Sustainable Design Graduation Studio – P5

Ali Bijani - 1393391

Topic

Digital manufacturing of freeform concrete

Digital manufacturing of reinforcement in a freeform concrete structure

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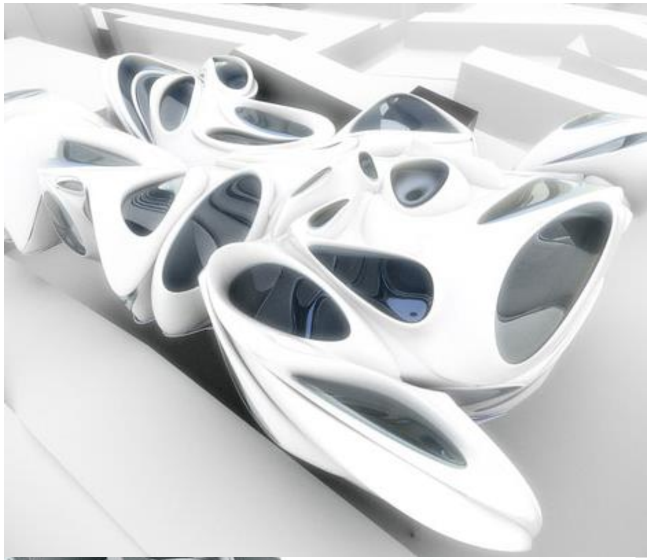
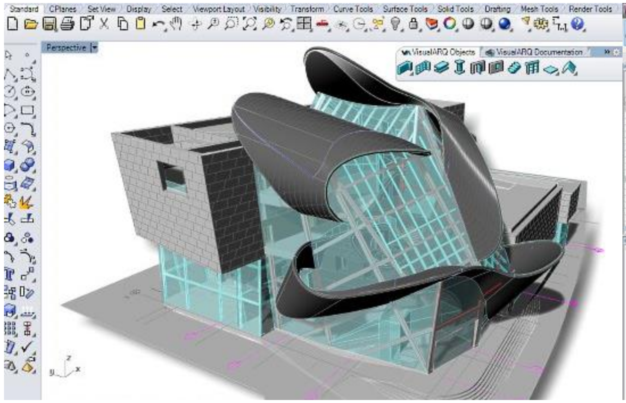
Freeform concrete Architecture

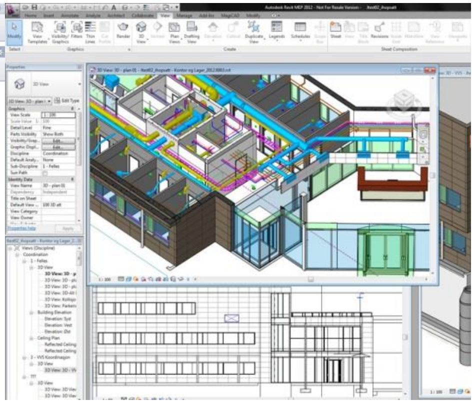
How we design

Design tools

- 3D modeling
  - Rhinoceros, Maya, 3D max,..
- Parametric design software's
  - Grasshopper, Autodesk Dynamo, Catia, ..
- BIM
  - Revit, ArchiCAD, Bentley, …



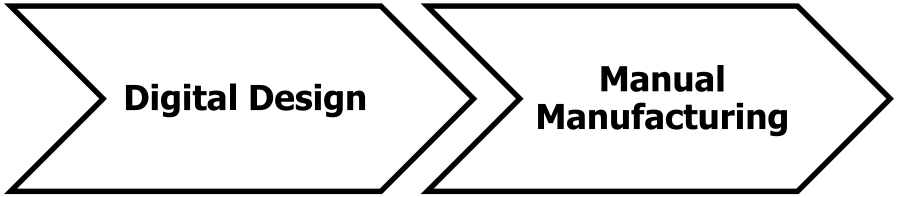




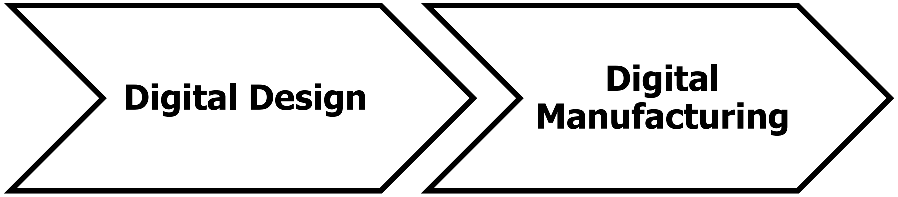
Problem 1

- Most of the conventional techniques are not suitable for freeform concrete

Currently



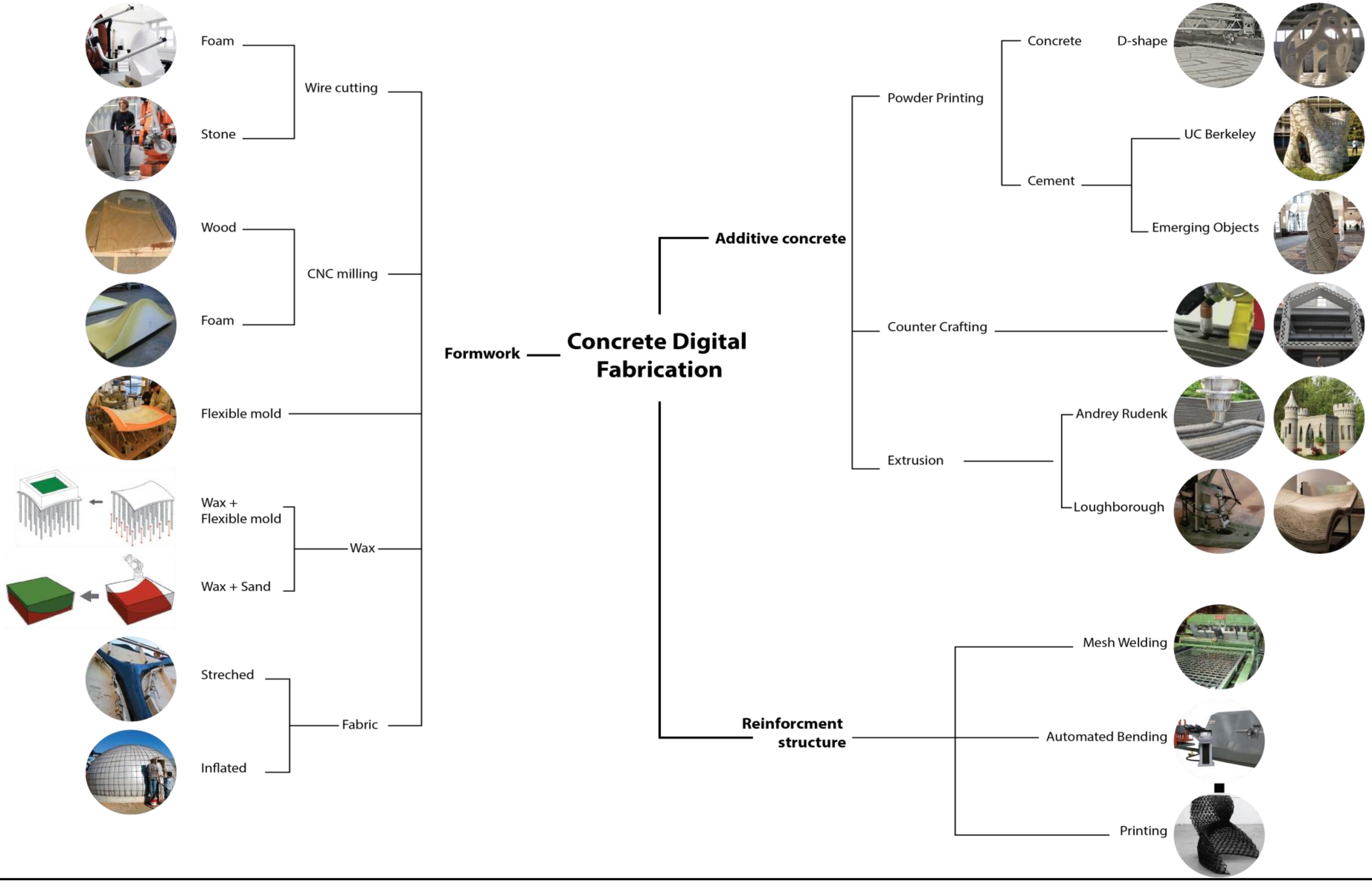
Future Goal



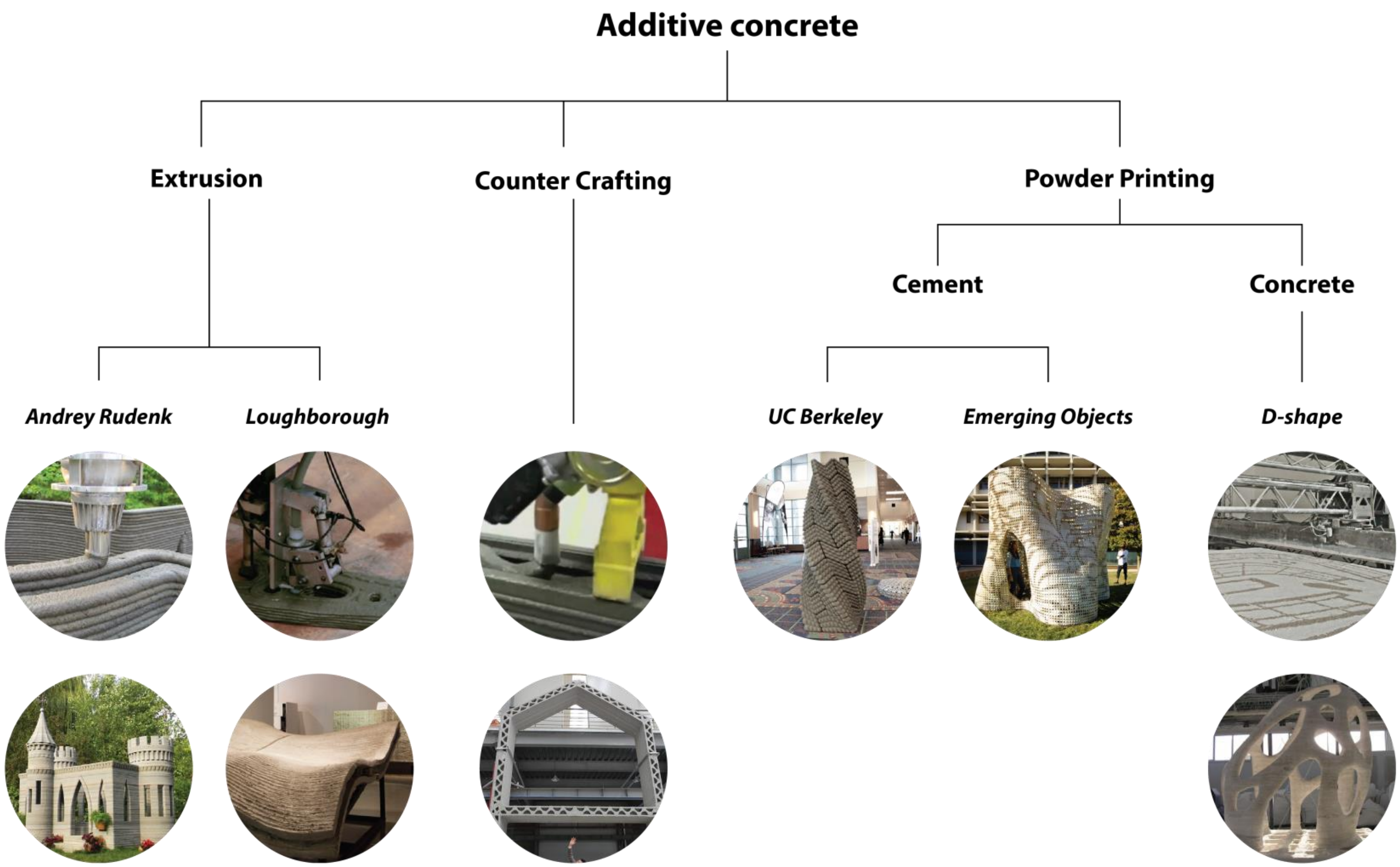
Main research question

- How digital manufacturing can be used to build freeform concrete structures ?

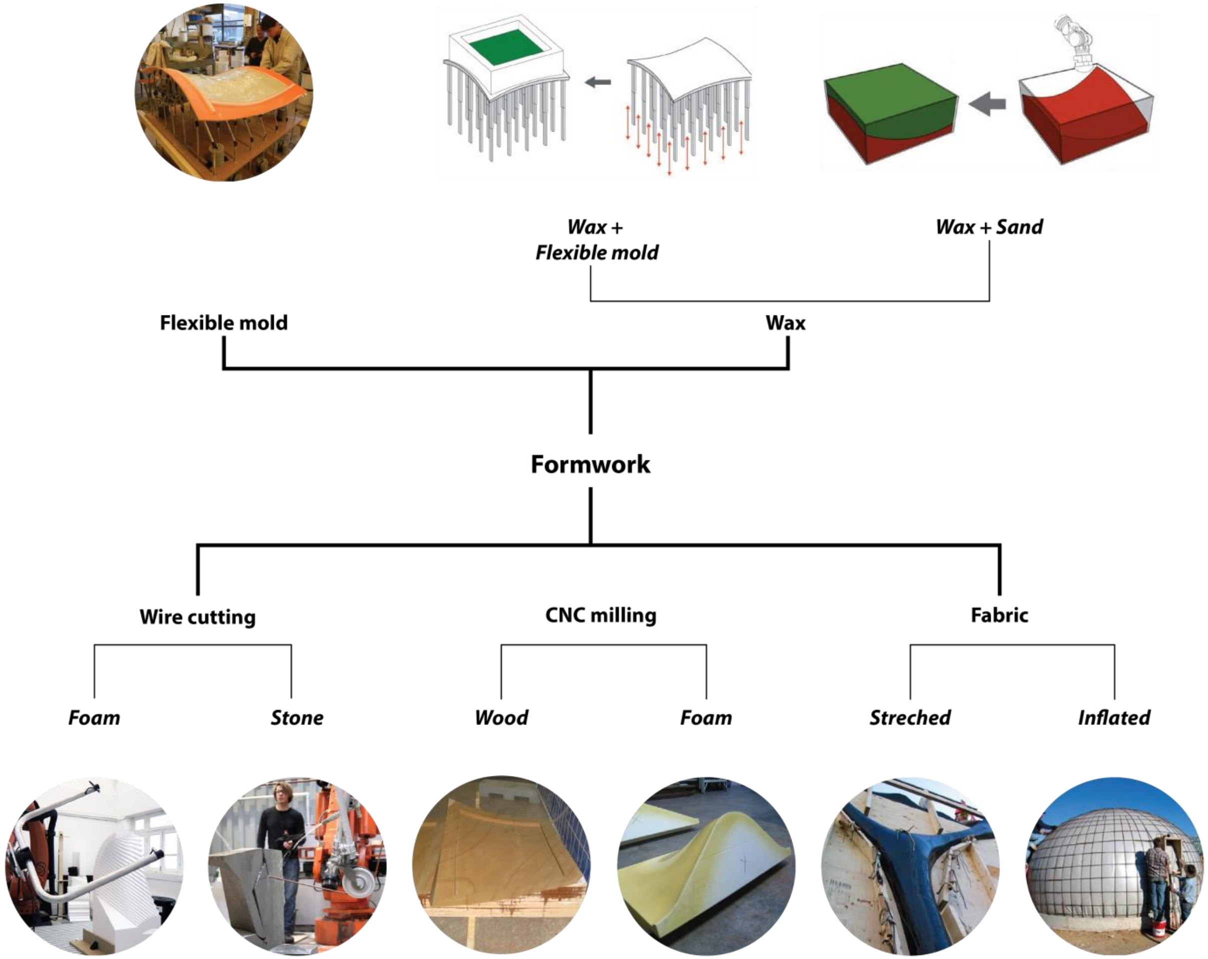
Digital manufacturing techniques



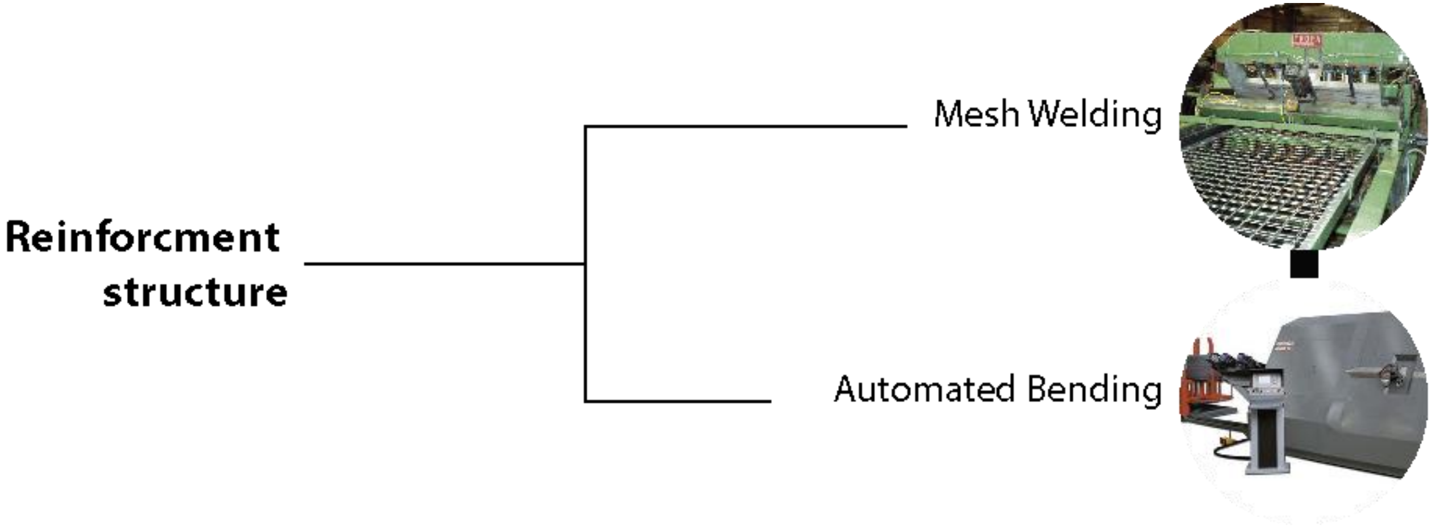
Concrete - Digital manufacturing
Additive Concrete



Concrete - Digital manufacturing
Formwork



Concrete - Digital manufacturing Reinforcement



Problem 2

- Lack of research in reinforcement field

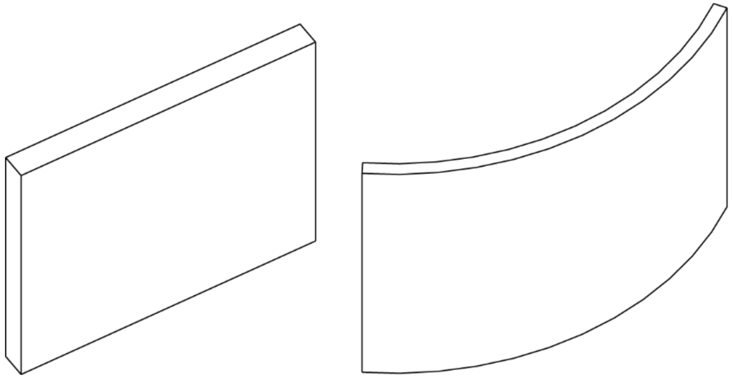
  - Reinforcement need is eliminated by use of fiber reinforcement technique
    - Panel elements
    - Not suitable for loadbearing structure

