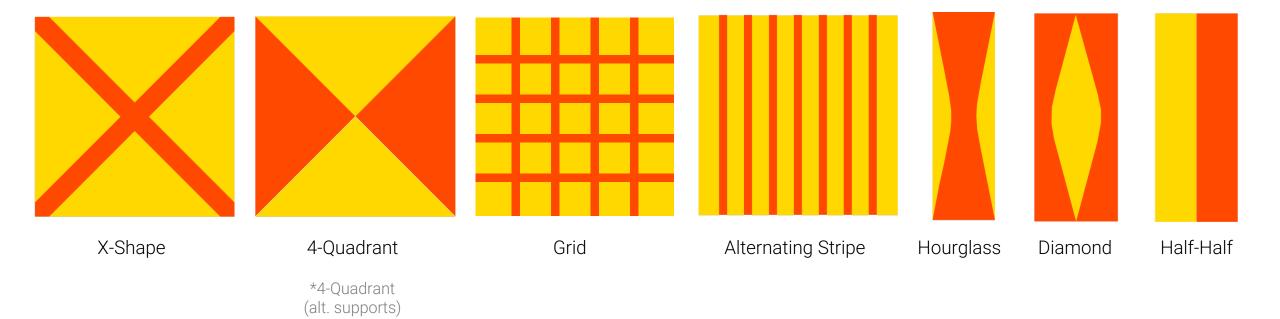




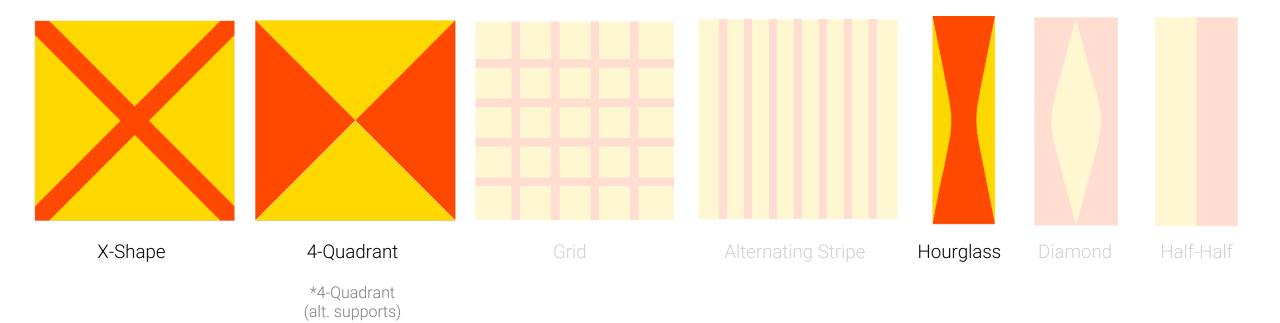




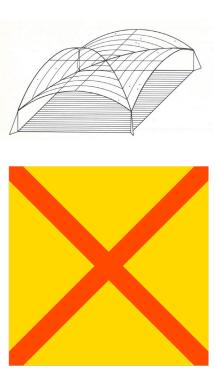
PATTERN TEMPLATES



PATTERN TEMPLATES

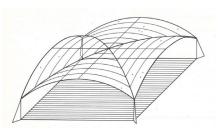


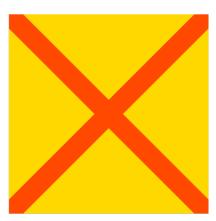




X-Shape

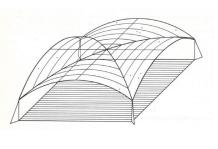






X-Shape

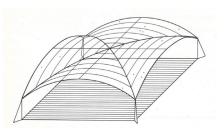


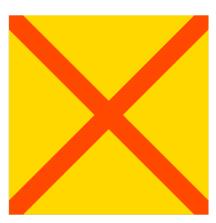




X-Shape





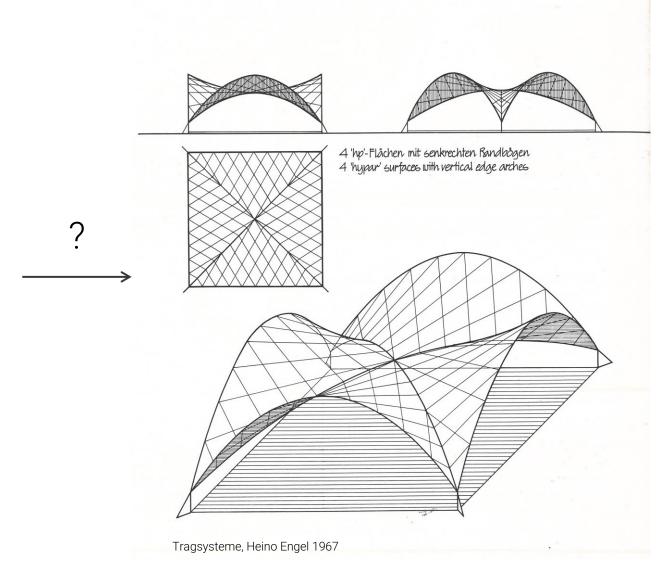


