The hybrid FRP & glass bridge

Research for a material adapted and optimized hybrid pedestrian bridge design

Student:
Arthur Blankenspoor

First mentor:
Ir. Joris Smits

Second mentor:
Dr. ir. Fred Veer

Delegate:
Prof. dr. Hans Wamelink

TU Delft

STRUCTURE:

1) Introducing the subject
2) Theoretical framework
3) Preliminary variants of design
4) Form-finding & optimization of design
5) Connections
6) Final design

STRUCTURE:

TUDelft

INTRODUCING THE SUBJECT

“New” and innovative materials in the building industry

TU Delft

INTRODUCING
THE SUBJECT

Especially popular in bridge design

TUDelft

INTRODUCING
THE SUBJECT

Expanded knowledge leads to improved designs

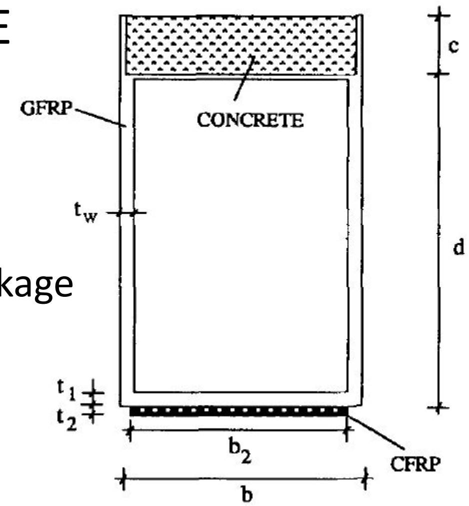
INTRODUCING THE SUBJECT

Further improvement of weaknesses:

Hybrid bridge structures

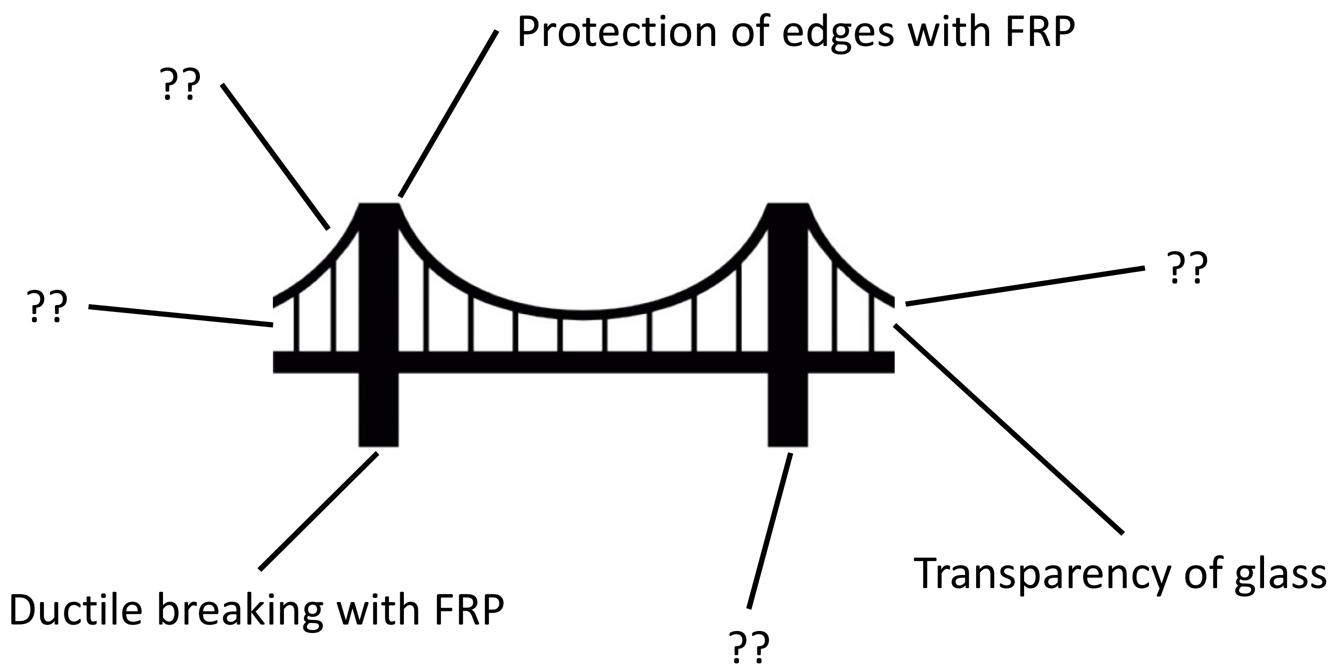
FRP & CONCRETE

- More stiffness
- Higher tensile strength
- Ductile post-breakage behaviour



TUDelft

OPPORTUNITY:
HYBRID FRP – GLASS BRIDGE



TUDelft

AIM OF RESEARCH

Find structural advantages & disadvantages

Material adapted

Pedestrian bridge

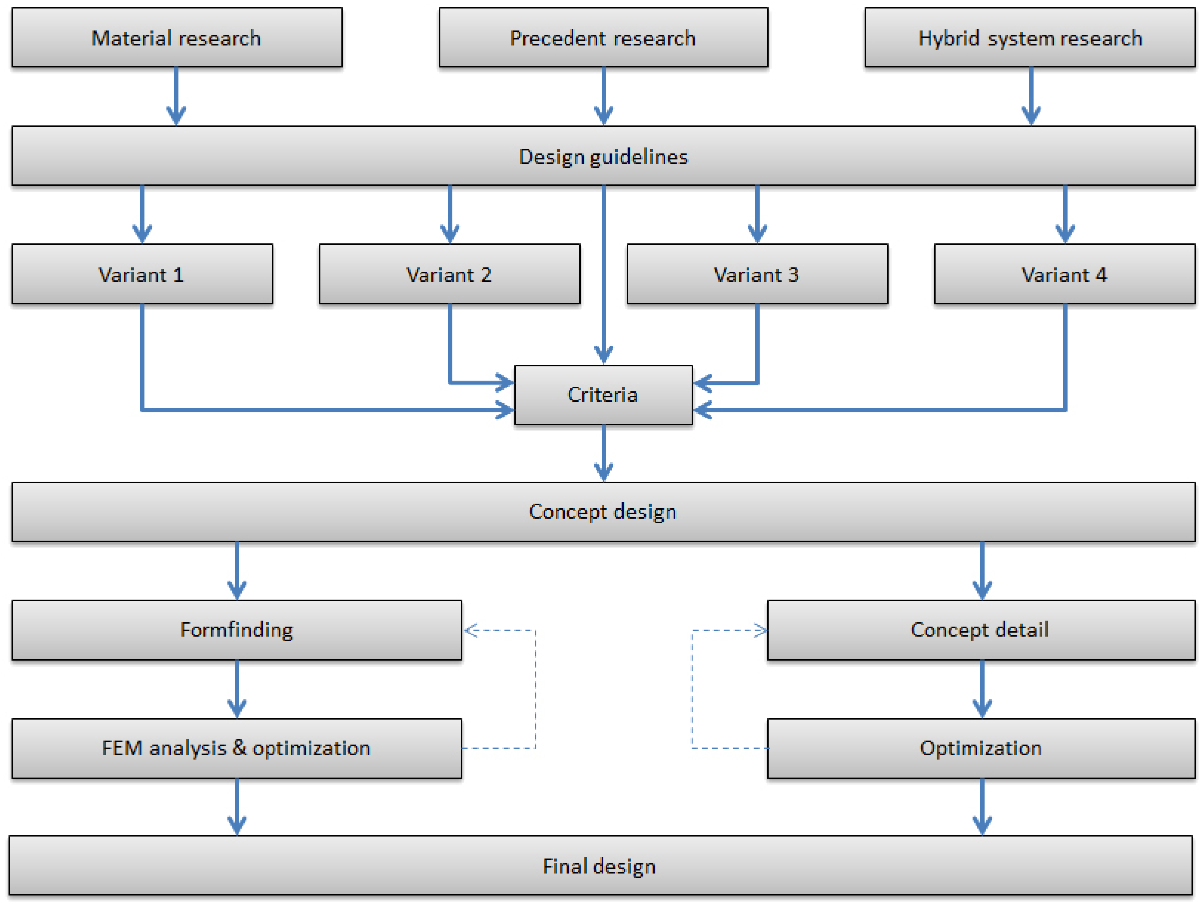
Medium long span length (about 30m)

TU Delft

MAIN RESEARCH QUESTION

“Can a hybrid pedestrian bridge with a loadbearing structure of FRP and reinforced structural glass be designed while making optimal use of the material properties of both materials?”

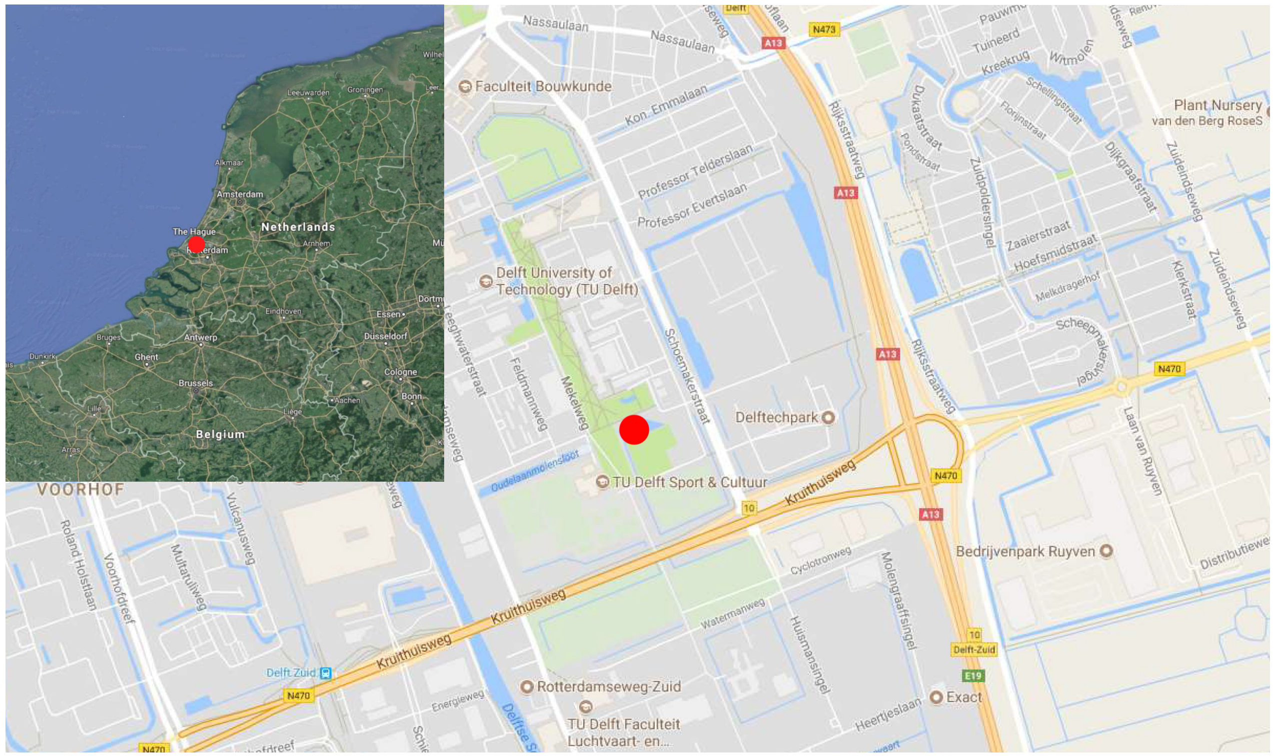
METHODOLOGY



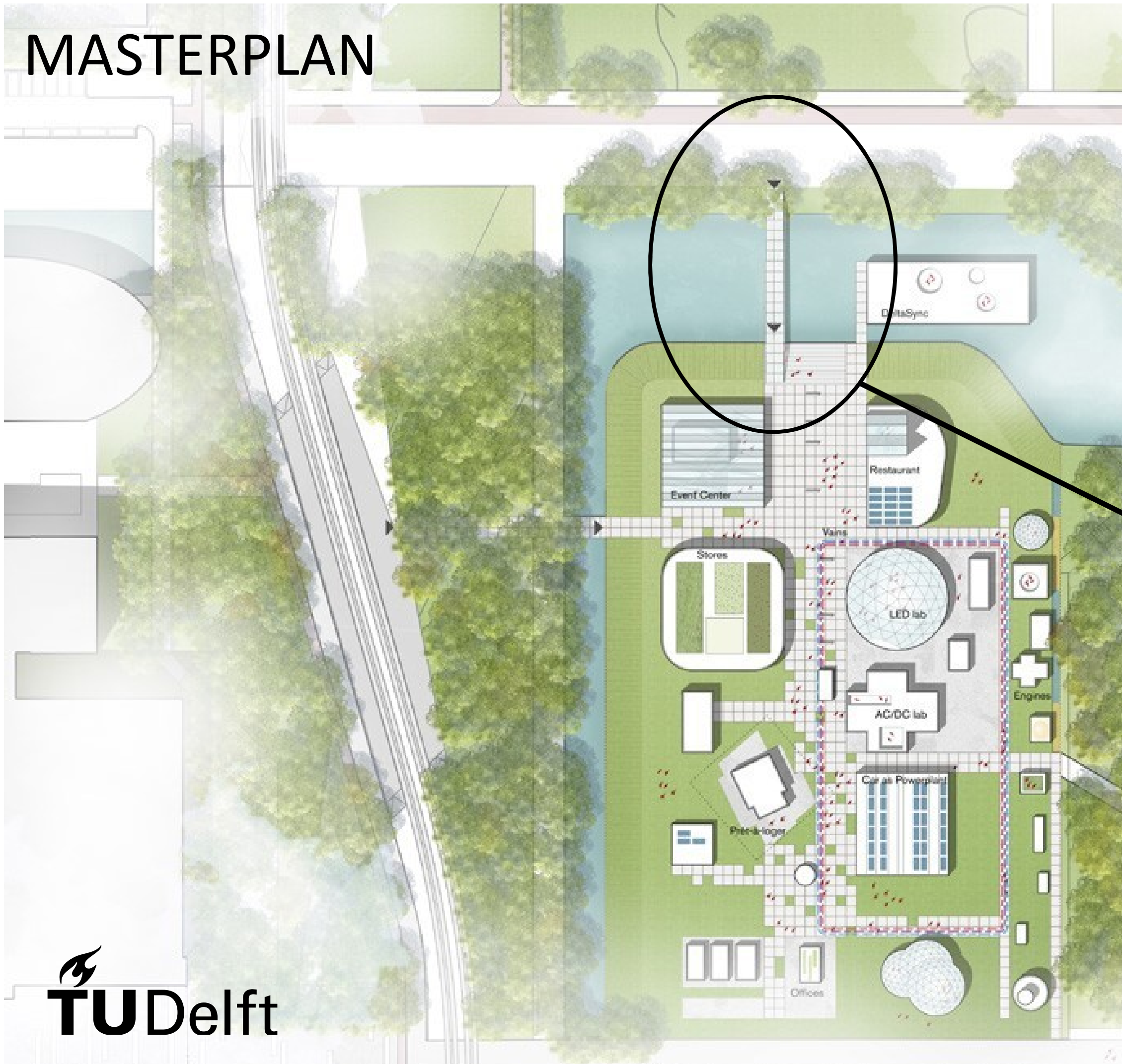
TUDelft

INTRODUCING THE SUBJECT

LOCATION



MASTERPLAN



Green Village

"Create a green future together"

"Experience the living & working environment in 10 to 15 years

Why here?

- Innovative material use
- Sustainable and durable solution
- Alternative entrance
  - Wheelchair accessible
  - Connects to infrastructure
- Transparent landmark as entrance
- Medium long span length (30m)

TU Delft


GREEN VILLAGE


TU Delft


GREEN
LLAGE
THE GREEN
VILLAGE
LAB
EVENT CENTER

PROGRAM OF REQUIREMENTS

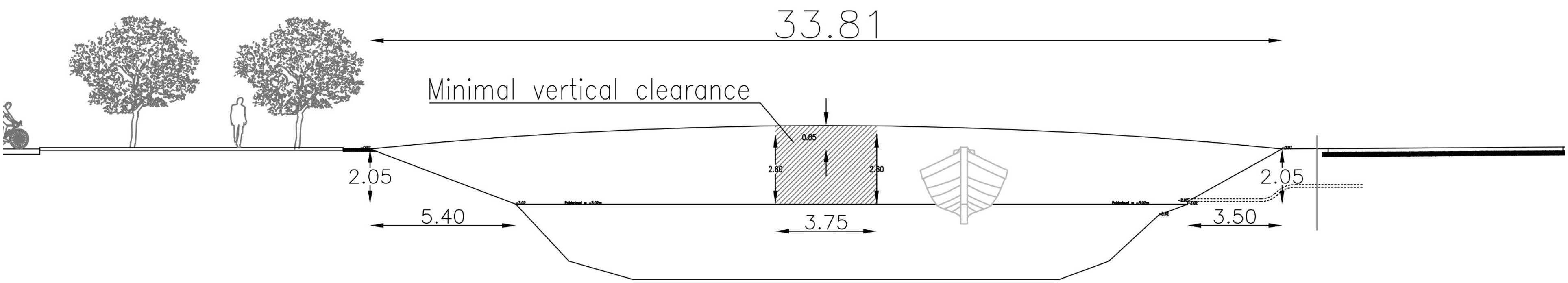
- Dimensions
  - According to location
  - Wheelchair accessibility
  - Vertical clearance