  - Developing formwork techniques
    - Conventional rebar techniques are used

How we construct

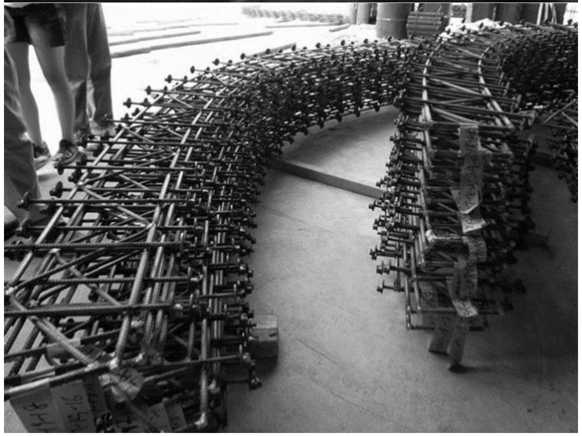
Conventional methods

- Developed for simple geometries

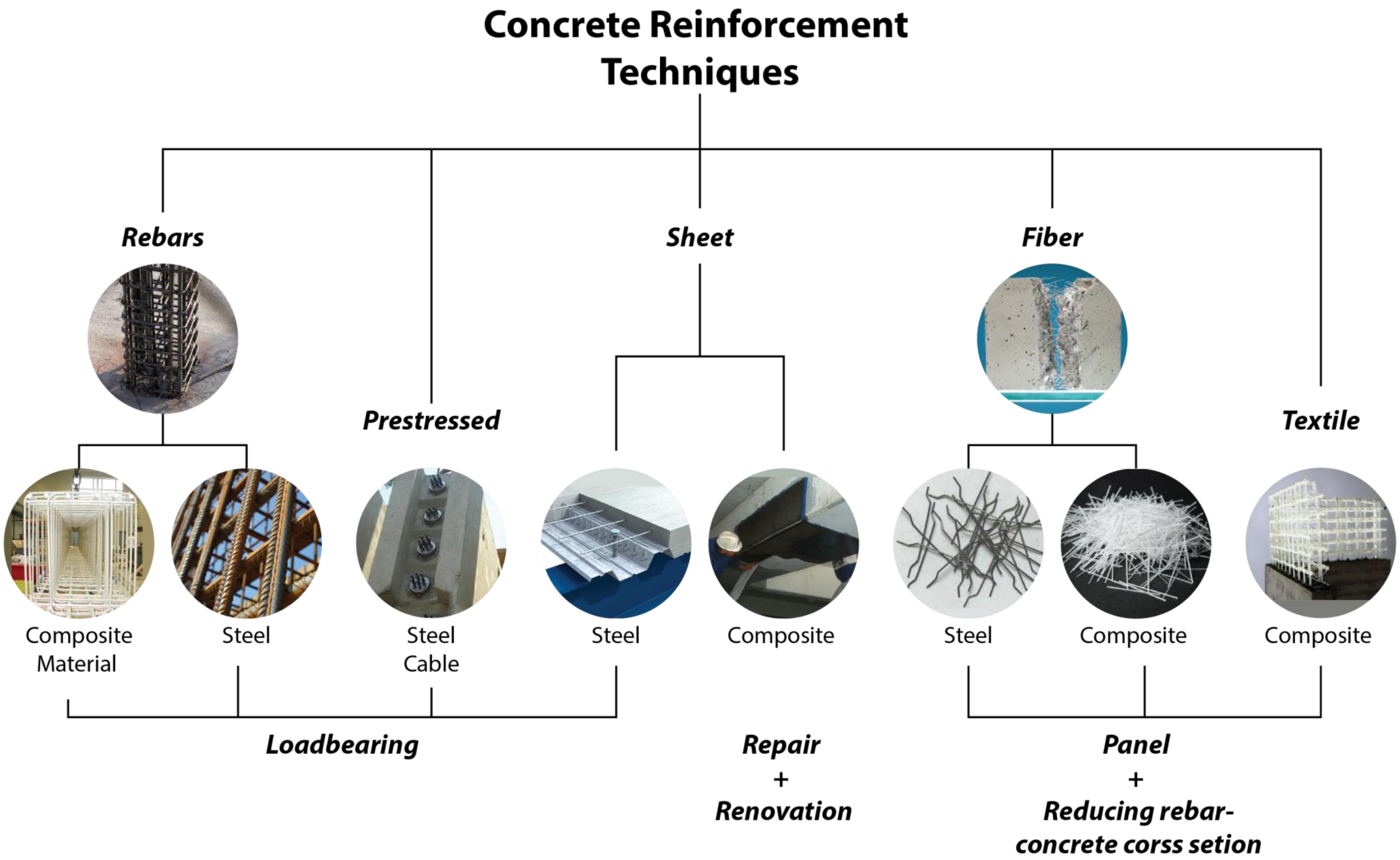


How we construct

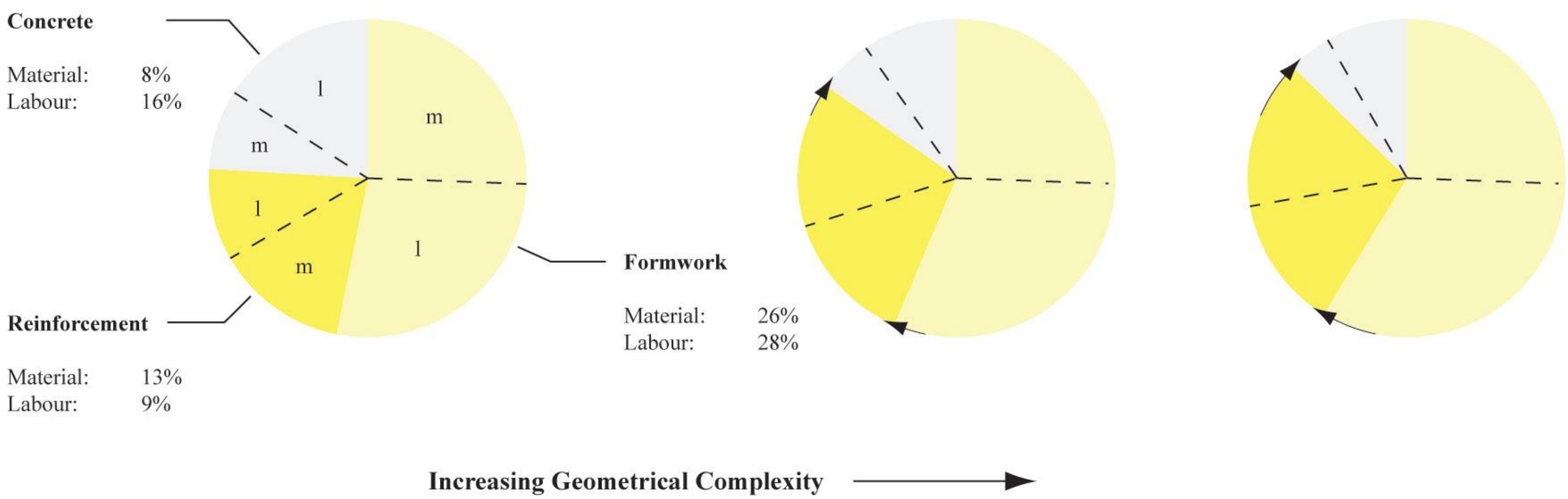
Conventional methods modification



Reinforcement techniques

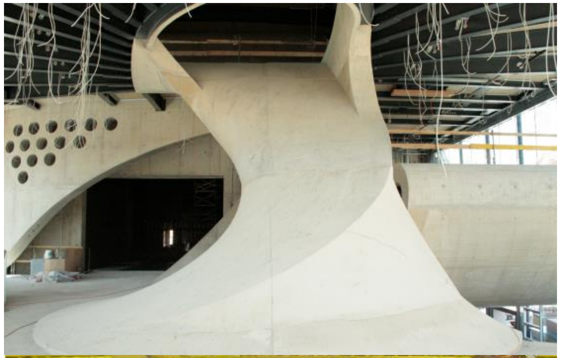


Production Cost of Reinforced Concrete



Modified research question

- How digital manufacturing can be used to build the reinforcement system in freeform concrete structure ?



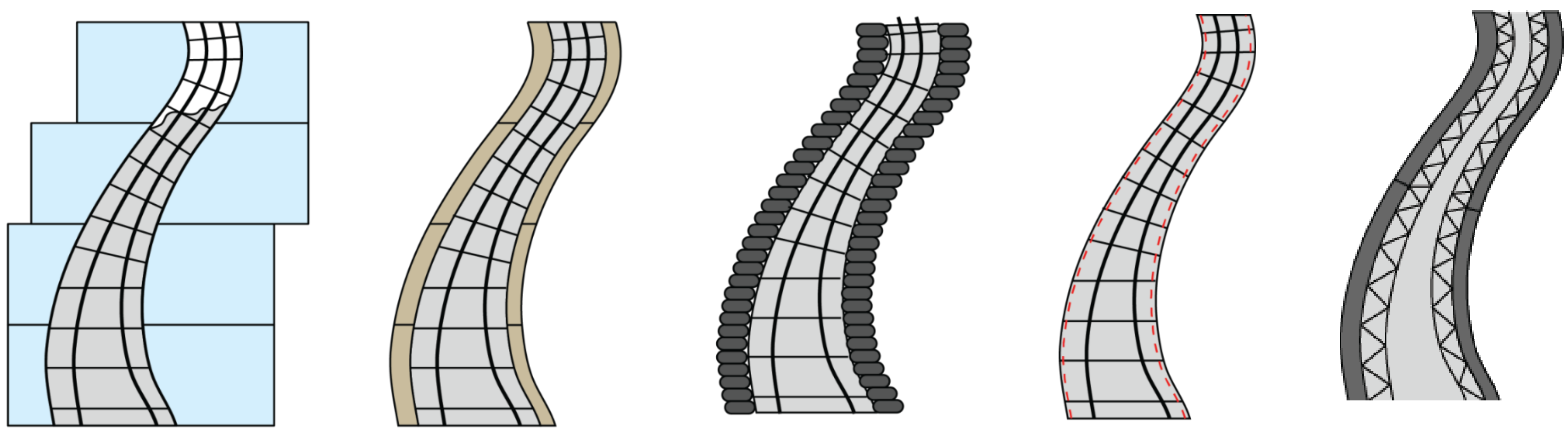
Summary

Focus of this research

SEASON 1

In search of new concepts

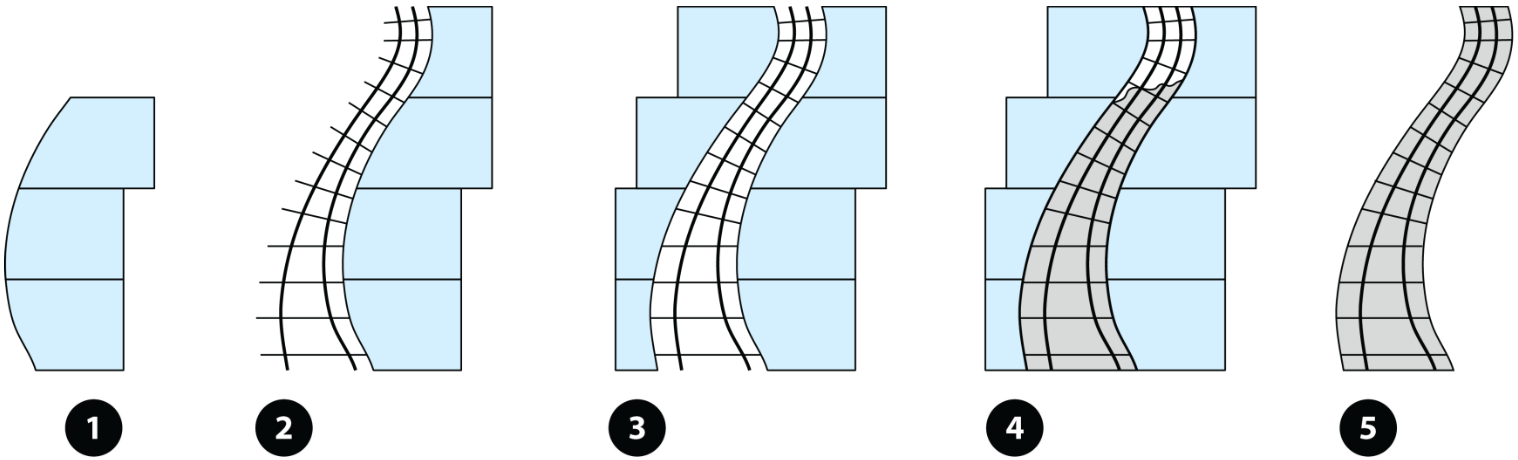
Freeform Reinforced Concrete Assembly Concepts



Option A **Option B** **Option C** **Option D**

Freeform Structure Construction process

Option A



Step 1
First side of Formworks get assembled

Step 2
Reinforcment structures are placed and positioned with the help of formwork

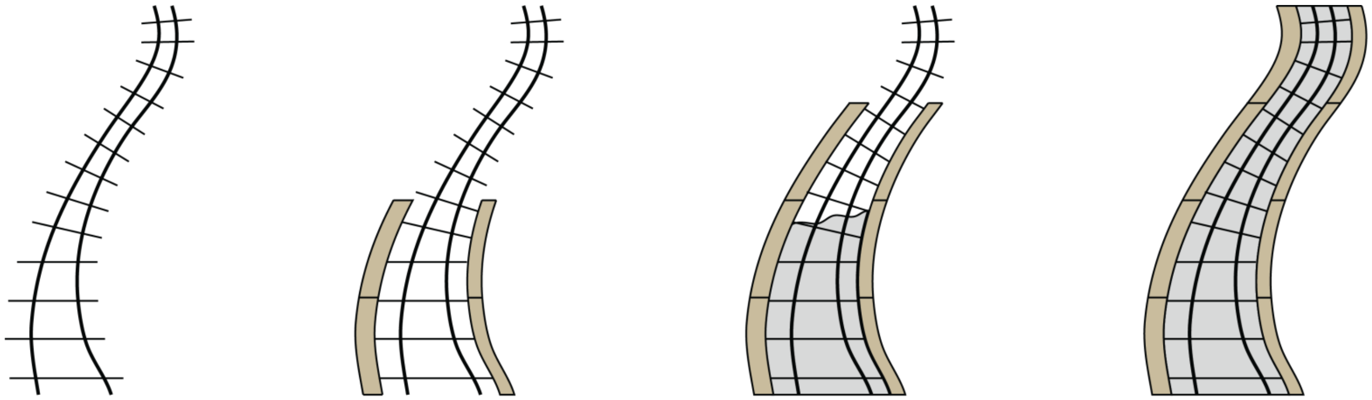
Step 3
Seother side of form-works are placed

Step 4
Concrete is poured in cavity

Step 5
Formworks are re-moved and structure get complete

Freeform Structure Construction process

Option B



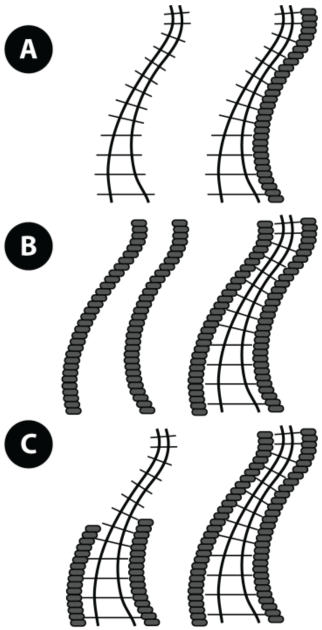
Step 1
Reinforcement structure is erected

Step 2
Clading material that have also formwork functionality get attached to reinforcement .

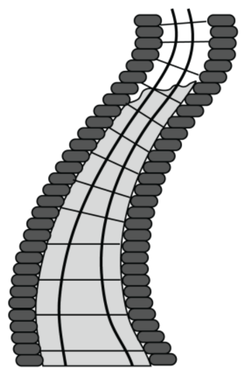
Step 3
Concrete is poured in the cavity

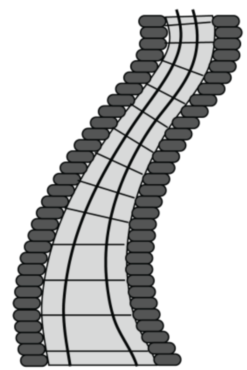
Step 4
Step2 and step 3 is reapetd till structure is complete

Freeform Structure Construction process



Option C





1 2

Step 1,2

A. Reinforcement structure is placed first and 3d printed panels are placed around it

B. Concrete formwork is printed first and rein-forcement is placed in it (countercrafting)

C. Counter formwork is printed around rein-frocement structure

3

Step 3

Concrete is poured in the cavity to complete the structure

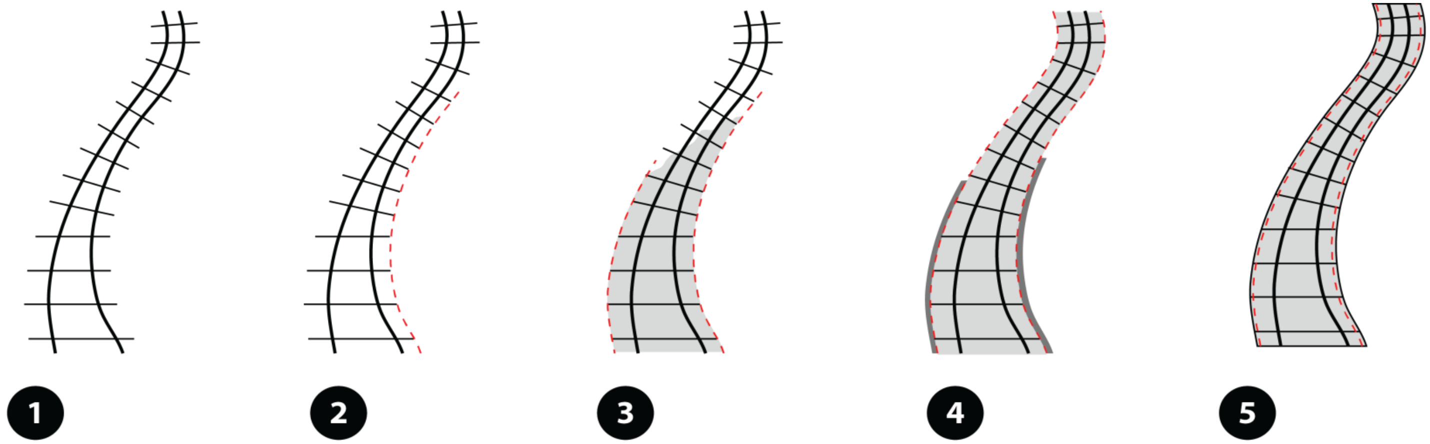
4

Step 3

Structure is complete

Freeform Structure Construction process

Option D



Step 1
Reinforcment structure is erected

Step 2
Open mesh fabric is place under the structure

Step 3
Concrete is sprayed on where mesh is located.

new layer of meshis added on top of it

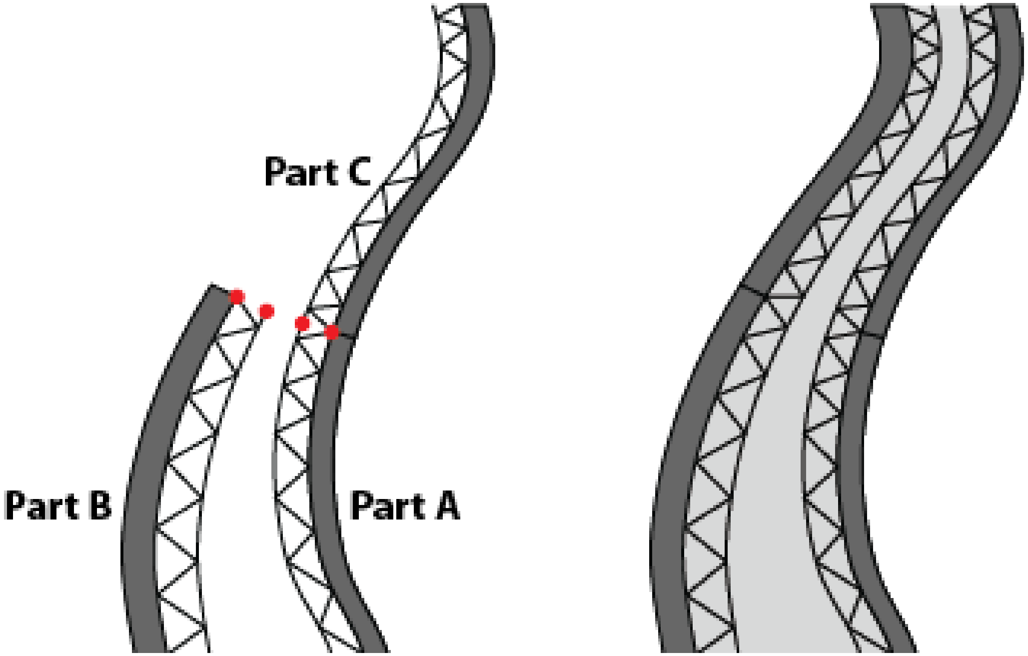
Step 4
Steps 2 and 3 are repeated till the hole structure is done

finishing layer of cement is added

Step 5
Structure is com-plete

Freeform Structure Construction process

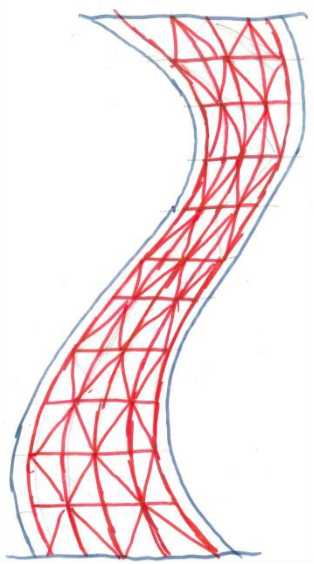
Option E



Reinforcement Concept based on manufacturing techniques

Reinforcement Concept design

3D printed mesh pattern



Material

Thermoplastic

Geometry

Any form in lattice structure format ++

Reinforcement optimization

Cell adjustment and creating duplicated lines +

Formwork integration possibility

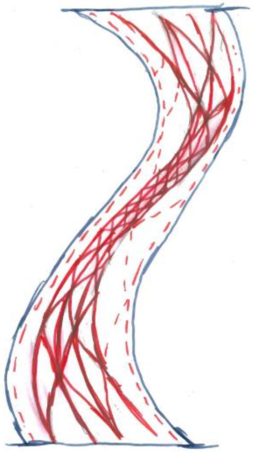
Yes ++

Waste during production

No ++

Reinforcement Concept design

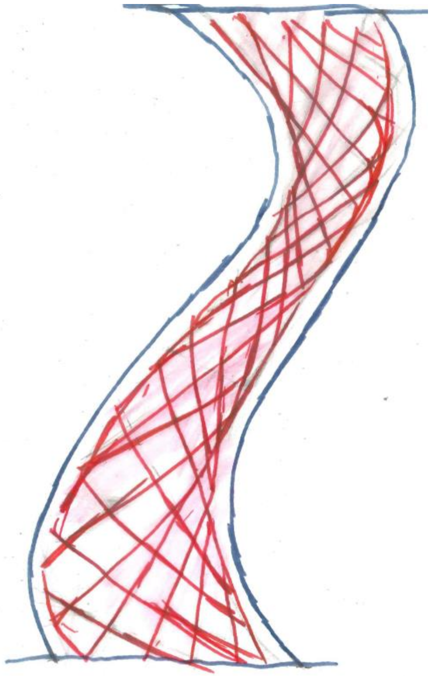
Metal Welding Mimicking tensile stress trajectory line