X-Shape

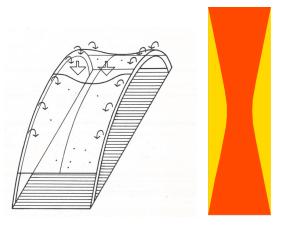






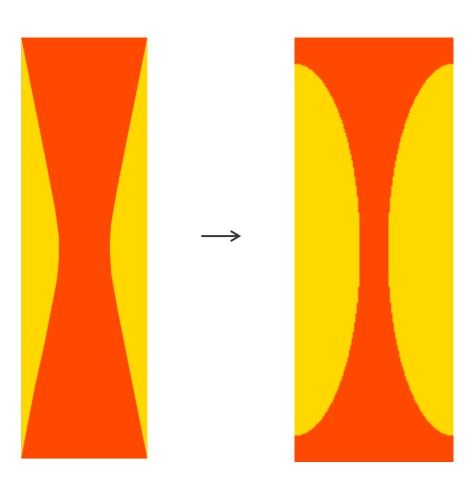




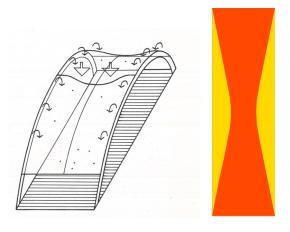


Hourglass



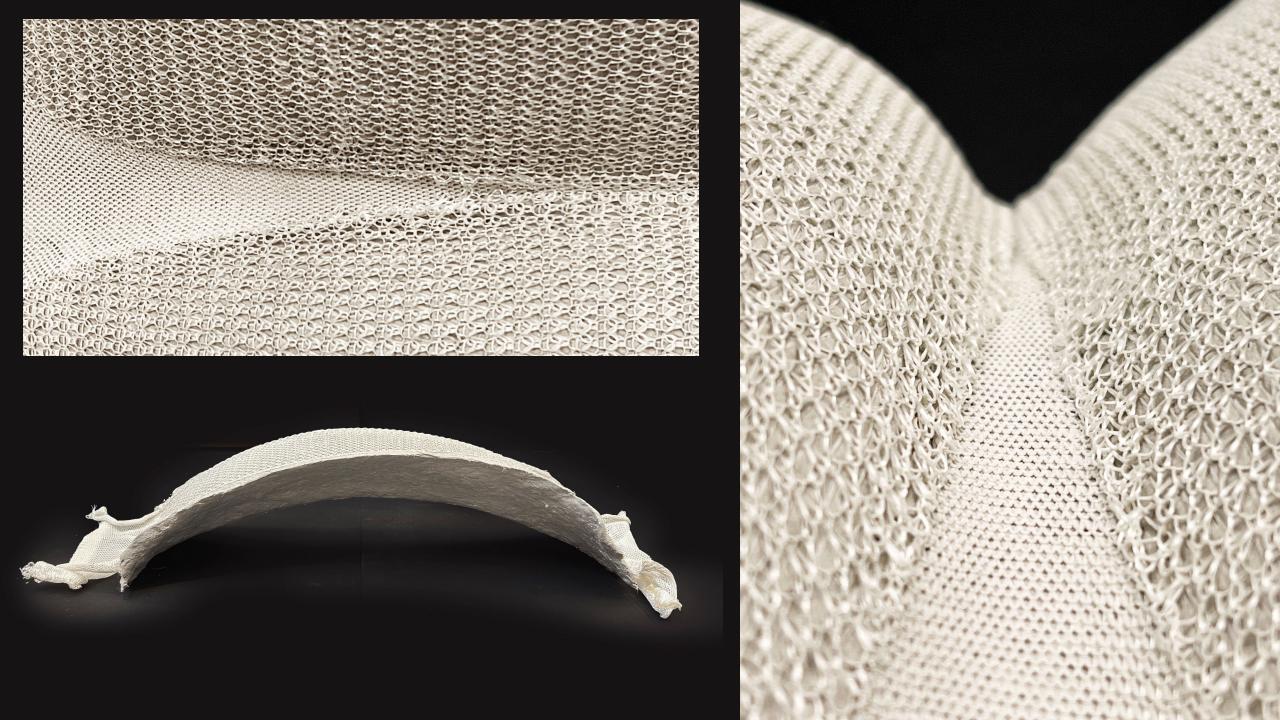


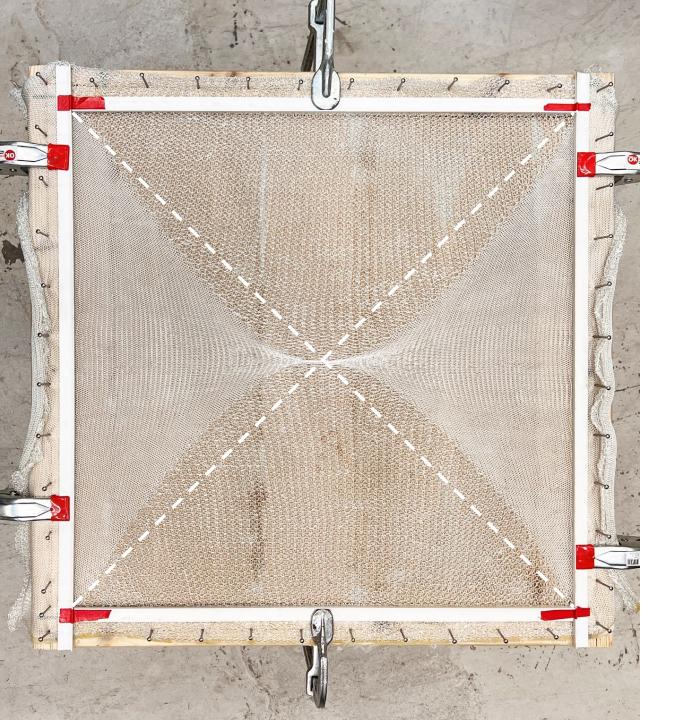


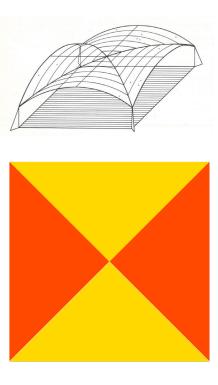


Hourglass



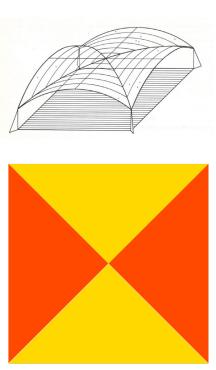






4-Quadrant





4-Quadrant



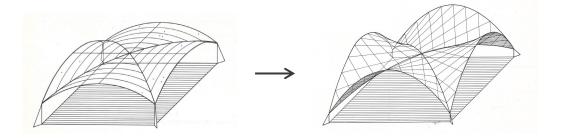