- Loading
  - According to NEN

- Safety – material dependent

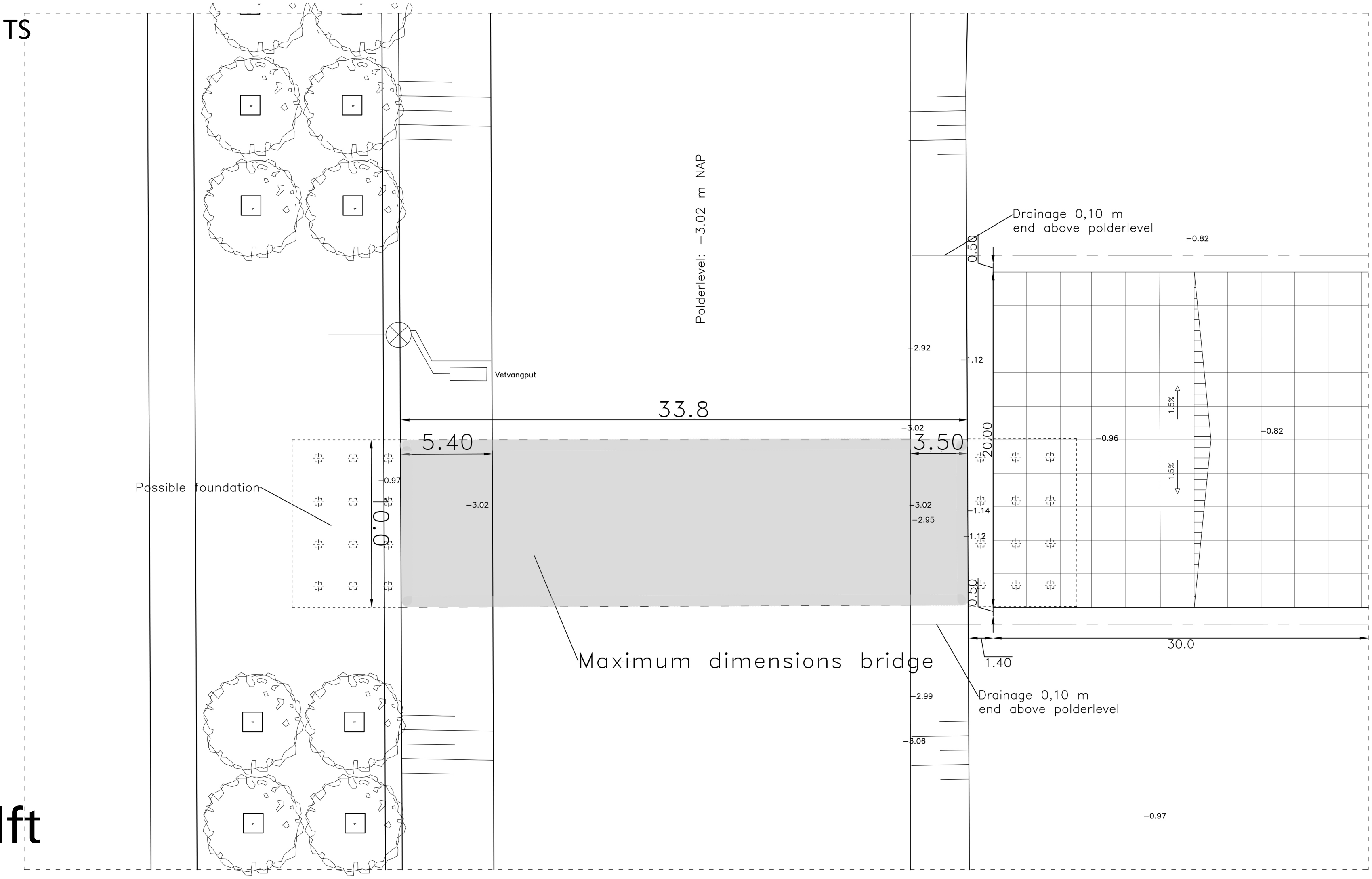
TU Delft

Dimensions



TU Delft

REQUIREMENTS



STRUCTURE:

1) Introducing the subject

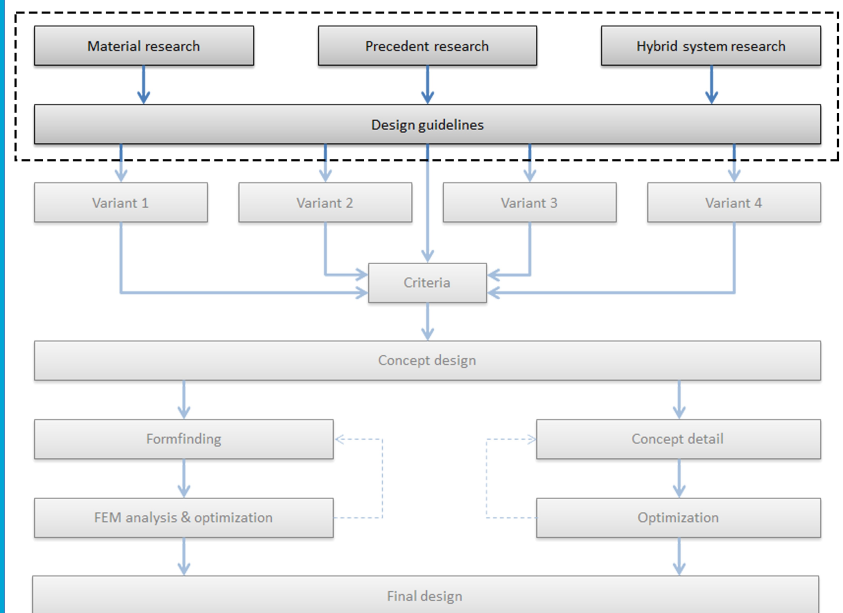
2) Theoretical framework

3) Preliminary variants of design

4) Form-finding & optimization of design

5) Connections

6) Final design



MATERIAL RESEARCH – DESIGN GUIDELINES

What are the (mechanical) properties of fibre reinforced polymers?

What are the (mechanical) properties of reinforced structural glass?

What precedents (structural glass and FRP) have been built and what are their structural characteristics?

What hybrid systems have been built and what are their structural characteristics?

TU Delft

THEORETICAL FRAMEWORK

FIBRE REINFORCED POLYMERS

Composite material:

- Fibers - strength
- Resin - distribution of loads
  - protection
  - prevents buckling

TU Delft

FIBRE REINFORCED POLYMERS

Fibers:

- Aramid
- Carbon
- Glass

FIBRE REINFORCED POLYMERS

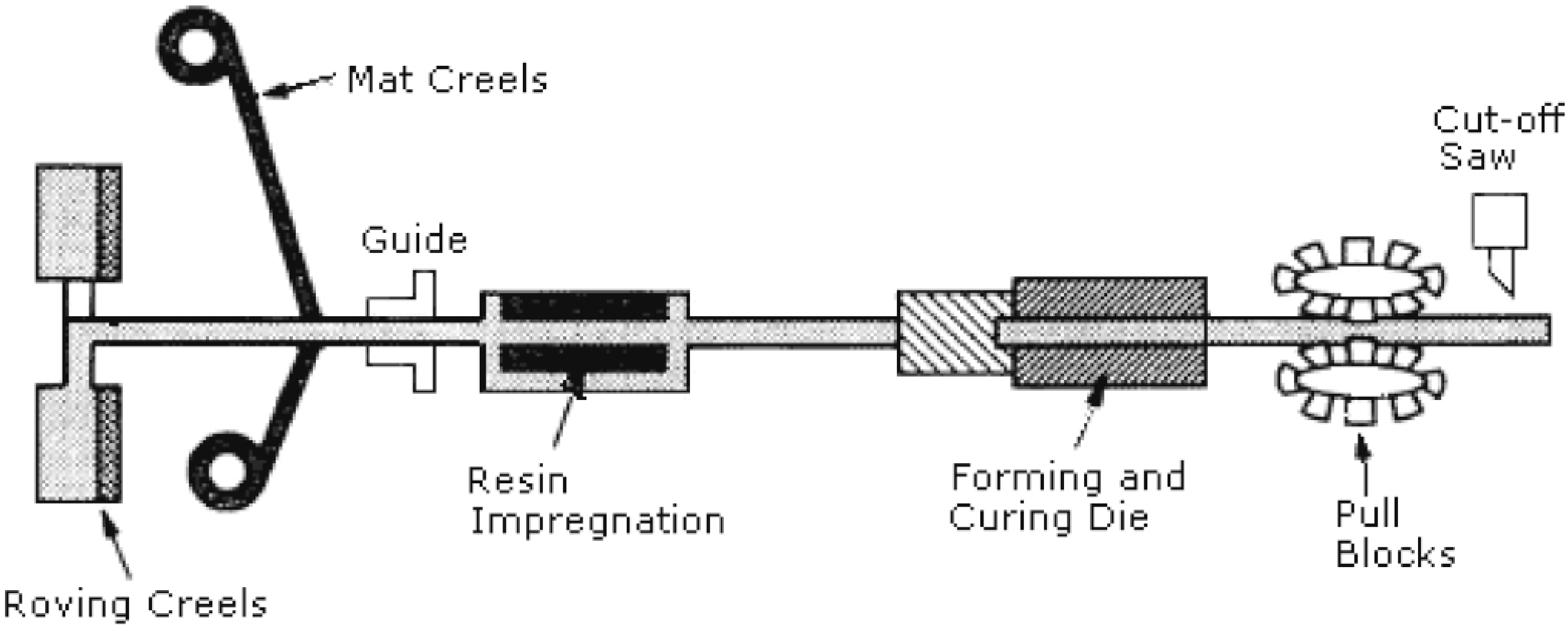
Resins:

- Polyester
- Epoxy
- Phenol

FIBRE REINFORCED POLYMERS

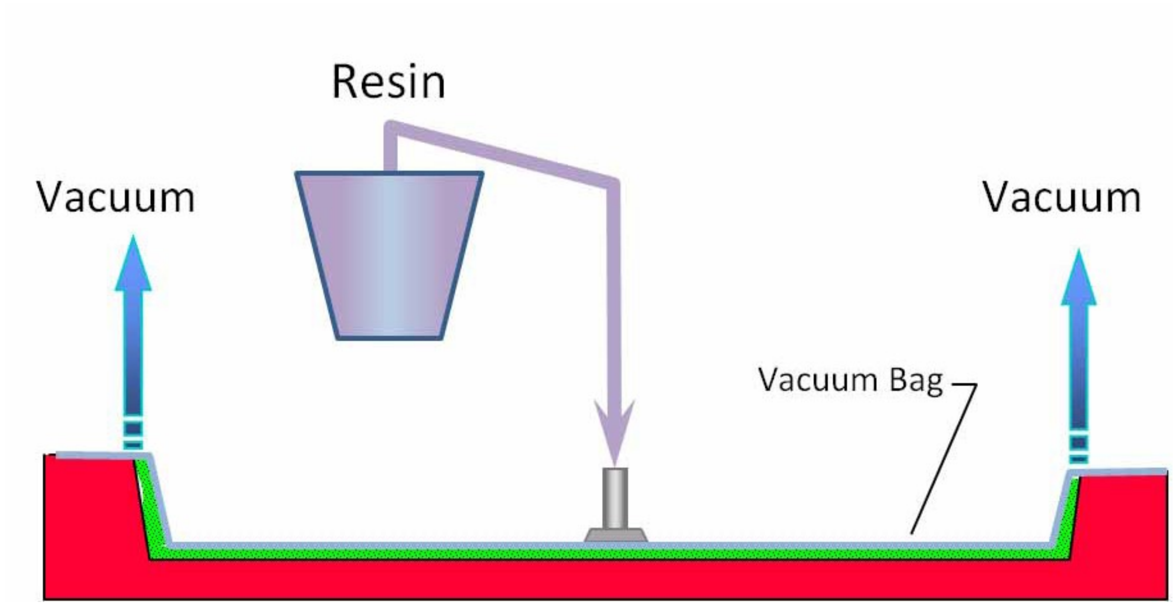
Predominant production processes:

- Pultrusion
- Vacuum infusion



- Structural shapes with constant cross-sections
- Cheap

TUDelft



- Uniform cross-sections & non-uniform cross-sections
- More expensive

TU Delft

STRUCTURAL GLASS

- Transparent
- Brittle

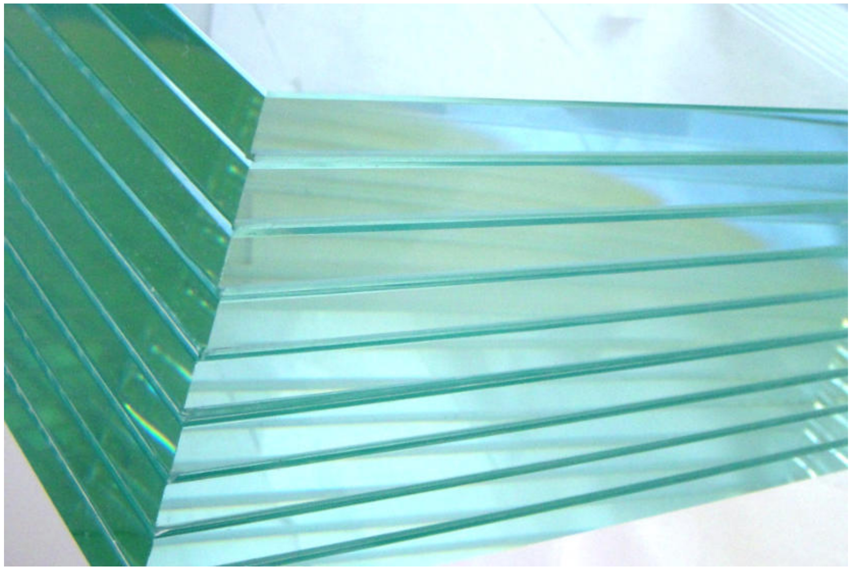
TU Delft

THEORETICAL FRAMEWORK

STRUCTURAL GLASS

Safety concepts:

- ✓ Redundancy
- Ductility
- Pre-stressing

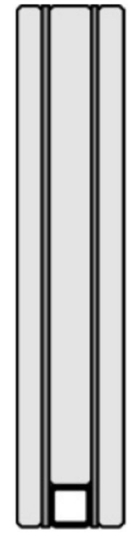


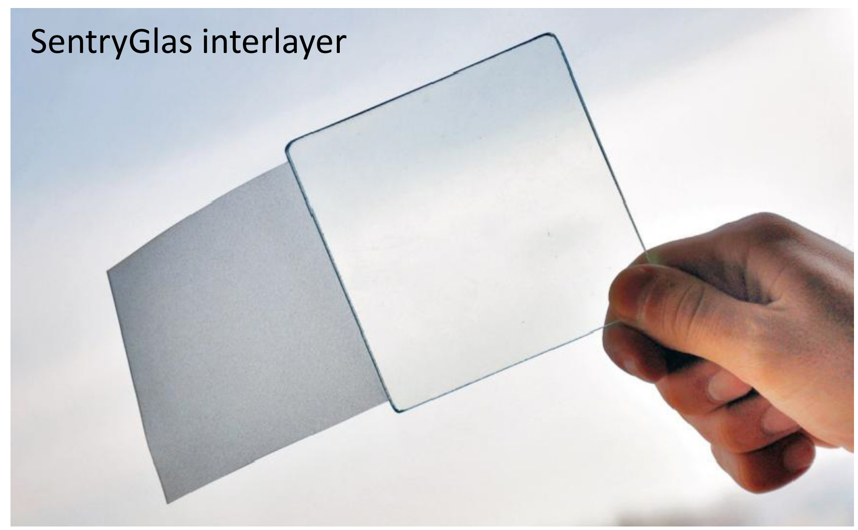
THEORETICAL FRAMEWORK

STRUCTURAL GLASS

Safety concepts:

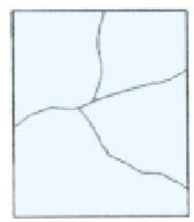
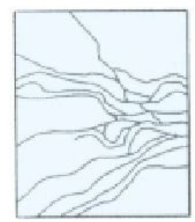
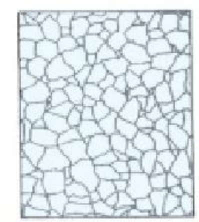
- Redundancy
- ✓ Ductility
- Pre-stressing

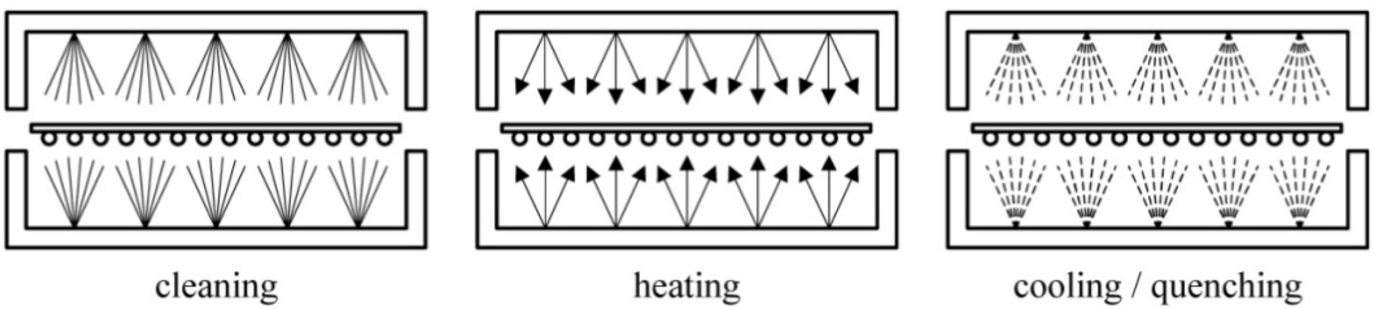




STRUCTURAL GLASS

✓ Pre-stressing

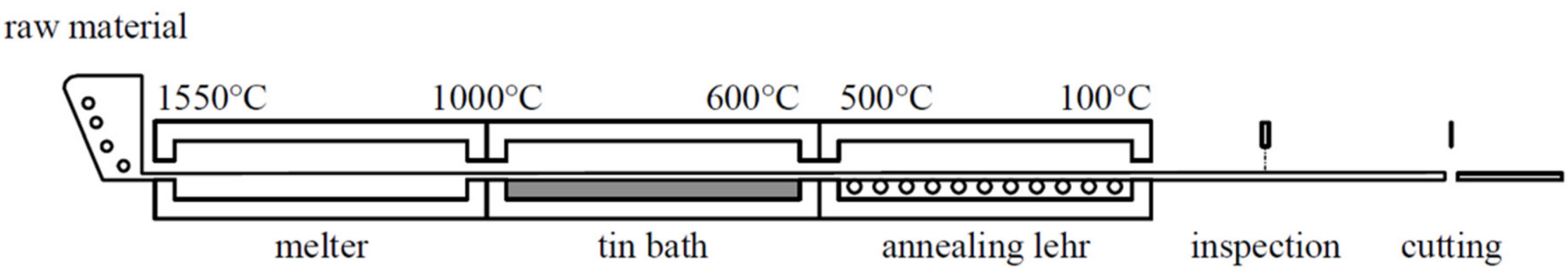
Terminology	Annealed glass	Heat-strengthened glass	Fully tempered glass
Fracture pattern			
Prestress level	Normal	Medium	High
Characteristic tensile bending strength	45 MPa	70 MPa	110 MPa



STRUCTURAL GLASS

Predominant production process:

- Float glass production



TU Delft

THEORETICAL FRAMEWORK

DESIGN GUIDELINES

FRP

Low stiffness (E-modulus)

Structural glass

High stiffness (E-modulus)

Design guideline:

Glass can stiffen the FRP structural members

TU Delft

DESIGN GUIDELINES

FRP

Sensitive to stress

Structural glass

Sensitive to stress

Design guideline:

Evade the use of bolted connections, use inserts when impossible

Use adhesive or interlocking connections instead

DESIGN GUIDELINES

FRP

Easy transportation

Structural glass

Difficult transportation

Design guideline:

Use small glass elements with protected edges, while FRP elements can be larger and unprotected

STRUCTURE:

