Angels can fly because they take themselves lightly.

-G.K Chesterton

Truss-to-GO!

A Novel Low-Tech Flax-FRP Technology for the **in-situ Construction of Lattice Structures**

Pavan Kumar Sathyamurthy
Building Technology, TU Delft AUBS
22 May 2024

Chapter 1:
WHY?

Lattice Structures are Efficient Structures

(generally)

Lattice Structures are Efficient Structures

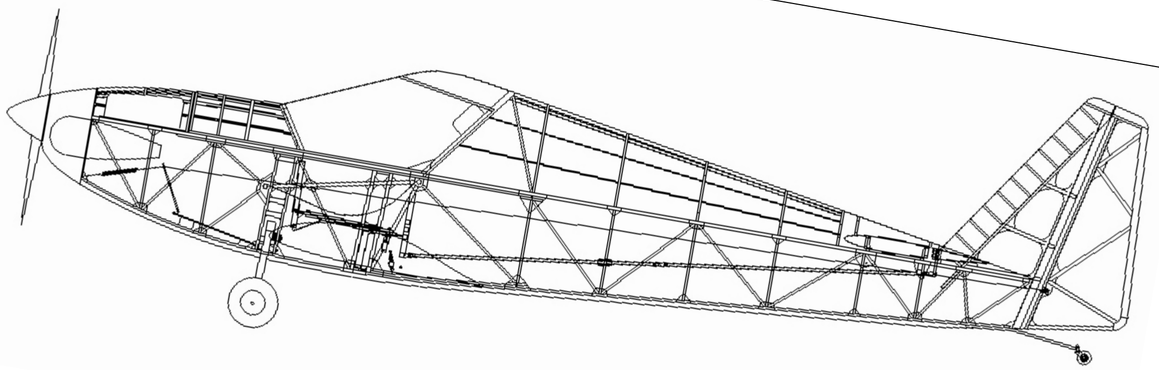
(generally)

Moulton Double Pylon
https://www.cyclesense.co.uk/m73b0s725p16741/MOULTON-Double-Pylon

Lattice Structures are Efficient Stru

(ge

Moulton Double Pylon
https://www.cyclesense.co.uk/m73b0s725p16741/MOULTON-Double-Pylon

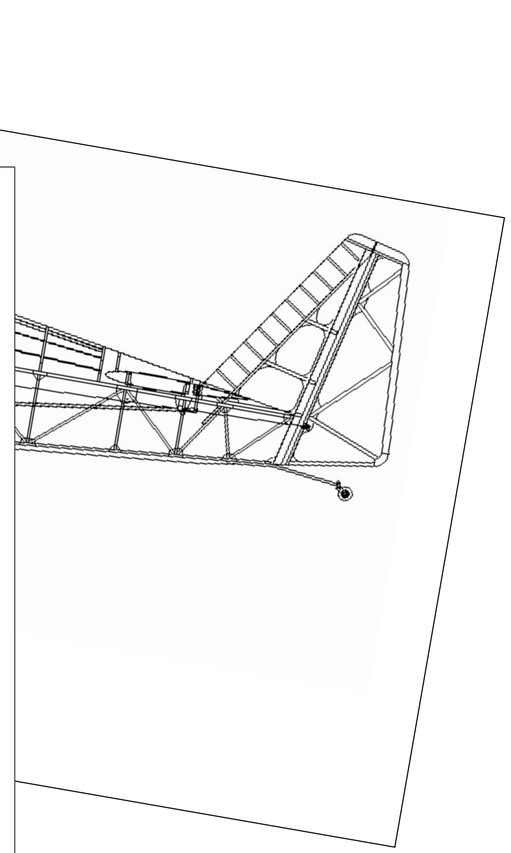


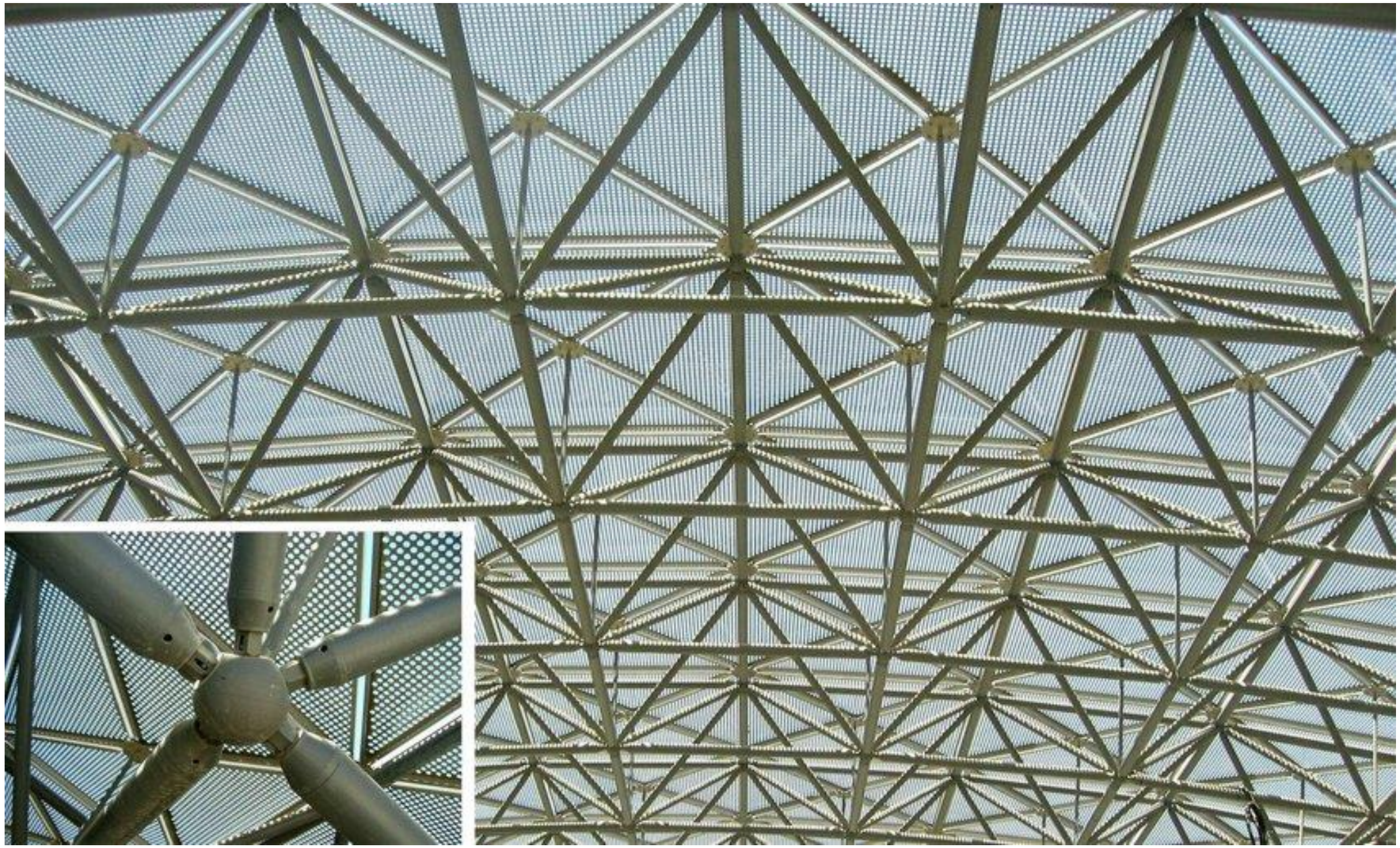
Robin Ultralight- Fuselage Construction

Lattice Structures are Efficient

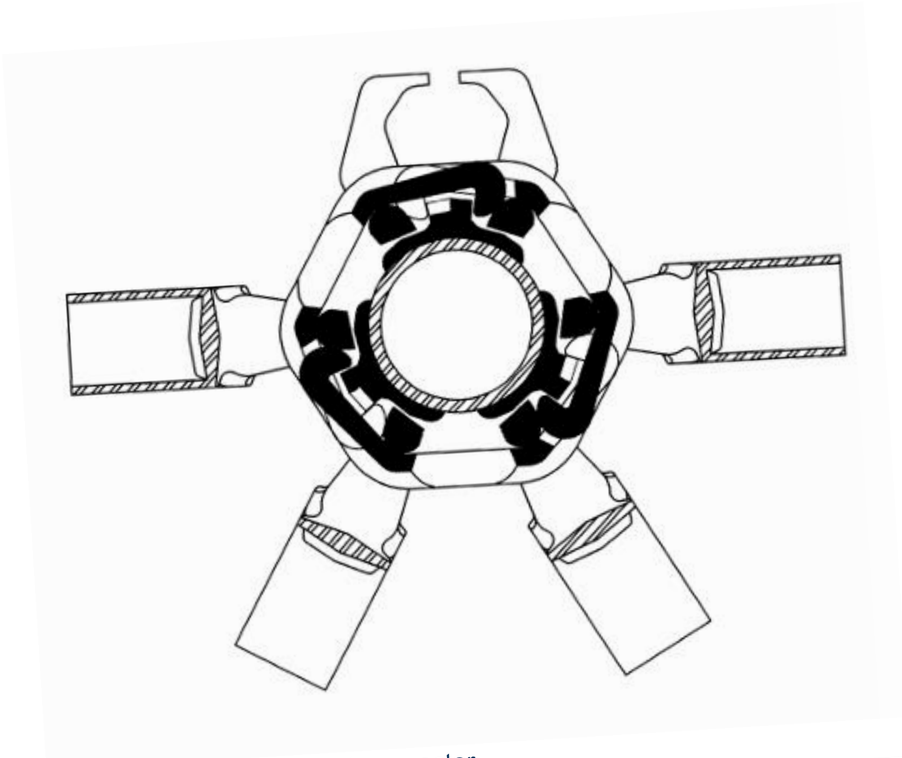
Moulton Double Pylon
https://www.cyclesense.co.uk/m73b0s725p16741/

Beatrixlaan Lightrailstation
ZJA Architects





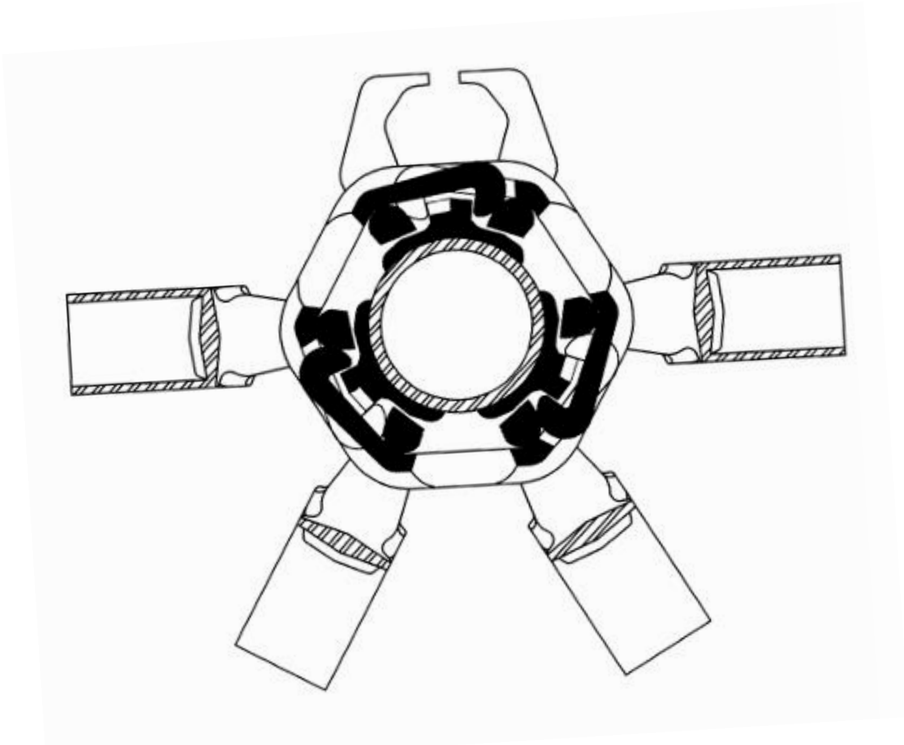
MERO KK square on square double layer space frame
Chilton, J.C. “Space Grid Structures.” 2002. 10.4324/9780080498188



Konrad Wachsmann's universal connector

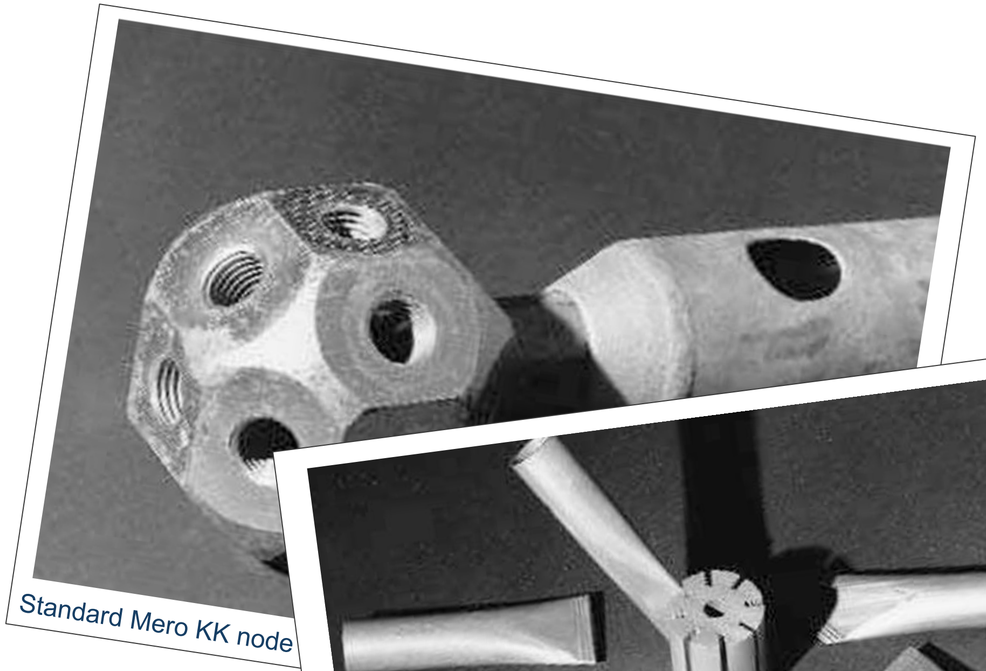
All images from:
Chilton, J.C. "Space Grid Structures." 2002. 10.4324/9780080498188

Standard Mero KK node with 18 threaded holes

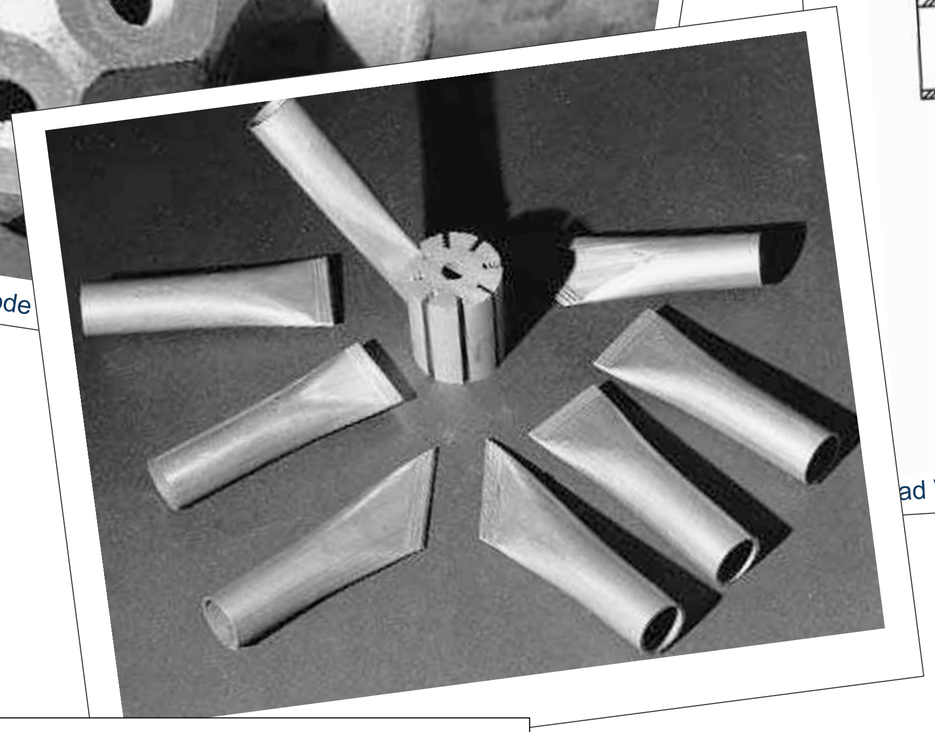


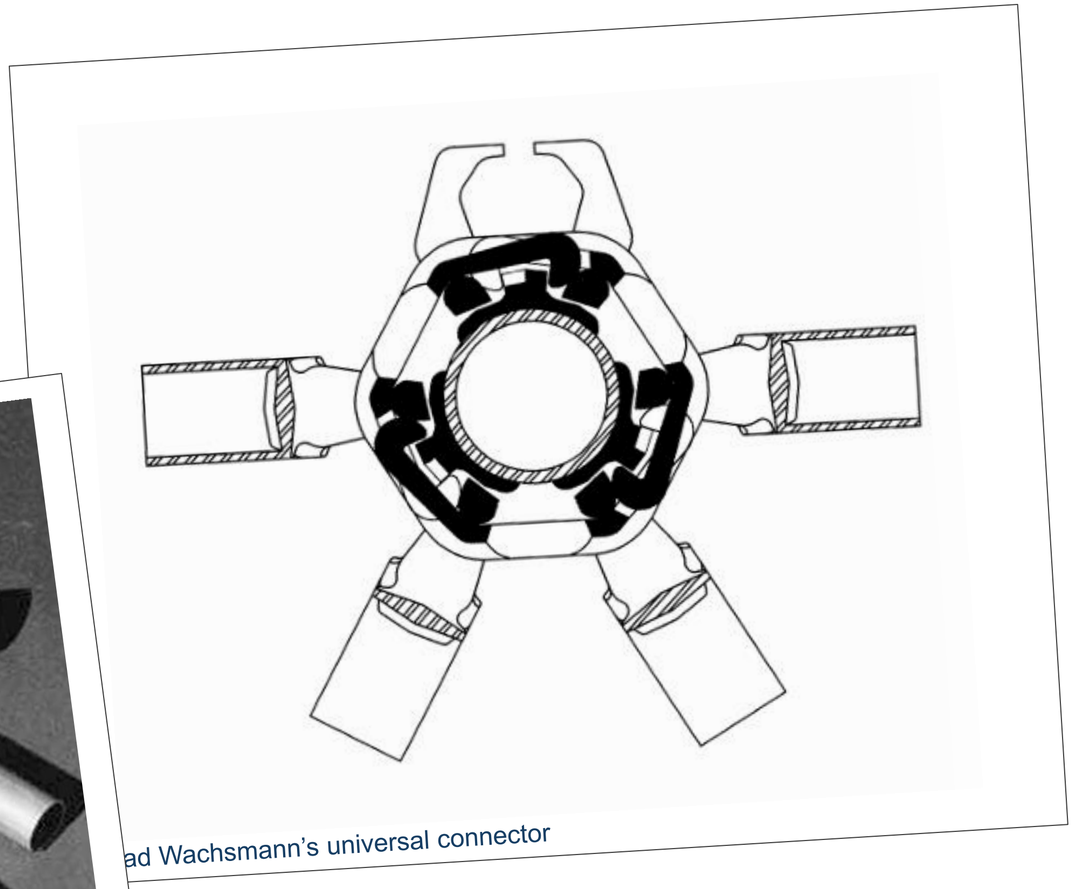
Konrad Wachsmann's universal connector

All images from:
Chilton, J.C. "Space Grid Structures." 2002. 10.4324/9780080498188



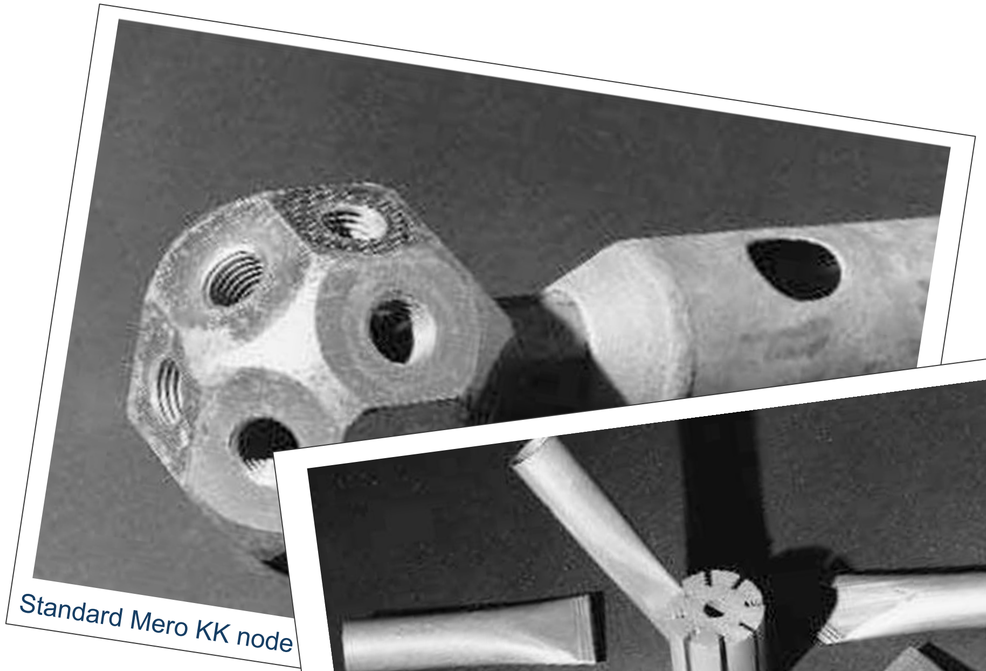
Standard Mero KK node



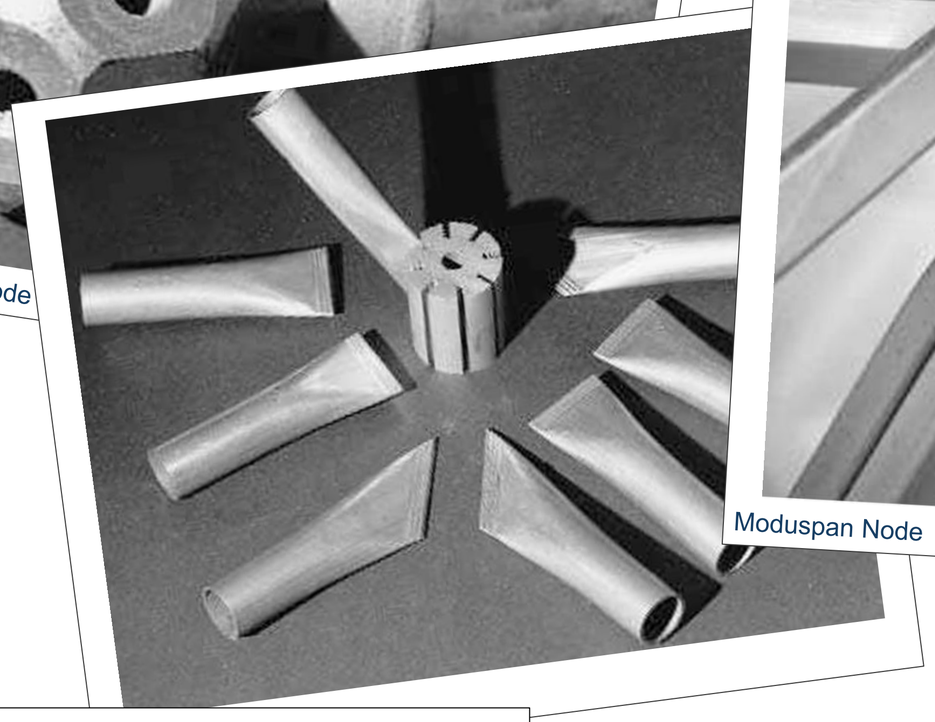


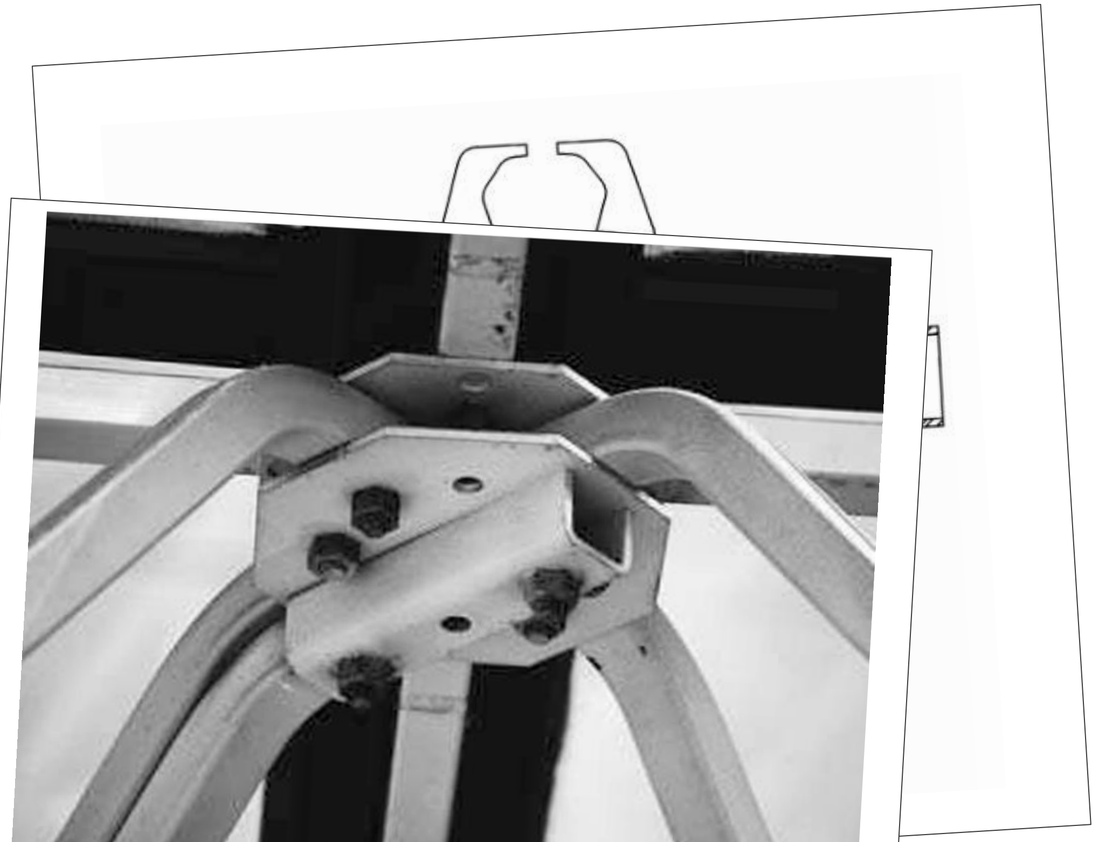
ad Wachsmann's universal connector

All images from:
Chilton, J.C. "Space Grid Structures." 2002. 10.4324/9780080498188



Standard Mero KK node





Moduspan Node

All images from:
Chilton, J.C. "Space Grid Structures." 2002. 10.4324/9780080498188

All images from:
Chilton, J.C. "Space Grid Structures." 2002. 10.4324/9780080498188

Figure 29 Orthographic documentation of the LCM beam structurally optimised using the proposed global morphing techniques (GMT): (1) cross section view; (2) plan view and (3) elevation view

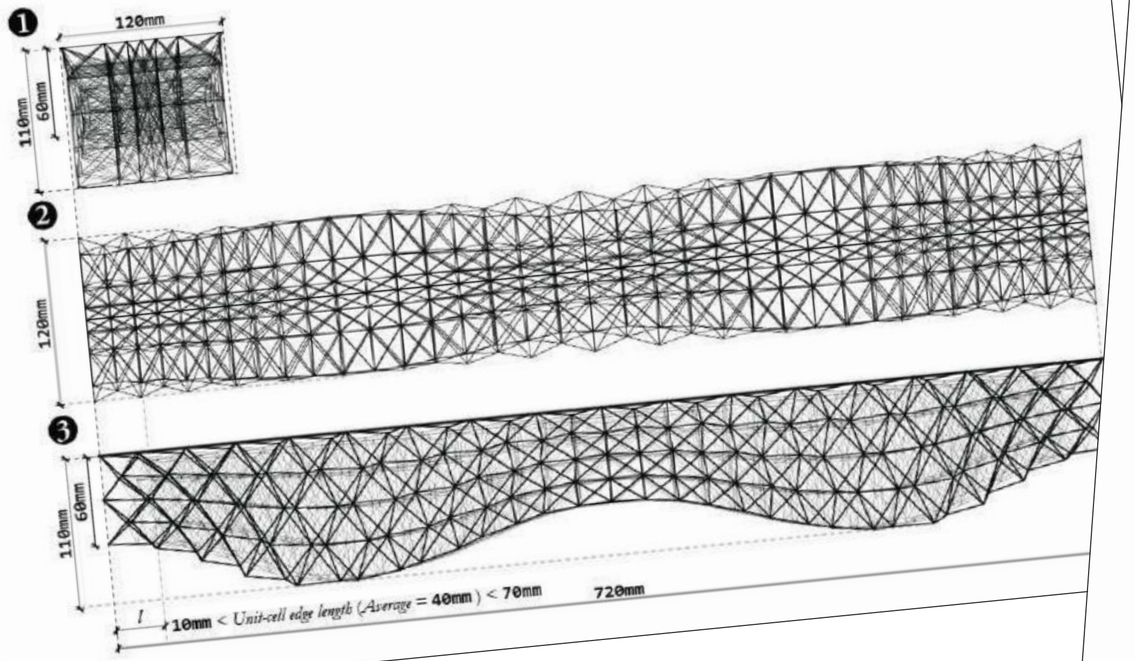


Figure 32 Photographic documentation of case study: (top) detail of joints; (middle) elevation view; and (bottom) plan view

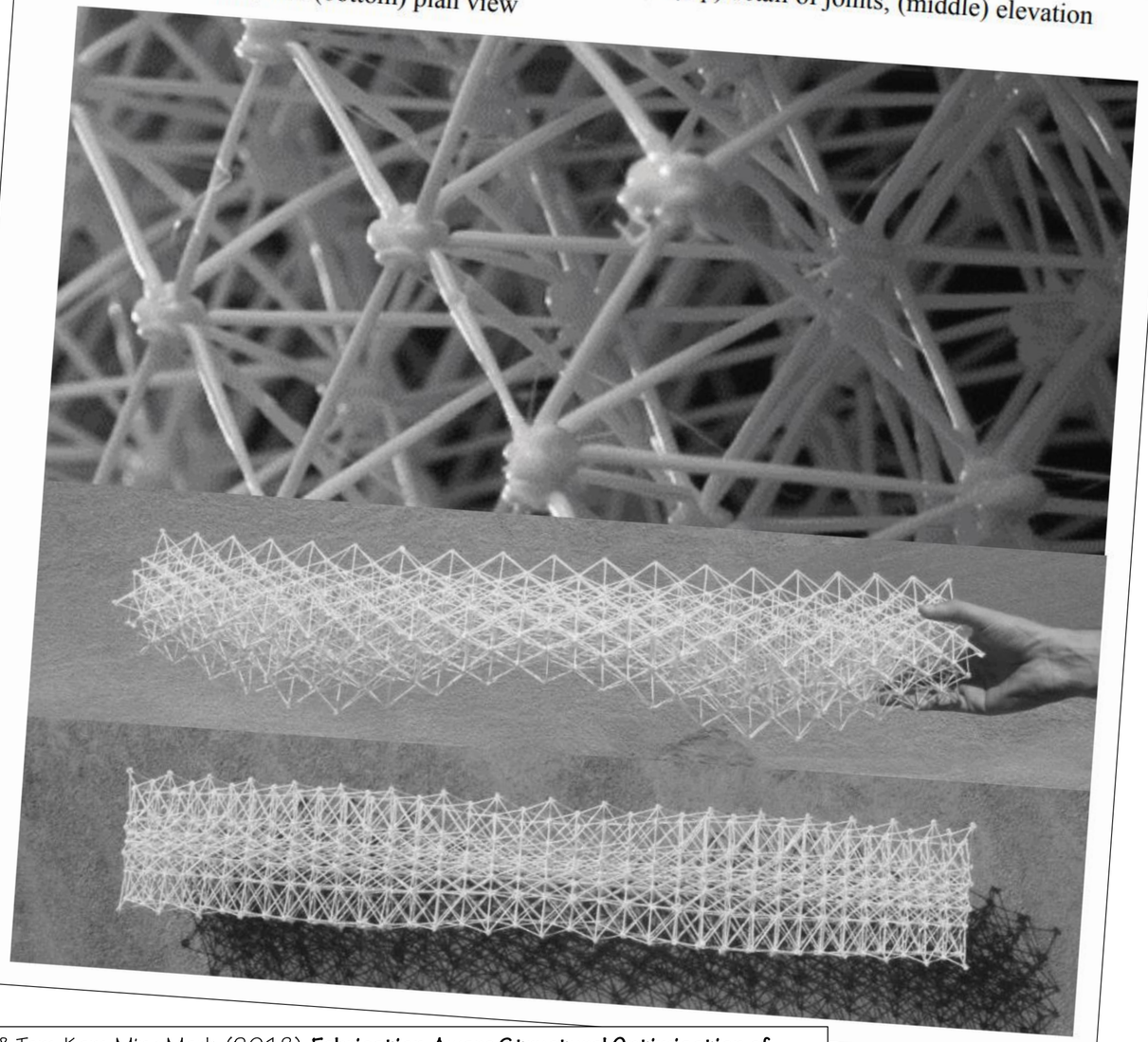
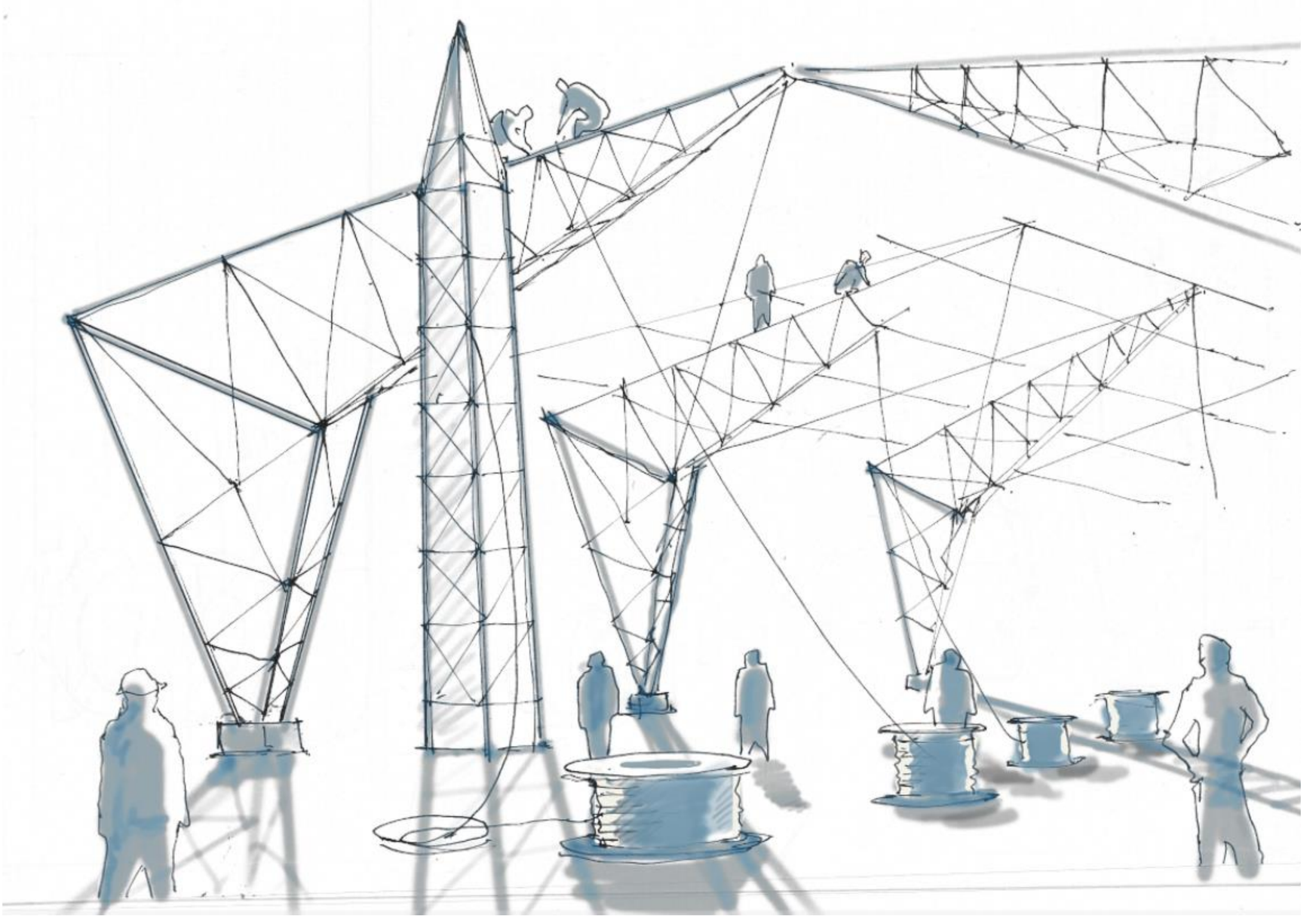
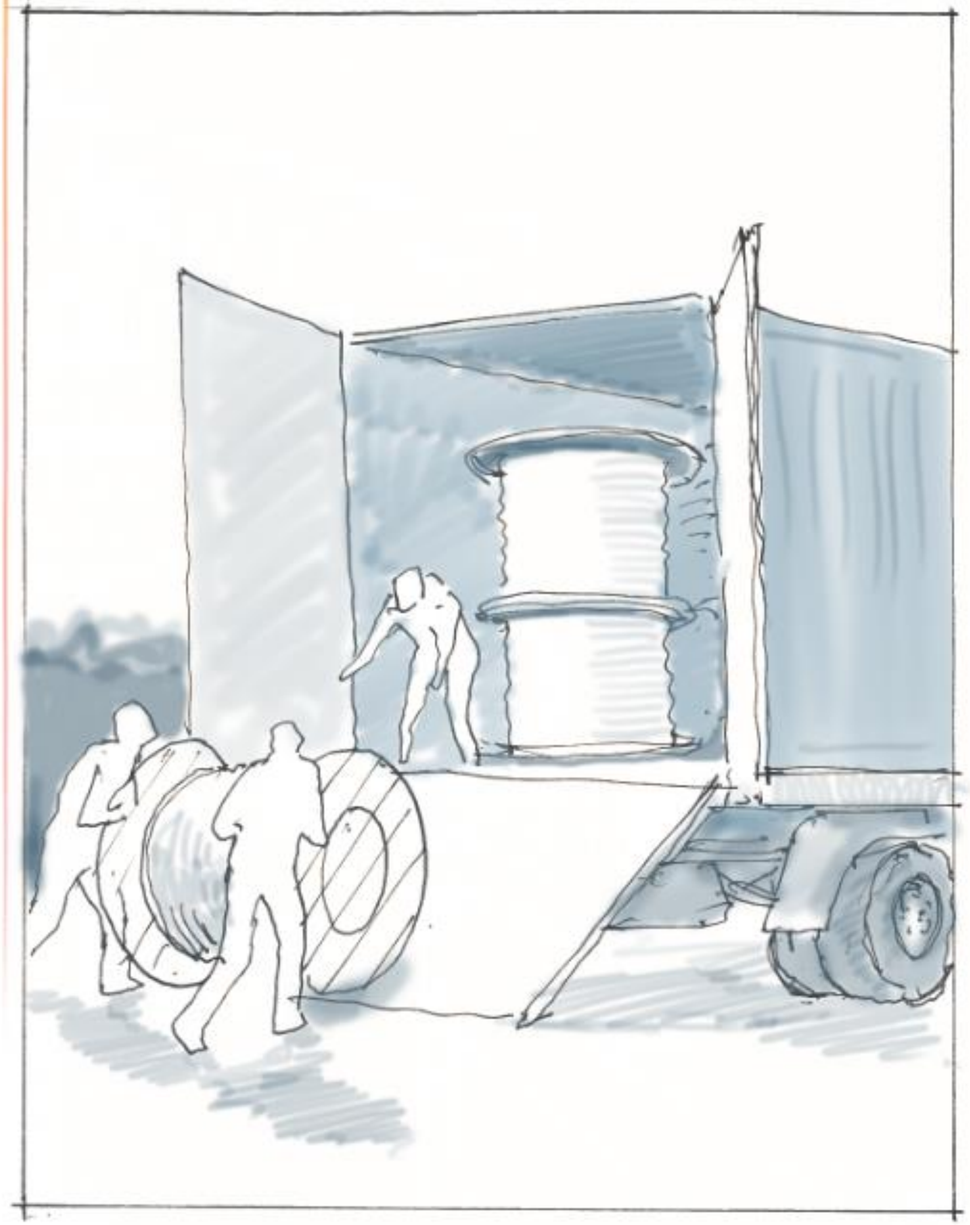


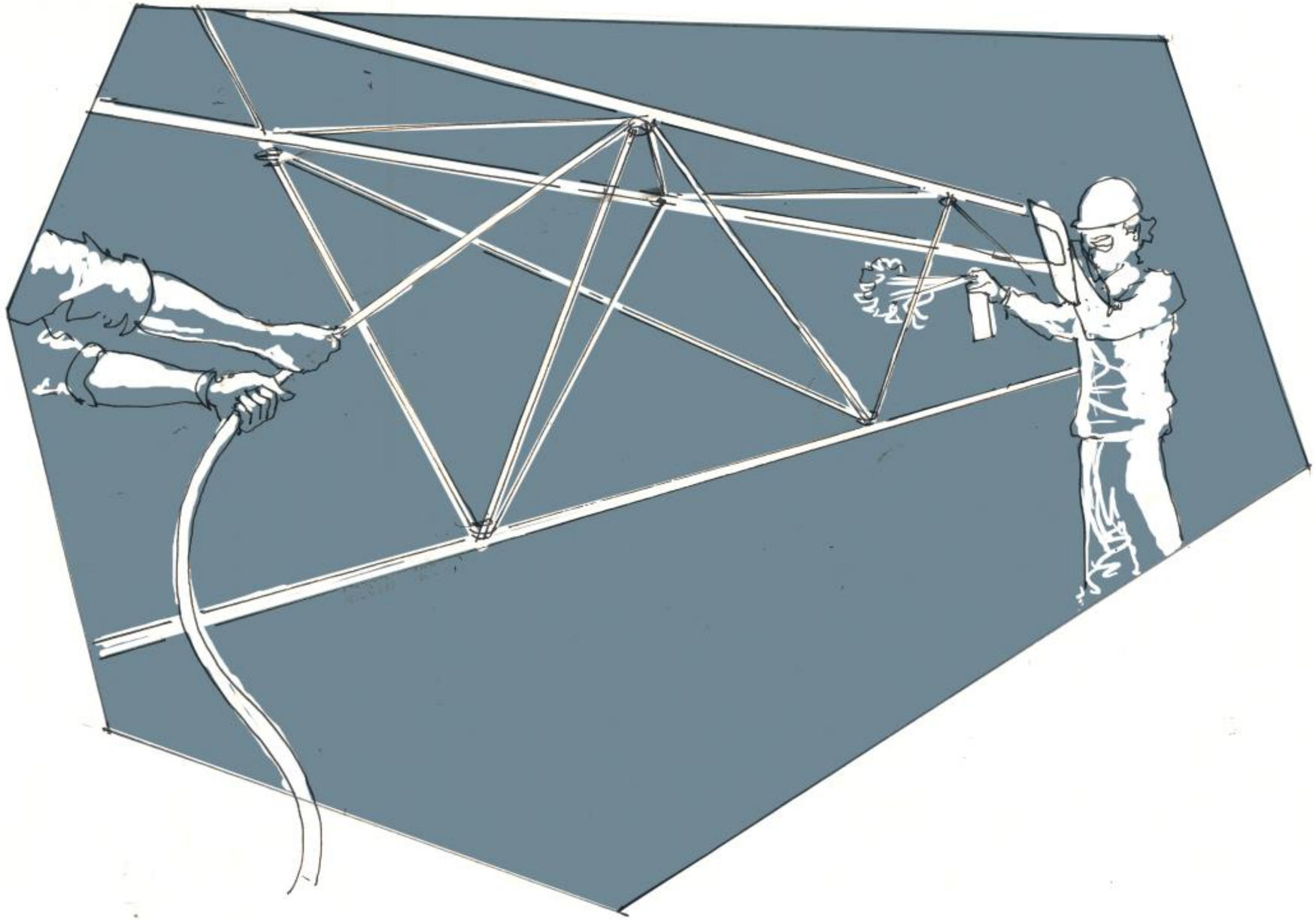
Image sourced from : Kim, Jasmine & Huang, Yijiang & Lavallee, Justin & Mueller, Caitlin & Gu, Mitchell & Marshall, Daniel & Tam, Kam-Ming Mark. (2018). **Fabrication-Aware Structural Optimisation of Lattice Additive-Manufactured with Robot-Arm. International Journal of Rapid Manufacturing.** 7. 120. 10.1504/IJRAPIDM.2018.10013888.

