3D printed bridge

AQTr – 19 September 2019

Stijn Joosten

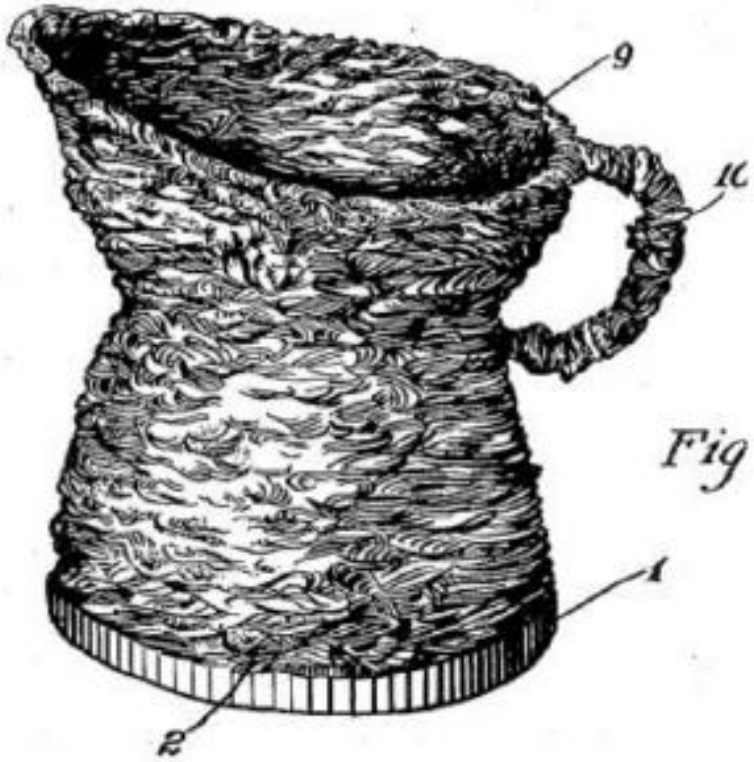
ARUP


crew

// Background
// Challenges
// Design
// Element testing
// Structural Analysis
// Full-scale testing
// Going forward

Background
From 3D-printing to digital fabrication

- 1926 patent: “the use of an electric arc as a heat source to generate 3D objects depositing molten metal in superimposed layers”



Fig

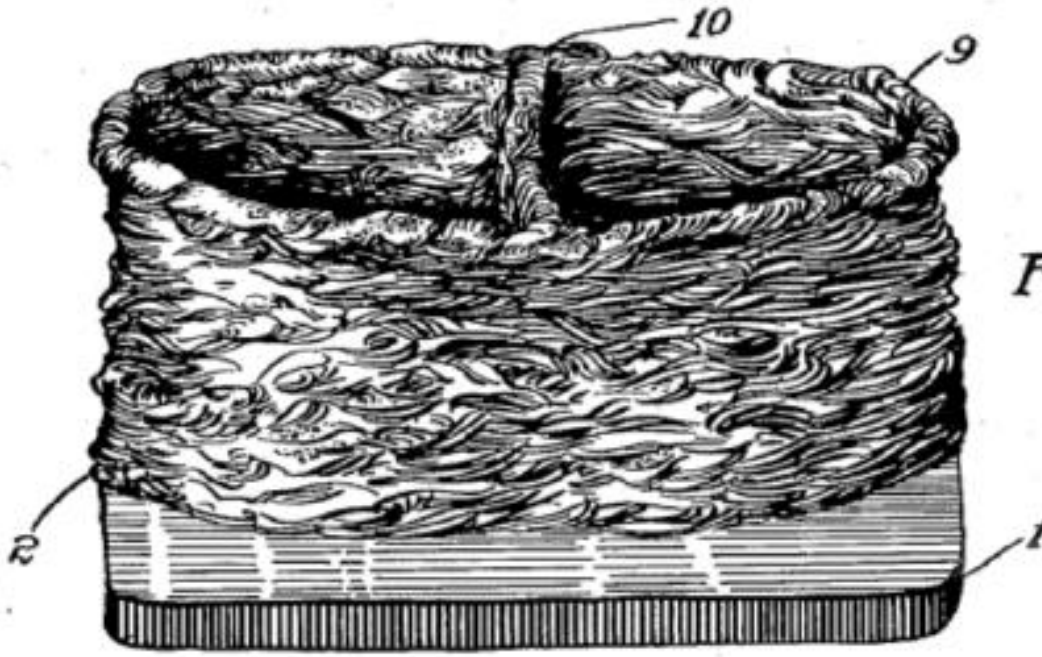
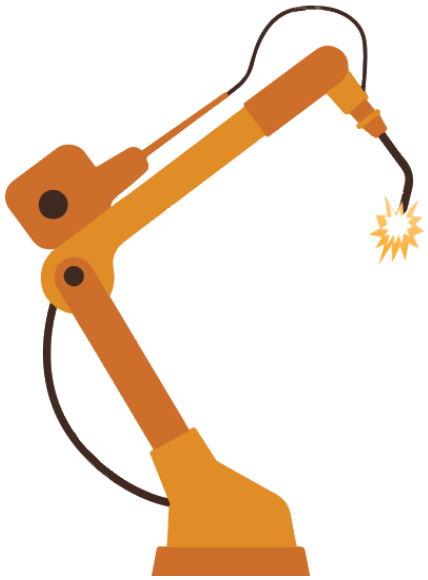


Fig. 2.

Background
From 3D-printing to digital fabrication

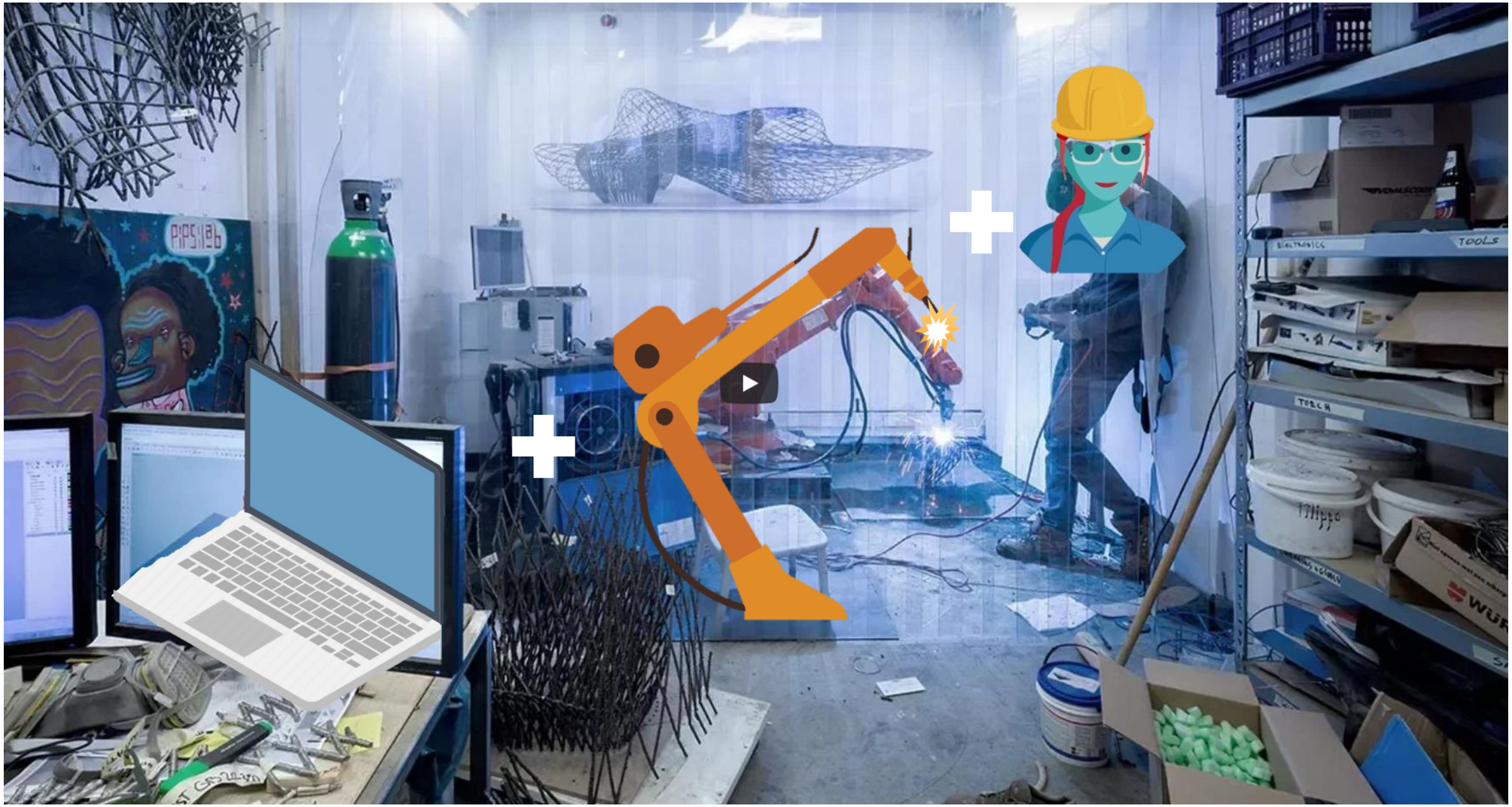
- Today:

  Welding robot + Computer + Engineer = Digital Fabrication



Background
Joris Laarman Lab – MX3D

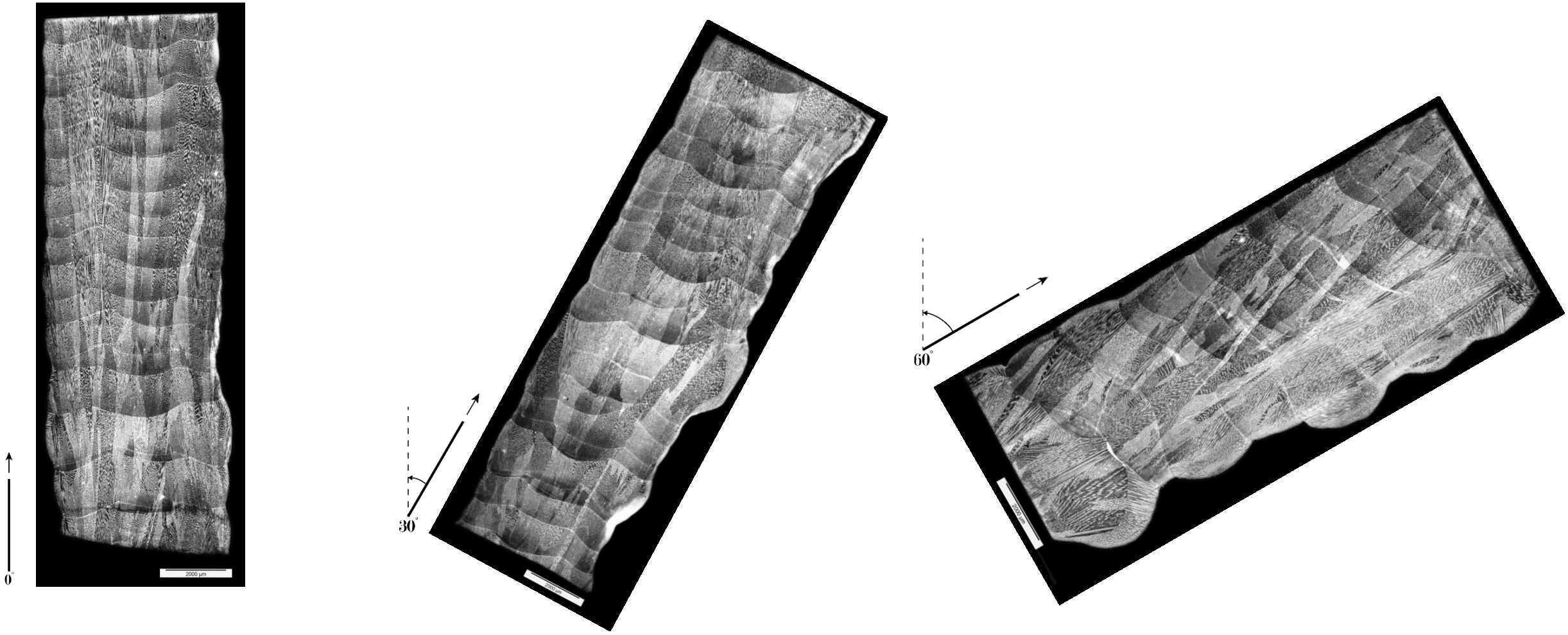

PIPSLAB
TOOLS
TORCH

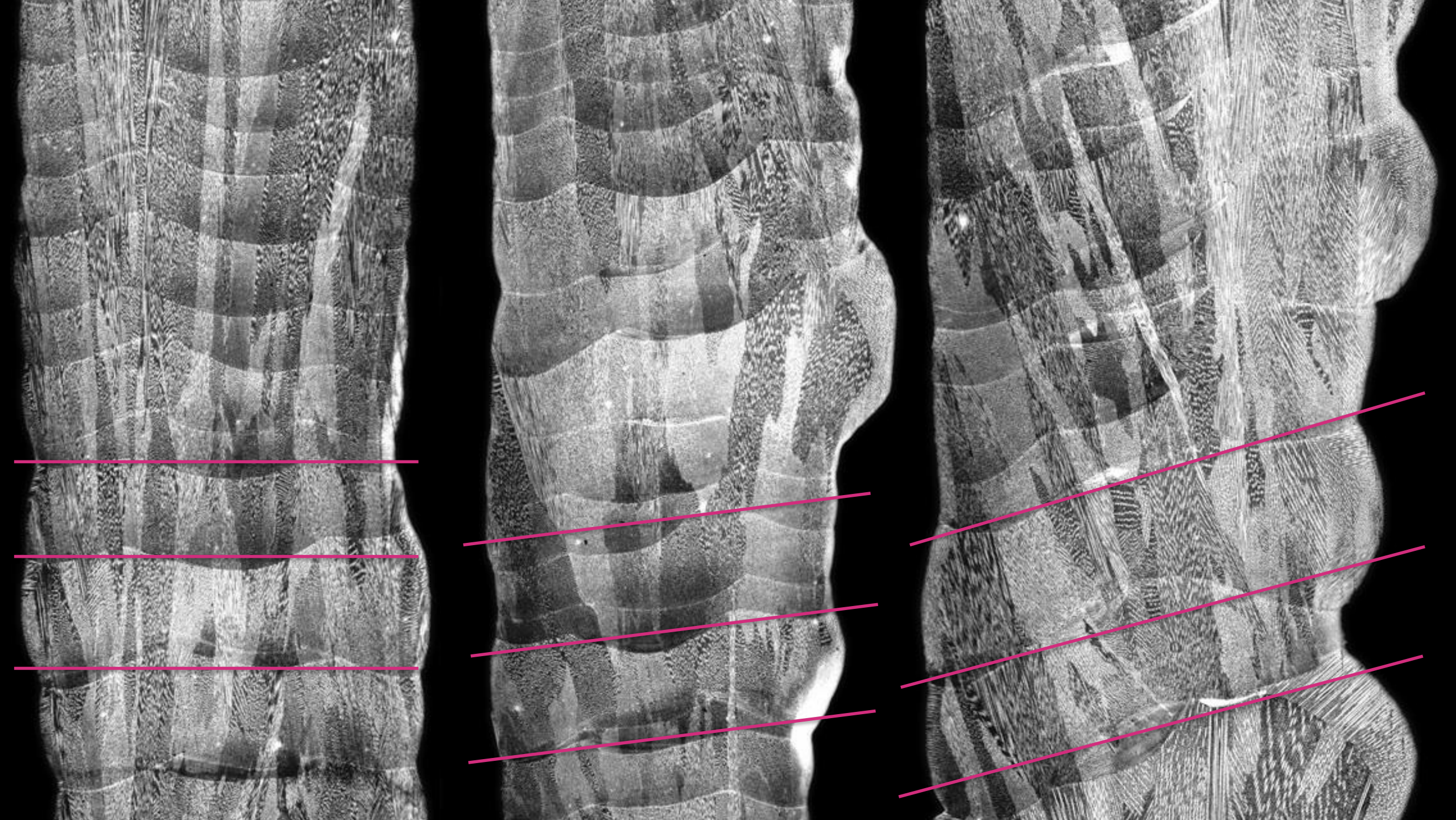

PIPSLab
TOOLS
TORCH

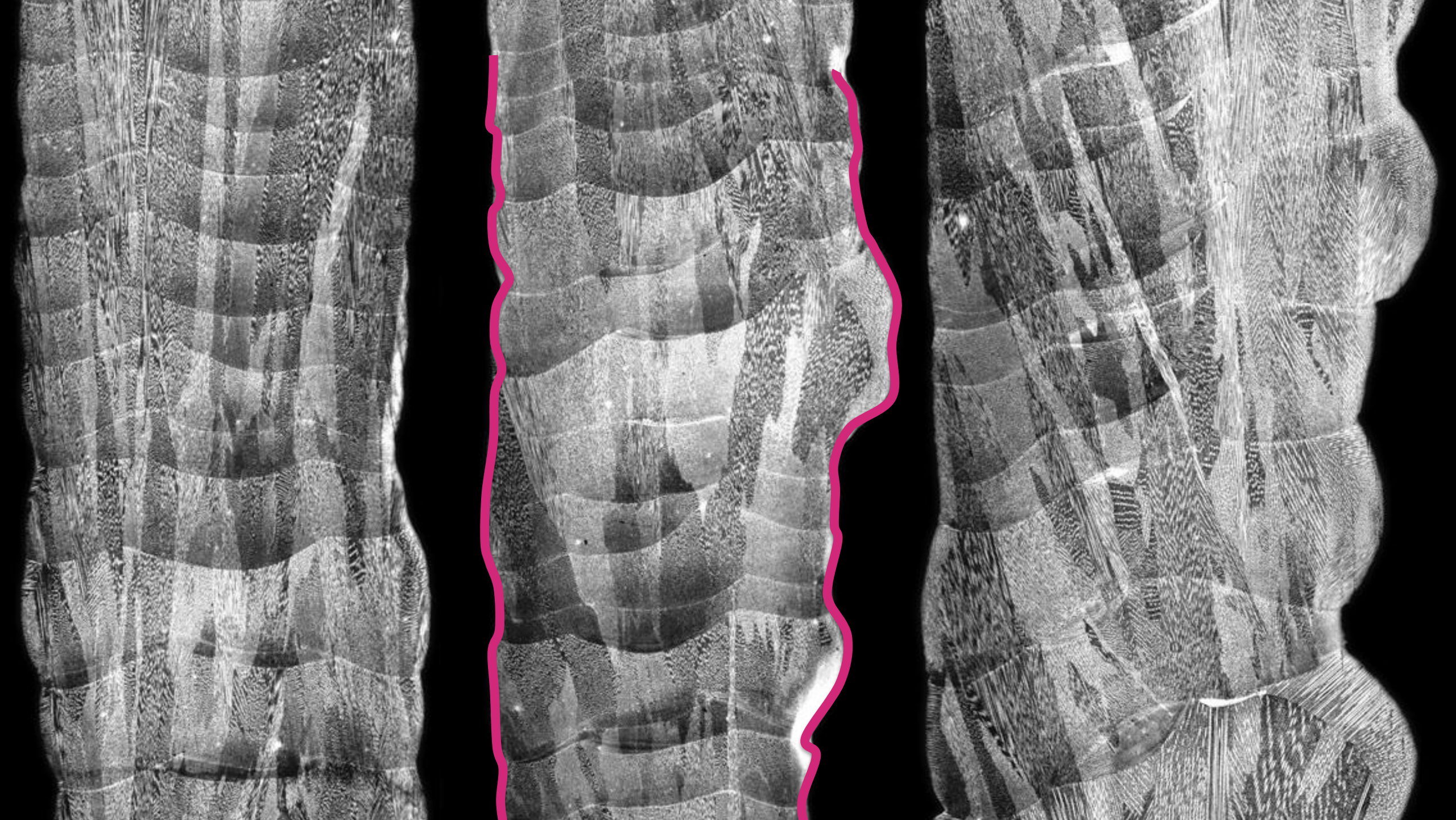
Challenges

3D printing challenges

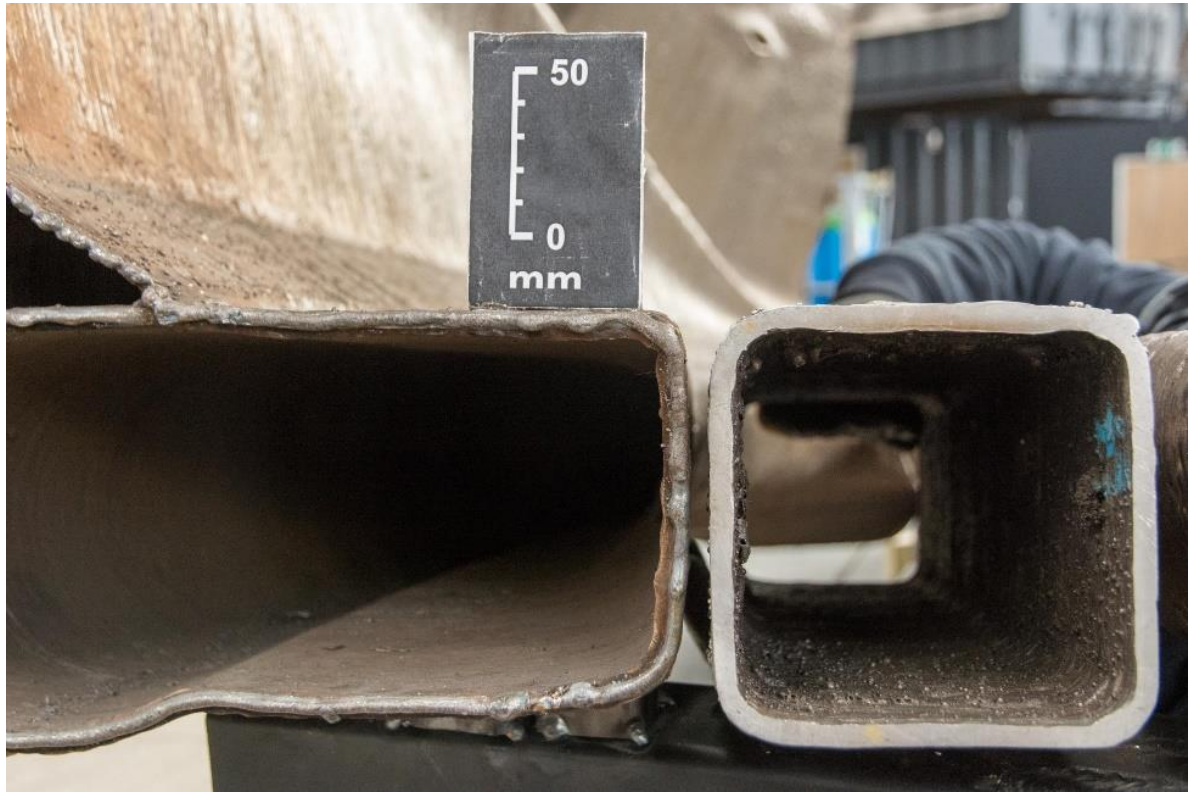
Challenges





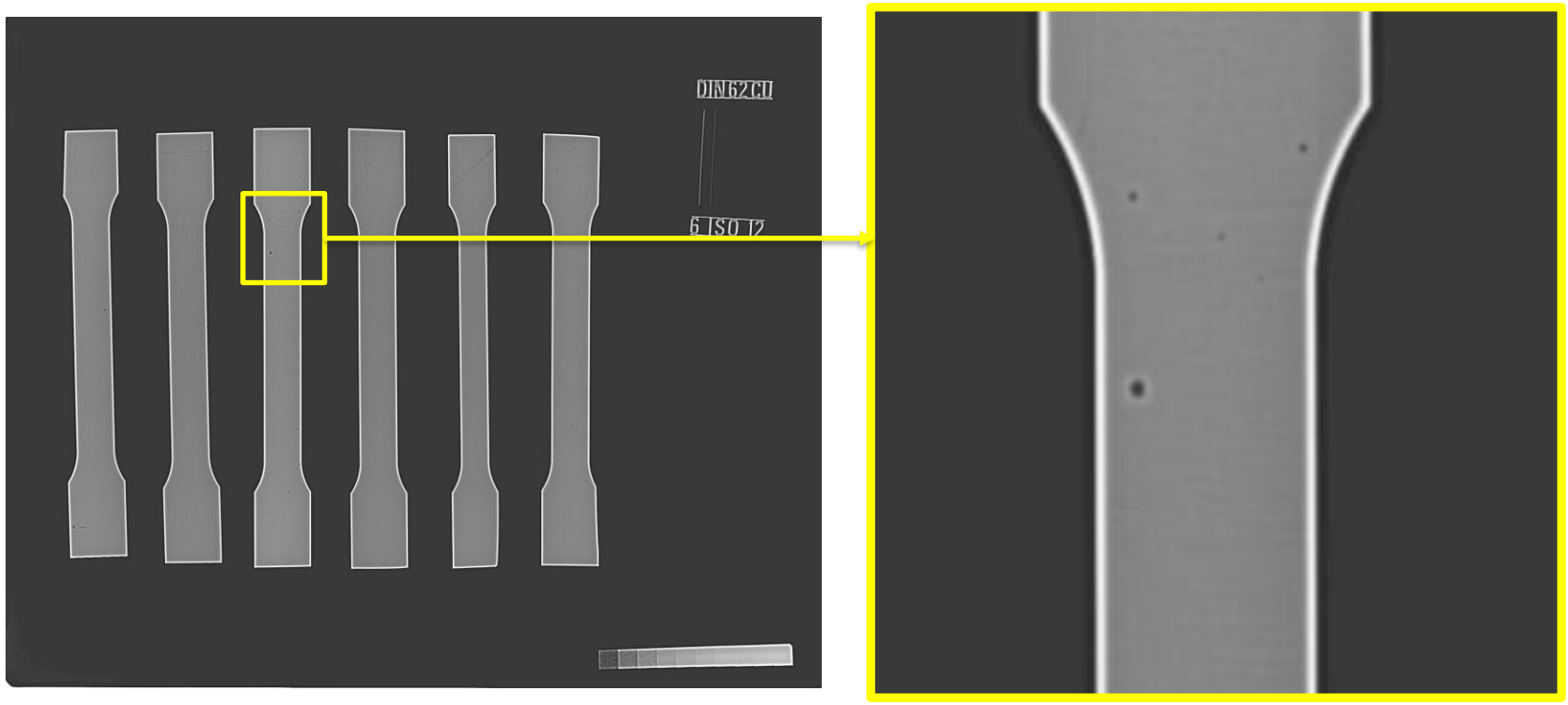


Challenges
Geometry

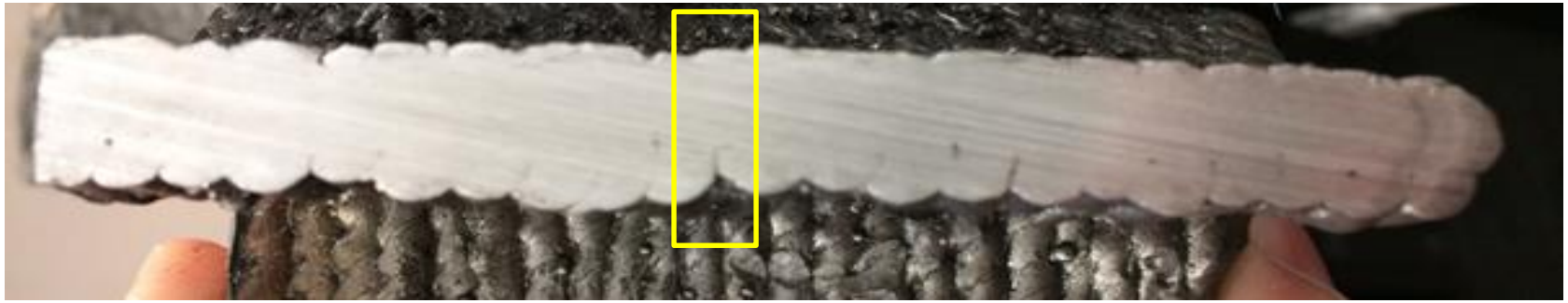


Challenges
Welding defects

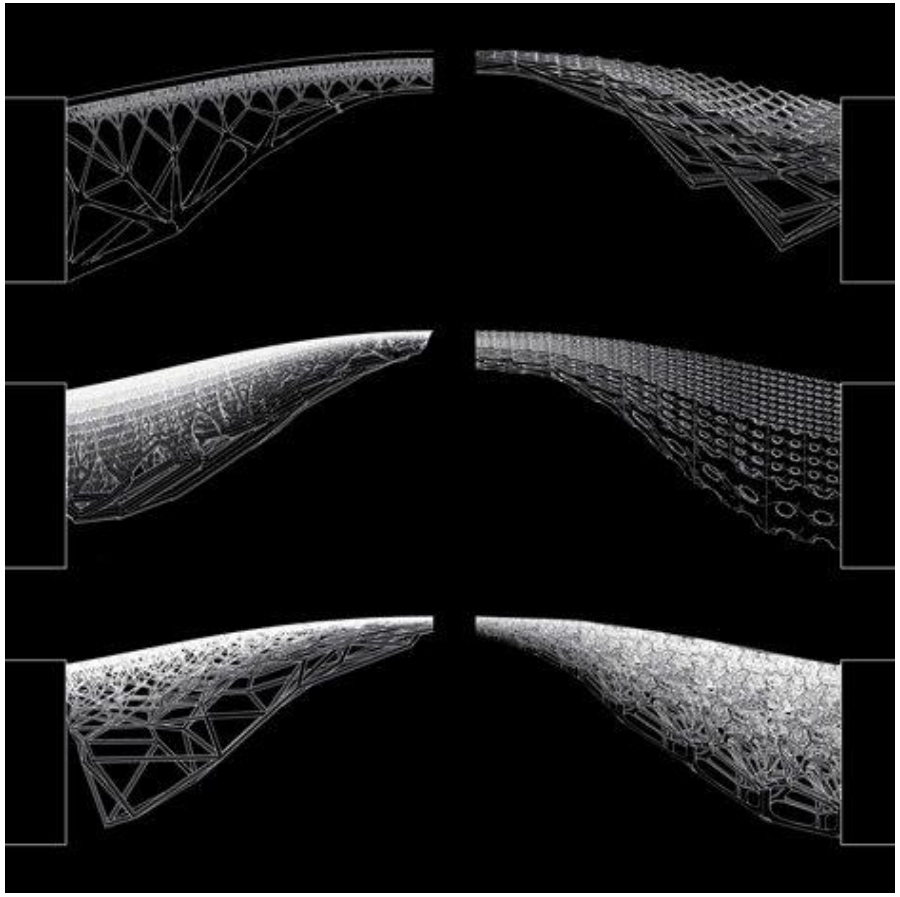
- Inclusions



- Lack of fusion



Challenges
Design



Design
First version MX3D

Design

Designing for 3D printing