1) Introducing the subject

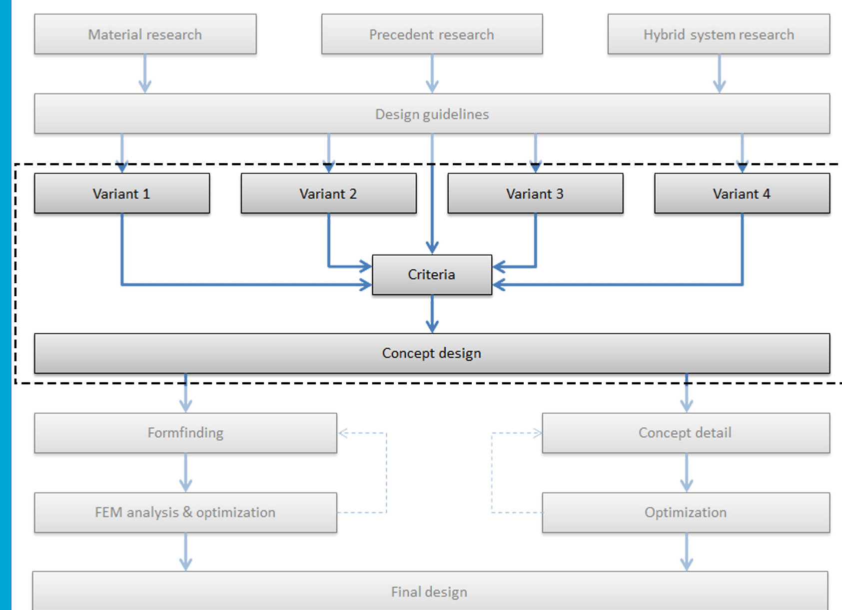
2) Theoretical framework

3) Preliminary variants of design

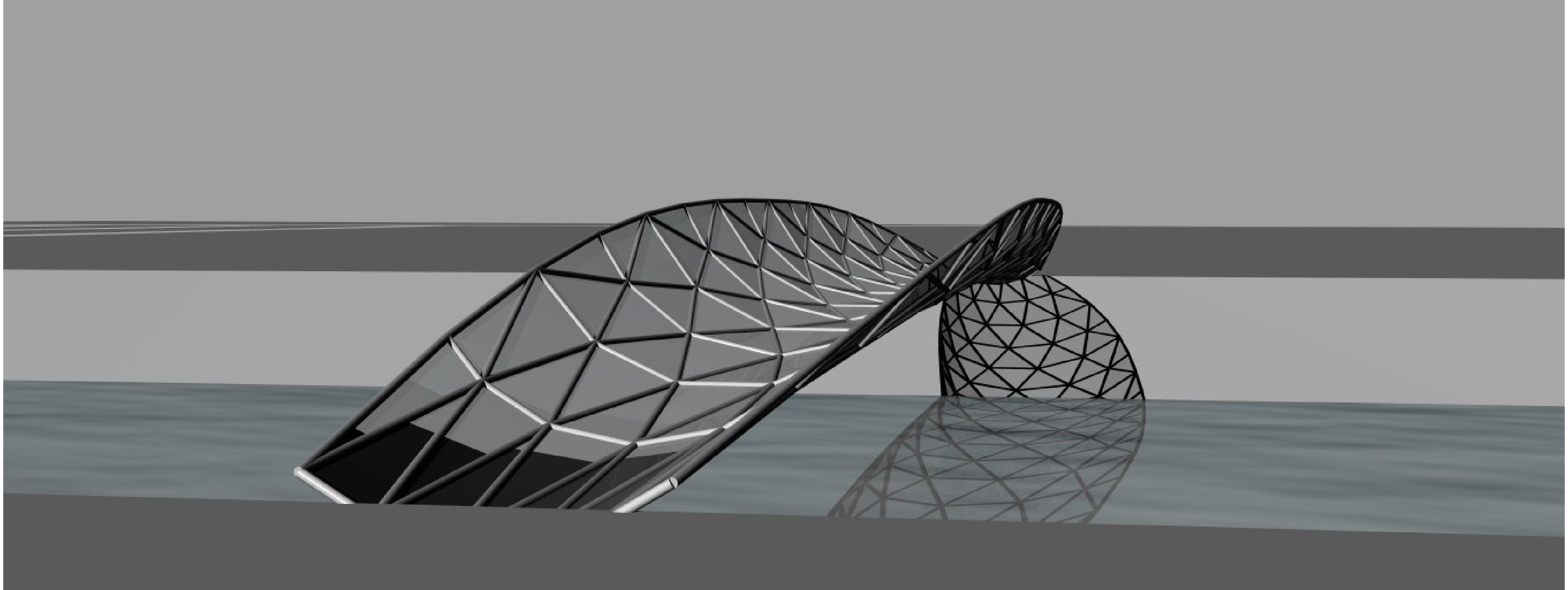
4) Form-finding & optimization of design

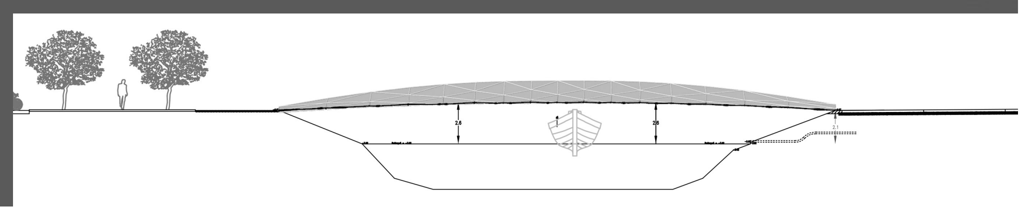
5) Connections

6) Final design



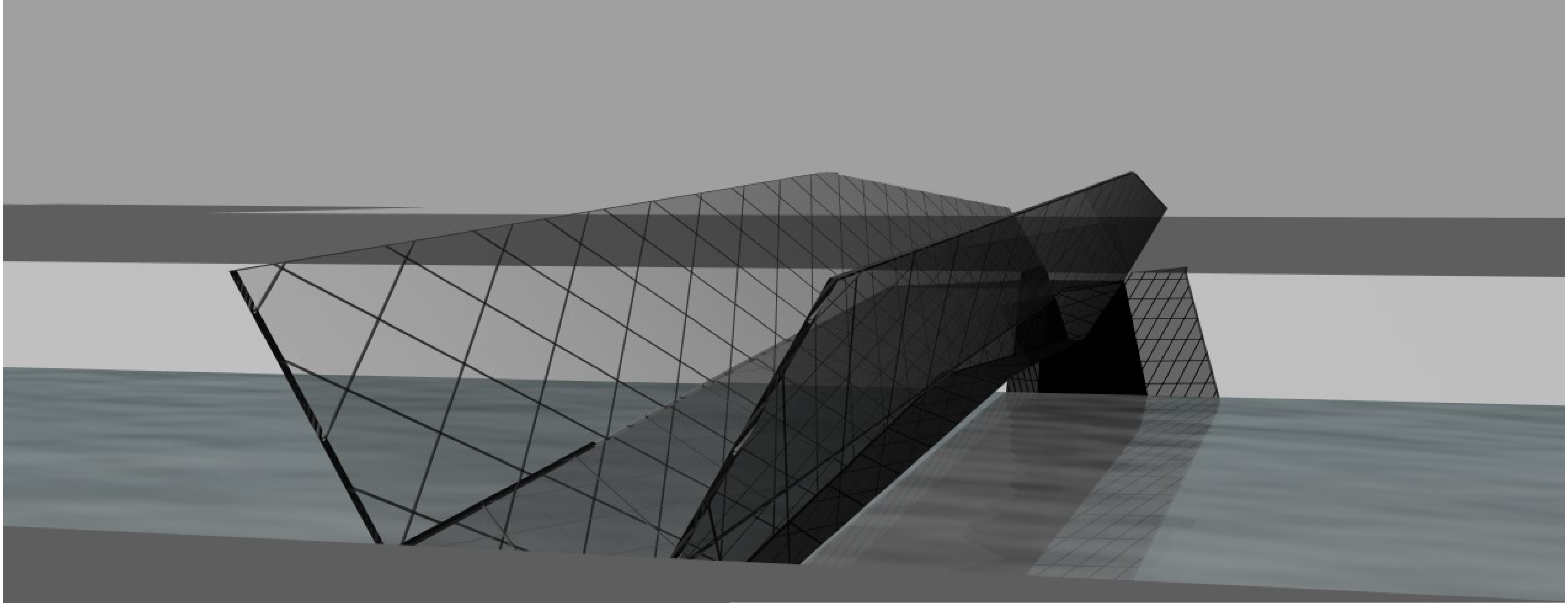
Variant 1 – Hybrid facetted shell

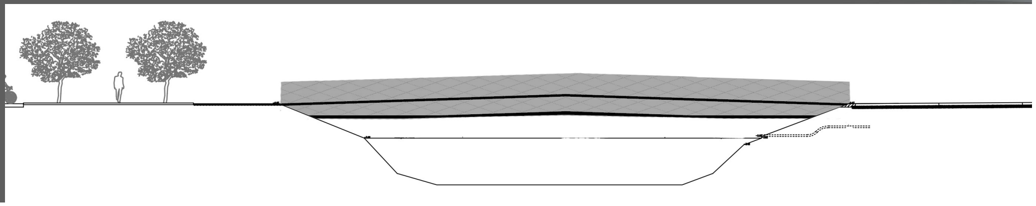




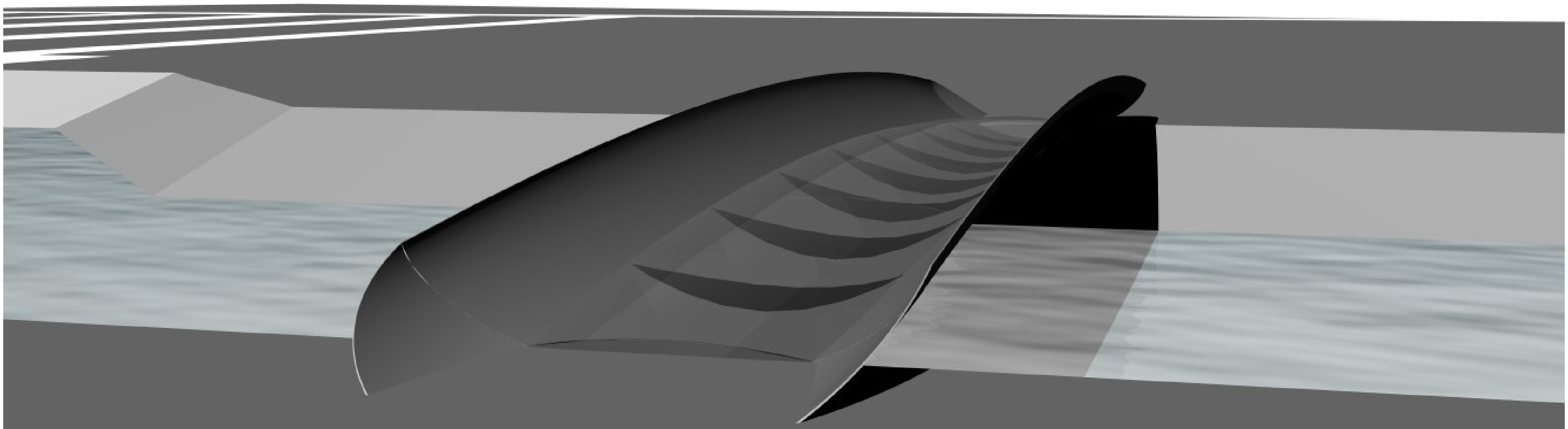
TU Delft

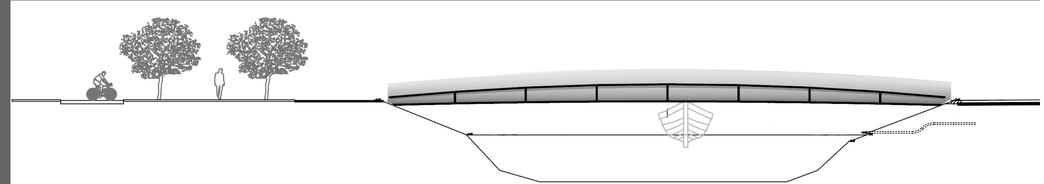
Variant 2 – FRP reinforced glass bridge



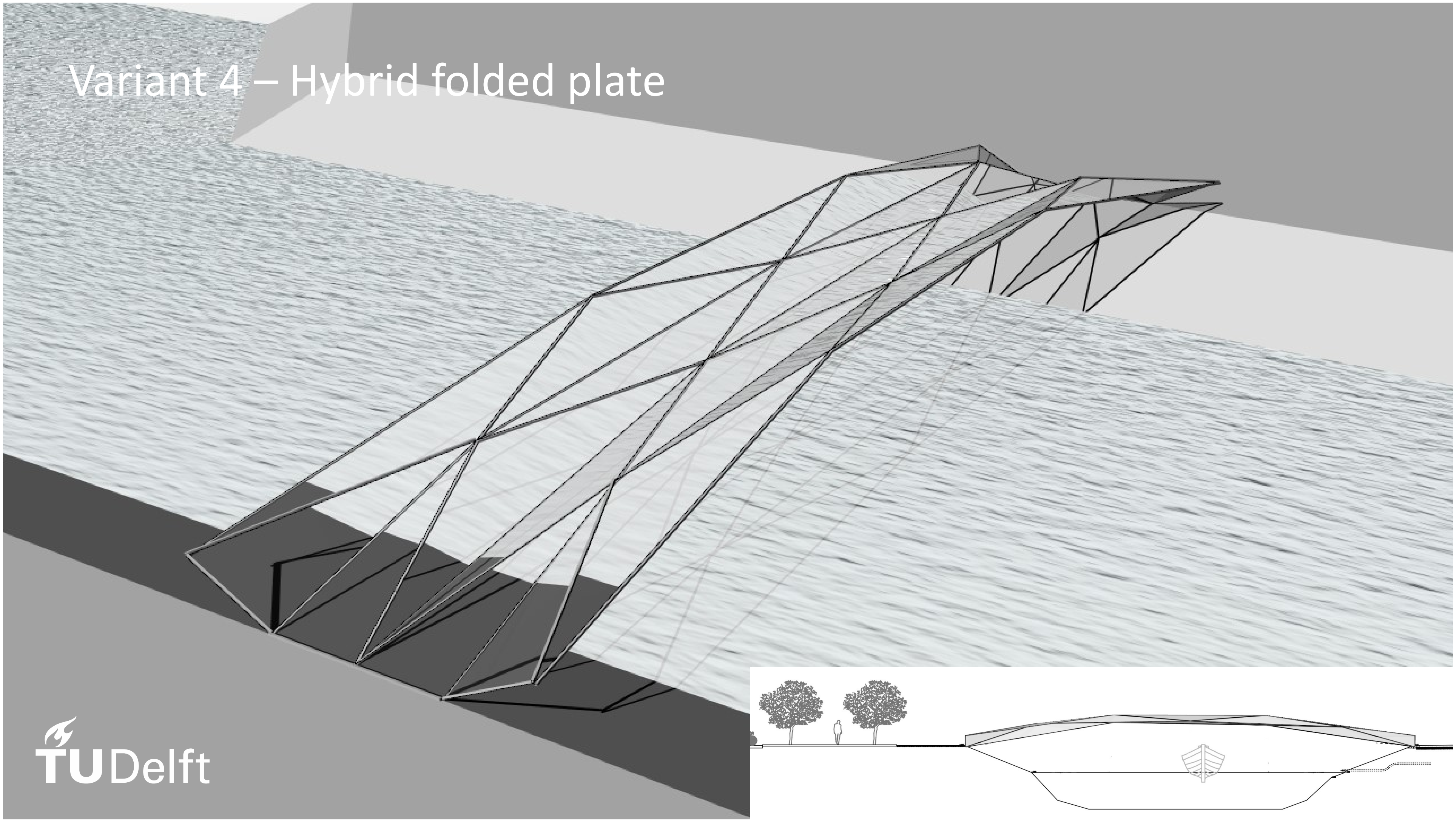


Variant 3 – Hybrid monocoque





Variant 4 – Hybrid folded plate



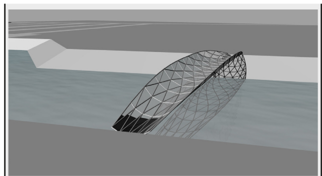
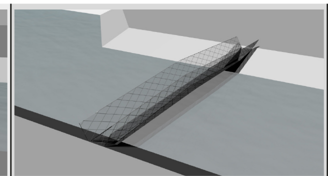
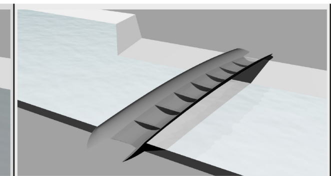
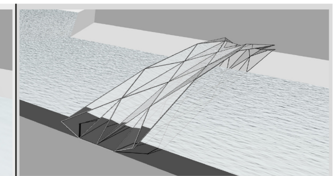
Design criteria:

- Strength & stability
- Transparency
- Safety

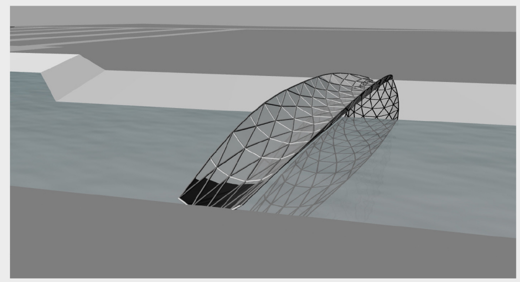
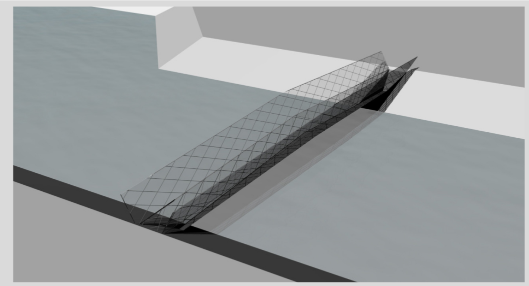
Secondary criteria:

- Transportation & assembly
- Weight
- Costs
- Sustainability & durability

GRADING

Ranking (design criteria)				
Strength & stability	○○○○	○	○○	○○○
Transparency	○○○	○○○○	○	○○
Safety	○○	○○○○	○○○	○
Total	9	9	6	6

GRADING

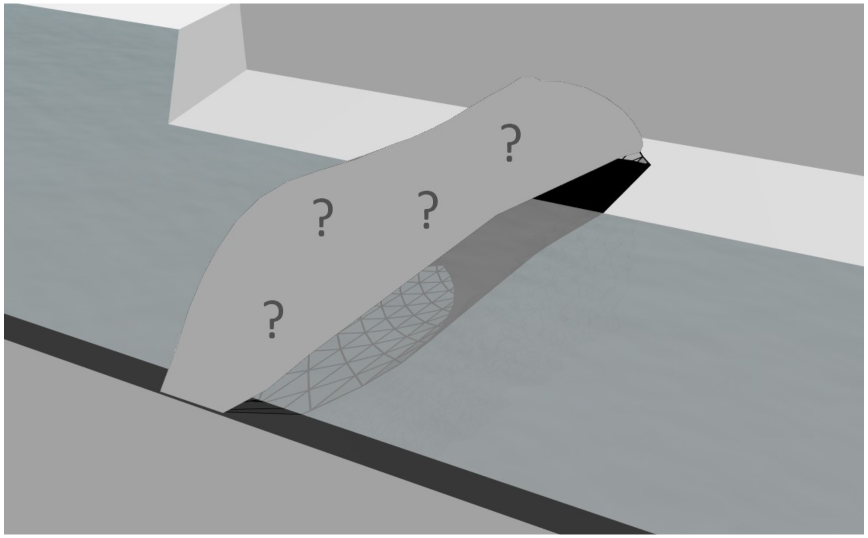
Ranking (secondary criteria)		
Transport & assembly	○ ○	○
Sustainability	○ ○	○
Costs	○ ○	○
Weight	○ ○	○
Total	8	4

CONCEPT
DESIGN

HYBRID FACETTED SHELL

What is the most efficient type of hybrid facetted shell considering the material properties of the applied materials?