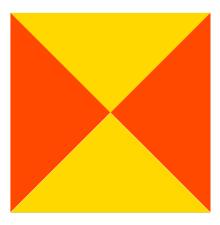












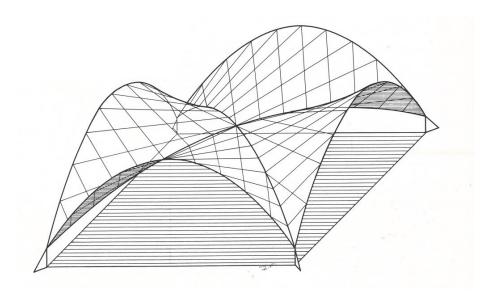
4-Quadrant *alt supports

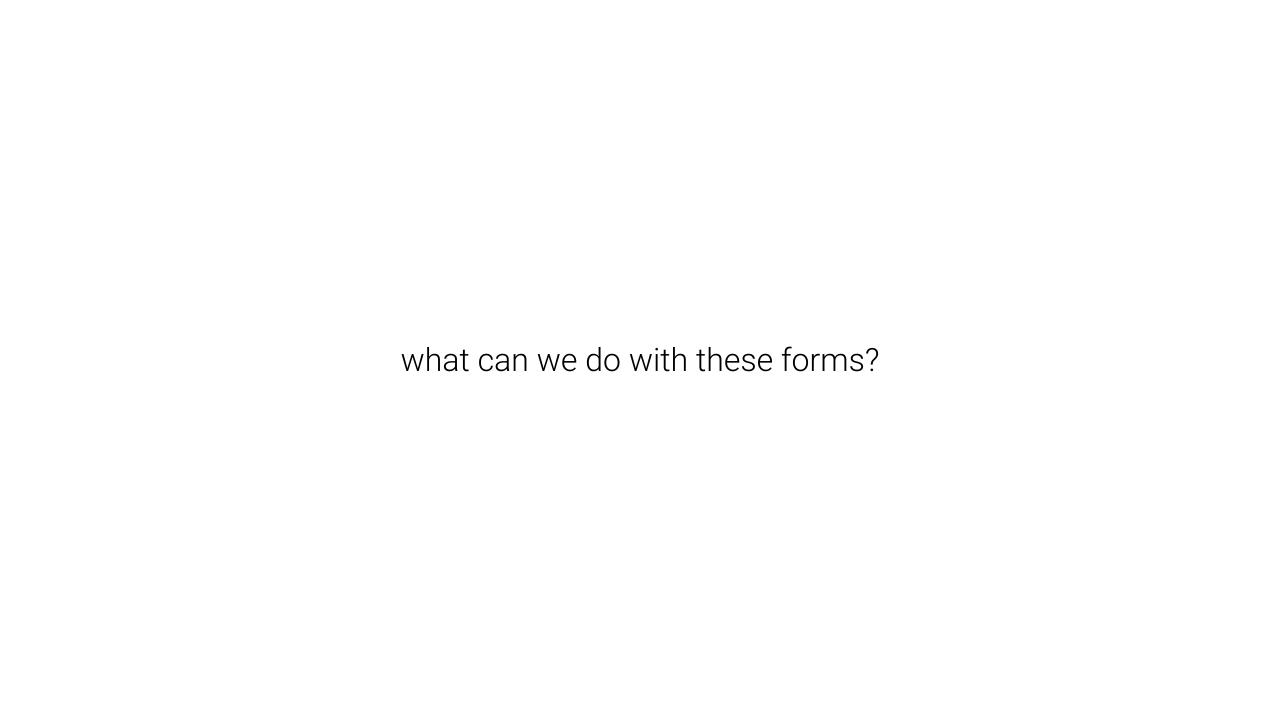




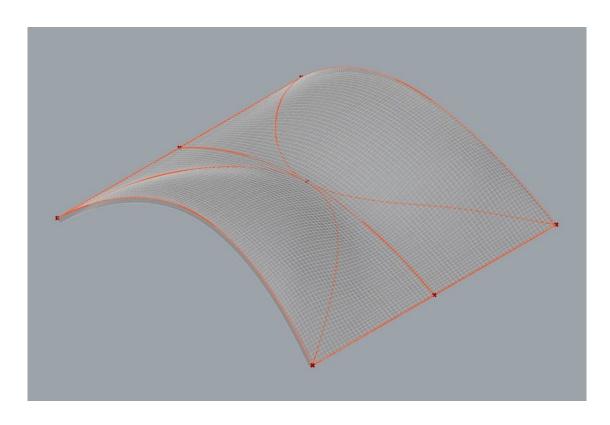




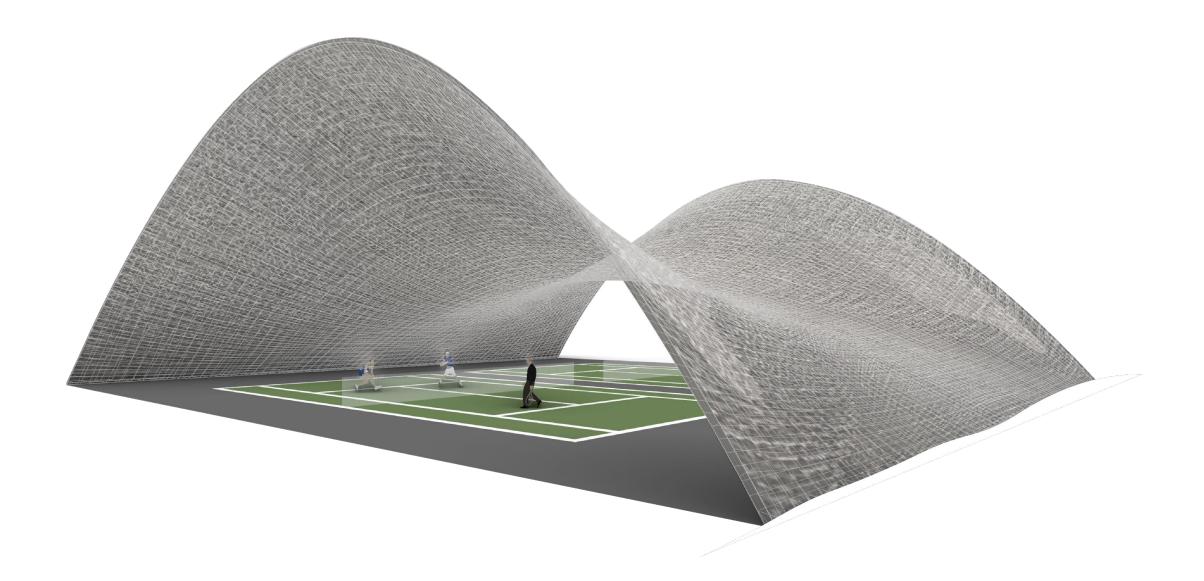


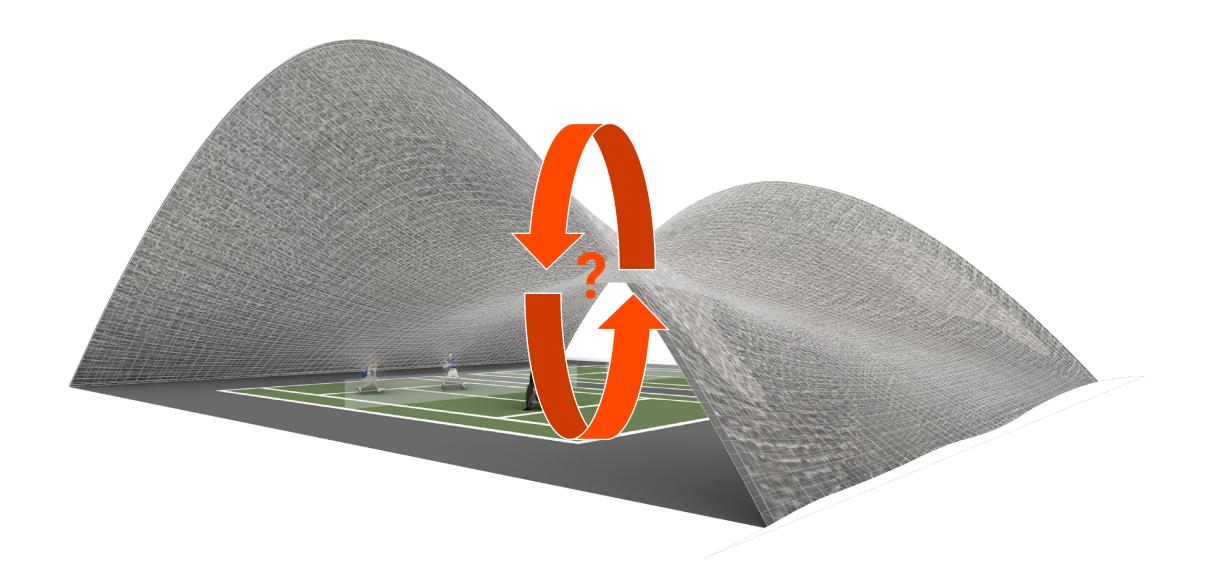


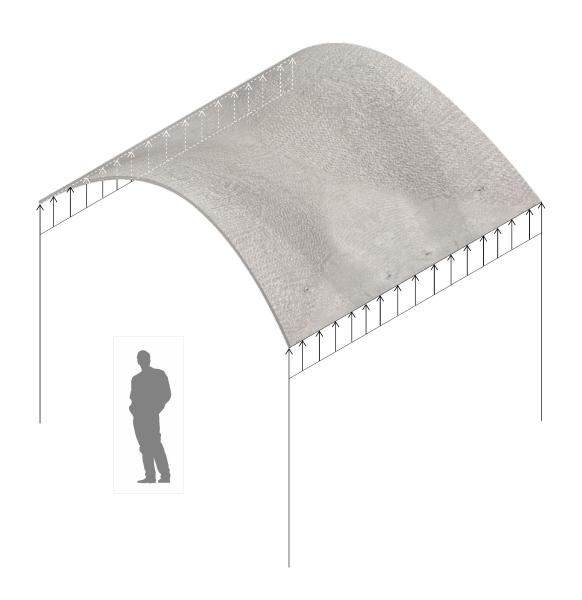


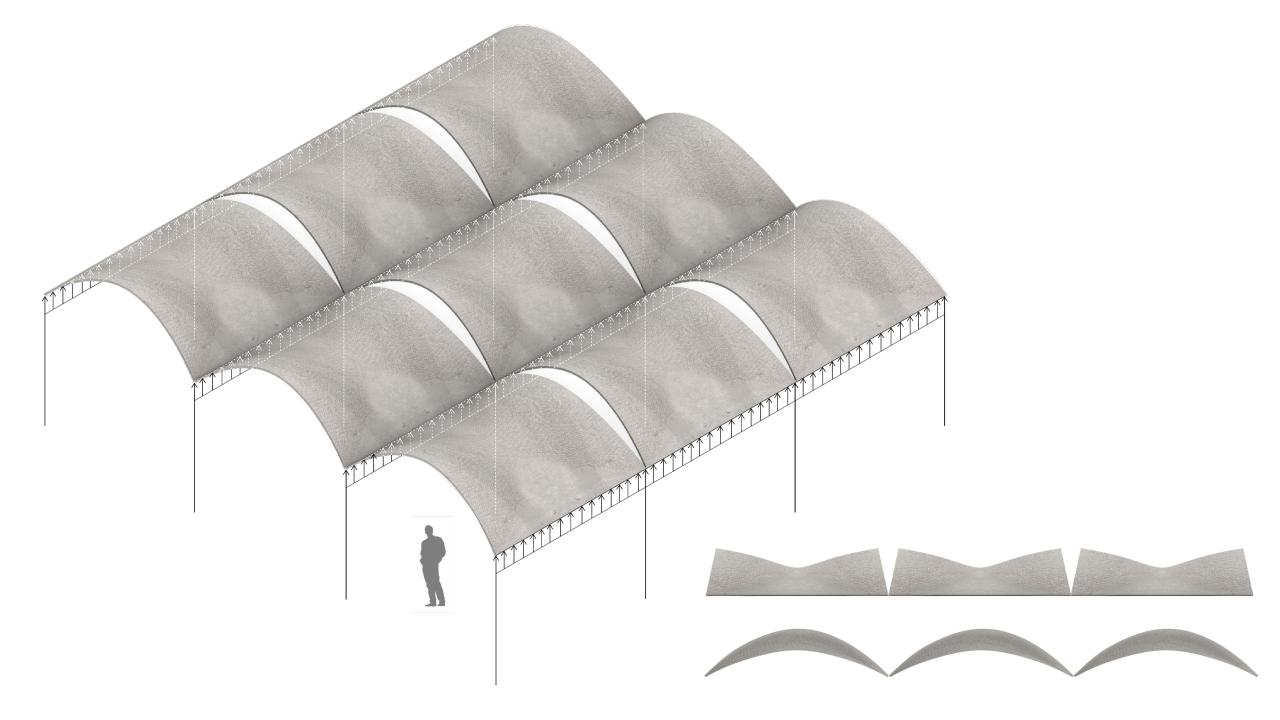


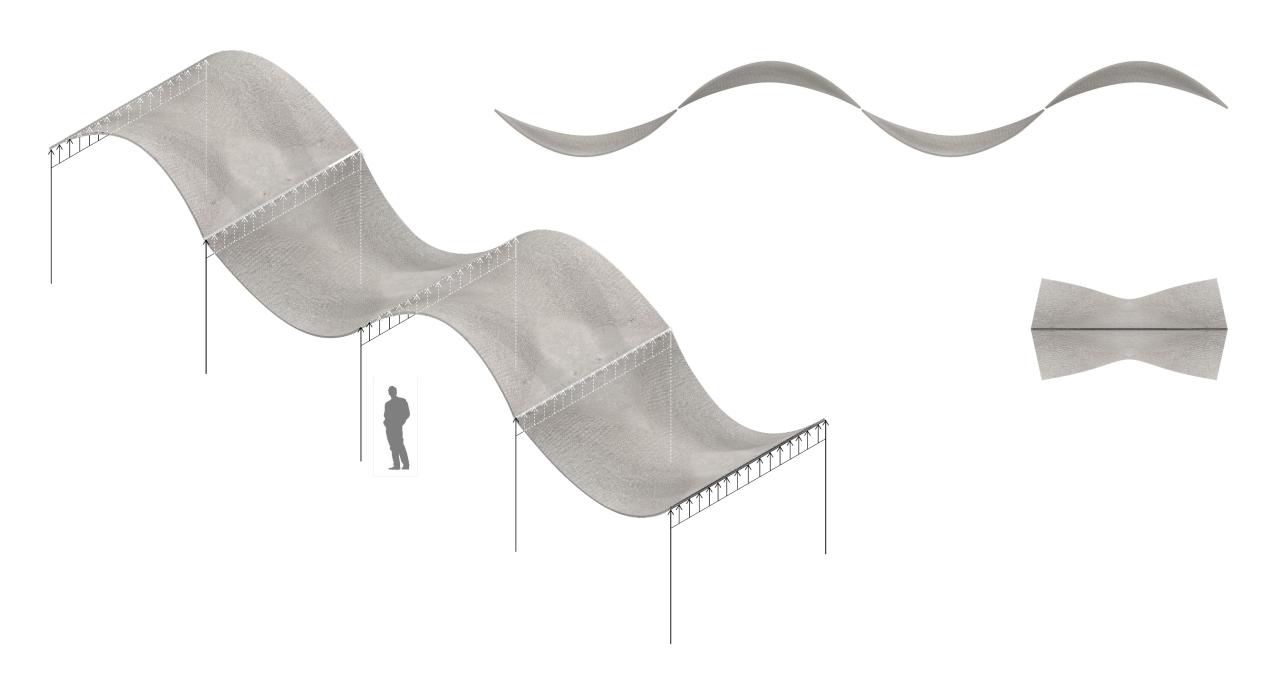
3D scanning + Parametrization in Grasshopper