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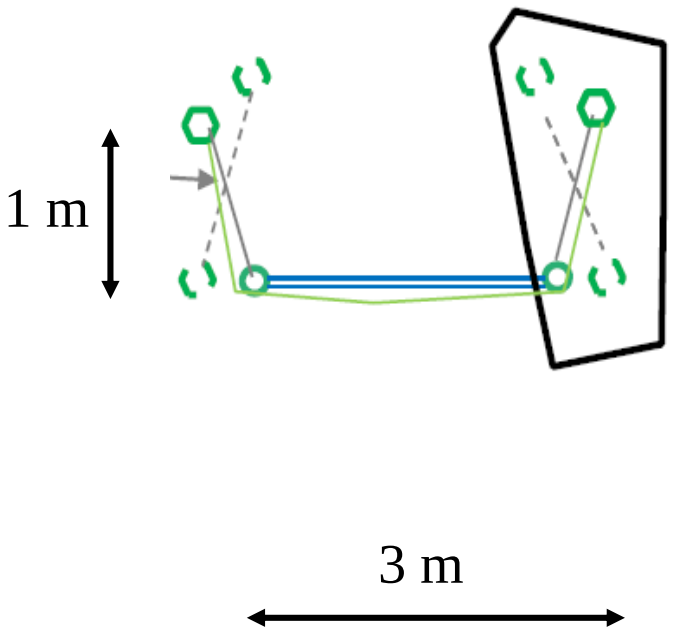
Design
Approach

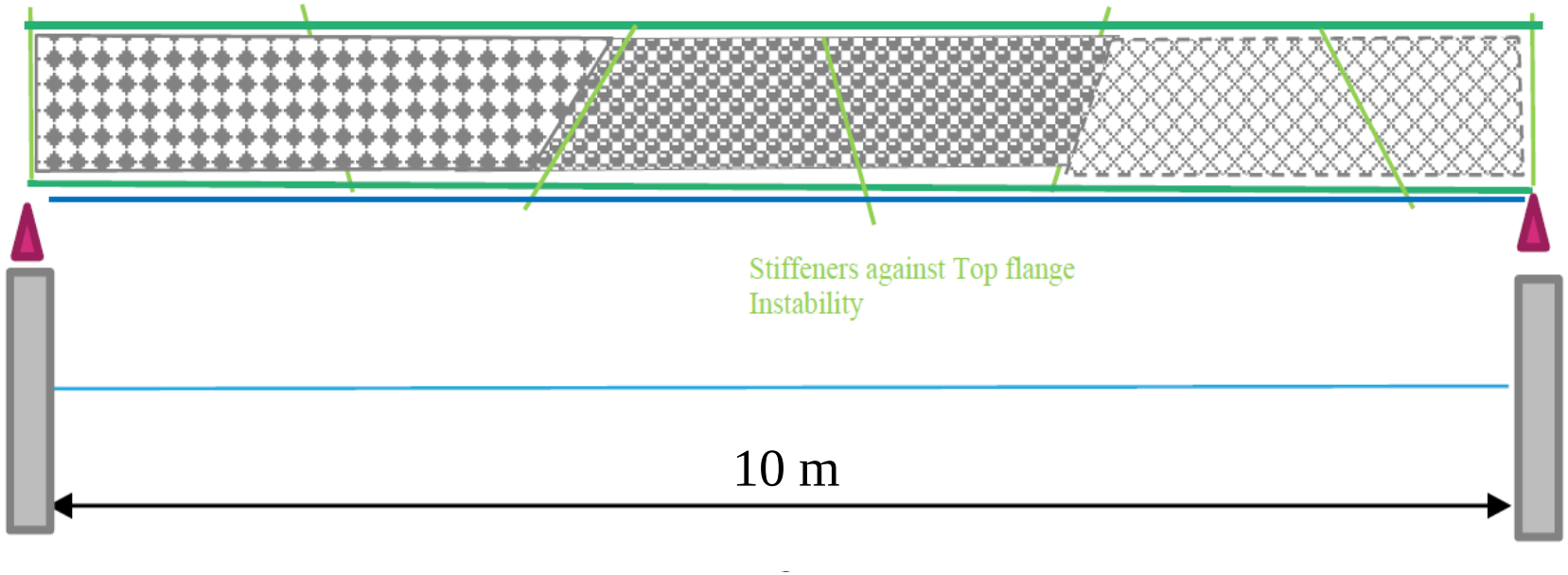
- Make a **robust design**, dealing with the specific **challenges** that come with 3D printing
- Perform **material tests** to find out structural properties
- Based on these tests, perform **structural analyses**
  - ICL (non-linear 2D shell model, one load case, no checks)
  - Arup model (used for design, simplified 1D beam model, all load combinations structural checks)
- Perform **full-scale tests** on the finished bridge, in order to **verify** the analysis
  - ‘SLS’ test before Dutch Design week
  - ULS test for final permit and placement in Amsterdam