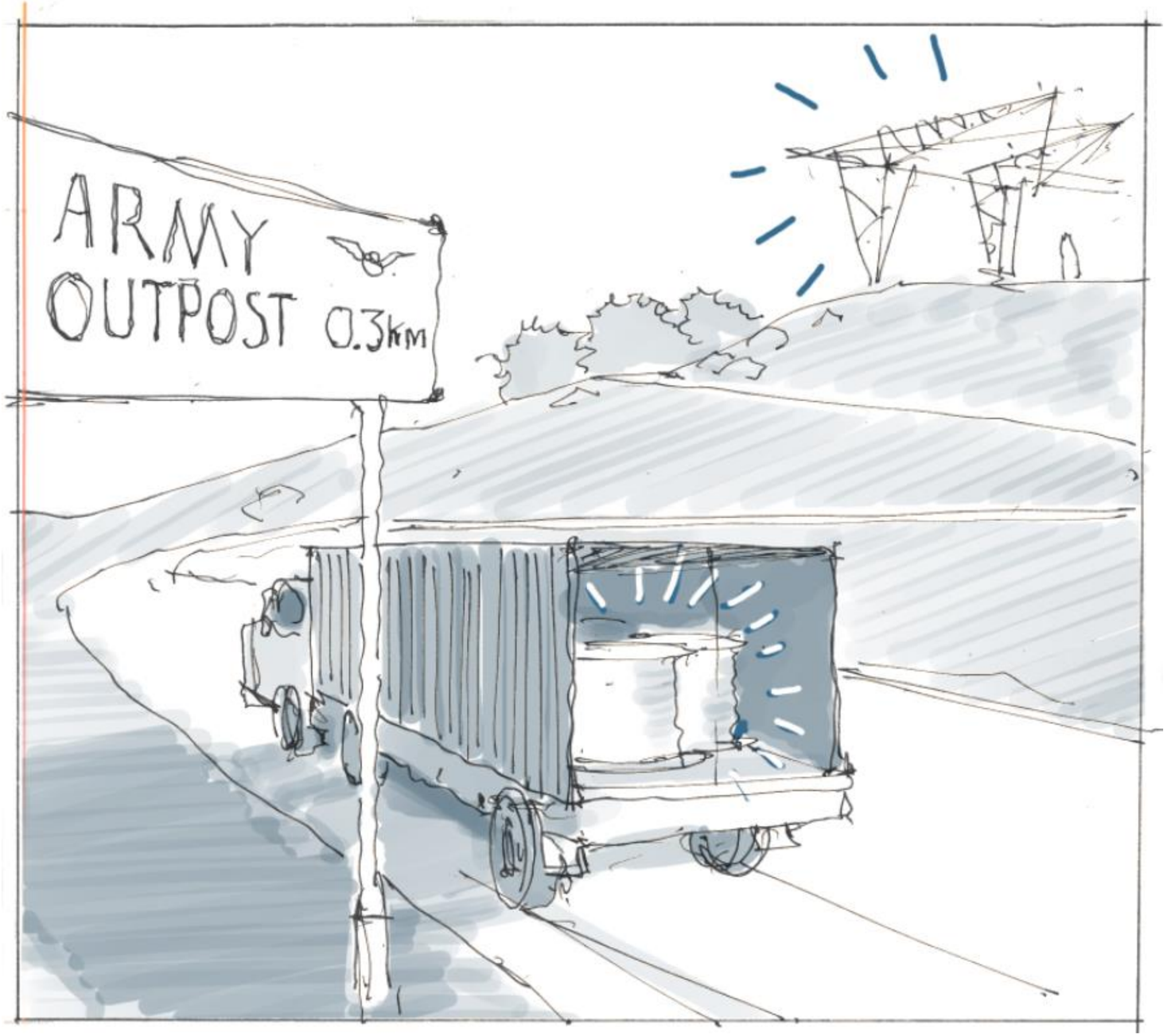
Chapter 2:
WHAT?

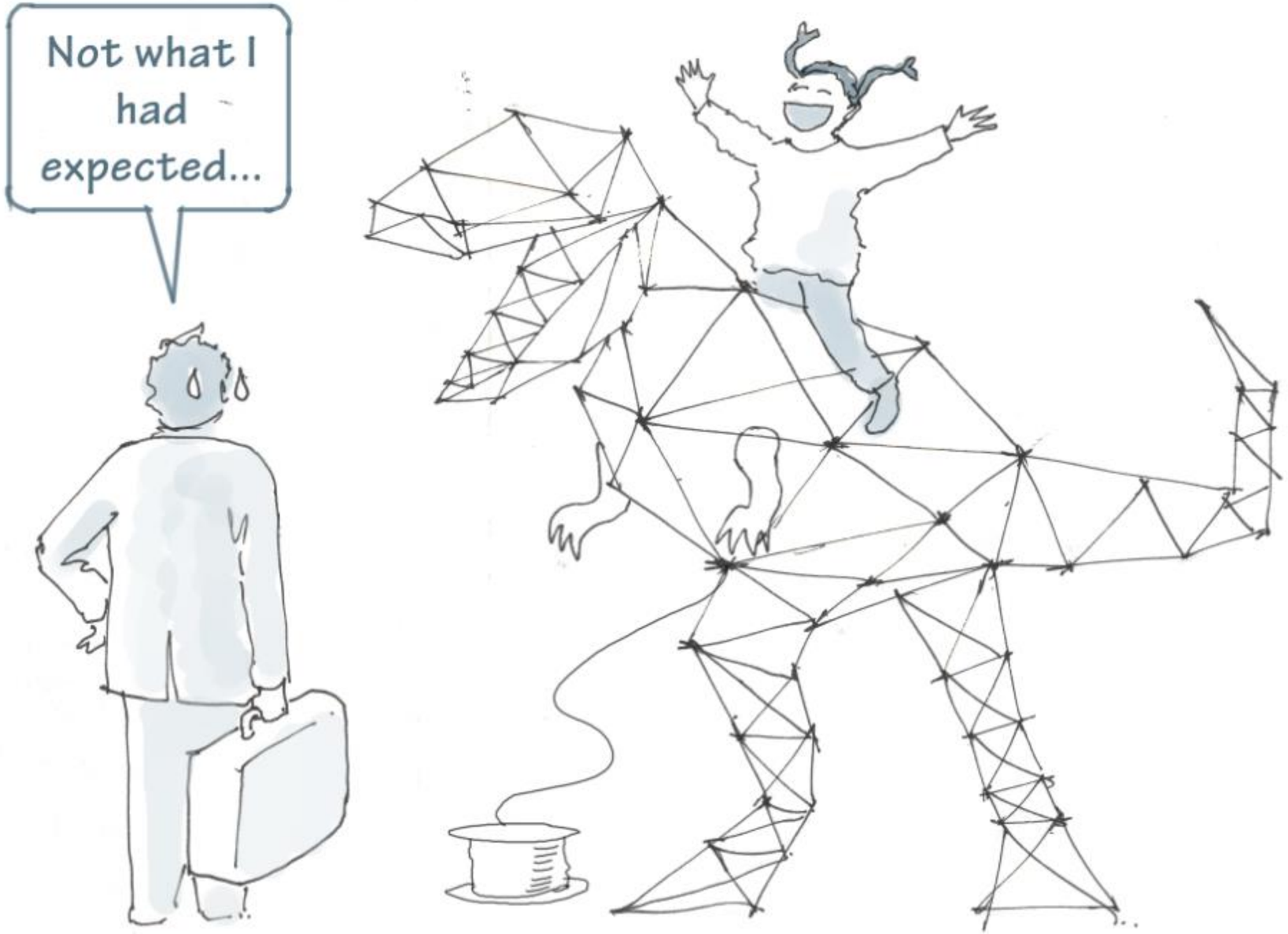


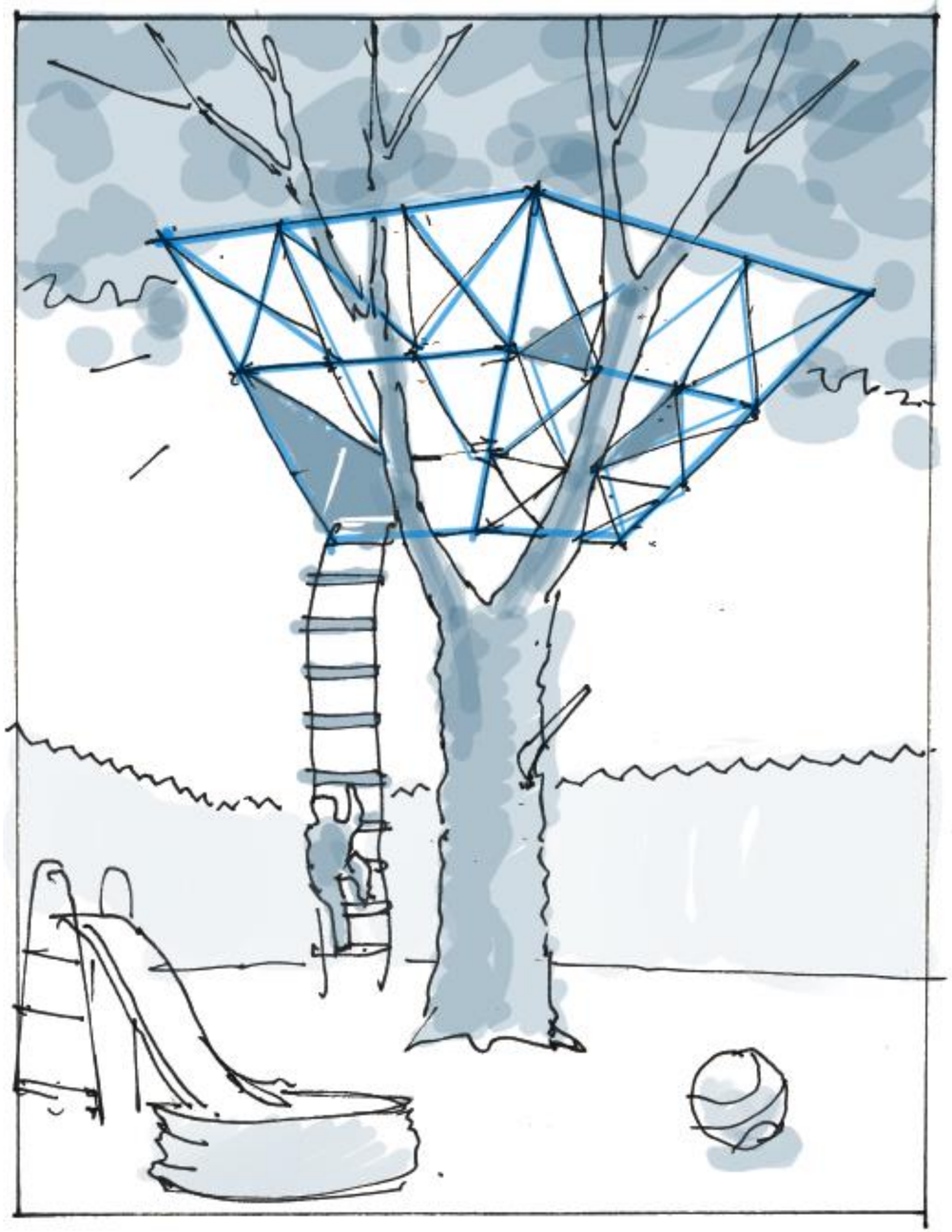


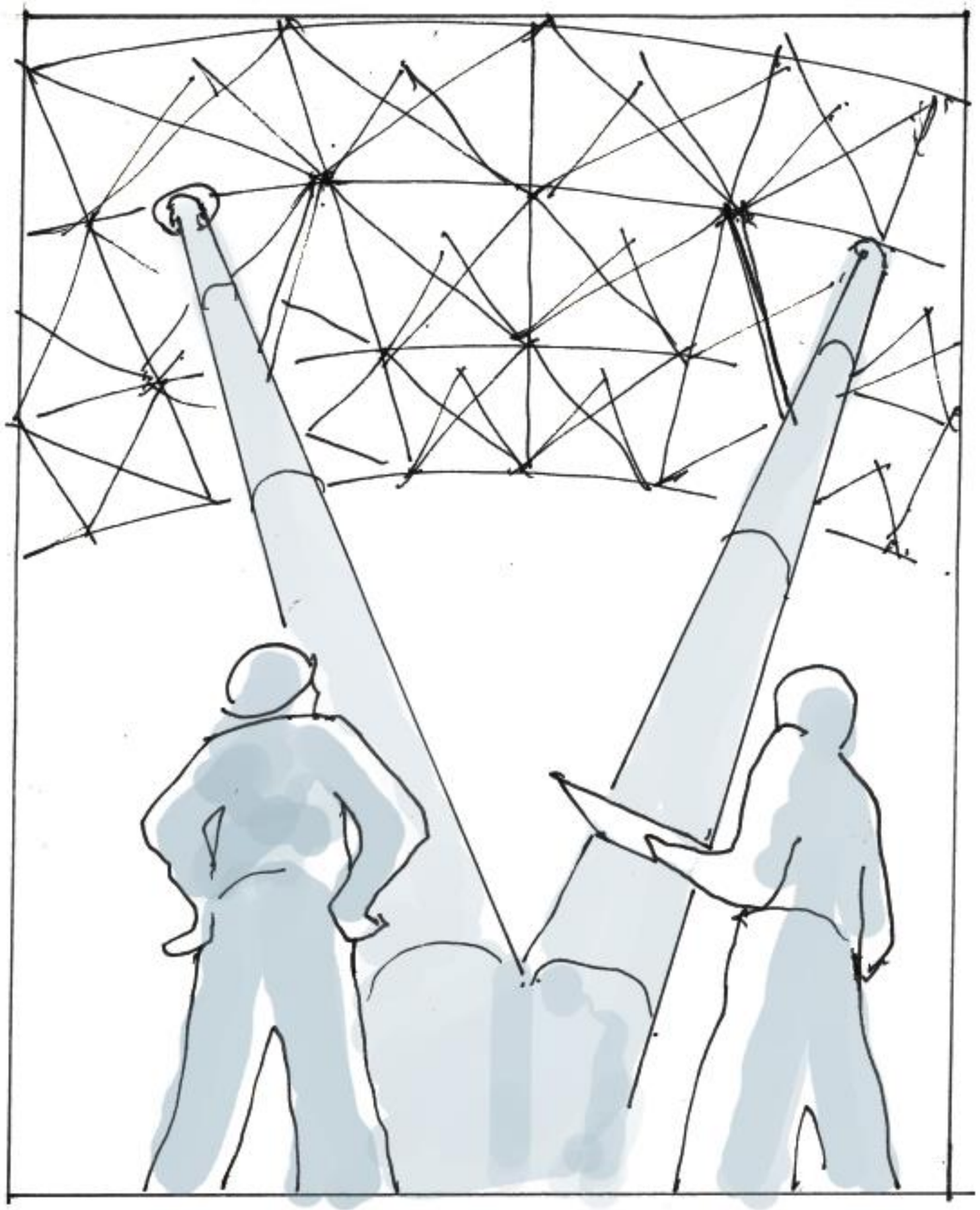
Six trusses to go, please!

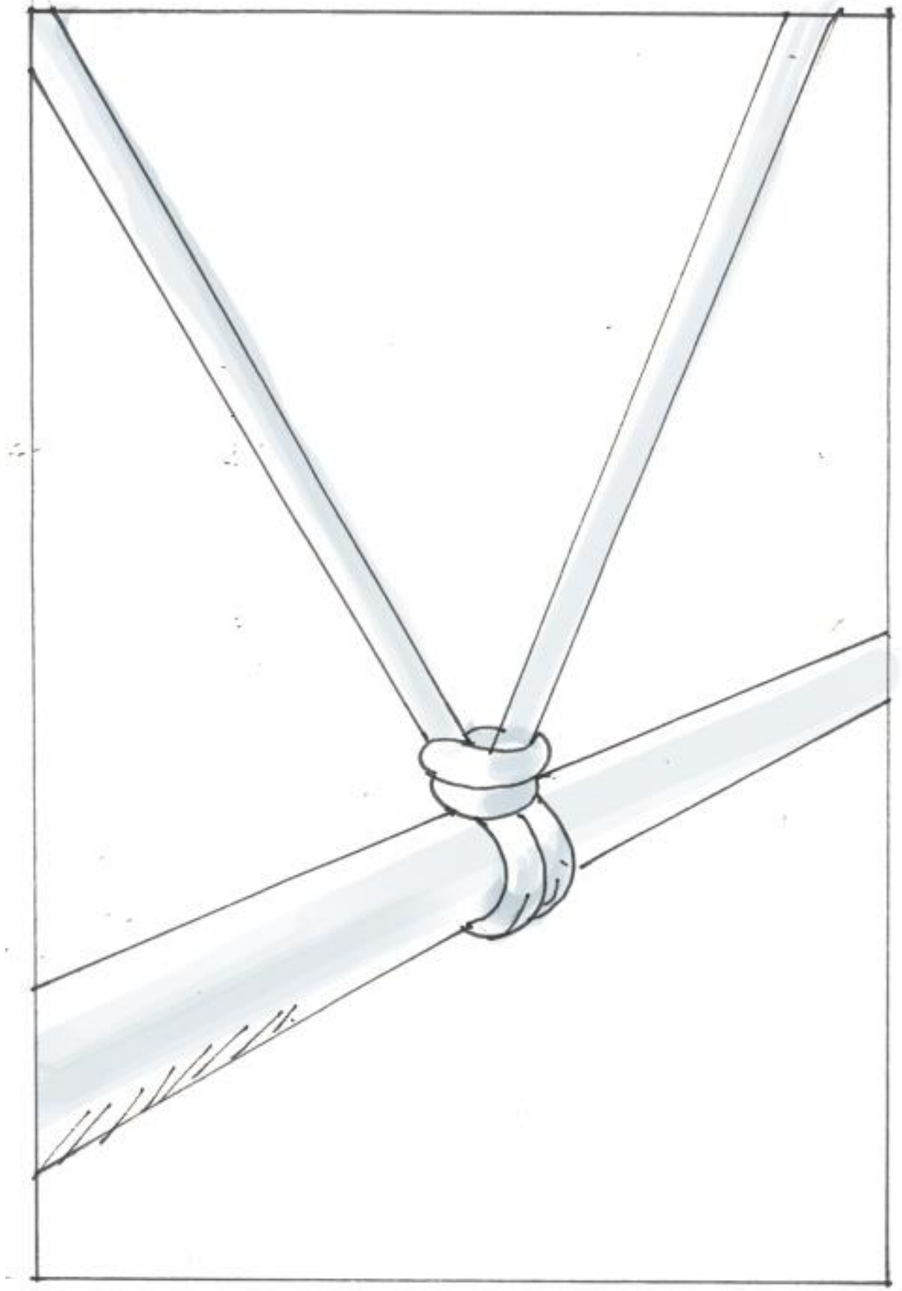



ARMY
OUTPOST
0.3km

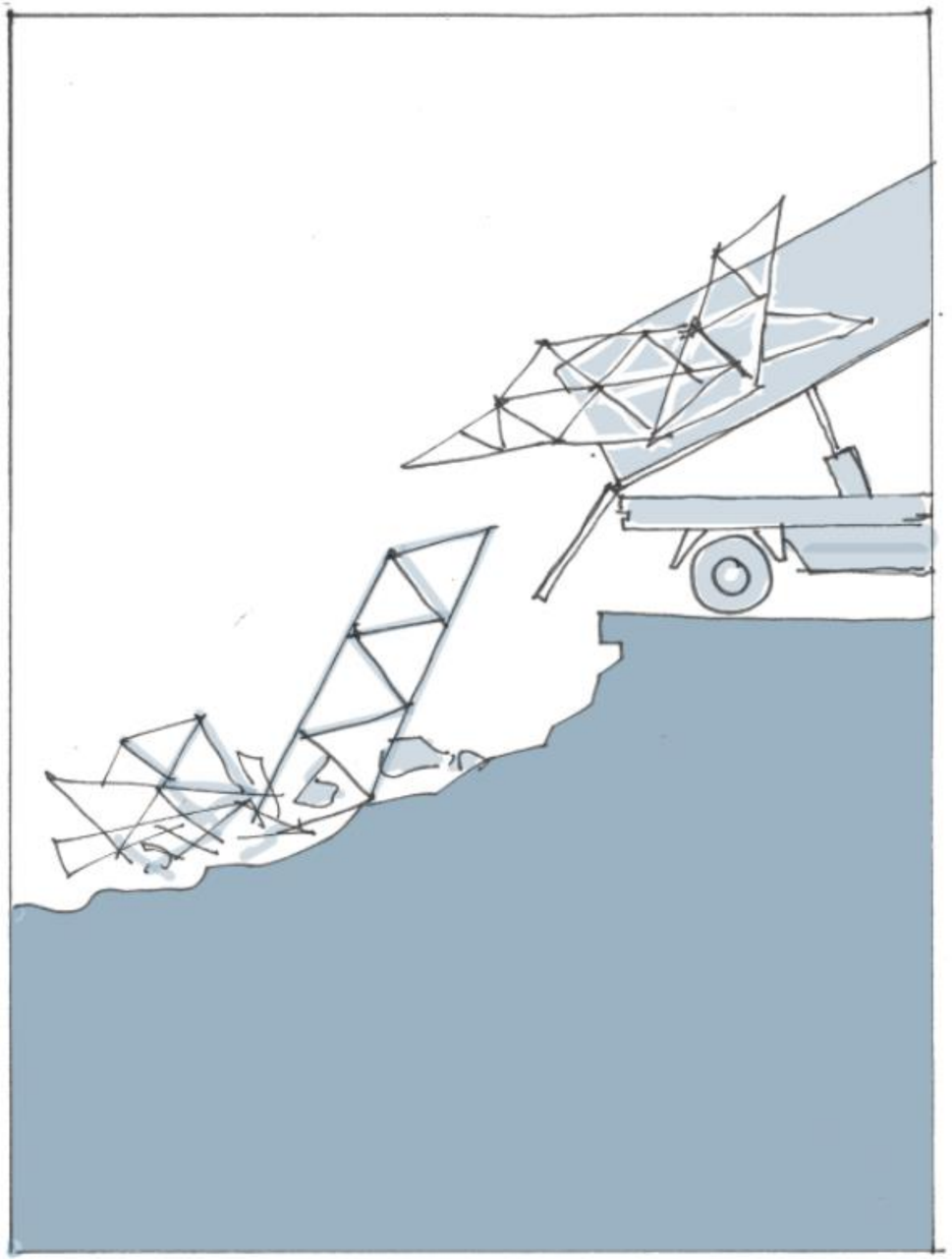

Not what I had expected...







HERE LIES
TREE-
HOUSE

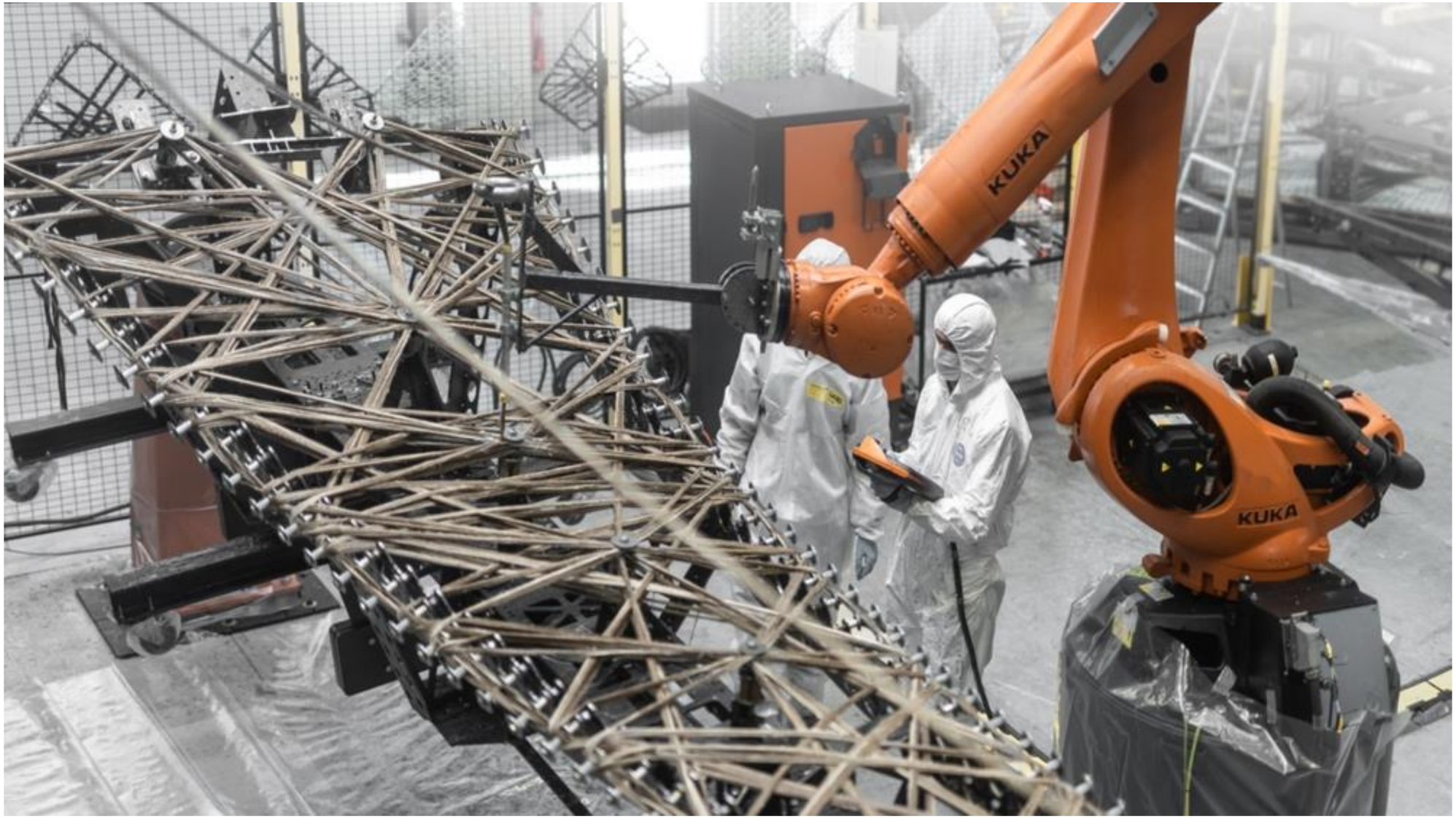


That's the Fantasy...

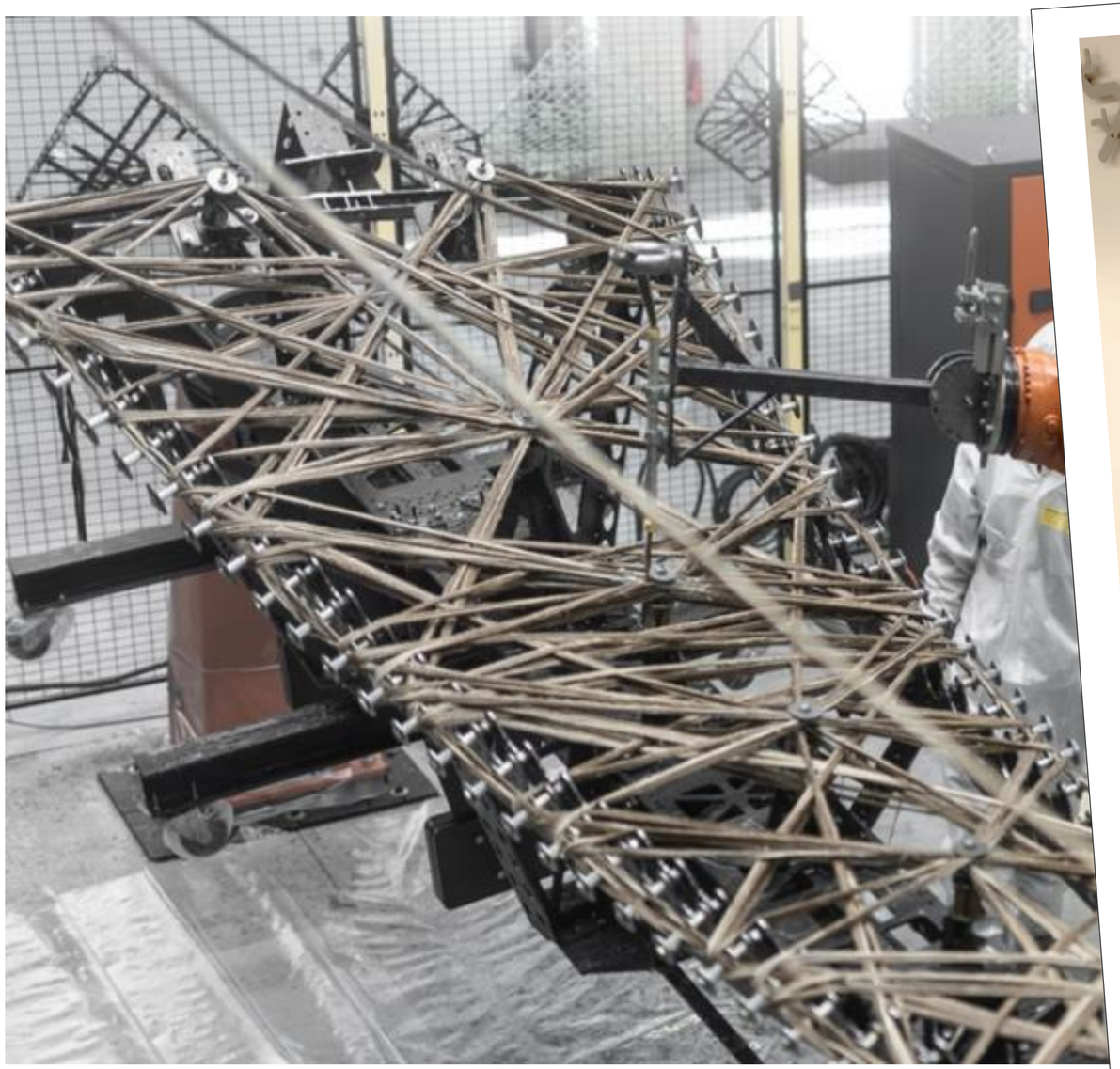
Literature

Figure 3: BUGA Fibre Pavilion, performative long-span application: top five components (left) @Roland Halbe, component fabrication (top-right), and assembly process (bottom-right) @ICD/ITKE University Stuttgart.

Image sourced from : Gil Pérez, Marta & Zechmeister, Christoph & Menges, Achim & Knippers, Jan. (2022). **Coreless filament-wound structures: toward performative long- span and sustainable building systems.**



livMatS Pavilion 202-21: Process Images and diagrams by ICD/ITKE/IntCDC, University of Stuttgart
https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/livMatS-pavilion-2020-21/



GPRP filament wound gridshell structure:

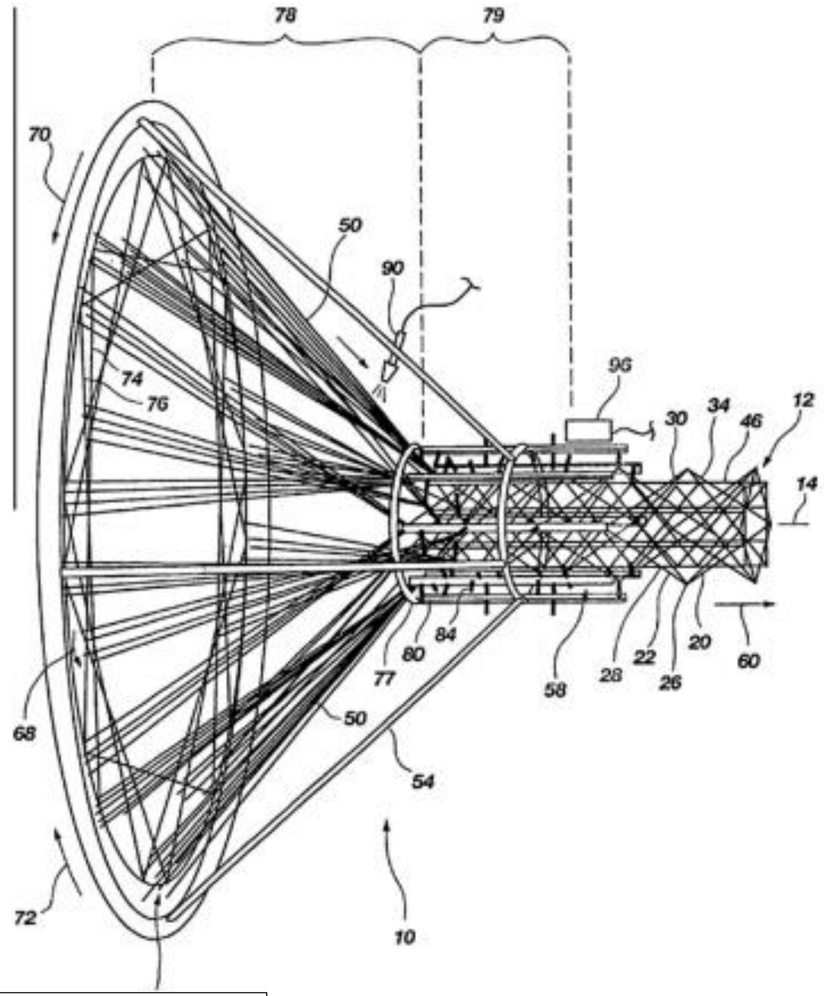
Credit: Pierre Mostert

livMatS Pavilion 202-21: Process Images and diagrams by ICD/ITKE/IntCDC, University of Stuttgart
https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/livMatS-pavilion-2020-21/

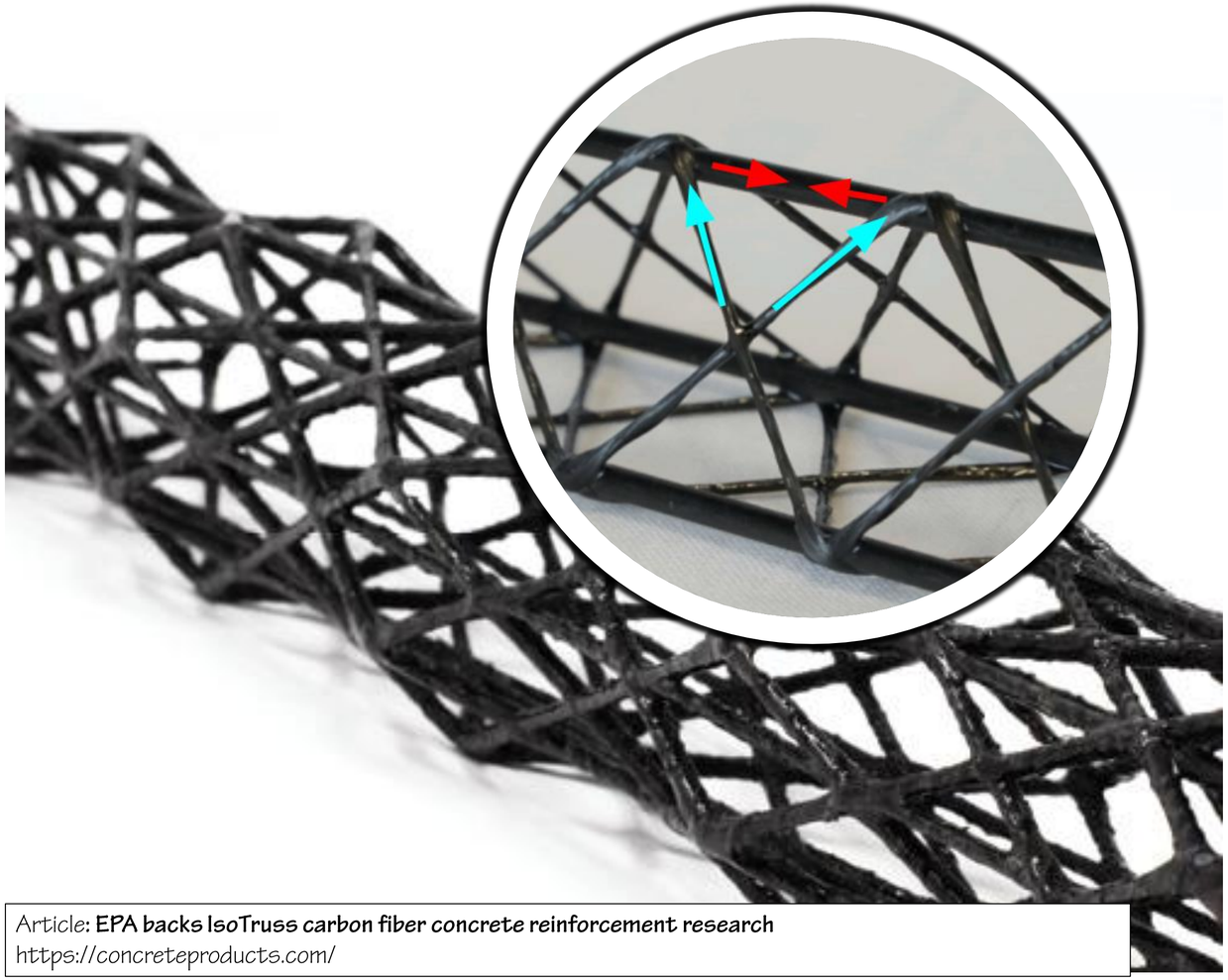
Thimmankudru bridge of Tonse, Karnataka

(c) Wikimedia Commons

Craftsmen from the Huinchiri community depend on teamwork to craft the bridge, the safety measures have been passed down through the generations and involve the entire community(Photo courtesy of Área de Expresiones Tradicionales y Costumbristas, Sub Dirección de Interculturalidad, Dirección Desconcentrada de Cultura del Cusco, image found on https://www.smithsonianmag.com/



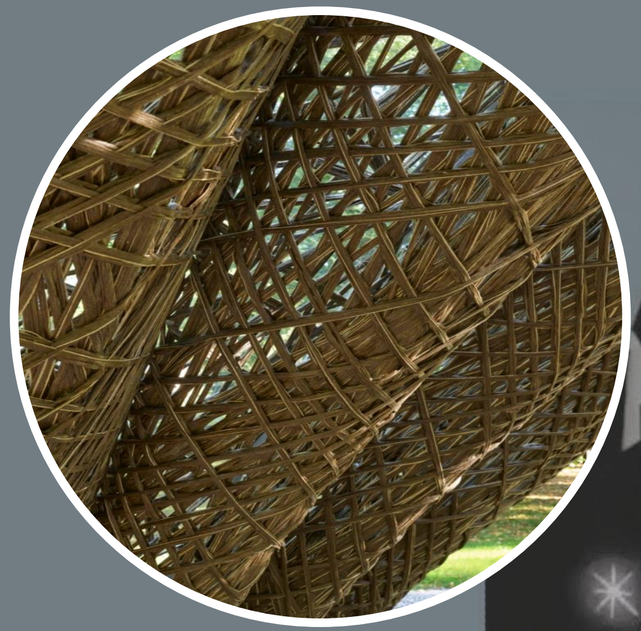
Schematic of isotruss braiding process

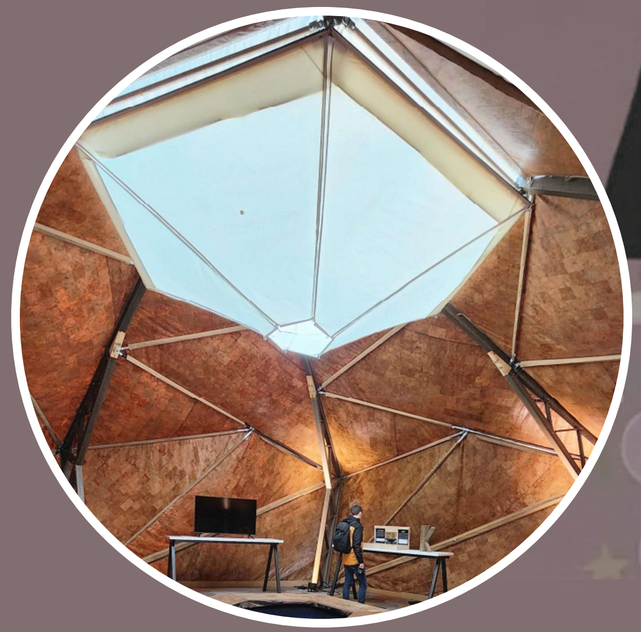


Article: **EPA backs IsoTruss carbon fiber concrete reinforcement research**
https://concreteproducts.com/

Jensen DHAD, Jensen MJ. 2010. **Continuous Manufacturing of Cylindirical Composite Lattice Structures**, In: International Conference on Textile Composites (TEXCOMP10), 2010

Photo, Bio-Based Pavilions, TU-E
Hannurkar, S. (2023)





THROW AT A WALL, SEE WHAT STICKS...

Research Question:

"Can a Novel **Bio-Based** FRP technology be designed and developed for the **In- Situ Construction** of **Lattice Structures** for Building Industry applications?"

Presentation Outline

- The Technology
- Comparison against the Usual Suspects
- Important Further research

Key Parameters:

- Structural Robustness
- Ease of Fabrication
- ‘Eco-friendly’-ness

Chapter 3:
HOW?

Product Design and Development

Part A

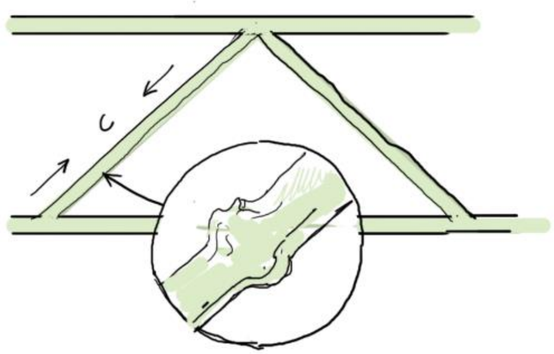
Develop Bespoke Cordage

Part B

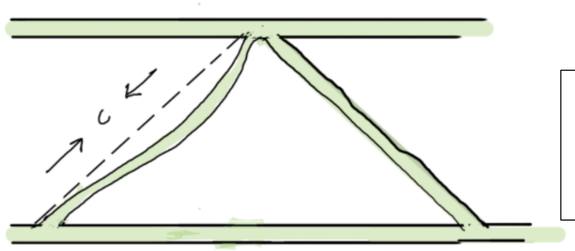
Develop Lattice Fabrication

Part A:
Making the cordage…

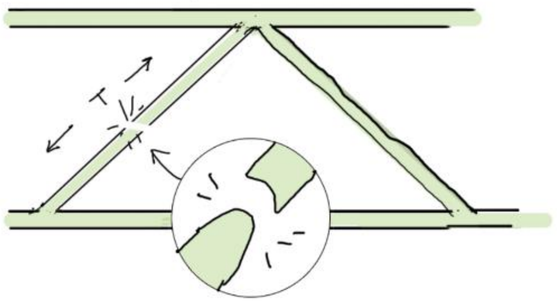
What do we want from our Cordage Composite?



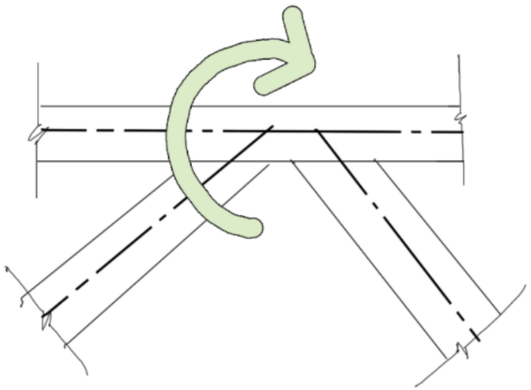
Squash Resistance



Buckling Resistance



Tensile Capacity



Joint stiffness

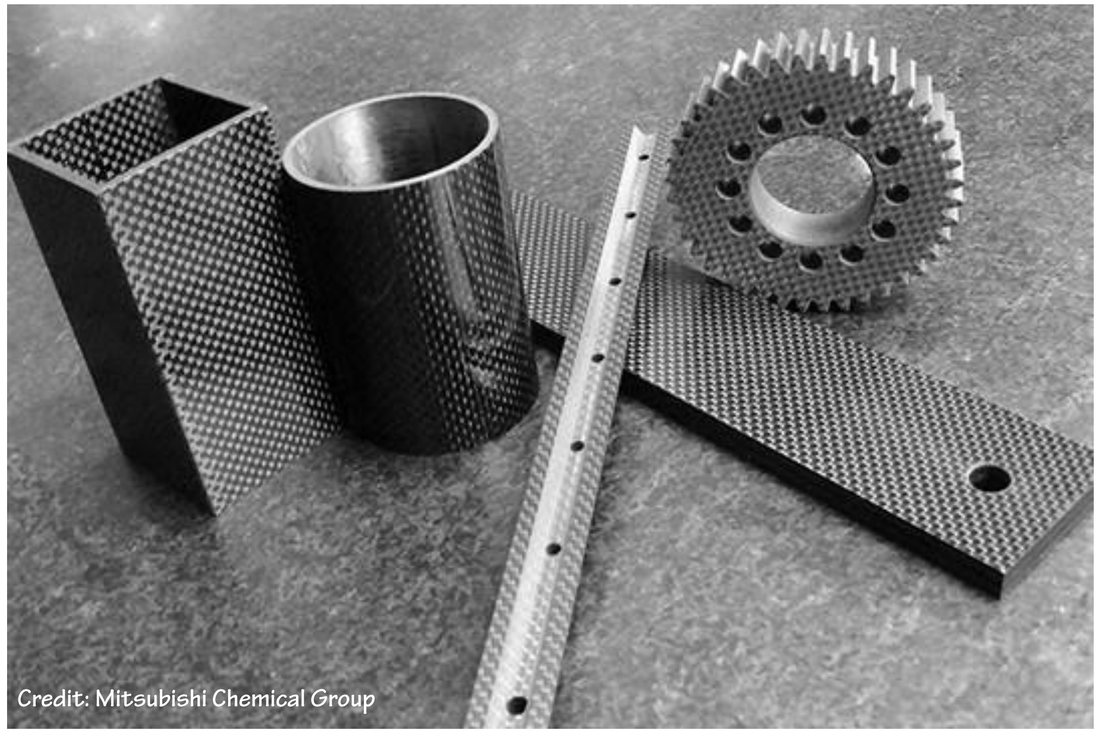
Part A:

The Magic Rope...

...a problem in FRP Engineering

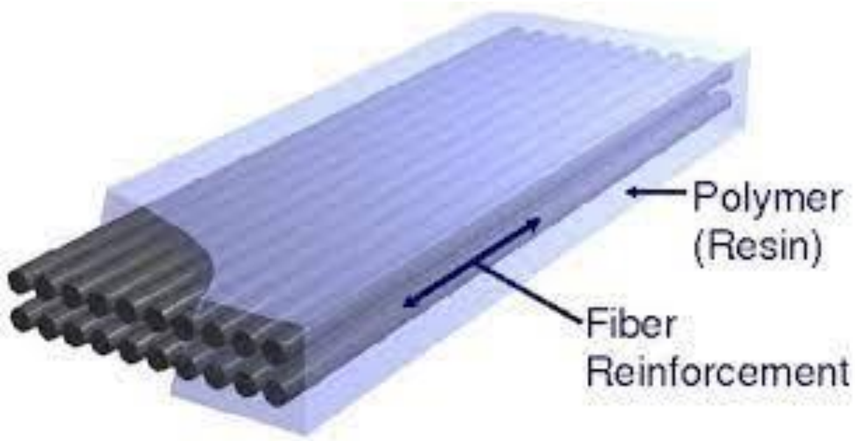
- Material Choices
- Fiber Topology

Some Things about Fiber Composites….