Optimizing a plate shell bridge



TU Delft

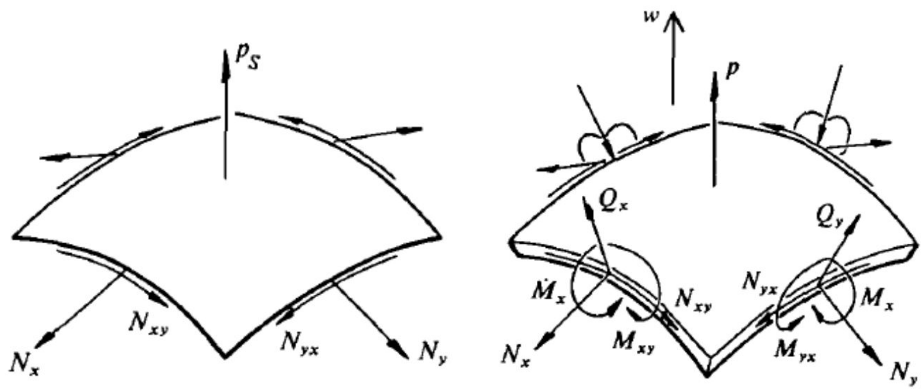
CONCEPT DESIGN

SHELLS

Three-dimensional curved surface with small thickness that resists load predominantly through membrane stresses

Features of a shell:

- Continuity
- Curvature
- Small thickness



CONCEPT DESIGN

FACETTED SHELLS

Three types of facetted shells:

- Grid shell
- Lattice structure
- Plate shell

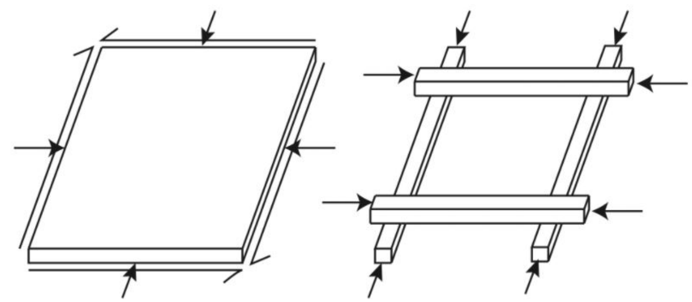
CONCEPT DESIGN

GRIDSHELL

Approximates smooth shell

Continuous curved elements

Can only resist forces in the direction of the element



TU Delft

CONCEPT
DESIGN

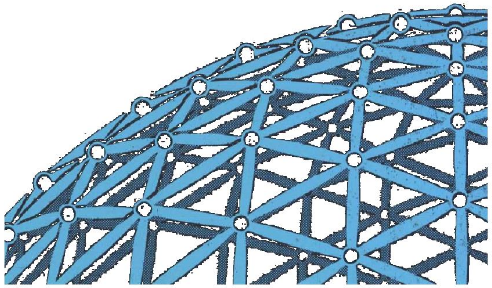
LATTICE STRUCTURE

Approximates smooth shell

Discrete straight elements connected in nodes

Can only resist forces in the direction of the element

More bending moments



CONCEPT DESIGN

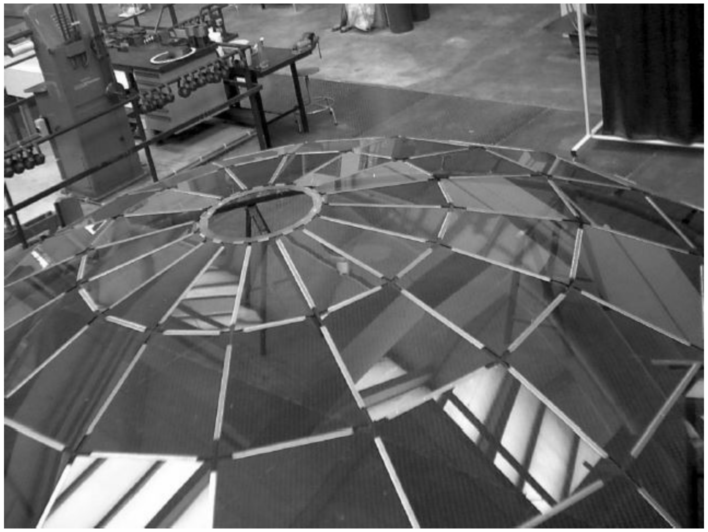
PLATE SHELL

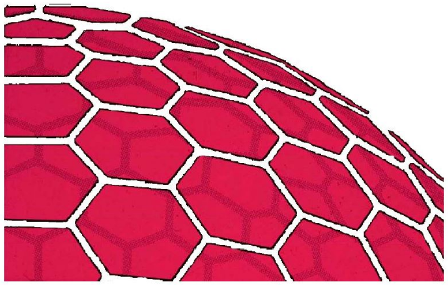
Approximates smooth shell

Discrete straight plate elements

Will resist loading through in-plane forces

More bending moments (plate bending)





CONCLUSION

Glass stiffening FRP main loadbearing structure:

- Large bending and torsional moments in glass
- Stress concentrations in glass

Glass as main loadbearing structure with FRP connections:

- Force transfer in FRP
- More transparency

→ Plate shell is the best type of facetted shell

STRUCTURE:

1) Introducing the subject

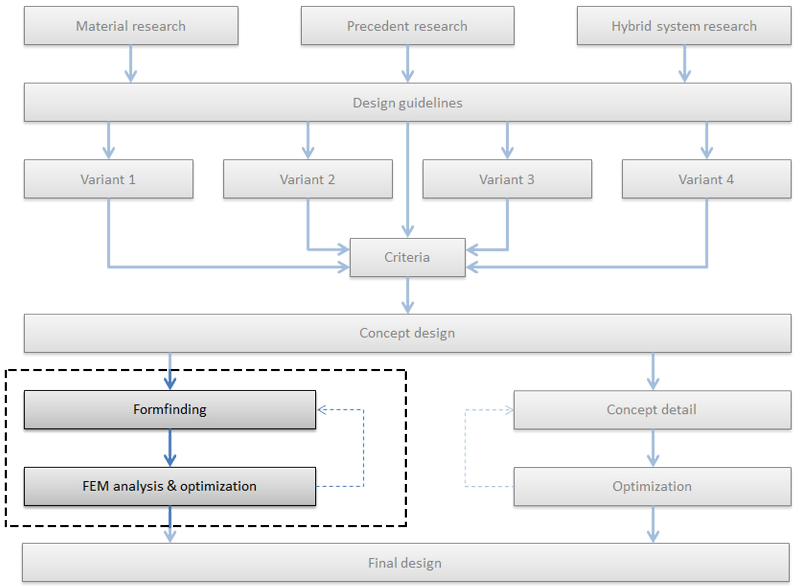
2) Theoretical framework

3) Preliminary variants of design

4) Form-finding & optimization of design

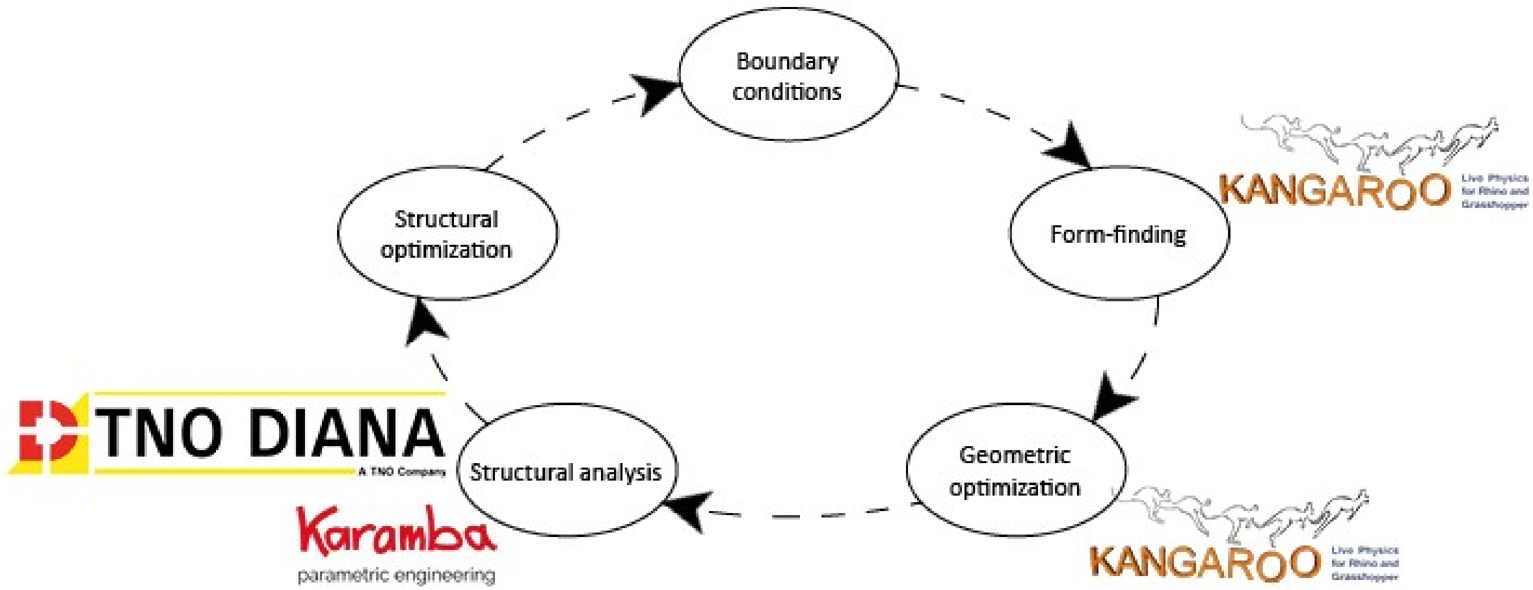
5) Connections

6) Final design

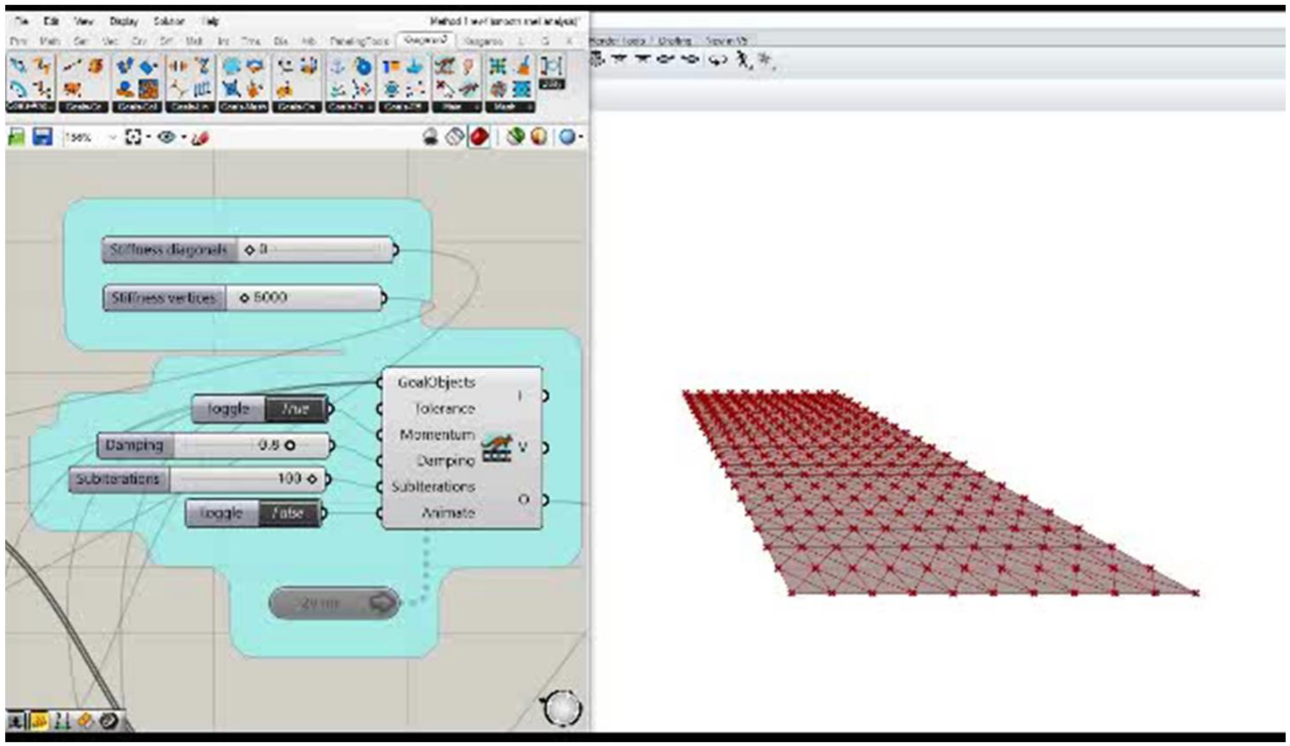


FORM-FINDING

What is the most efficient facetted shell in terms of shape and sizes of the shell?



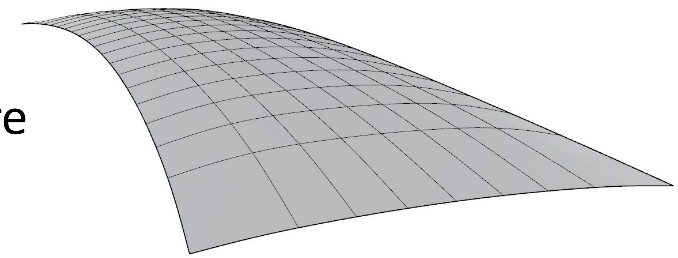
FORM-FINDING



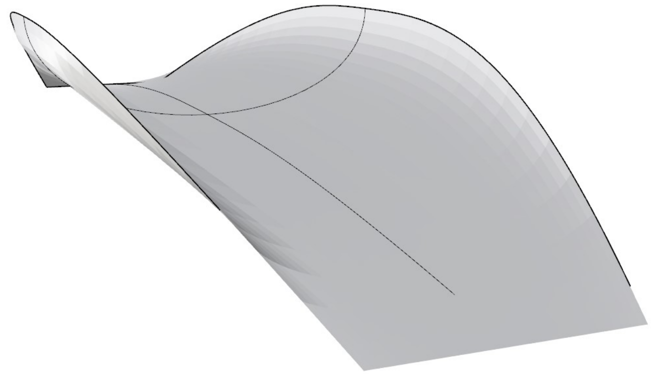
ANALYSIS & OPTIMIZATION

SMOOTH SHELL VARIANTS

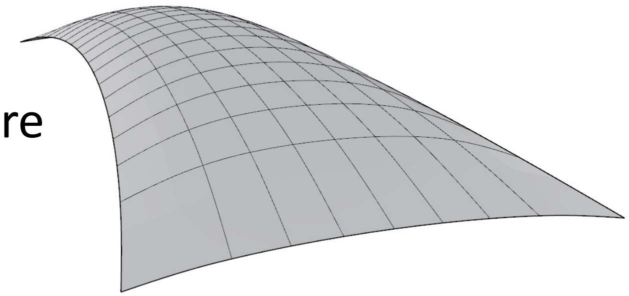
Variant 1: convex with low curvature



Variant 2: concave



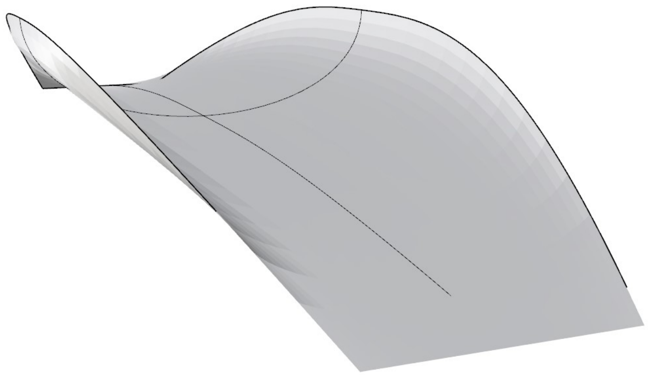
Variant 3: convex with higher curvature



TU Delft

ANALYSIS & OPTIMIZATION

RESULTS



Concave shell has “natural” parapet

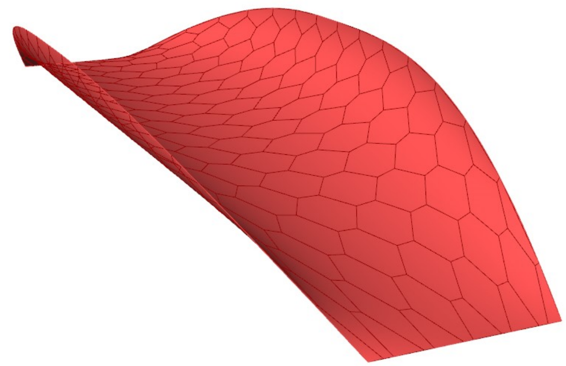
Convex shells’ stability will be compromised when a parapet is created (high stresses)