Material
Steel
Geometry
Any form - Trajectory tensile stress lines **+**
Reinforcement optimization
Mimicking stress lines in a 3D boundary **+++**
Formwork integration possibility
No **--**
Waste during production
No **++**

Reinforcement Concept design

Woven fiber filaments



Material

Continuous fibers

Geometry

Line based hallow tube **--**

Reinforcement optimization

Cell adjustment and creating duplicated lines **+**

Formwork integration possibility

Yes **++**

Waste during production

Pinned cross sections **+**

Reinforcement Concept design

Fiber placement with epoxy on rotating mold

Material

Continuous fibers

Geometry

Geodesic line based hallow structure **+**

Reinforcement optimization

In a 2d boundary – Adding extra geodesic lines where its needed **++**

Formwork integration possibility

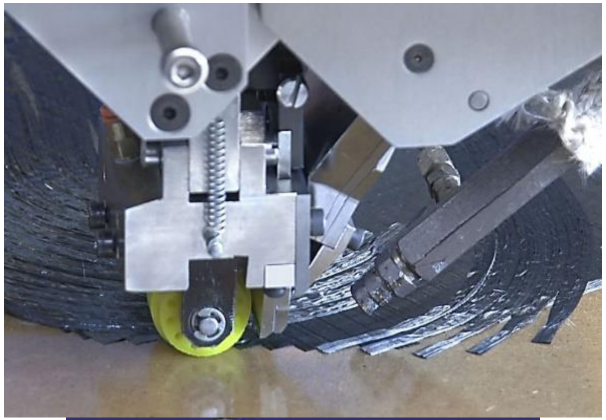
Yes only by increase of line density **+**

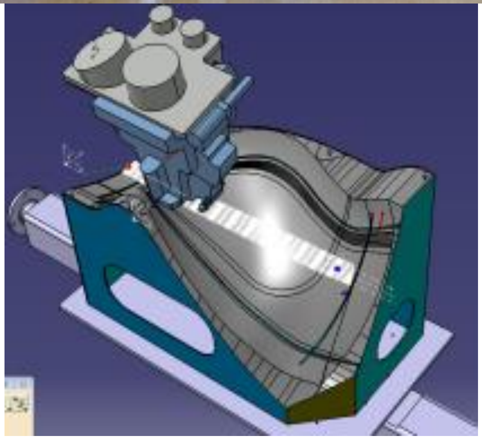
Waste during production

Yes rotating mold **--**

Reinforcement
Concept design

Fiber placement with epoxy on fixed mold





Material

Continuous fibers

Geometry

Freeform 2D plane **±**

Reinforcement optimization

In a 2d boundary – Adding any extra lines **++**

where its needed

Formwork integration possibility

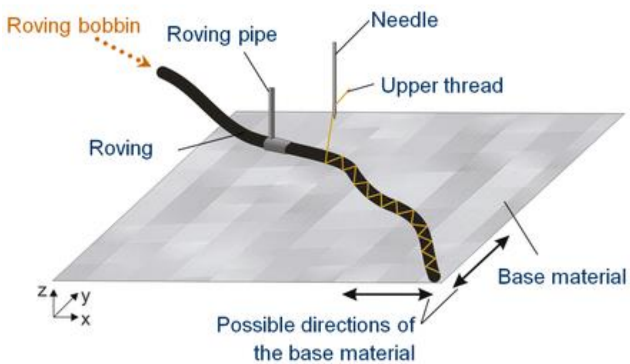
No **-**

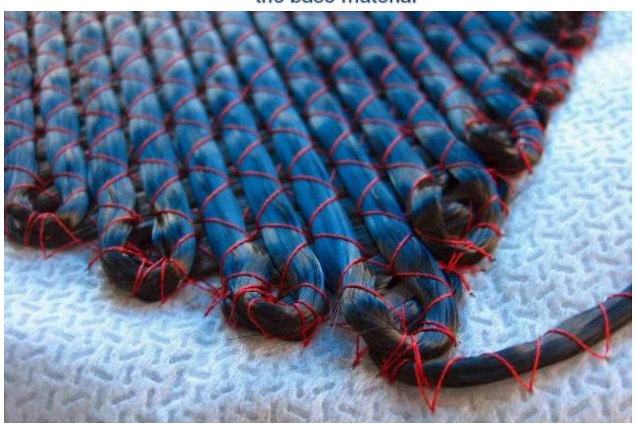
Waste during production

Yes Fixed mold **--**

Reinforcement Concept design

Fiber knitting technique





Material

Continuous fibers

Geometry

Textile 2D plane ±

Reinforcement optimization

In a 2d boundary – Adding extra lines where its needed ++

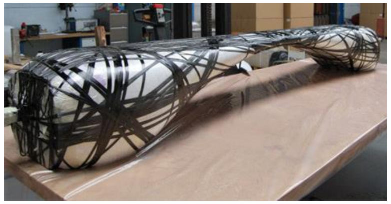
Formwork integration possibility

No -

Waste during production

Yes/No Supporting mold for the textile ±

Graduated Reinforcement Concept



Thermoplastic

Printed lattice mesh — **Geometry** **Formwork integration** **Waste**

Fiber

Knitting technique — **Reinforcement optimization**

Placement on rotating mold — **Reinforcement optimization**

Steel

welding — **Reinforcement optimization**

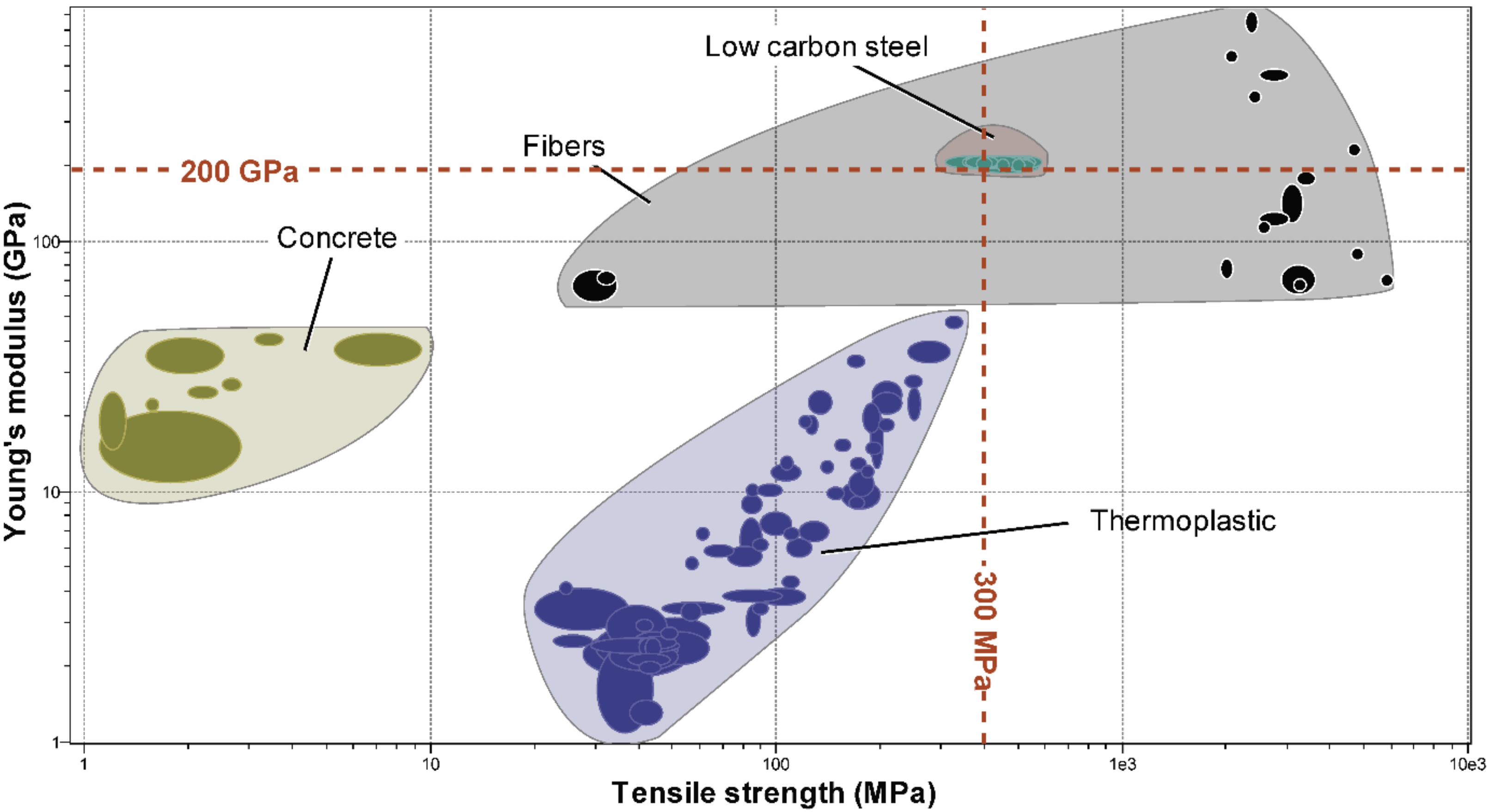
Material study

- **Physical strength**
  - **Advice**
- **Compatibility with Concrete**
- **Selecting compatible materials**
  - **Price , ect ..**

Steel does not need further study, it's an established reinforcement material

Material study

Material strength



Material study

Comparing it with steel and advice

Thermoplastic mesh system

- Lower Young Modulus and tensile strength
  - This system will be more denser than steel reinforcement

  Advice:

  No or upgrade the strength of material

Fiber based system

- Higher Young Modulus and tensile strength
  - This system will be lighter than steel reinforcement

  Advice:

  YES

Material study

Concrete compatibility

Chemical Character

Elementary material	pH
Fresh cement	>12.5
Low alkali cement	12.7 to 13.1
High alkali cement	13.5 to 13.9
High alumina cement	11.4 to 12.5
Mixing water for concrete	6 to 9
Sea water	7.5 to 8.4
Hardened cement paste with ingress of sea water	12.0
Class F fly ash	>13.2
pH of silica fume concrete	>12.5

- It's a strong Alkali material -

Material study

Concrete compatibility

CES database Criteria for compatibility

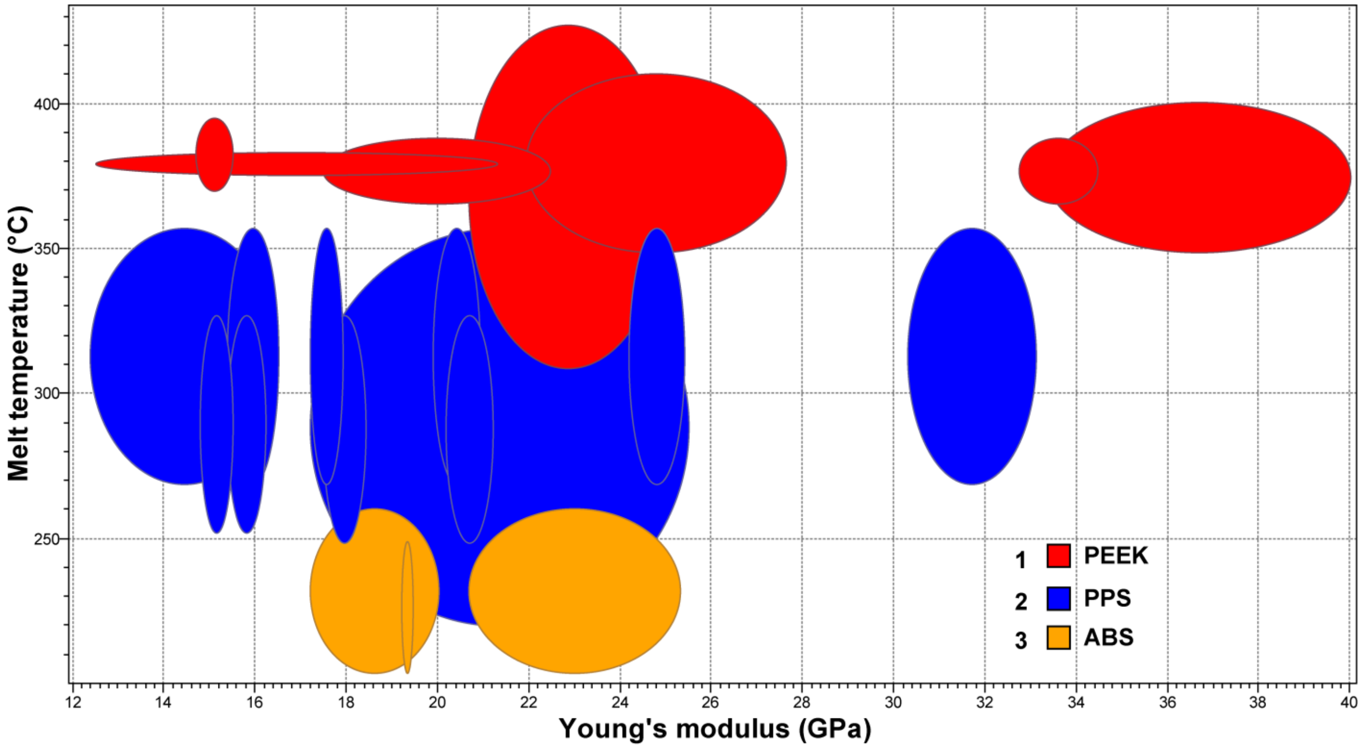
criteria	Rating
Water (fresh)	Excellent
Water (salt)	Excellent
Weak alkali	Excellent
Strong alkali	Excellent or Acceptable