What is a Fiber Composite?

- reinforcing FIBER
- Integrating Matrix

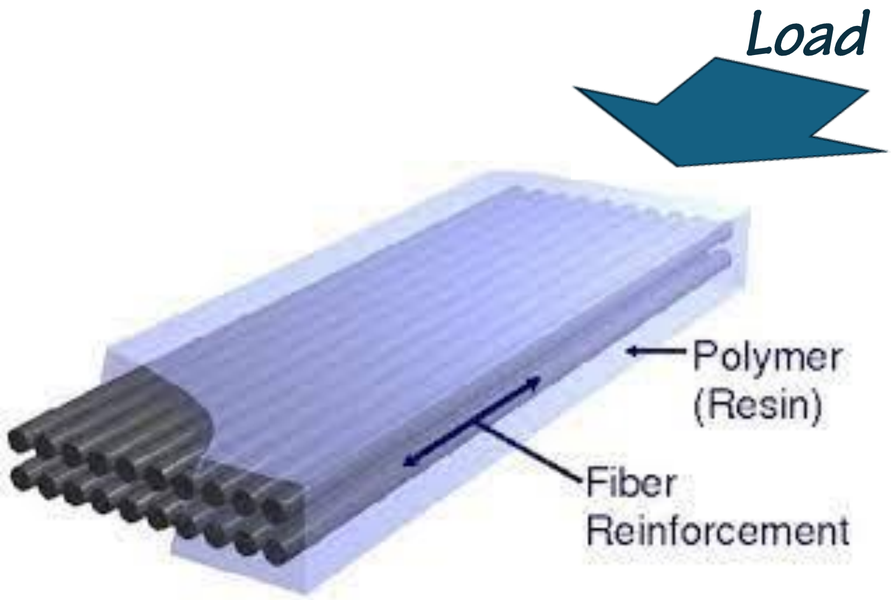


Credit: Mitsubishi Chemical Group

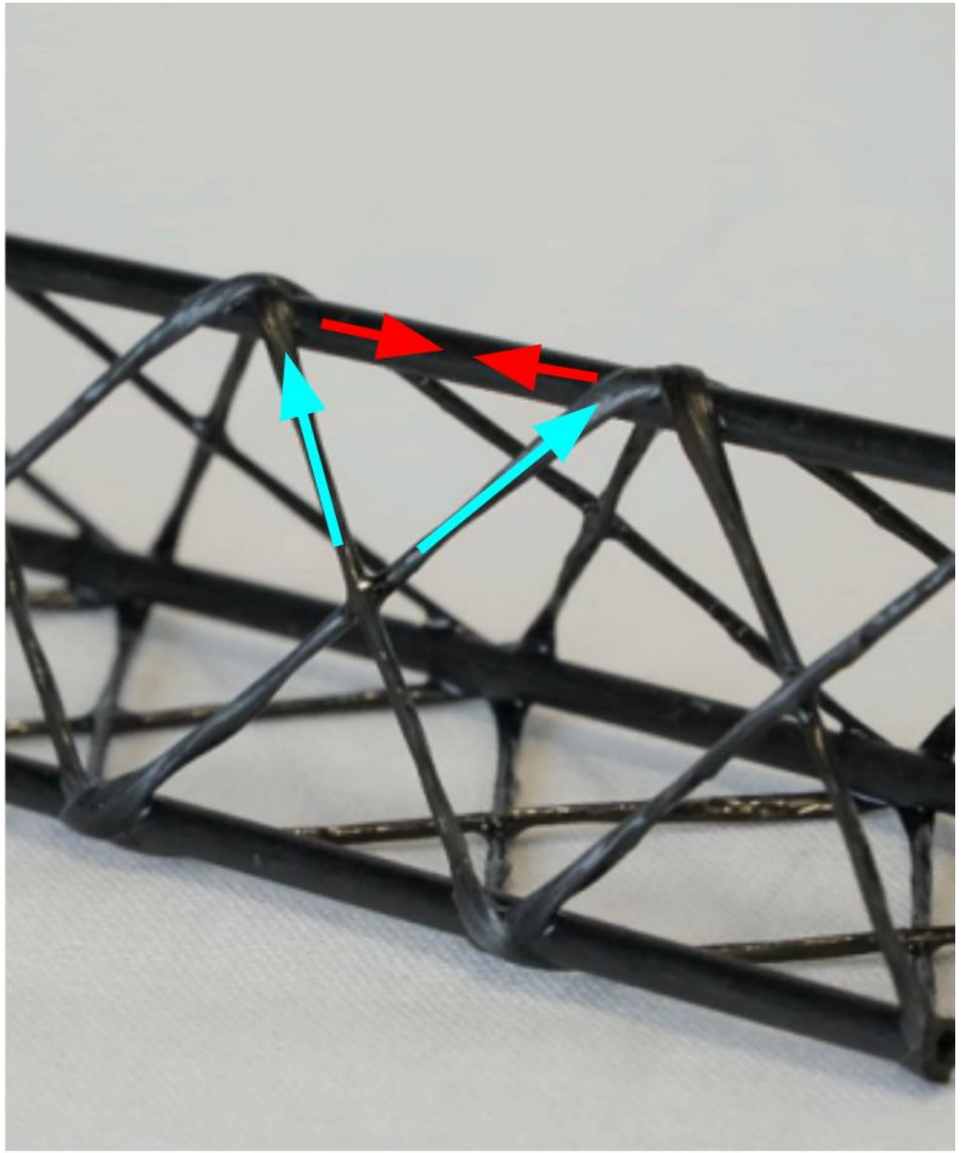
Textile CFRP used In a bike frame (Octavio Passos/Getty images)

Some concepts…

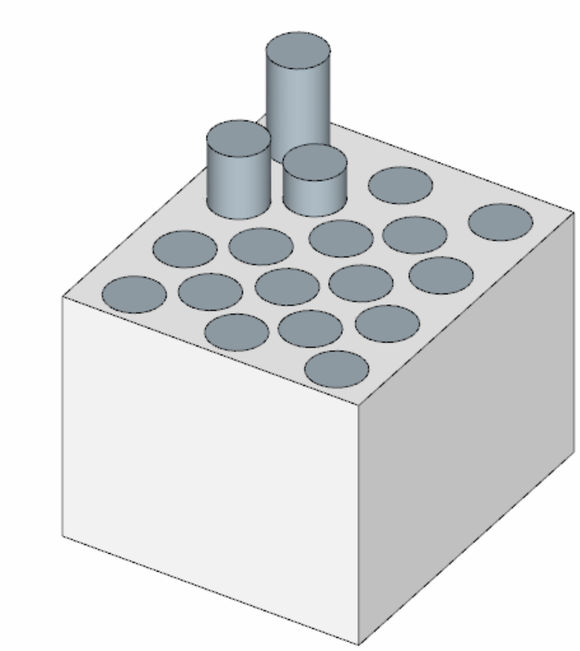
Line up the Fibres!



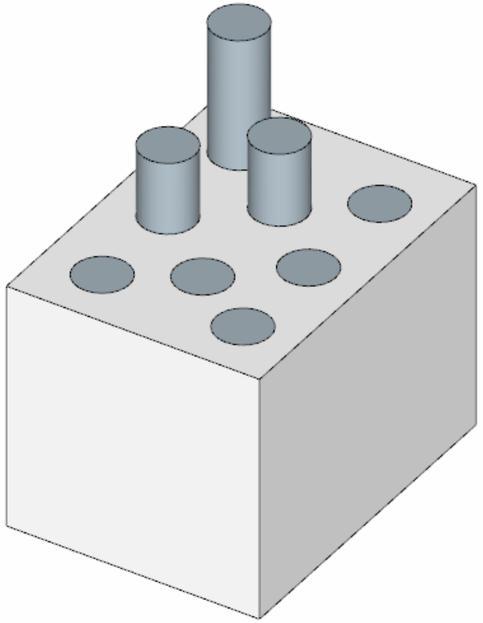
Credit: Mitsubishi Chemical Group



‘Fiber Volume Fraction (FVF)’

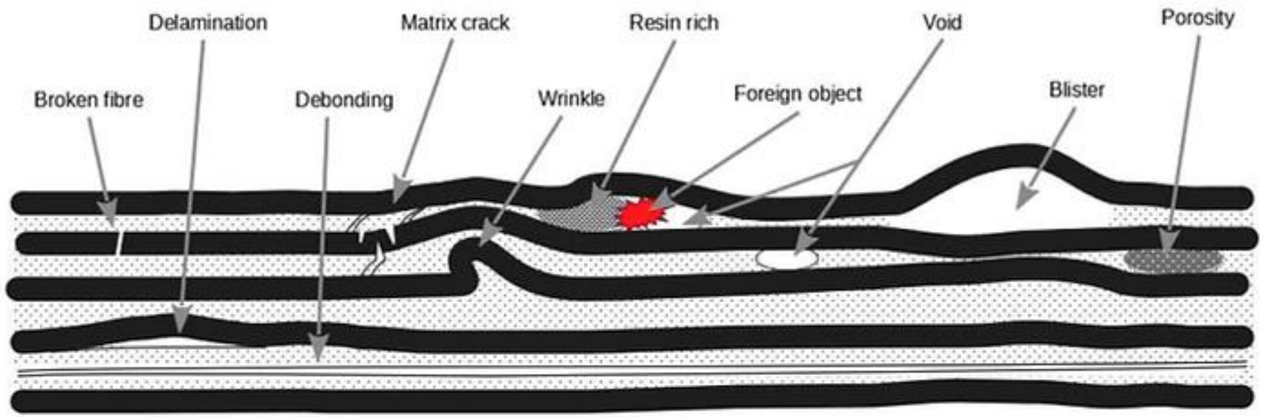


FVF = 50%



FVF = 20%

‘Consolidation’



Manufacturing defects and damages, How to Identify the Defects and Damage in Composites Materials and Structures?

https://www.addcomposites.com/post/defects-and-damage-in-composite-materials-and-structures

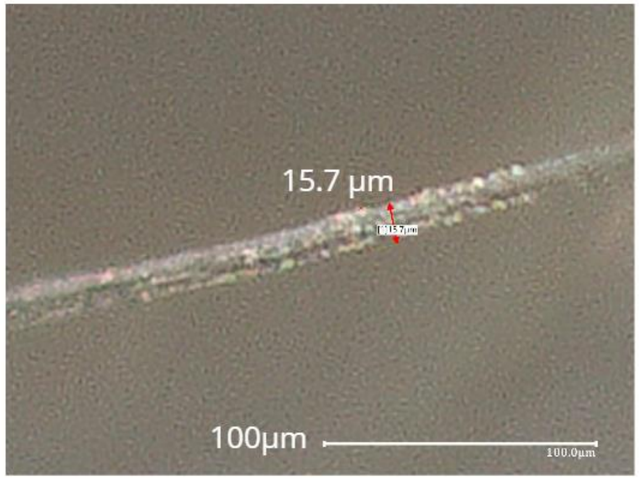
Vacuum Bagging of Composite

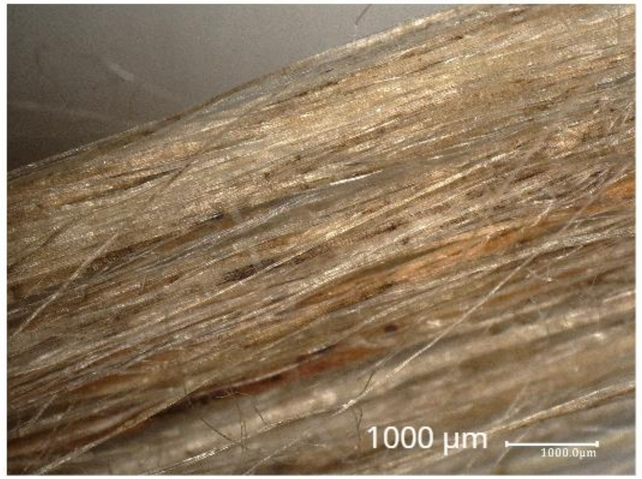
Material Choices: **Fiber**

Fibre	Density	Young's Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)
Sugar palm	1.5	10.4	421.4	9.8
Bamboo	0.6–1.1	11–17	140–230	-
Cotton	1.5–1.6	5.5–12.6	287–597	7–8
Flax	1.54	27–85	345–2000	1–4
Hemp	1.47	17–70	368–800	1.6
Jute	1.44	10–30	393–773	1.5–1.8
Kenaf	1.2	14–53	240–930	1.6
Ramie	1.5–1.56	27–128	400–1000	1–4

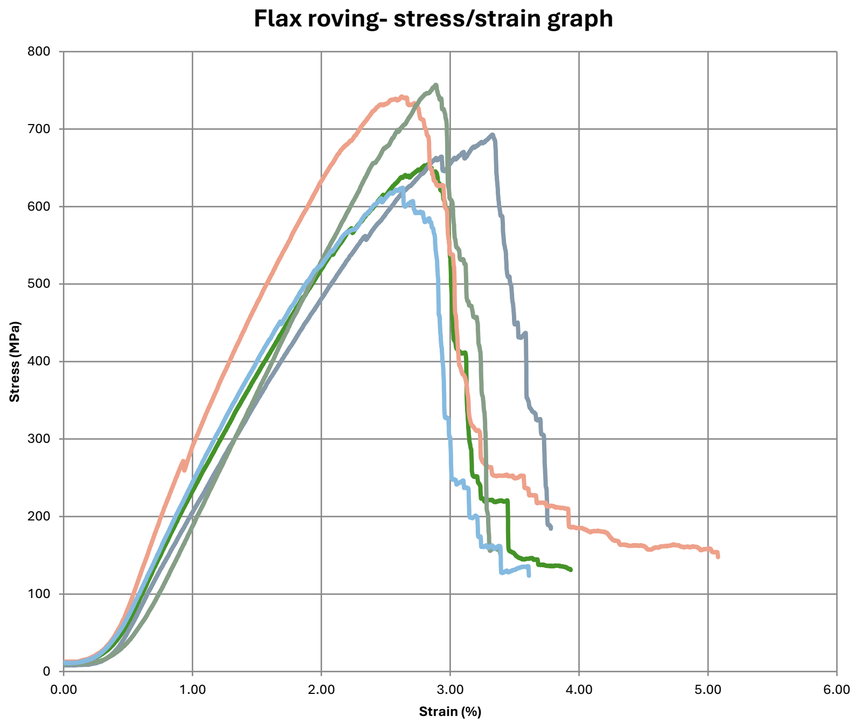
Fig: **Mechanical Properties of Different Plant Fibres** (Oksman et al., 2003; Aisyah et al., 2021; Faruk et al., 2012)

Flax Roving *as seen under a microscope (own source)*





Experimental Phase- Part A



specimen	Tensile failure stress (Mpa)	Young's modulus (MPa)
1	654.8928301	55744.63739
2	692.9225849	52335.96833
3	741.9048324	66449.89426
4	757.1668369	61603.38704
5	624.327751	57961.74275
average	694.242967	58819.12595

Material Choices: **Resin**

- Site –Curable
- High-Performance
- Bio –Based
- B state at Room temperature

Westlake Epoxy

ResiCare

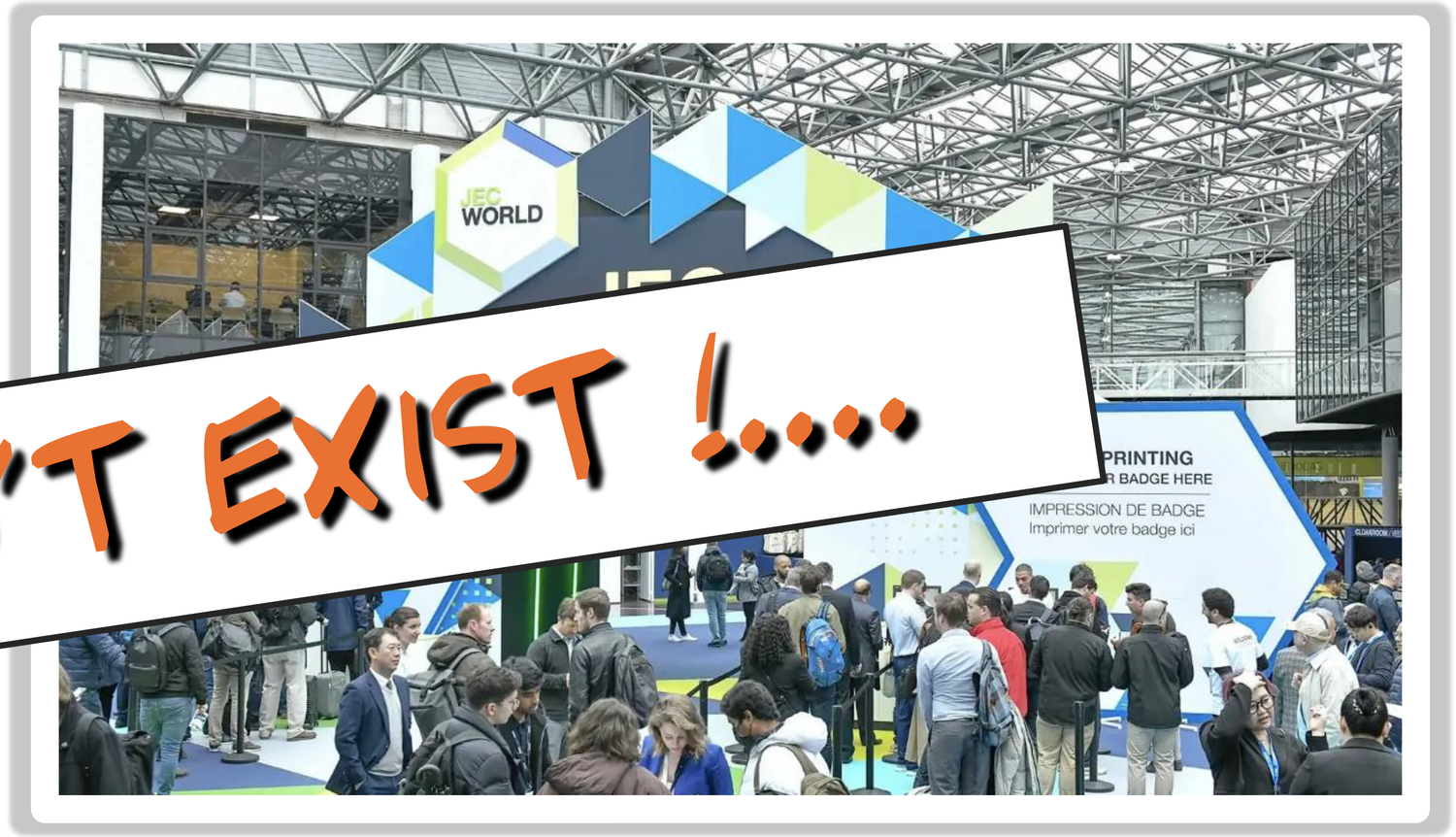
Sicomin Epoxy Systems

ADITYA BIRLA CHEMICALS

ORSON RESINS & COATINGS

Material Choices: **Resin**

- Site –Curable
- High-Performance
- Bio –Based
-



DOESN'T EXIST !....

Westlake Epoxy

ResiCare

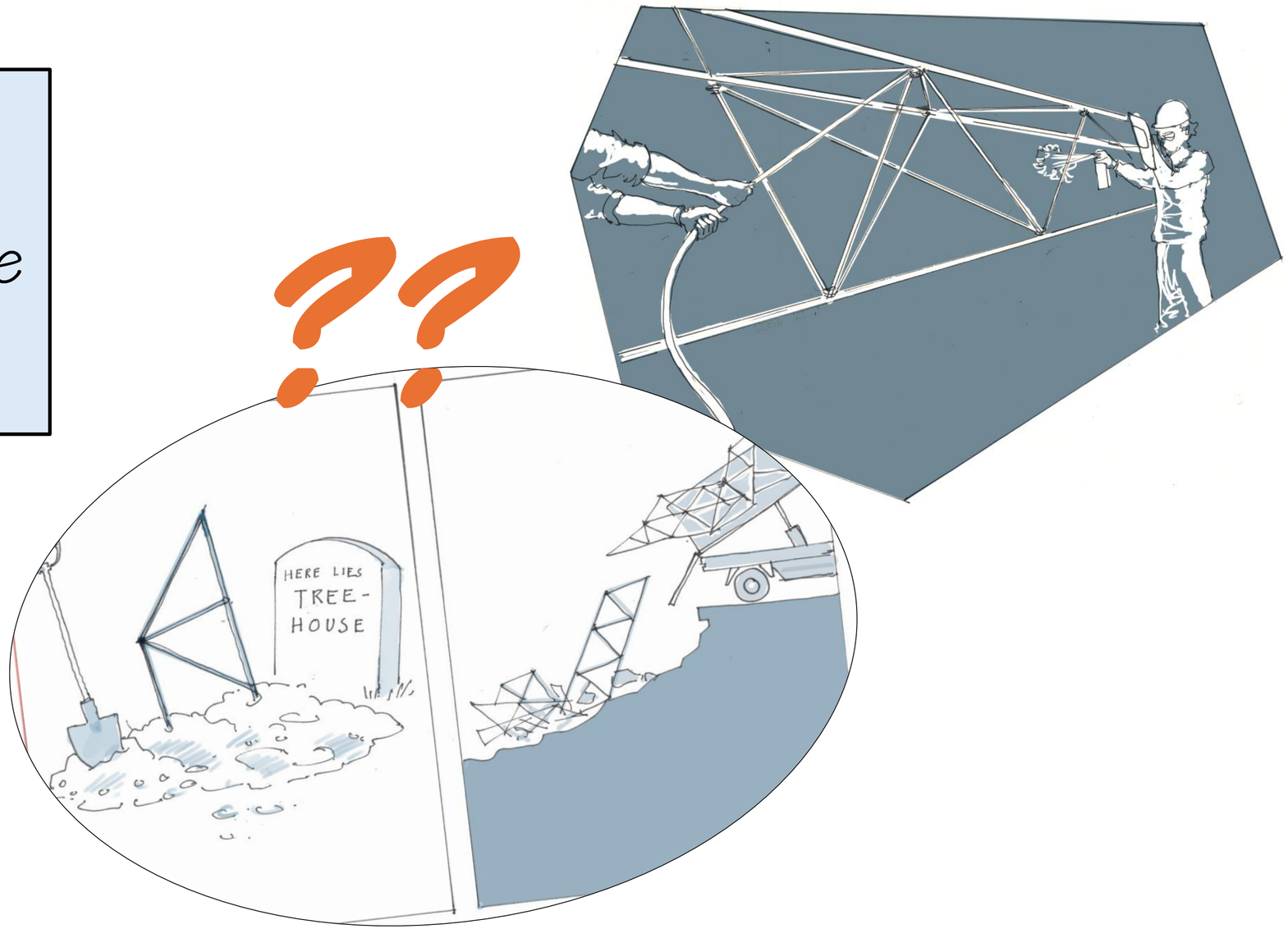
Sicomin Epoxy Systems

ADITYA BIRLA CHEMICALS

ORSON RESINS & COATINGS

Material Choices: **Resin**

- Site -Curable?
- High-Performance
- Bio -Based?



Substitute Resin

Epikote + Epikure
04901

Westlake
Epoxy

How to Make the Rope? **Topology- Braiding**

Method	Remarks	Decision
1. Filament Winding	Better suited to elements of shorter lengths and larger diameters. Not feasible for continuous cordage	Unsuitable
1. Pultrusion	Produces continuous elements, with fibres axially aligned, but includes a curing process (heated die) that outputs rigid segments	unsuitable
1. Roll Wrapping (by hand)	Cannot be used for continuous process, better for short segments of pipes. Challenges of scalability	Unsuitable
1. Braiding	Can be used for continuous cordage production. Resin impregnation can be a separate process (either on individual tows or the rope as a whole)	Potentially suitable
1. Twining	Can be used for continuous cordage production. Resin impregnation can be a separate process (either on individual tows or the rope as a whole)	Potentially suitable
1. CO-mingling/ air-jet texturing	Can be used for continuous cordage production. The polymer is mixed into the fibers as the cordage is made.	Potentially suitable

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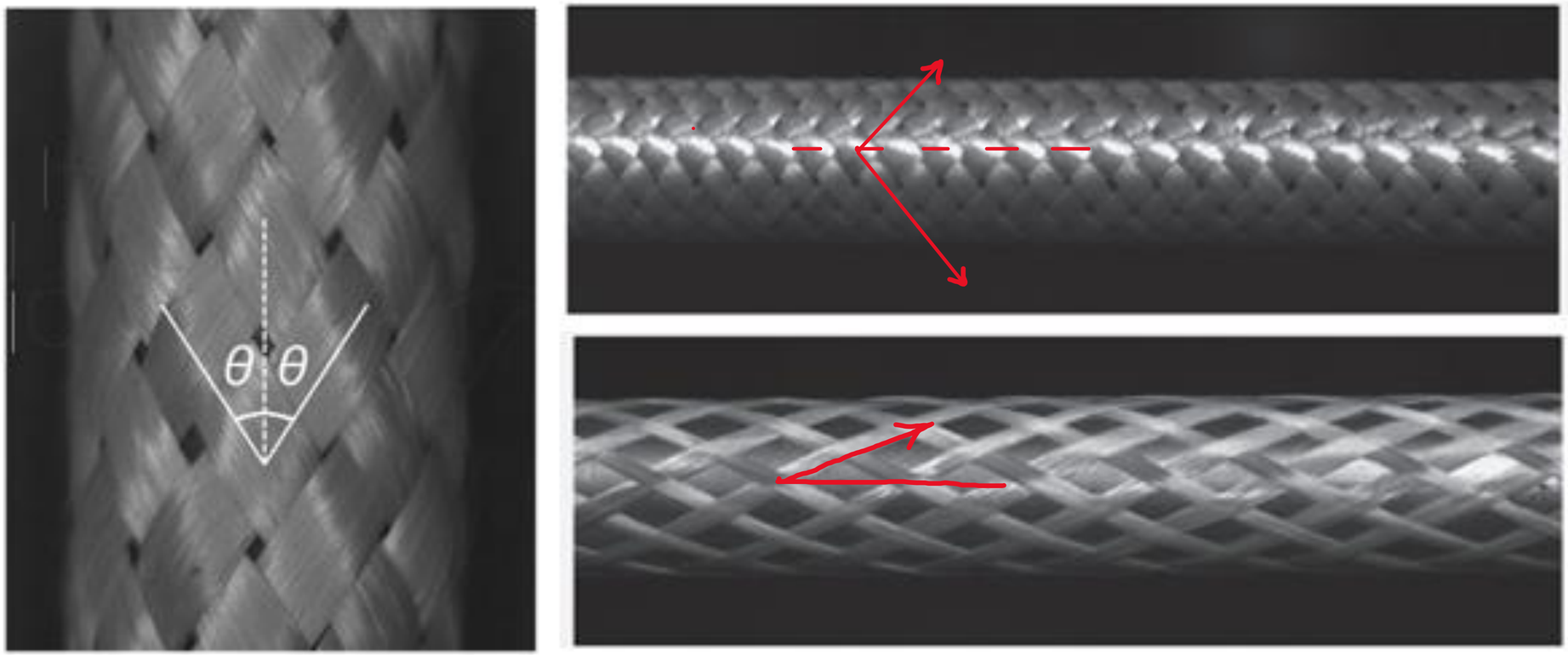
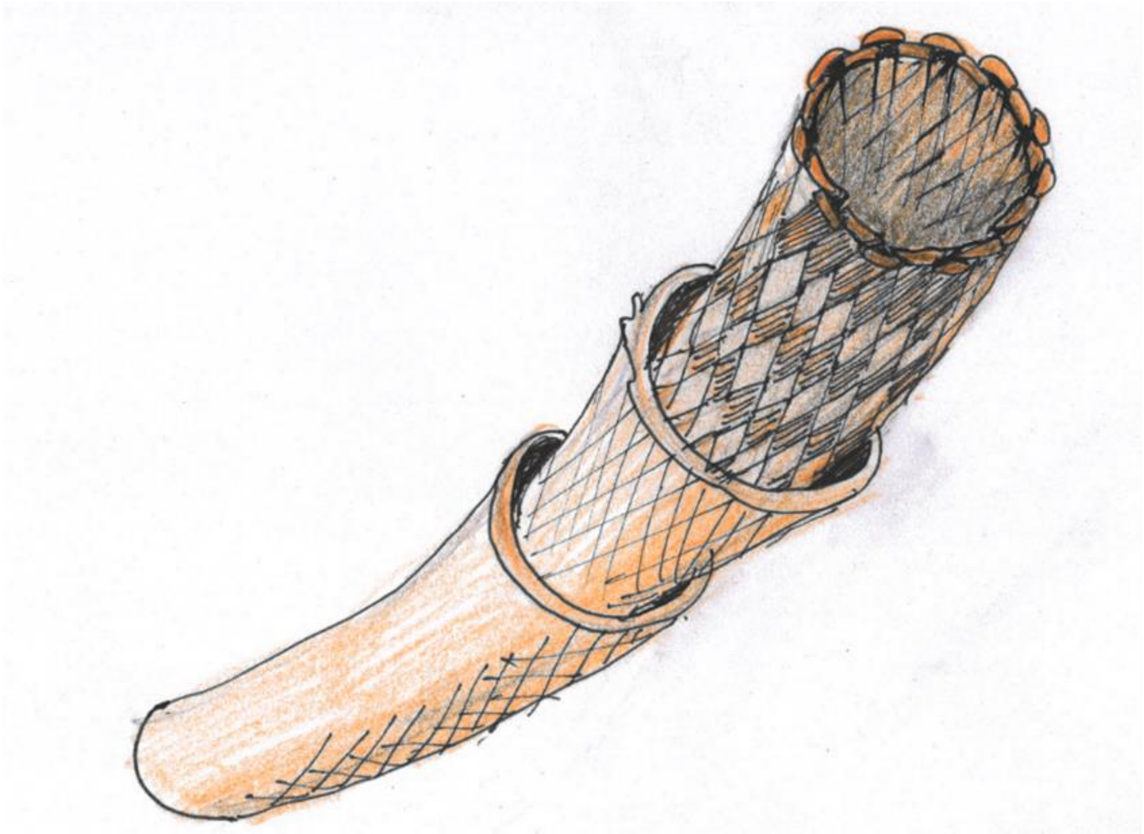
How to Make the Rope? **Topology- Braiding**

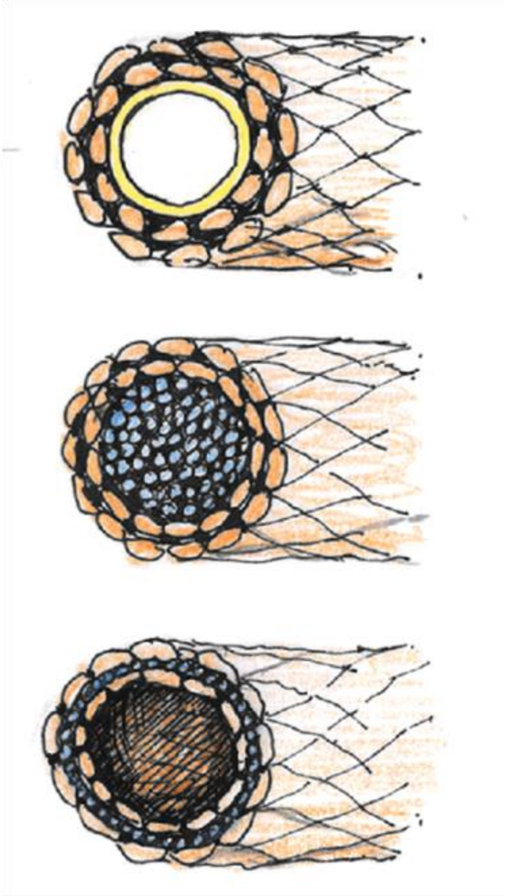


Braid angle in a graded rope, b. Deep and shallow braid angles creating different fiber alignments with the rope axis (Carey, 2017)

How to Make the Rope? **Topology- Braiding**

Overbraiding over a braid to create a 'coaxial' layup (Kyosev, 2015)

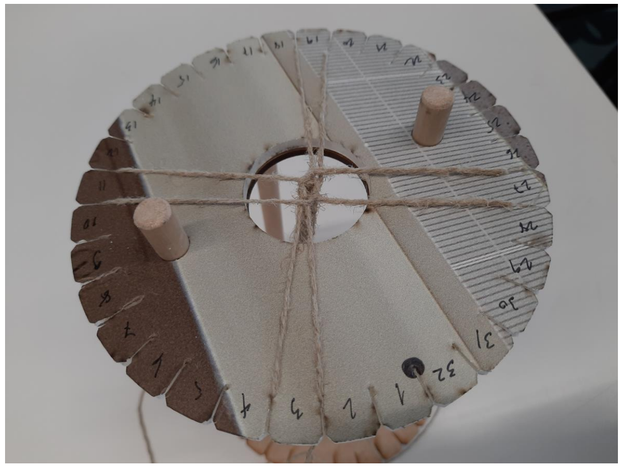


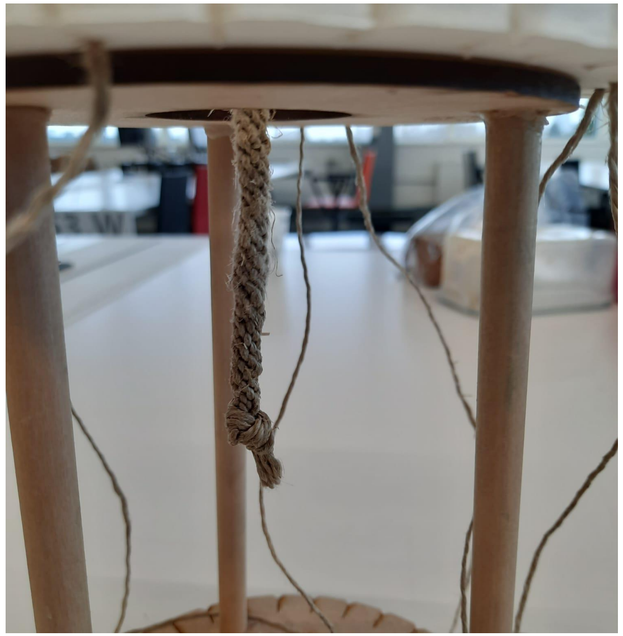


Braiding Consolidation Hypothesis

...we'll get there later

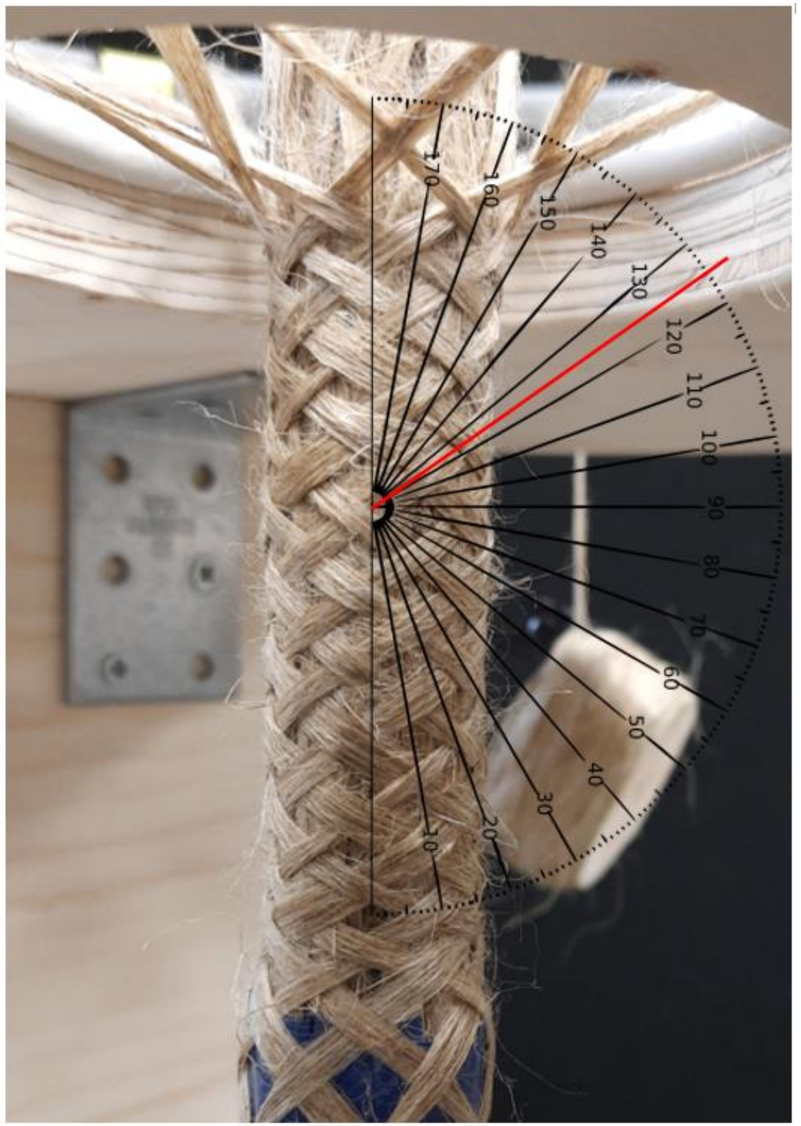
The Braid Machine!

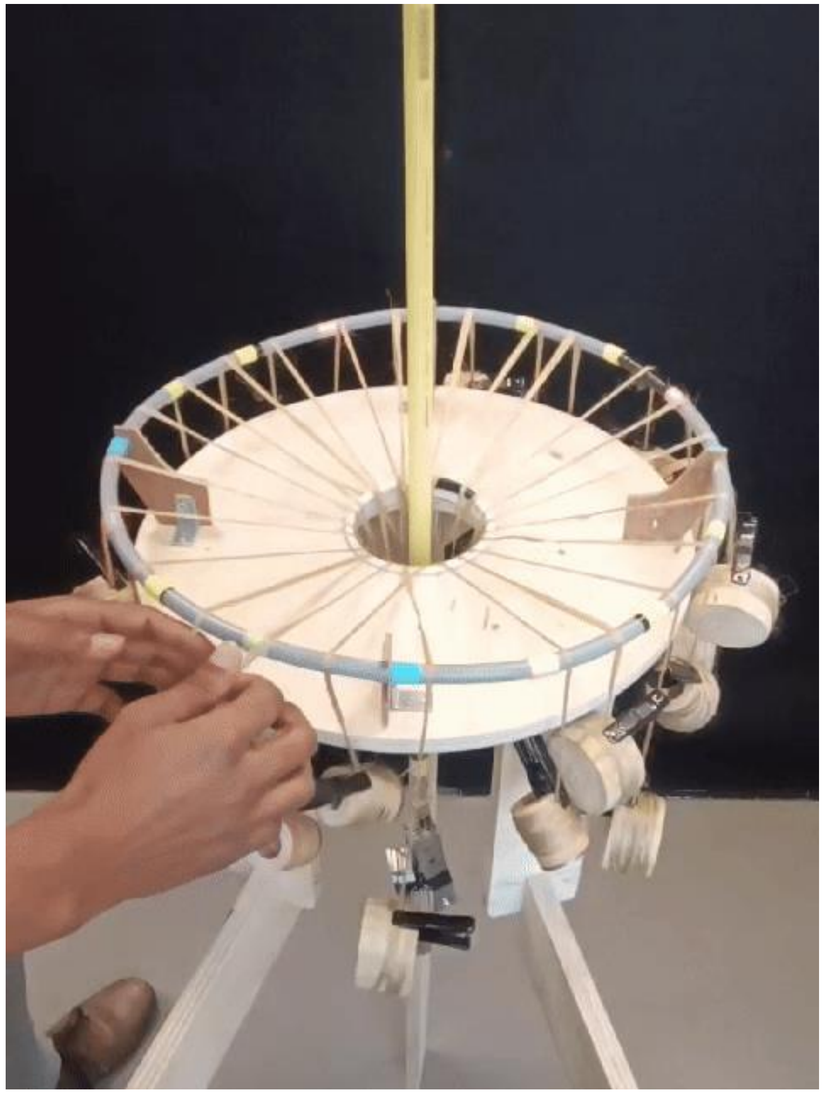




The Braid Machine!

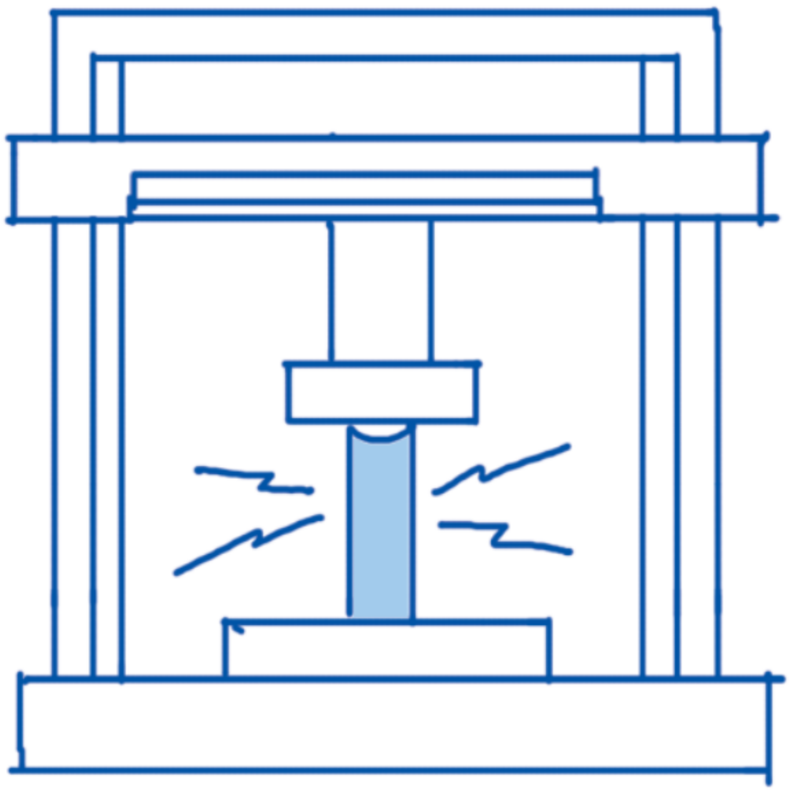
Multiple Braid Angles!





60 min/layer/85cm
A 6 layer braid takes
6 hrs+ changeover time
= 7-7.5hrs

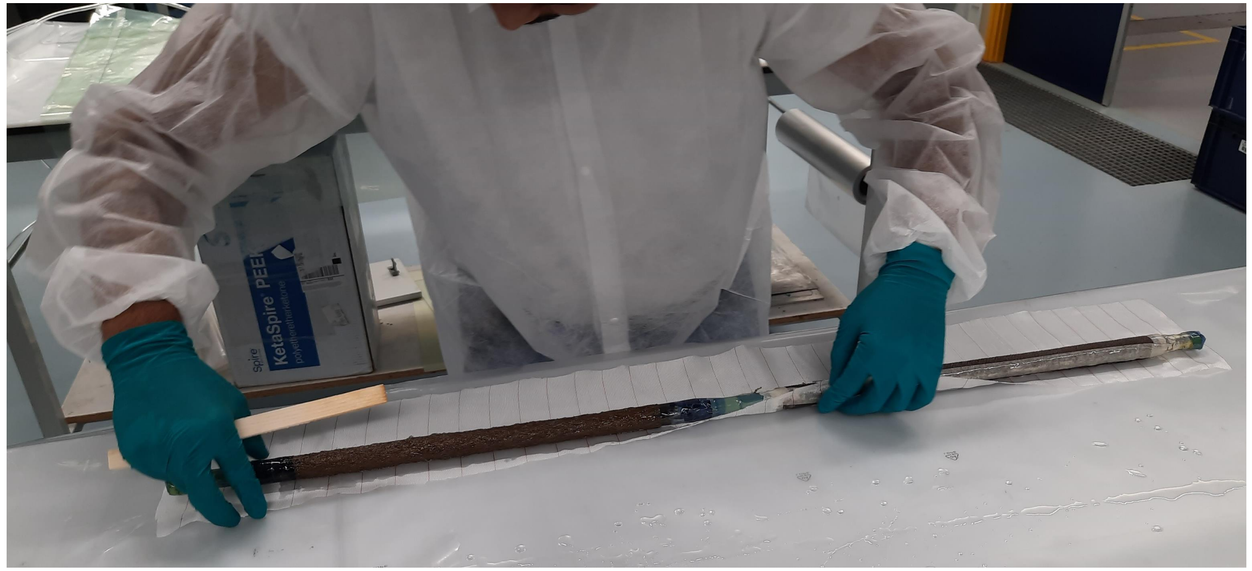
Experimental Phase!