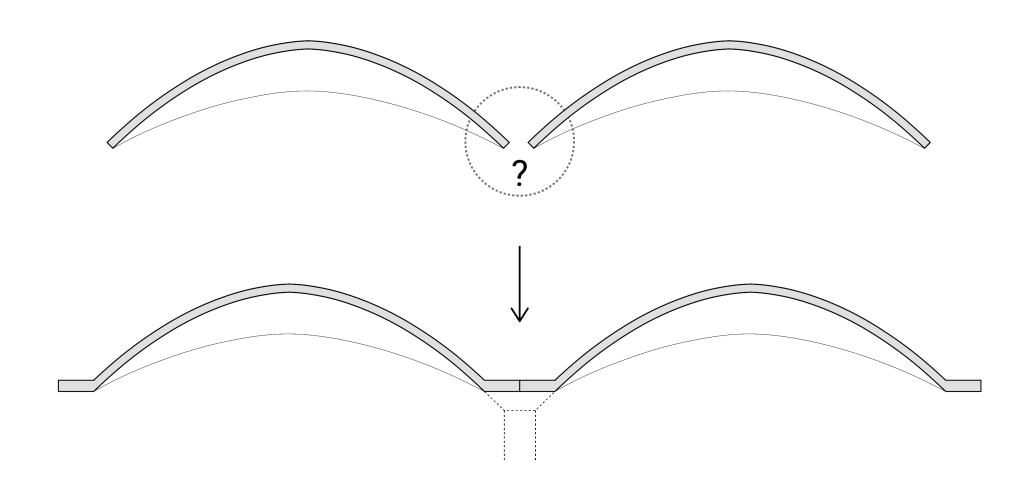


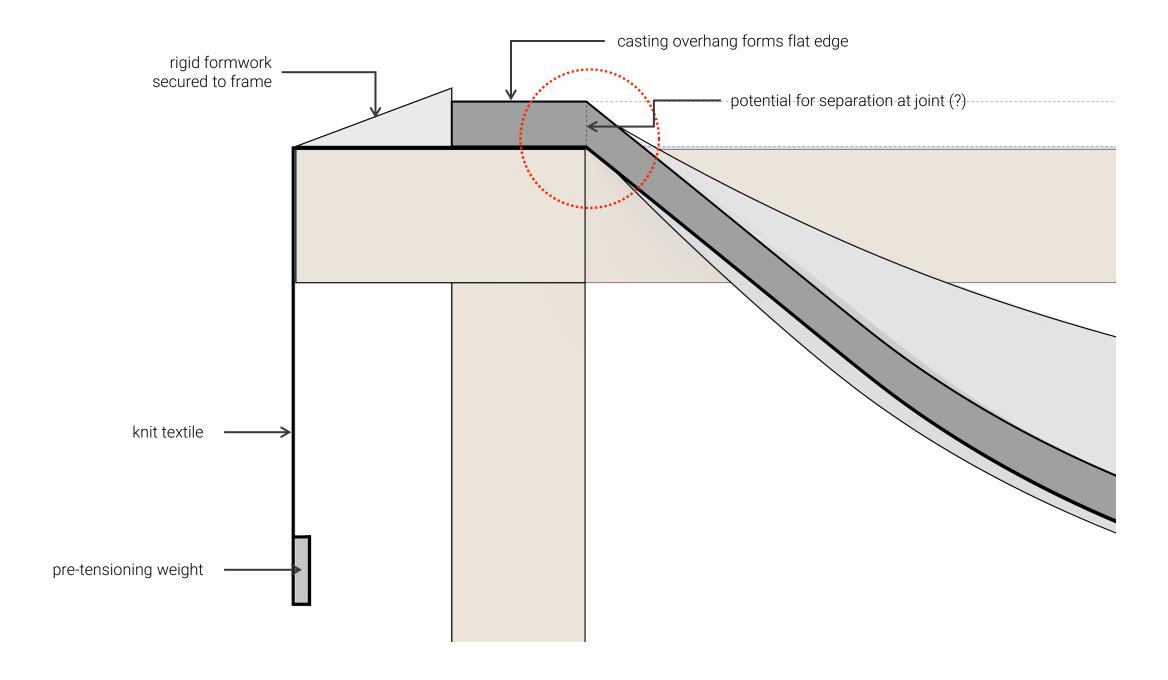


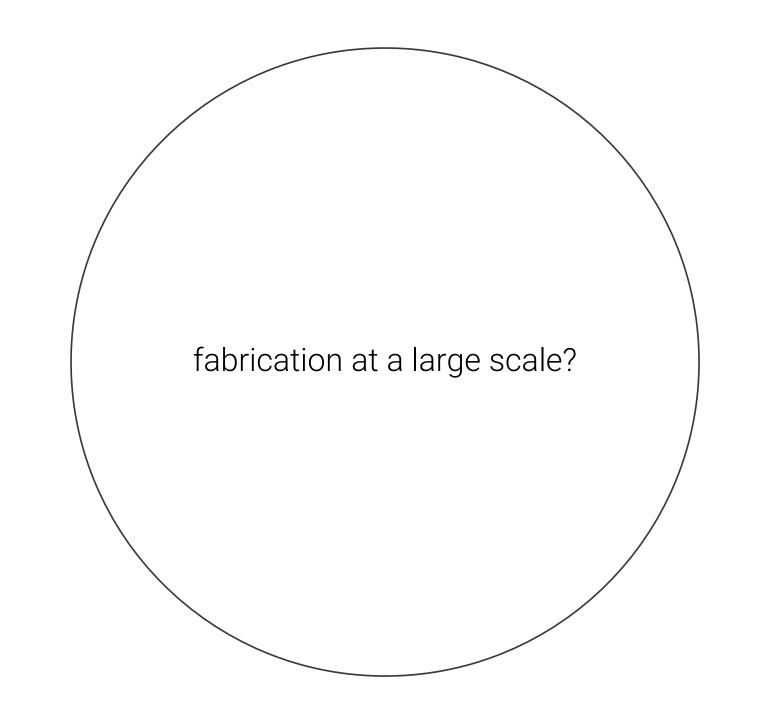


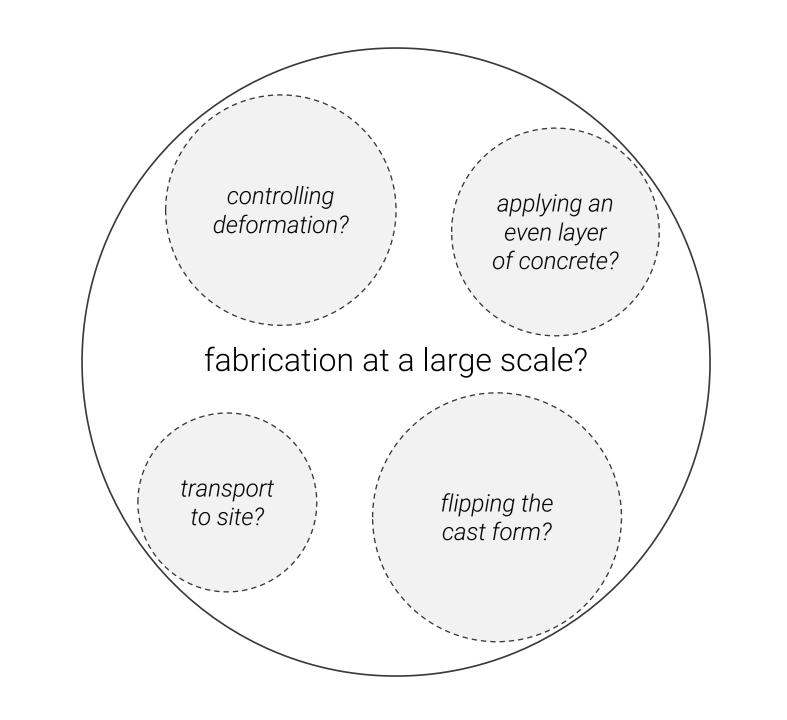


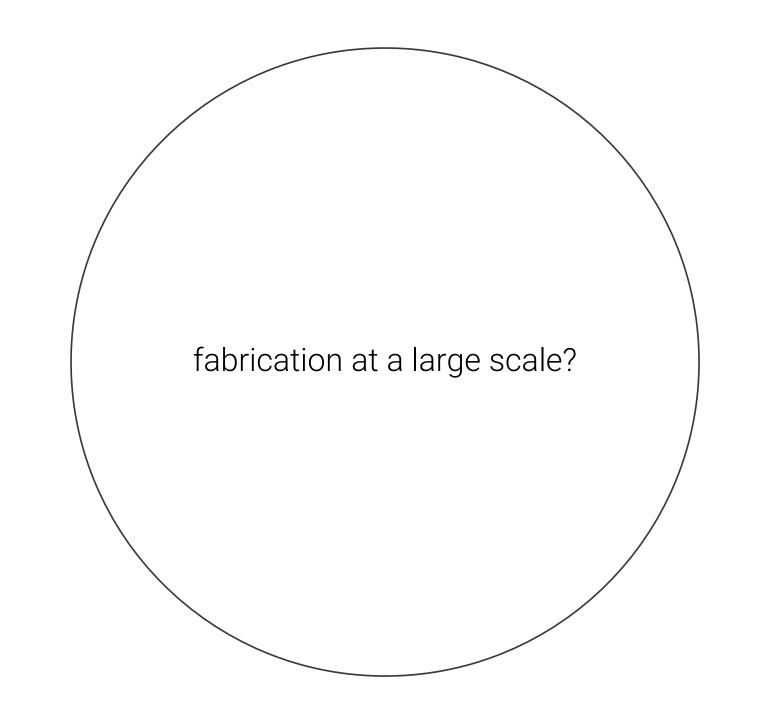