Design
Structural concept

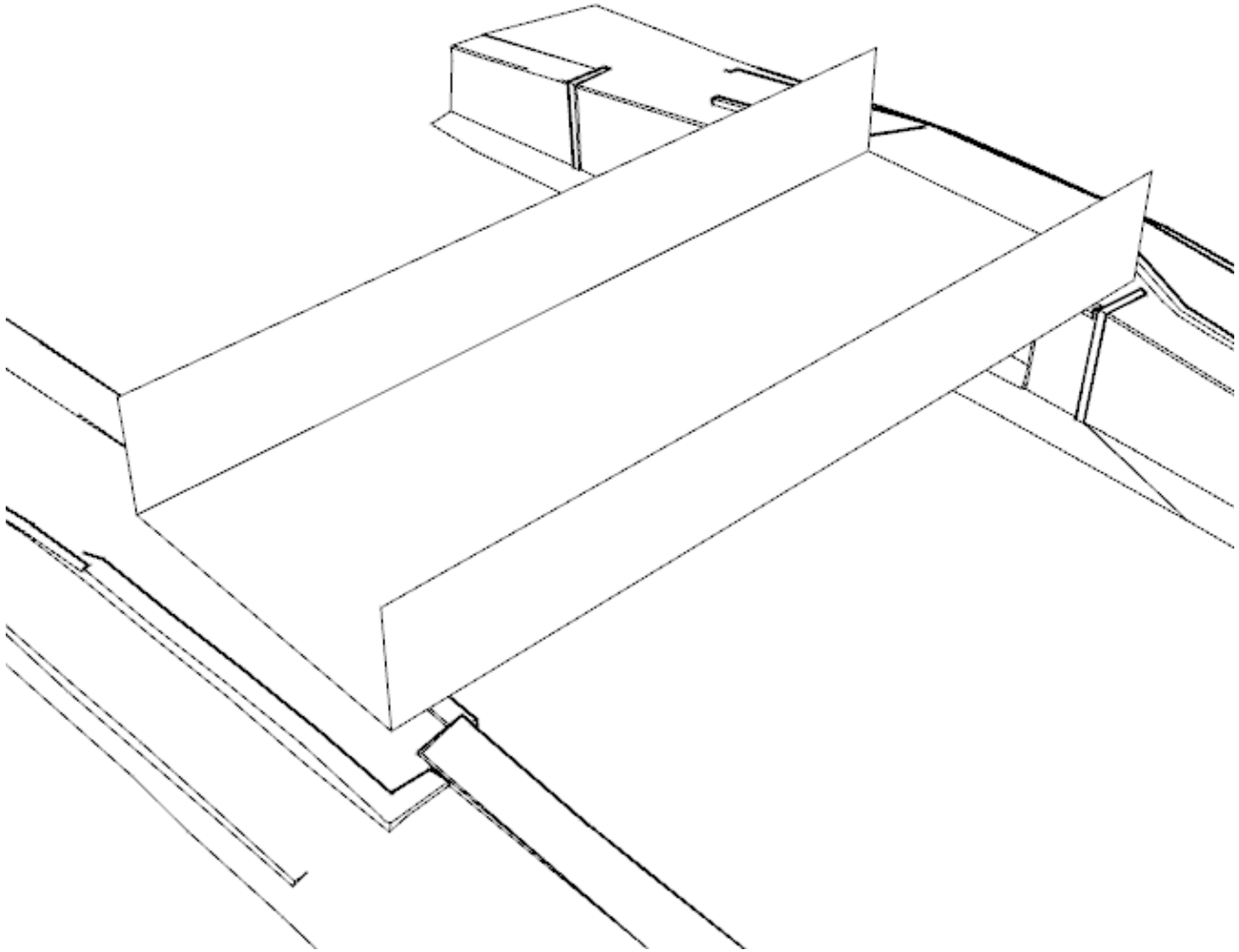
Cross section



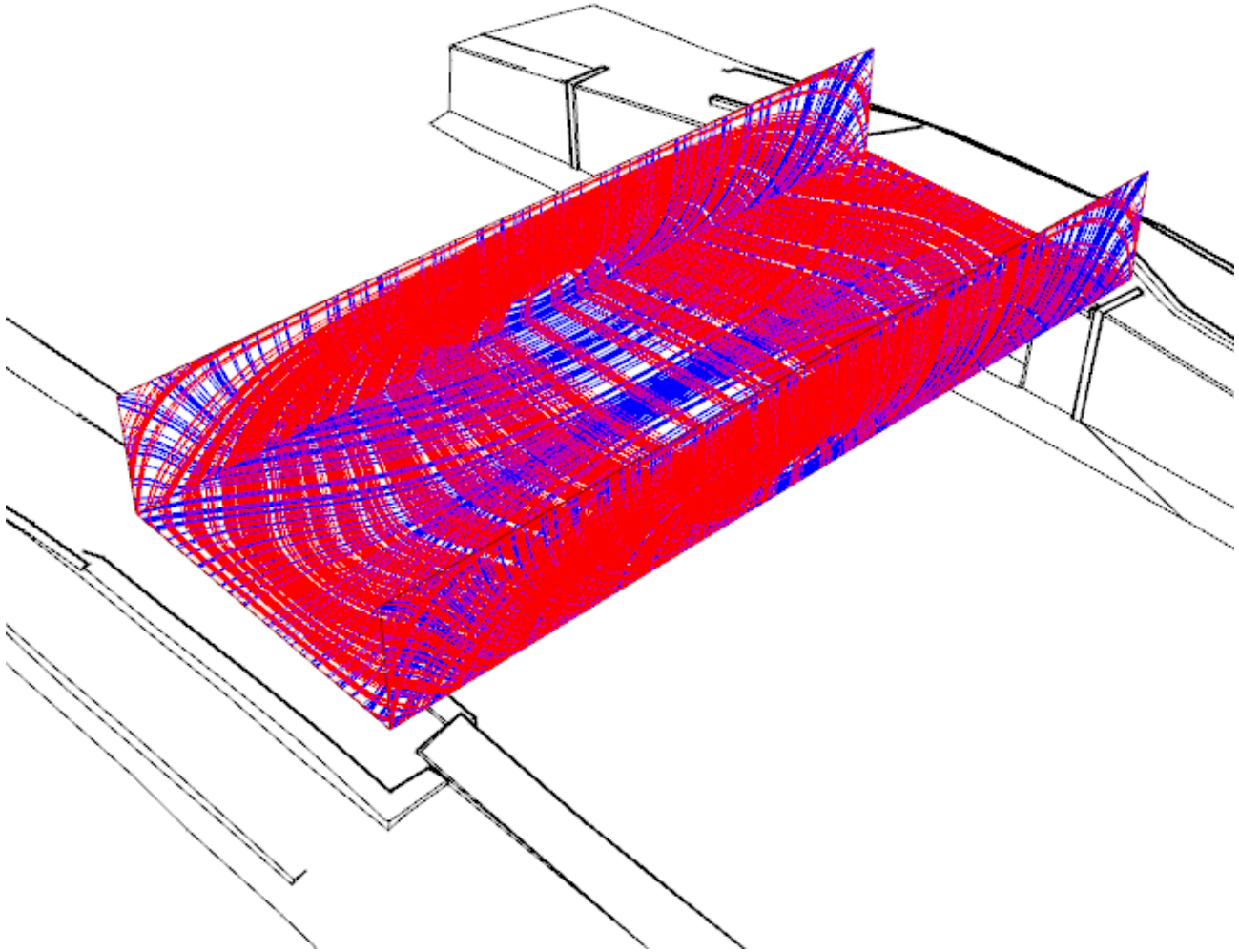
Elevation



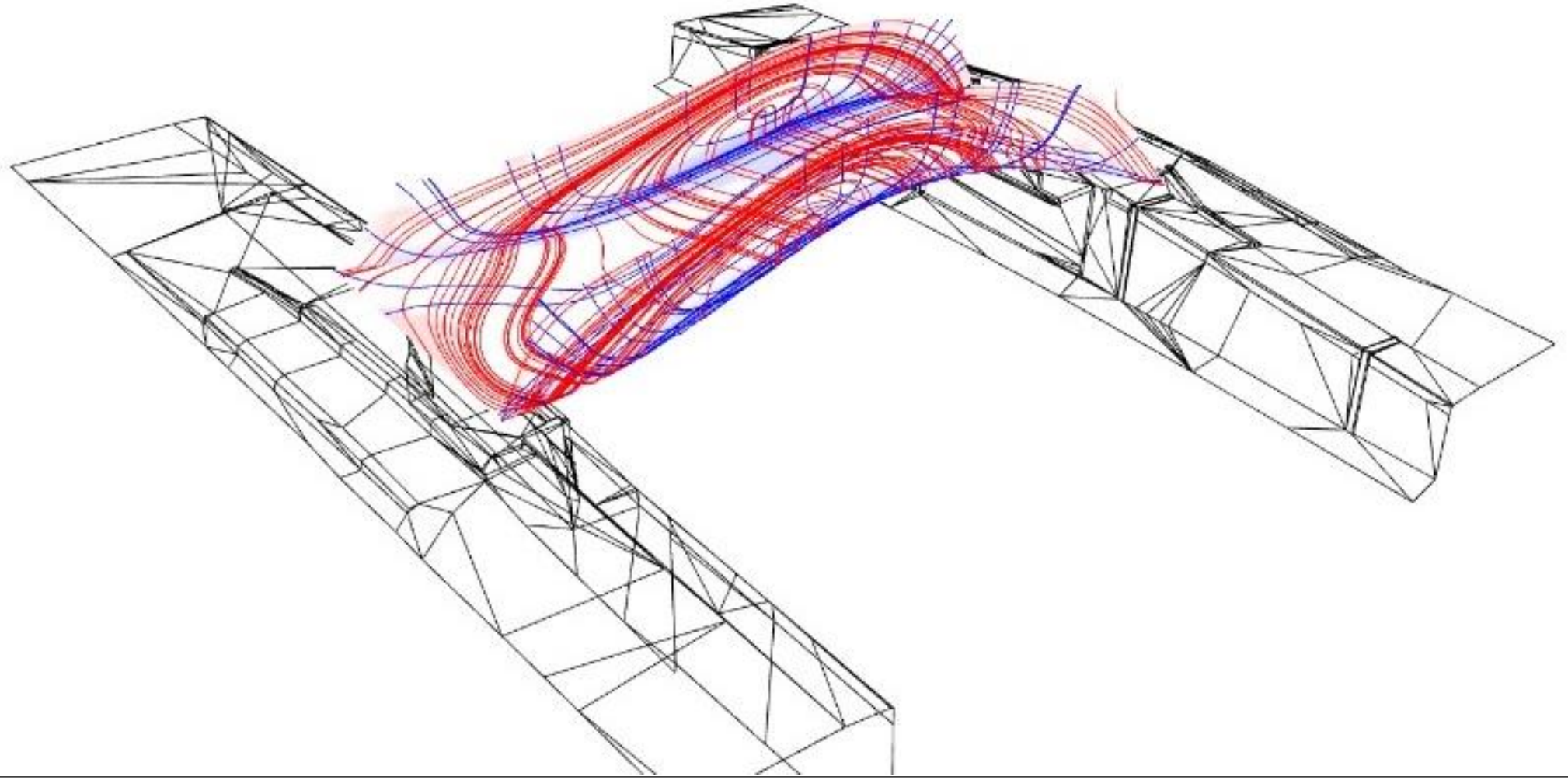
Design
Form finding



Design
Form finding



Design
Form finding

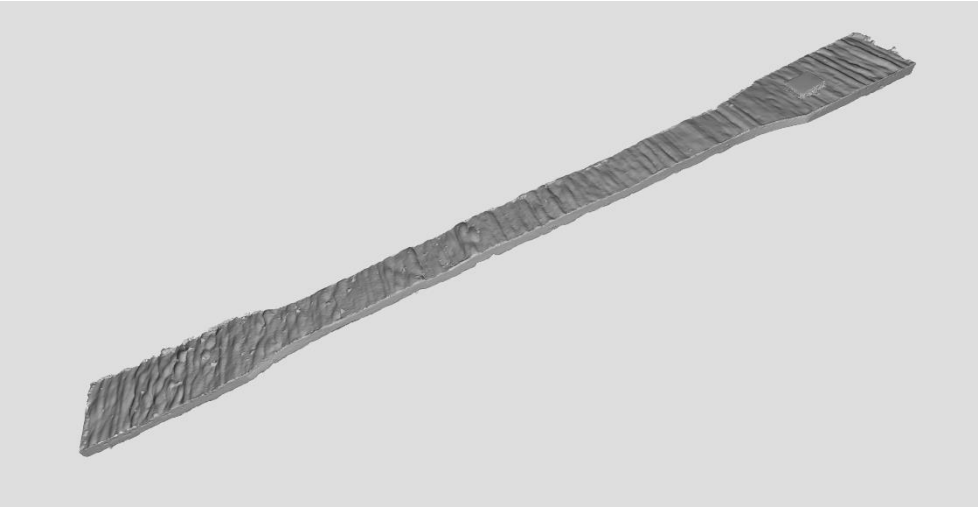


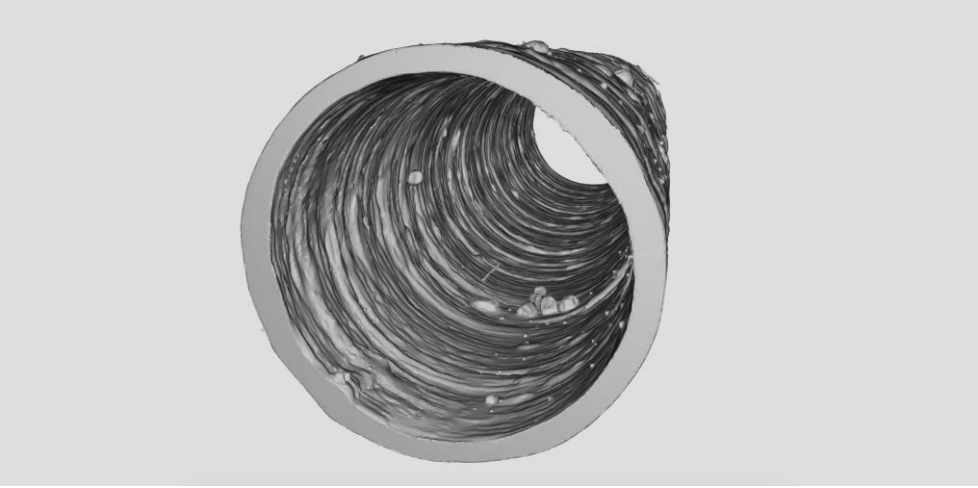
Design
Preliminary design

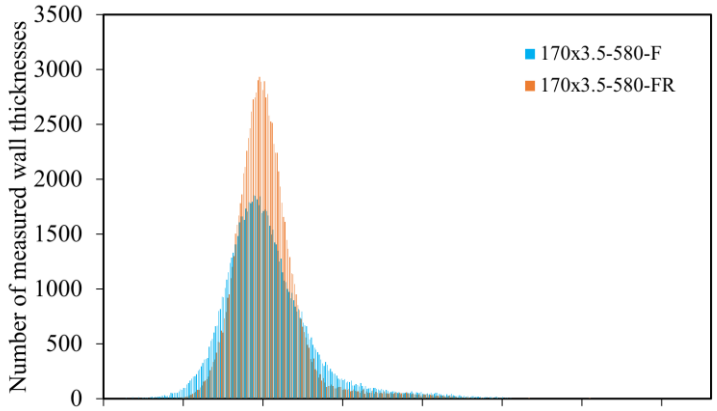
Testing

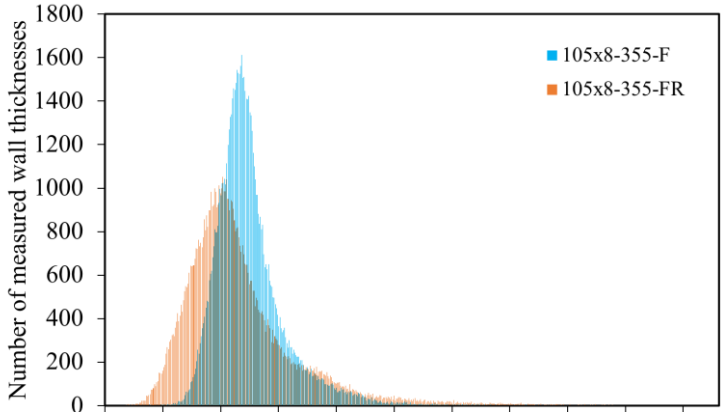
Design by experiments

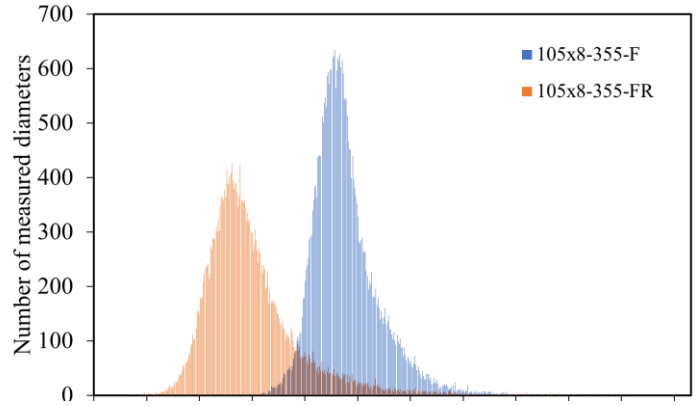
Testing
Geometry



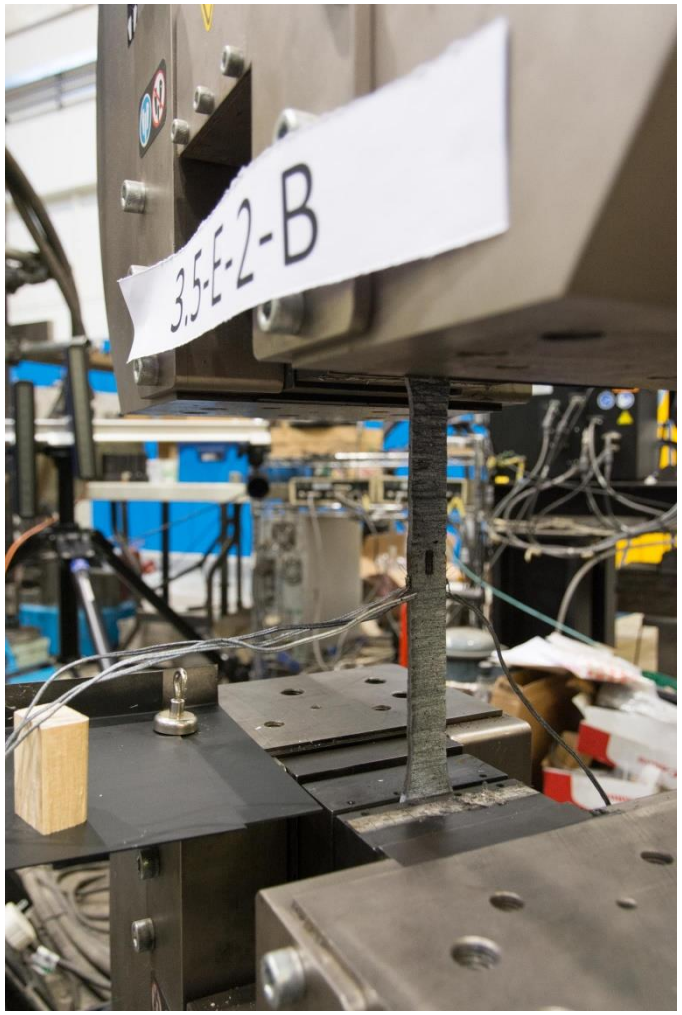




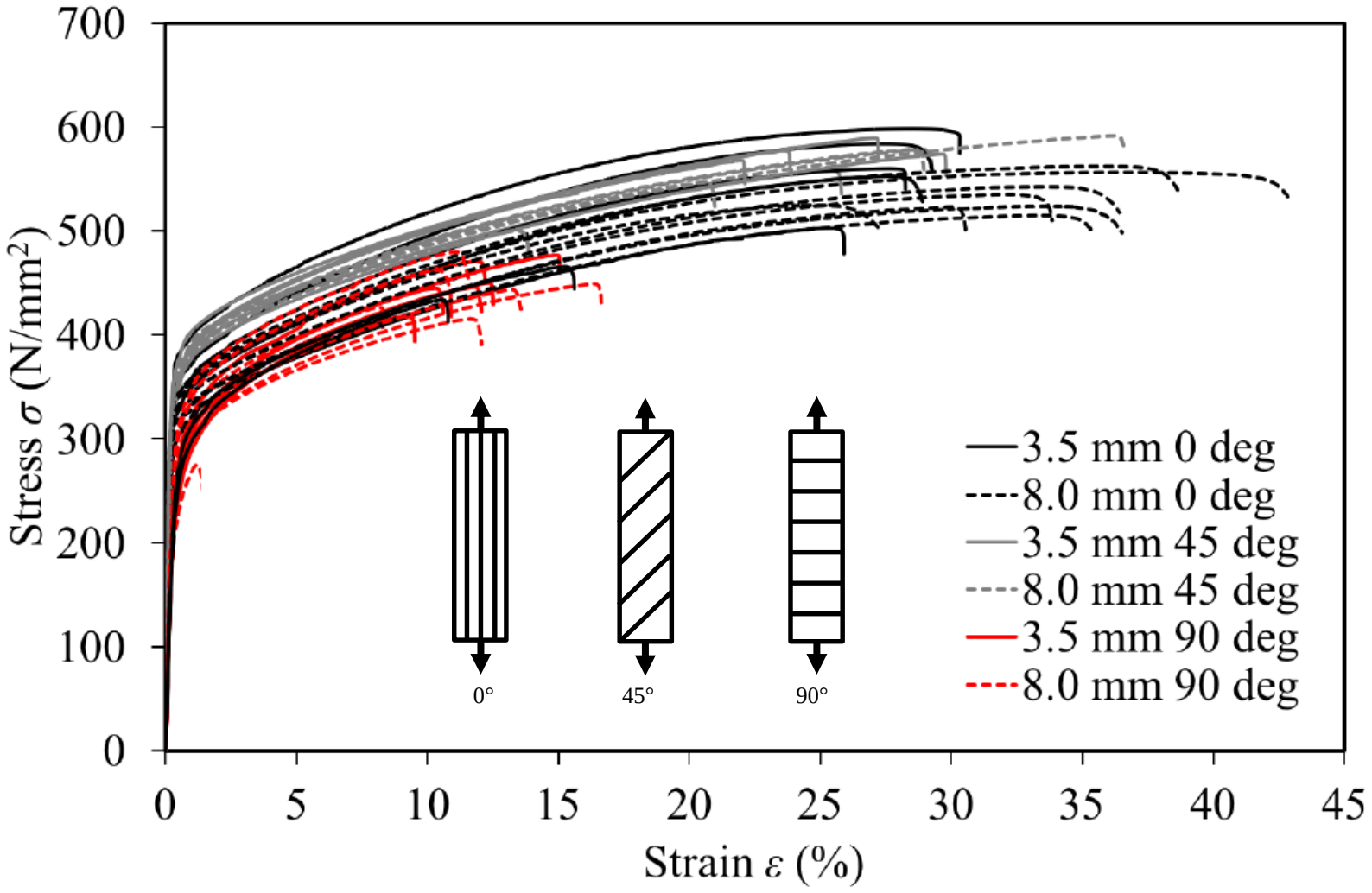




Testing
Material



Testing
Material



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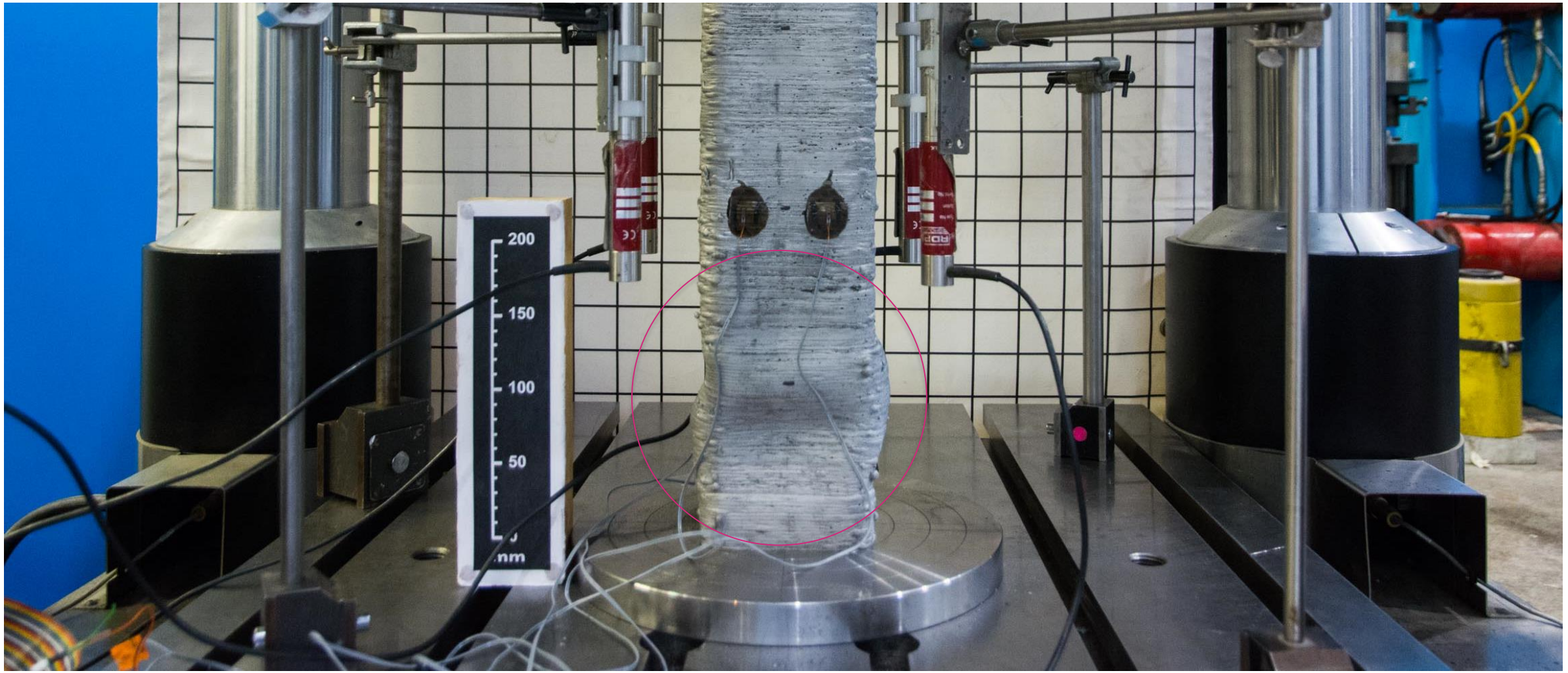
Testing
Material



Structural analysis

Showing that we have tackled all the challenges

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Structural analysis
Starting points

- CC1
- Design life 5 years (temporary, 3 years)
- Design values: NEN – EN1990 – Annex D