Concave shell has higher curvature, less bending moments & least deformation

TU Delft

GEOMETRIC OPTIMIZATION

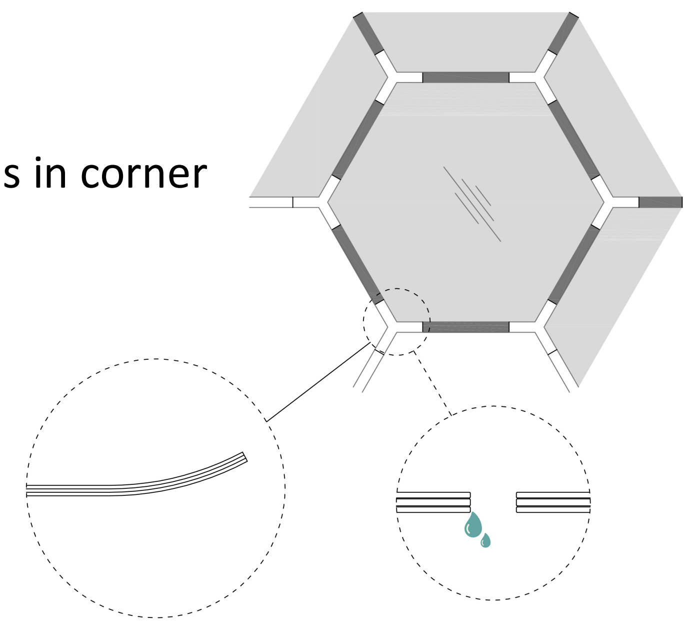
TESSELLATION



Hexagonal tessellation for least concentrated nodal forces

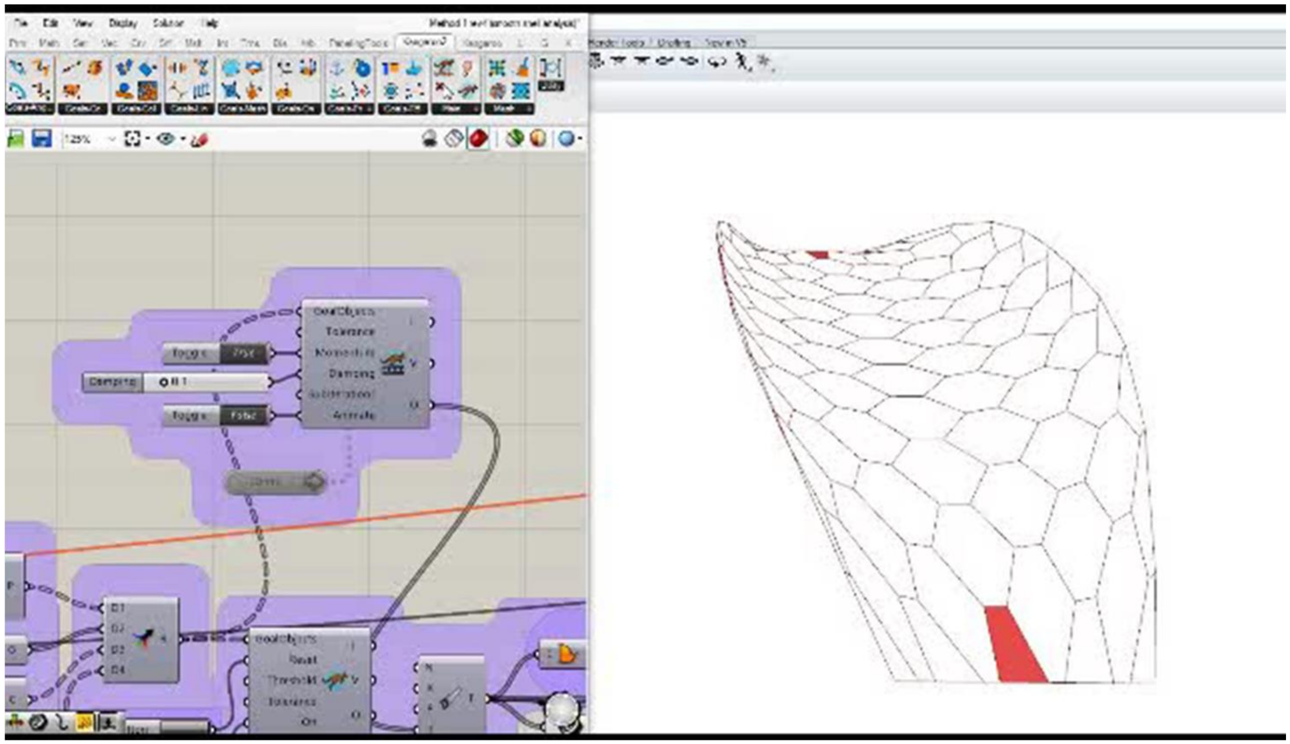
Connections shortened:

- Minimal stress concentrations in corner
- Water drainage



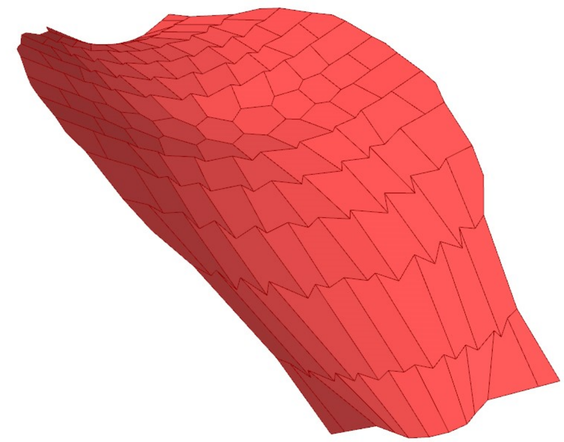
GEOMETRIC OPTIMIZATION

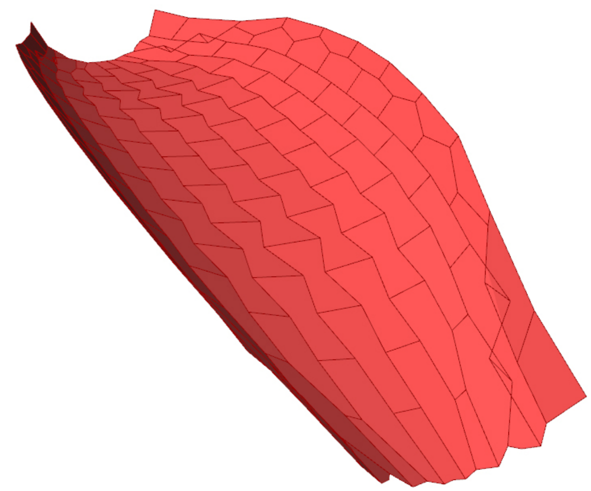
TESSELLATION

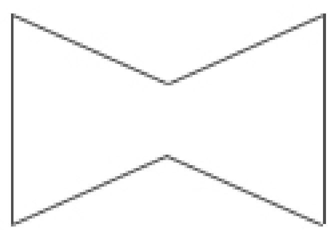


TESSELLATION

Complications during hexagonal tessellation



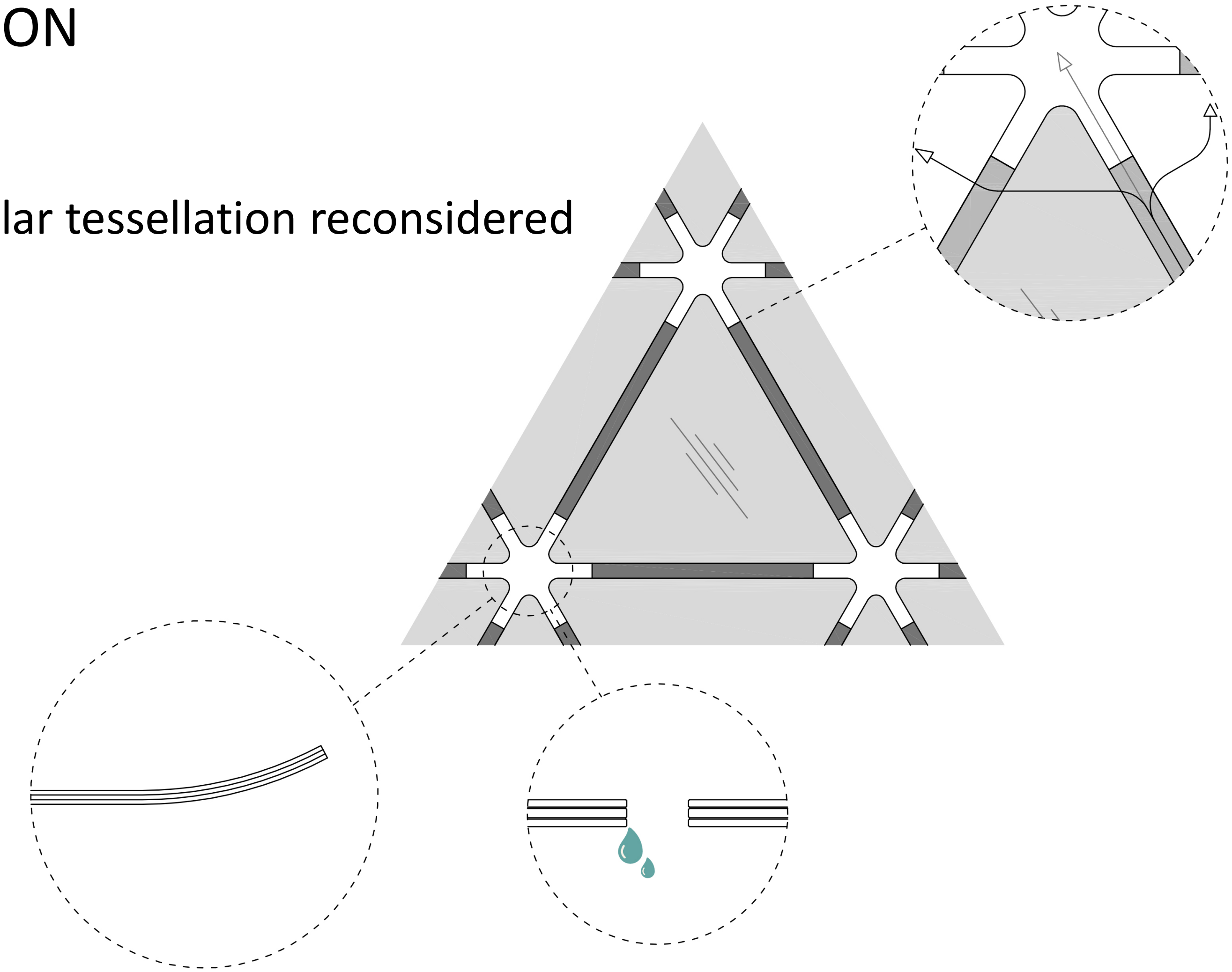




GEOMETRIC
OPTIMIZATION

TESSELLATION

Triangular tessellation reconsidered

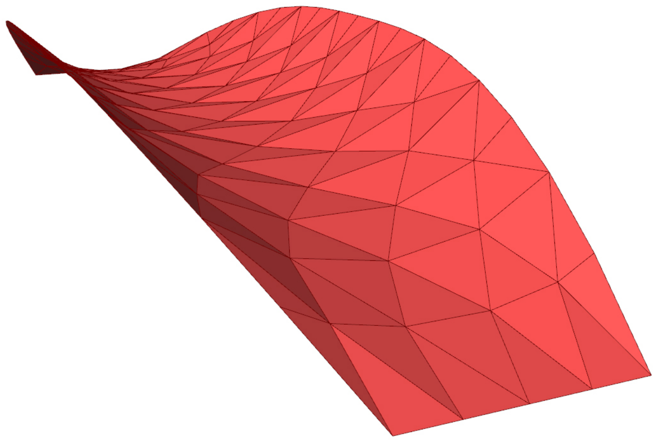


TU Delft

GEOMETRIC OPTIMIZATION

GEOMETRIC OPTIMIZATION

Regular triangular tessellation



TU Delft

GEOMETRIC OPTIMIZATION

Dimensions plate should be optimized

Embedded FRP sheet:

- Better distribution forces
- Higher axial stiffness

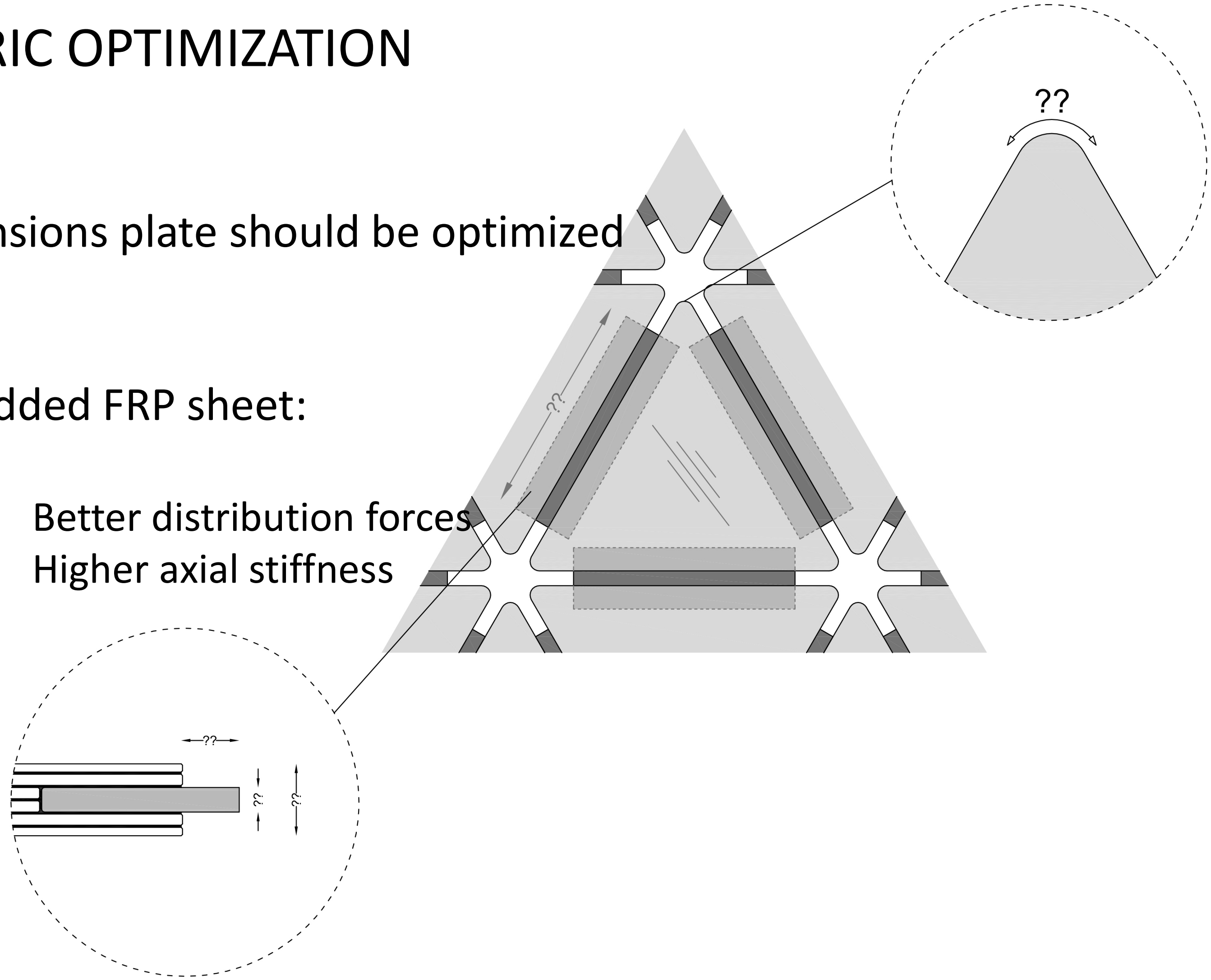


PLATE SHAPE

Variant 1

Protruding - 16mm
Thickness - 10mm
Fillet - 114mm

Variant 2

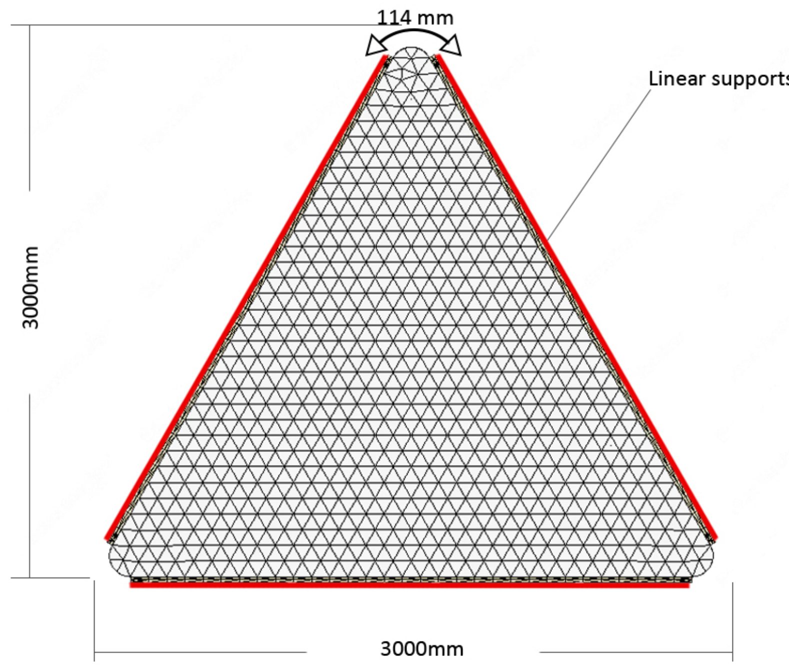
Protruding - 32mm
Thickness - 16mm
Fillet - 114mm