Material study

Compatible thermoplastic material

Melting point VS Young modulus

Standard 3d printer can reach temp of 280°

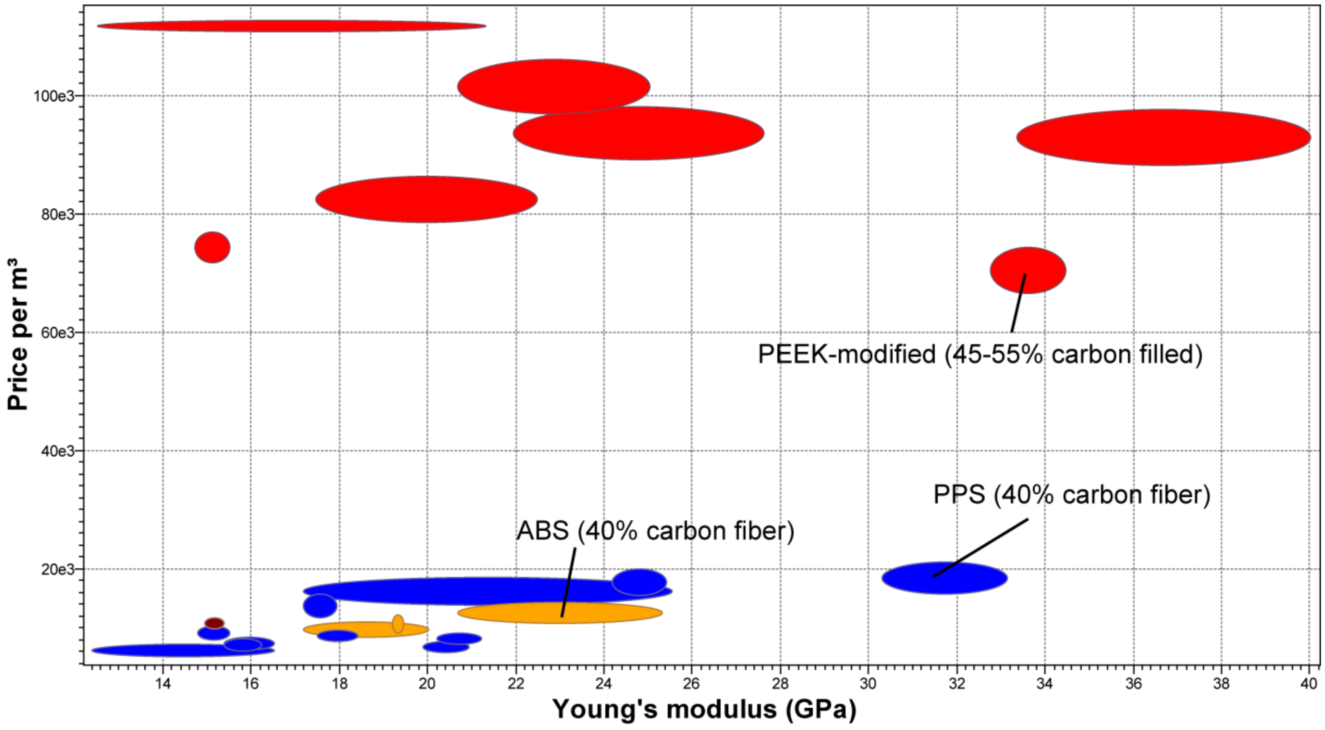


Material study

Material selection

Compatible thermoplastic material

Price per volume VS Young modulus

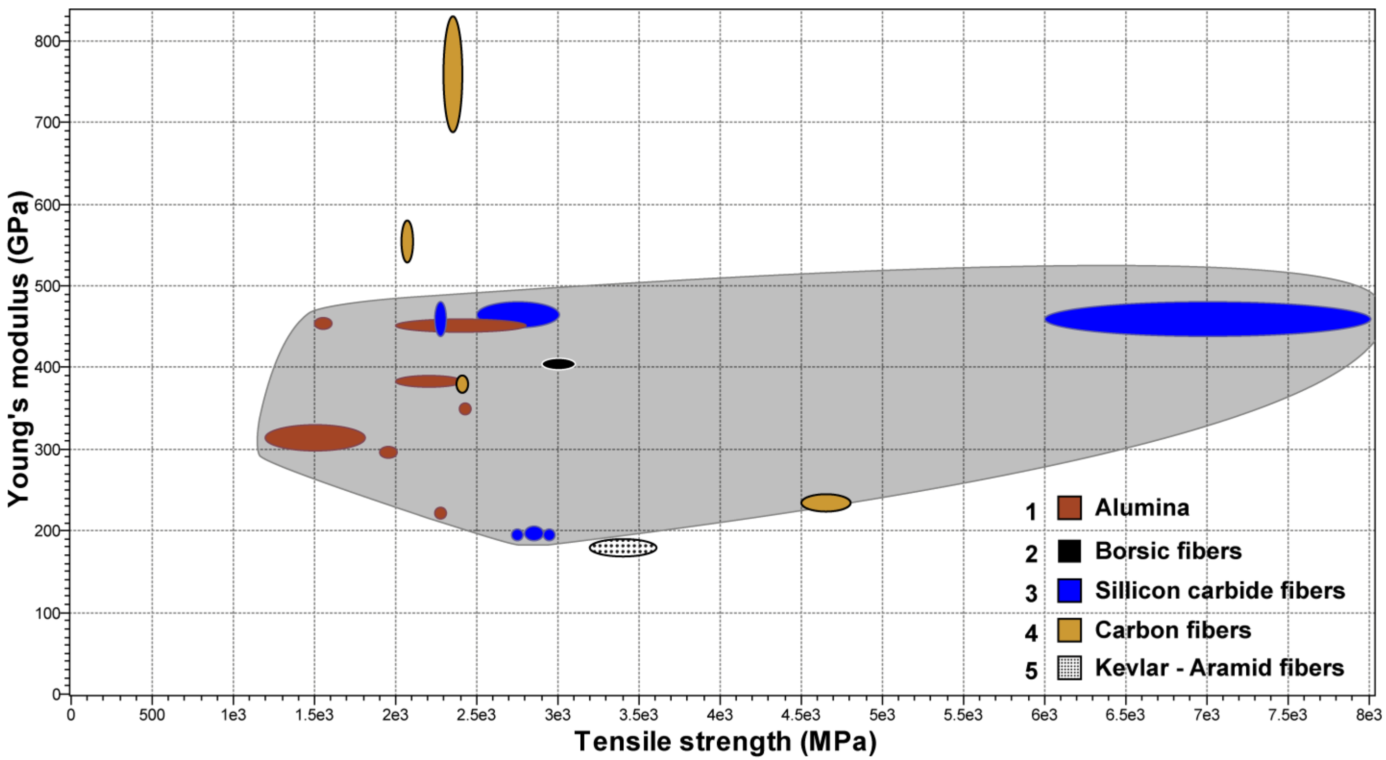


Material study

Material selection

Compatible fiber material

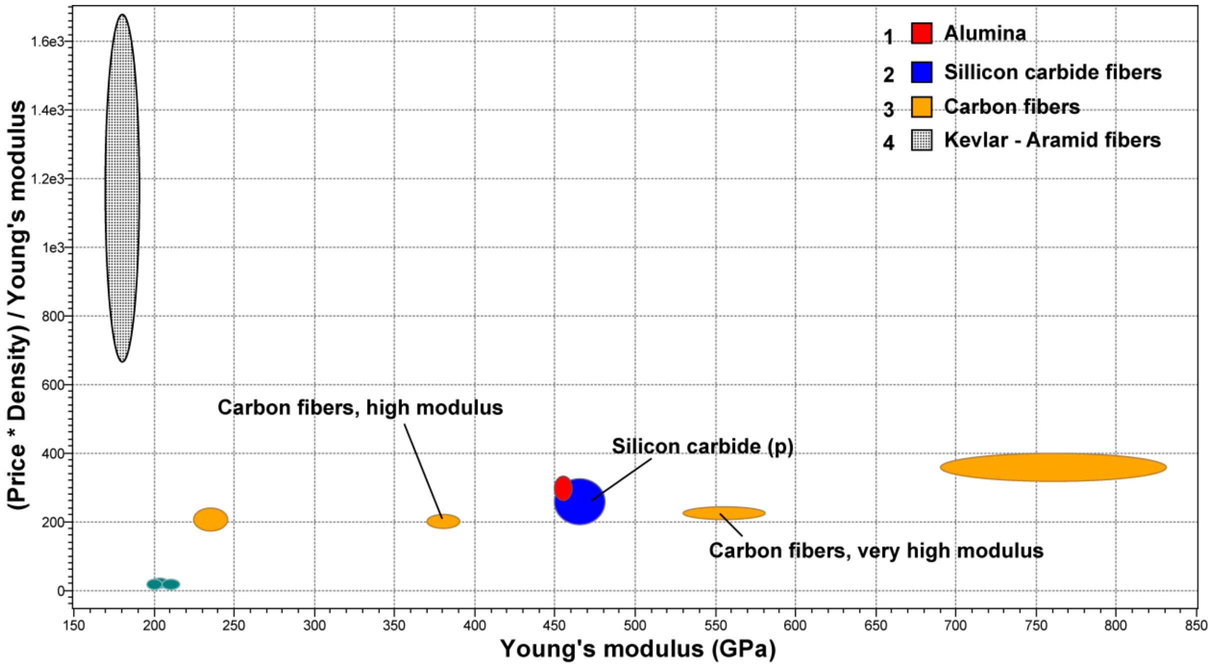
Tensile strength VS Young modulus



Material study

Compatible fiber material

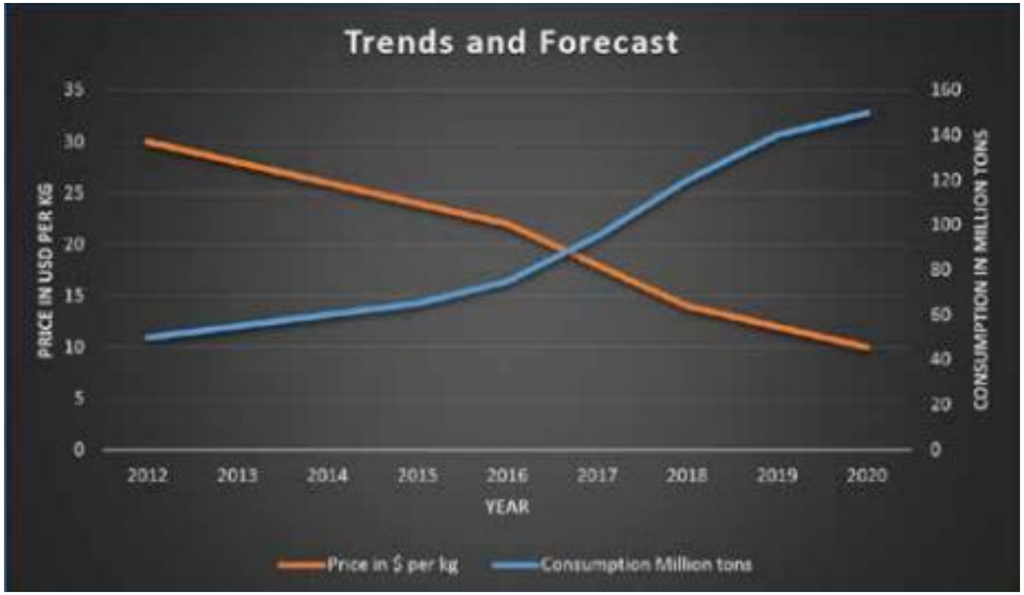
Price per volume of material needed for reinforcement VS Young modulus



Material study

Compatible fiber material

Price for a fiber based system is 10 to 15 time higher than steel



Prices will drop in future as fiber production technology advances

Material study

Selected materials

Fiber

- Silicon carbide (p)
- Carbon fiber Very high modulus
- Carbon fiber high modulus

Thermoplastic

- ABS (40% carbon fiber) – *Suitable with standard 3d printers*
- PPS (40% carbon fiber)
- PEEK (45-55% carbon filled)

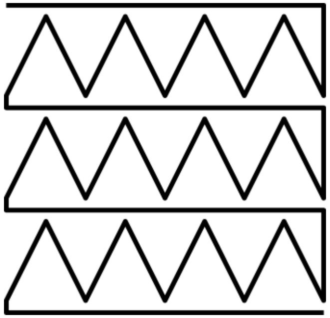
Converting reinforcement concepts to designs

Based on material study feedback

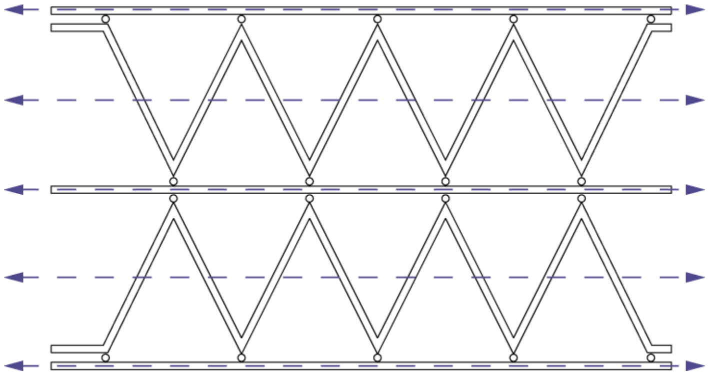
Thermoplastic mesh Design

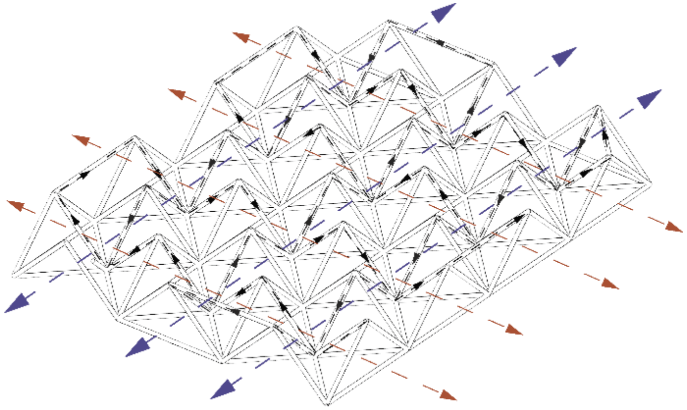
Design issues

- **Material strength**
  - Low young modulus



- **Geometrical strength**
  - Geometry has at least on weak axis

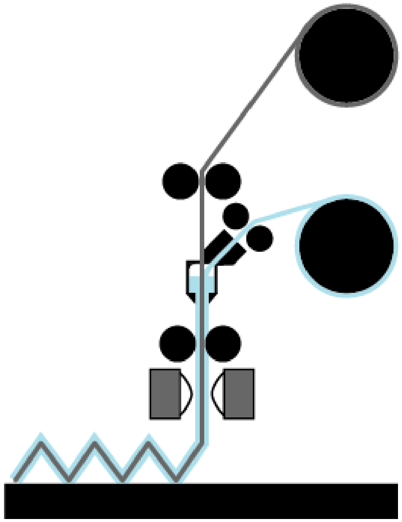


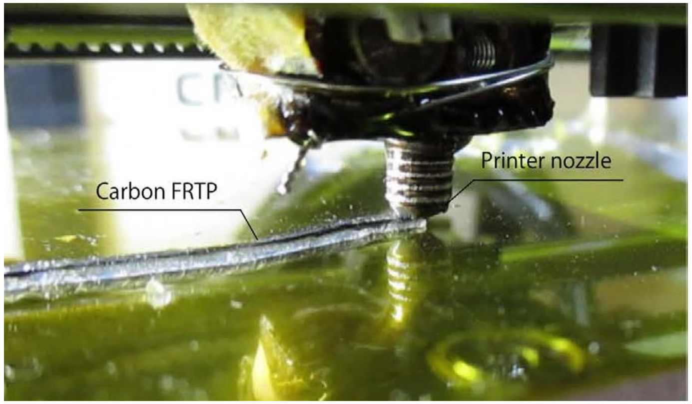


Thermoplastic mesh Design

Design issues

- **Material strength**
  - Reinforce thermoplastic material with continuous fibers
  - Not tested for mesh type of geometry



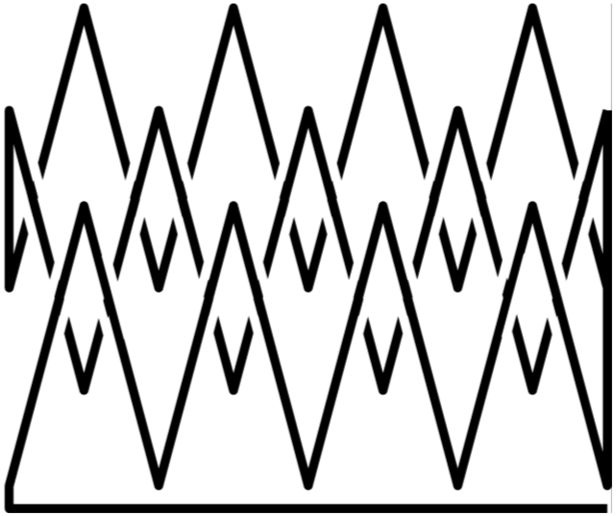


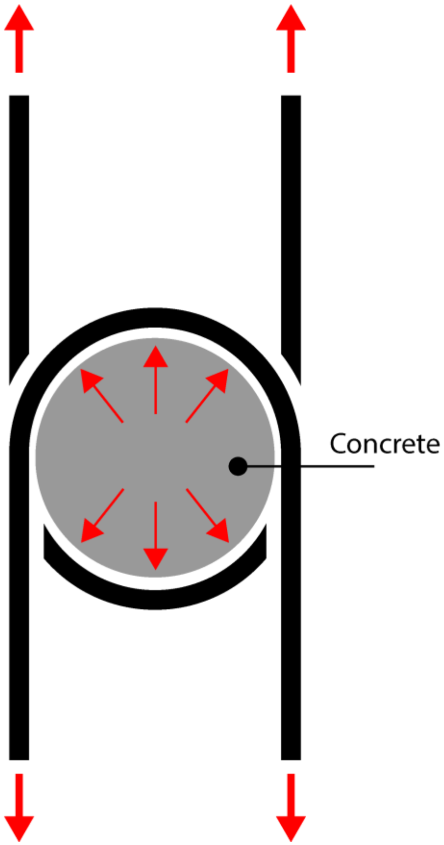
Thermoplastic mesh Design

Design issues

- **Geometrical strength**
  - Overlapping system

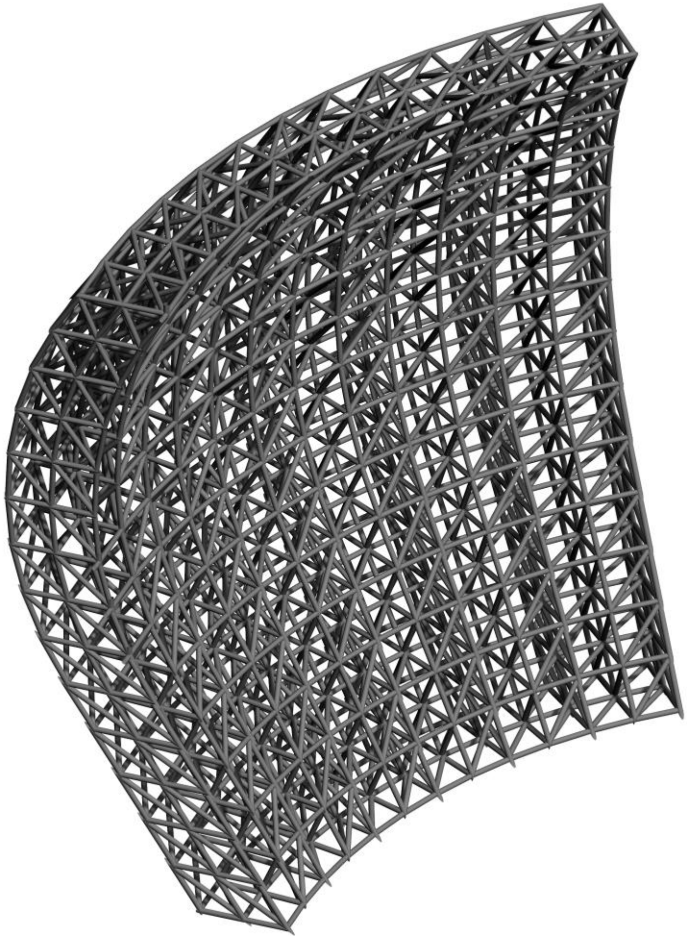
Not feasible due to its high complexity





Thermoplastic mesh Design

Final Design

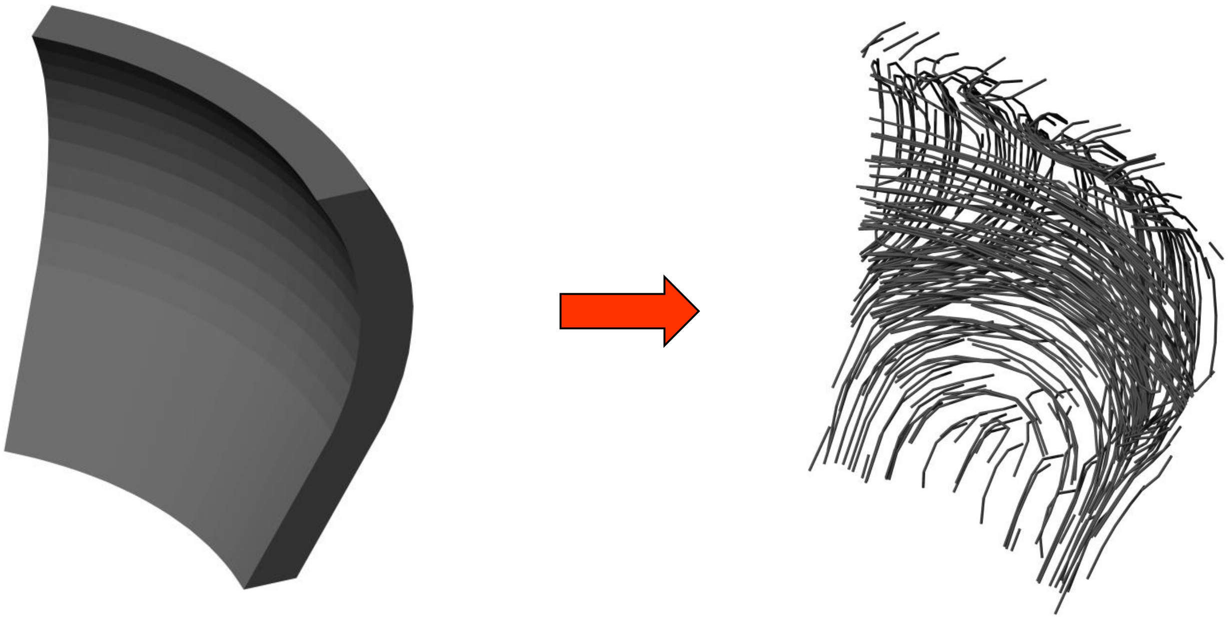


Not practical

Geometric strength not solved

Metal welding Design

Tensile trajectory lines



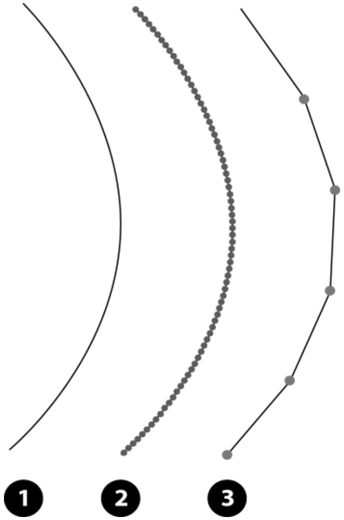
Welding of the entire reinforcement structure

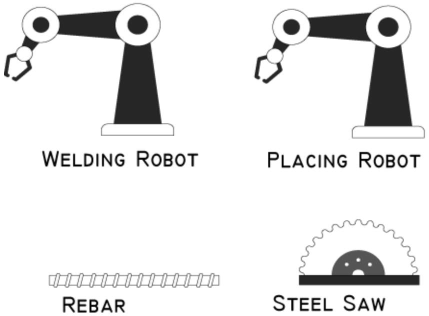
- *Time intensive*
- *High energy demand*
- *It's a non self standing structure*

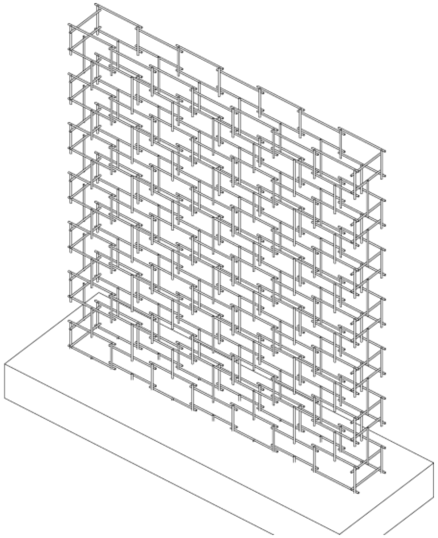
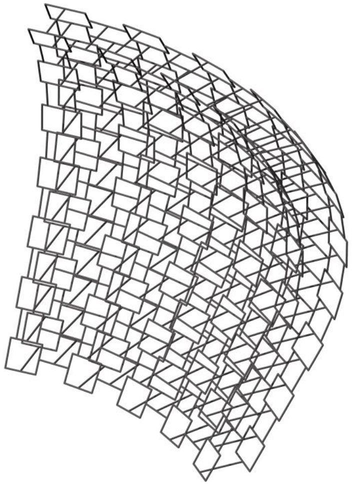
Metal welding Design

Steel lattice mesh





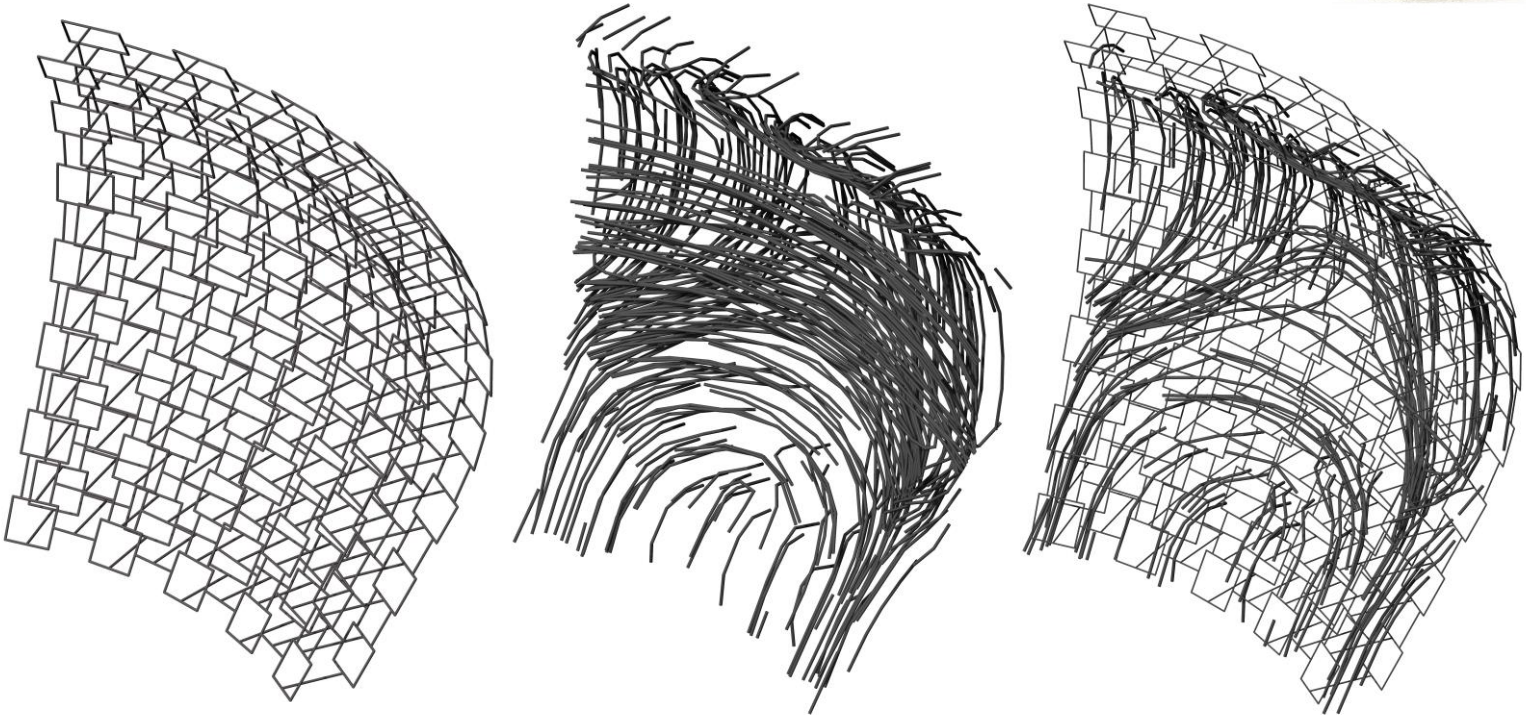


welding segments instead of whole structure

- *Less time*
- *Less energy*
- *More tools are necessary*

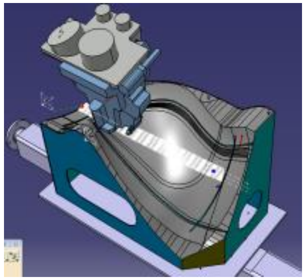
Metal welding Design
Final design



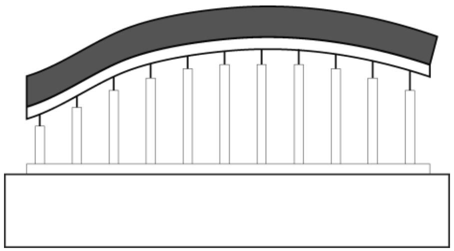
Practical
Need to get further designed

Fiber Placement Design

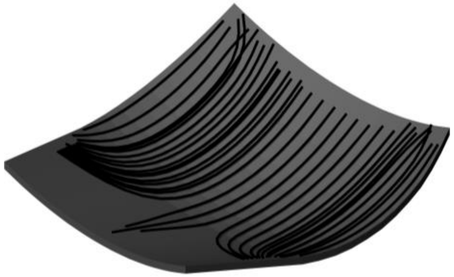
Flexible Mold + embedded concrete panels