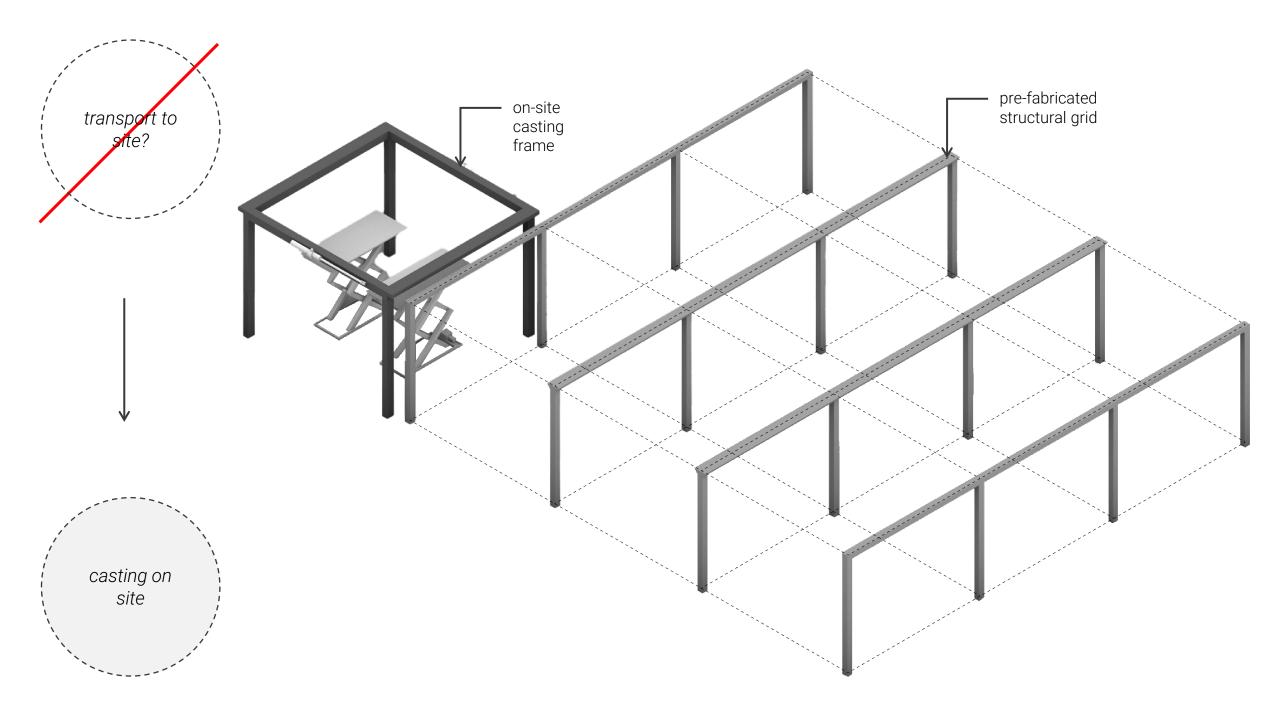






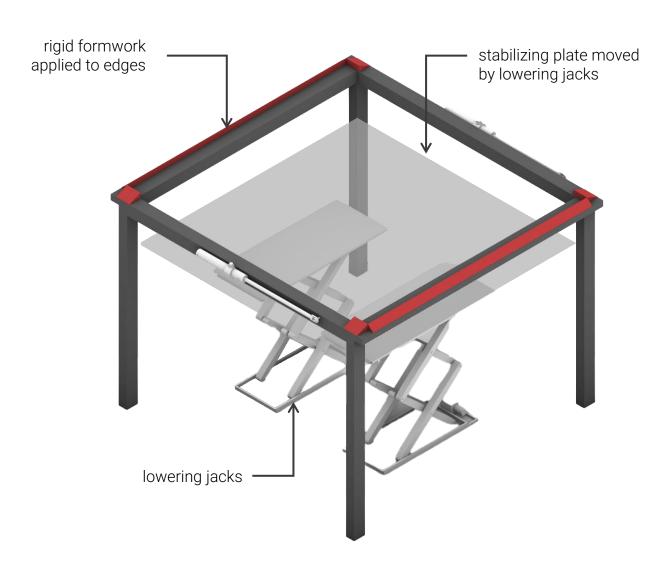


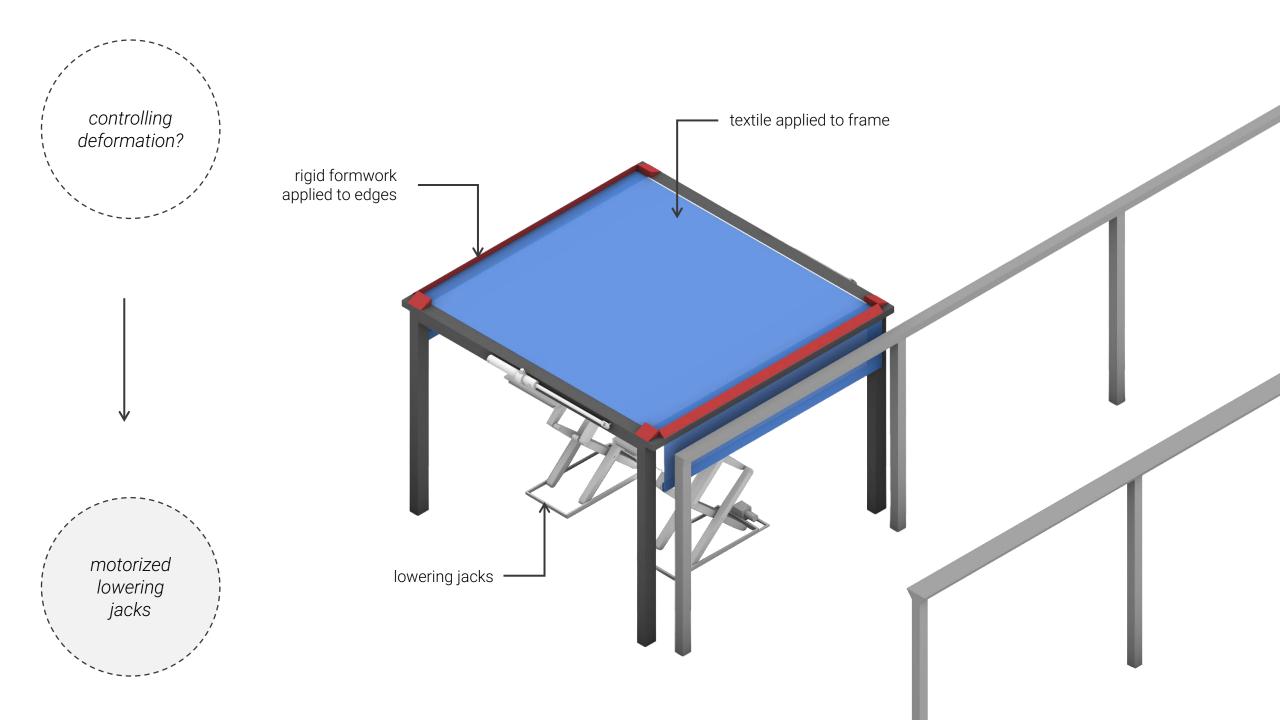


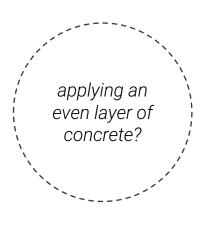