Variant 3

Protruding - 16mm
Thickness - 10mm
Fillet - 38mm

Variant 4

Protruding - 32mm
Thickness - 10mm
Fillet - 114mm

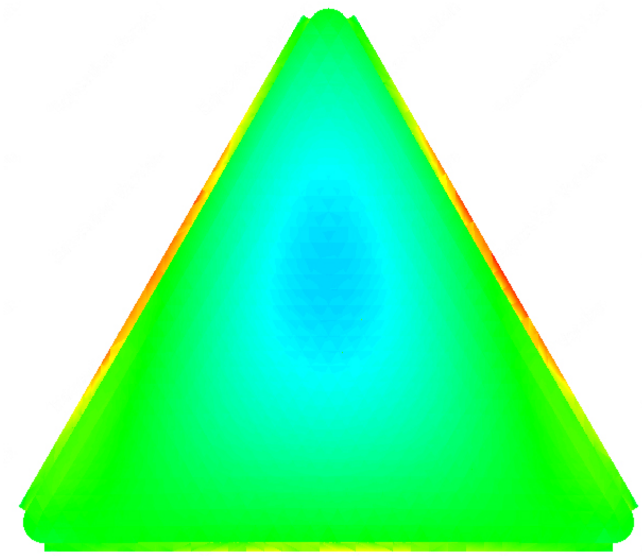


RESULTS

No significant influence rounding corners & length of connected edge

Larger protruding length

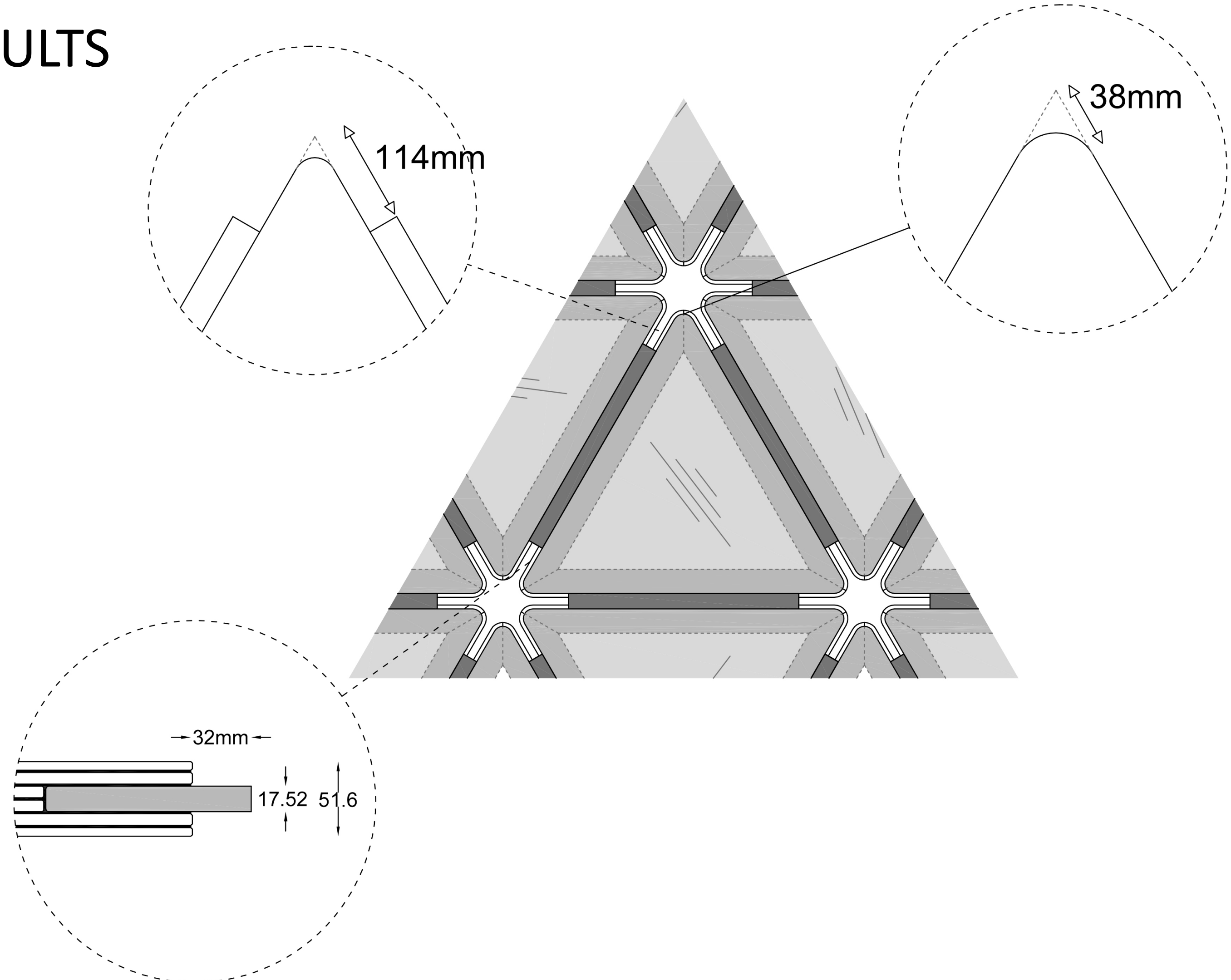
Larger thickness embedded sheet



TU Delft

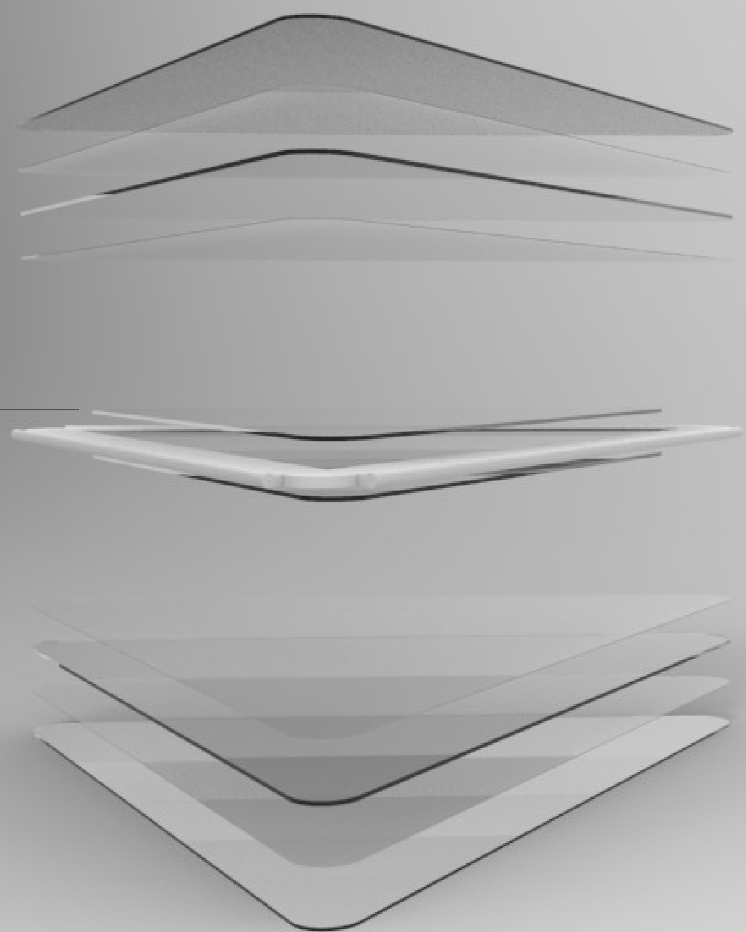
ANALYSIS & OPTIMIZATION

RESULTS



ANALYSIS & OPTIMIZATION

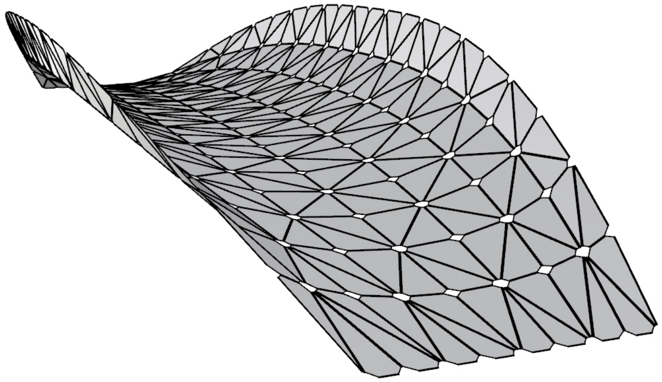
RESULTS

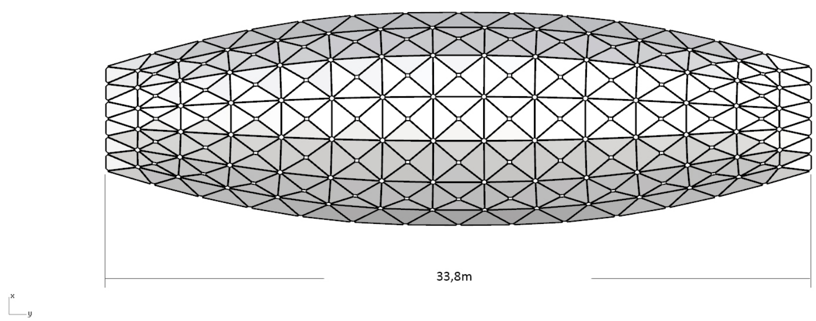


TU Delft

TOPOLOGY

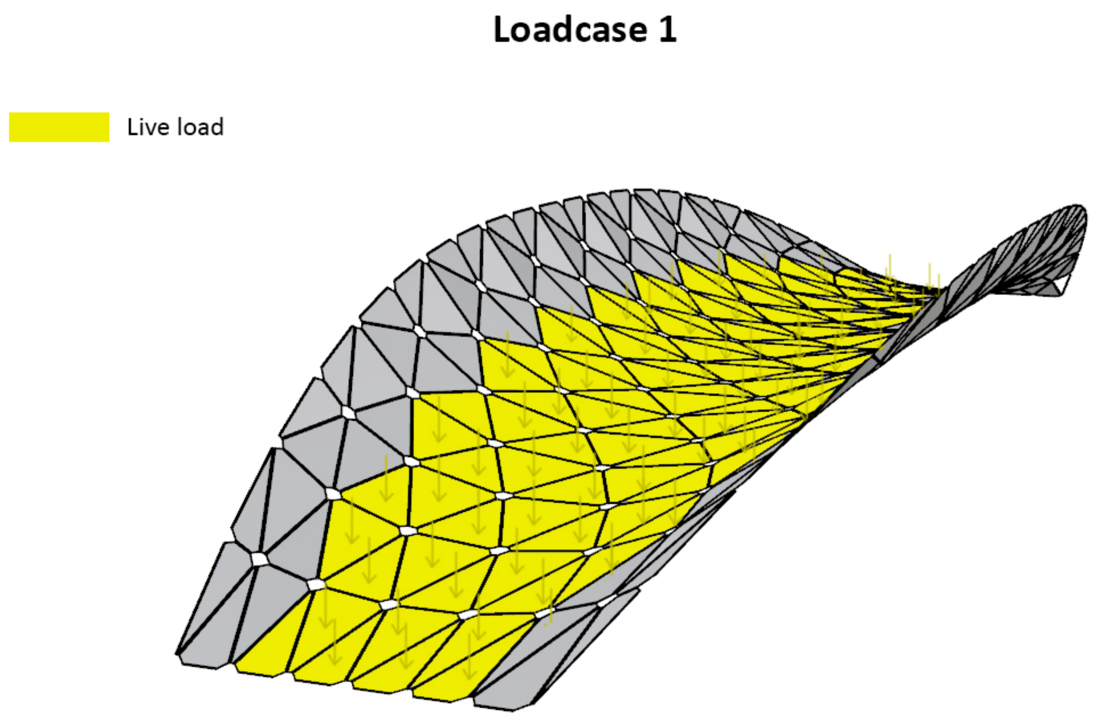
Three topological variants tessellated with different triangular panels





ANALYSIS & OPTIMIZATION

LOADS ACCORDING TO NEN



TU Delft

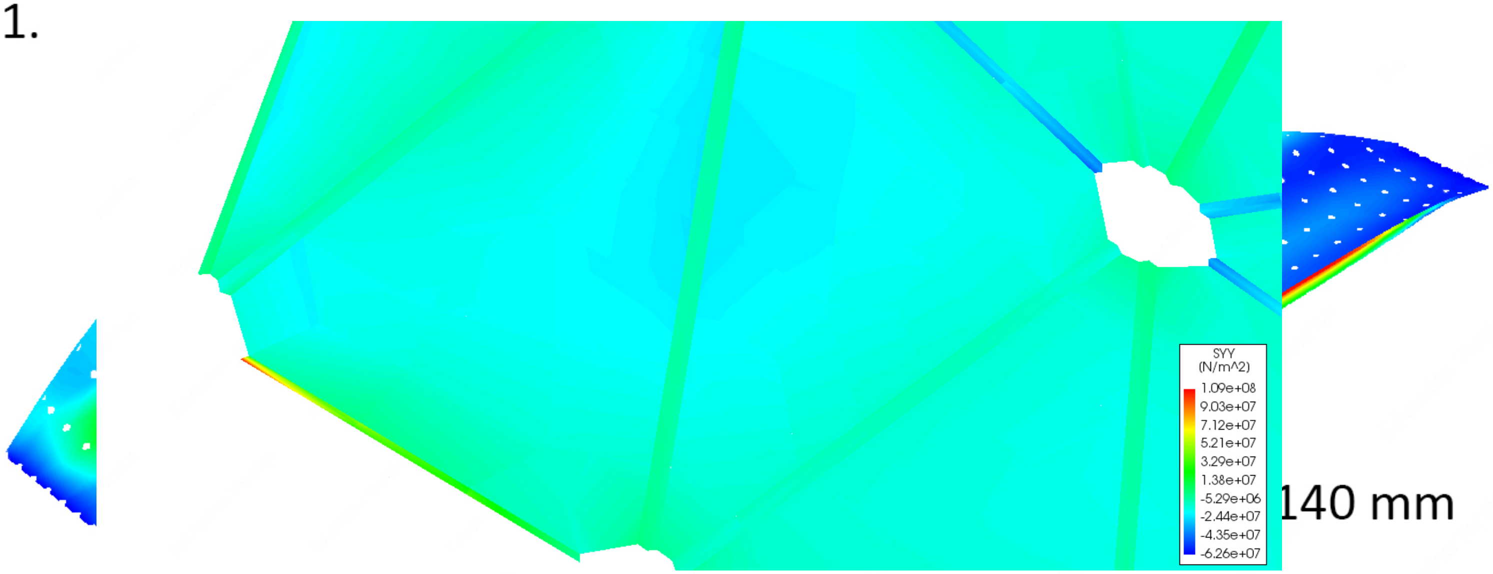
ANALYSIS & OPTIMIZATION

RESULTS

Variant 2 shows the least deformation & stresses

High concentrated stresses at supports

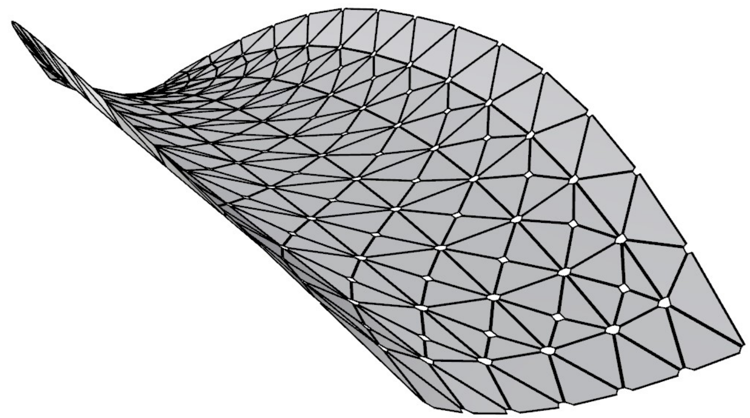
1.



140 mm

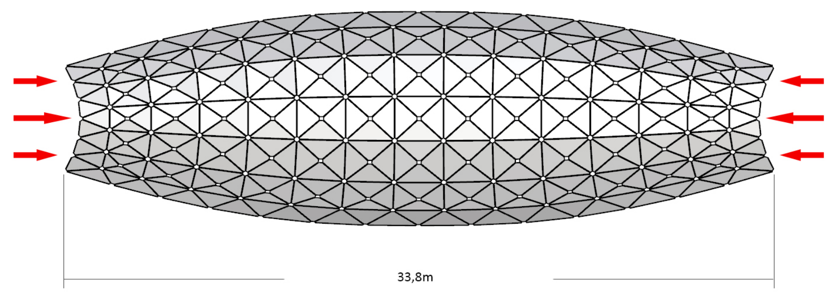
ANALYSIS & OPTIMIZATION

CURVATURE AT SUPPORTS



Introducing curvature for better shell behaviour

Limited to requirements



ANALYSIS & OPTIMIZATION

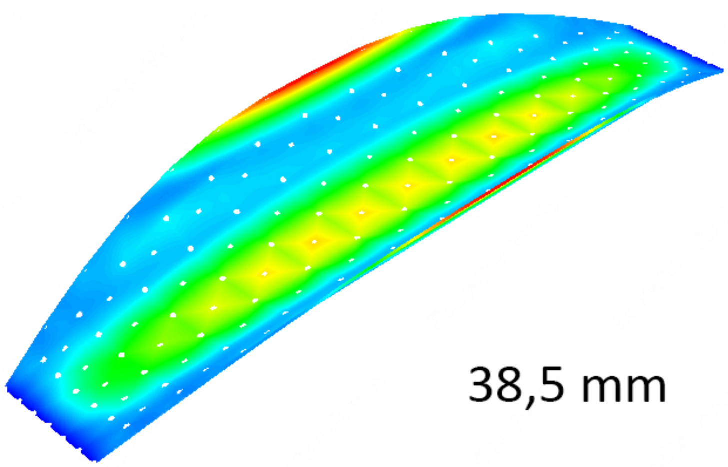
RESULTS

Lower overall stresses

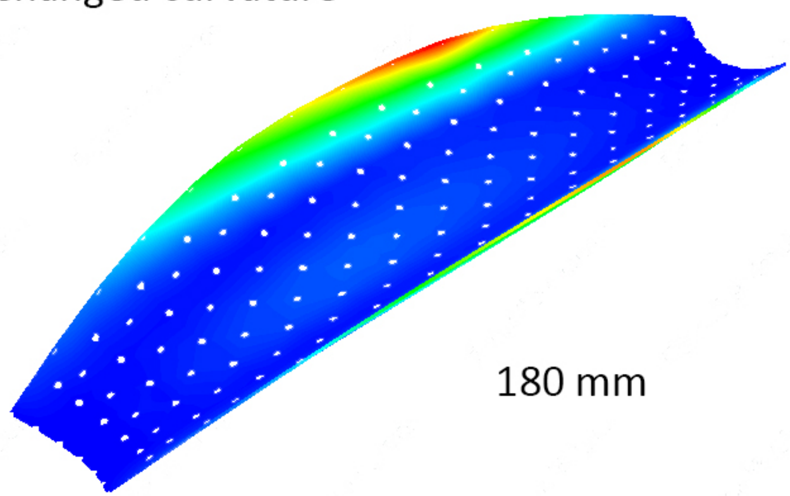
Similar deformation

2.