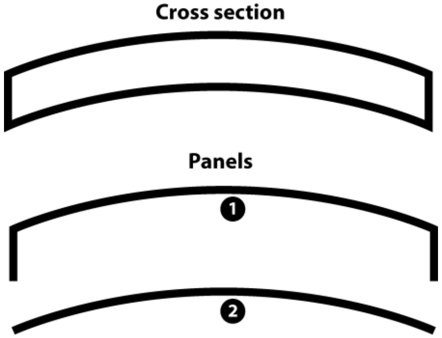
- Connecting panels reinforcement structures are challenging
- No possibility for sharp edges
- Flexible mold size is limited to 1.5x1.5m



Flexible Mold Concrete Panels



Placing fibers on concrete panels



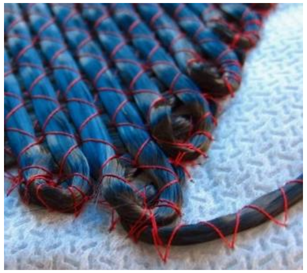
Connecting panels

Not practical

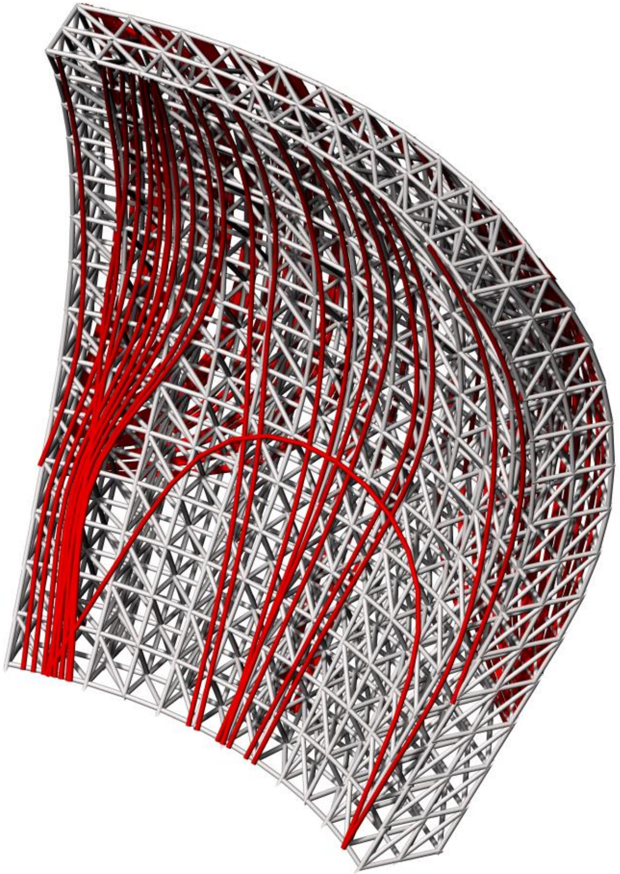
Not the best option at the moment
Further research might create a better option out of it

Mixed concept design

Lattice mesh + Fiber knitting



- **Geometric problem of mesh is solved by the exterior layer**
- **High reinforcement optimization of fibers system are achieved**
- **Fiber placement system does not create waste**
- **Reinforcement system is not panelized**

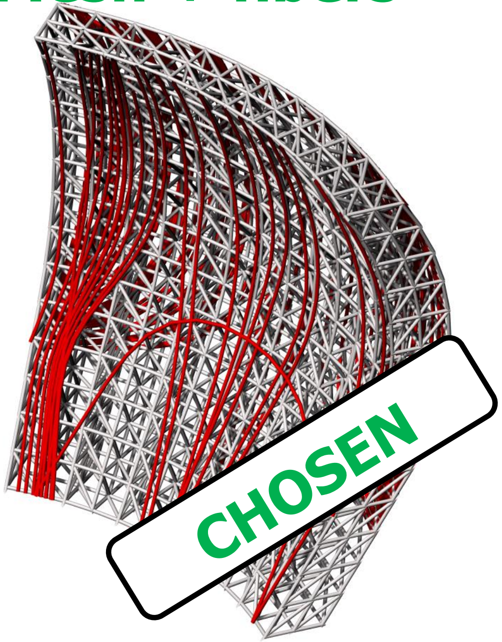


Practical

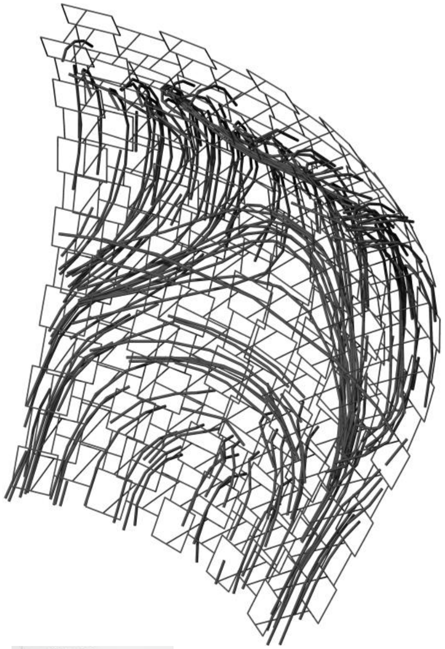
Need to get further designed

Practical reinforcement design

Mixed concept
Mesh + fibers




Metal welding
Steel mesh



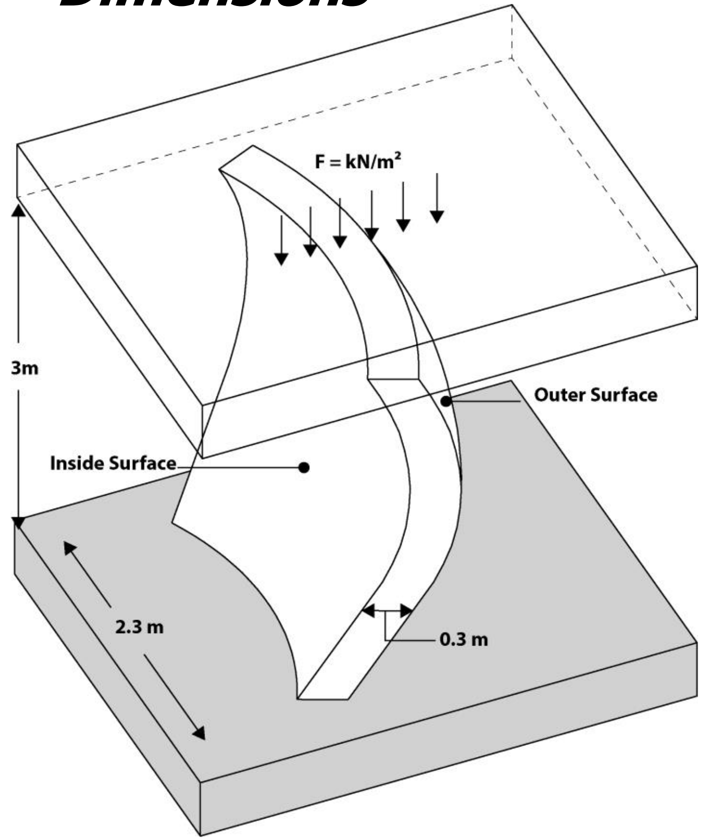

Season 2
Final Design

Applying the selected reinforcement system to a freeform structure

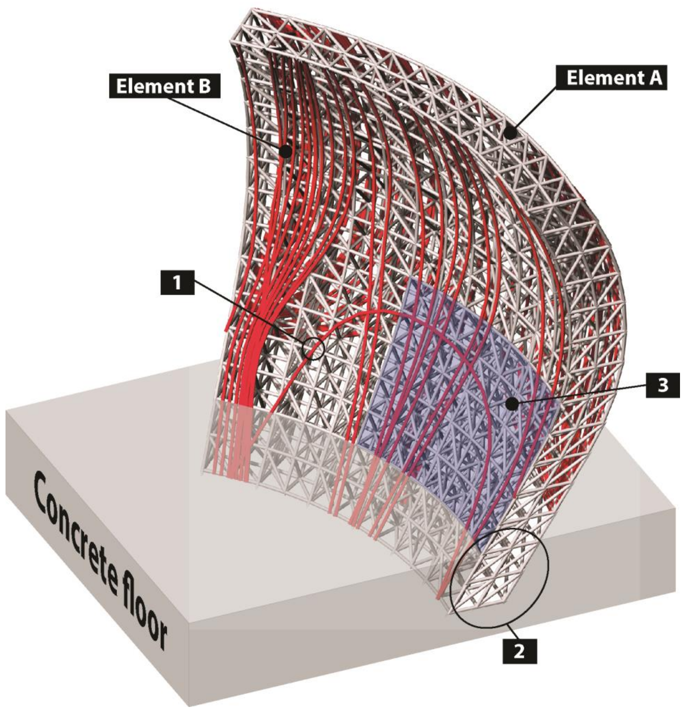
Chosen reinforcement system

Defining a geometry for detailing

Dimensions



Points that need development



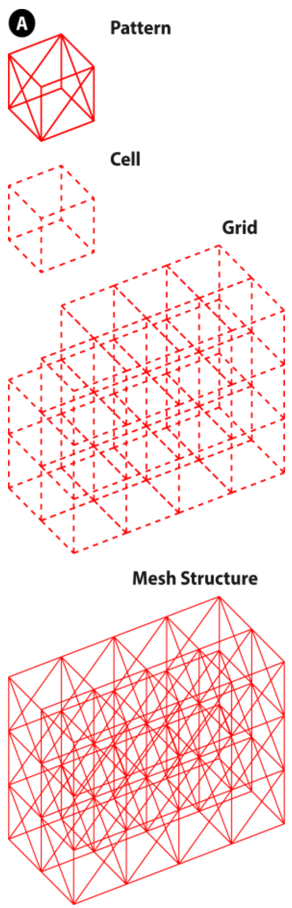
Mesh structure
requirements

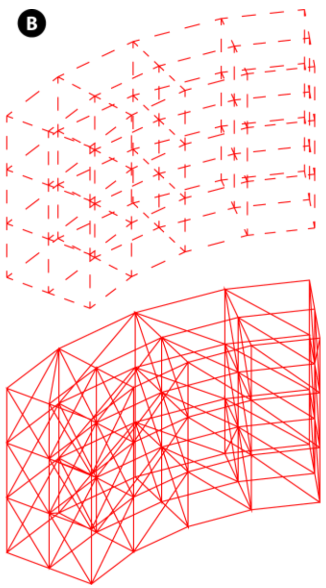
- Mesh structure printed with continuous fibers reinforced ABS material
- A Mesh system consisting out of one continuous line