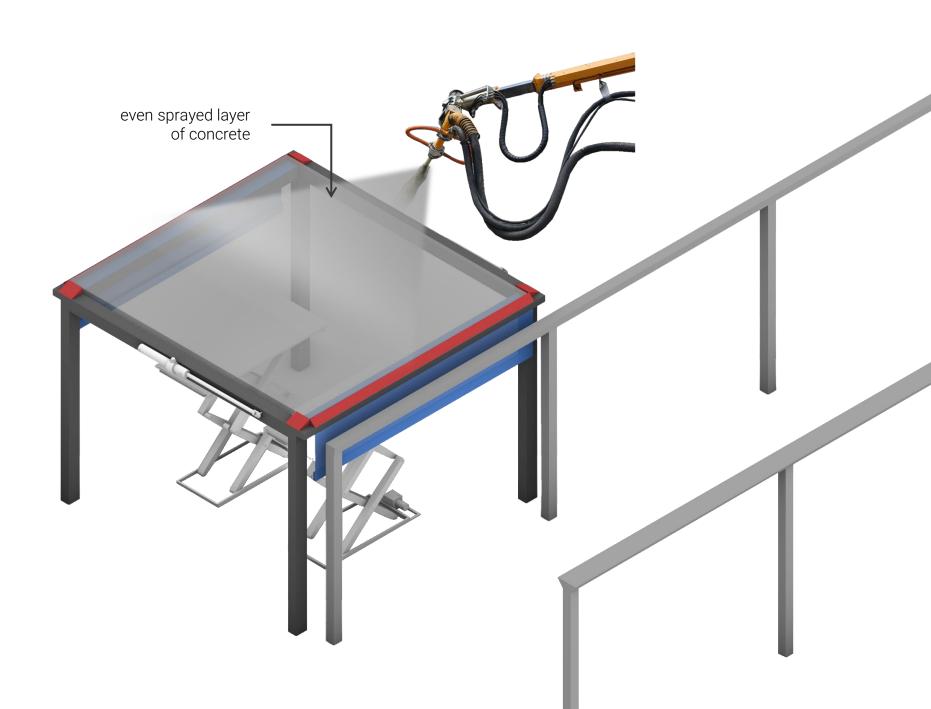


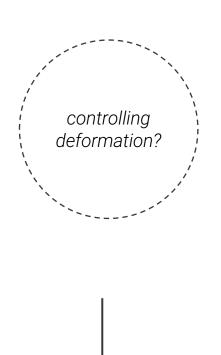




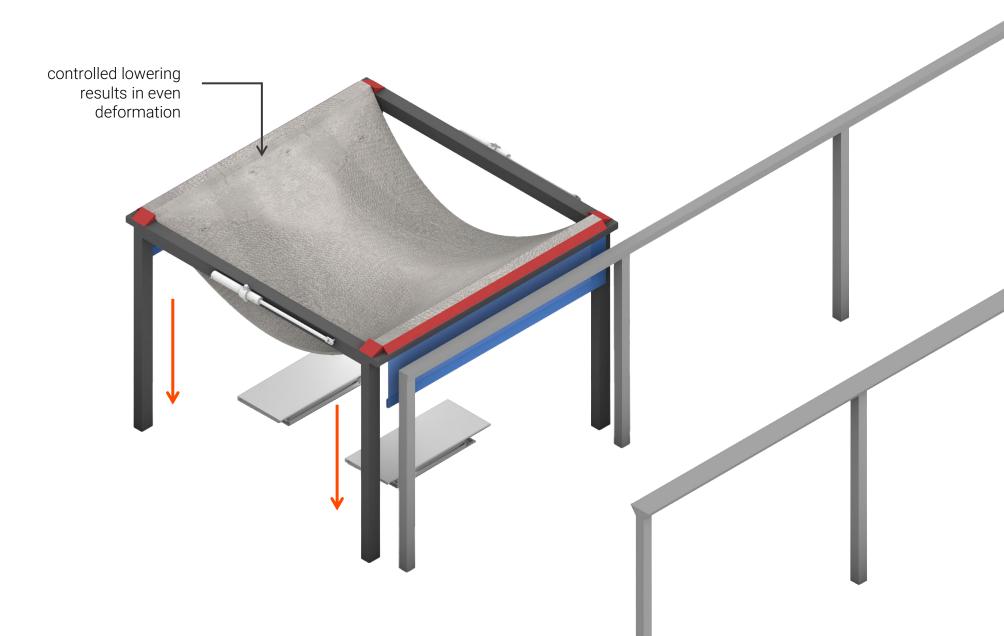


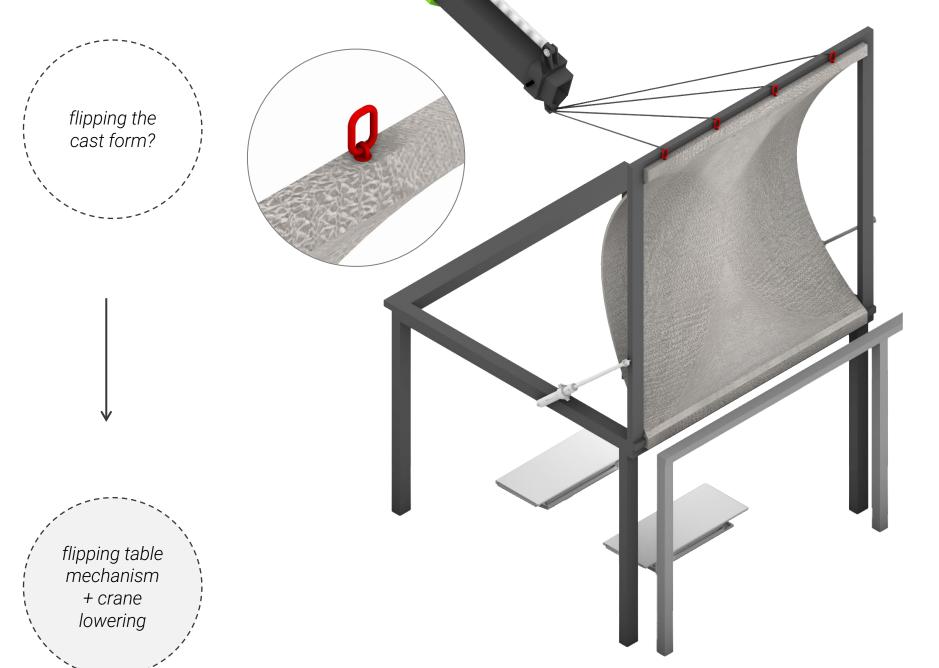
spraying application