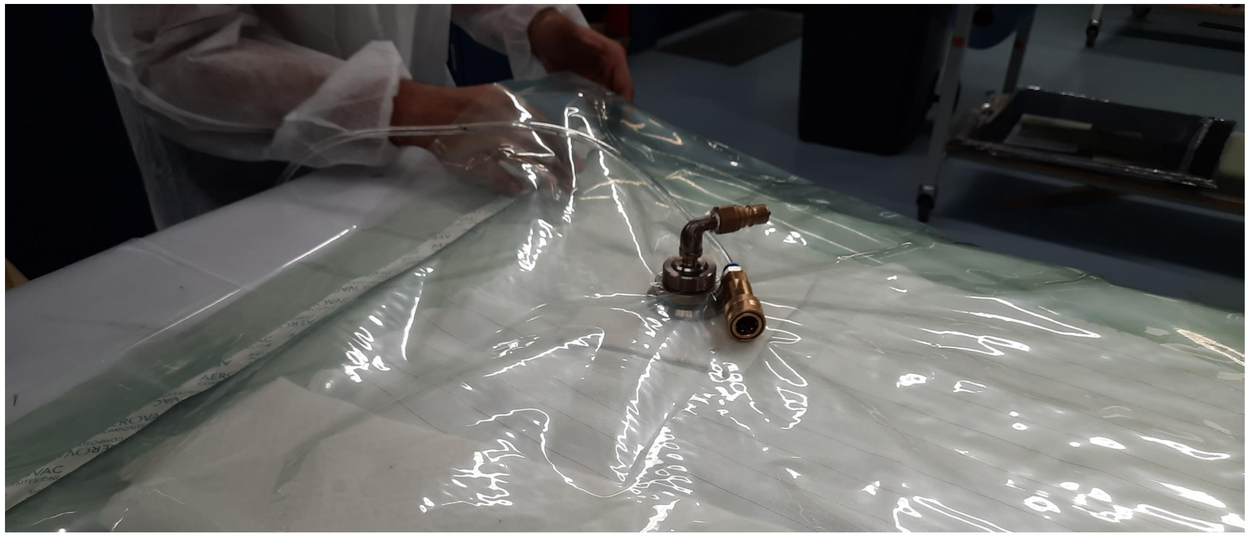


Isolated Section of composite

- Tensile Capacity?
- Compressive capacity?
- Comparison against steel/aluminium etc

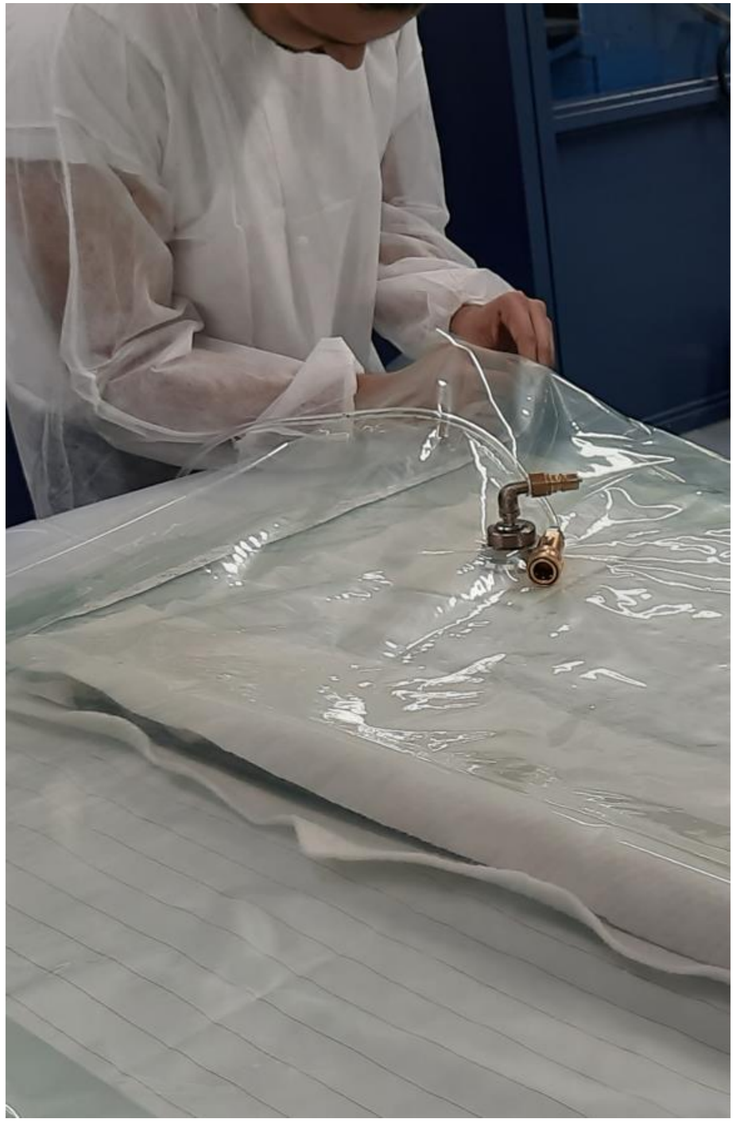
Part A.1: 3-Layer Braided vs. Woven

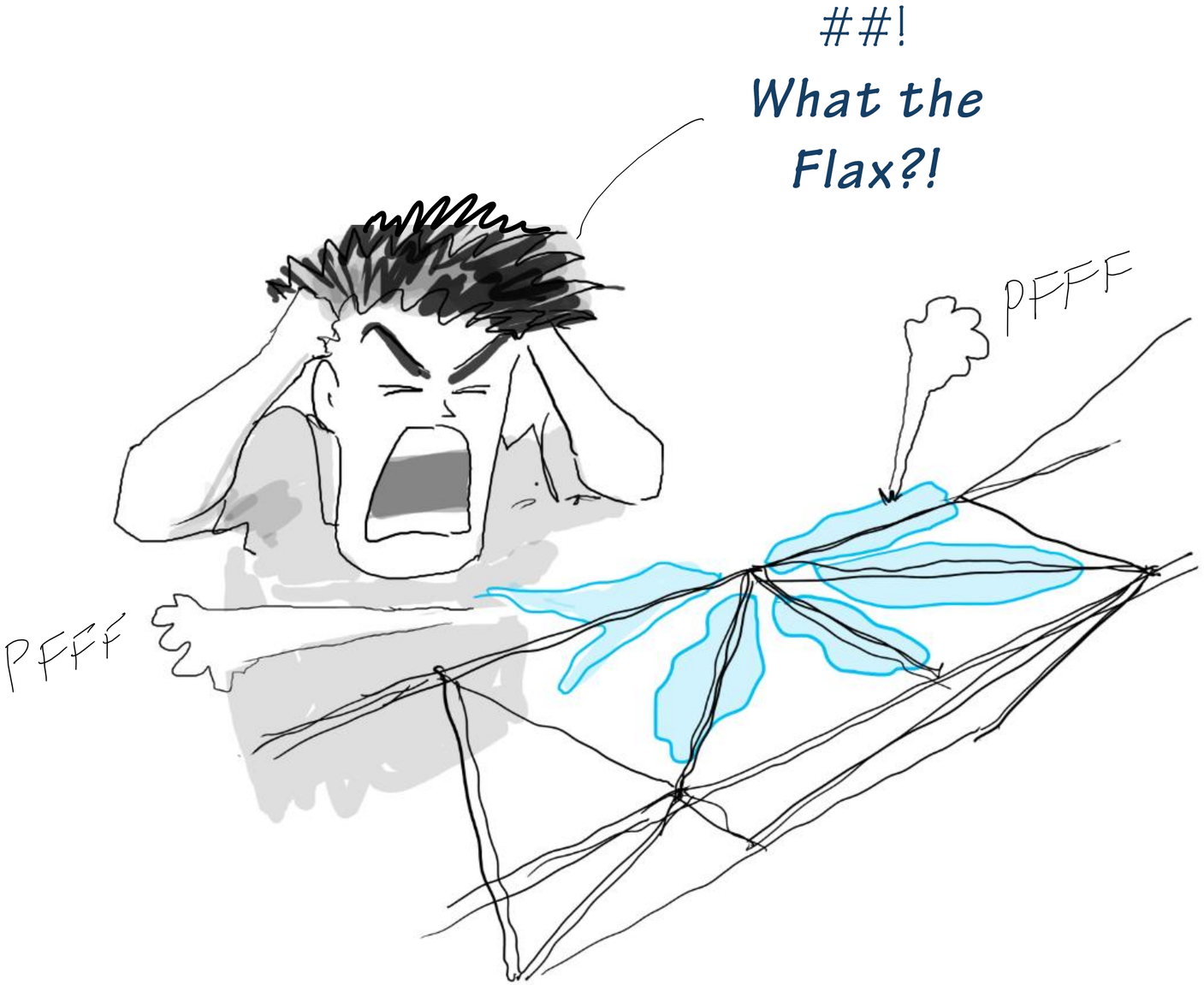




Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible
6-Layer Braided +15/-15	Vacuum Bag	Compression	43.9	**56.6**	Wall thickening doesn't help
6-Layer Braided +15/-15	Post-Tensioning	Compression	24.2	**77.5**	Not as effective as vac bag but more site feasible
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	26.9	**61.36**	Shallow braid Lateral reinforcement makes it worse
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	20.5	**53.34**	Filament winding Lateral reinforcement makes it worse
6-Layer Braided +15/-15	Vacuum Bag	Tensile	53	**145**	Have to correct for lower FVF!
				~75	Corrected for FVF of 25%

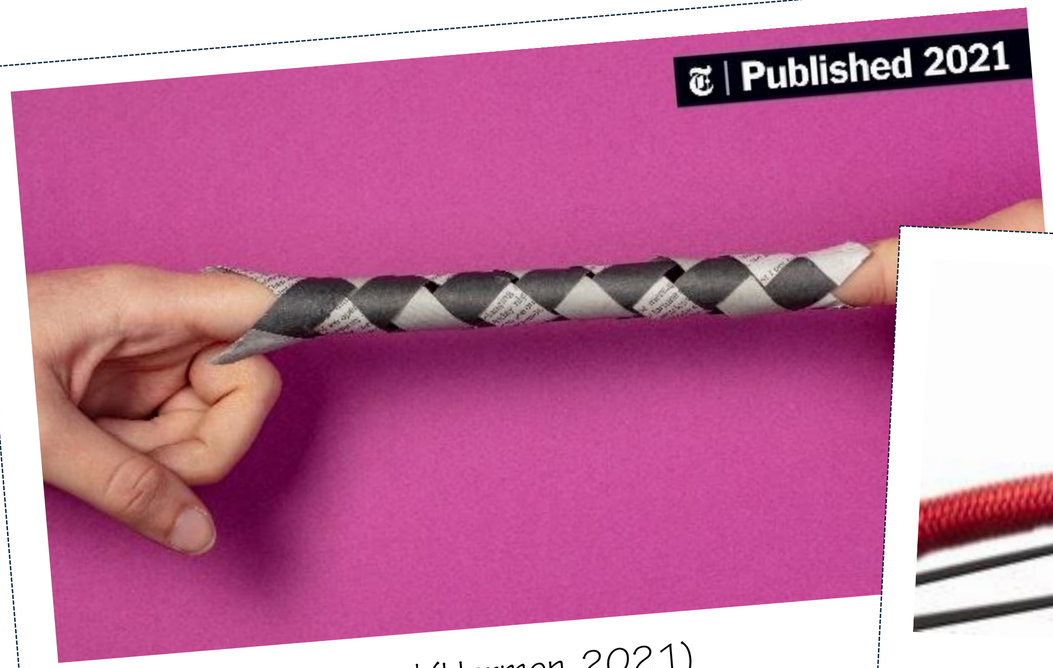
Part A.: **The Consolidation Problem**





Braiding Consolidation Hypothesis

Part A.: **The Consolidation Problem**

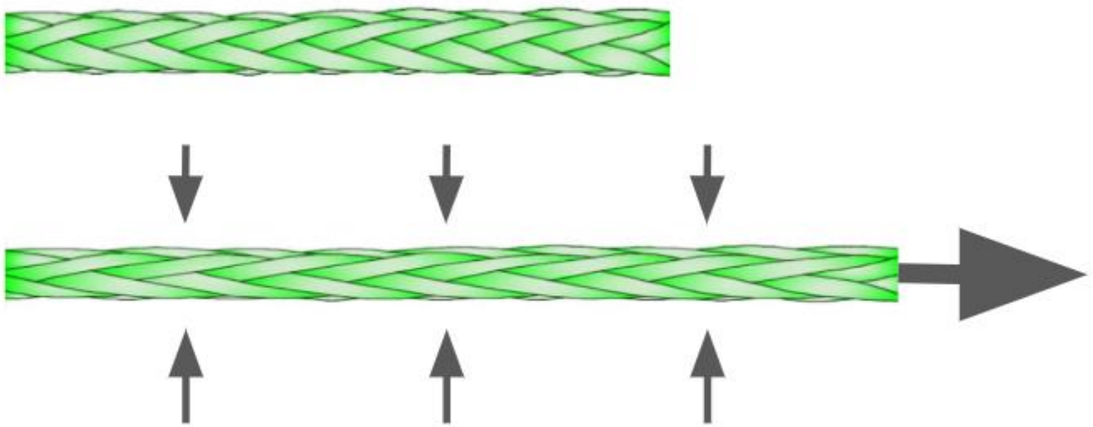


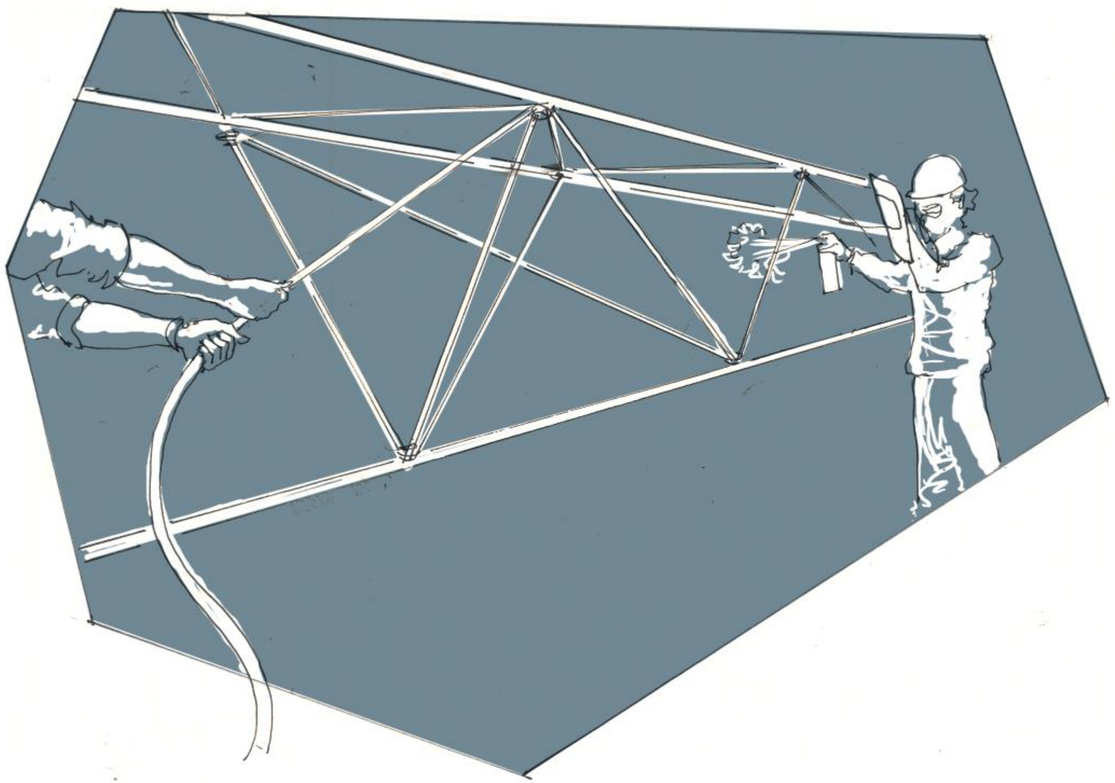
A Chinese 'finger-trap' (Harmon, 2021)

. A Ronstan Constrictor Clutch (Courtesy: Hamilton Marine)

Part A.: **The Consolidation Problem**

Axial Tension for Lateral Constriction





Can we consolidate without a vacuum bag?

YES

Part A: Conclusions

- We've figured out the Fiber Architecture
- We can do consolidation with Braid constriction
- Tension: ~75MPa
- Compression ~75Mpa

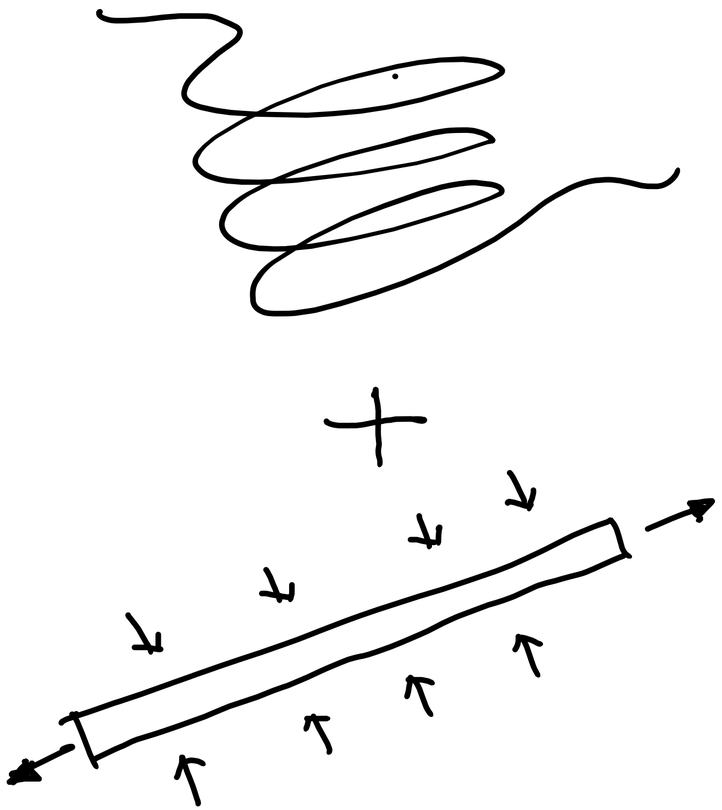
OK, but how to build a truss?

Part B:

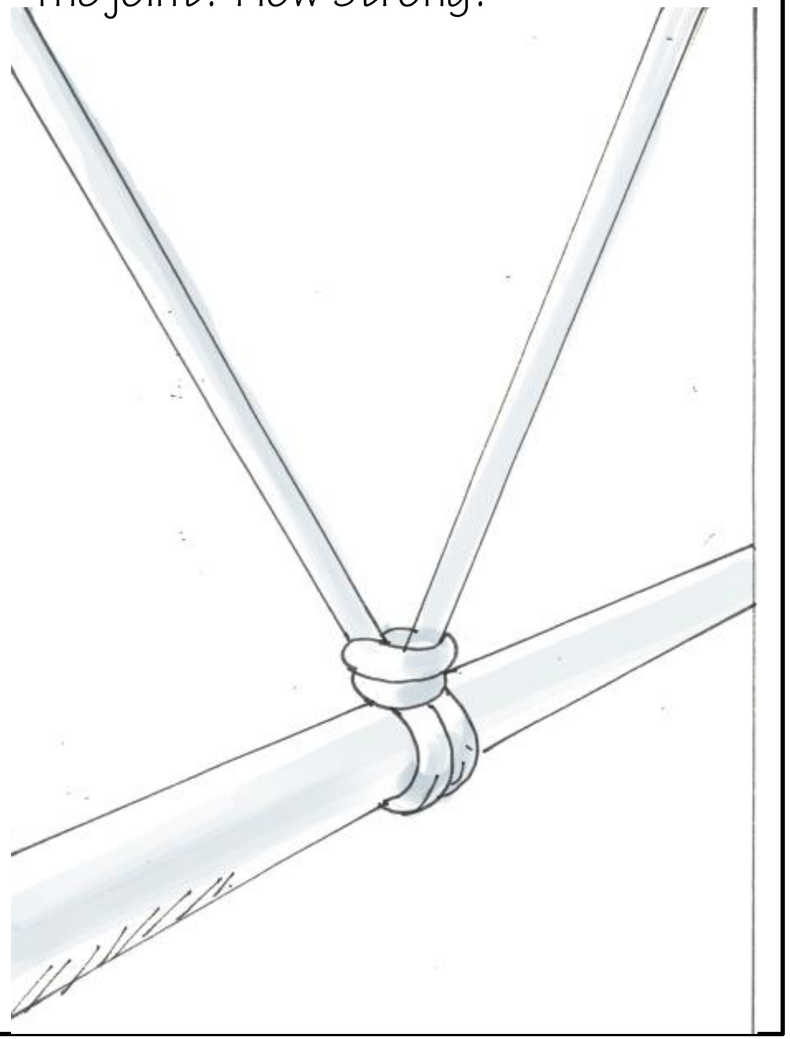
Truss Making…

Part B; **Main Points**

Post tensioning? Flexi rope?



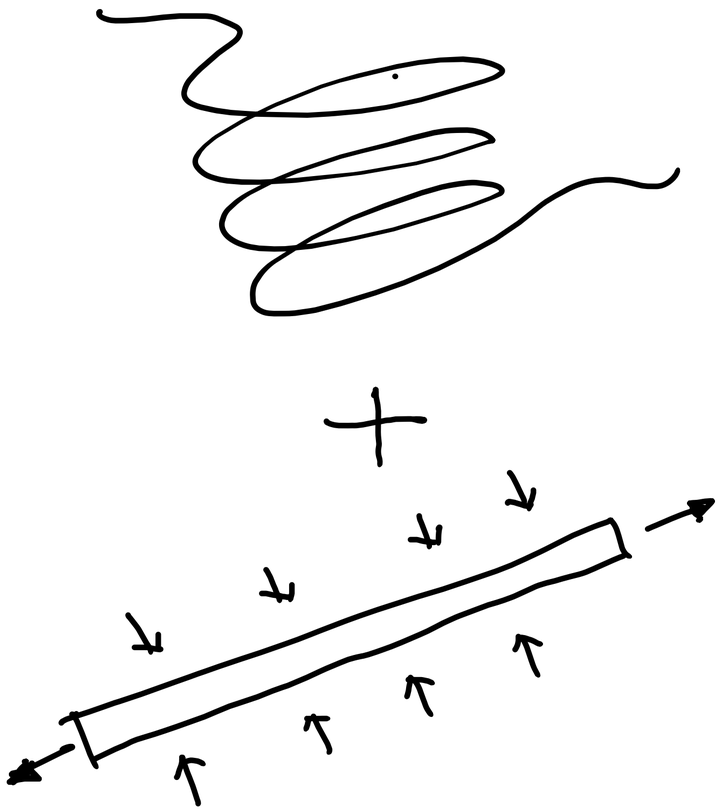
The joint? How strong?



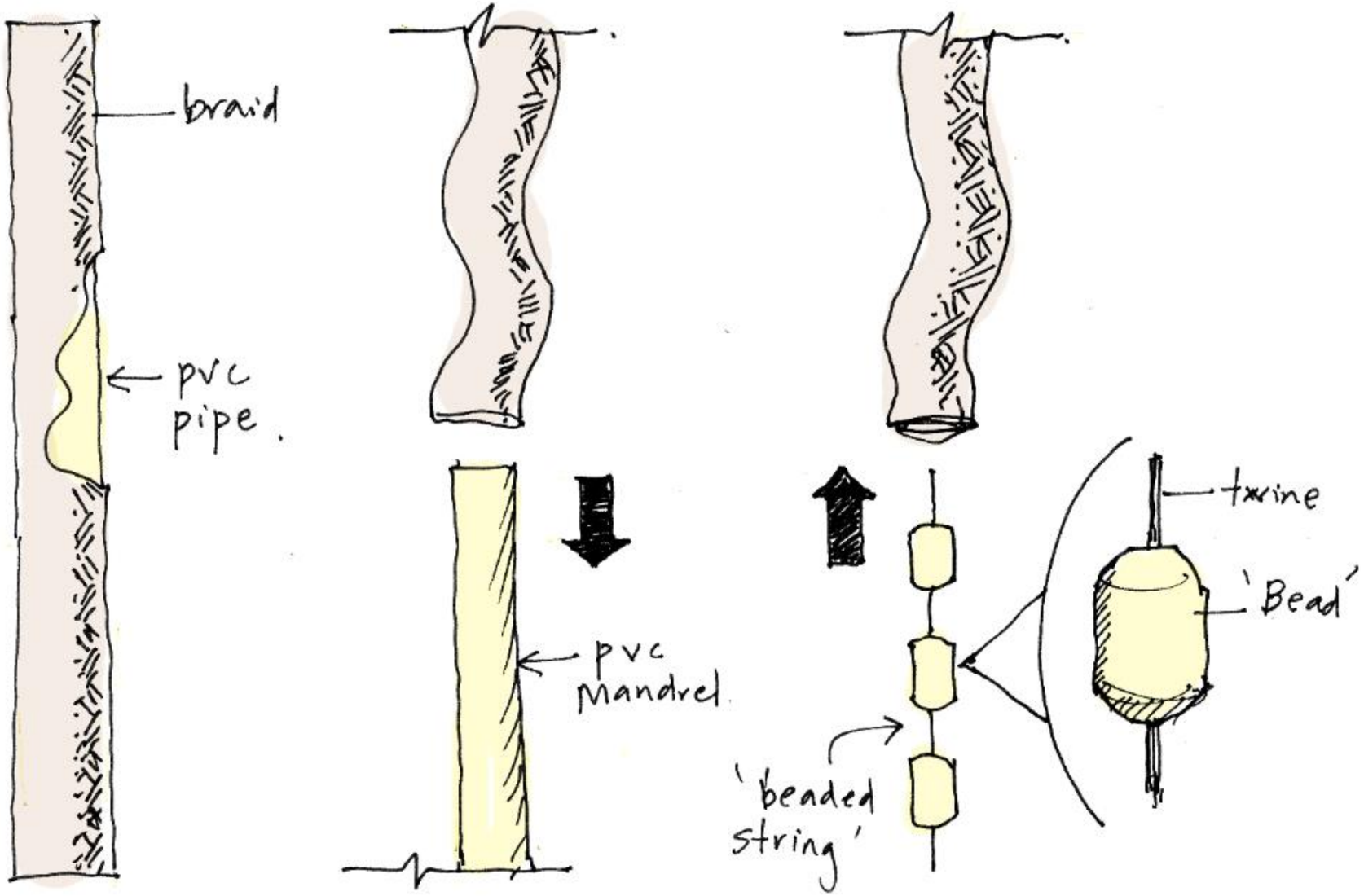
How to Build?

Part B; **Main Points**

Post tensioning? Flexi rope?



Part B; **The Discontinuous Mandrel**



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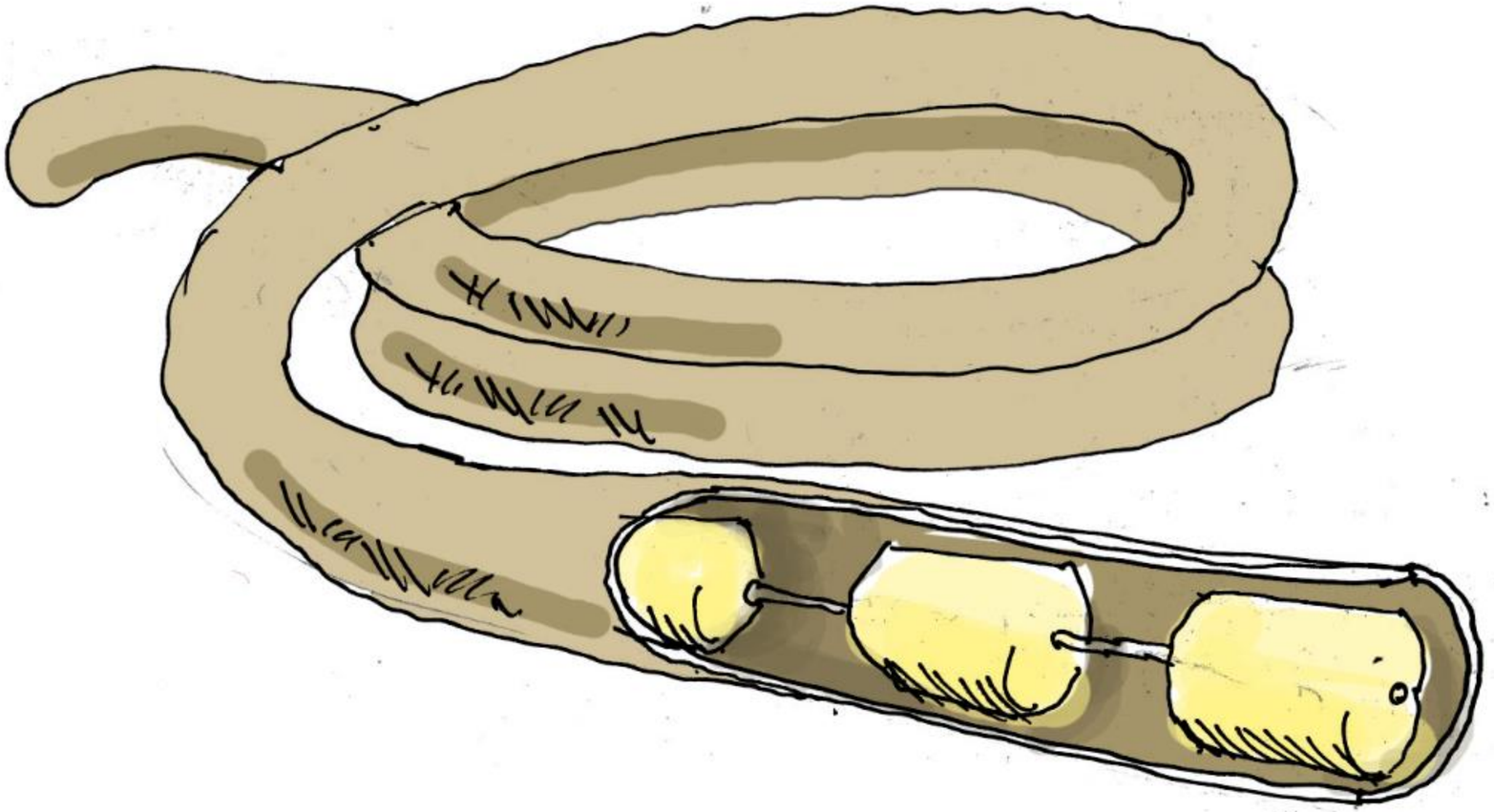

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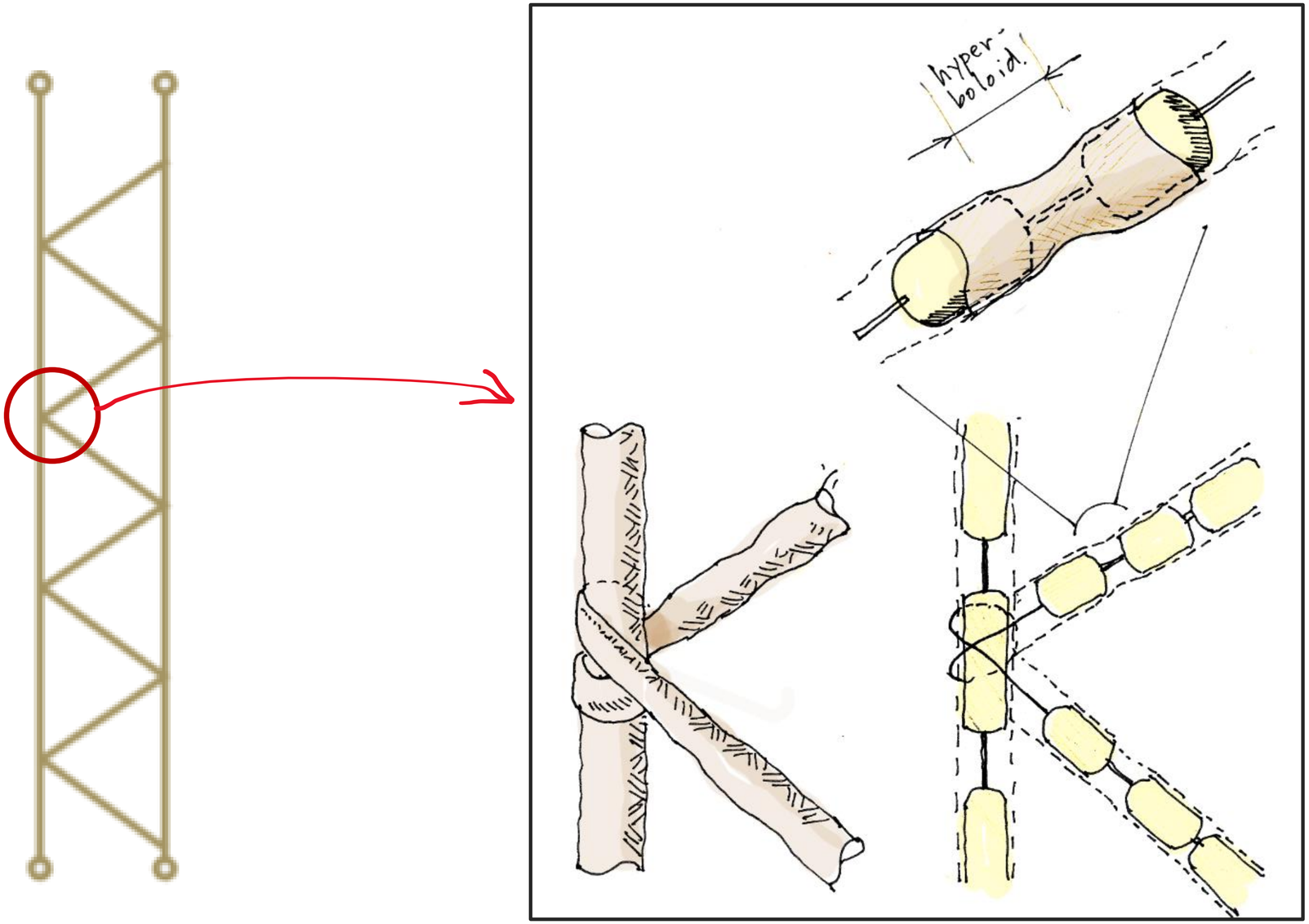

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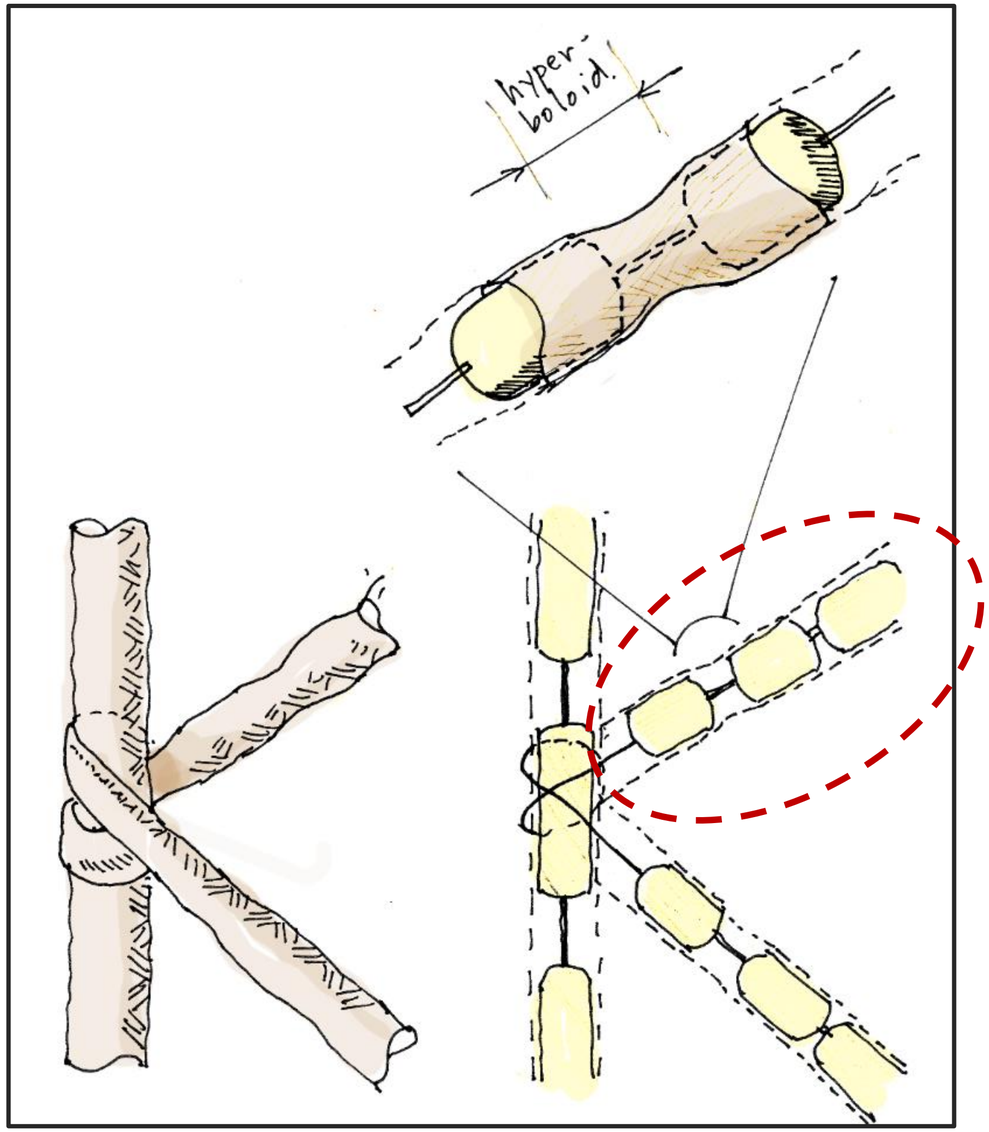

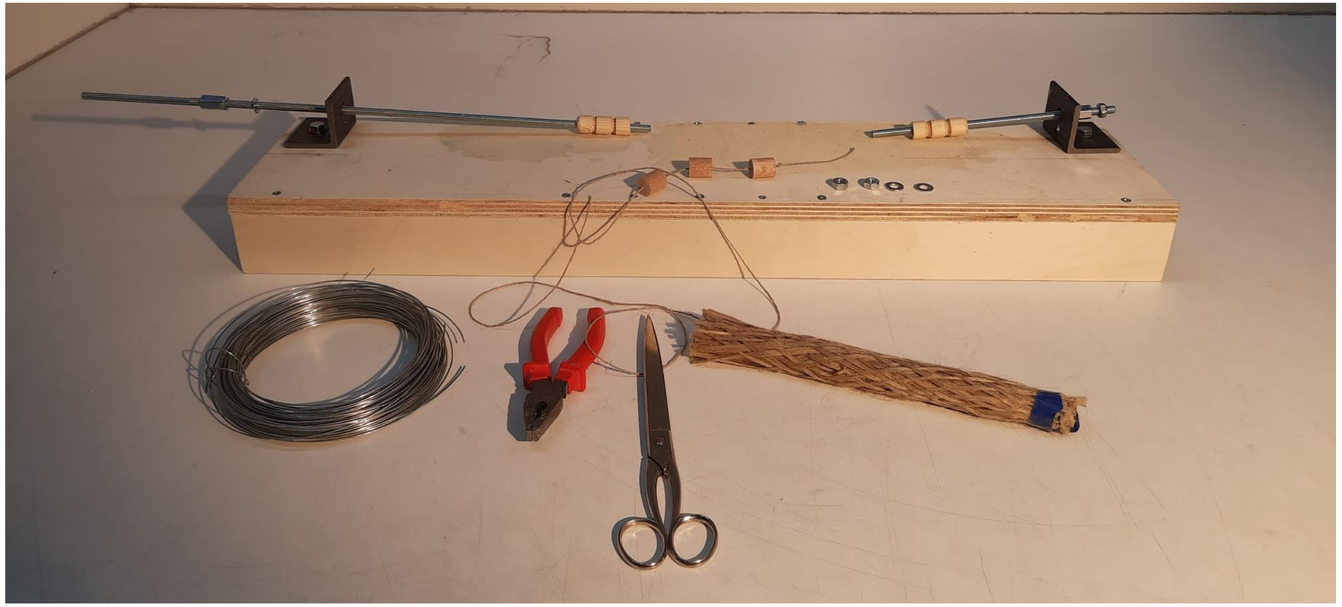

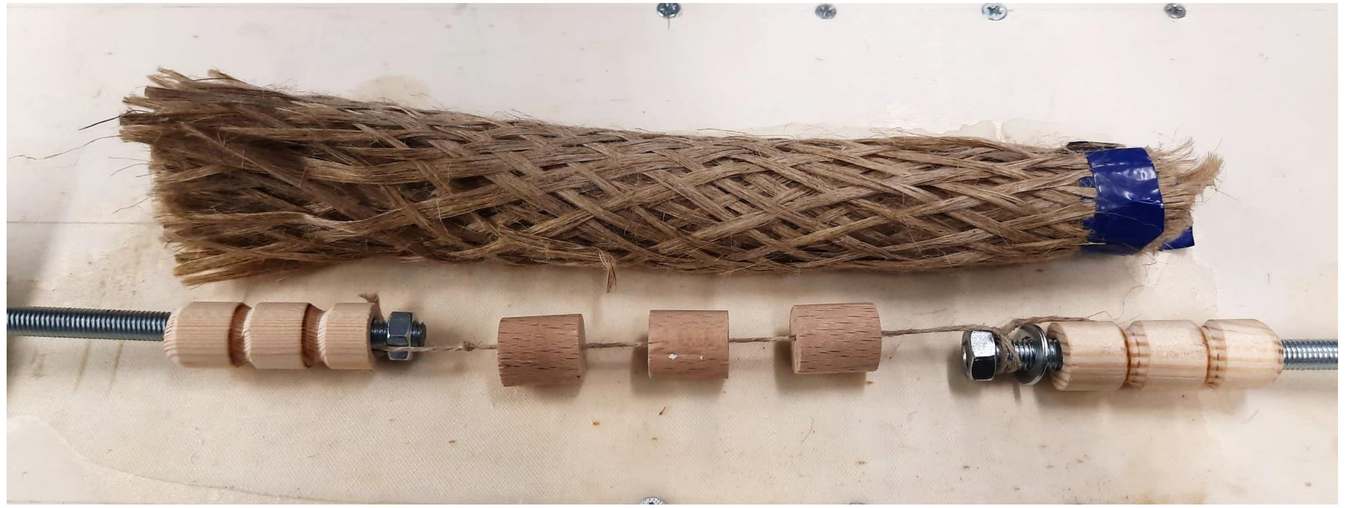

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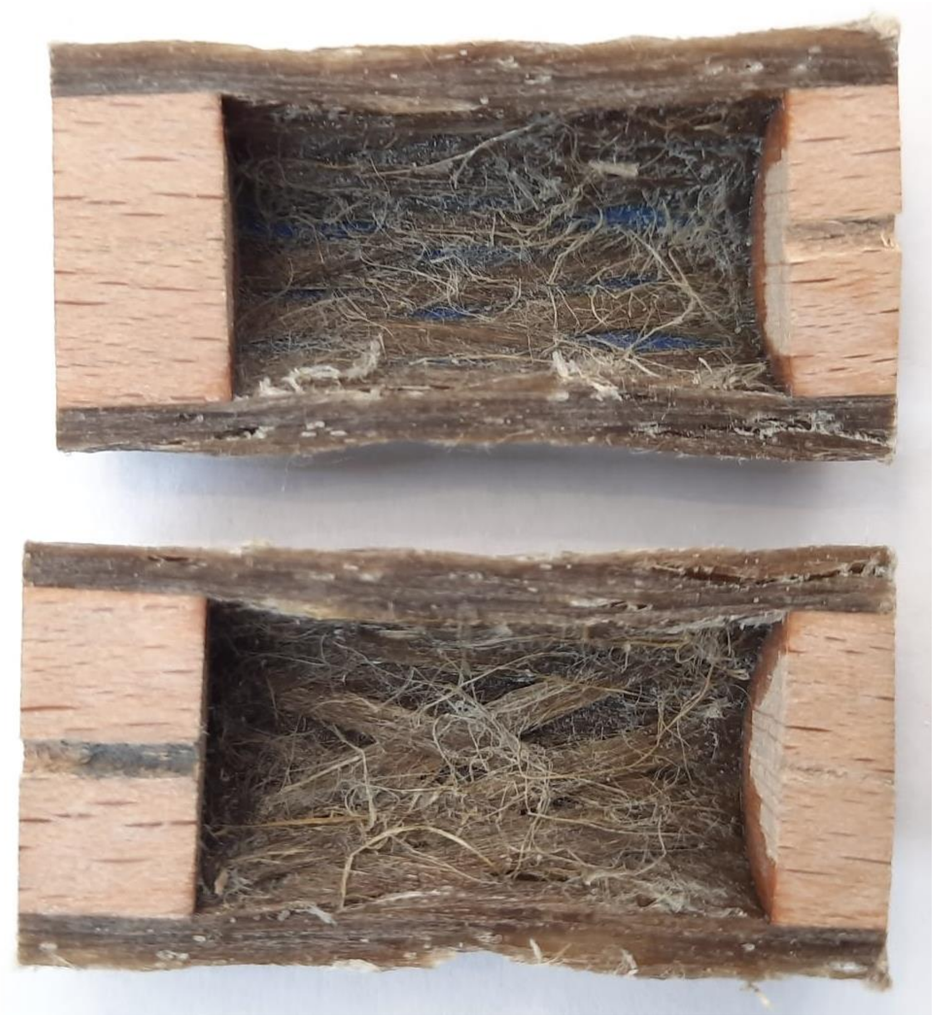

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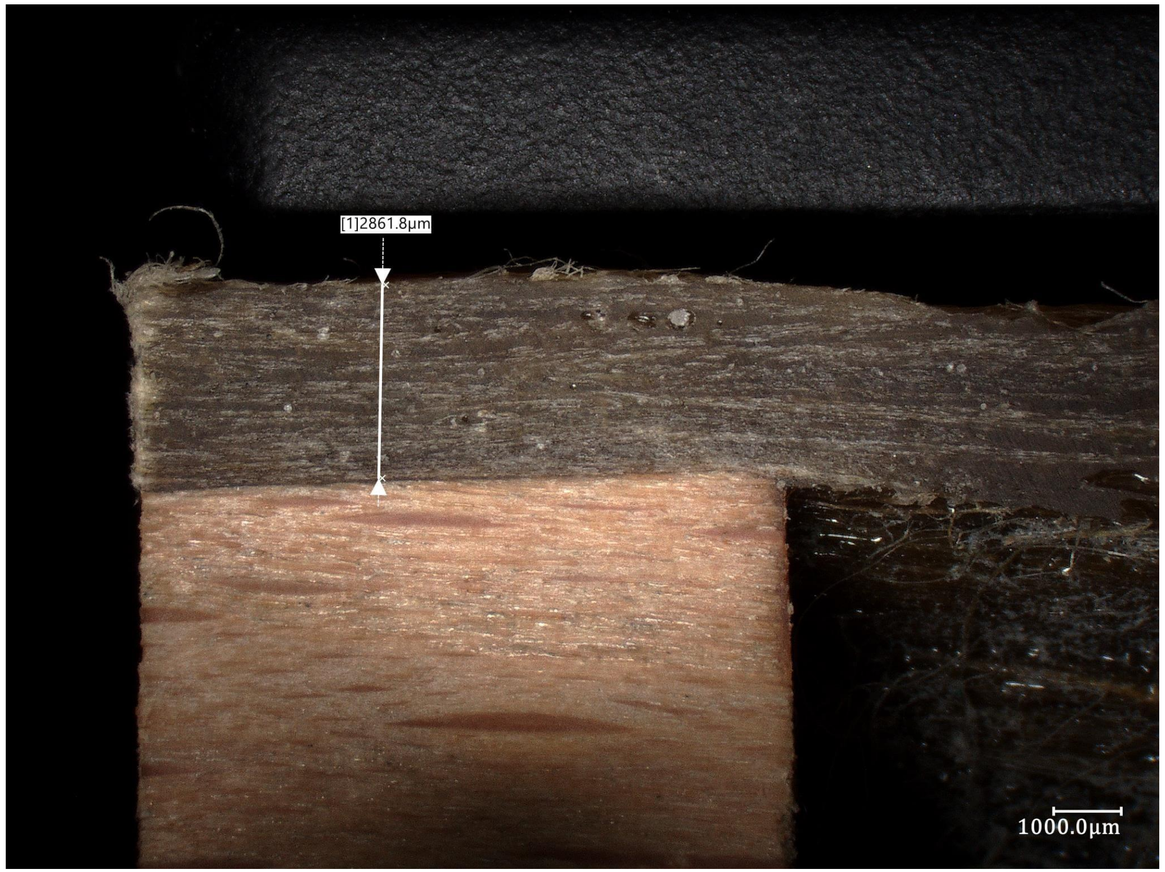