Mesh structure

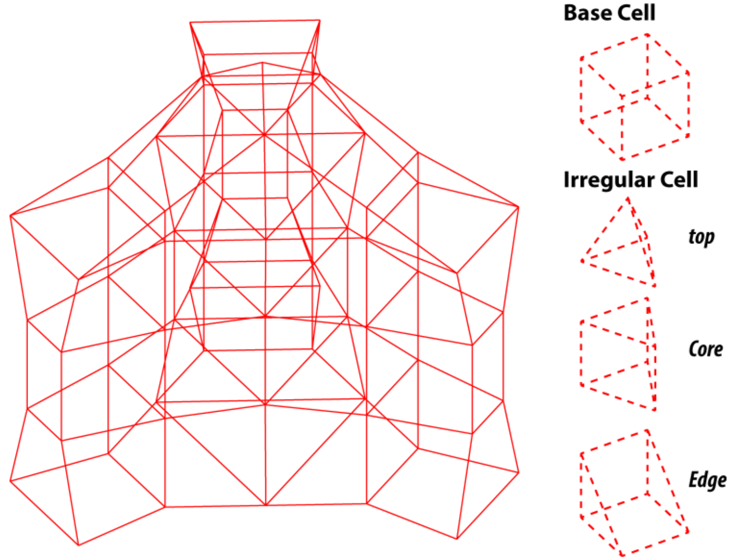
Mesh systems

One cell based grid





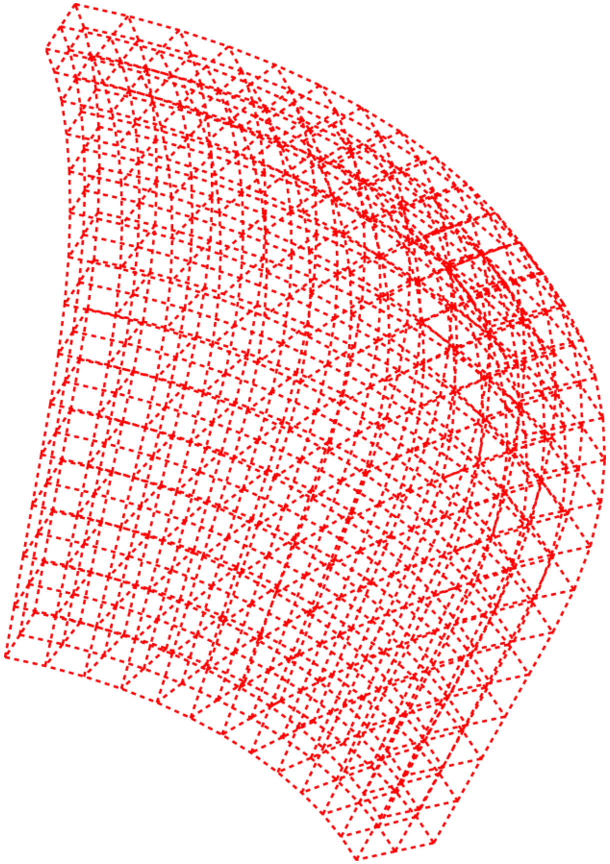
Multi cell based grid



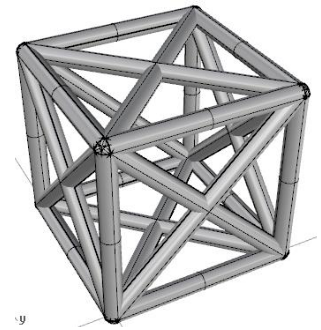
Mesh structure

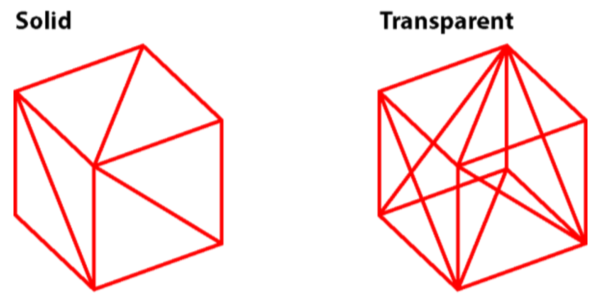
Defining a grid and a pattern

One cell based grid



Cell pattern





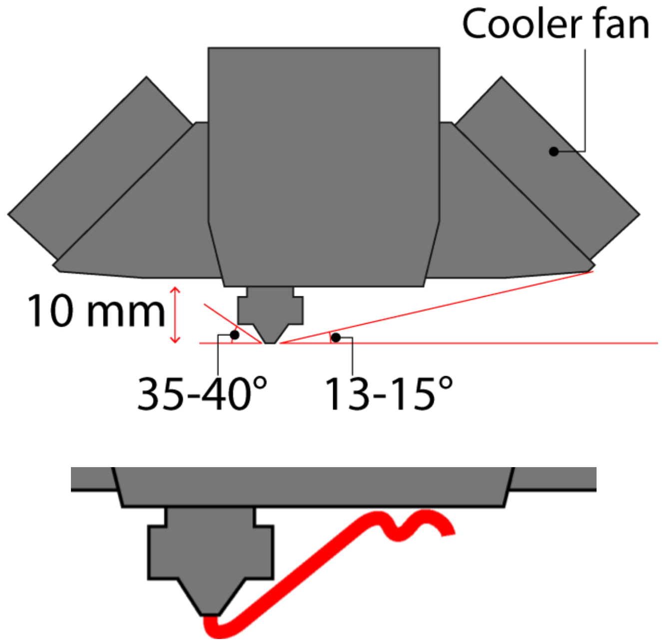
Mesh structure

FDM (3d printer) system limitation

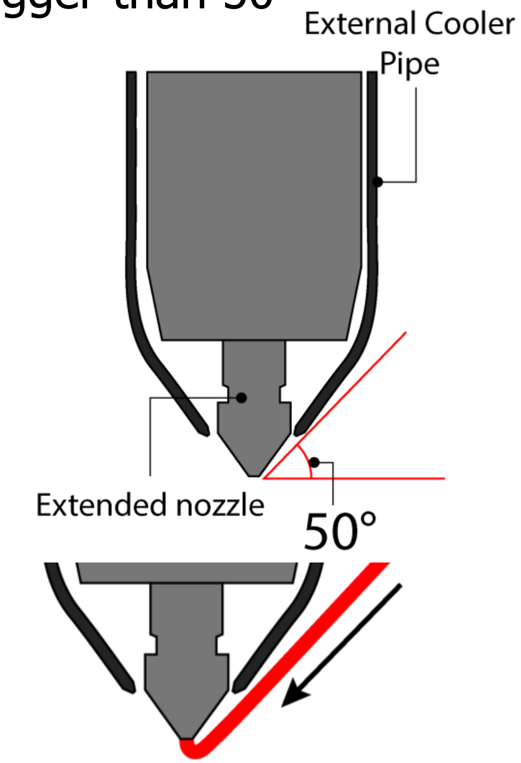
Downward printing collision issues

Downward printed lines should not have an angle bigger than 50

Standard setup



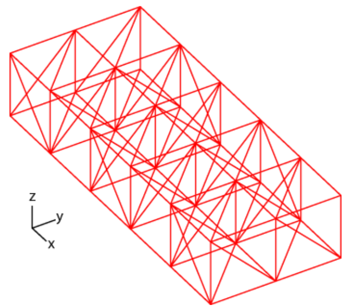
Modified setup



Mesh structure

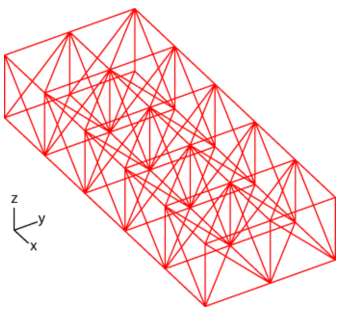
Converting mesh to a continuous line

Multi pattern, one cell based grid system

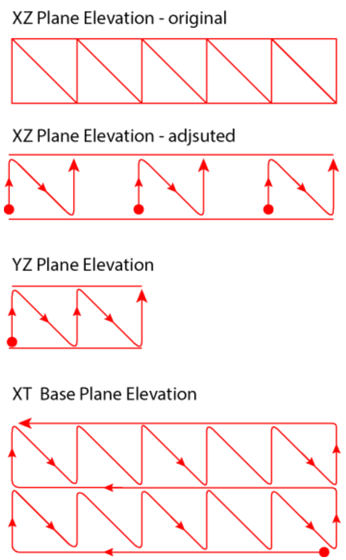


Result

Original

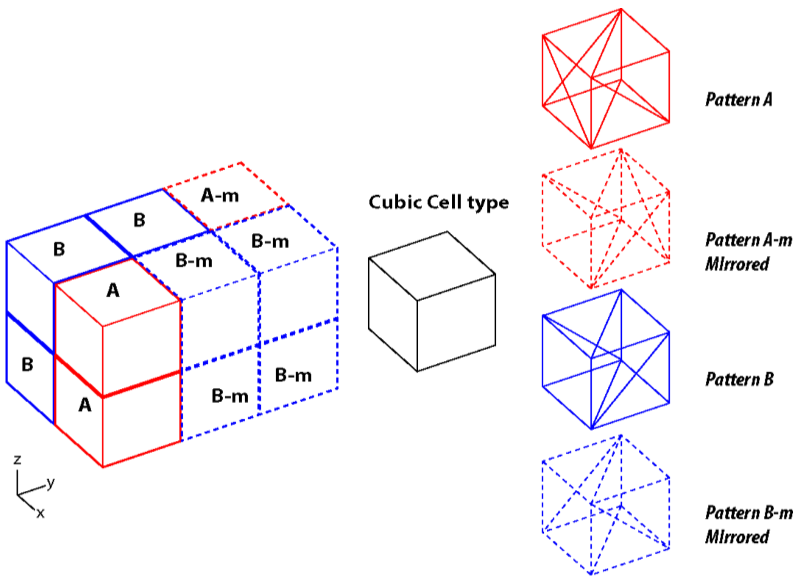


Modifications



New system

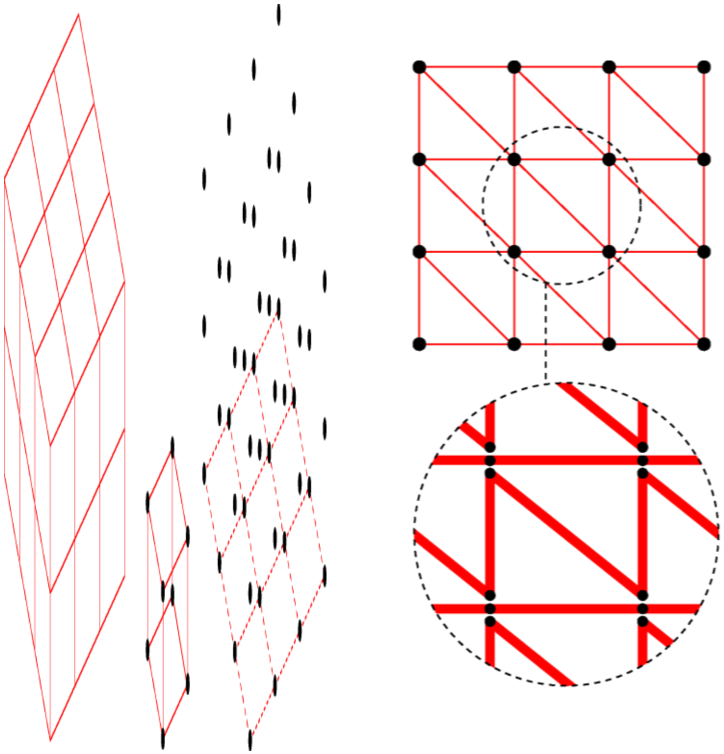
For continuity



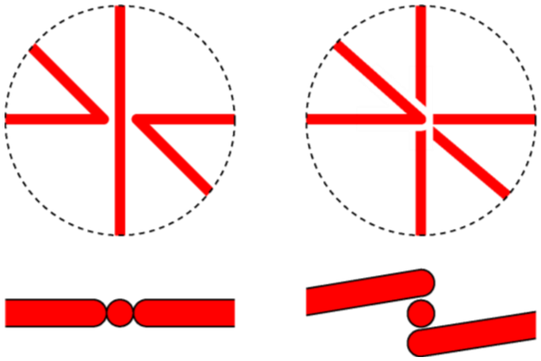
Mesh structure

Converting continuous mesh to practical executable design

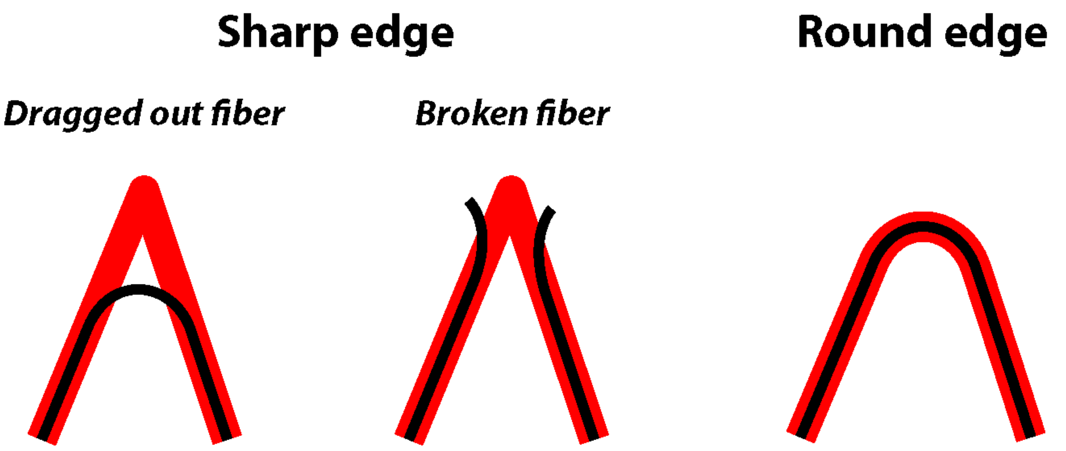
Line thickness



Internal supports



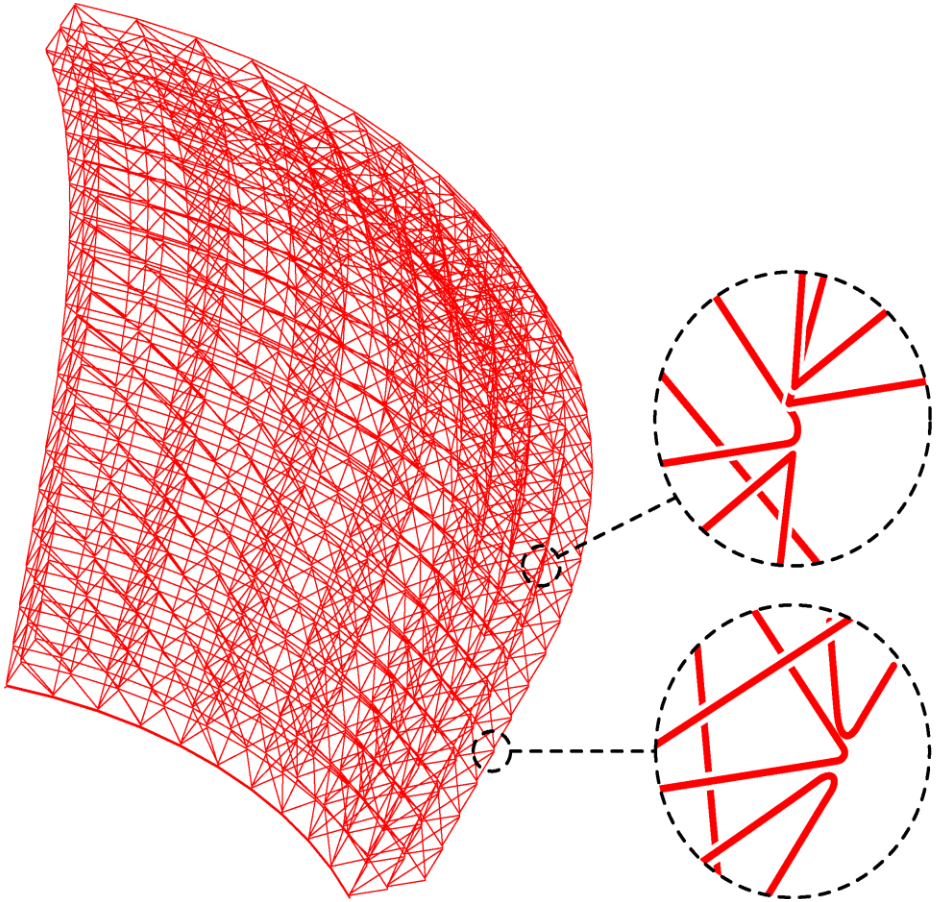
Mesh structure
Carbon fiber integration design adjustments



- Instant cooling
- Low speed print

Mesh structure

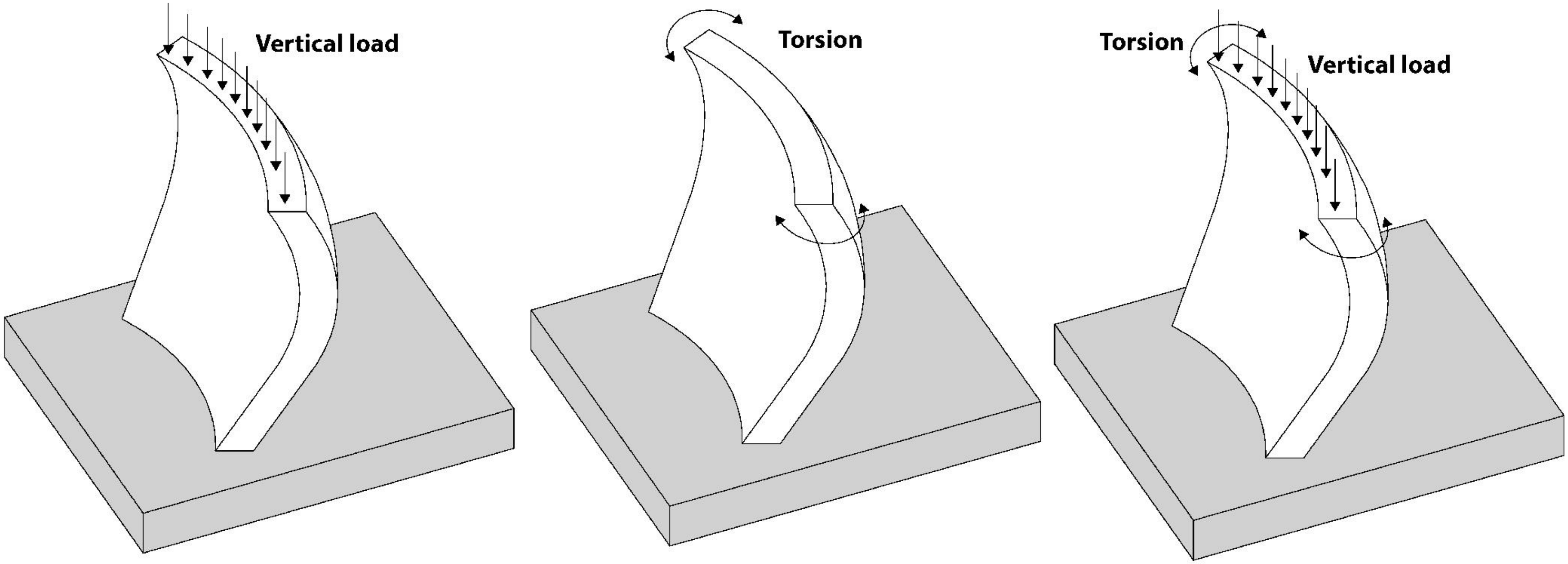
Final mesh design



Future investigation

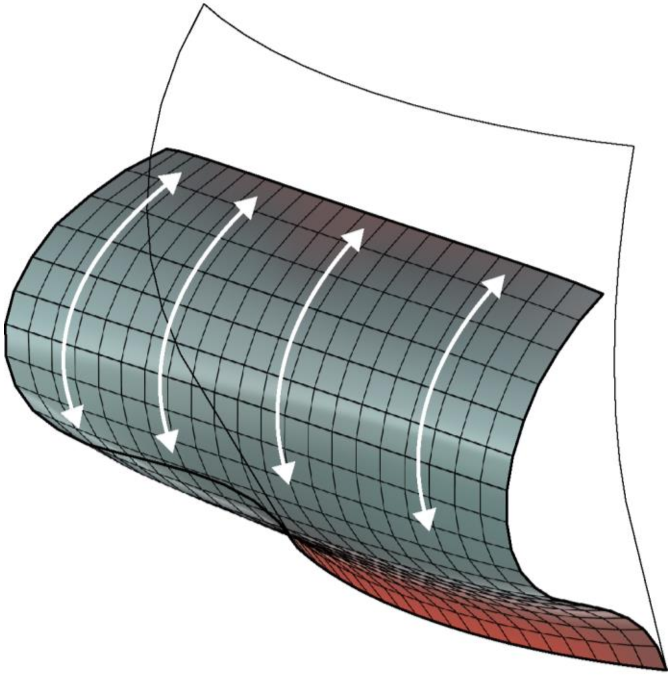
- Investigate other mesh patterns
  - *After transformation*
- Structural calculation for the needed line thickness

Outer Fiber reinforcement layer
Defining global load cases

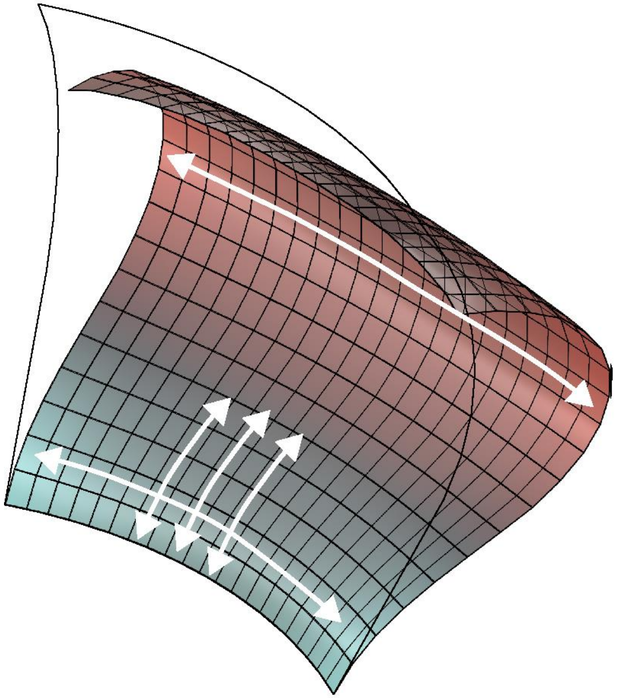


Outer Fiber reinforcement layer
Analyzing deformation and bending directions

Outside



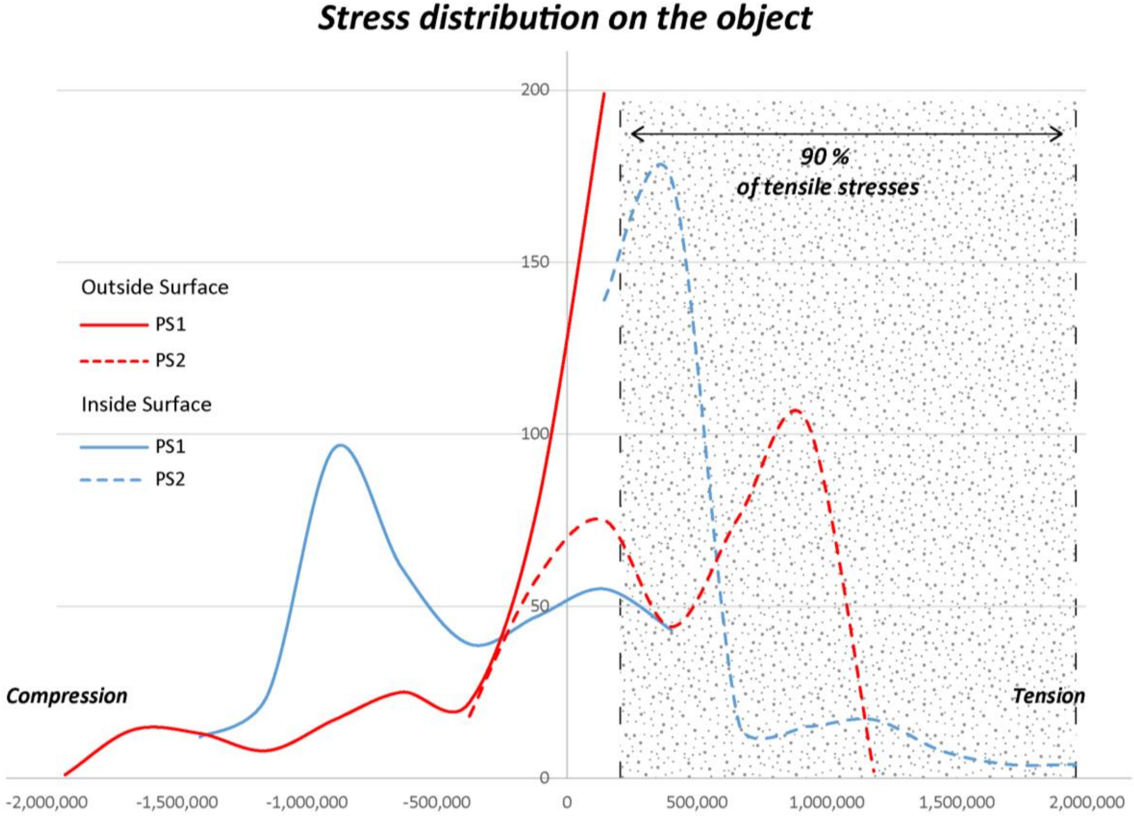
Inside



Outer Fiber reinforcement layer

Defining reinforcement needed points

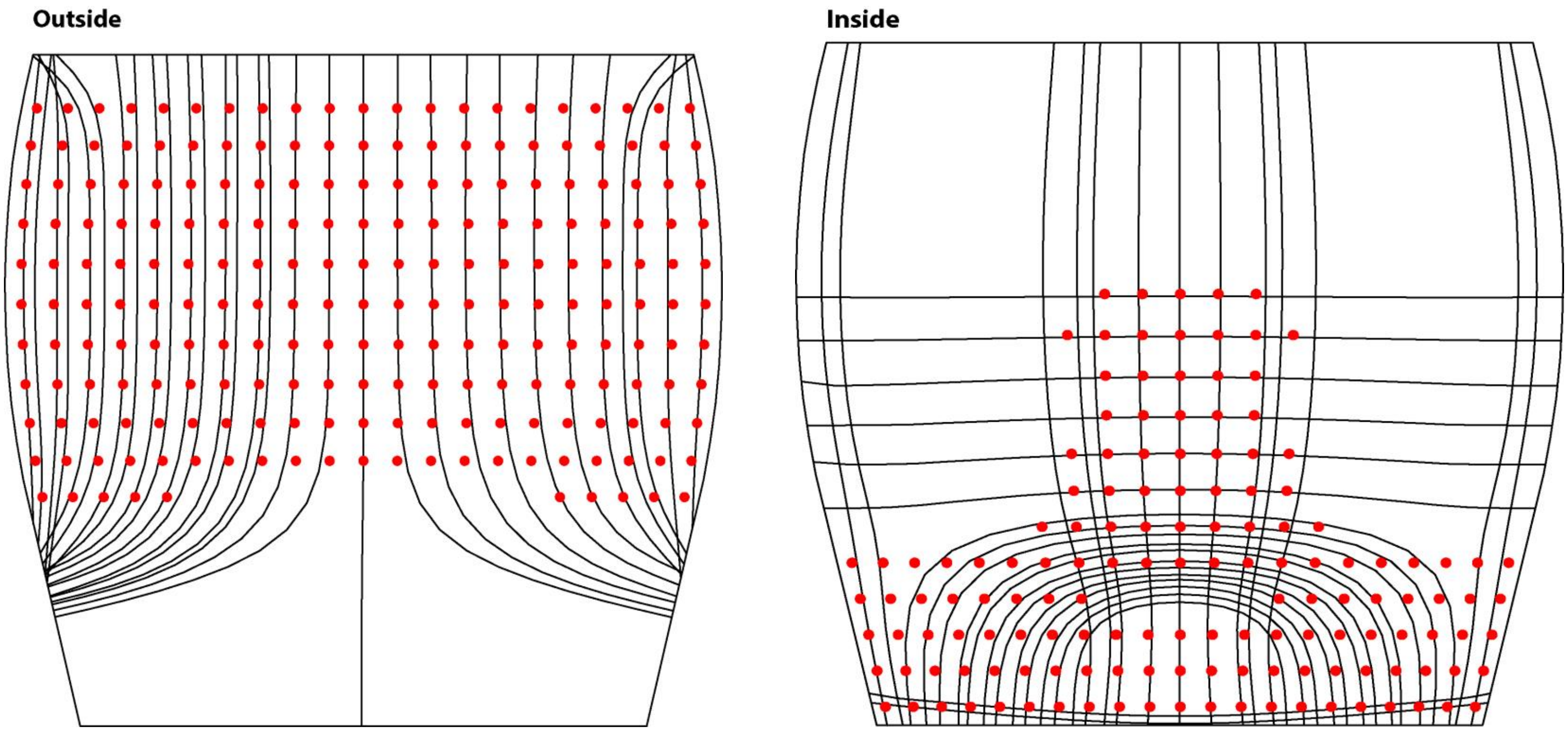
Structure is loaded for maximum concrete compression strength