motorized lowering jacks



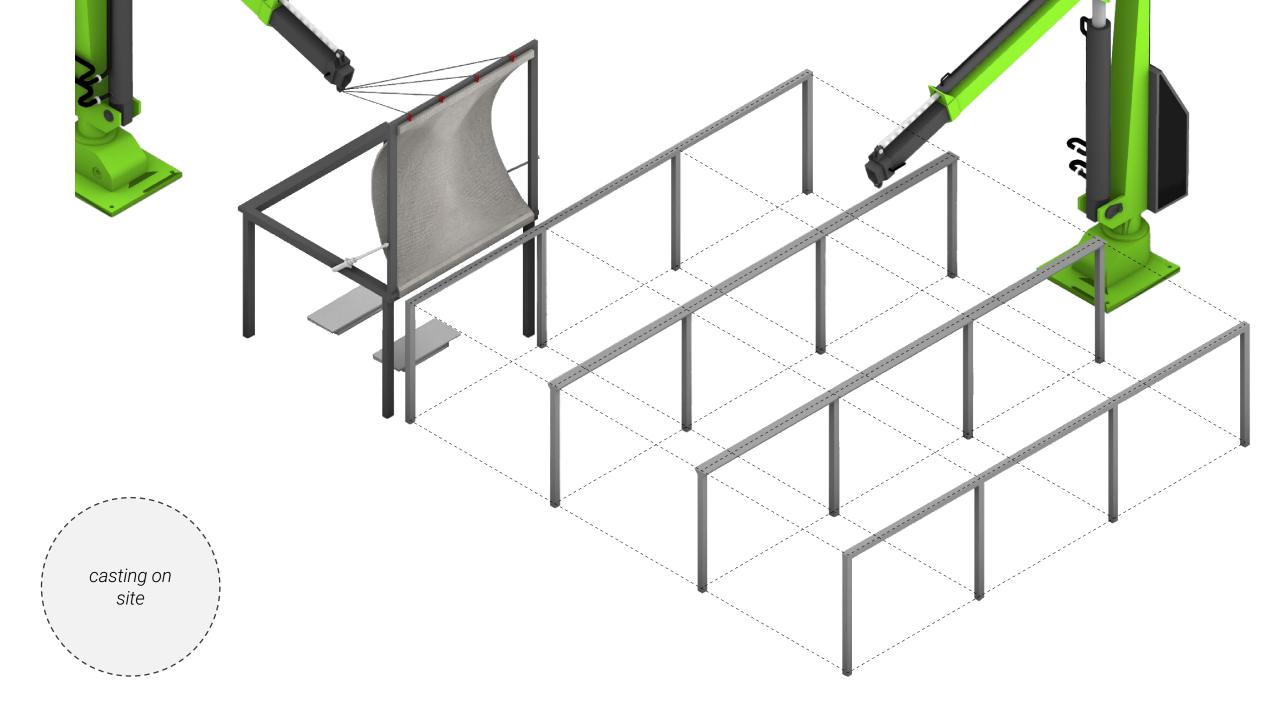


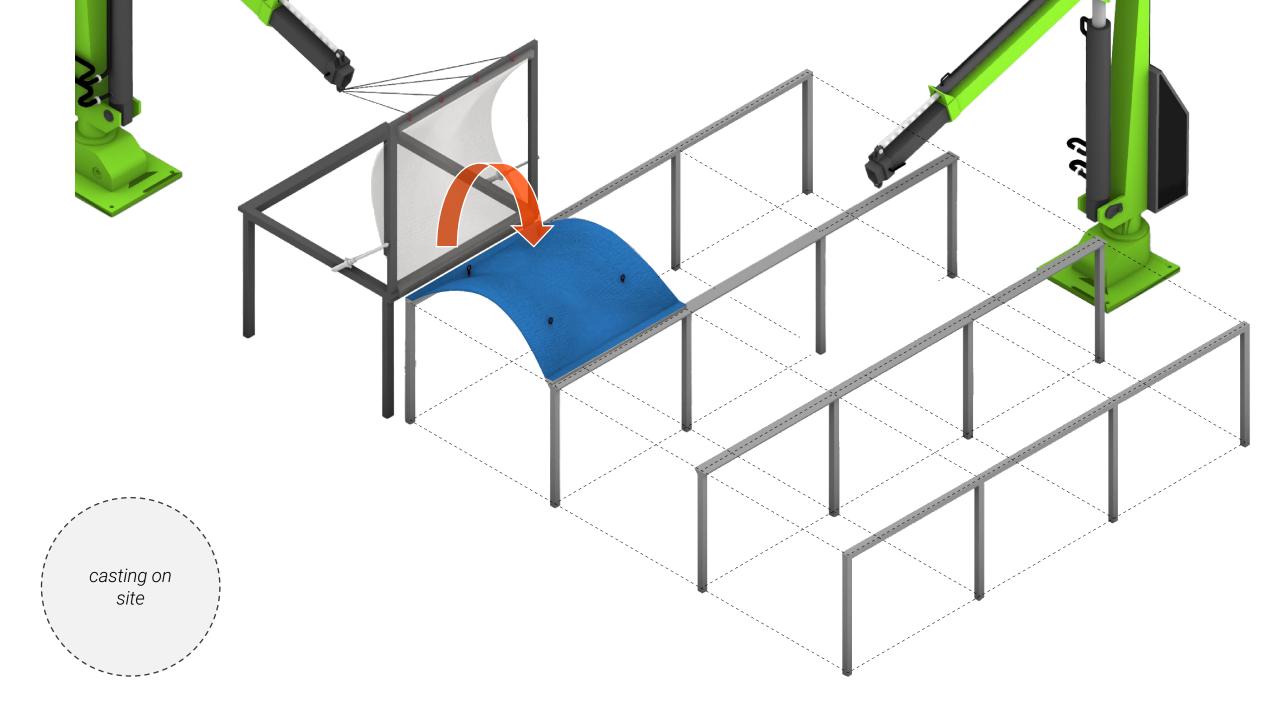


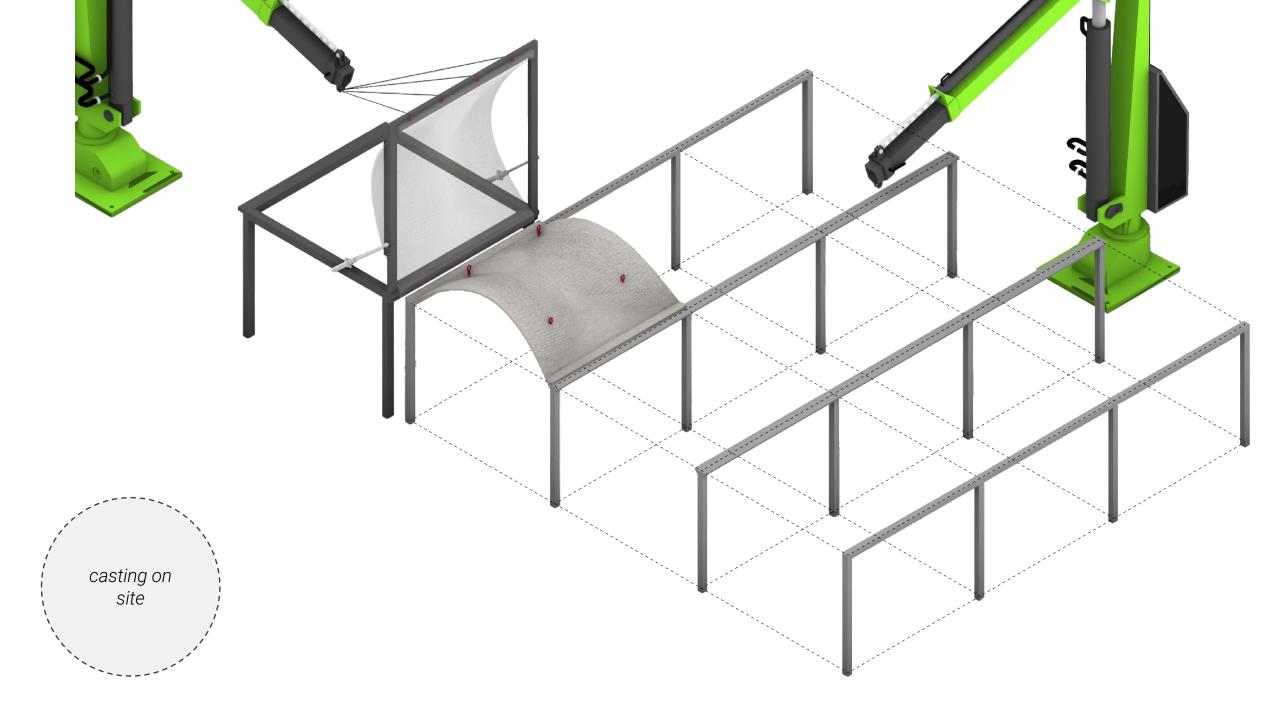
Flipping Table (Industries D. Labonte)