(1) The design value X_d for X should be found by using :

$$X_d = \eta_d m_X \{1 - k_{d,n} V_X\} \quad \text{(D.4)}$$

In this case, η_d should cover all uncertainties not covered by the tests.

(2) $k_{d,n}$ should be obtained from table D2.

Table D2 - Values of $k_{d,n}$ for the ULS design value.

n	1	2	3	4	5	6	8	10	20	30	∞
V_X known	4,36	3,77	3,56	3,44	3,37	3,33	3,27	3,23	3,16	3,13	3,04
V_X unknown	-	-	-	11,40	7,85	6,36	5,07	4,51	3,64	3,44	3,04

- t based on measurements
- E(100-190GPa) calibrated by testing

Force distribution

Structural checks

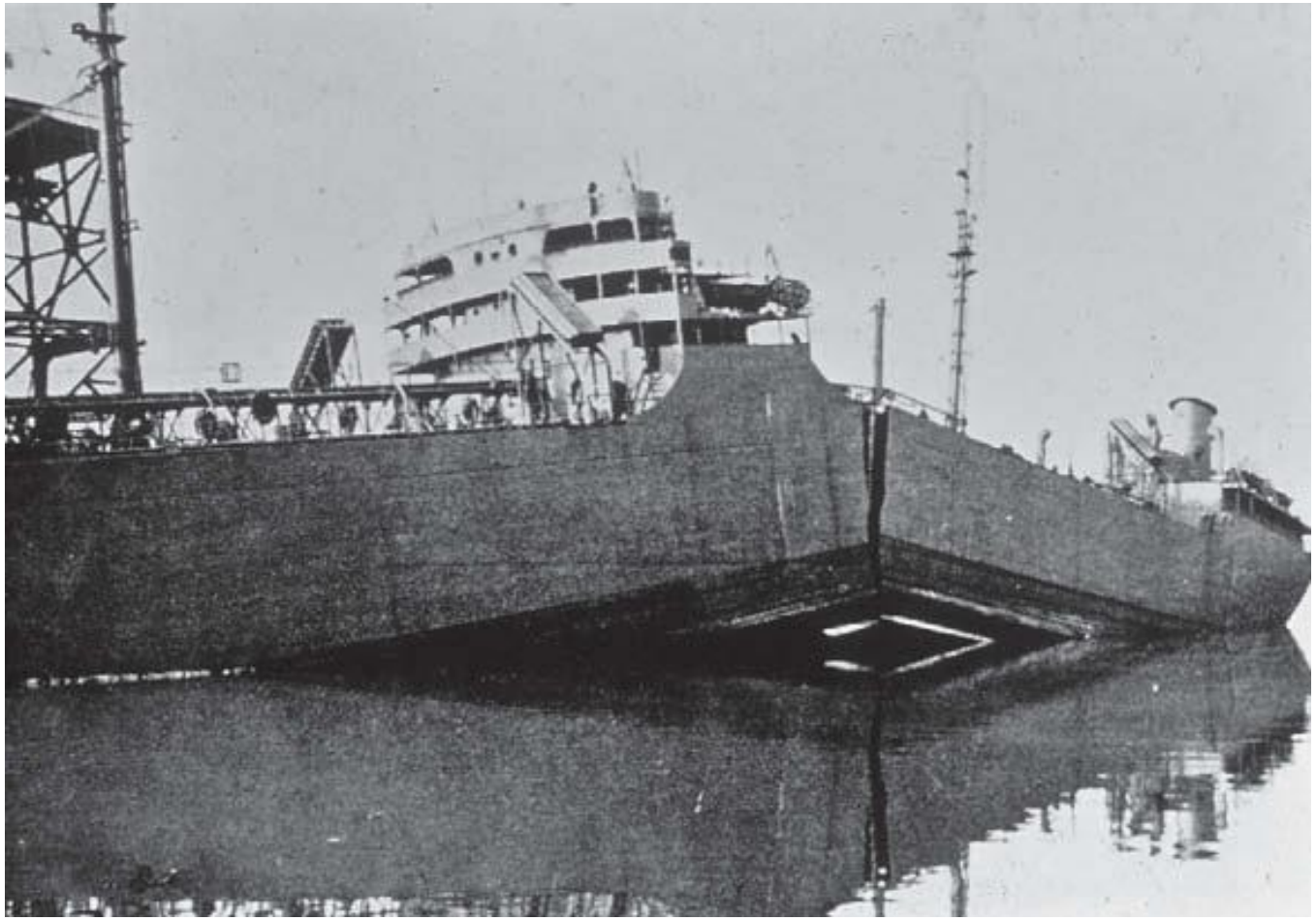
Nominal	Average	Characteristic	Design
t= 3,5mm	3,57mm	3,14mm	**2,81mm**
t= 7mm	6,96mm	6,08mm	**5,41mm**
f_y= 240MPa	267MPa	235MPa	**202 MPa**
f_u= 585MPa	571MPa	518MPa	**462 MPa**

Structural analysis
Approach

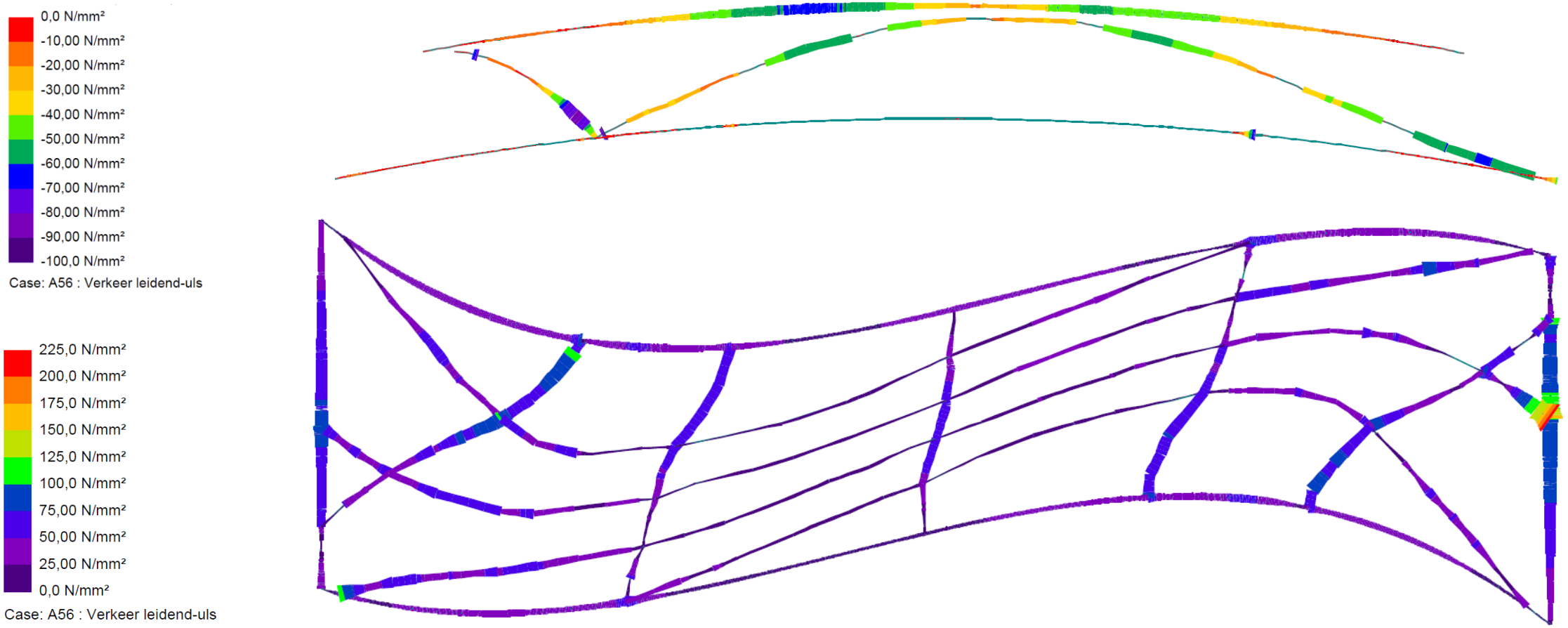
- Check stresses;

- Focus on sudden failures;
  - (Global) instability;
  - Crack growth – brittle failure;

- Mitigate risk:
  - Robust design;
  - Inspections;
  - Live monitoring.