Outer Fiber reinforcement layer

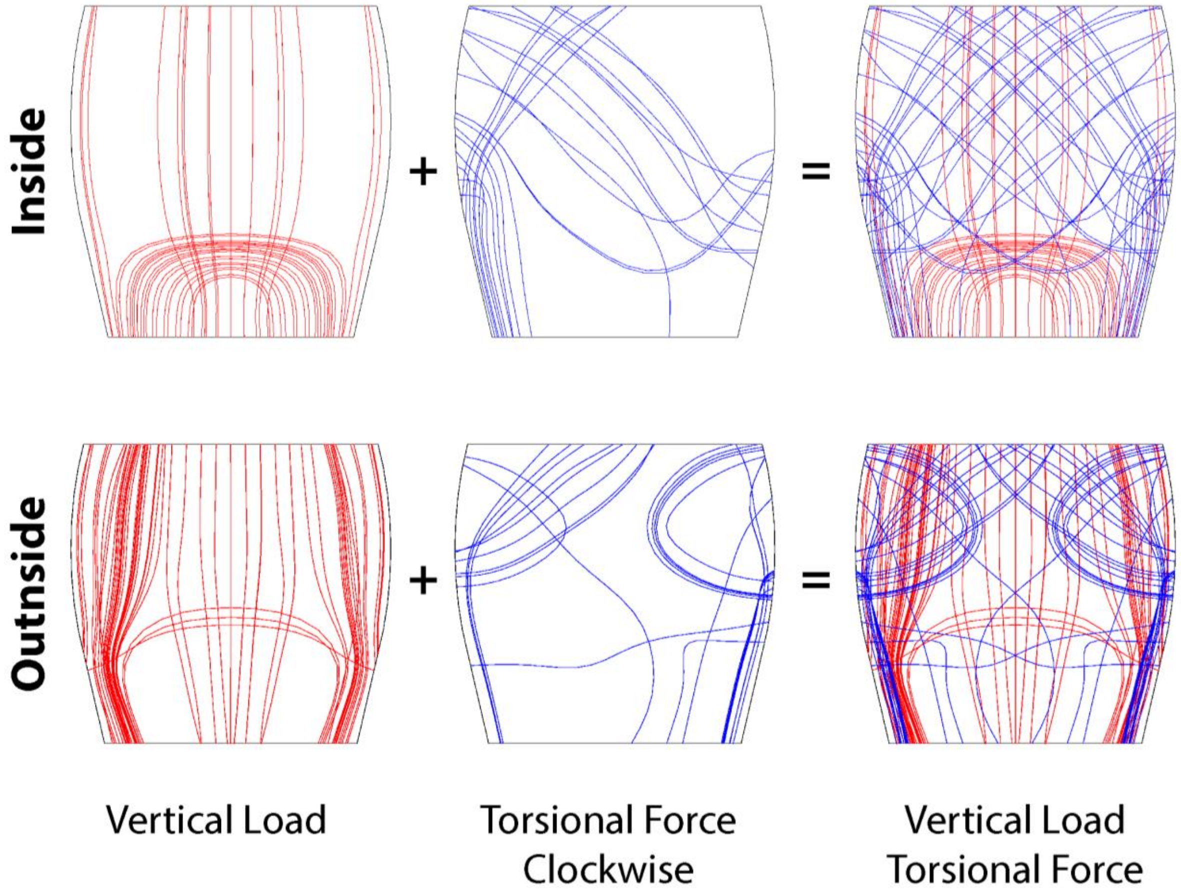
Defining reinforcement needed points

Tensile principal stress trajectory lines



Outer Fiber reinforcement layer

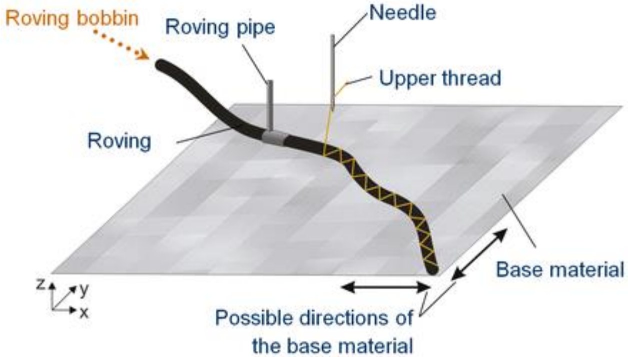
Defining reinforcement path



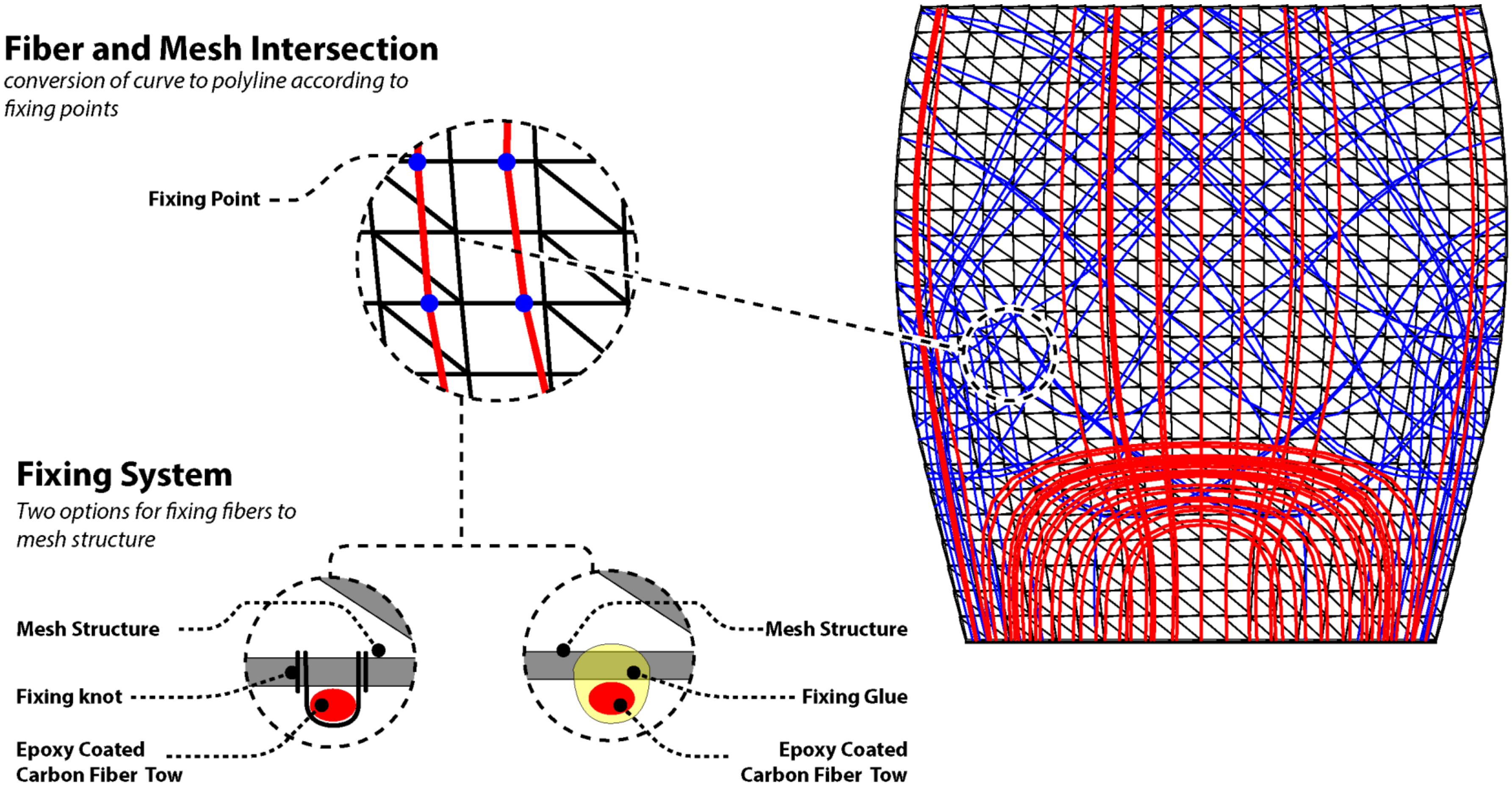
Outer Fiber reinforcement layer
Fiber placement on mesh

Knitting inspired fiber placement system

- *Fixing with knot*
- *Fixing with glue or thermoplastic mesh material*



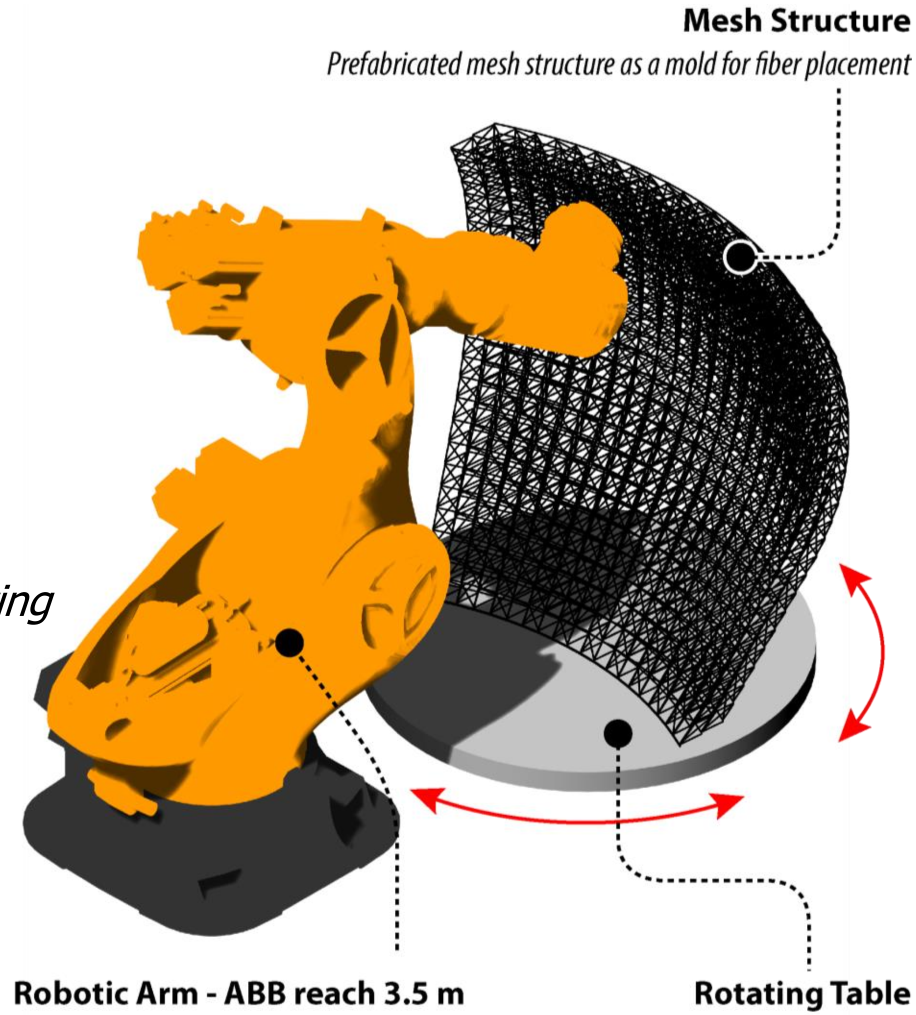
Outer Fiber reinforcement layer
Fiber placement on mesh



Outer Fiber reinforcement layer

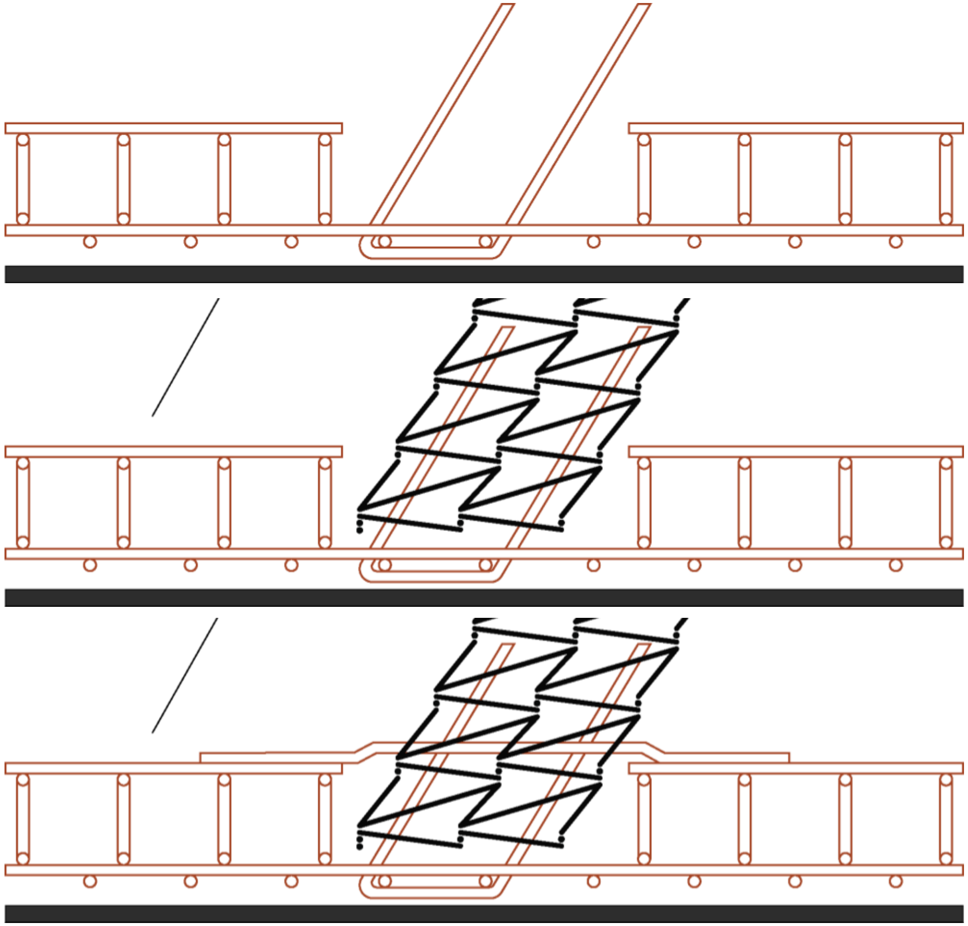
Manufacturing setup

- **Robotic arm**
  - ***Tools :***
    - *Fiber navigator head*
    - *Knitting head*
  - ***Materials***
    - *Carbon fiber row*
    - *Epoxy tank*
    - *Glue or material need for knitting*
- **Rotating table**
- **Printed mesh structure as mold**



Connection with conventional reinforcement

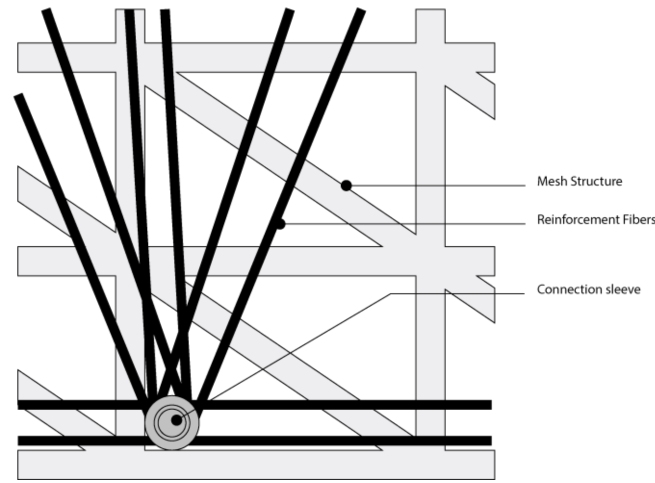
System 1 indirect connection

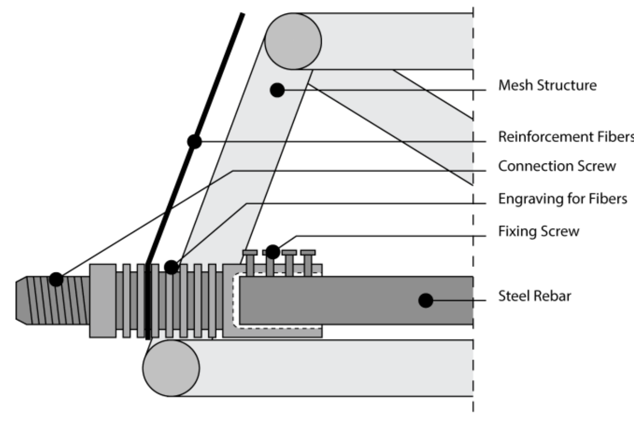


Connection with conventional reinforcement

System 2 Direct connection

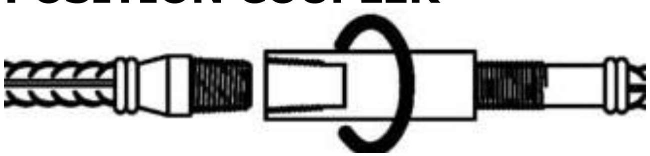
Wrapping fibers around a modified steel rebar sleeve



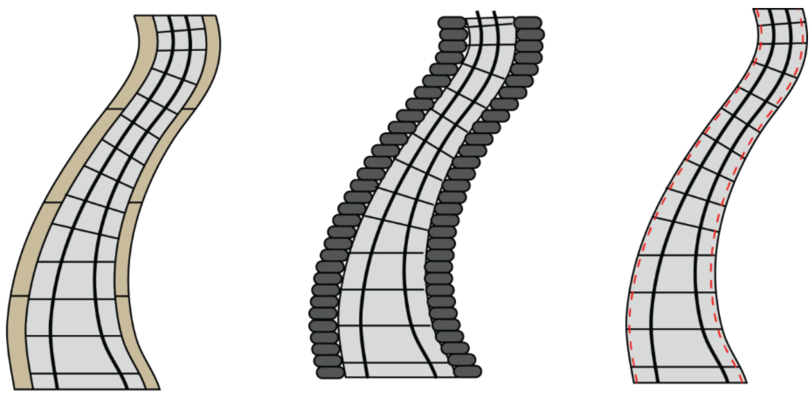


Screw lock system

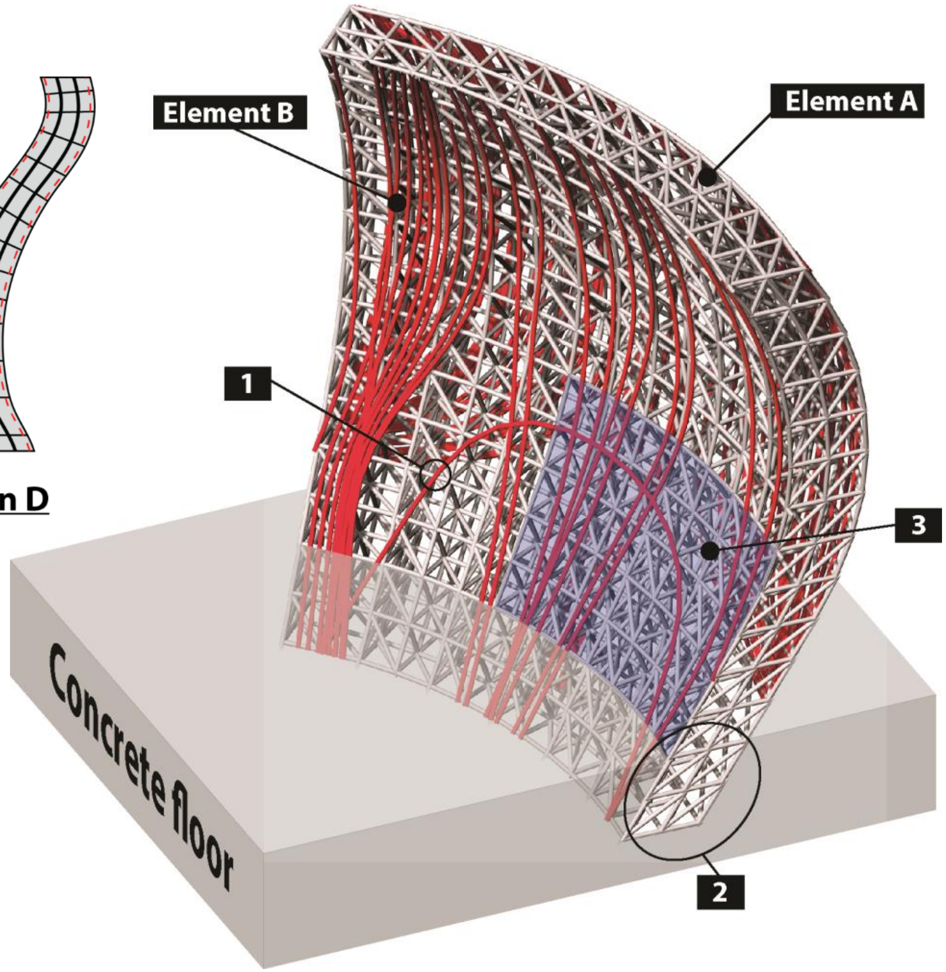
POSITION COUPLER



Concrete injection
Formwork strategy (3)

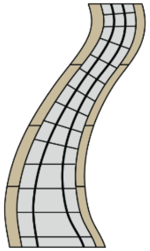


Option B   Option C   Option D



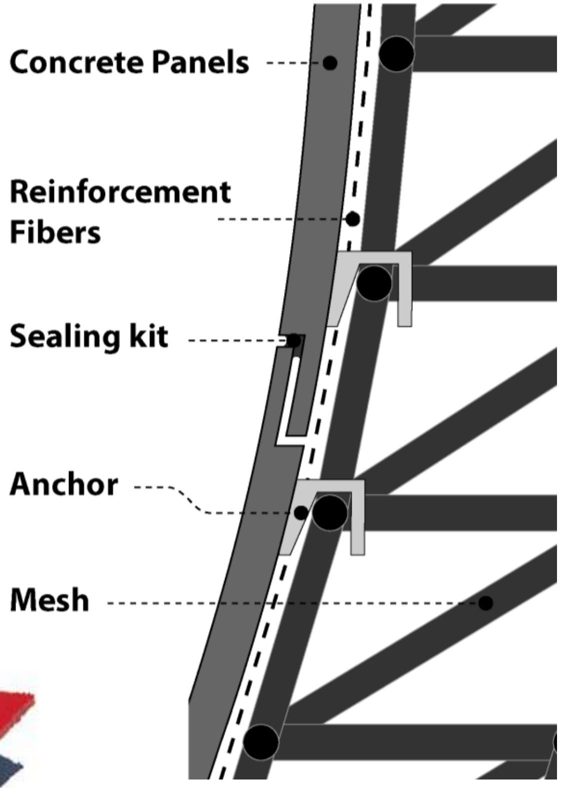
Concrete injection

Embedded concrete formwork



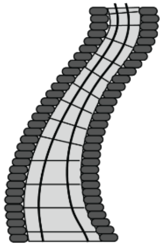
Flexible Mold system

+ Smooth finished surface
+ No waste
- Limited geometrical curvature
- No sharp edges are possible
- Extra weight for mesh structure