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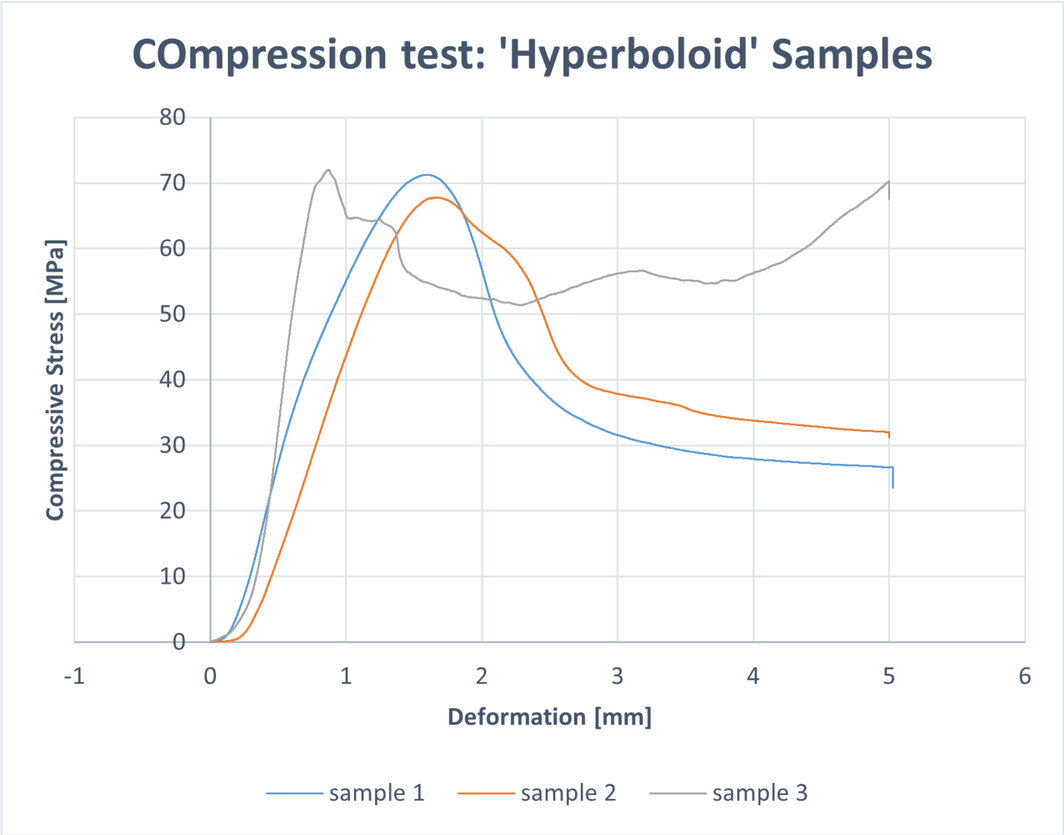
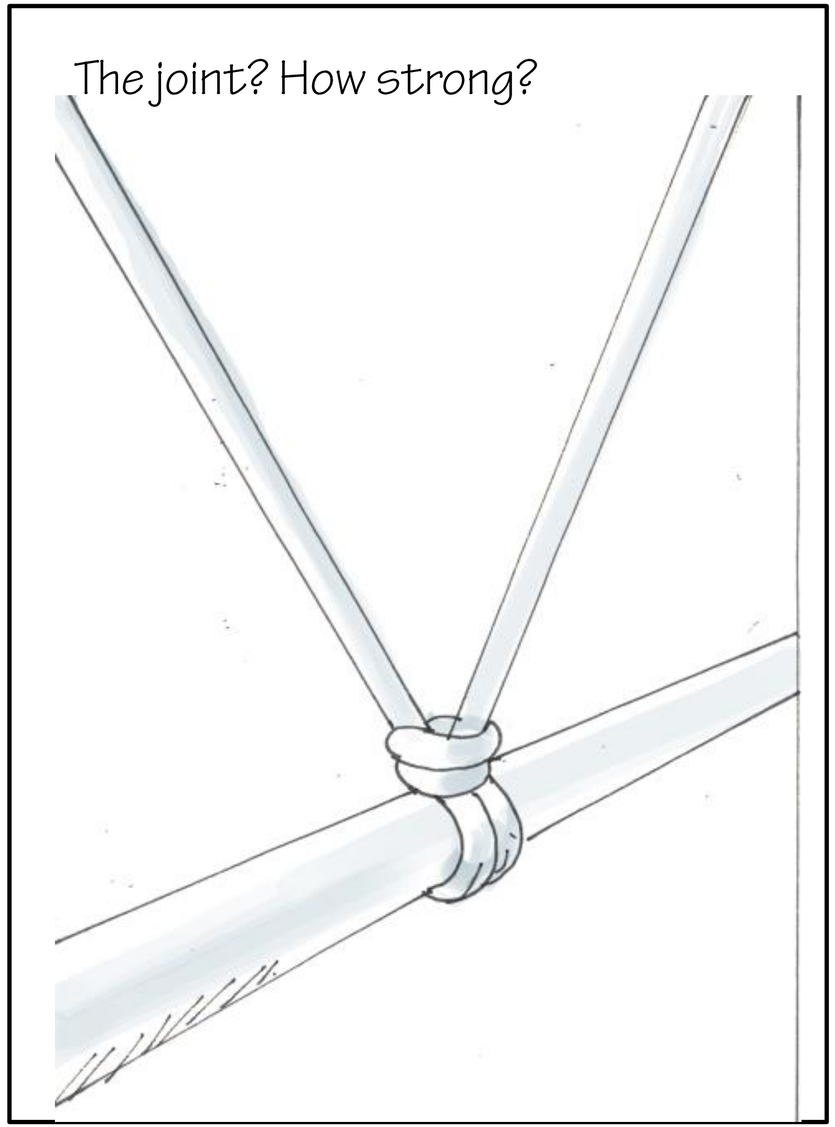
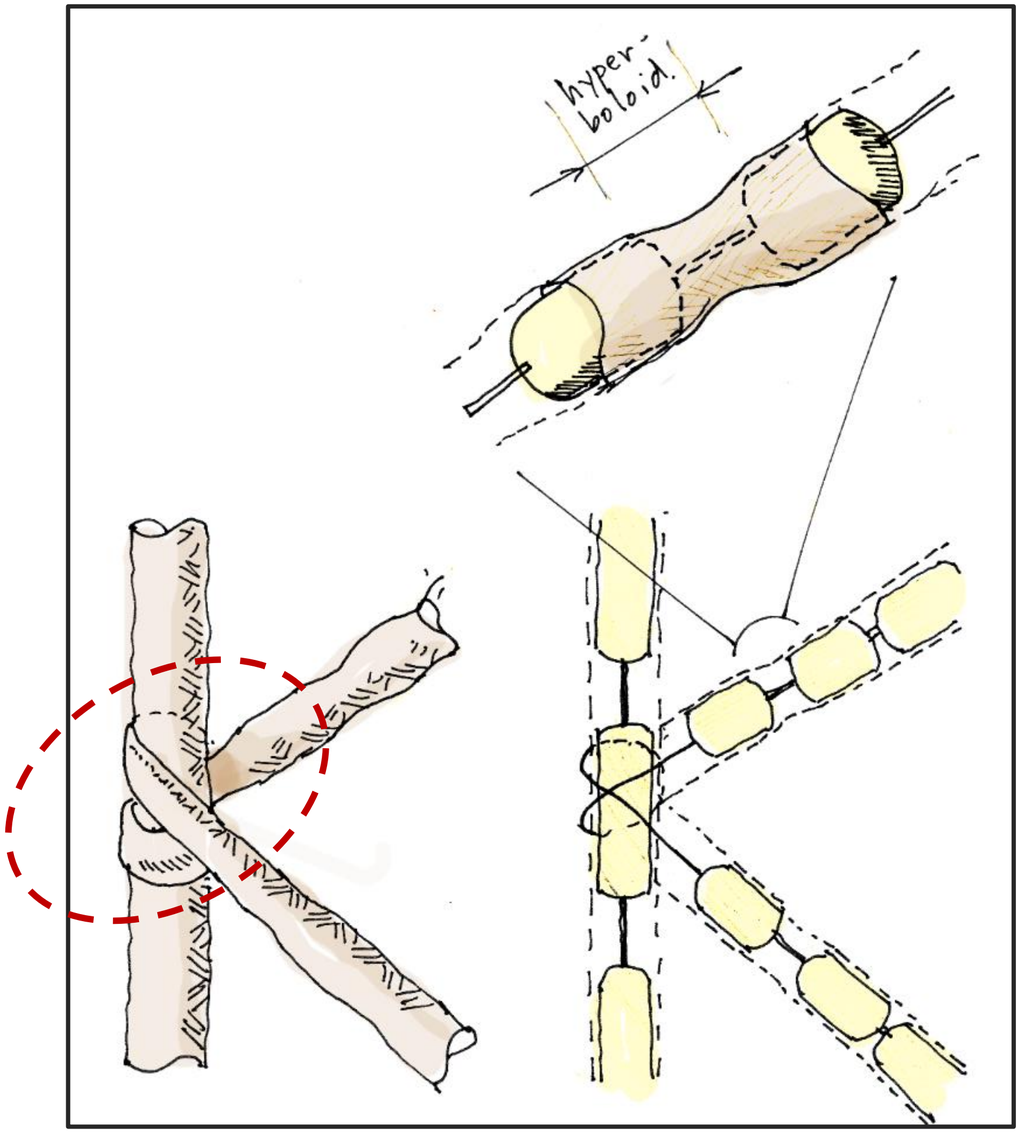
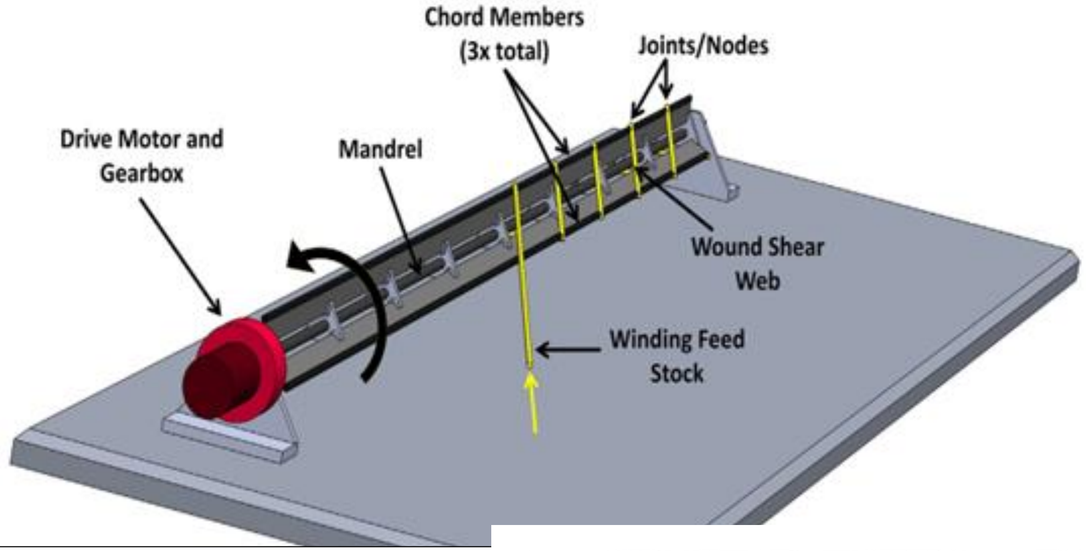


sample	max compressive stress [Mpa]
1	71.22238498
2	67.79407552
3	72.01468099
avg	**~ 70 MPa**

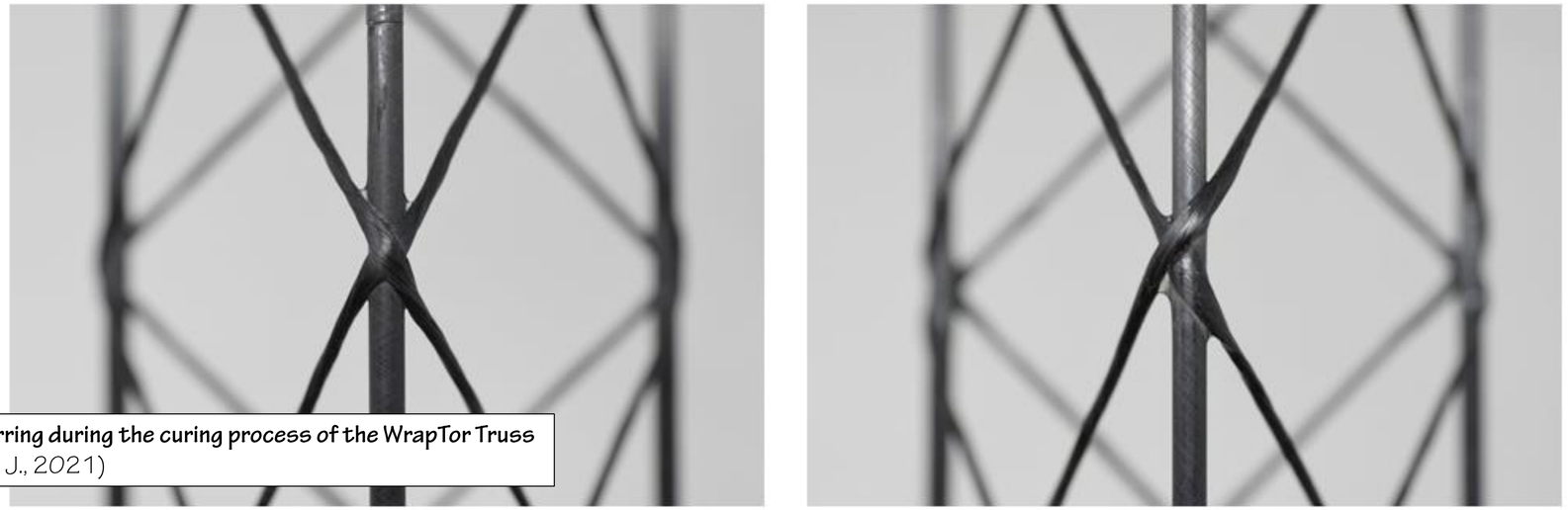
Part B; **Joint Making!**




hyper-
boloid.



Schematic of the robotic filament winding process of t truss'. (Hunt, Wisnom, & Woods, 2019)

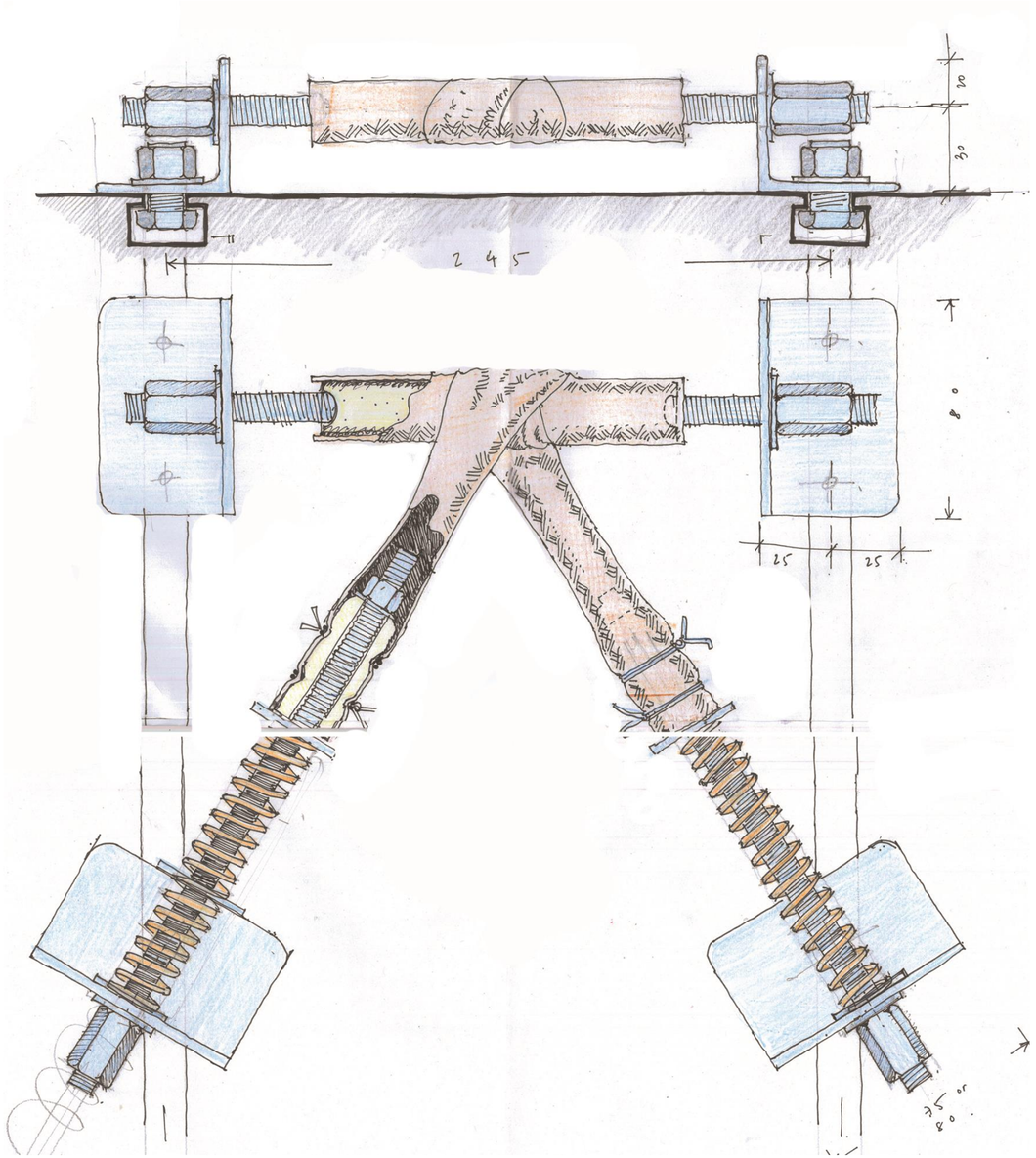


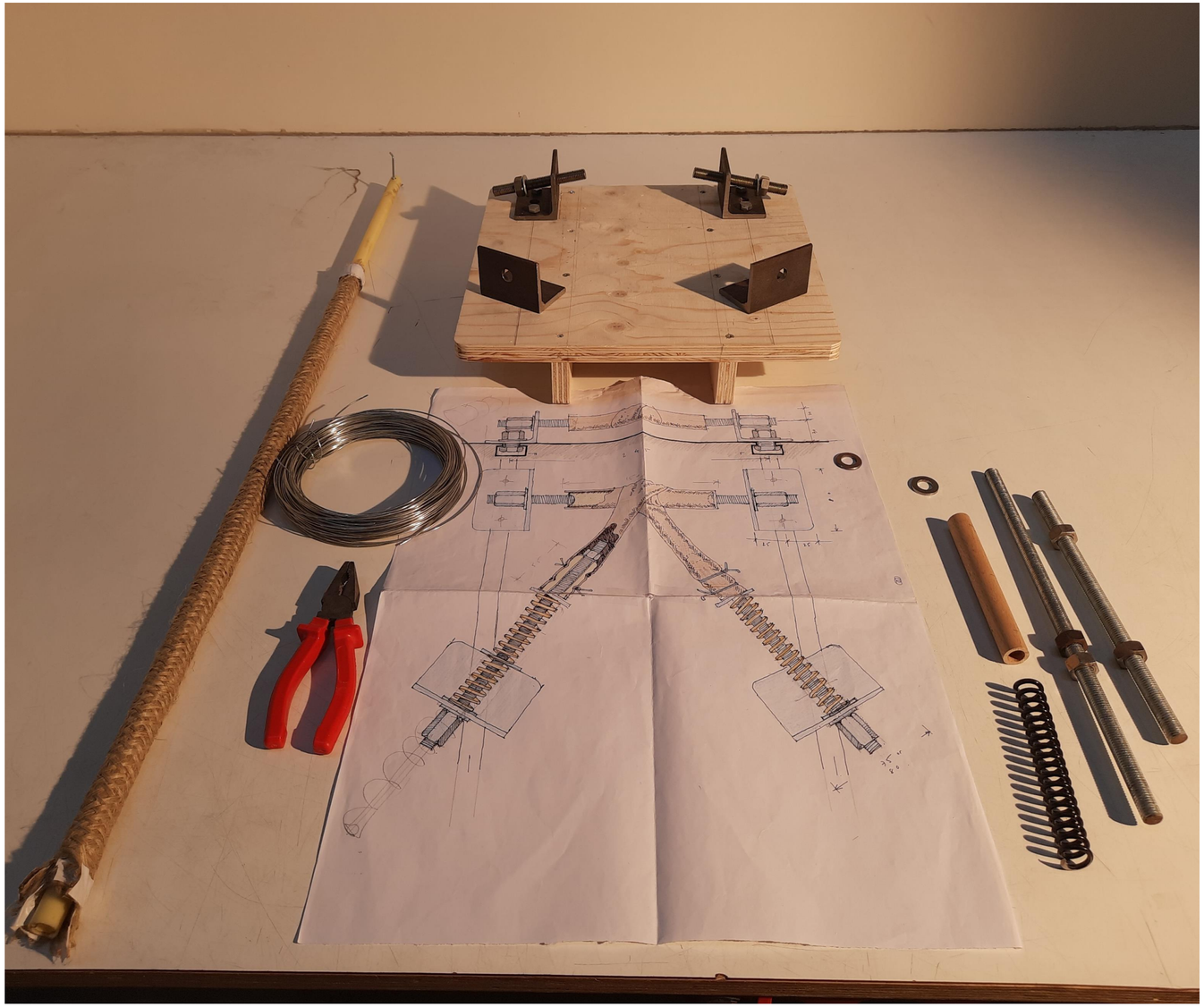
Joint slippage occurring during the curing process of the WrapTor Truss Fabrication (Hunt C. J., 2021)

(a) (b)

Part B; **Joint Fabrication**

Part B; **Joint Fabrication**





Part B; **Joint Fabrication**

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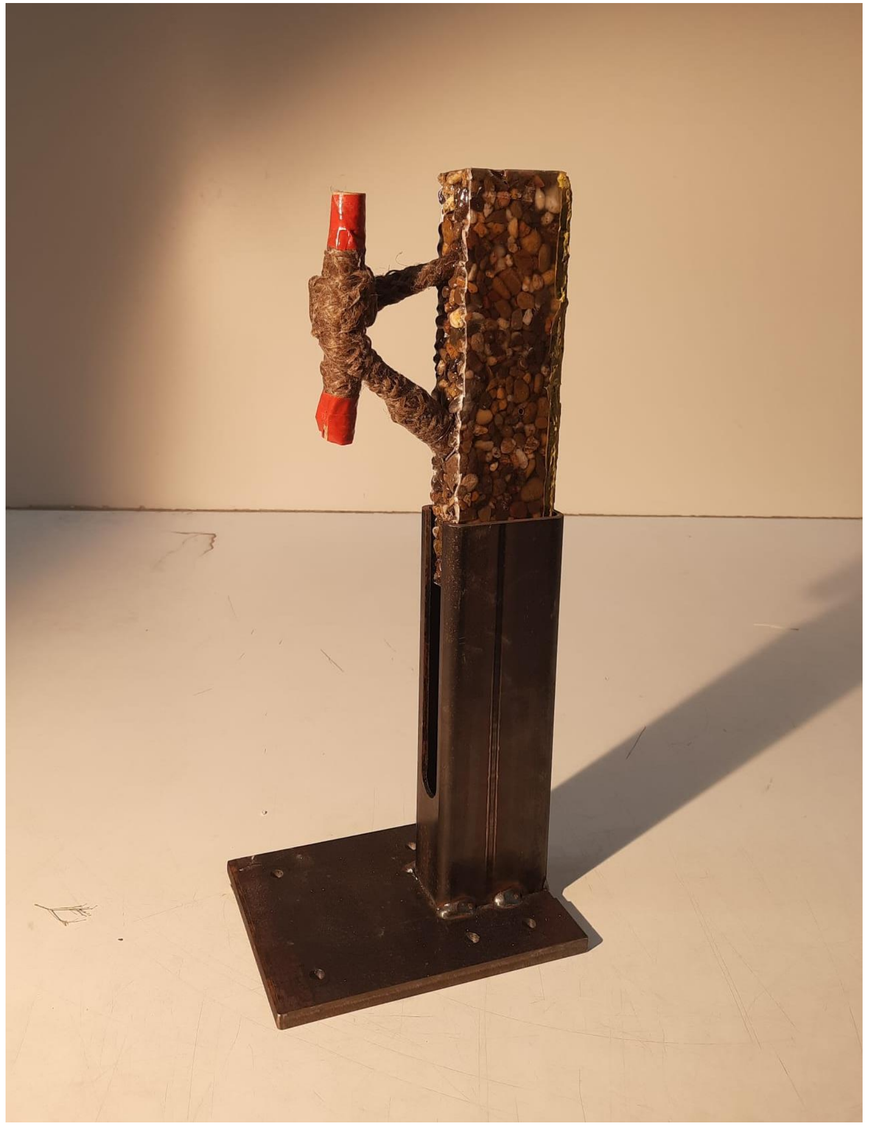
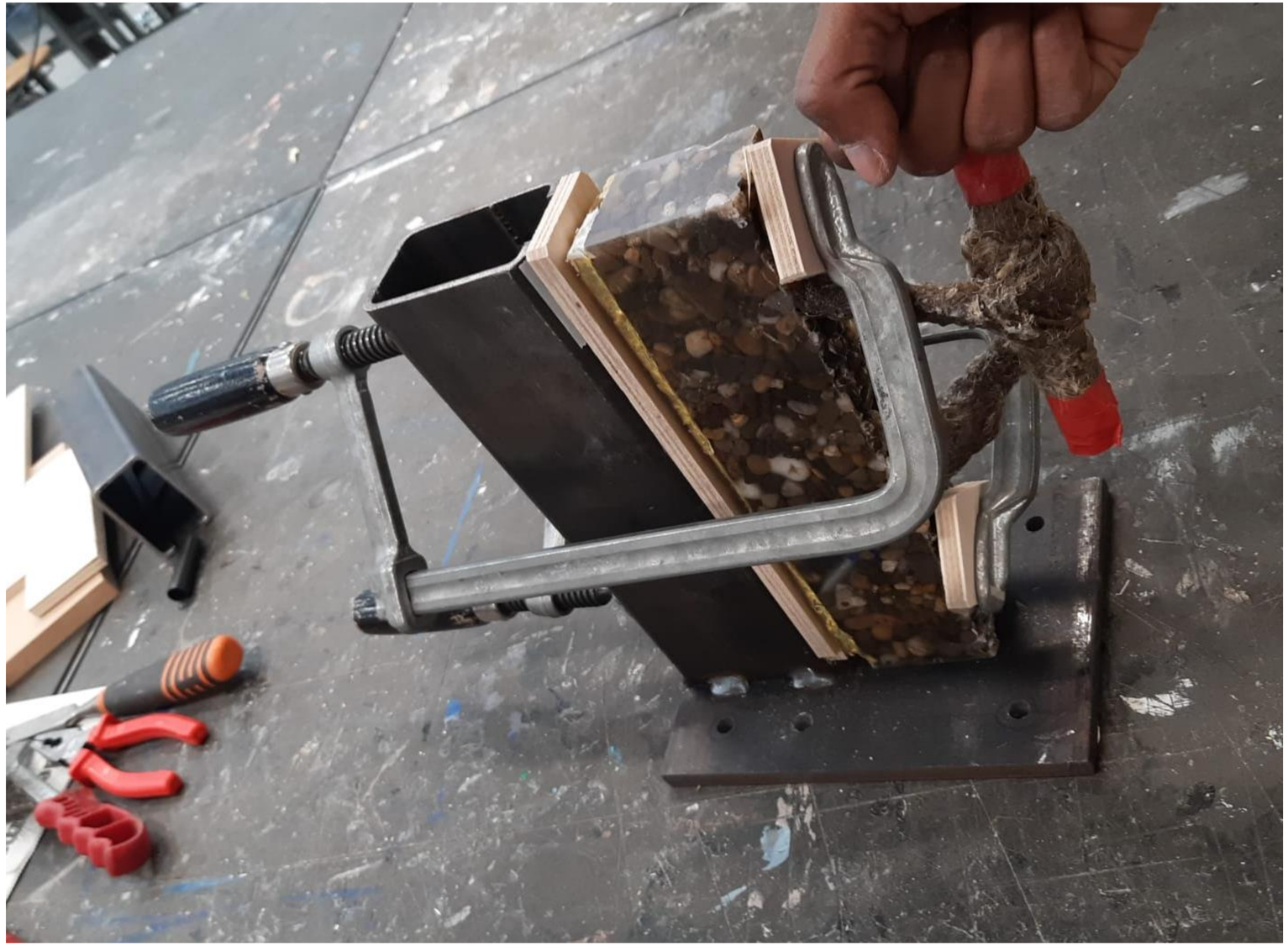
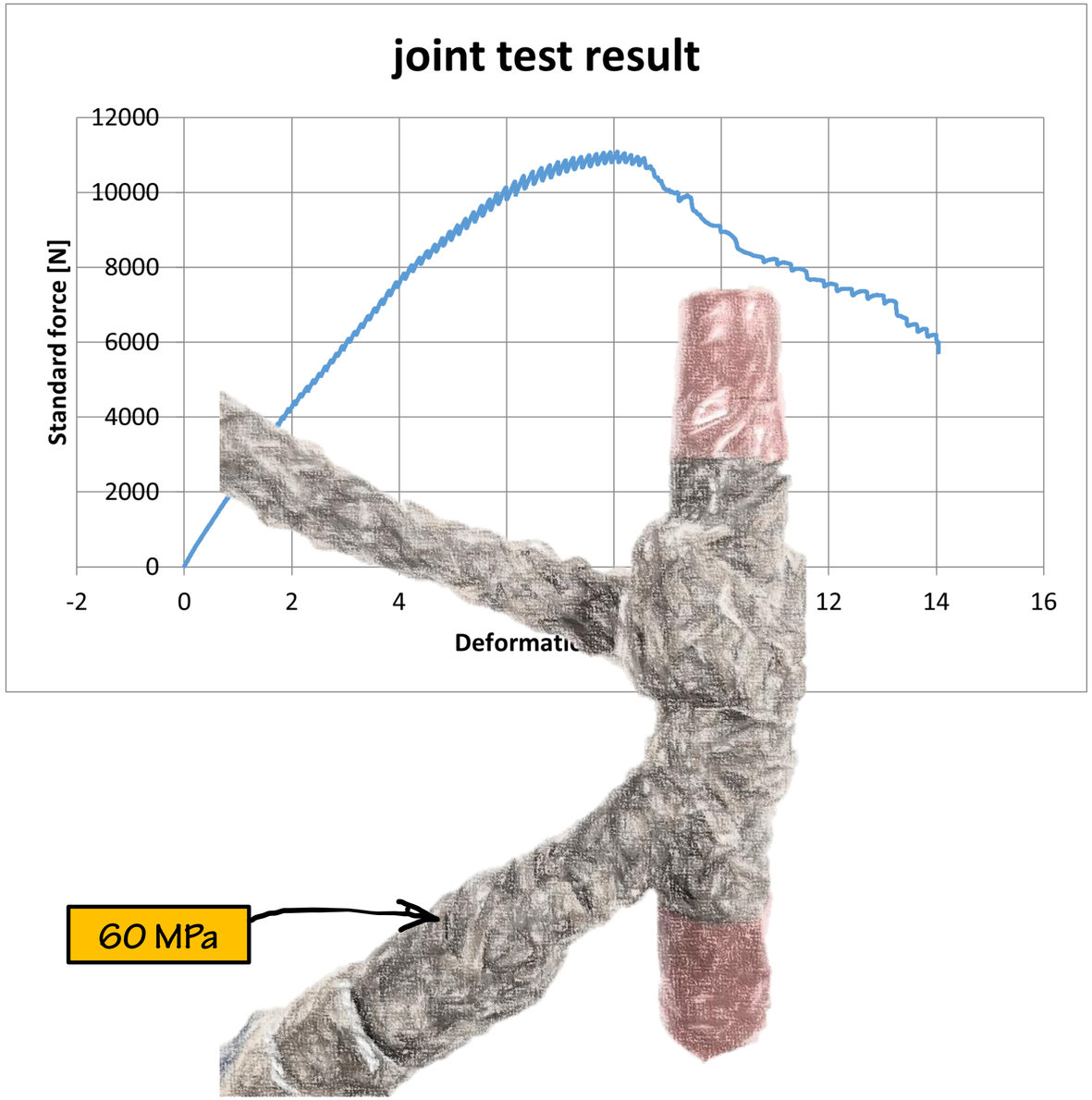




Part B; **Joint Fabrication**



The Joint weakens the system to a factor of 0.8 x strut capacity

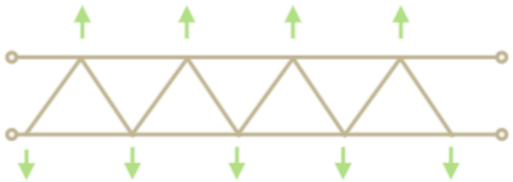
How to Build?

Part B: **Construction**

Step 1: Chord Setup+ tensioning

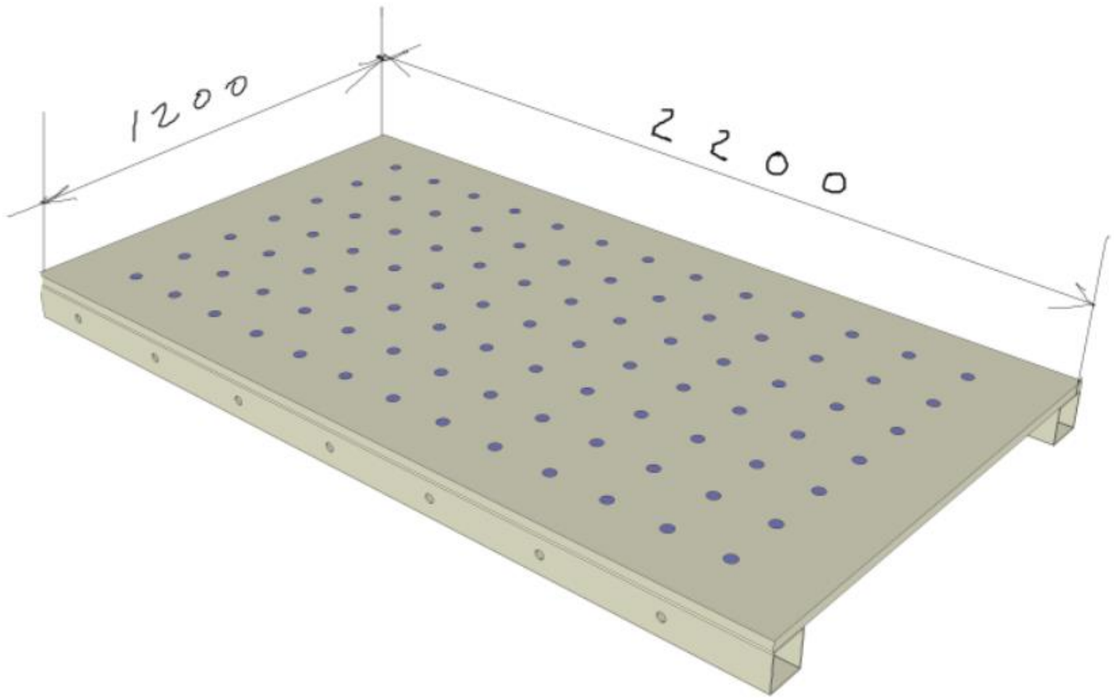
Step 2: Tying of Struts

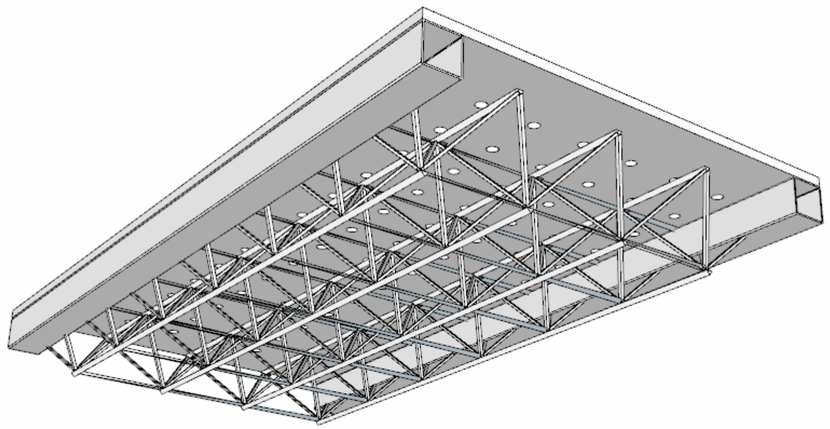
Step 2.5: Resin Application



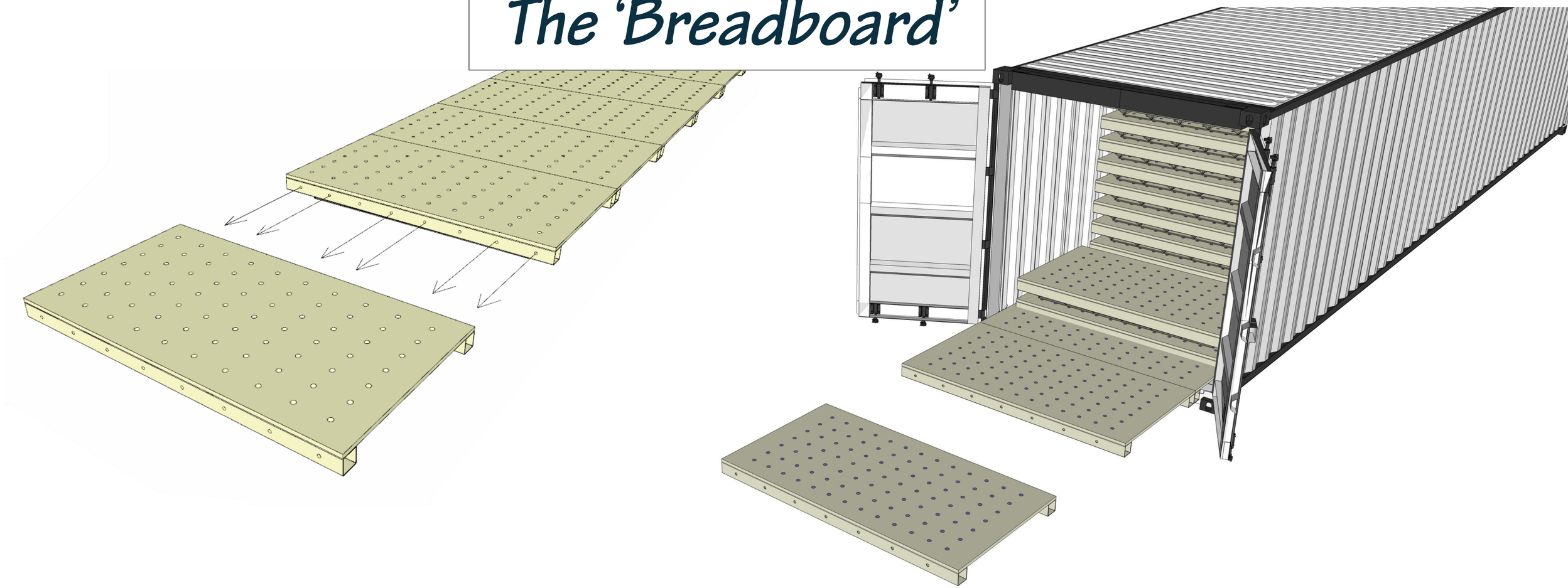
Step 3: Strut tensioning

The 'Breadboard'



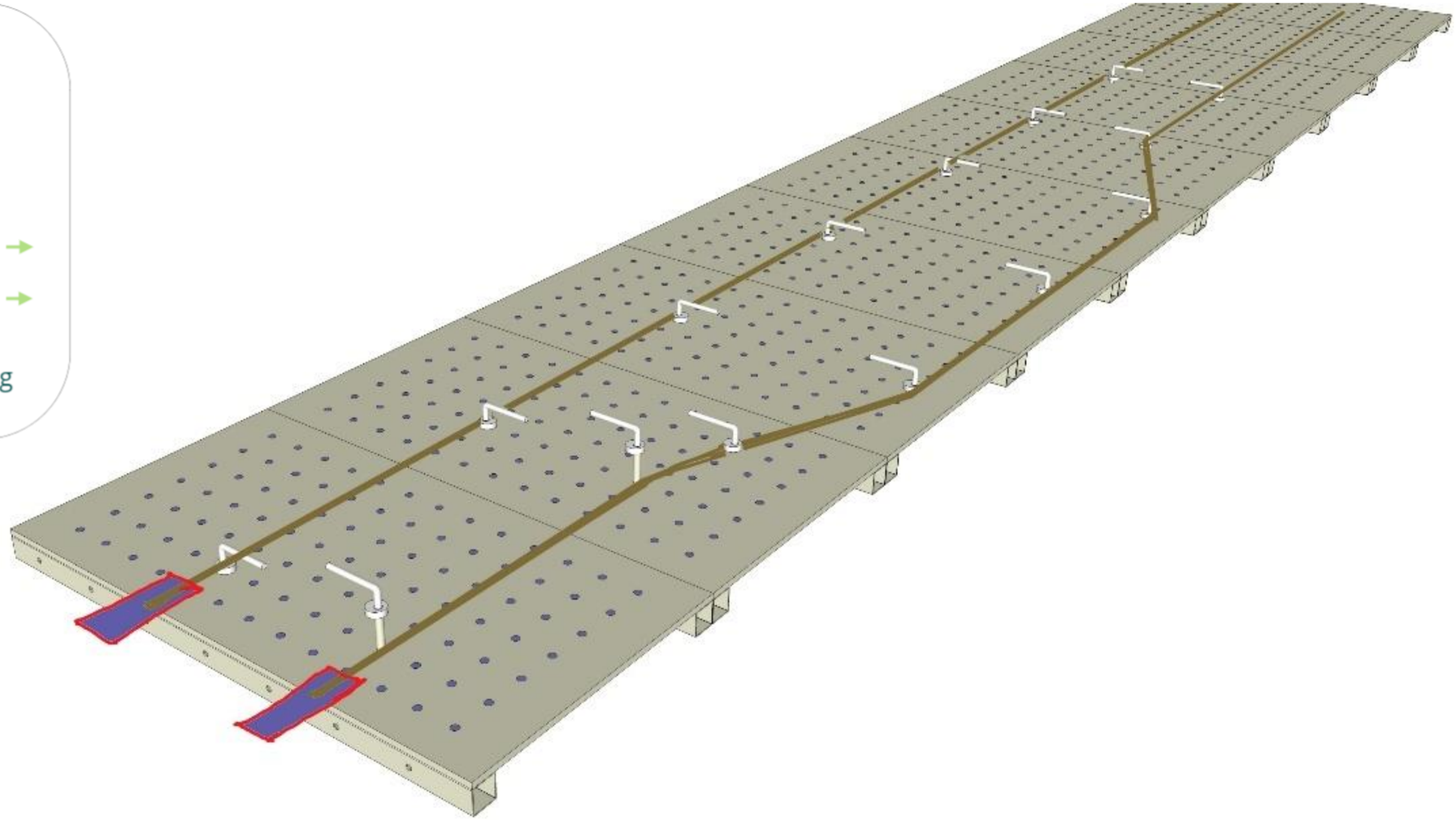


The 'Breadboard'