Changed curvature



38,5 mm



180 mm

TU Delft

STRUCTURE:

1) Introducing the subject

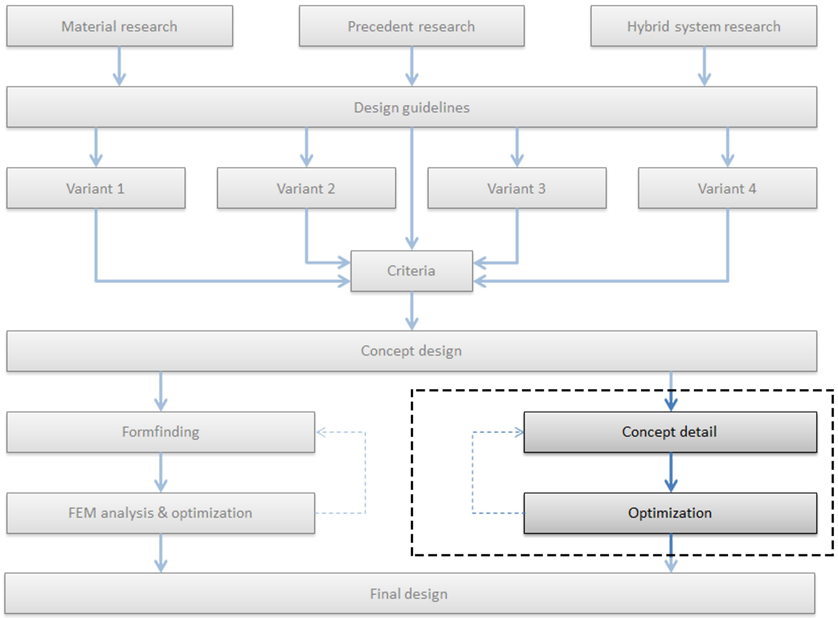
2) Theoretical framework

3) Preliminary variants of design

4) Form-finding & optimization of design

5) Connections

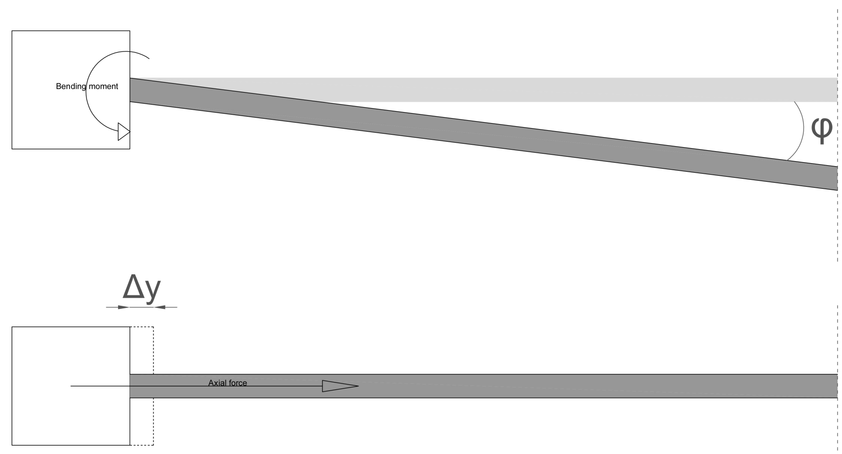
6) Final design



CONNECTIONS

Transfer loads between plates:

- Bending moments
- In-plane loads
- Shear forces
- Torsional moments



Depending on:

- Overall shell behaviour
- Stiffness plates
- Stiffness connection detail

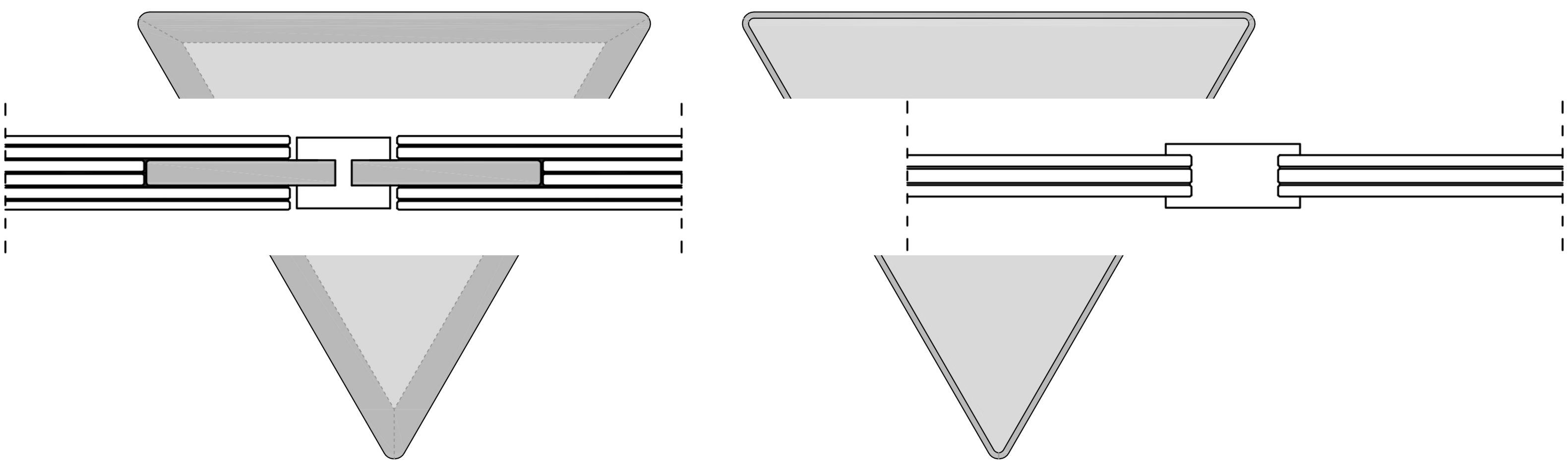
TU Delft

CONNECTIONS

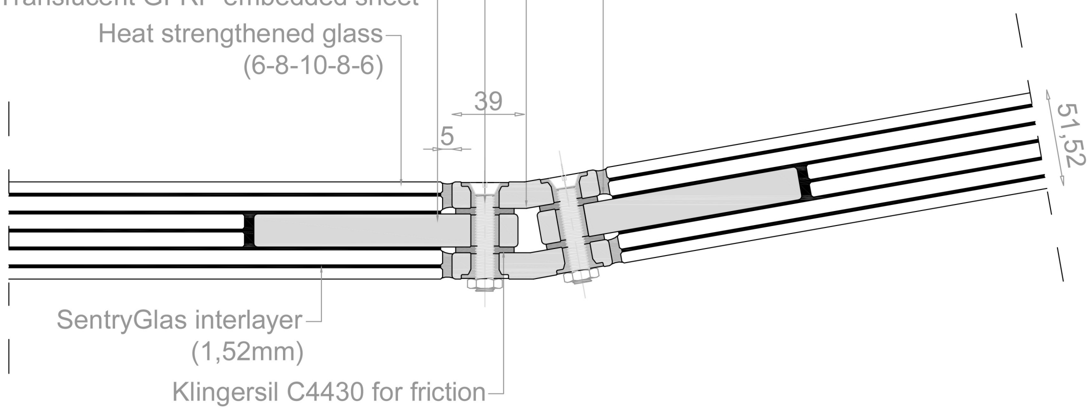
Plate embedded between glass – why?