Concrete injection

Embedded concrete formwork



Option C

FDM produced system

+ sharp edges are possible

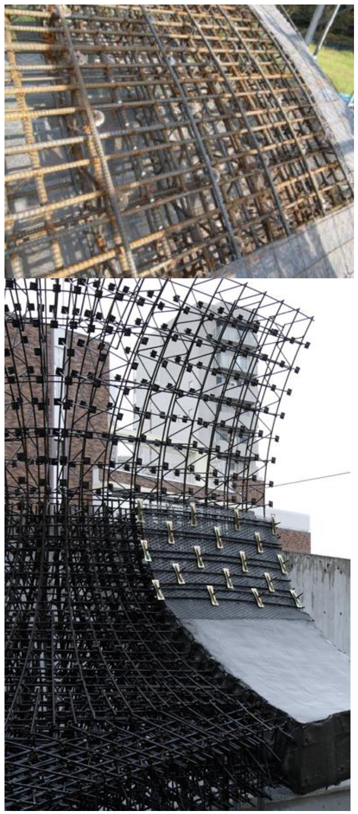
+ No waste

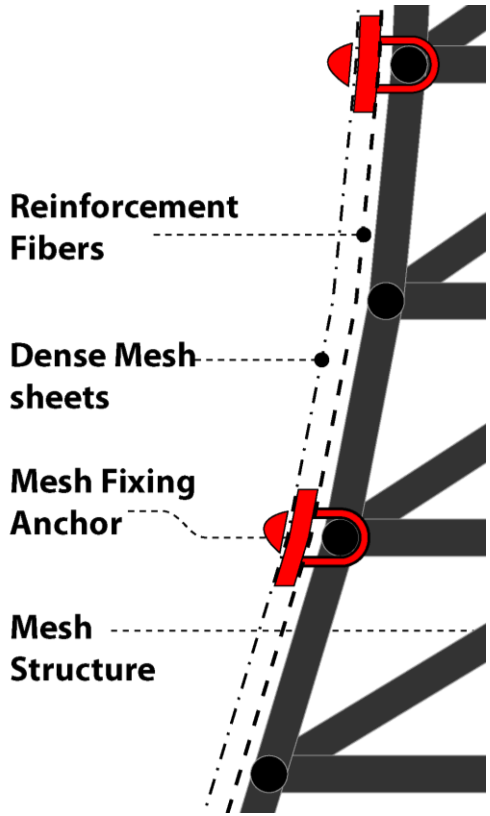
- Horizontal print pattern are visible

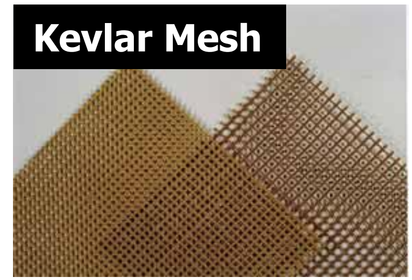
- Extra weight for mesh structure

Concrete injection

Dense mesh sheet embedded formwork



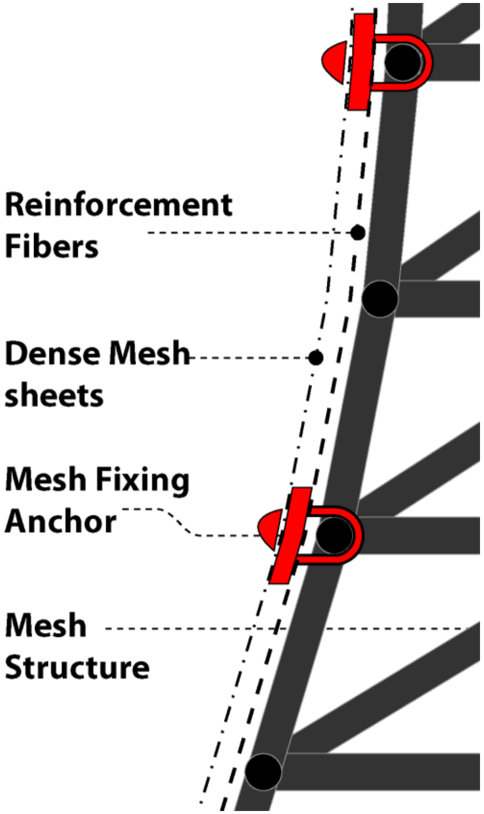




Concrete injection

Dense mesh sheet embedded formwork

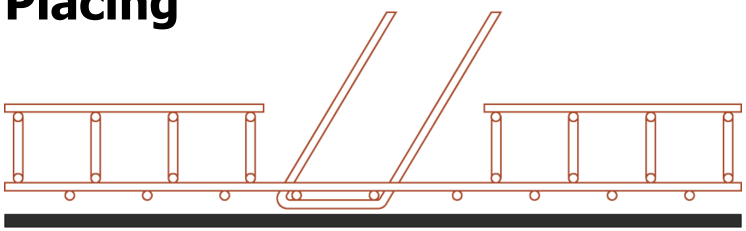
+ sharp edges are possible
+ No waste
+ Less material used
+ Negligible added weight for mesh structure
- Rough finished surface
- Finishing cement layer might be required for a decent surface

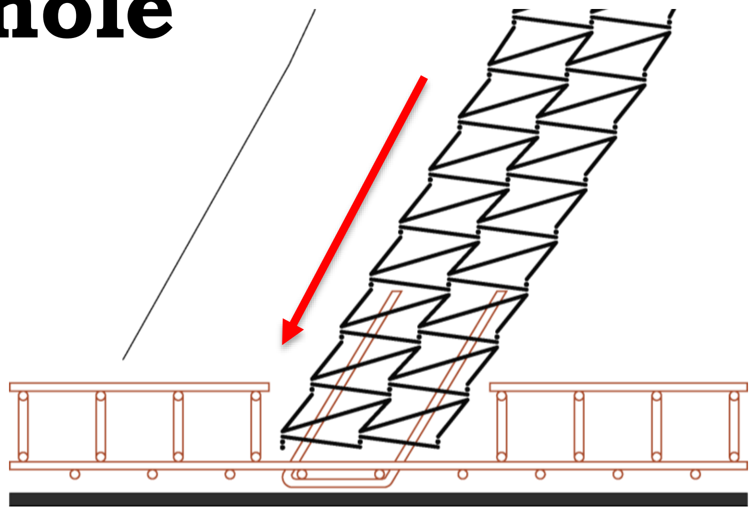


Assembly of the whole system

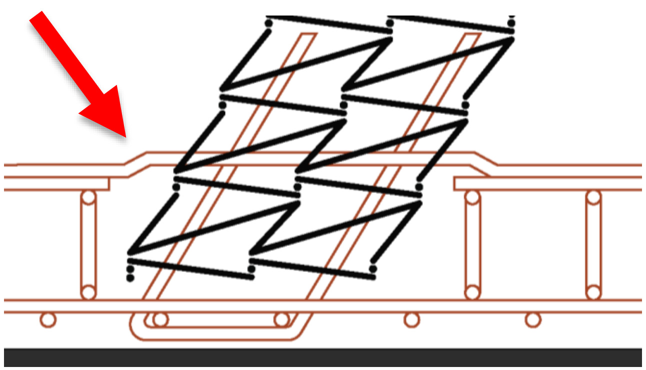
Assembly of the whole system

Placing

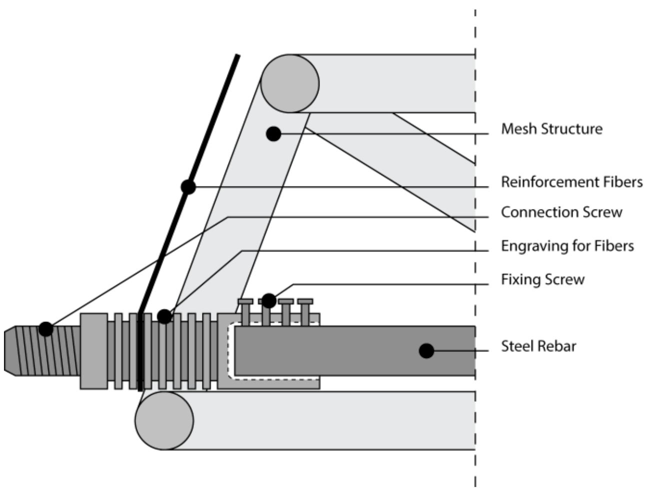




Fixing

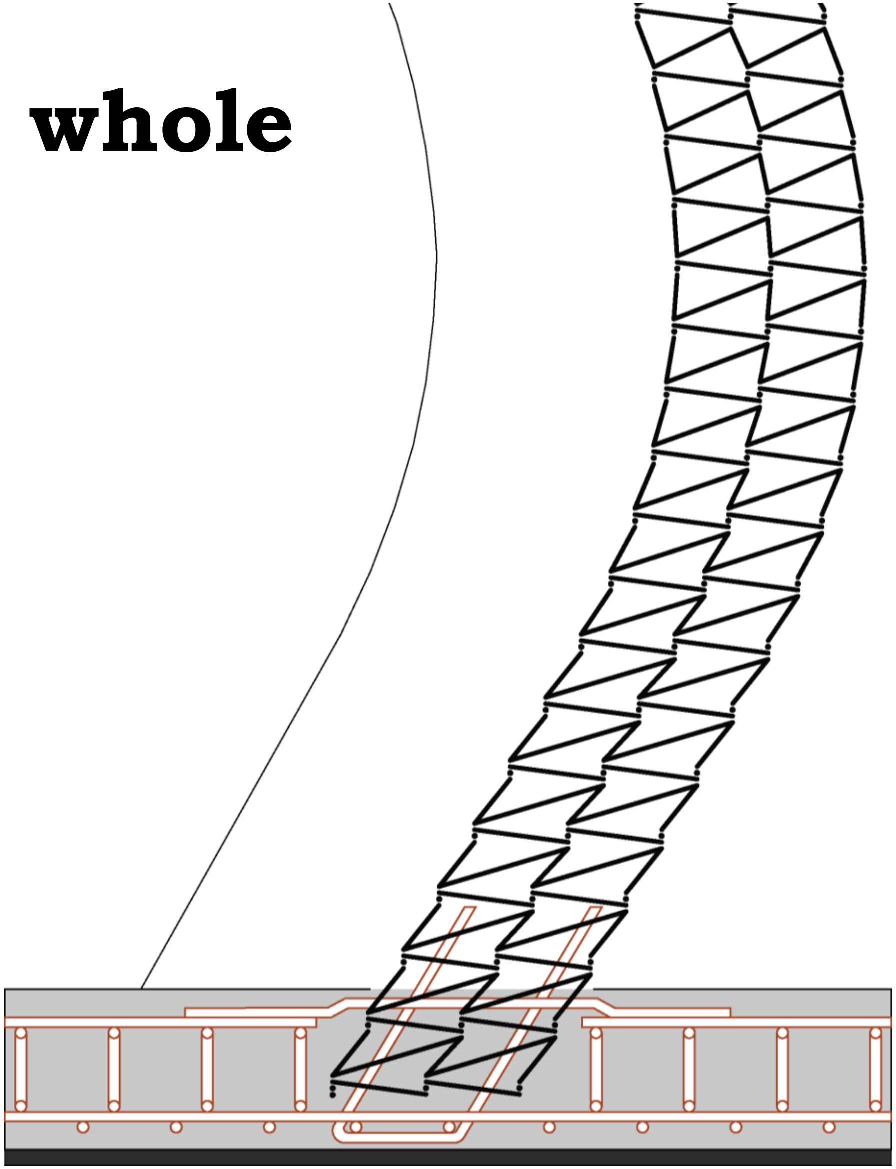


OR



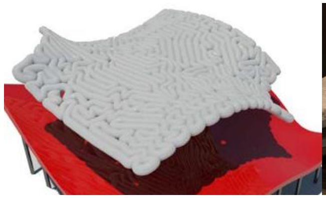
Assembly of the whole system

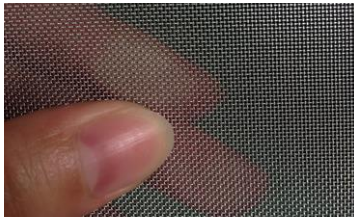
Add concrete till floor level

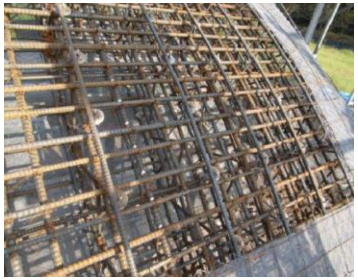


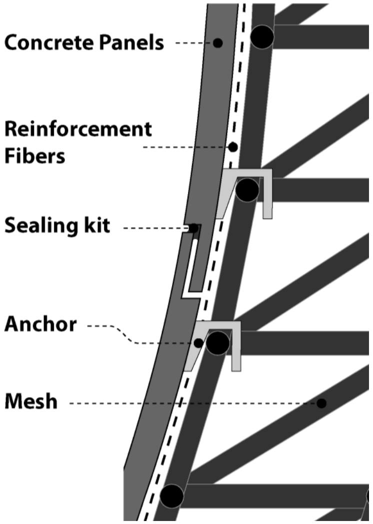
Assembly of the whole system

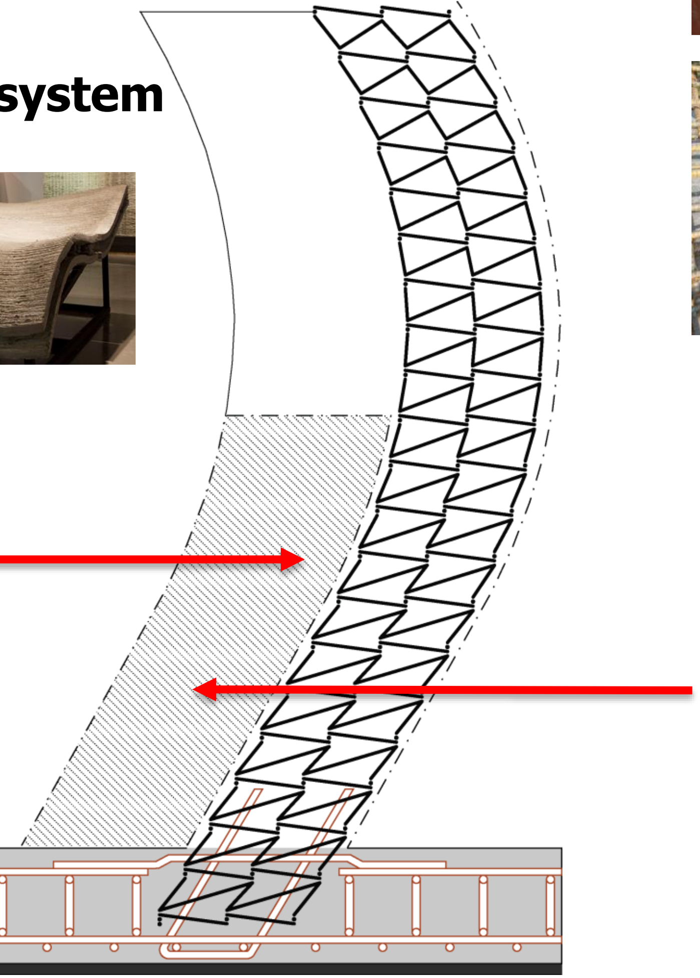
Adding the formwork system

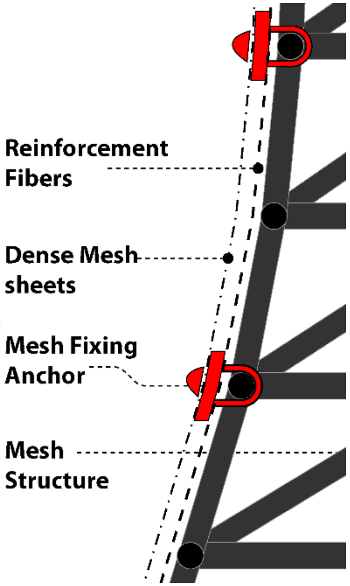






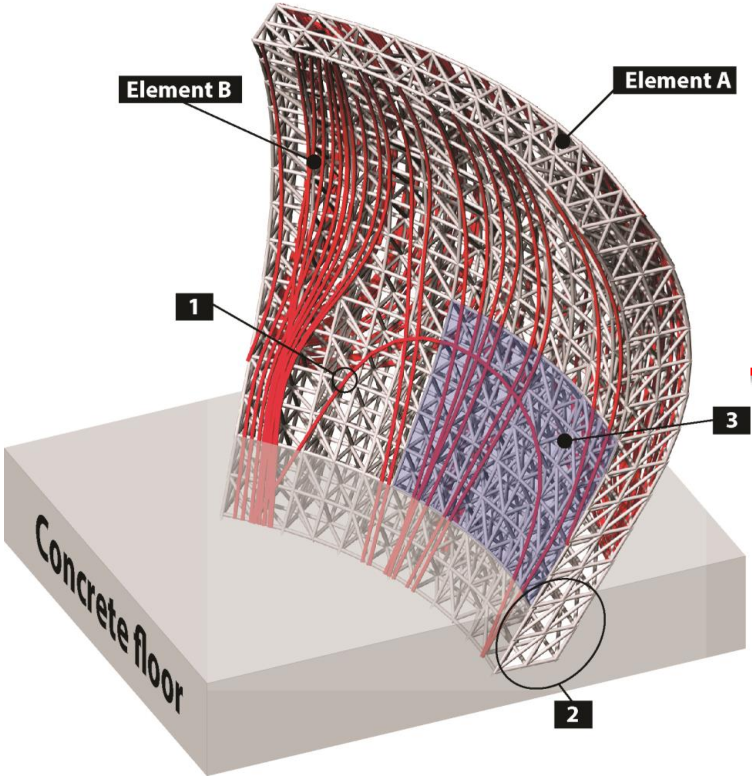


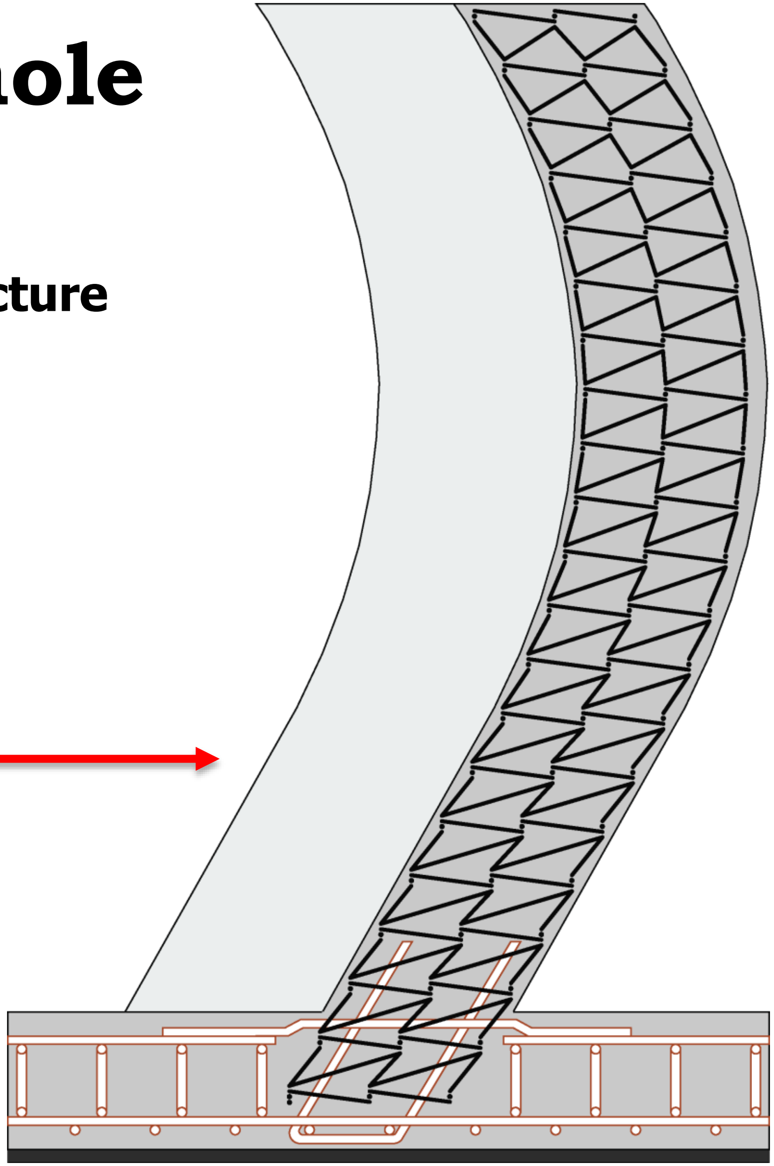




Assembly of the whole system

Injecting concrete in the mesh structure





END OF SEASON 2

SEASON 3
Future plan