Structural analysis
Stresses



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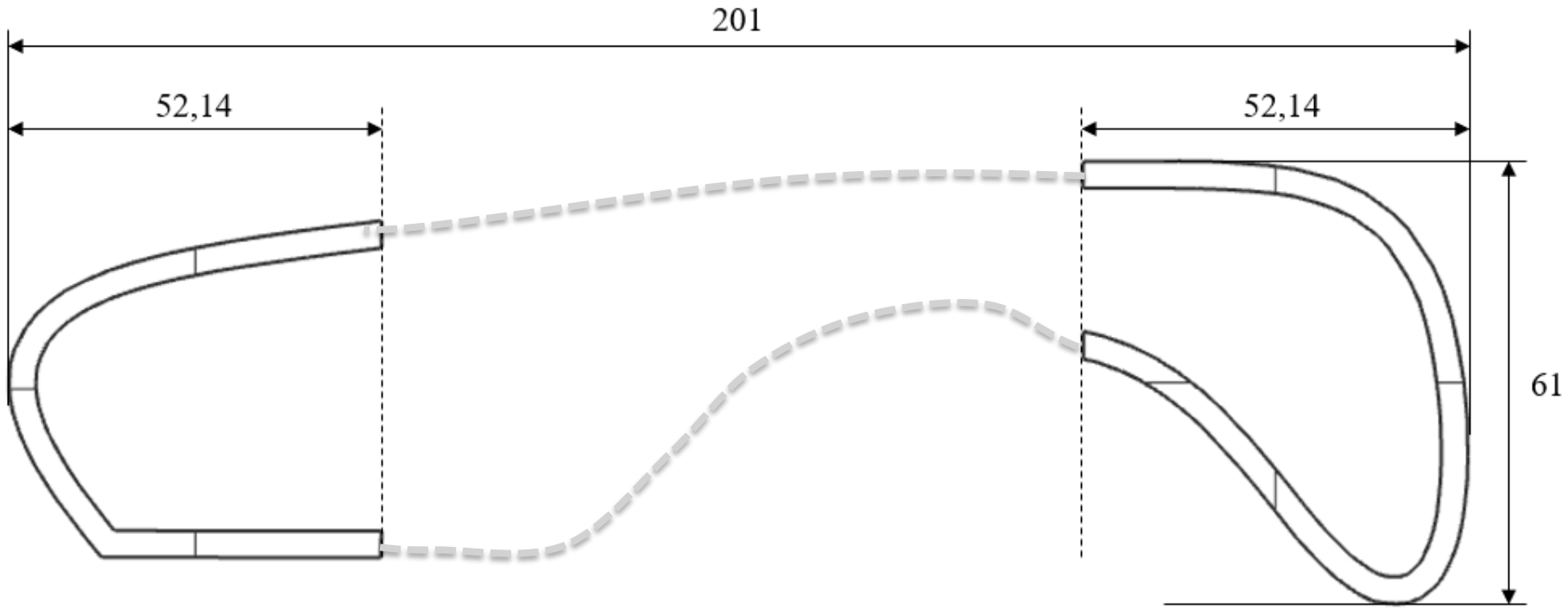
Structural analysis
Reduced cross sections



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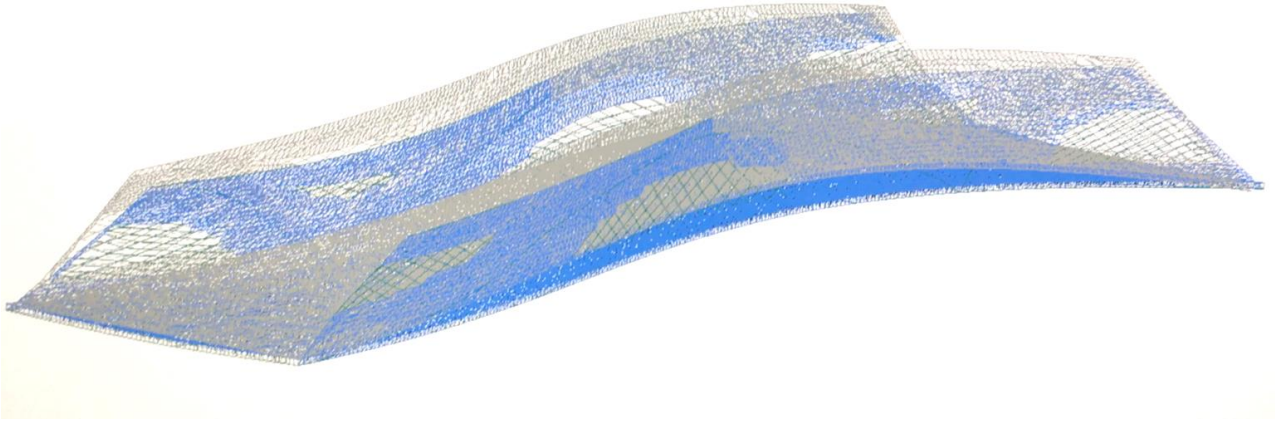
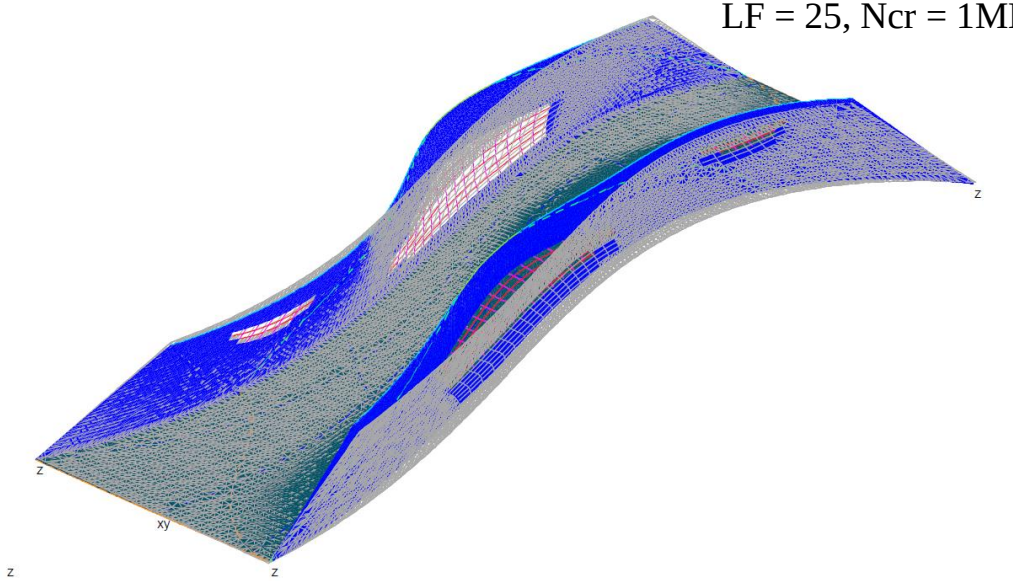
Structural analysis
Buckling and dynamic behaviour

- Buckling load factor >> 10
- Eigenfrequency > 5,0 Hz

1st mode, f = 6,4 Hz

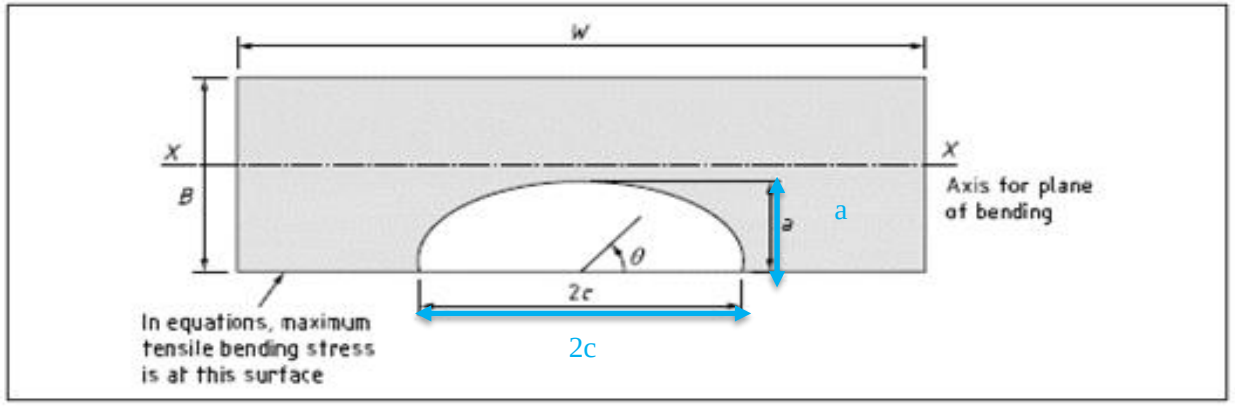


LF = 25, Ncr = 1MN



Structural analysis
Fracture mechanics

- Objective: Assess acceptability of weld flaws
- Outcome (conservative assumptions): All flaws in critical areas > 2mm in depth to be repaired
  - But how to inspect?



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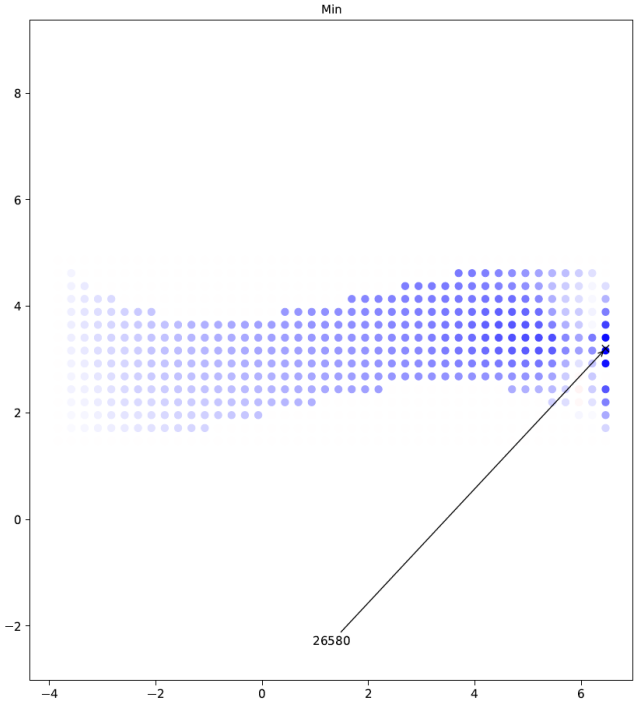
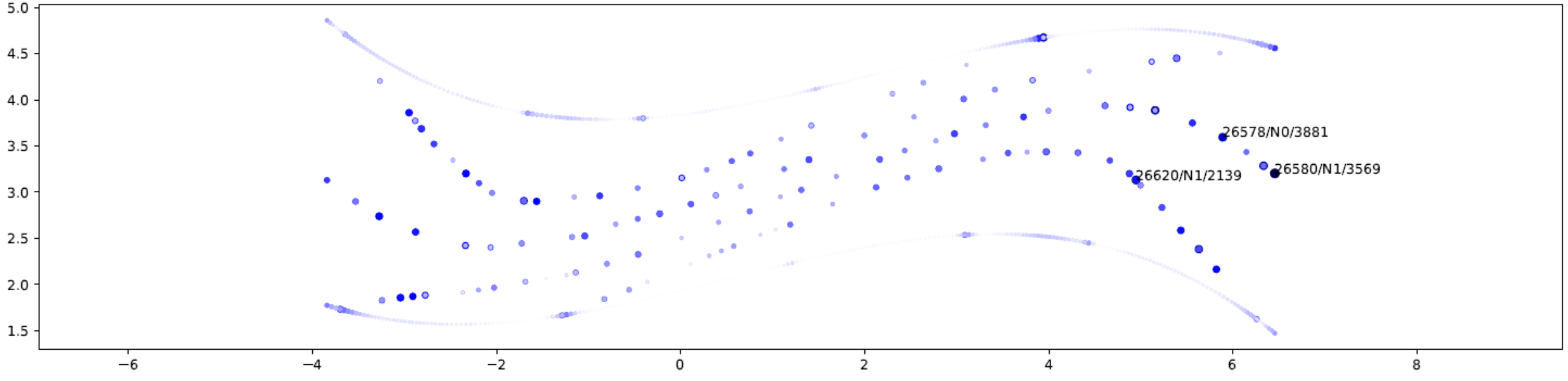
Structural analysis
Influence analysis

- Selection of critical elements;
  - Pedestrian loading;
  - Police horse loading (point load, 7 kN);
  - Load optimization