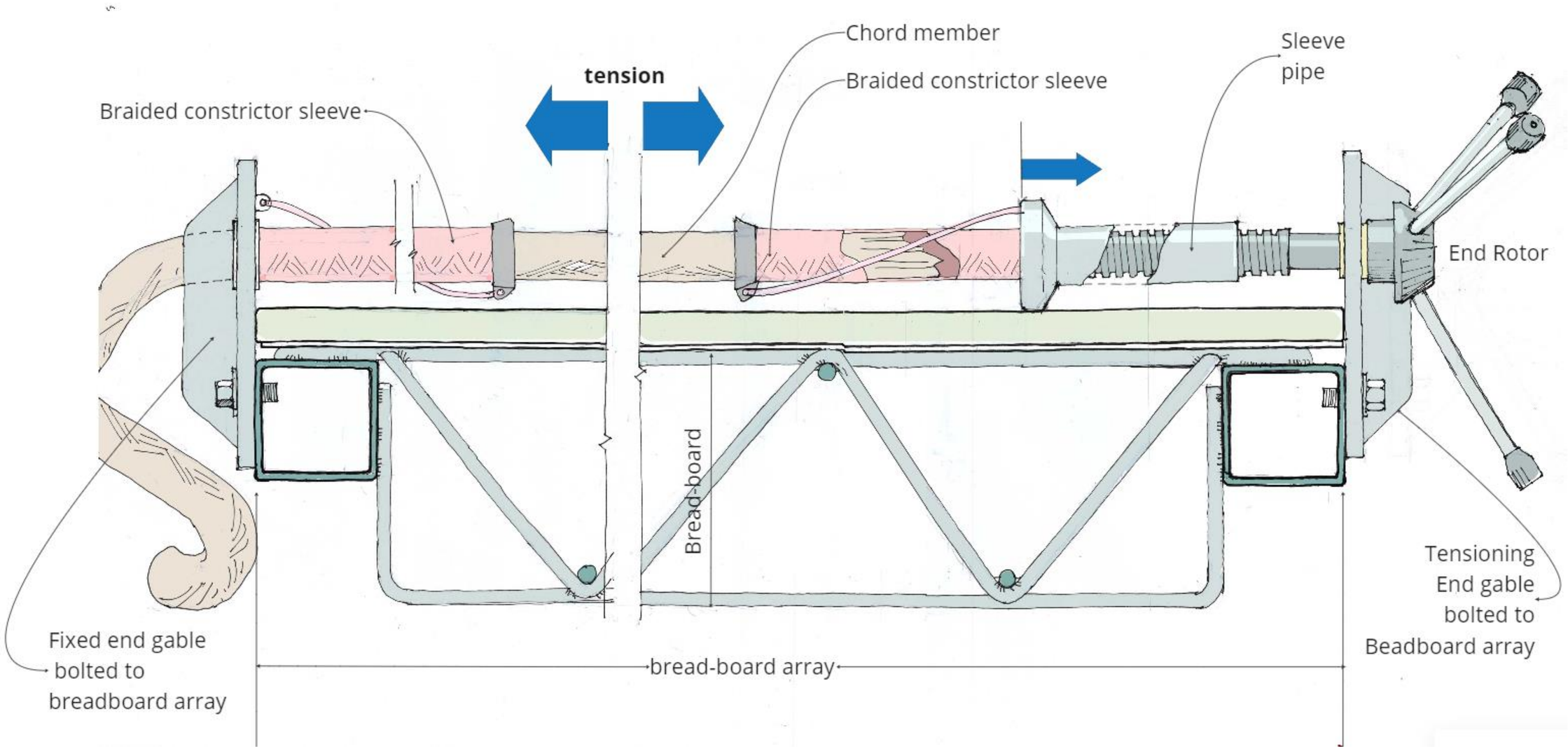


Part B: **Construction**

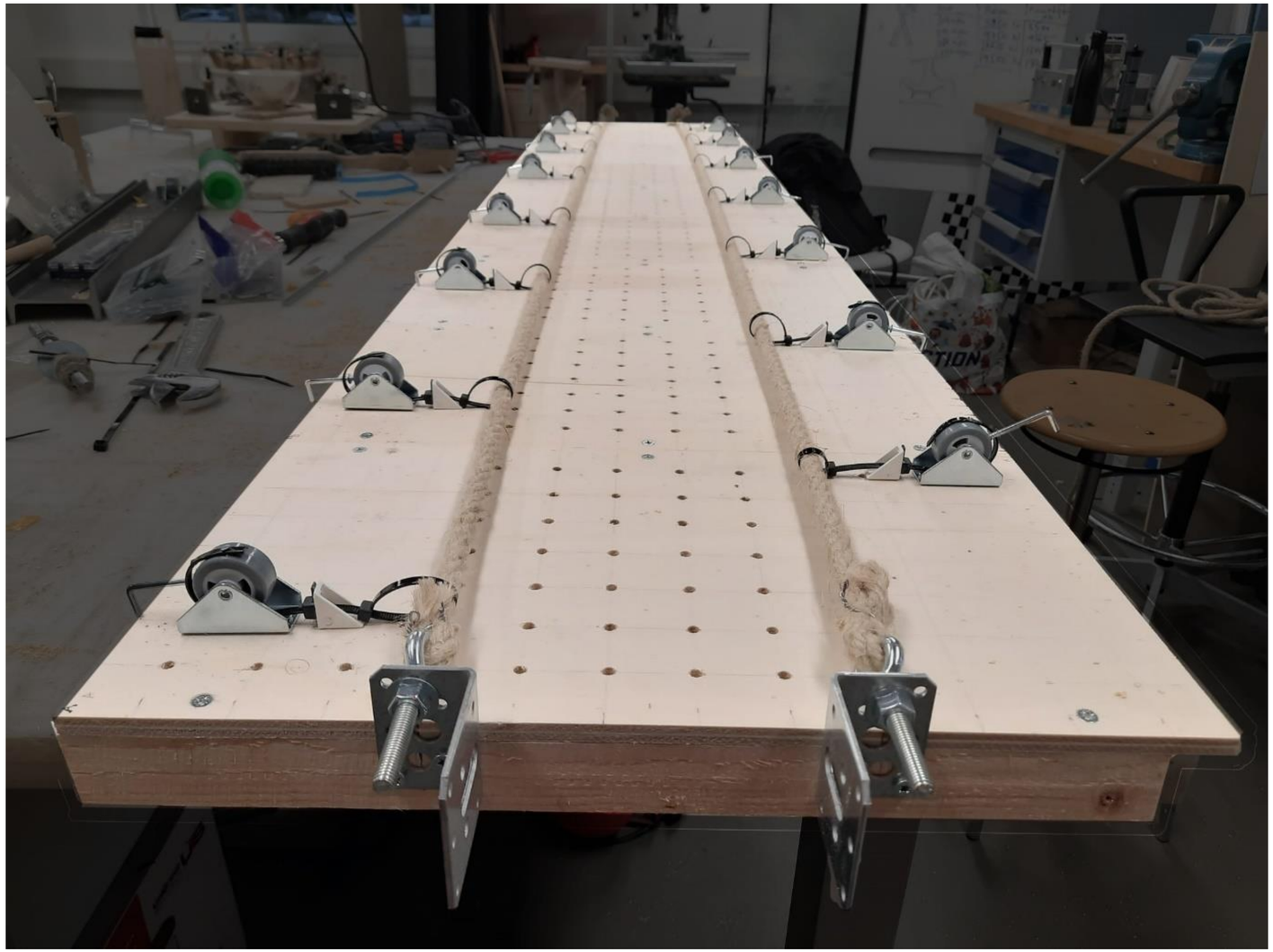
Step 1: Chord Setup+ tensioning



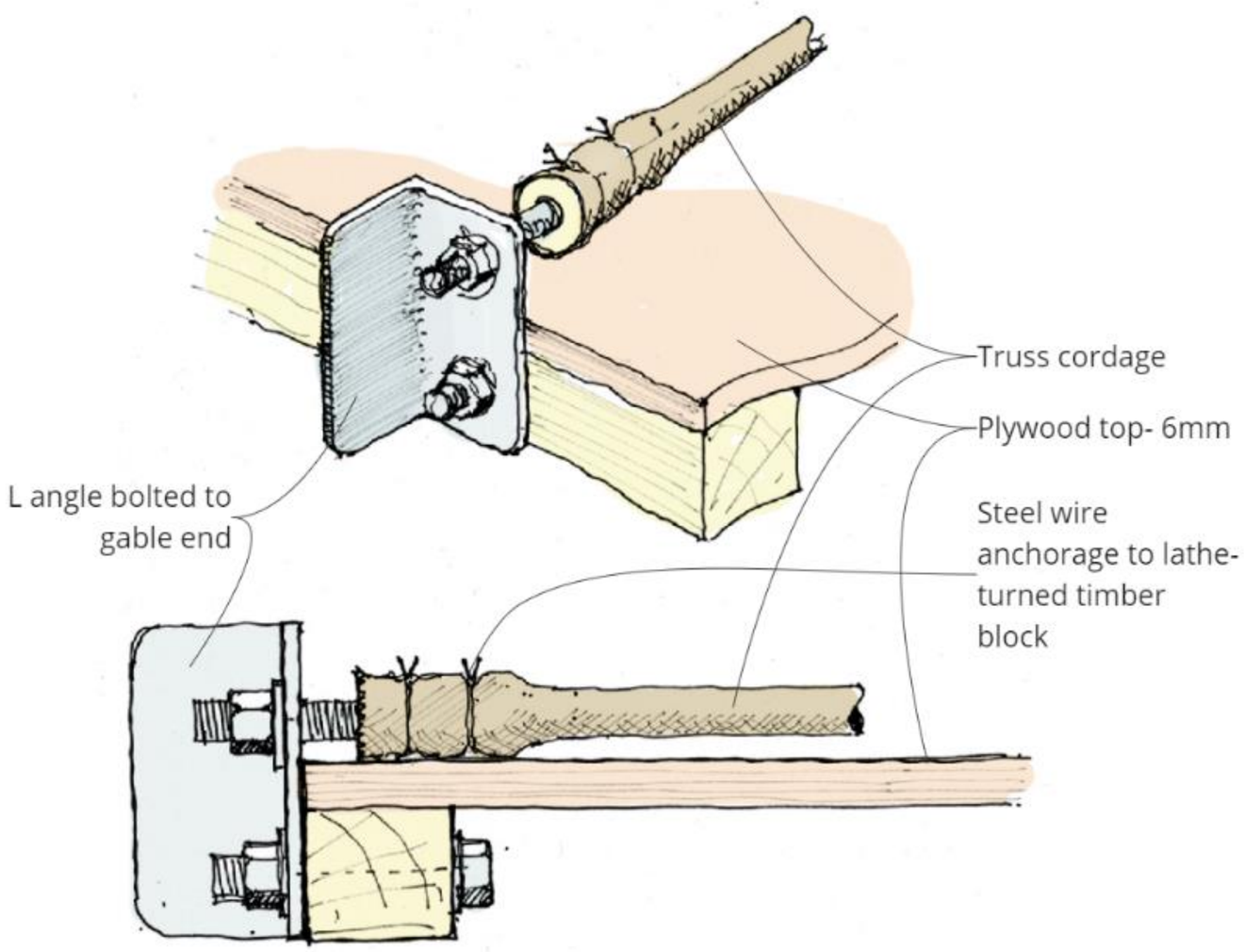
Part B: **Construction**



Part B: **Construction**



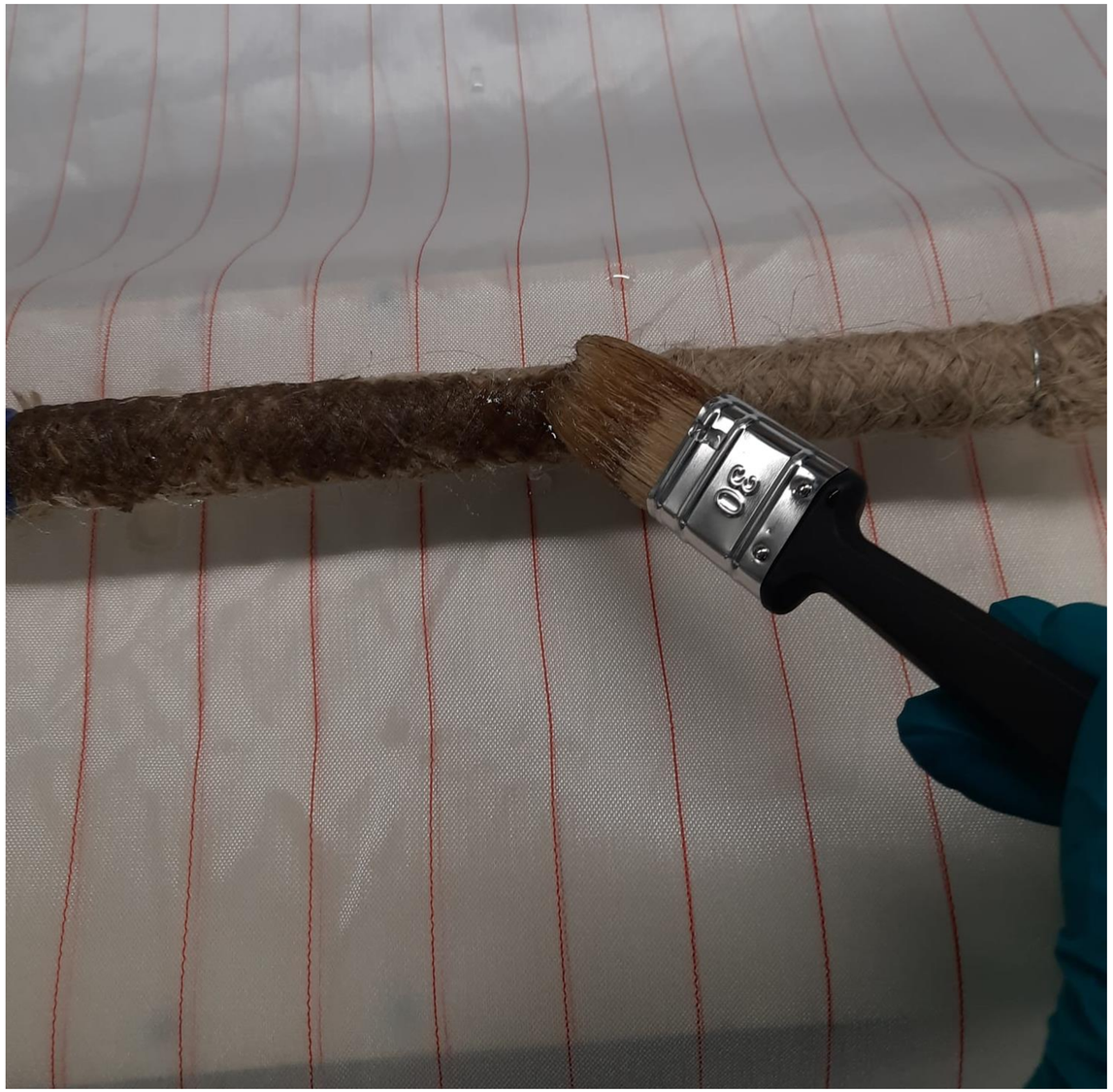
Part B: **Construction**



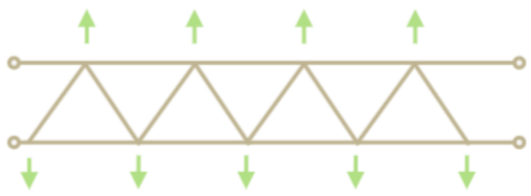
Part B: **Construction**

Part B: **Construction**

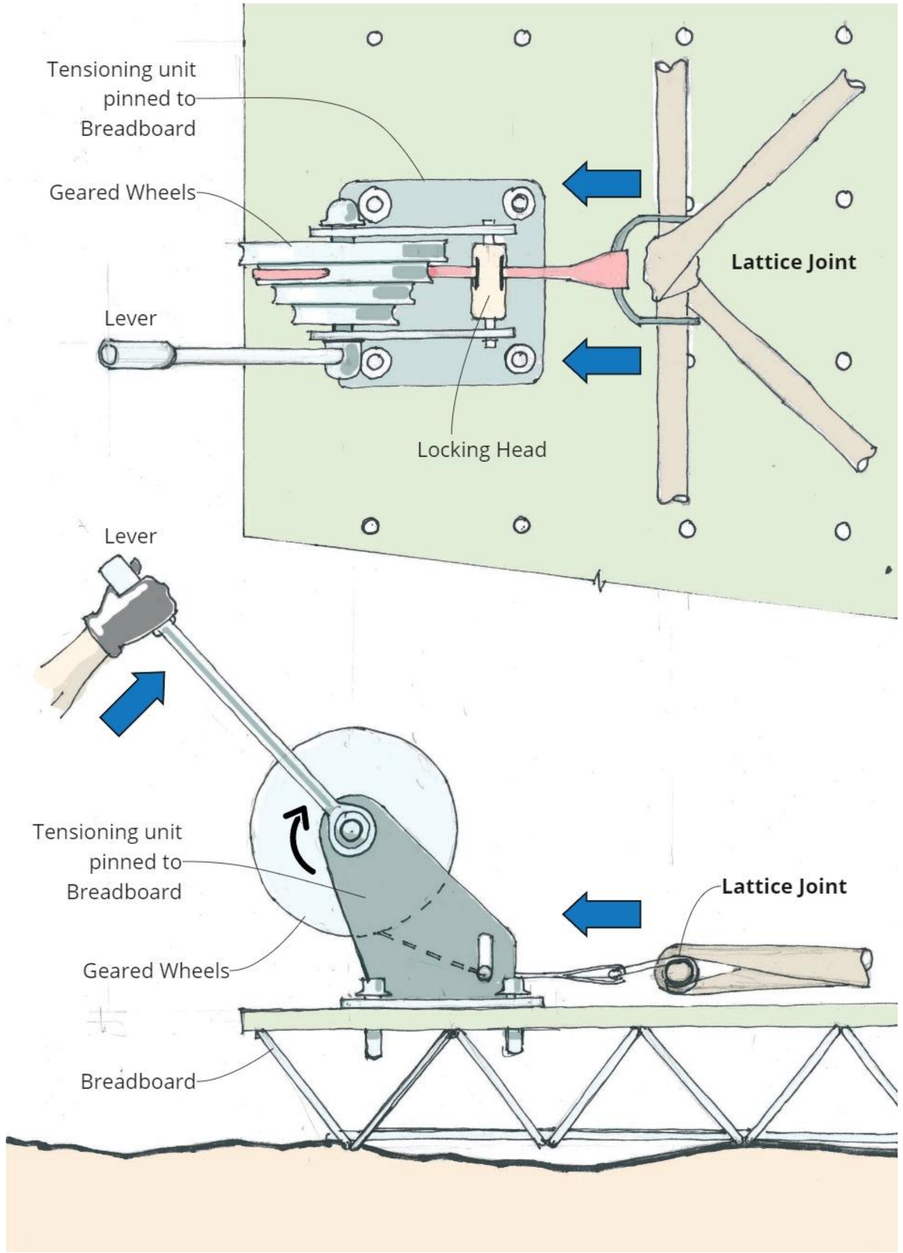
Step 2.5: Resin Application



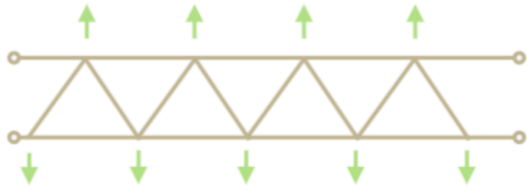
Part B: **Construction**



Step 3: Strut tensioning



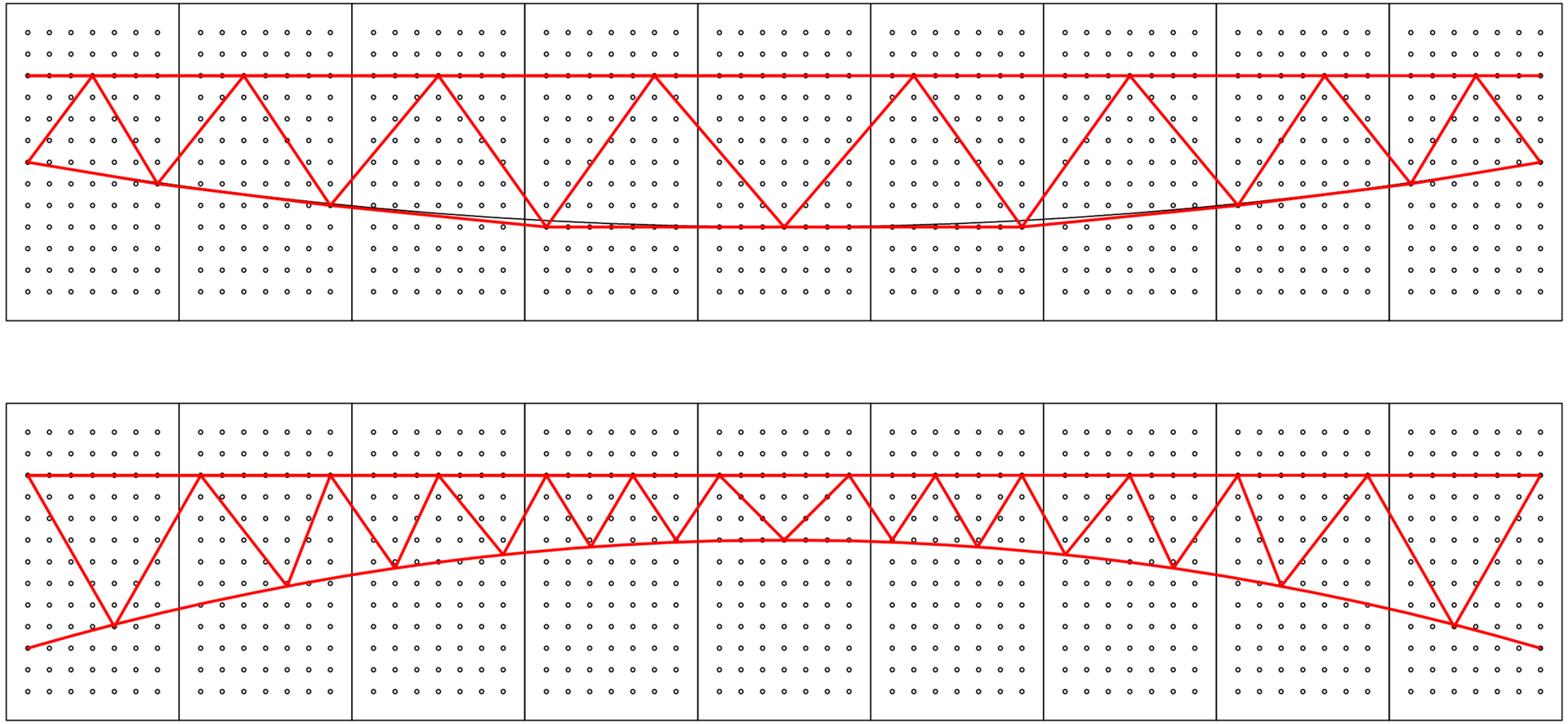
Part B: **Construction**



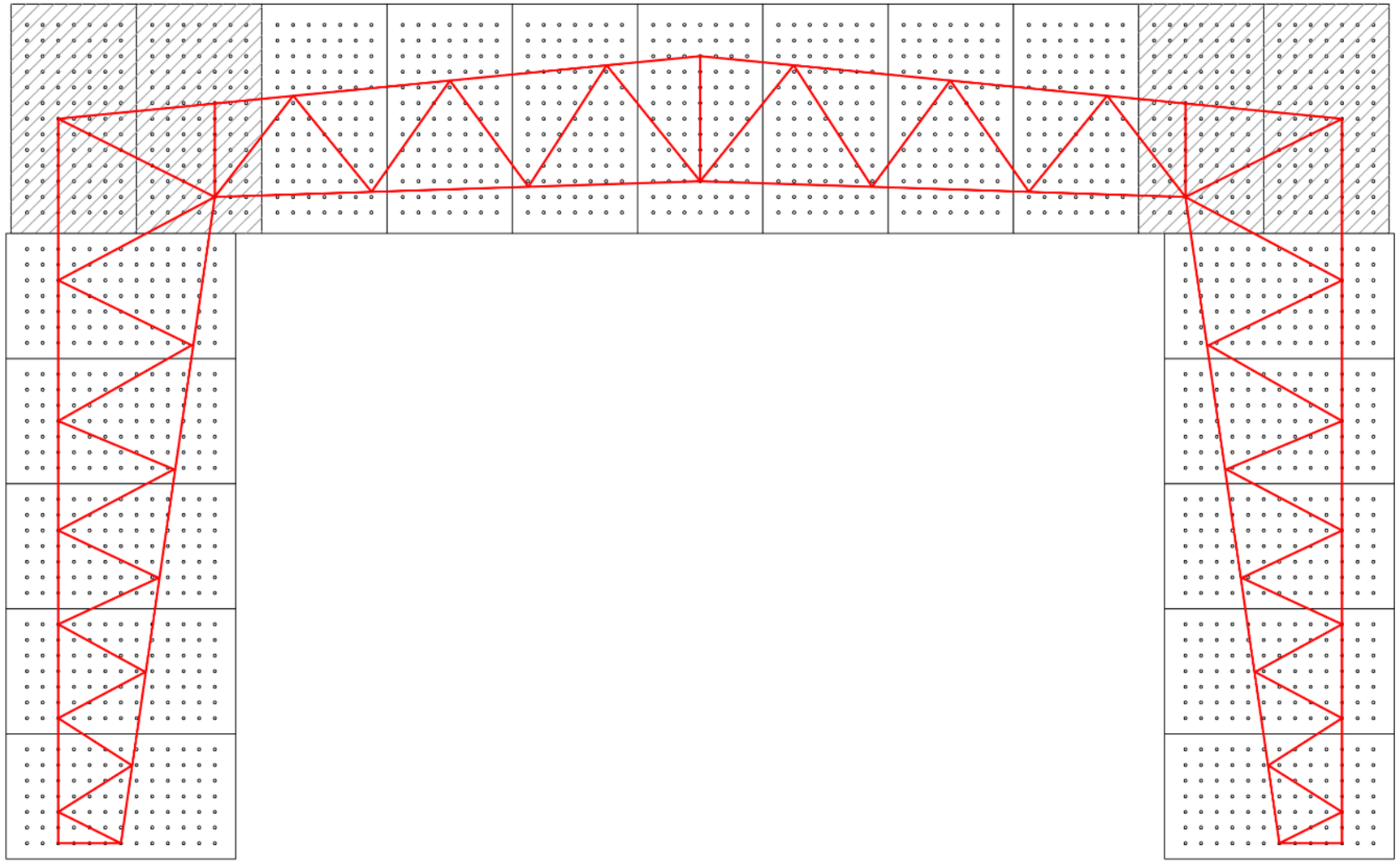
Step 3: Strut tensioning

Voila! (point at model!)

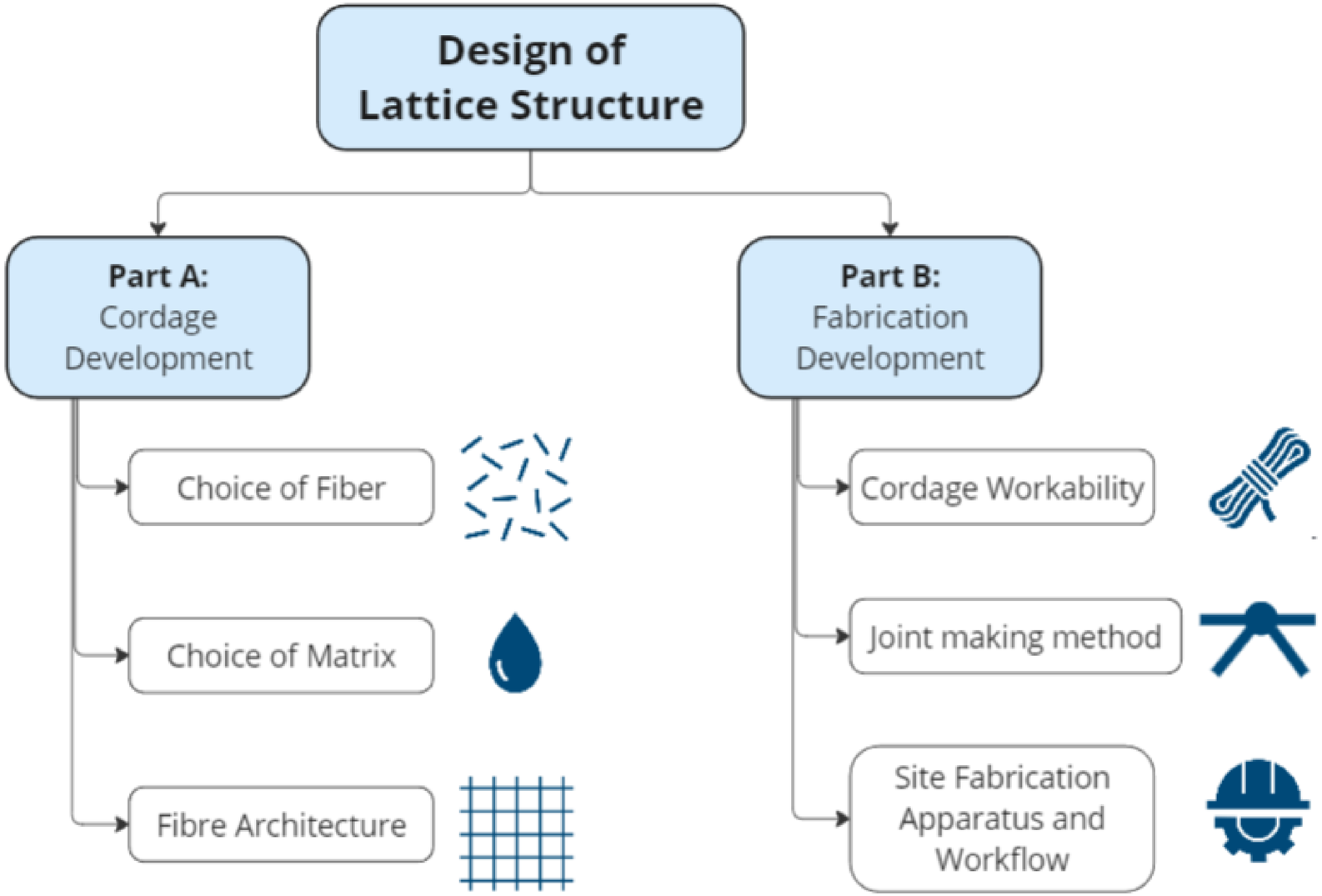
Part B: **Construction**



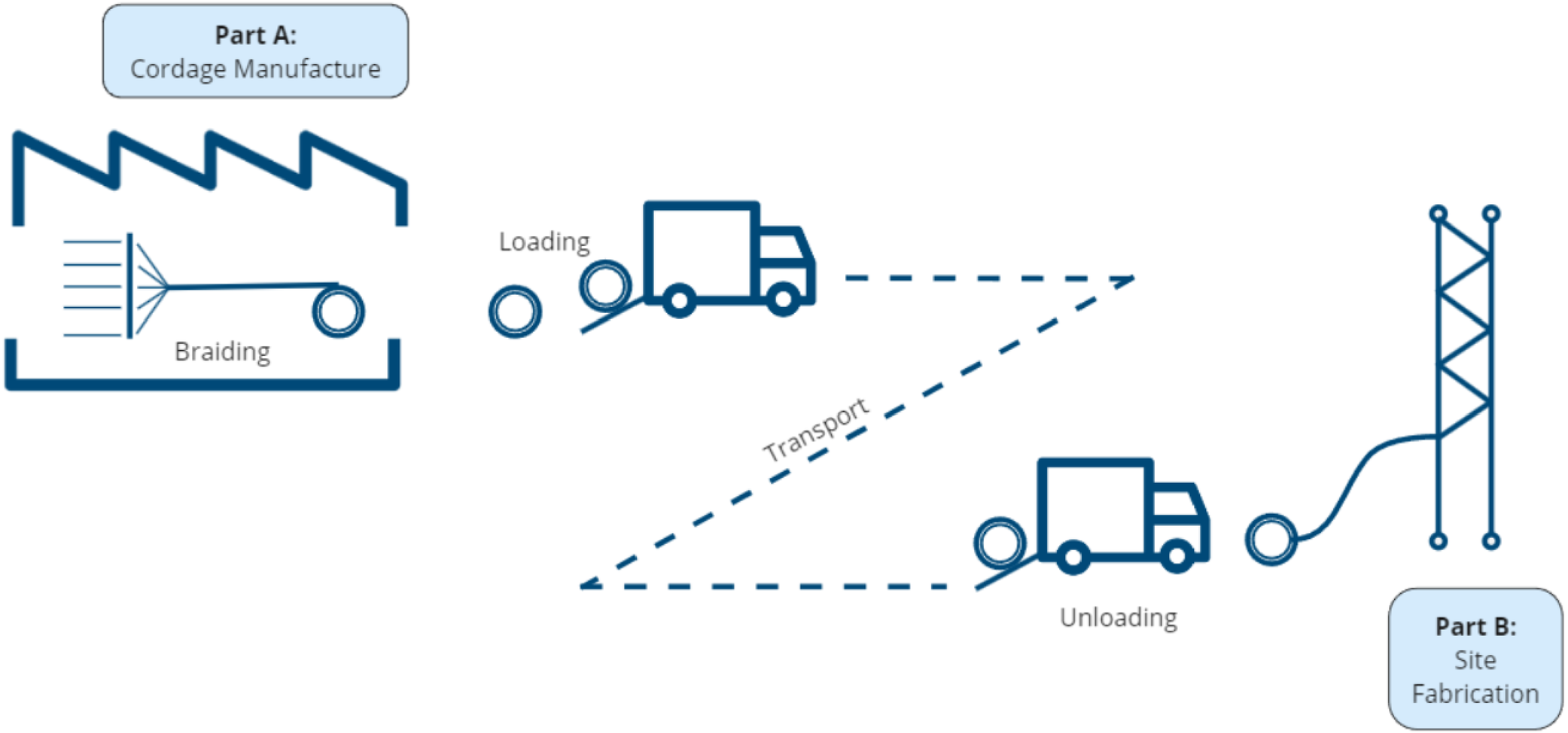
Part B: **Construction. What if....**



What we've got so far…

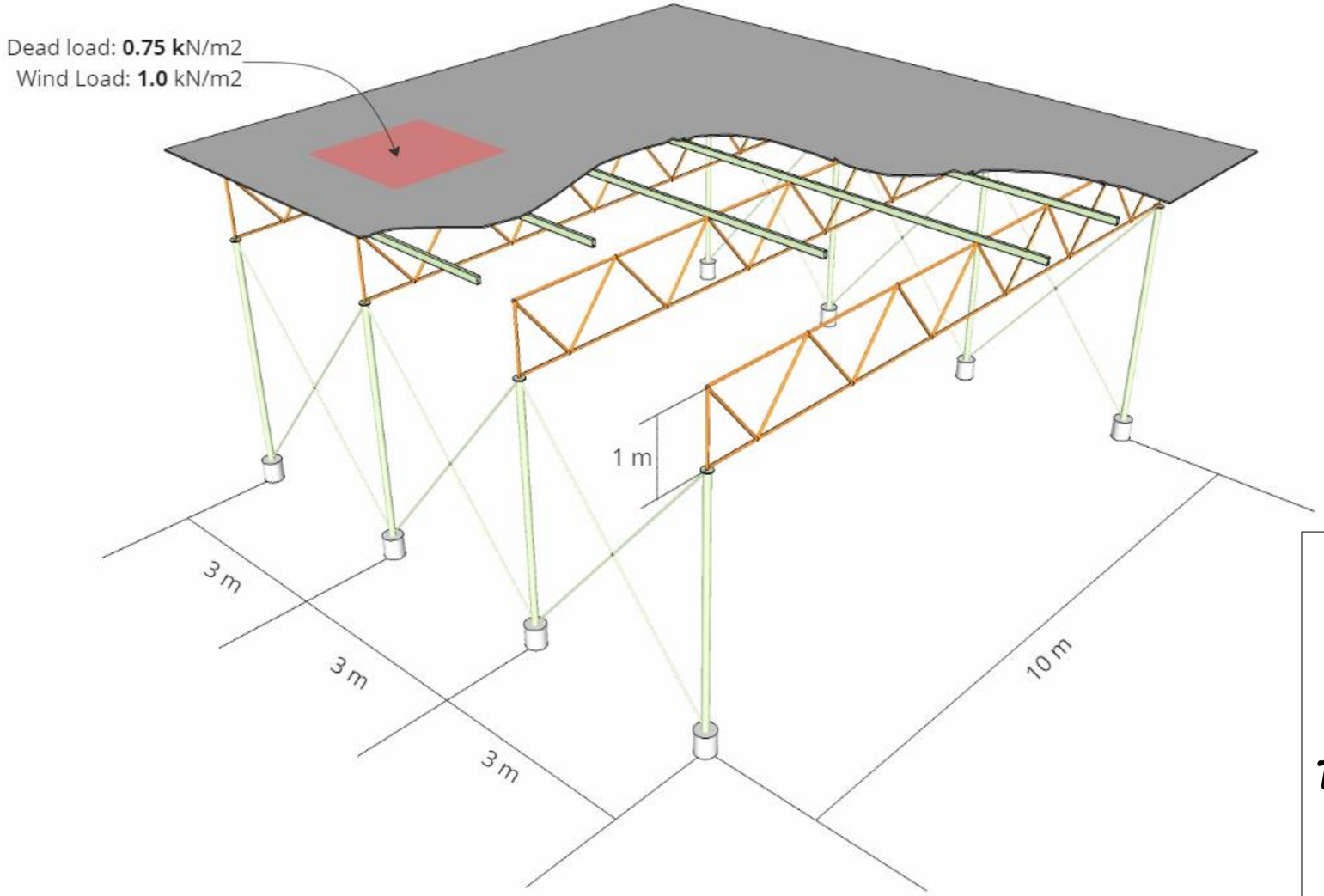

Design of Lattice Structure
Part A: Cordage Development
Part B: Fabrication Development
Choice of Fiber
Choice of Matrix
Fibre Architecture
Cordage Workability
Joint making method
Site Fabrication Apparatus and Workflow

Workflow proposal



How does it compare to the Usual Suspects?

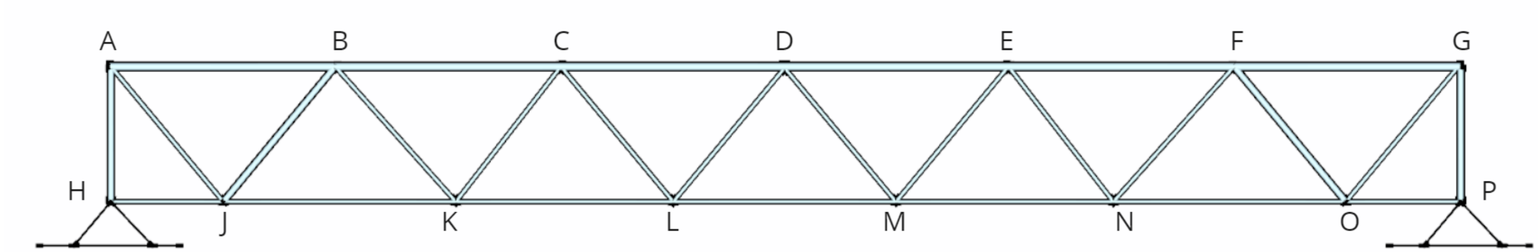
Part C: A Design Problem



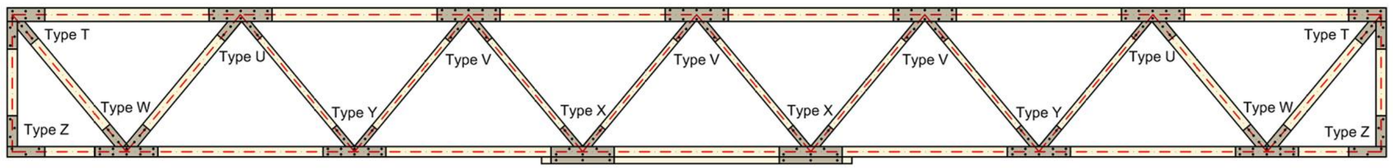
Prepare a design in Steel, Wood, and the novel Flax technology. Then do an Eco-Audit.

Part C: A Design Problem

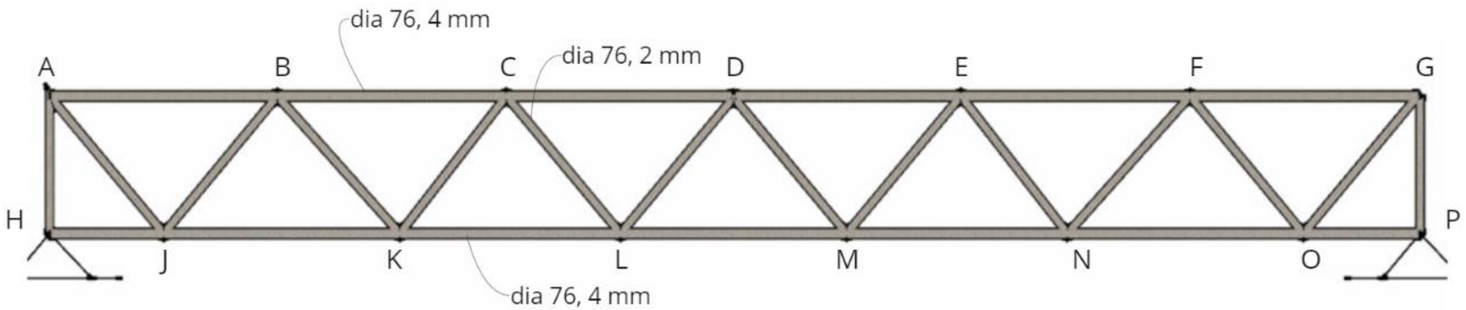
Steel



Wood



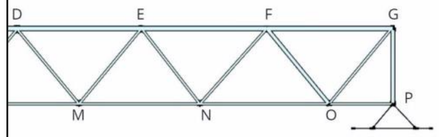
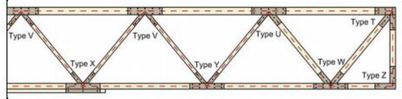
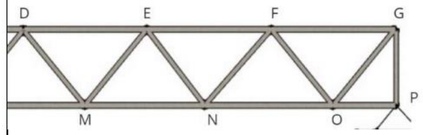
Truss to GO



Part C: A Design Problem

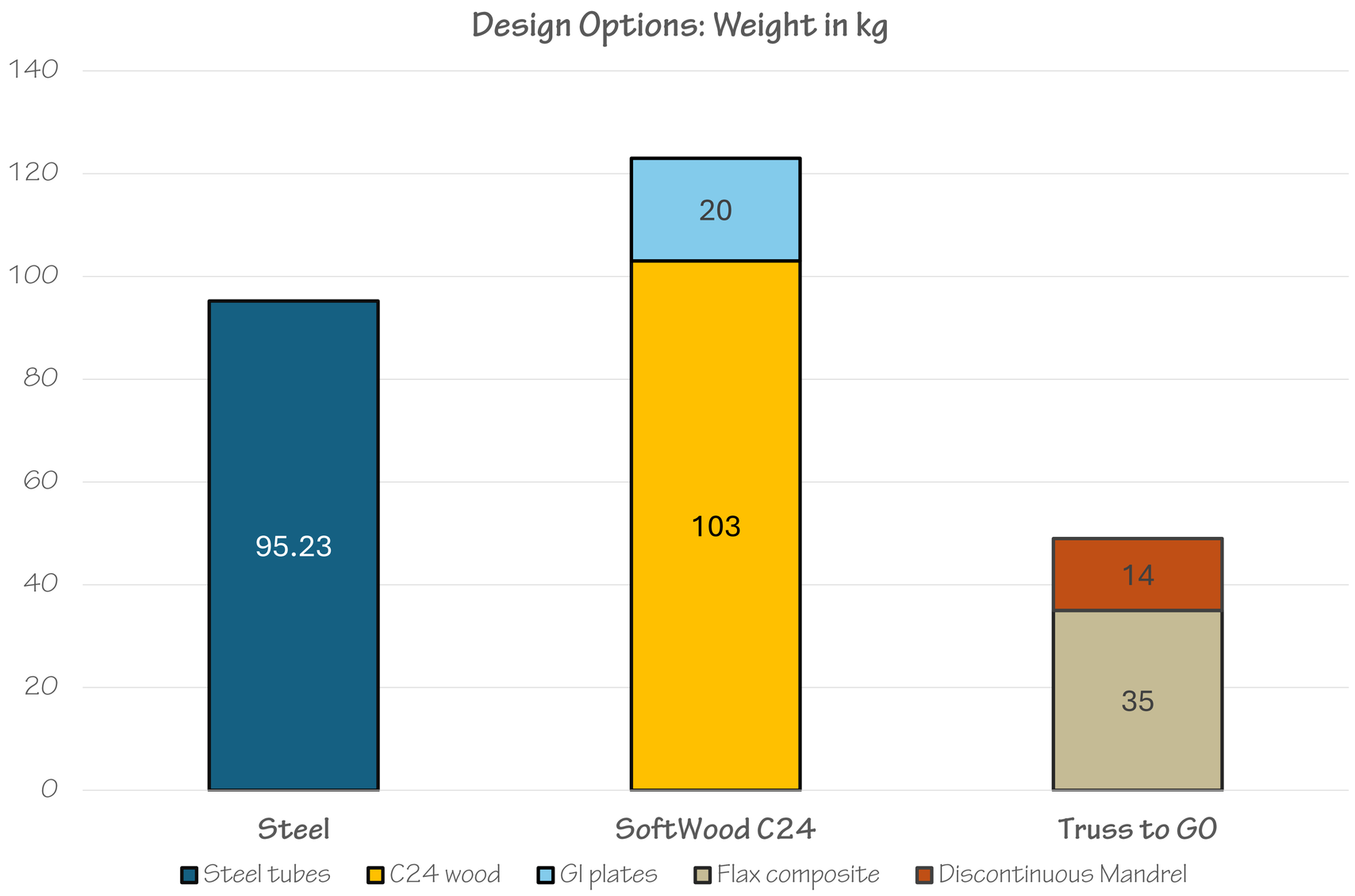
Audit:

- Weight
- Embodied Energy
- Embodied CO2
- Cost?
- Ease of fabrication?