- Distribution forces
- No added height to connection detail

- Equal thermal expansion coefficient



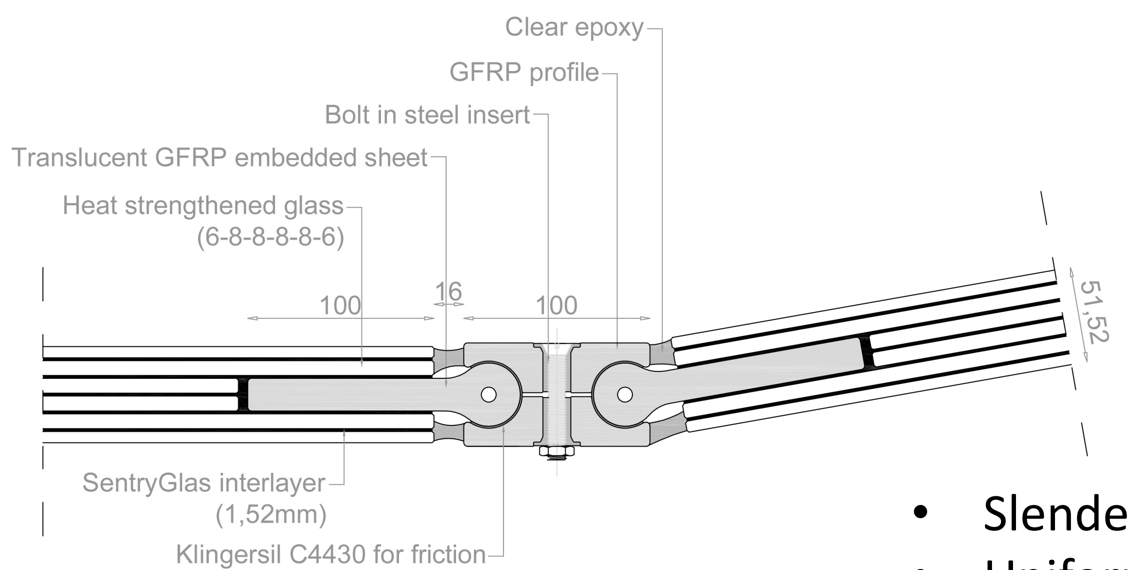
PROPOSED CONNECTION 1



- Slender
- Stresses around bolts

TU Delft

PROPOSED CONNECTION 2

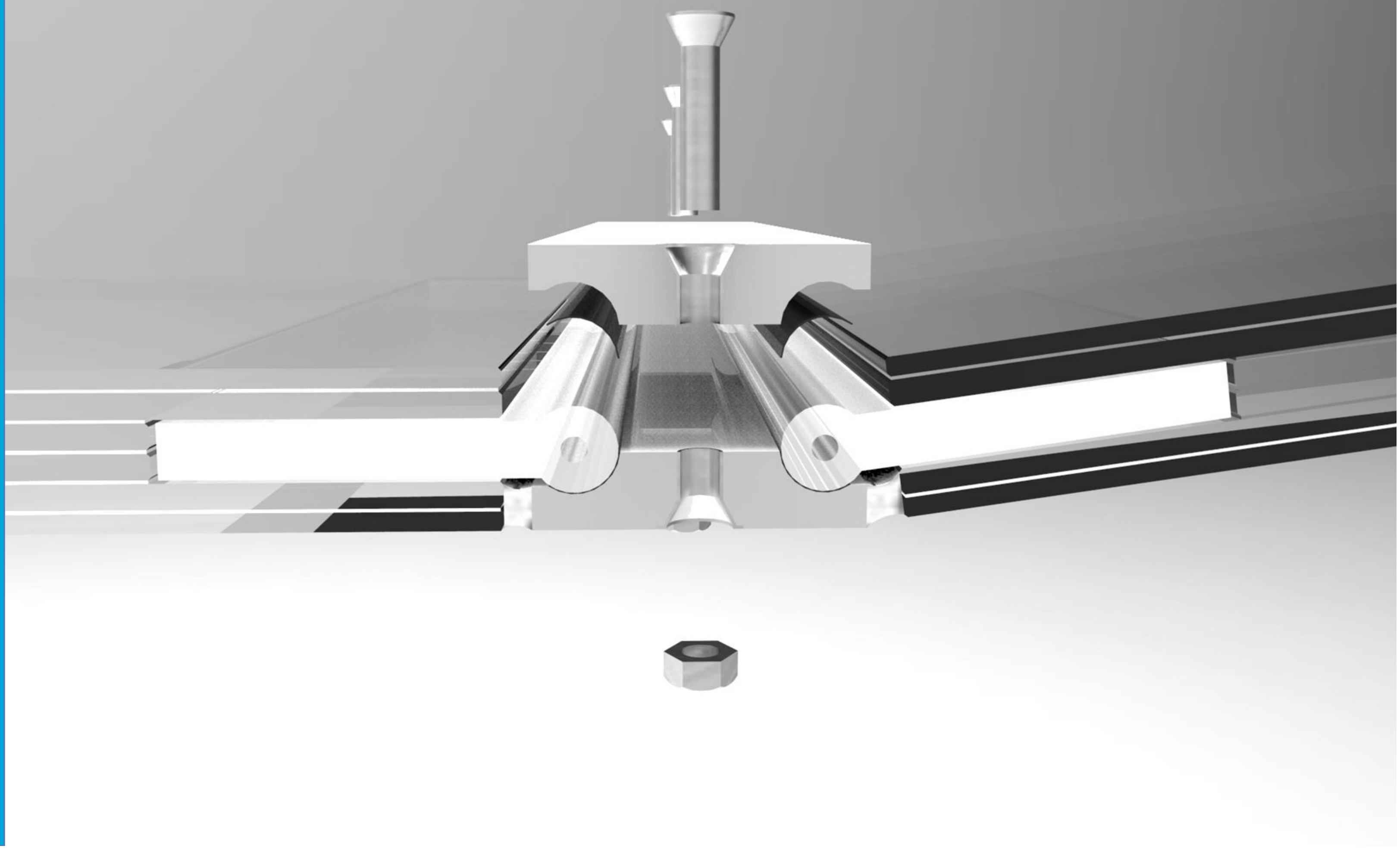


- Slender
- Uniform production
- No stress concentrations

- Less axial stiffness

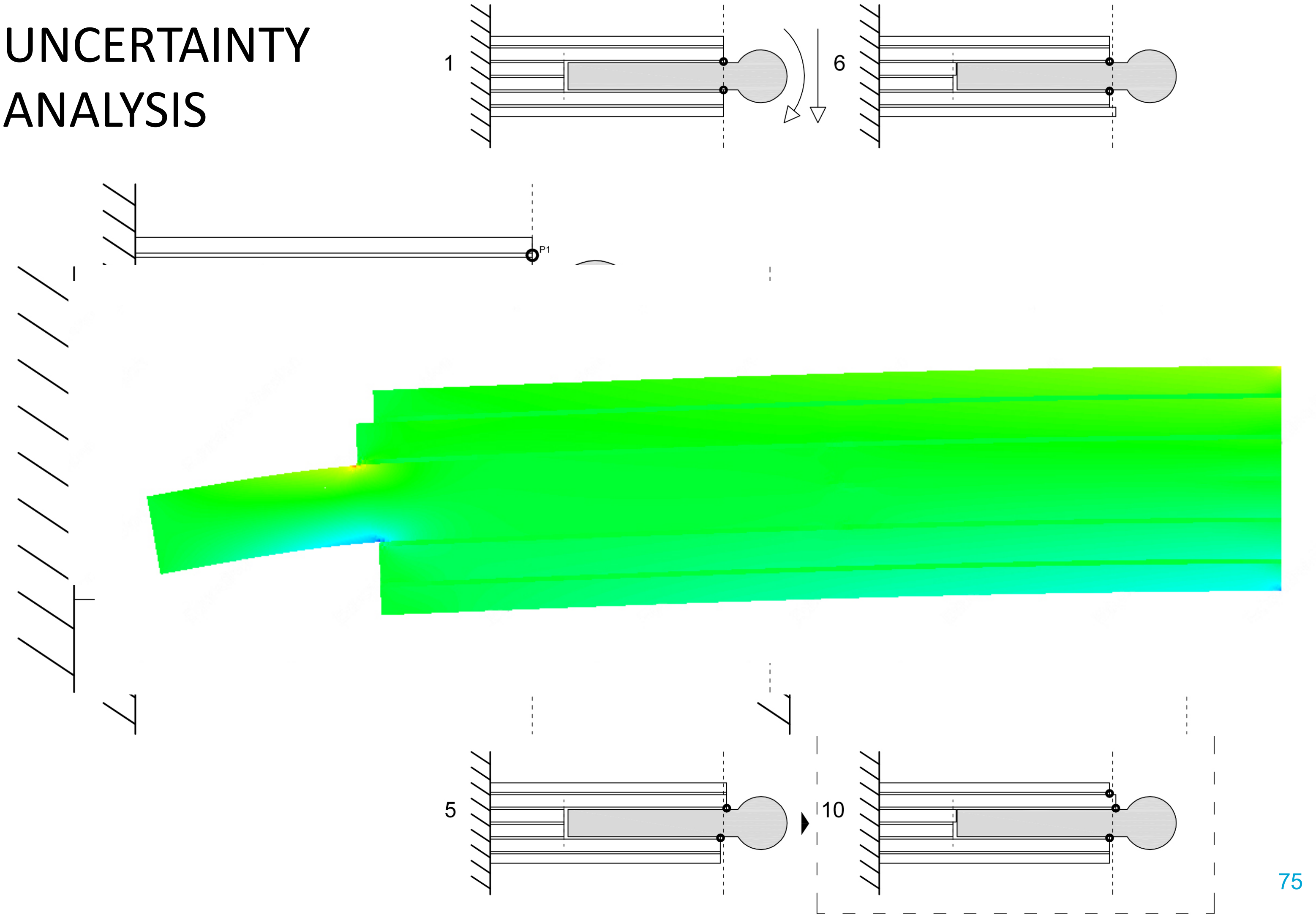
CONNECTIONS

PROPOSED CONNECTION 2



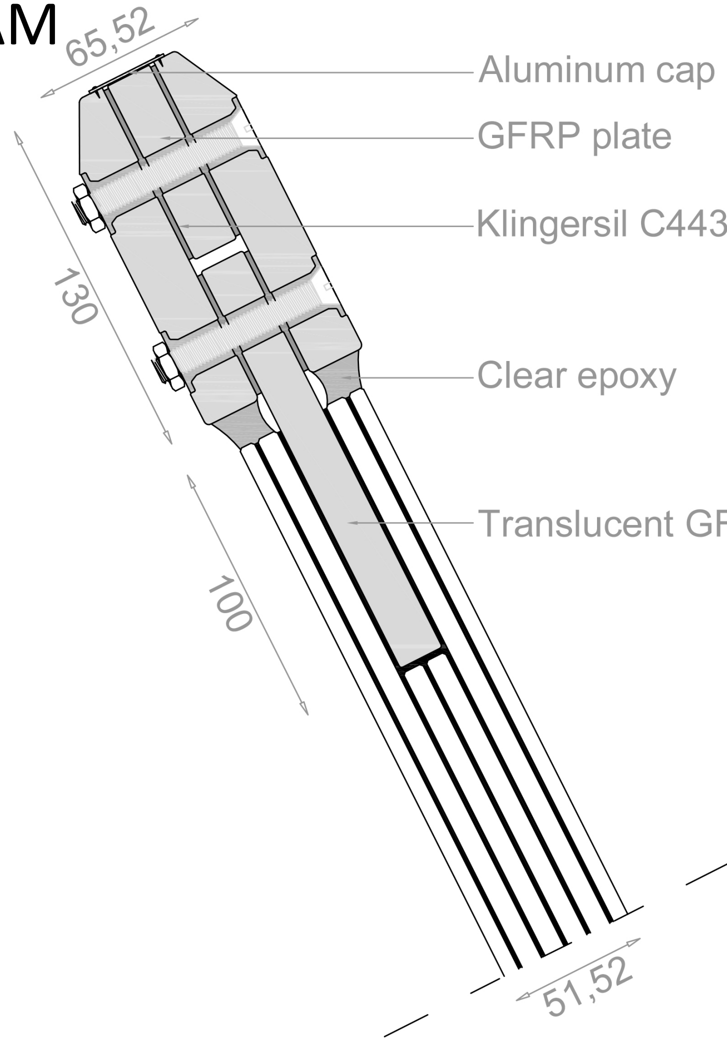
CONNECTIONS

UNCERTAINTY ANALYSIS



CONNECTIONS

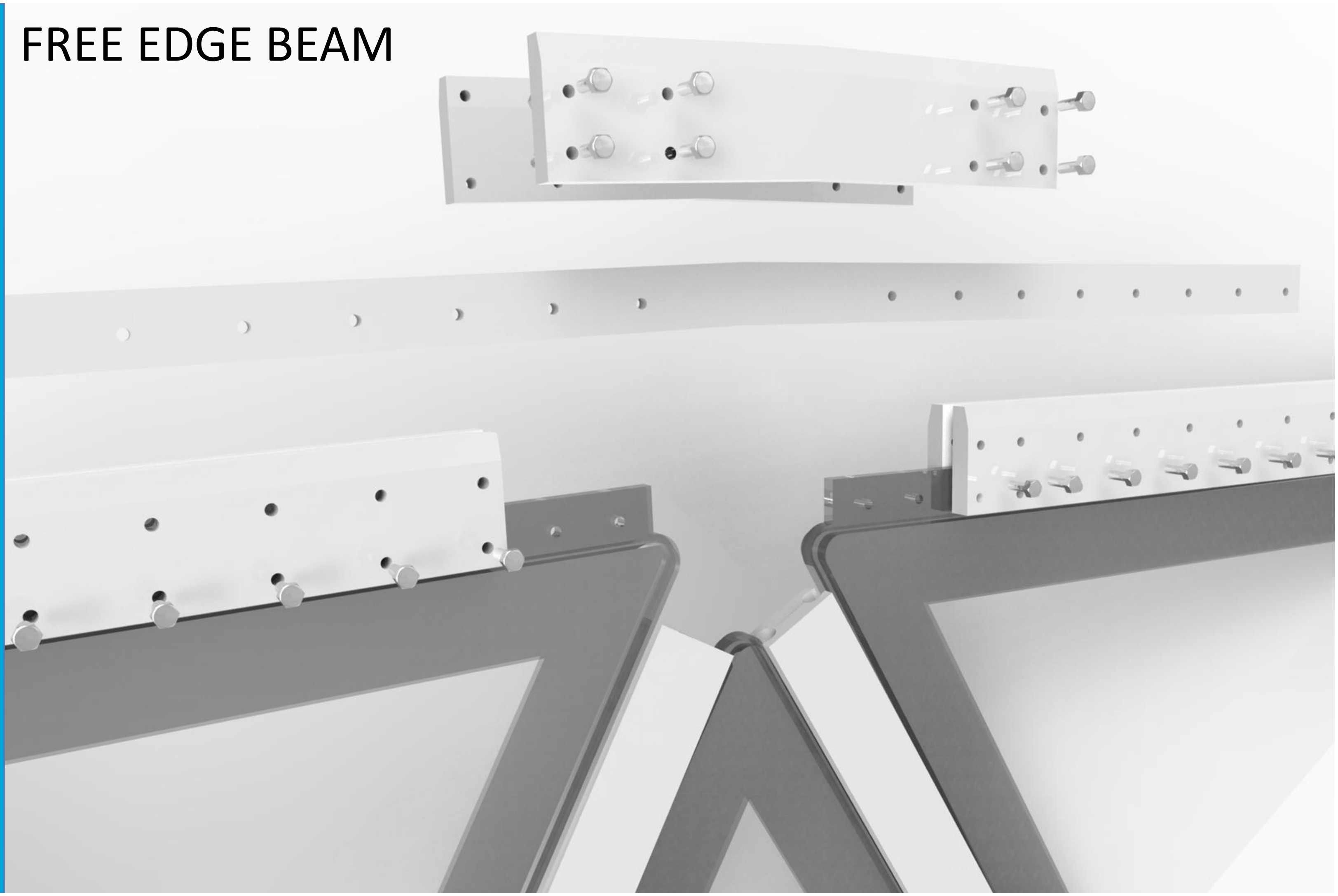
FREE EDGE BEAM



TU Delft

CONNECTIONS

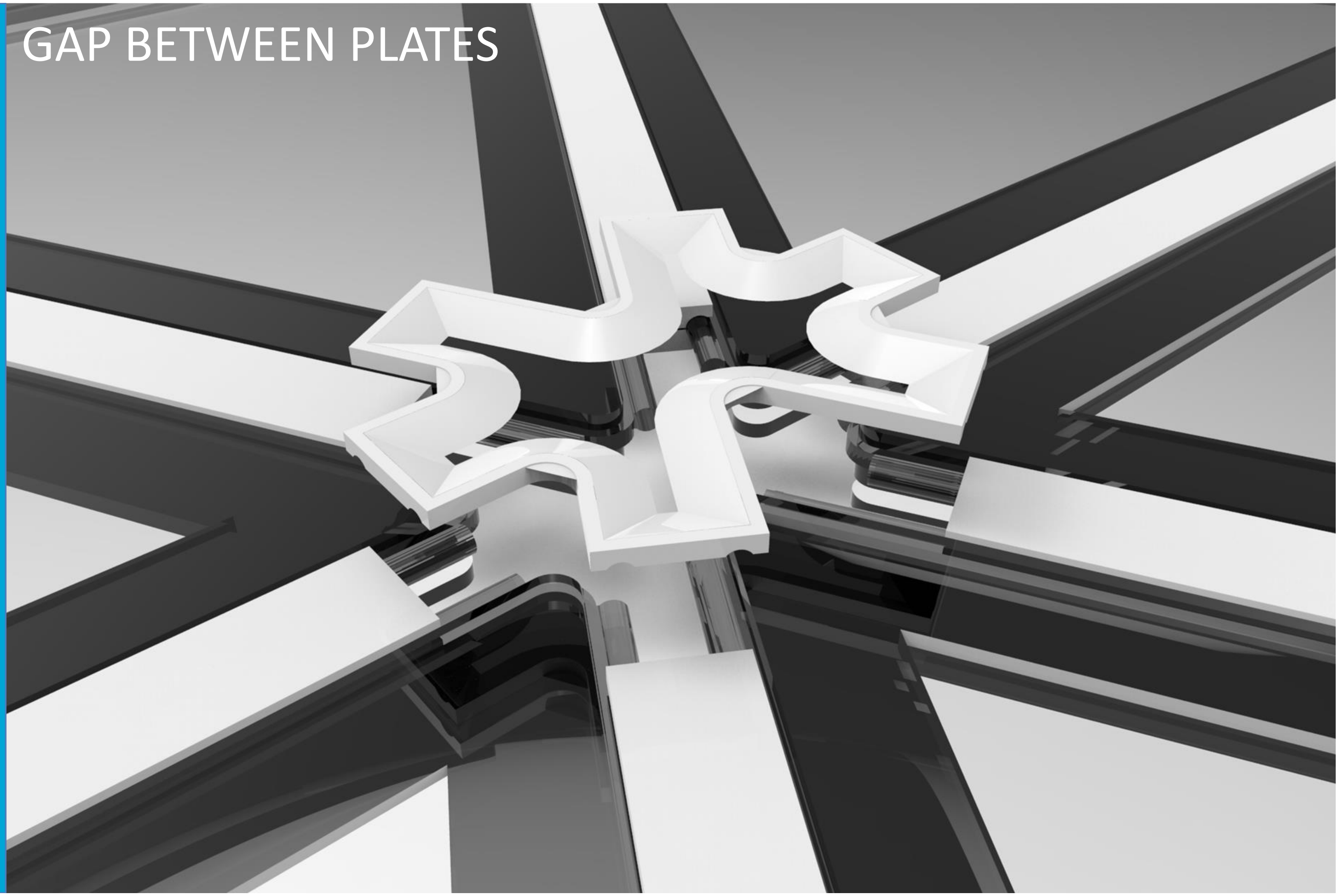
FREE EDGE BEAM



TU Delft

CONNECTIONS

GAP BETWEEN PLATES



TU Delft

FABRICATION

Quasi-isotropic:

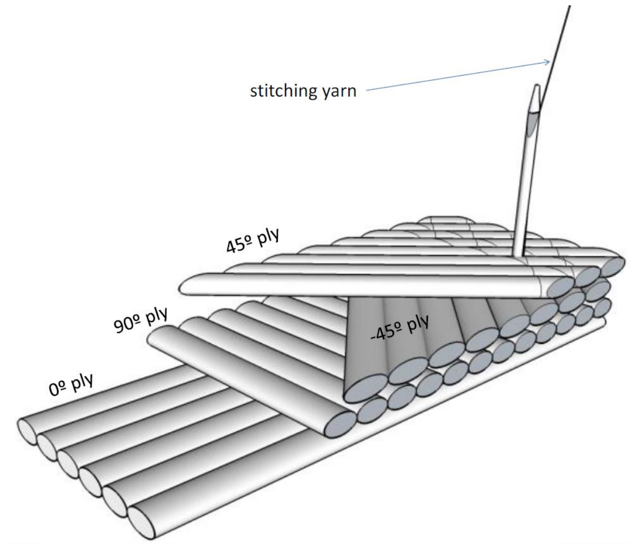
- Non-linear loading

Glassfibre reinforced polymers:

- Cheapest, most sustainable & widely used
- Translucent

Epoxy resin:

- High corrosion resistance
- Good thermal properties
- High strength



TU Delft

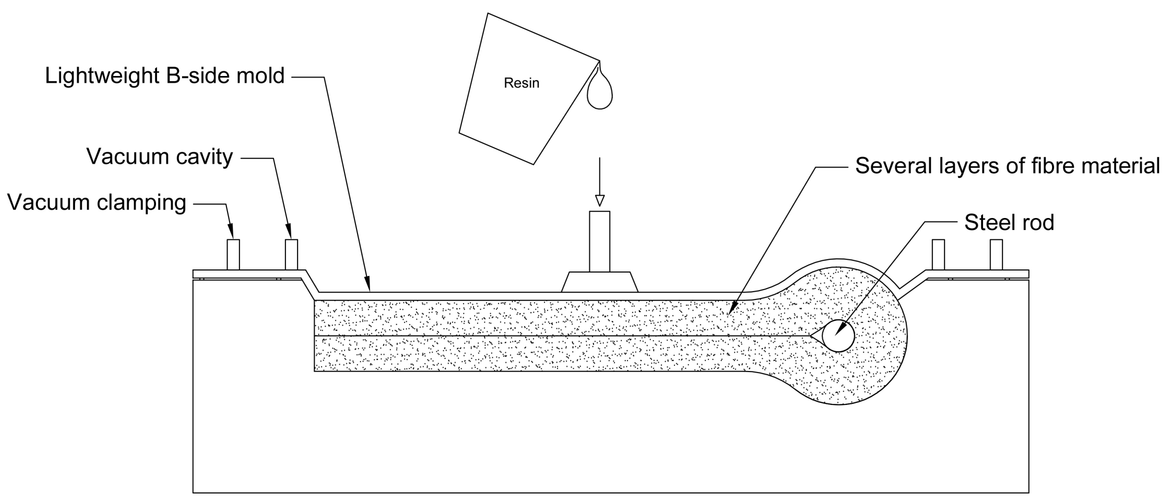
FABRICATION

GFRP embedded sheet:

- Vacuum moulding
- Cut to exact shape
- Laminated between glass

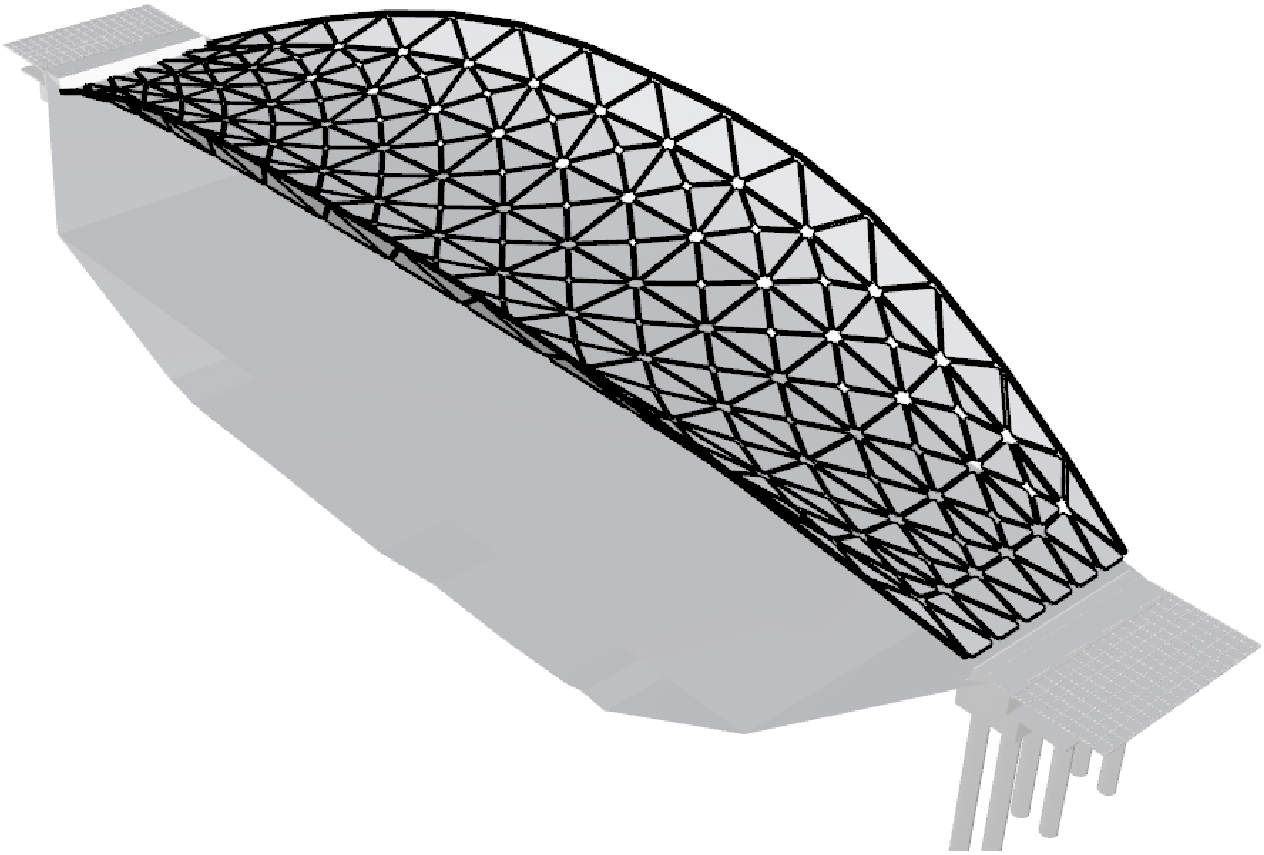
Joint profiles:

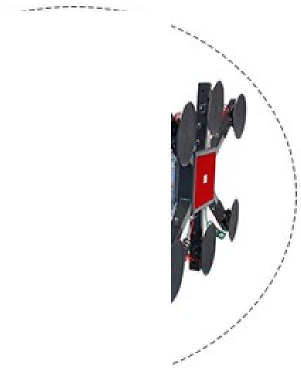
- Pultrusion
- Cut to shape



CONNECTIONS

ASSEMBLY





TU Delft

STRUCTURE:

1) Introducing the subject

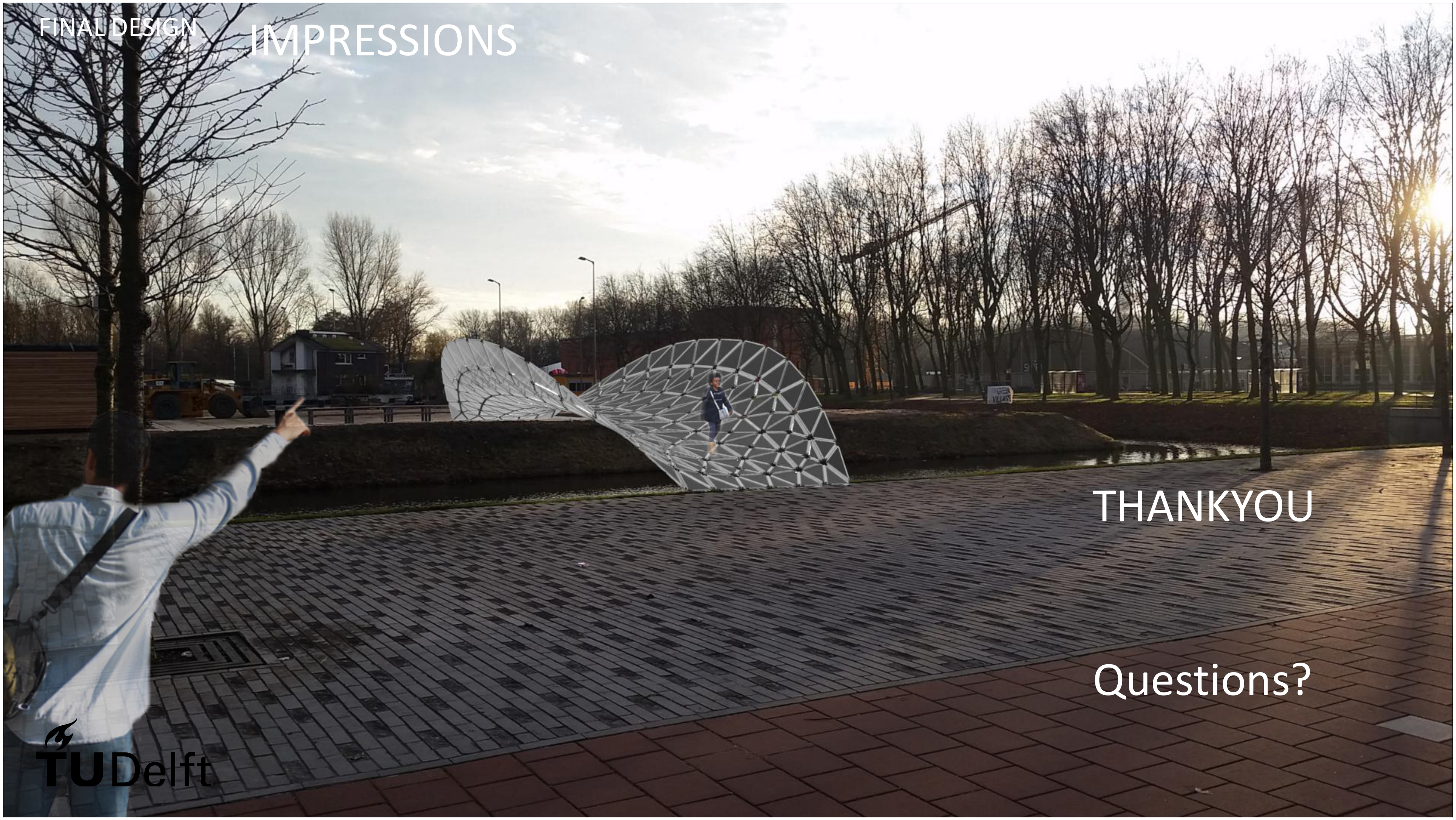
2) Theoretical framework

3) Preliminary variants of design

4) Form-finding & optimization of design

5) Connections

6) Final design


FINAL DESIGN
IMPRESSIONS
THANKYOU
Questions?
TUDelft

THEORETICAL FRAMEWORK

STRUCTURAL GLASS

Material characteristics:

- High stiffness
- High compressive strength
- High chemical resistance
- High density

- Brittle
- Low toughness
- Low thermal shock resistance
- Highly sensitive to stress concentrations

TU Delft

THEORETICAL FRAMEWORK

FIBRE REINFORCED POLYMERS

Material characteristics:

- Composite material
- An-isotropic to quasi-isotropic
- Low density
- High specific strength
- High durability
- High freedom of form (mouldability)
- Brittle
- High (initial) material costs
- Sensitive to heat

TUDelft