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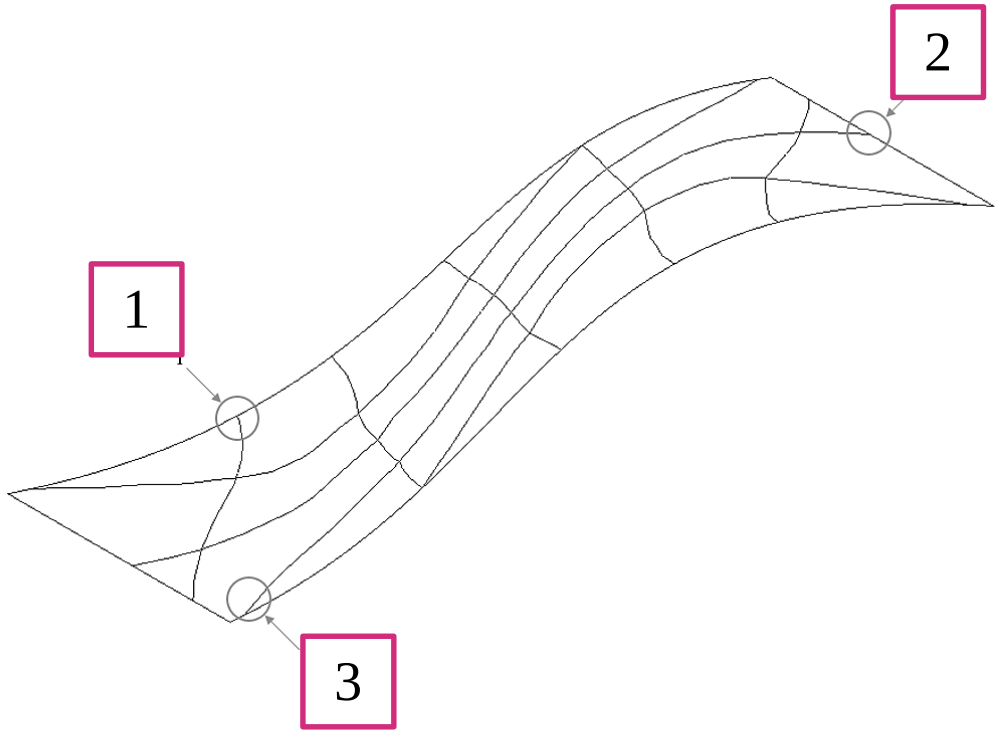
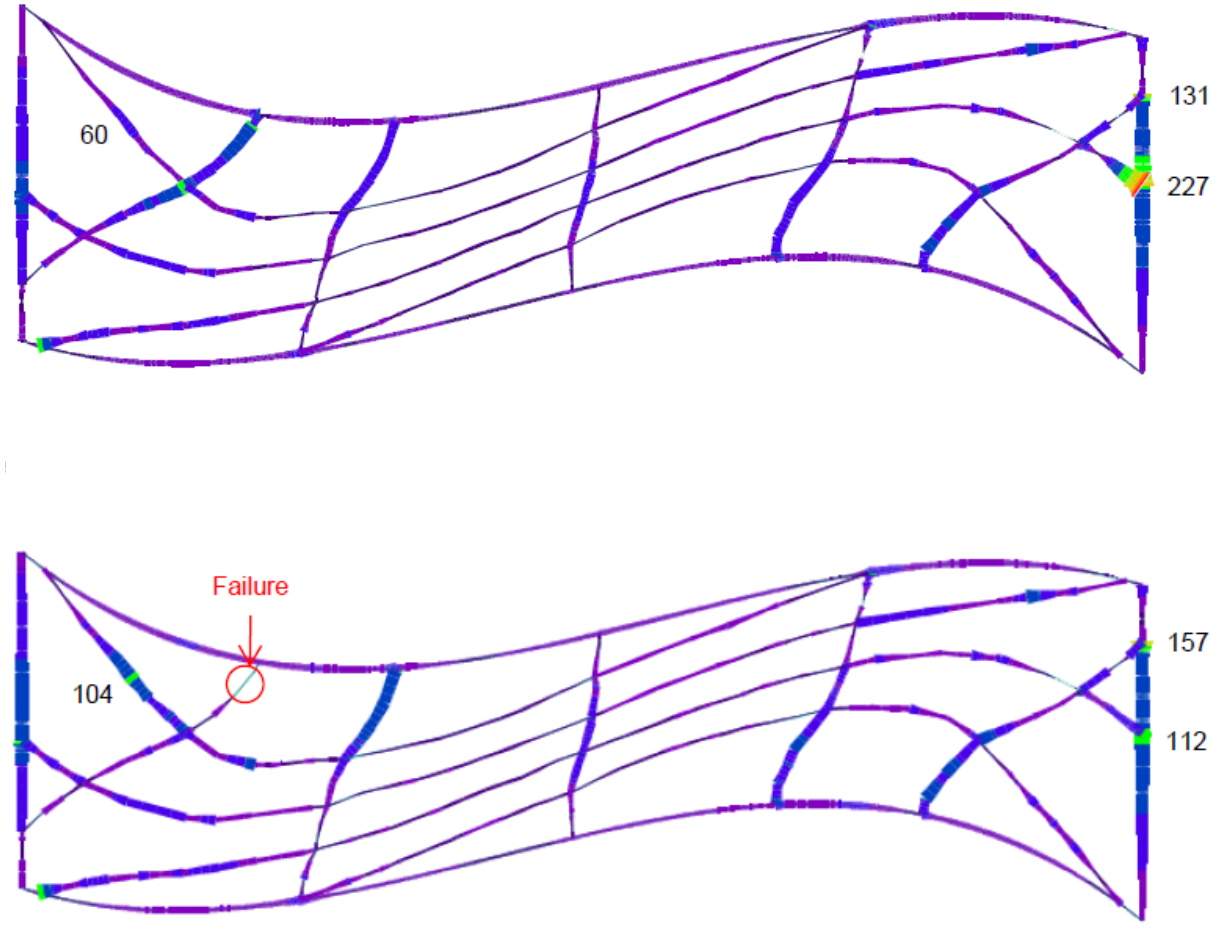
Structural analysis
Robustness



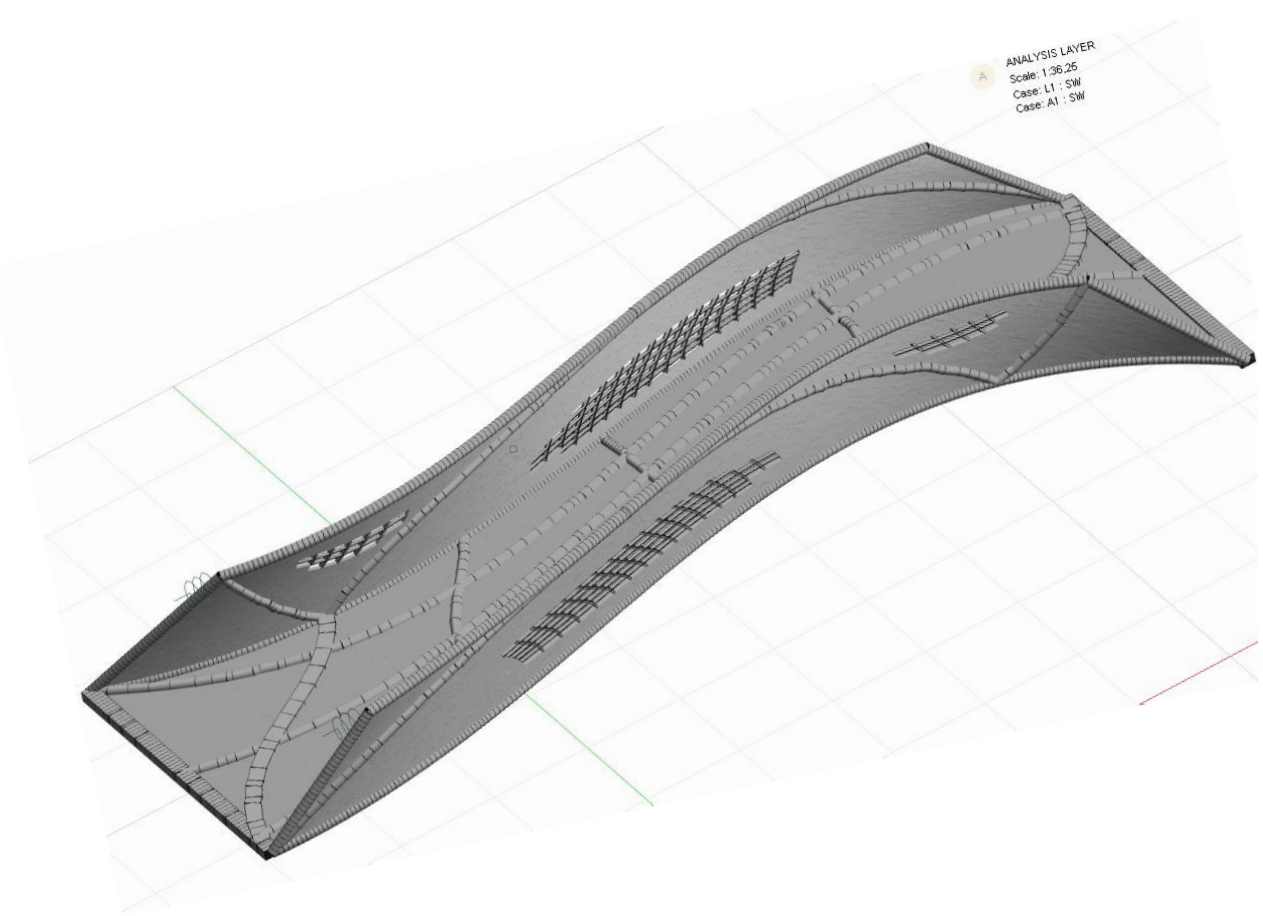


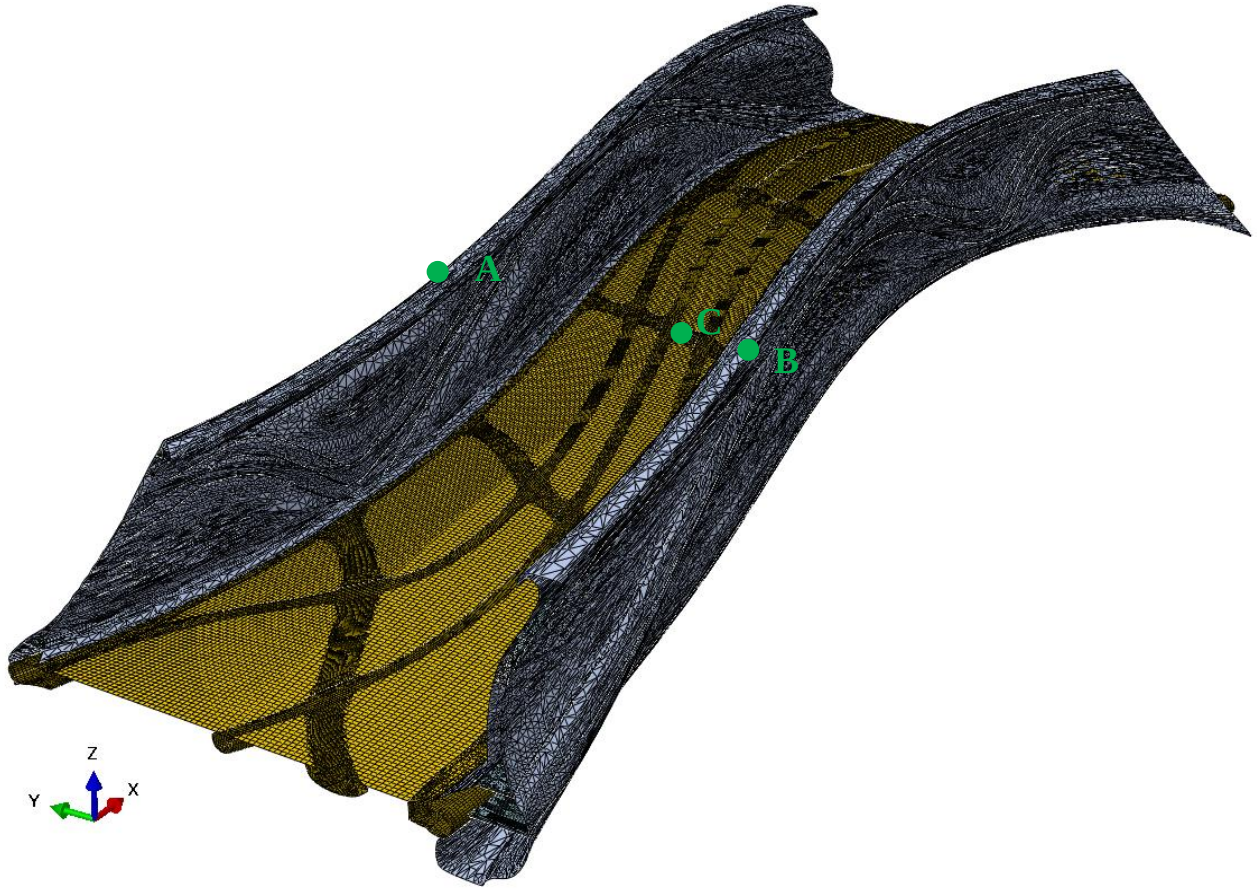
Full-scale testing

Were we right?

Full-scale testing
Structural model comparison

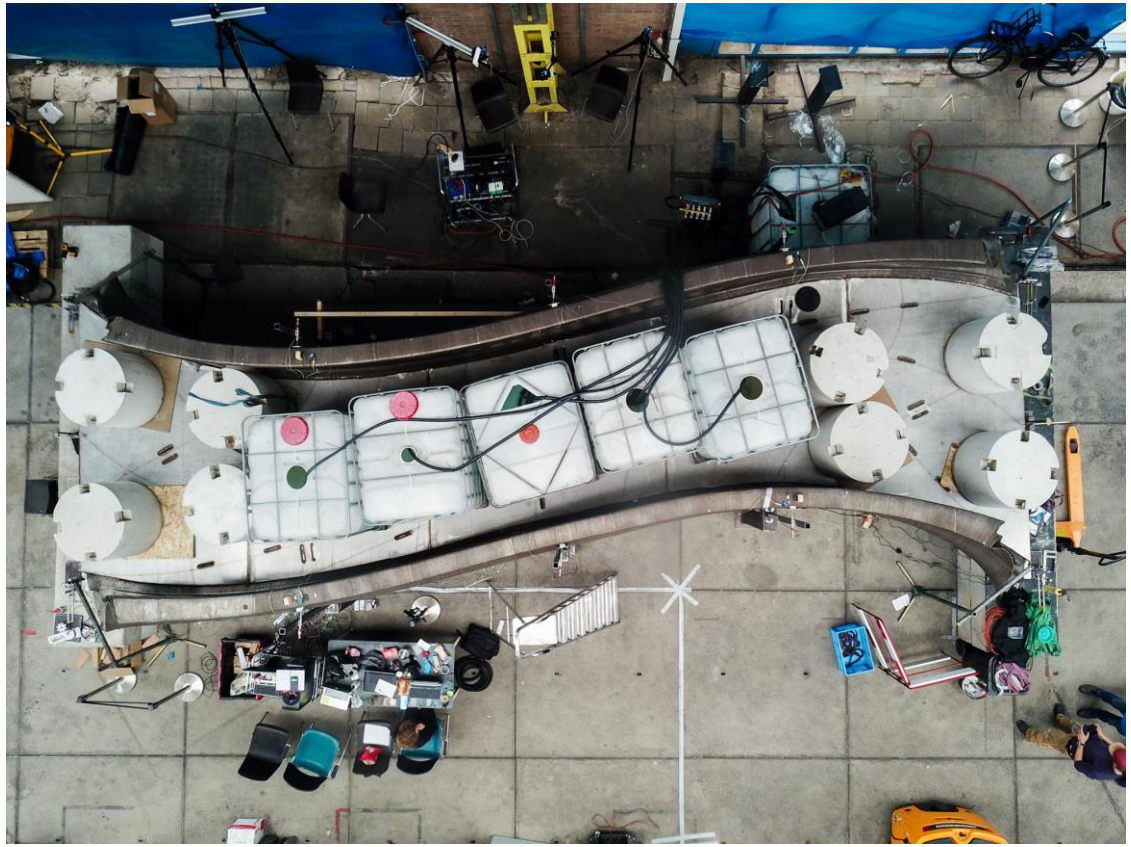
- GSA (Arup) and Abaqus (Imperial College London) predictions