Truss Design	Product Weight (kg)	embodied energy					embodied CO2			
		material/ process	qty	unit	MJ/unit	total (MJ)	qty	unit	kg CO2/unit	total (kg)
 Design in Steel Tubes	95.23	primary: low	95.23	kg	31.7	3018.791	95.23	kg	2.3	219.029
		roll forming	95.23	kg	2.9	276.167	95.23	kg	0.21	19.9983
		welding	672	cm	0.041	27.552	672	cm	0.0035	2.352
		cutting	neglected		0	0	0		0	
		total				*3322.51*				*241.379*
 Design in C24 Softwood	129.98	**Timber sections**								
		primary proc	102.88	kg	11	1131.68	102.88	kg	0.36	37.0368
		coarse mac	20	kg	1.3	26	20	kg	0.1	2
		Connection Plates (50% waste)								
		primary proc	40.77	kg	31.7	1292.409	40.77	kg	2.3	93.771
		roll forming	40.77	kg	2.9	118.233	40.77	kg	0.21	8.5617
		laser cutting	607.8	cm	0.1875	113.9625	607.8	cm	0.015	9.117
		total				*2682.28*				*150.487*
 Design in Truss to GO	49.96	**cordage (flax)**								
		primary proc	8.87	kg	2.75*	*24.3925*	8.87	kg	0.46	4.0802
		cordage (epoxy)								
		primary proc	26.6	kg	120	3192	26.6	kg	5.9	156.94
		cordage (manufacture)								
		production	49.9	kg	**unknown**		49.9	kg	**unknown**	
		timber blocks								
		primary proc	14.5	kg	11	159.5	14.5	kg	0.36	5.22
		fine machin	14.5	kg	10	145	14.5	kg	0.65	9.425
		total				*3520.89*				*175.665*

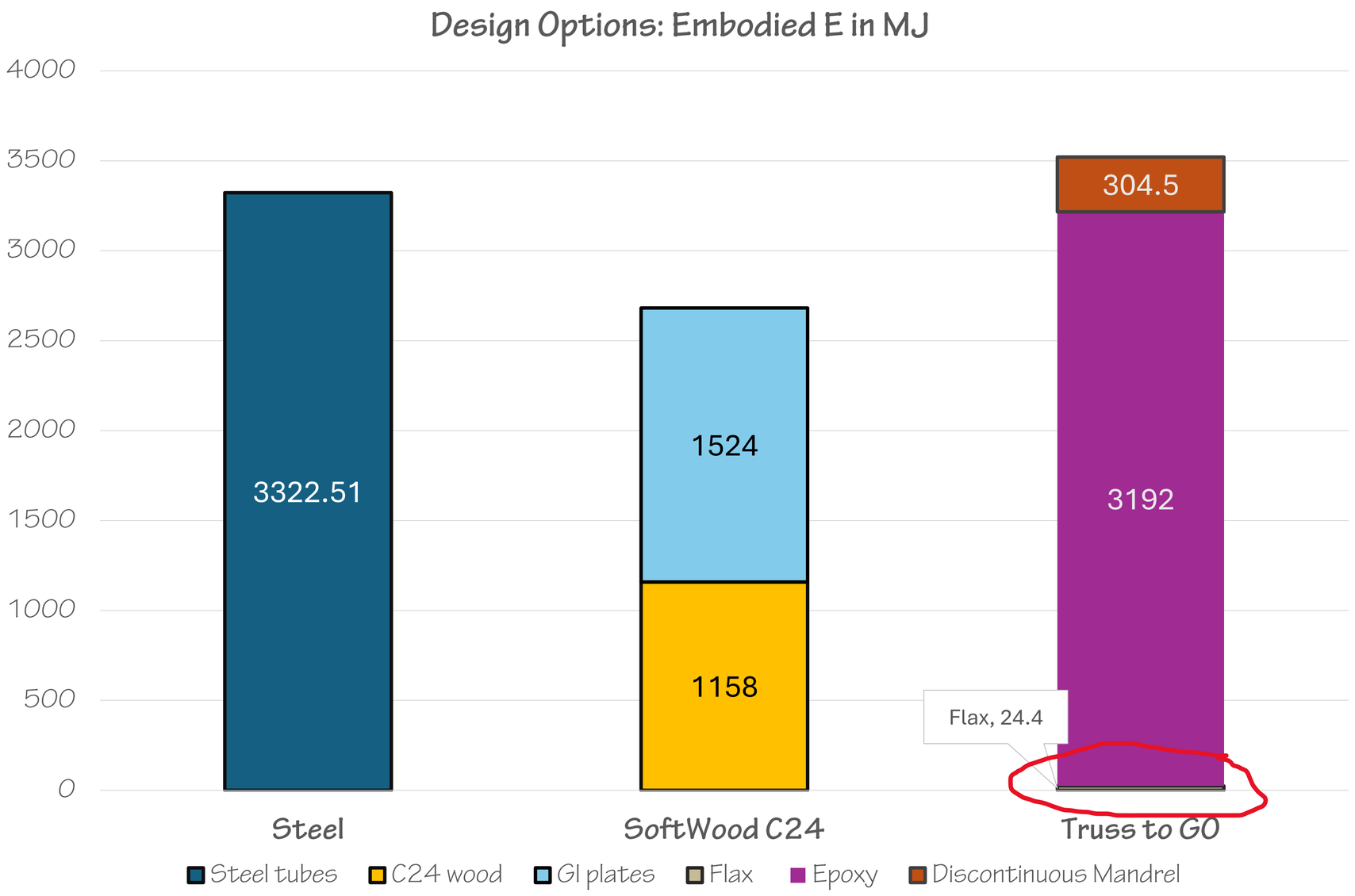
Part C: A Design Problem

Weight



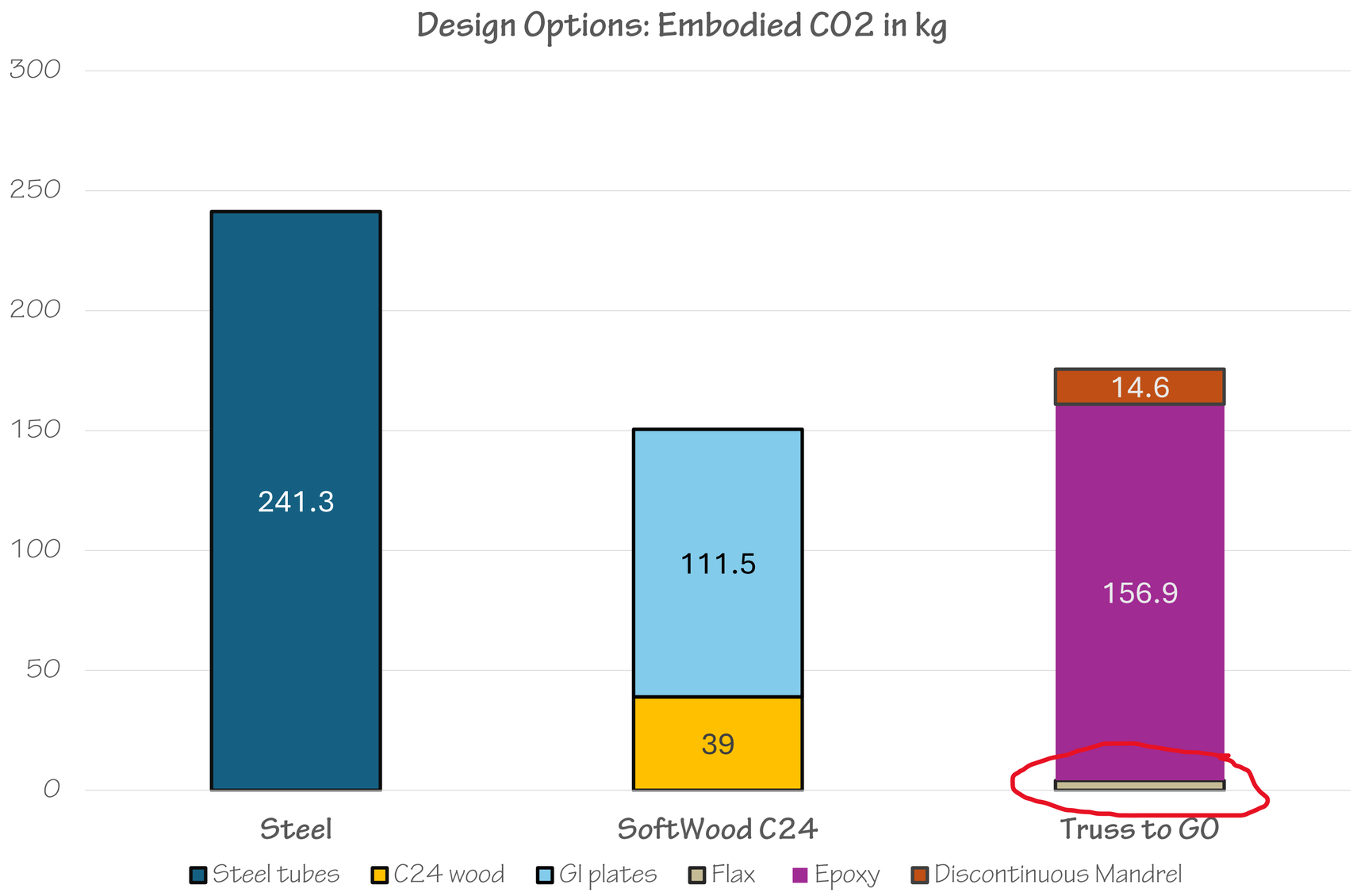
Part C: A Design Problem

Embodied E



Part C: A Design Problem

Embodied CO2



Ease of constructability

Conclusions and Further Research

Can the Chemistry be Improved?

- We don't have the right resin (polymer)
- The right resin is important to get right.
- Cure Mechanics?

Buckling Capacity of Strut to be Checked

- E Modulus of composite is lower (3-30MPa)
- Makes It more vulnerable.

Effects of Workmanship?

- Is the Whole as good as the sum of its Parts?
- Partial safety factor?

Effects of Creep, Fatigue and Weathering to be checked

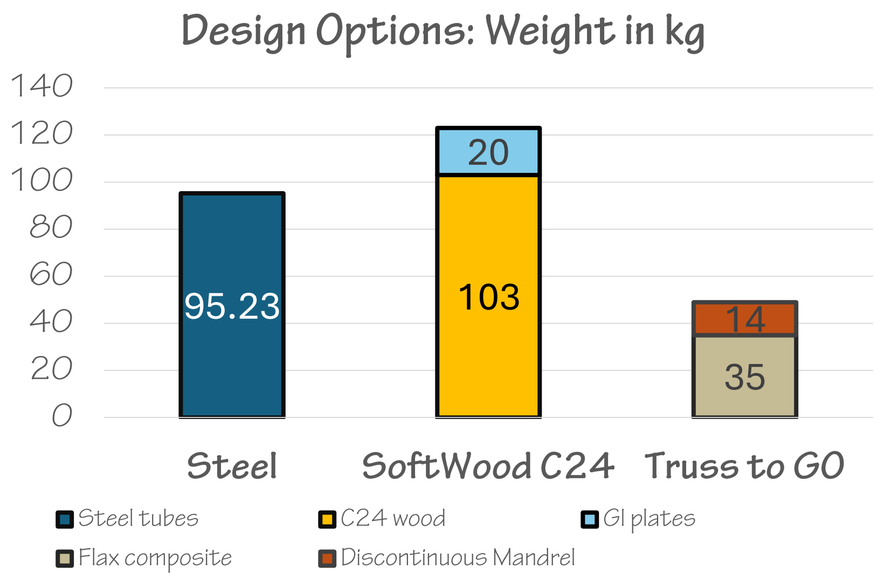
Building construction Assembly??

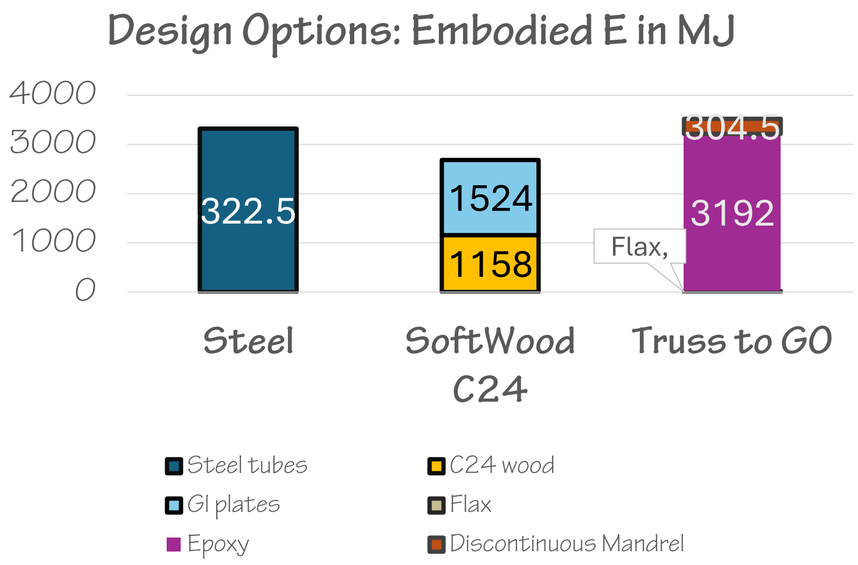
- How to connect it to sub-structure and super-structure?

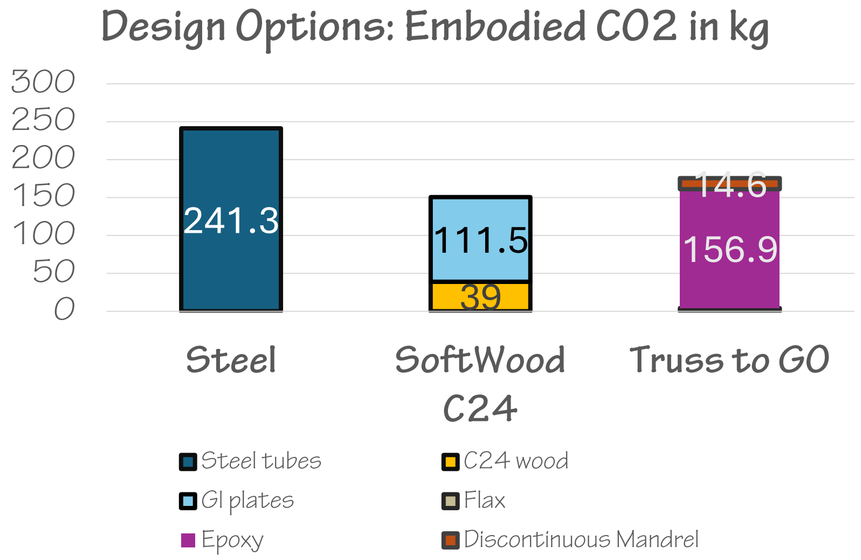
Research Question:

"Can a Novel **Bio-Based** FRP technology be designed and developed for the **In- Situ Construction** of **Lattice Structures** for Building Industry applicati

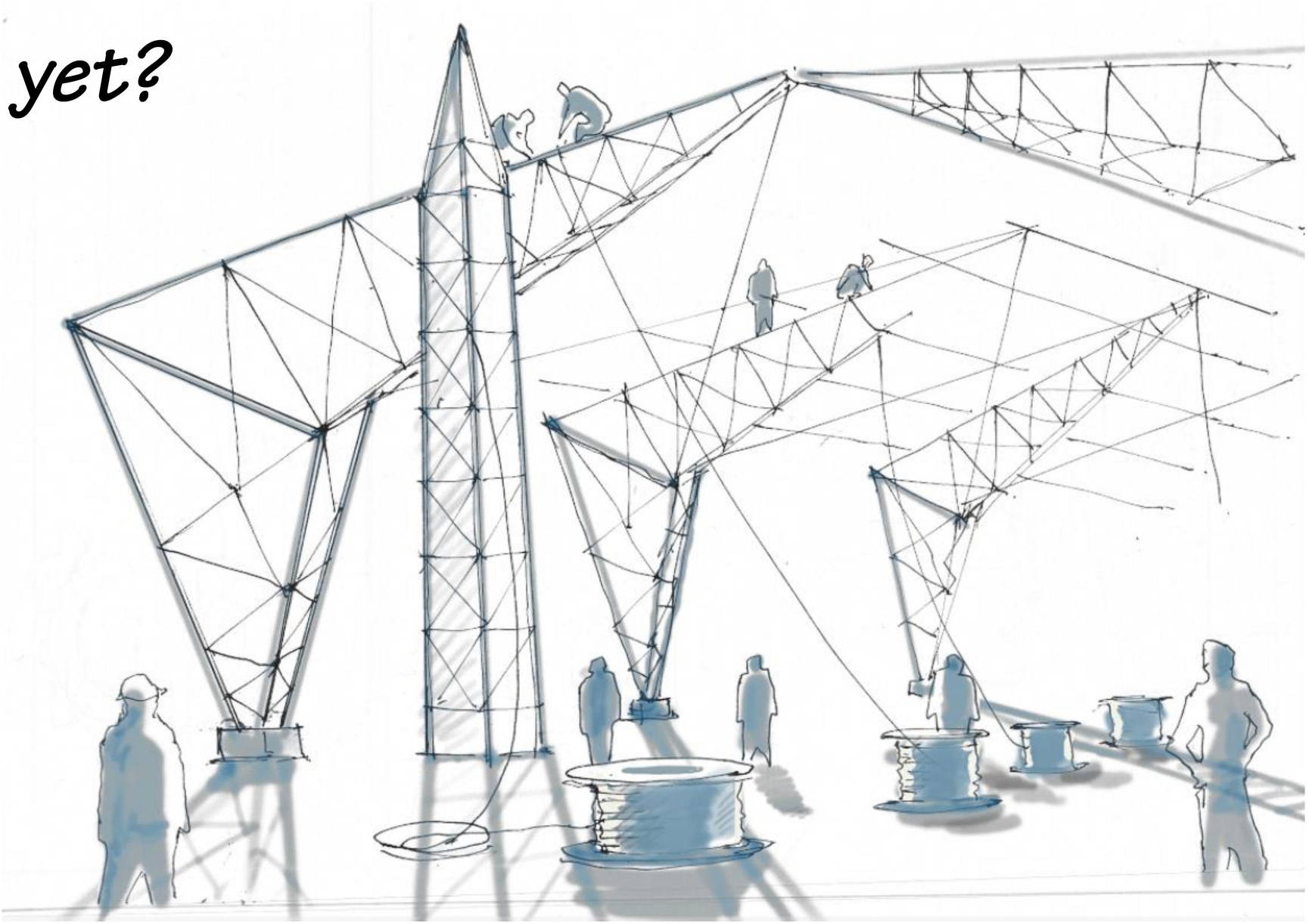
YES!


Design Options: Weight in kg
140
120
100
80
60
40
20
0
95.23
20
103
14
35
Steel
SoftWood C24
Truss to GO
Steel tubes
C24 wood
GI plates
Flax composite
Discontinuous Mandrel


Design Options: Embodied E in MJ
4000
3000
2000
1000
0
322.5
1524
1158
304.5
3192
Flax,
Steel
SoftWood C24
Truss to GO
Steel tubes
C24 wood
GI plates
Flax
Epoxy
Discontinuous Mandrel


Design Options: Embodied CO2 in kg
300
250
200
150
100
50
0
241.3
111.5
39
14.6
156.9
Steel
SoftWood C24
Truss to GO
Steel tubes
C24 wood
GI plates
Flax
Epoxy
Discontinuous Mandrel

Are we here yet?



WHAT'S NEXT?

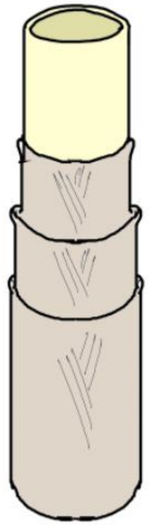
QUESTIONS?

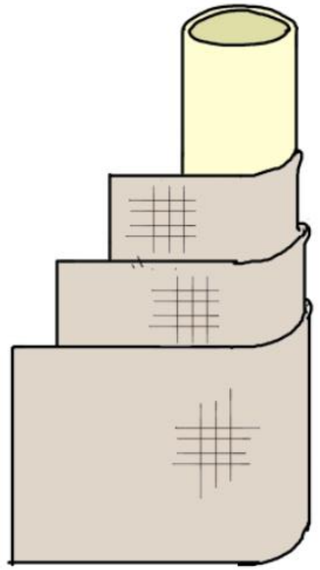
Appendix

Experimental Phase!

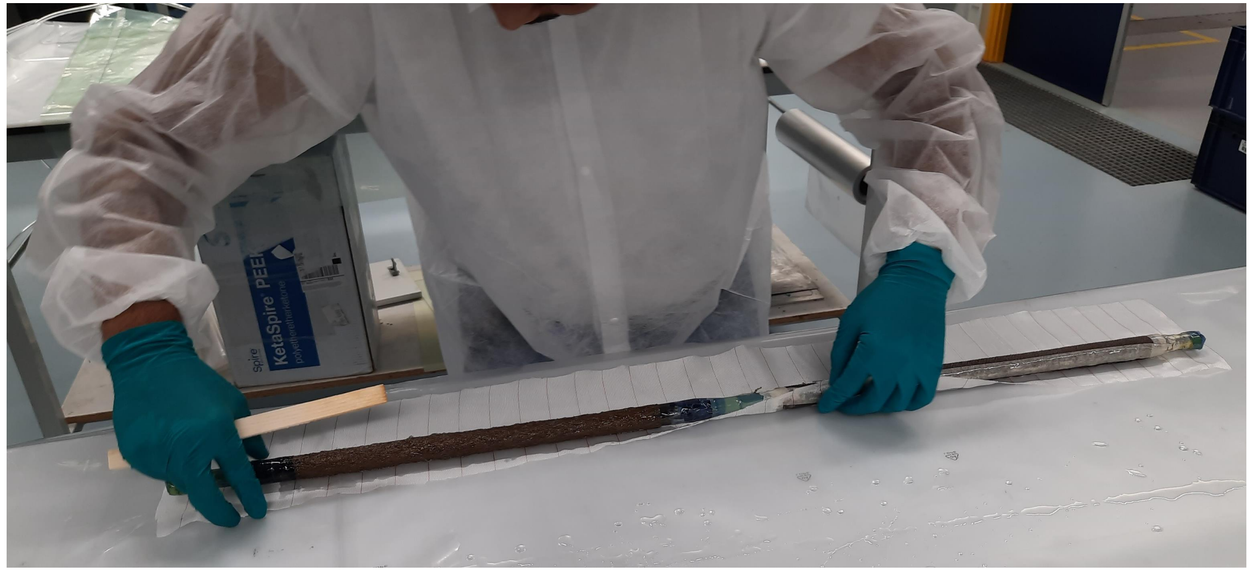
1. Are we making proper braids?
2. What is the fuss with the fiber orientation?

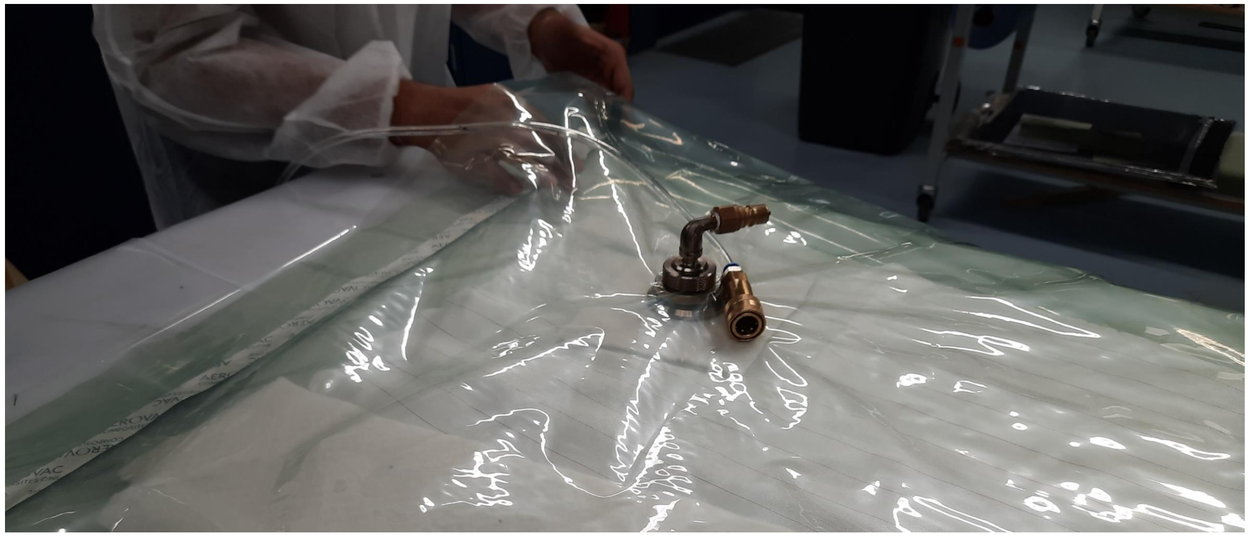
Part A.1: **3-Layer Braided vs. Woven**





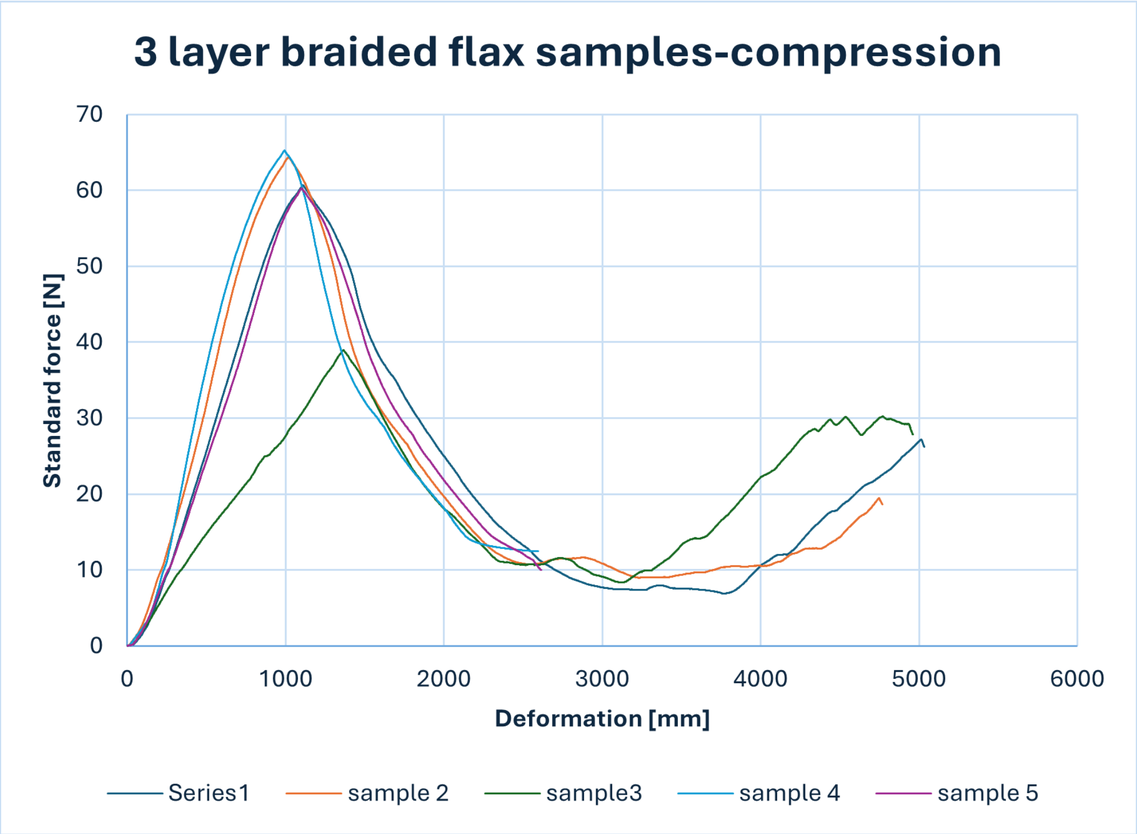
Part A.1: 3-Layer Braided vs. Woven

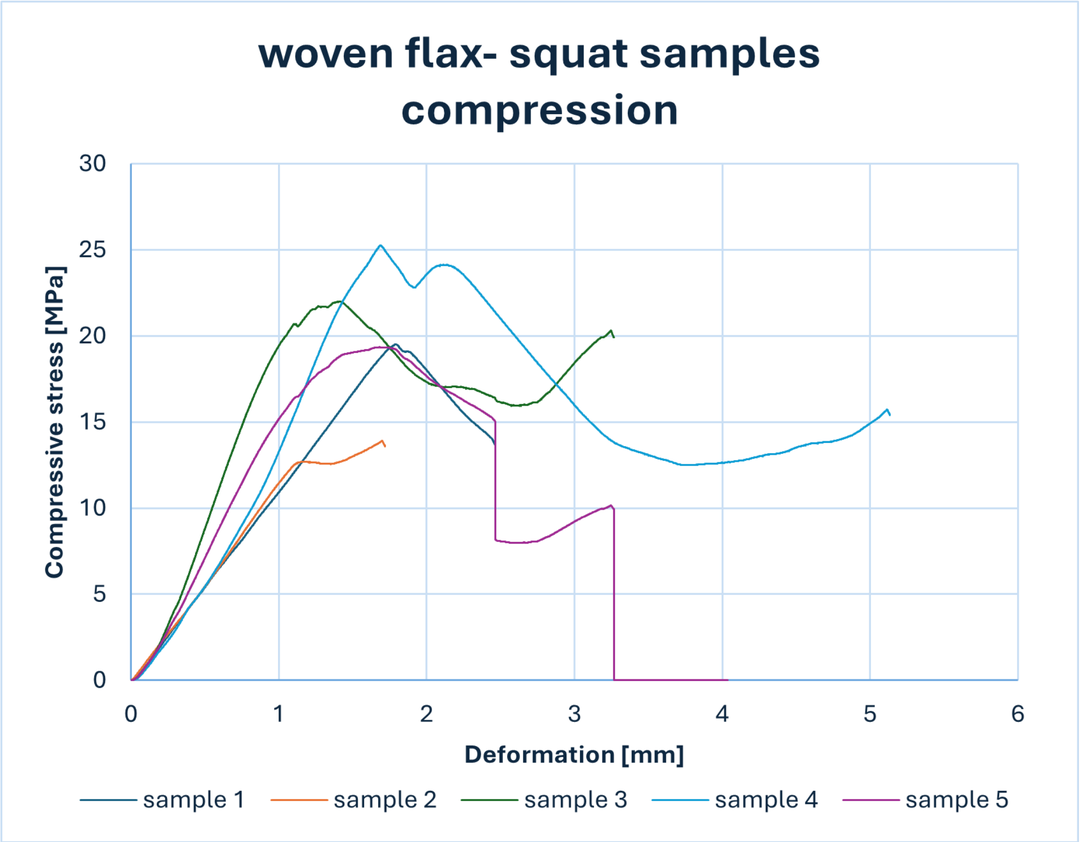




Part A.1: 3-Layer Braided vs. Woven

Part A.1: 3-Layer Braided vs. Woven





FVF: 44.92%

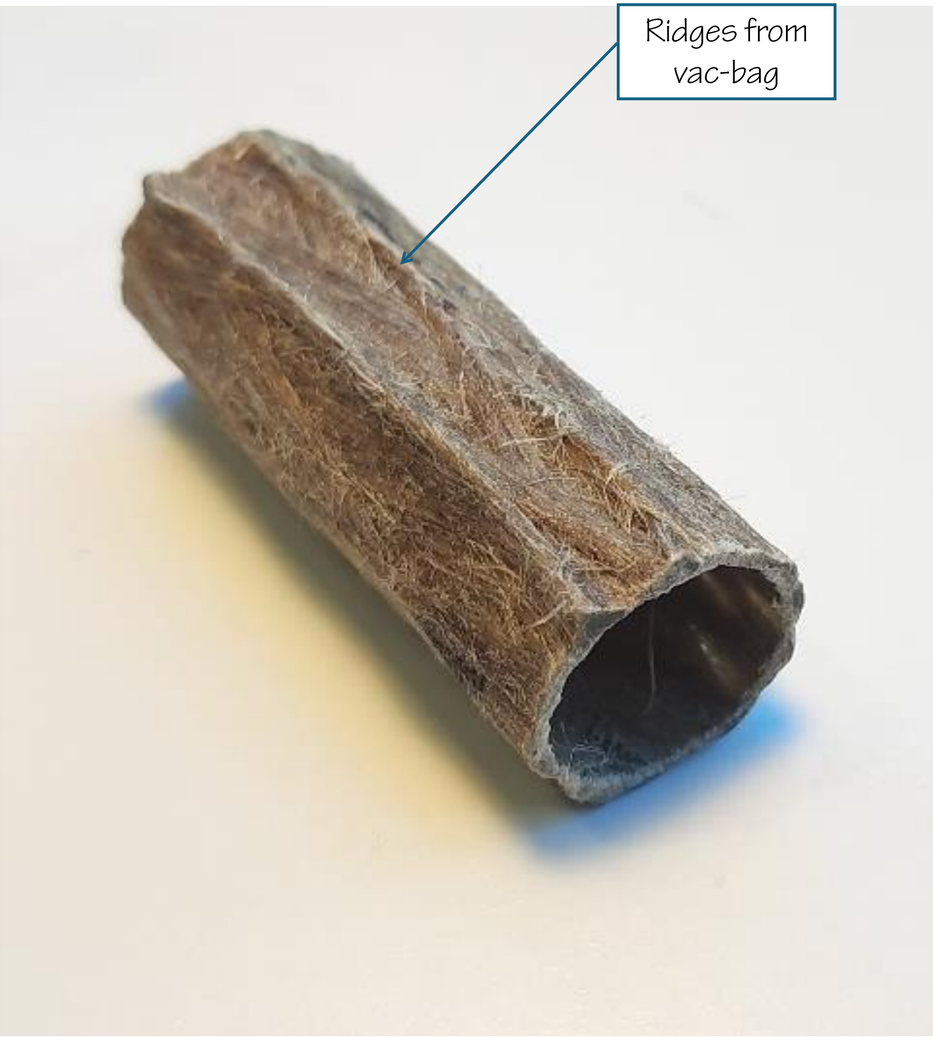
sample	failure stress compression (MPa)
1	60.70201527
2	64.42036577
3	38.9624606
4	65.24859619
5	60.30960915
average	**57.9286094**

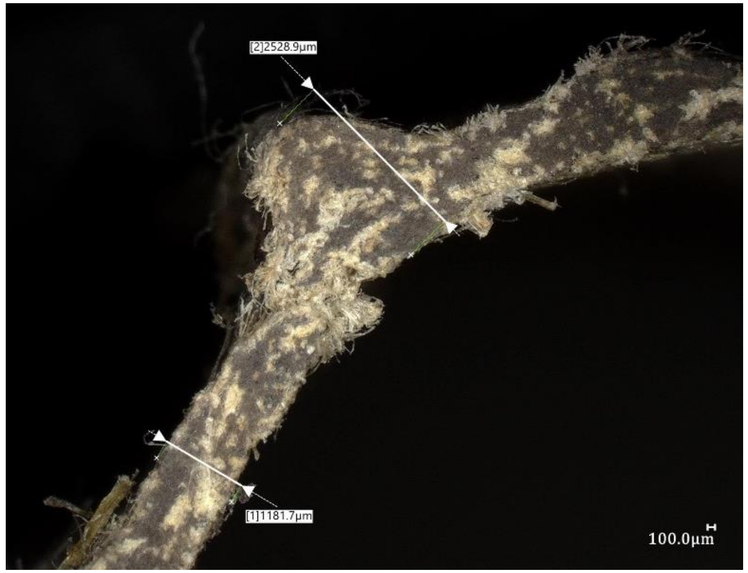
FVF: 43.76%

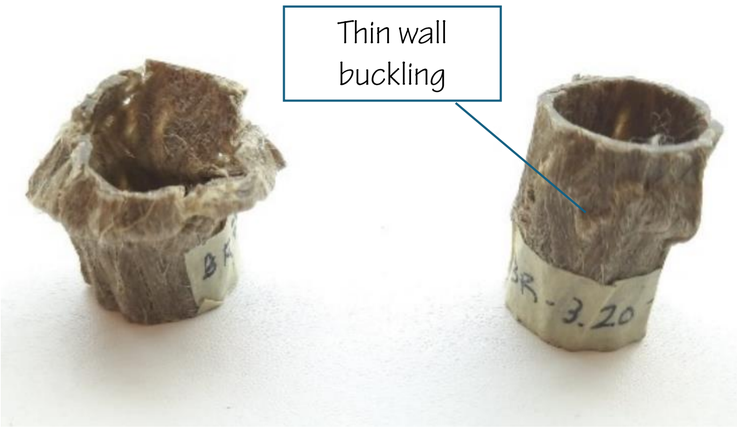
sample	failure stress compression (MPa)
1	19.51699969
2	13.91726951
3	21.99339104
4	25.27137363
5	19.34459282
average	**20.00872534**

Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible

Part A.1: **3-Layer Braided vs. Woven**

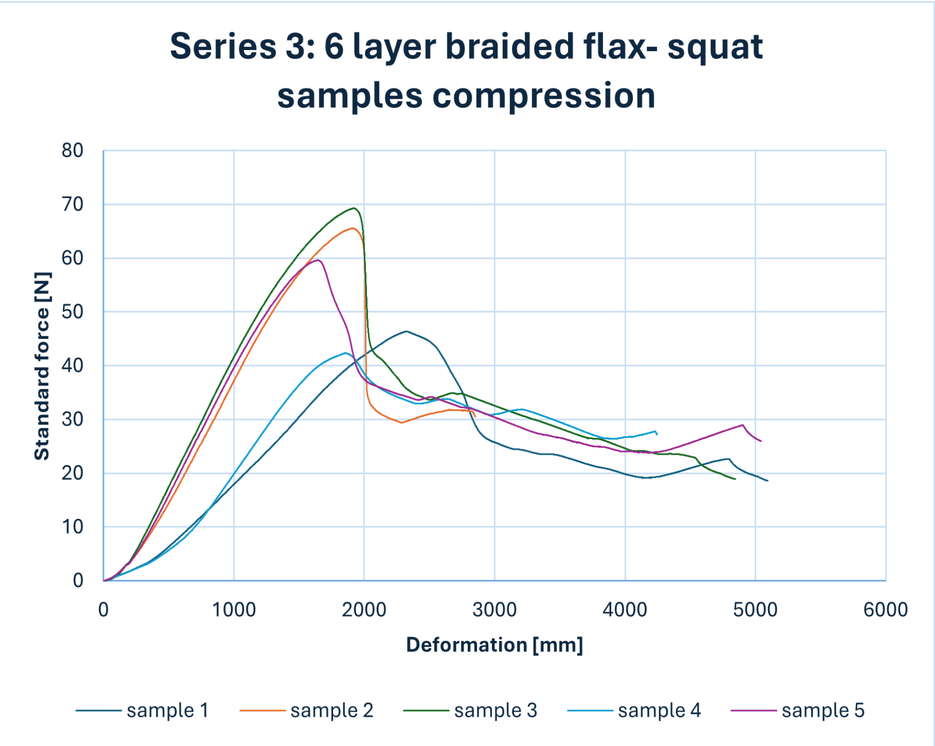






Will a thicker wall help?

Part A.2: 6-Layer Braided



FVF: 43.9%

sample	failure stress compression (MPa)
1	46.40
2	65.58
3	69.32
4	42.34
5	59.63
average	**56.66**

Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible
6-Layer Braided +15/-15	Vacuum Bag	Compression	43.9	**56.6**	Wall thickening doesn't help

I can't get away with a vacuum bag!... Not on site!

Can we consolidate without a vacuum bag?

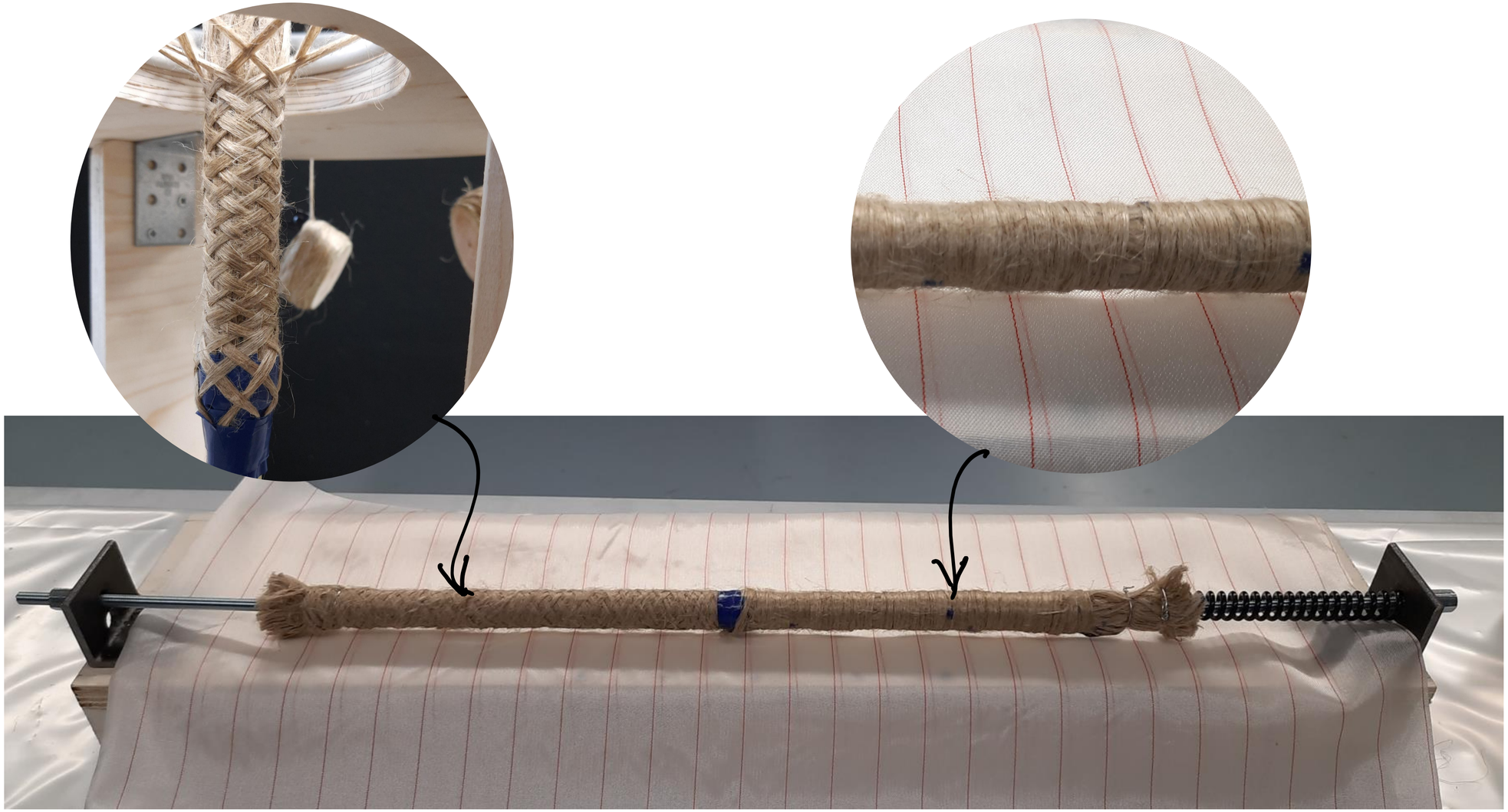
Part A3.: **Post-Tensioned Sample**

Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible
6-Layer Braided +15/-15	Vacuum Bag	Compression	43.9	**56.6**	Wall thickening doesn't help
6-Layer Braided +15/-15	Post-Tensioning	Compression	24.2	**77.5**	Not as effective as vac bag but more site feasible

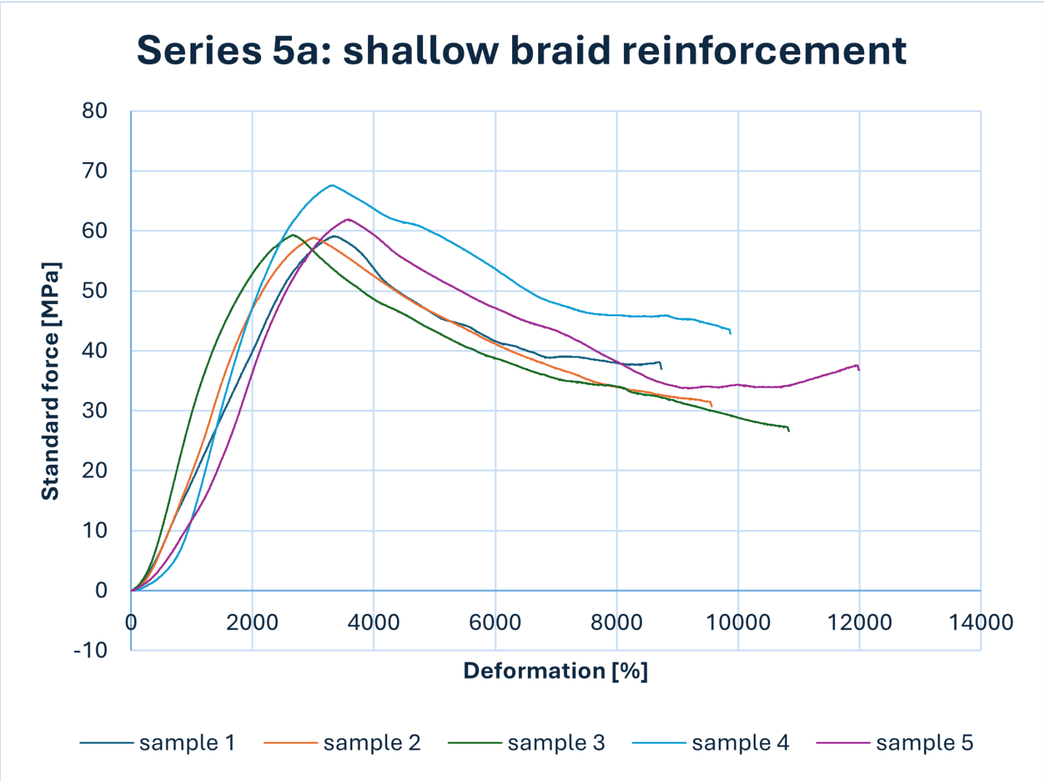
Part A3.: **Patterns in Failure Mode**

Will a lateral confinement help?