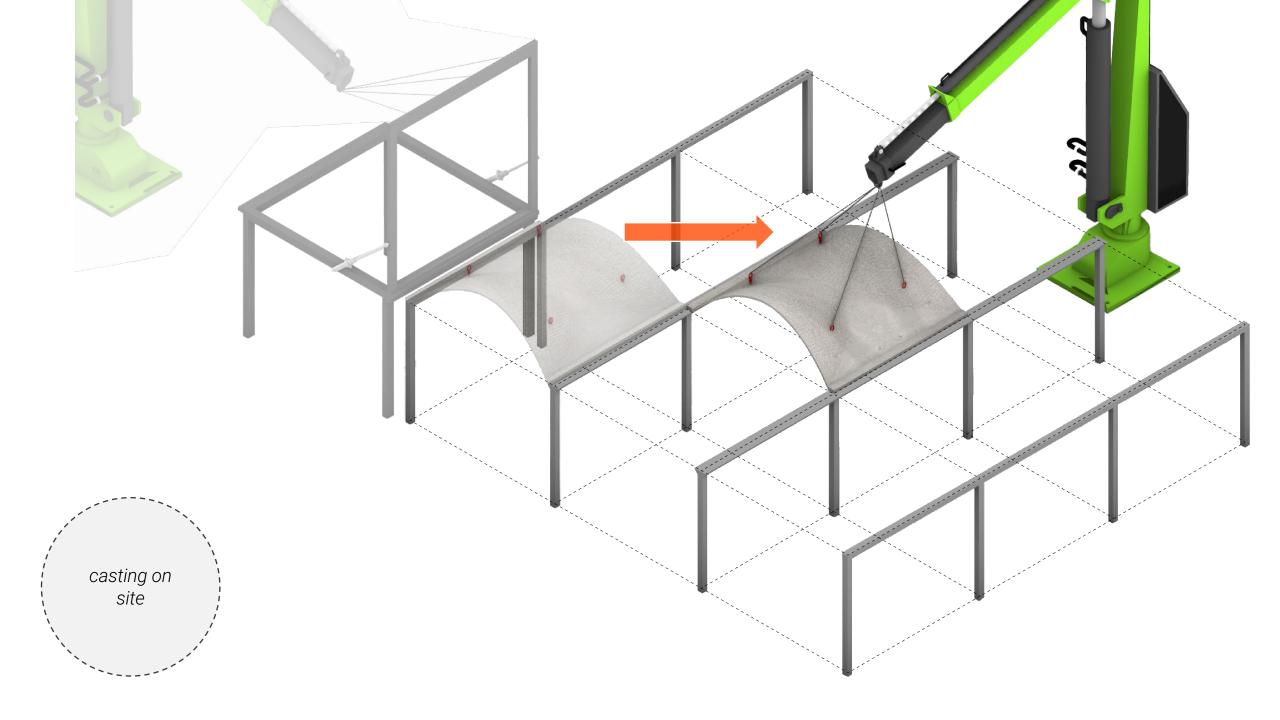


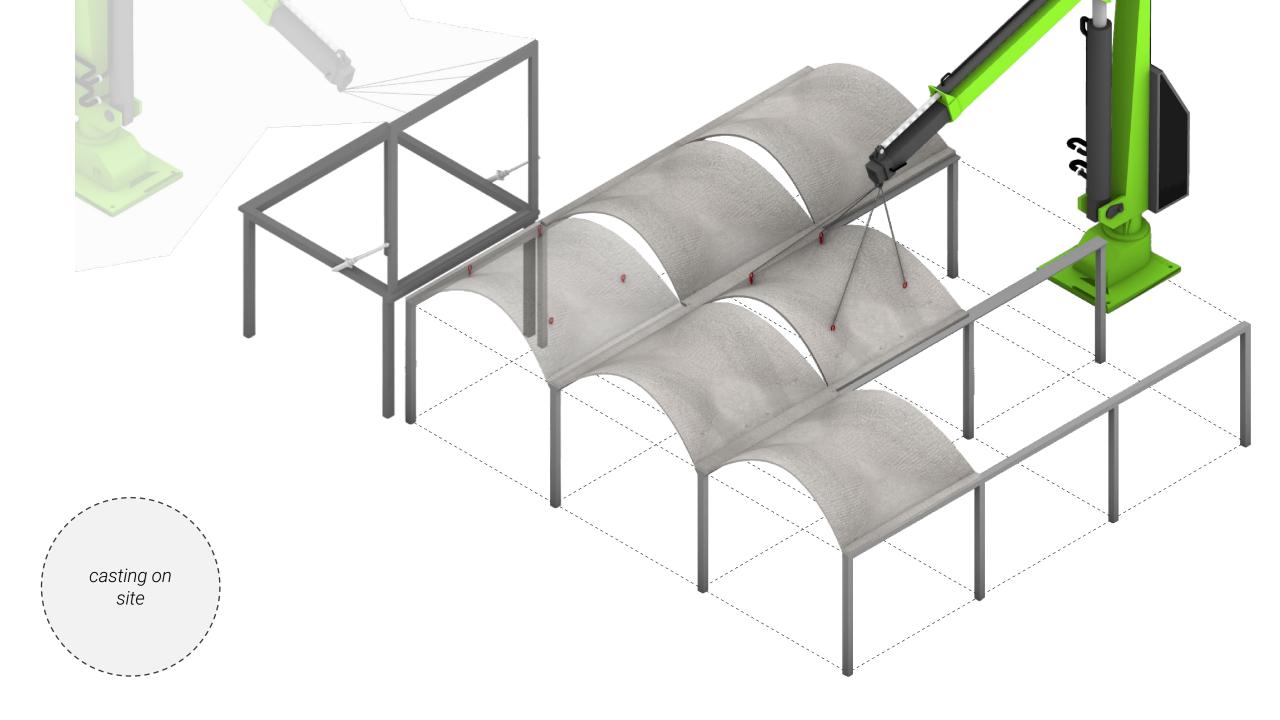
Crane Lowering (Oriental Shirashi Corp)













completed structure!

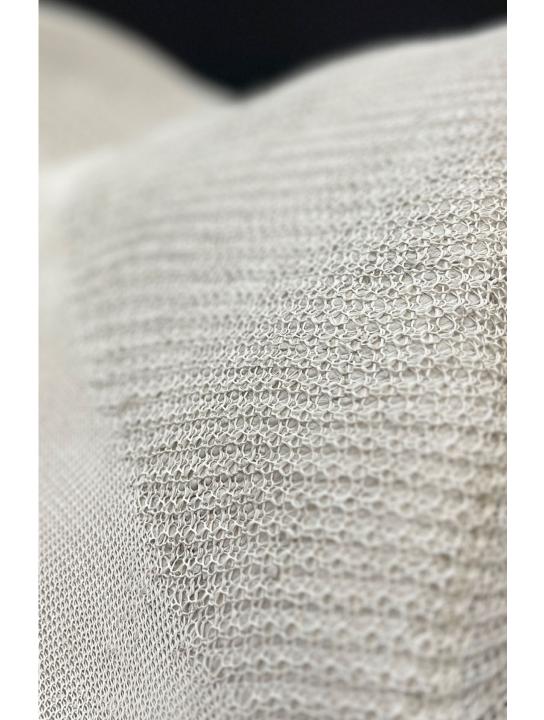




KEY FINDINGS + REFLECTION

REFLECTION + KEY FINDINGS:

- different patterns exhibit distinct deformation behavior
- most patterns behave differently in the weft versus warp direction
- the choice of pattern is key in designing CNC knit flexible formwork
- calibration between theoretical information and the realities of knit textiles is always necessary
- scaling up this technology presents added complexities which require advanced solutions



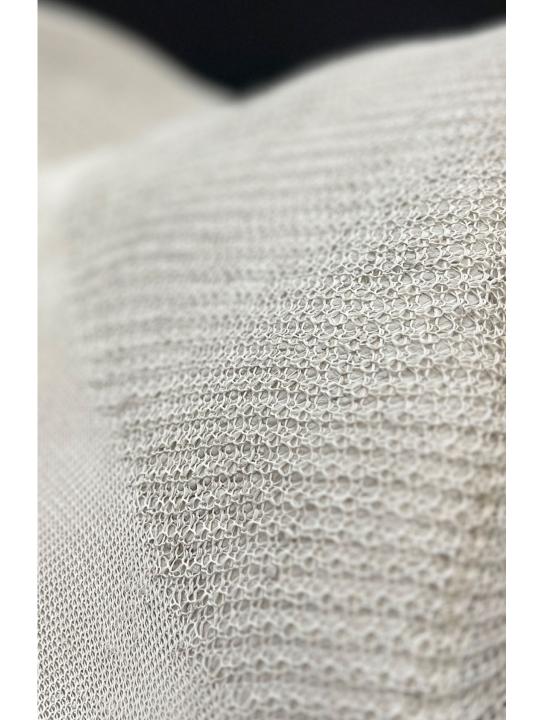
LIMITATIONS OF THE RESEARCH:

- designing knit patterns for specific situations requires specialized skills and time
- specialized knowledges makes it difficult to integrate into mainstream construction
- controlling deformation is difficult implications for structural uniformity and replicability at a large scale
- It is difficult to model / predict the behavior of knit textiles



FUTURE WORK:

- more research into modelling knit textile behavior
- developing more precise calibration process for pattern combination
- optimizing pattern templates for specific structural requirements
- exploring larger-scale applications in more detail



THANK YOU!