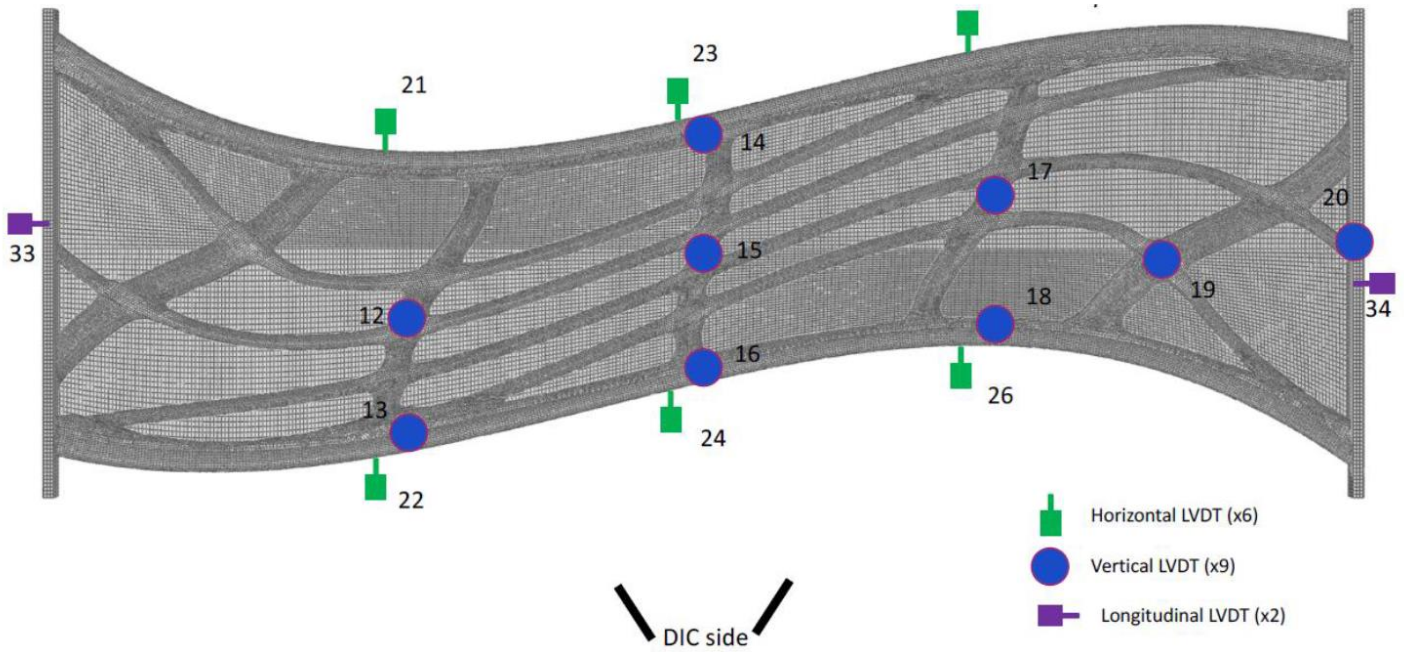
Full-scale testing
‘SLS’

Vertical: 115kN (ca. 4-5 kN/m2)



Horizontal: 3 x 7,5 kN

Full-scale testing
‘SLS’



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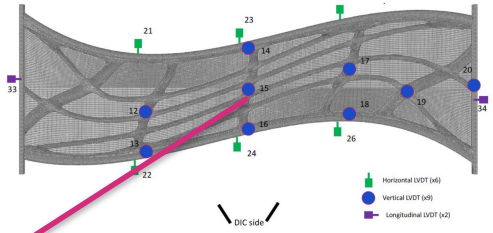
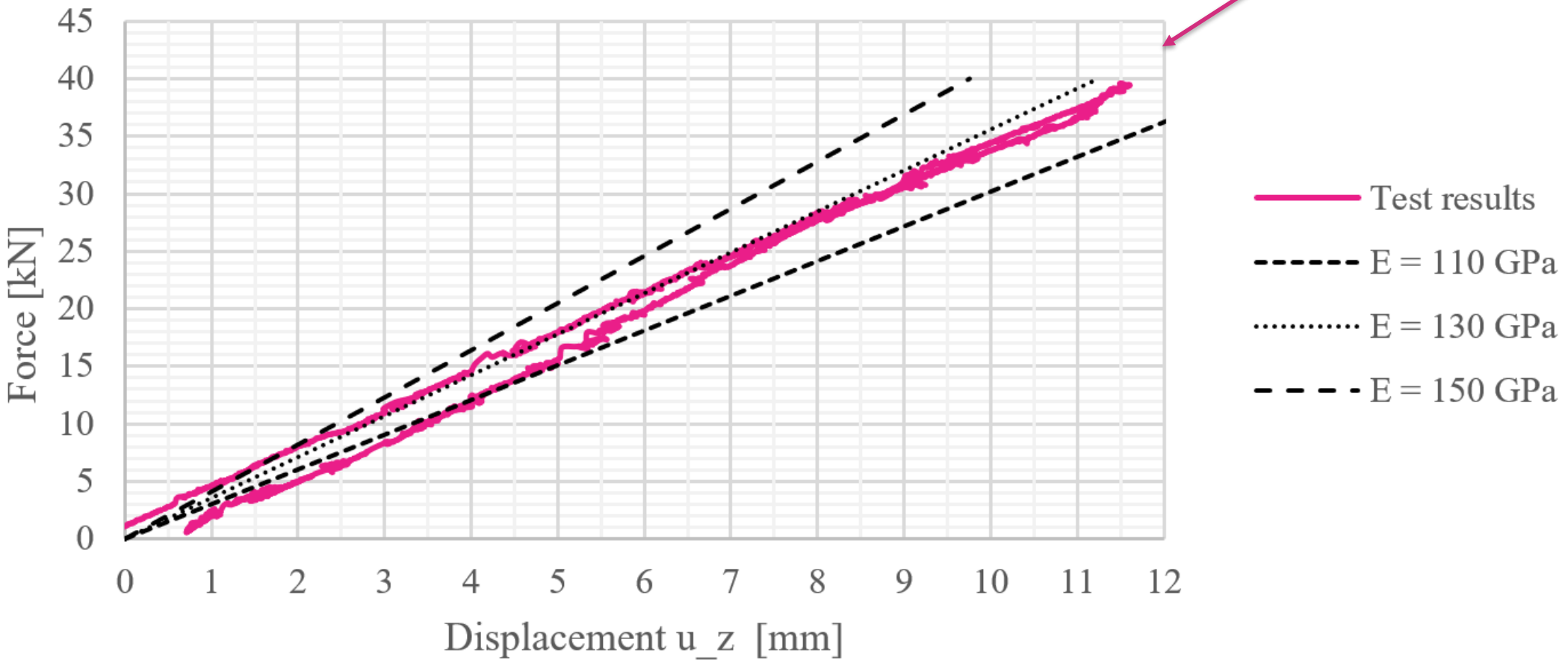
Full-scale testing

‘SLS’





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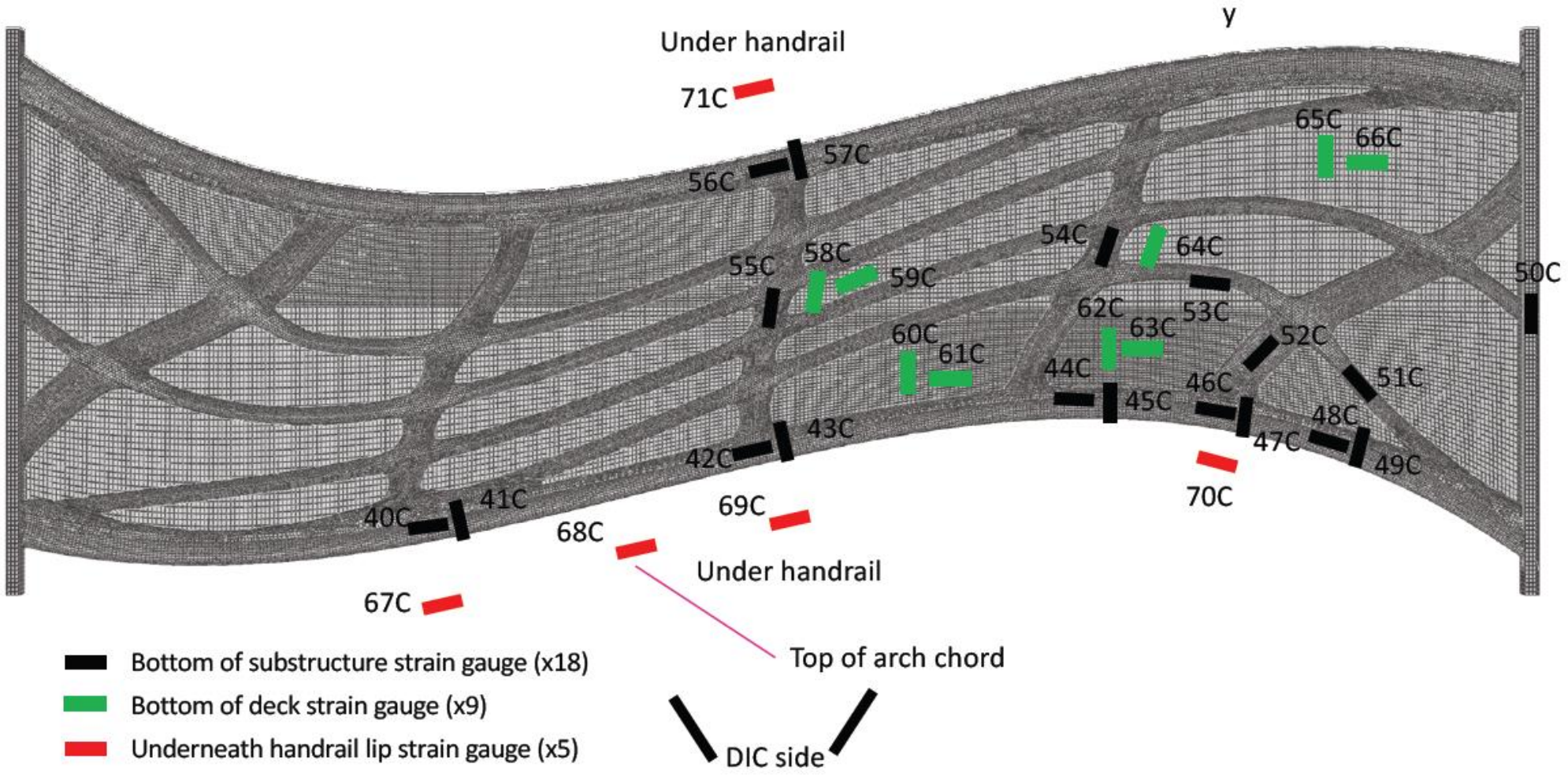
Going forward

And now?

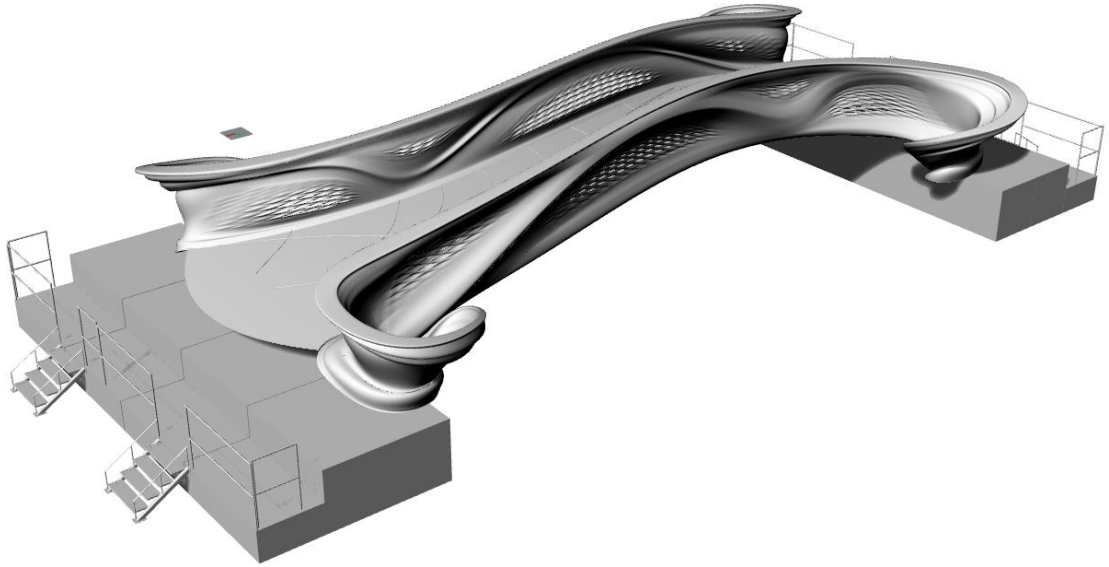
Going forward

A smarter bridge project



Going forward
Full-scale ULS load testing

Going forward
1, 2, 3, print?



AT OUR ROBOT WORKSHOP IN AMSTERDAM

Project Mx3D printed bridge
Location the Netherlands
Client Municipality of Amsterdam

Key facts

// *12,5m long, 1,95 to 3 m wide*
// *10,3m span, 23,3m2*
// *3D printed steel: 4500kg -1100km welding wire*
// *Dutch Design Week: Q4-2018*
// *EC proof load: This week!*