Part A4.: **Post-Tensioned Sample + Lateral consolidation**

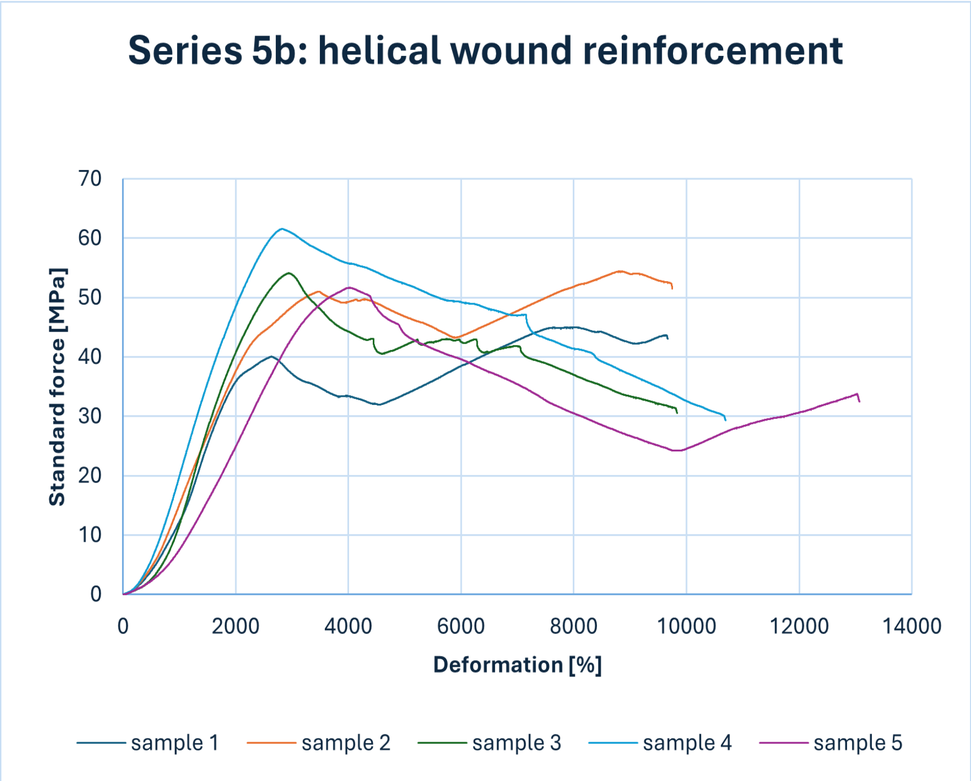


Part A4.: Post-Tensioned Sample + Lateral consolidation



FVF: 26.9%

sample	failure stress compression (MPa)
1	59.11327854
2	58.89656212
3	59.31268373
4	67.62202965
5	61.89871879
average	**61.36865457**

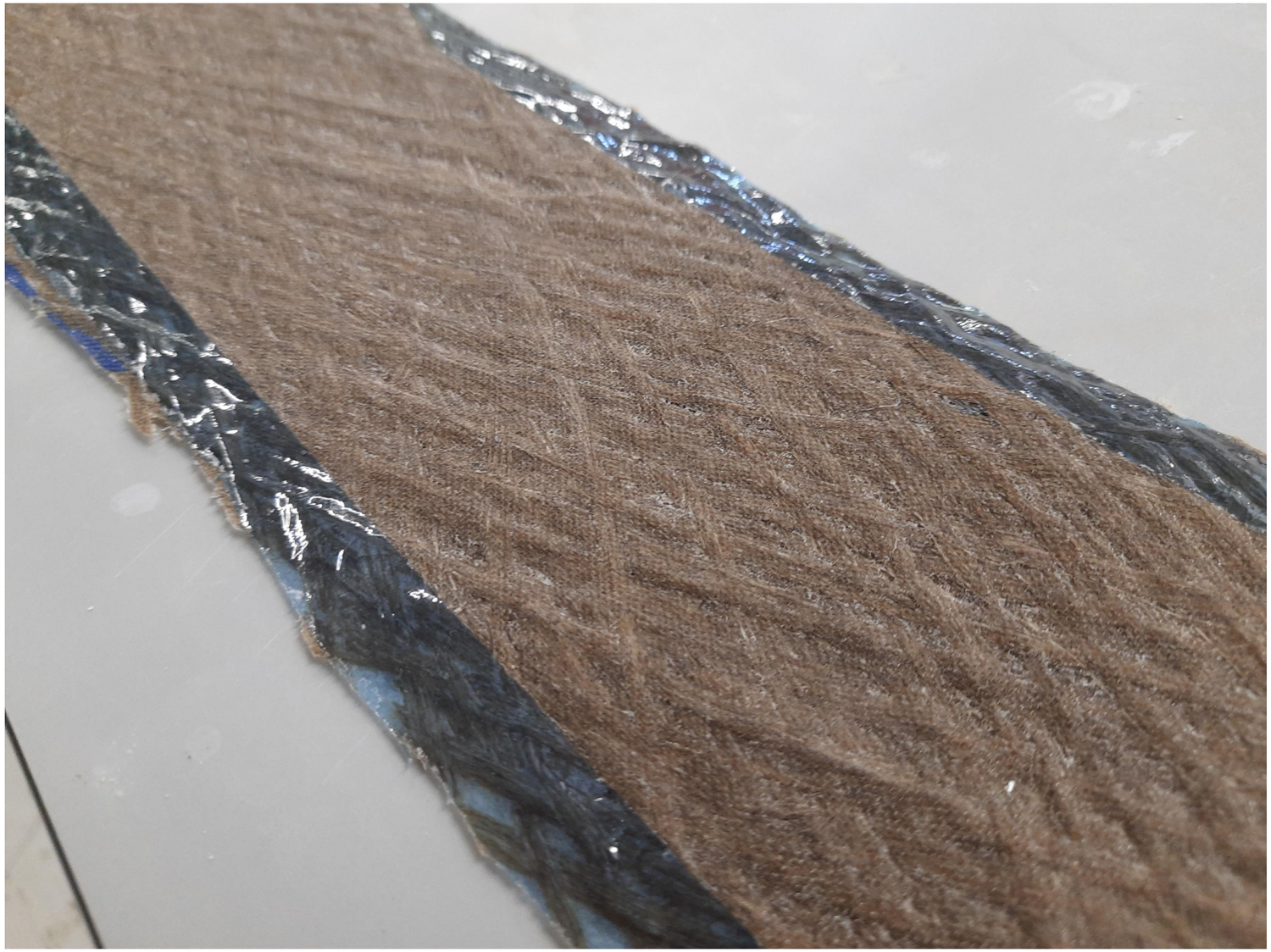


FVF: 20.5%

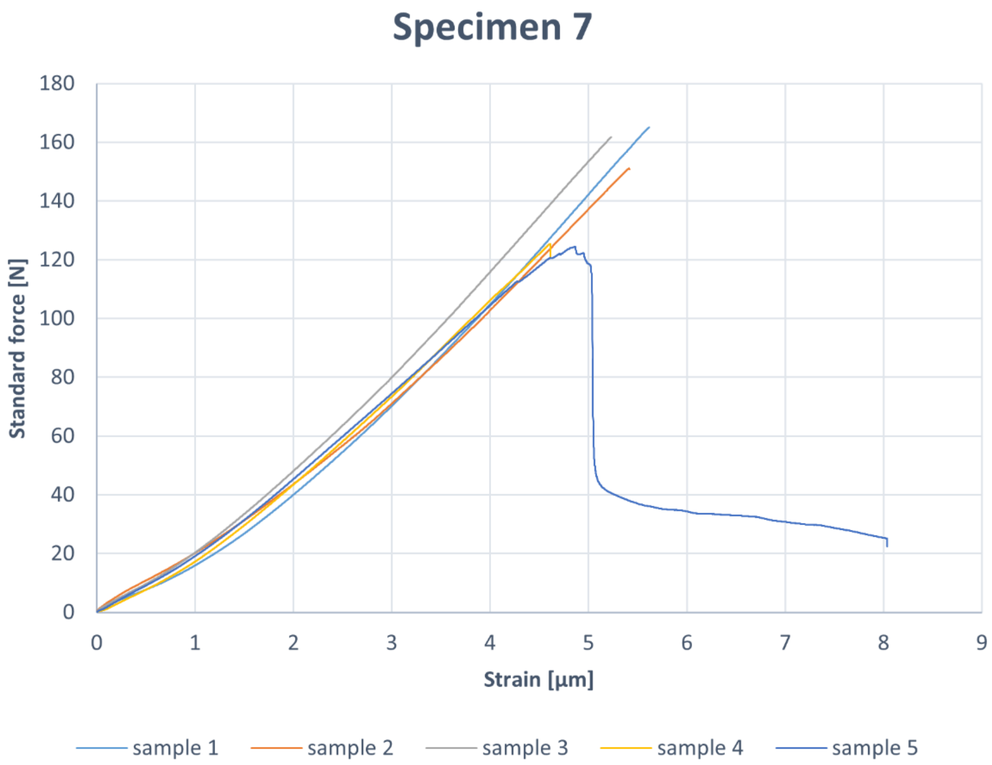
sample	failure stress compression (MPa)
1	44.9796469
2	54.40431489
3	54.12390125
4	61.57799026
5	51.64432528
average	**53.34603571**

Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible
6-Layer Braided +15/-15	Vacuum Bag	Compression	43.9	**56.6**	Wall thickening doesn't help
6-Layer Braided +15/-15	Post-Tensioning	Compression	24.2	**77.5**	Not as effective as vac bag but more site feasible
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	26.9	**61.36**	Shallow braid Lateral reinforcement makes it worse
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	20.5	**53.34**	Filament winding Lateral reinforcement makes it worse

Part A5.: **Tension Tests**



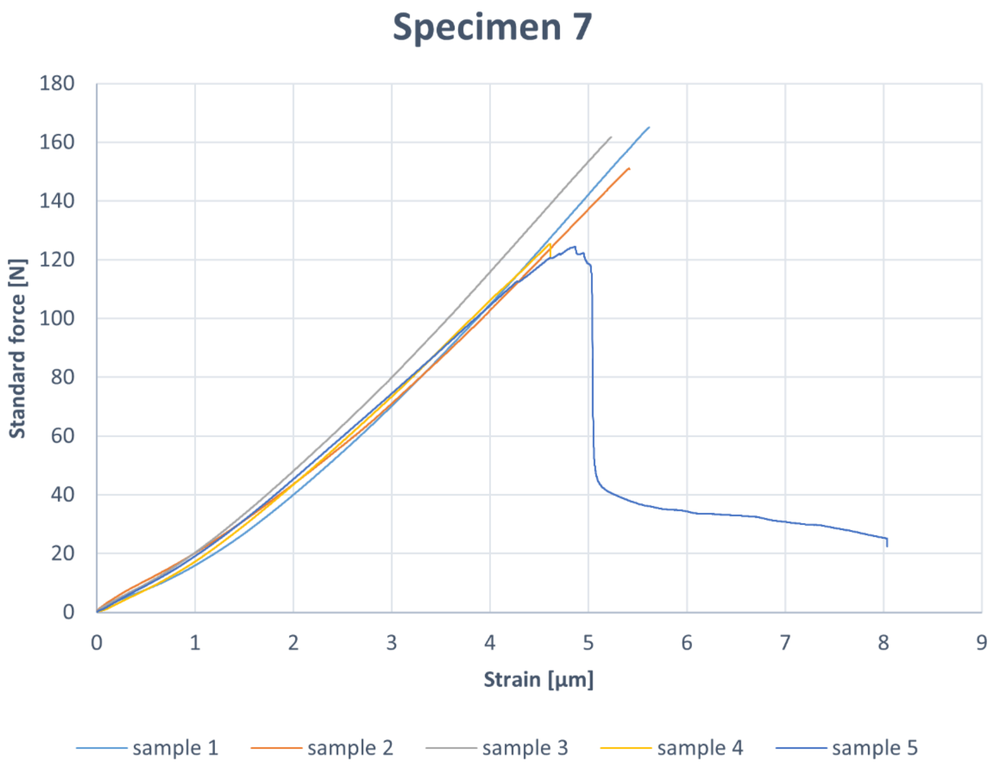
Part A5.: **Tension Tests**



FVF: 53%

sample	failure stress compression (MPa)
1	164.985199
2	151.1396179
3	161.6764374
4	125.3889542
5	124.4748764
average	**145.533017**

Part A5.: **Tension Tests**

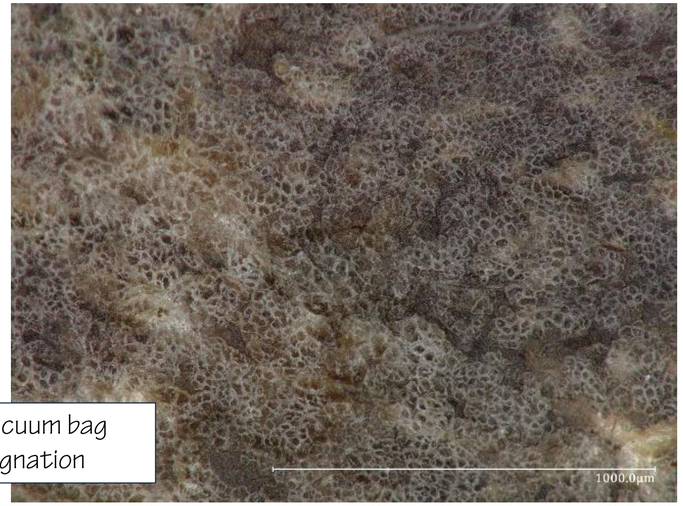


FVF: 53%

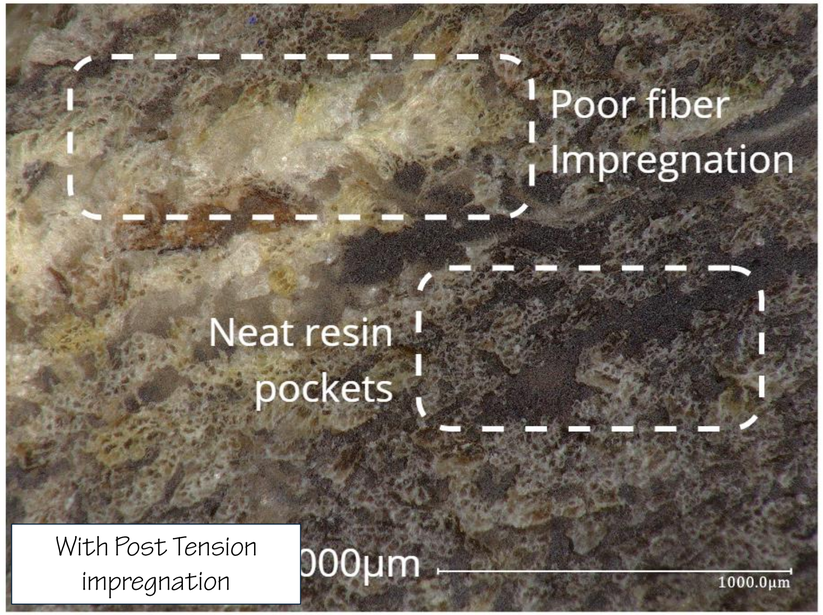
sample	failure stress compression (MPa)
1	164.985199
2	151.1396179
3	161.6764374
4	125.3889542
5	124.4748764
average	~~145.533017~~ 75MPa

Sample	Compaction	Test	FVF (%)	Strength (Mpa)	Remarks
3-Layer Braided +15/-15	Vacuum Bag	Compression	44.92	**57.9**	Benefits from fiber angle
Twill Weave 0/90	Vacuum Bag	Compression	43.76	**20**	Terrible
6-Layer Braided +15/-15	Vacuum Bag	Compression	43.9	**56.6**	Wall thickening doesn't help
6-Layer Braided +15/-15	Post-Tensioning	Compression	24.2	**77.5**	Not as effective as vac bag but more site feasible
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	26.9	**61.36**	Shallow braid Lateral reinforcement makes it worse
6-Layer Braided +15/-15	Post tensioning + Lateral Reinforcement A	Compression	20.5	**53.34**	Filament winding Lateral reinforcement makes it worse
6-Layer Braided +15/-15	Vacuum Bag	Tensile	53	**145**	Have to correct for lower FVF!
				~75	Corrected for FVF of 25%

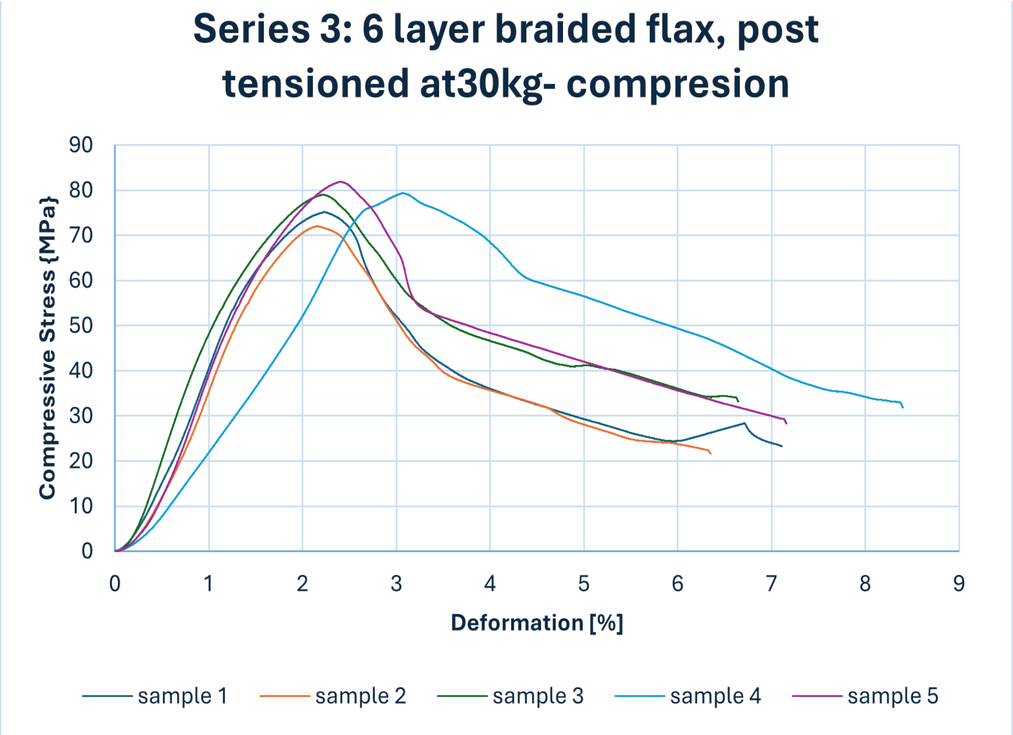
Part A3.: **Post-Tensioned Sample**



With Vacuum bag impregnation



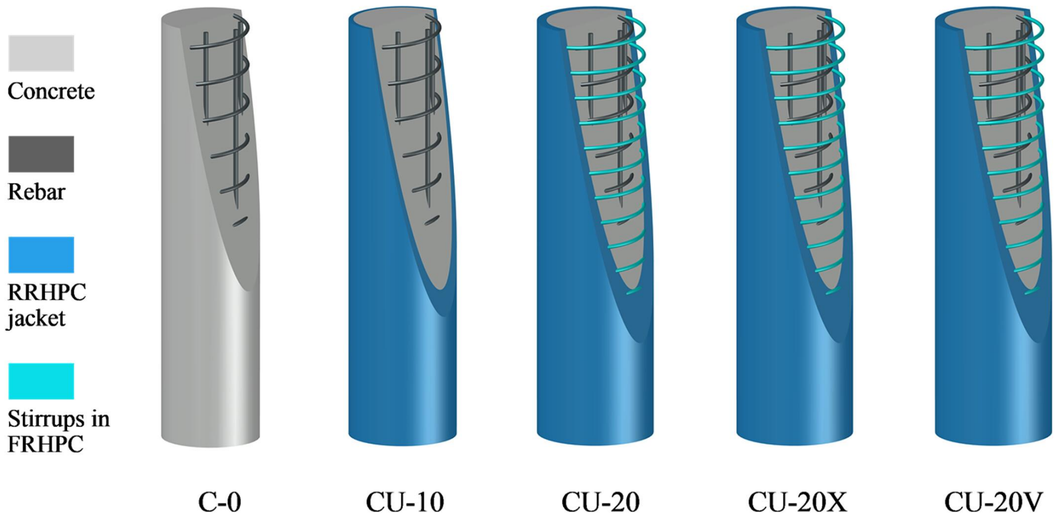
With Post Tension impregnation



FVF: 24.2%

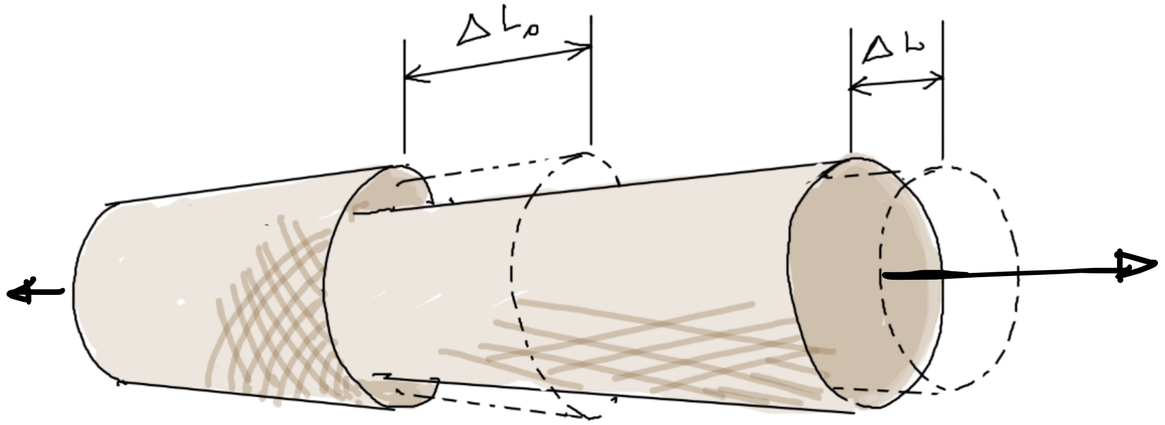
sample	failure stress compression (MPa)
1	75.20228078
2	72.07438759
3	79.06672569
4	79.39097182
5	81.92195714
average	**77.5312646**

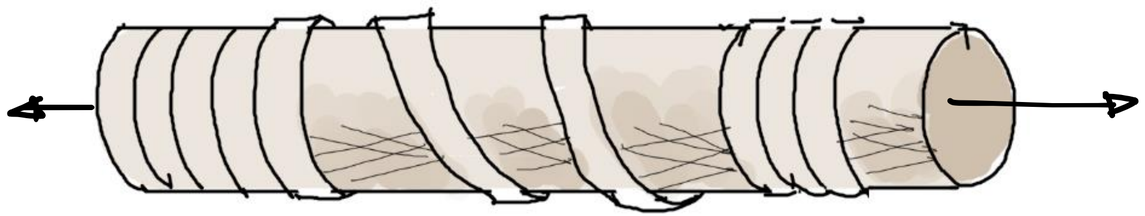
Part A4.: **Post-Tensioned Sample + Lateral consolidation**



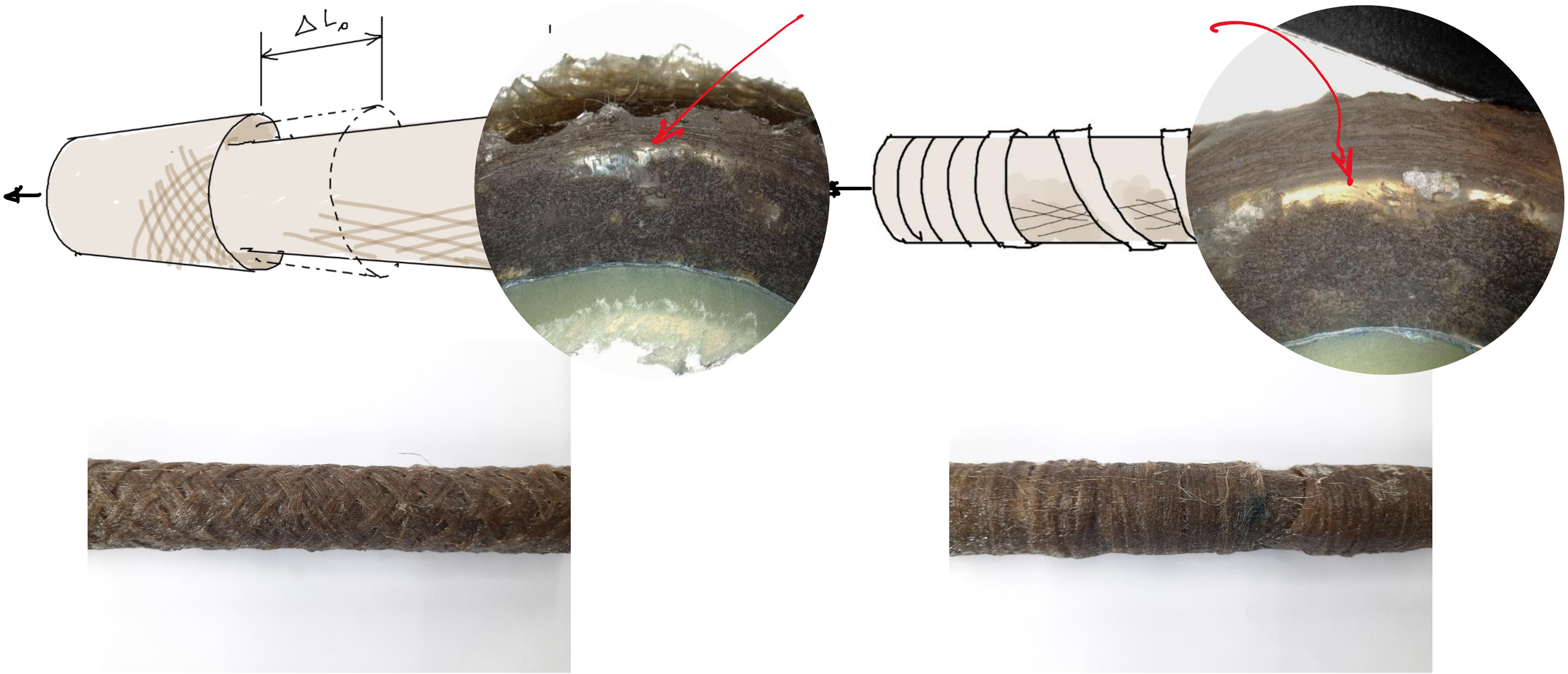
Lu, C.-L., Ouyang, K., Wang, Q., Zhu, W.-X., Chen, H.-Q., Lei, Z.-X., & Qin, Z.-J. (2022). Axial behavior of RC column strengthened with laterally reinforced FRHPC jacket. *Structural Concrete, 23*(3), 1718-1734. https://doi.org/10.1002/suco.202100896

Part A4.: **Post-Tensioned Sample + Lateral consolidation**



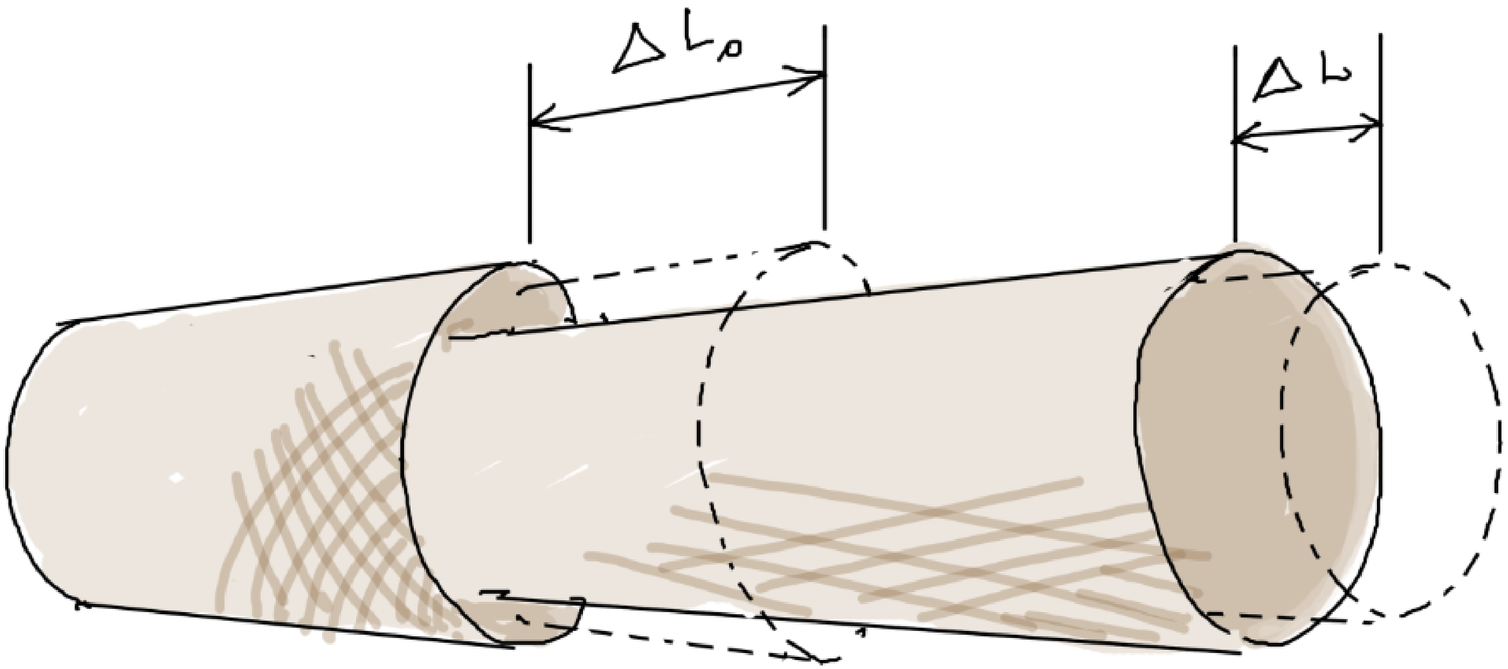


Part A4.: **Post-Tensioned Sample + Lateral consolidation**

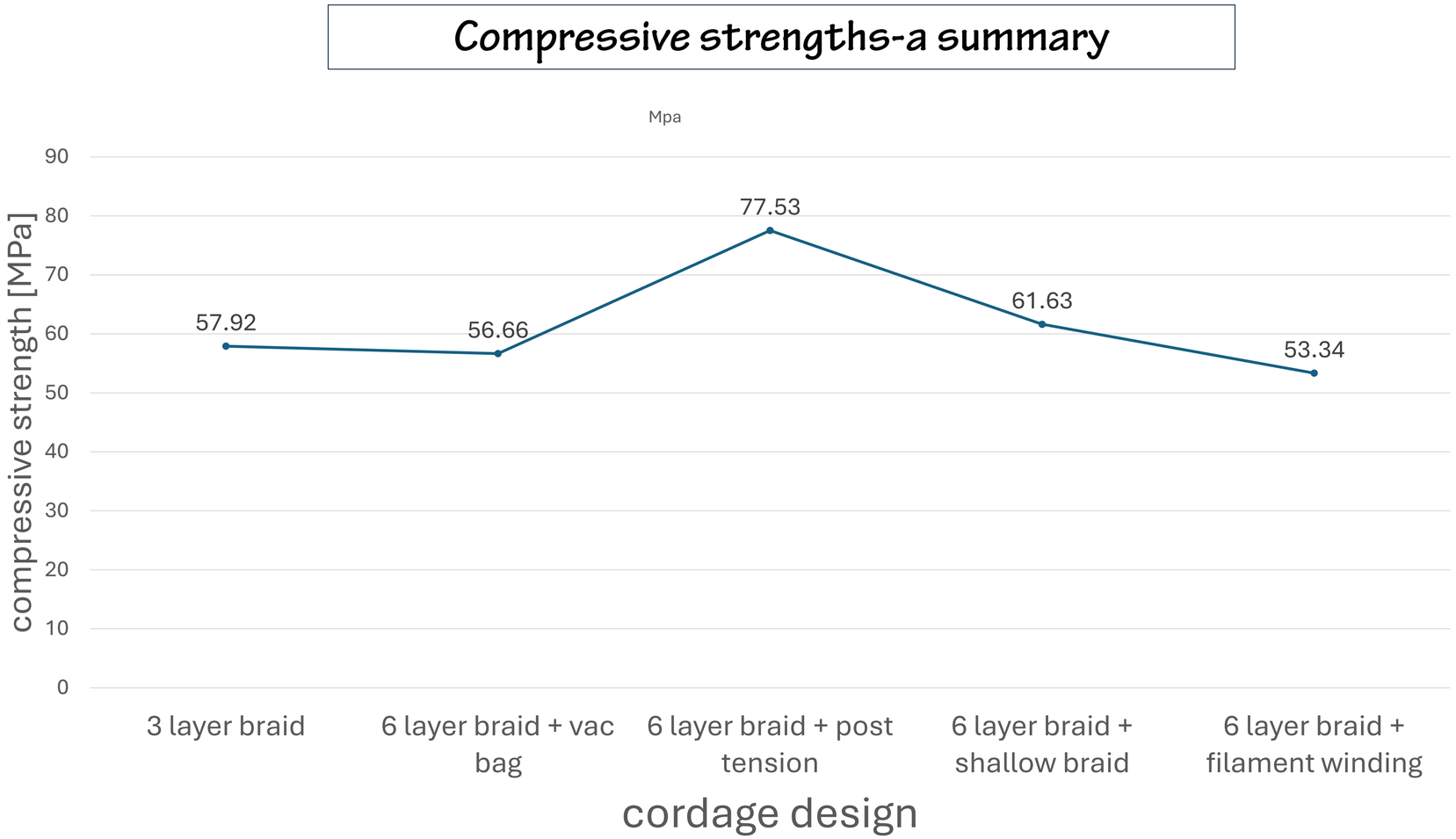


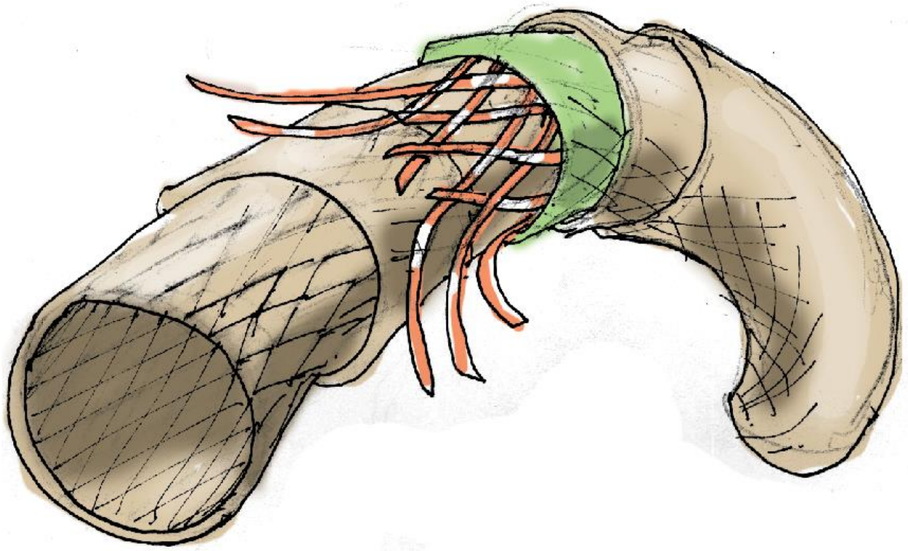
Part A4.: **Post-Tensioned Sample + Lateral consolidation**

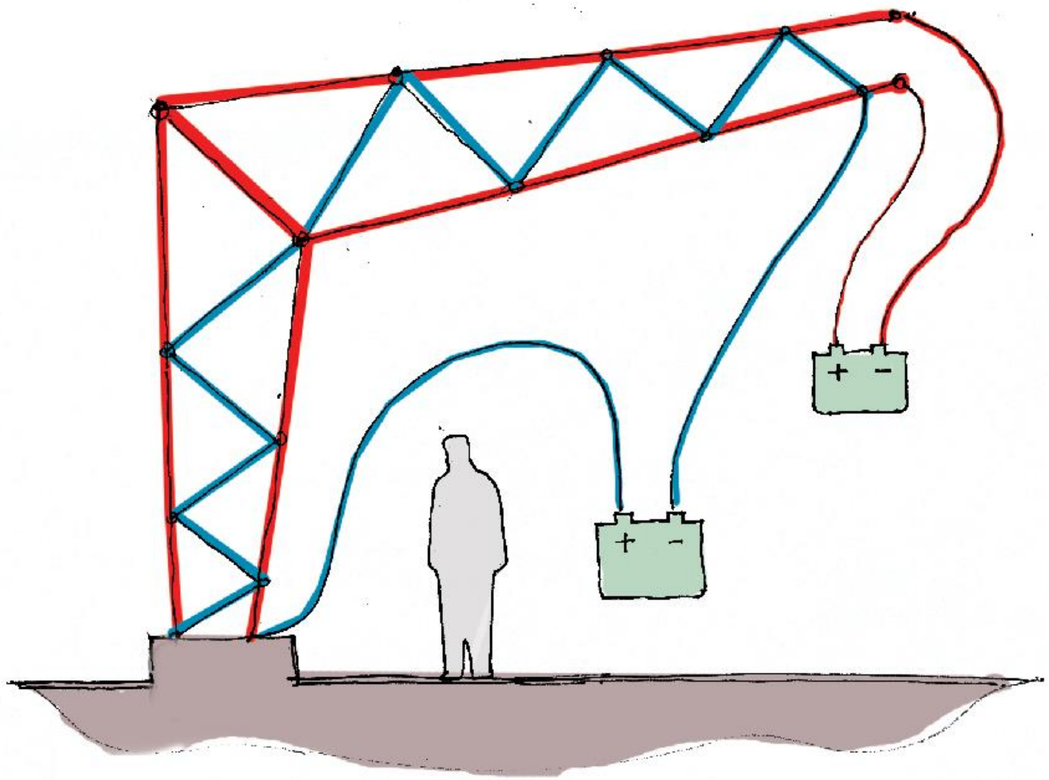
No mixing braid angles!

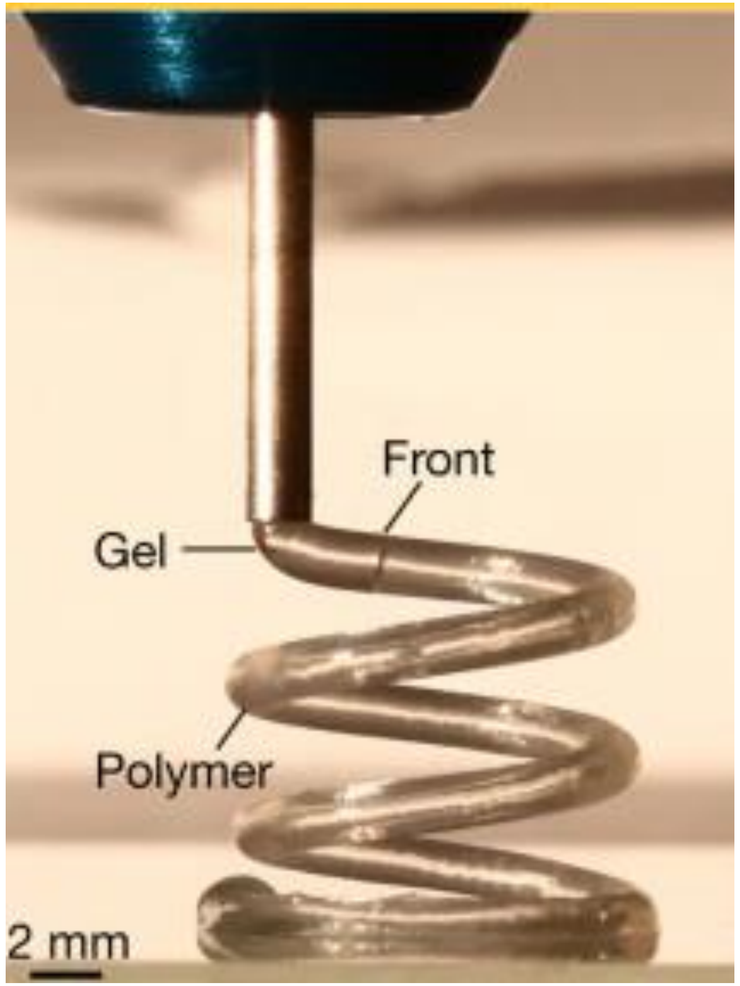
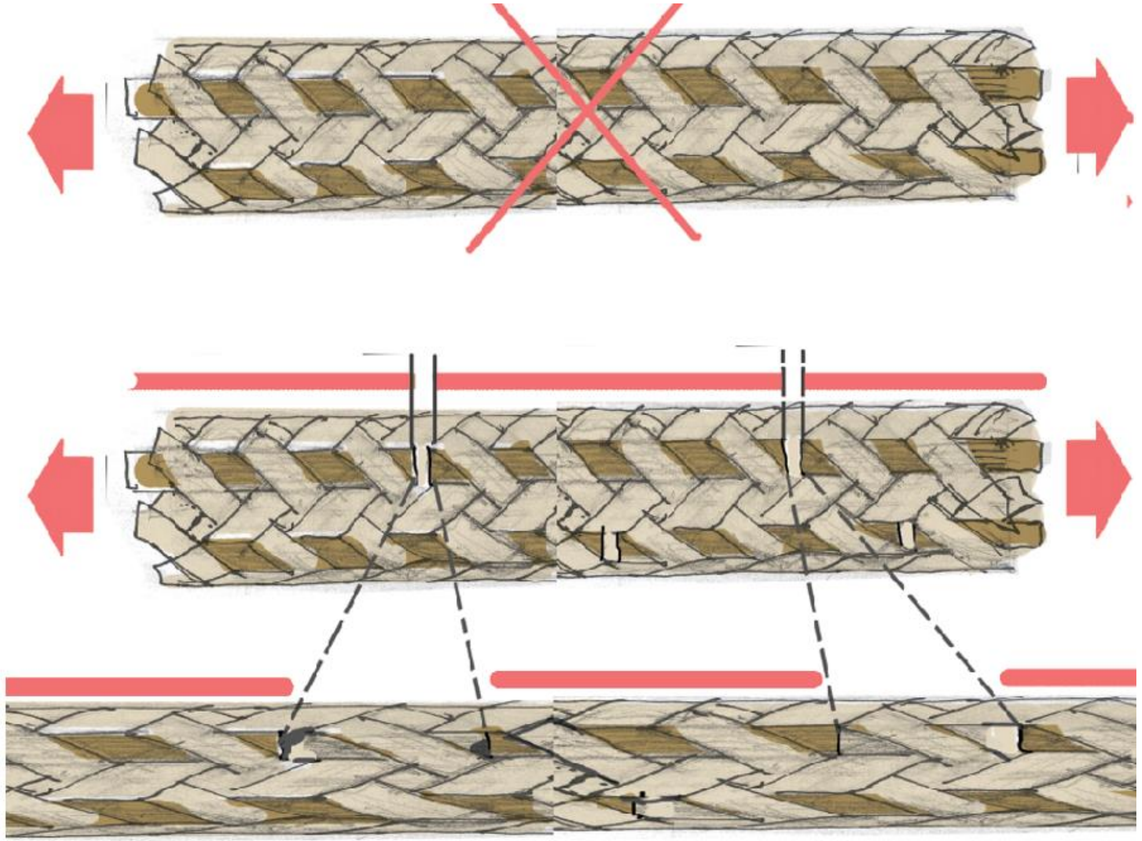
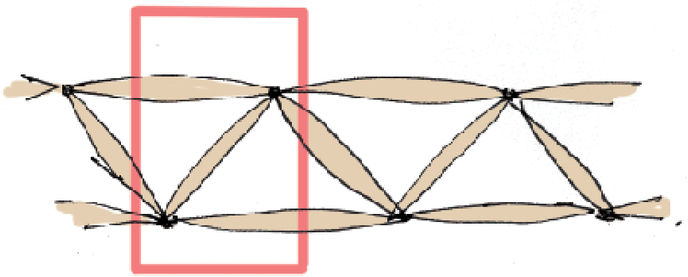
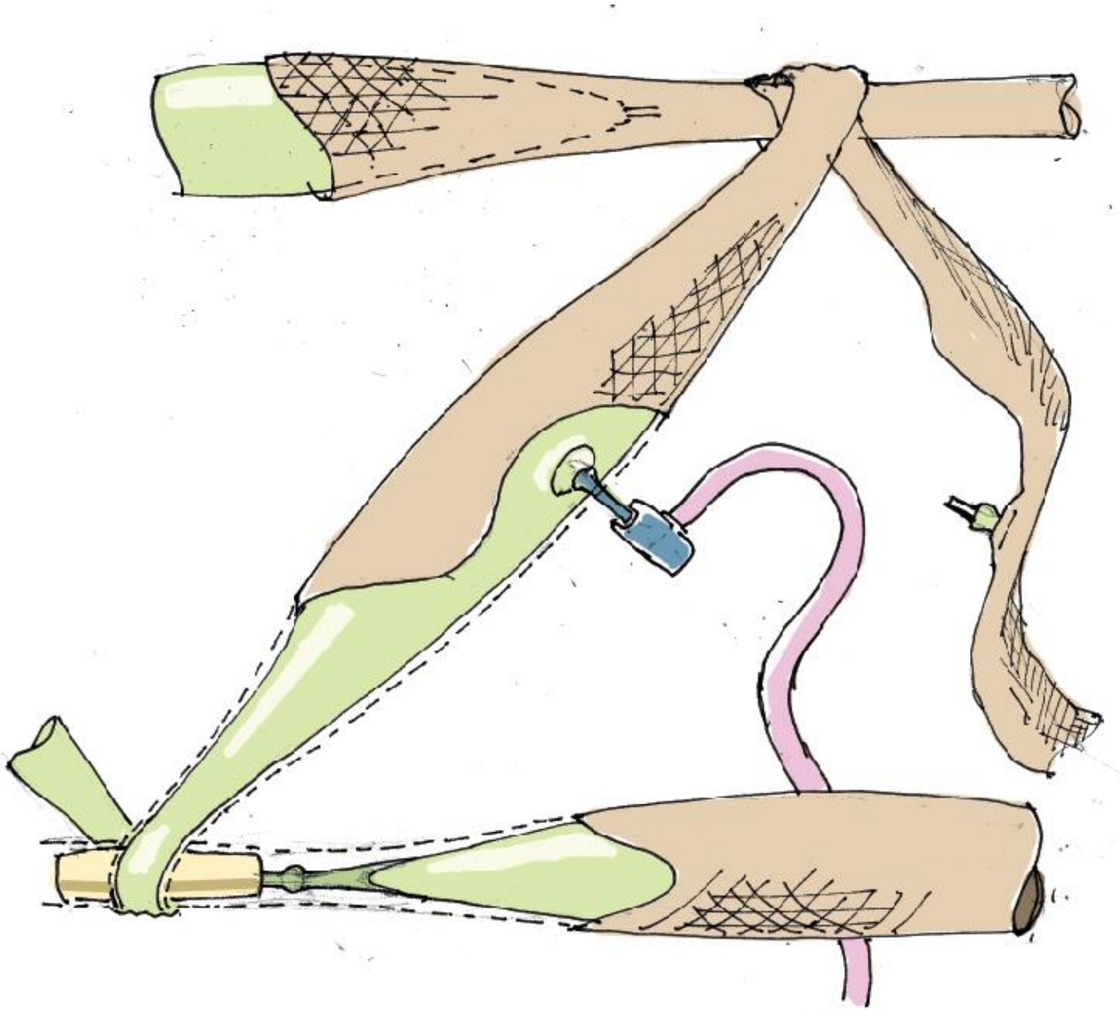


Part A.: Some observations- compression








Front
Gel
Polymer
2 mm