Die traditionelle Zahnträgerbauweise neu interpretiert

Architektur

Masterthesis

Miro Bannwart

…und wie es dazu kam….

2006 – 2009 Zimmermannslehre bei Ryf Holzbau in Rümligen in Bern

2009 – 2013 Arbeit als Zimmermann und Berufsmaturität

2013 – 2017 Bachelor of Arts in Architecture BFH/AHB Bern / Burgdorf

2017 – 2019 ITECH Architektur Master of Science in Architecture

ITECH Architektur Masterprogram in Stuttgart

Integrative Technologies and architectural design Research

Landesgartenschau Exhibition Hall
© ICD/ITKE/IIGS University of Stuttgart 08 Freeform structure CLT

ICD/ITKE Research Pavilion 2013-14
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Supervisors: Prof. Achim Menges, Prof. Jan Knippers
Advisers: Hans - Jakob Wagner, Simon Bechert
Student: Miro Bannwart

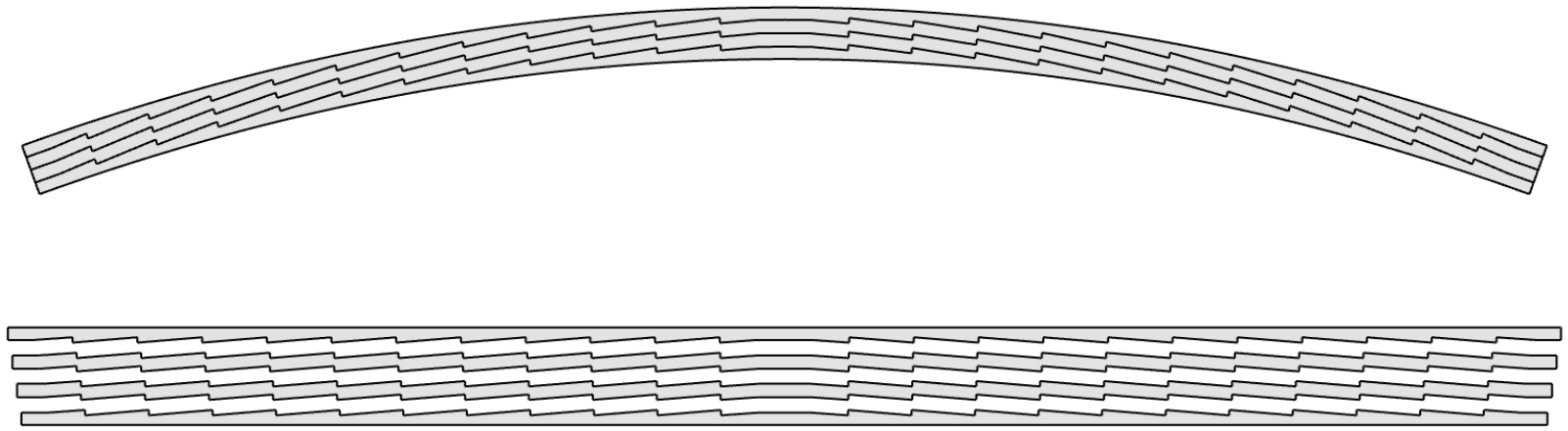
welcome

b-CTC

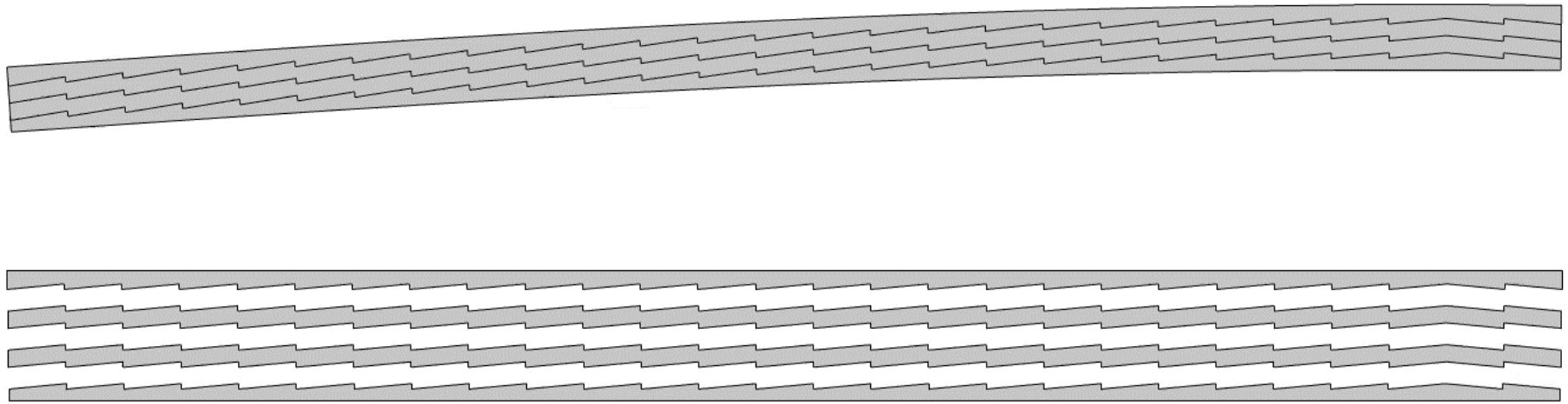
Bent - Computational Tooth Construction

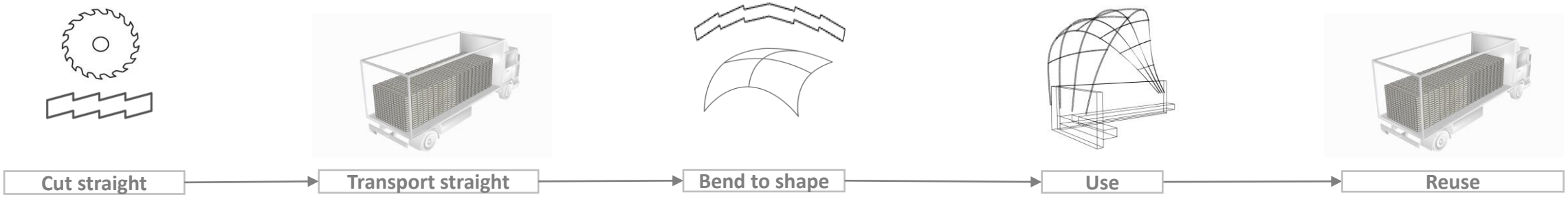
www.b-ctc.ch

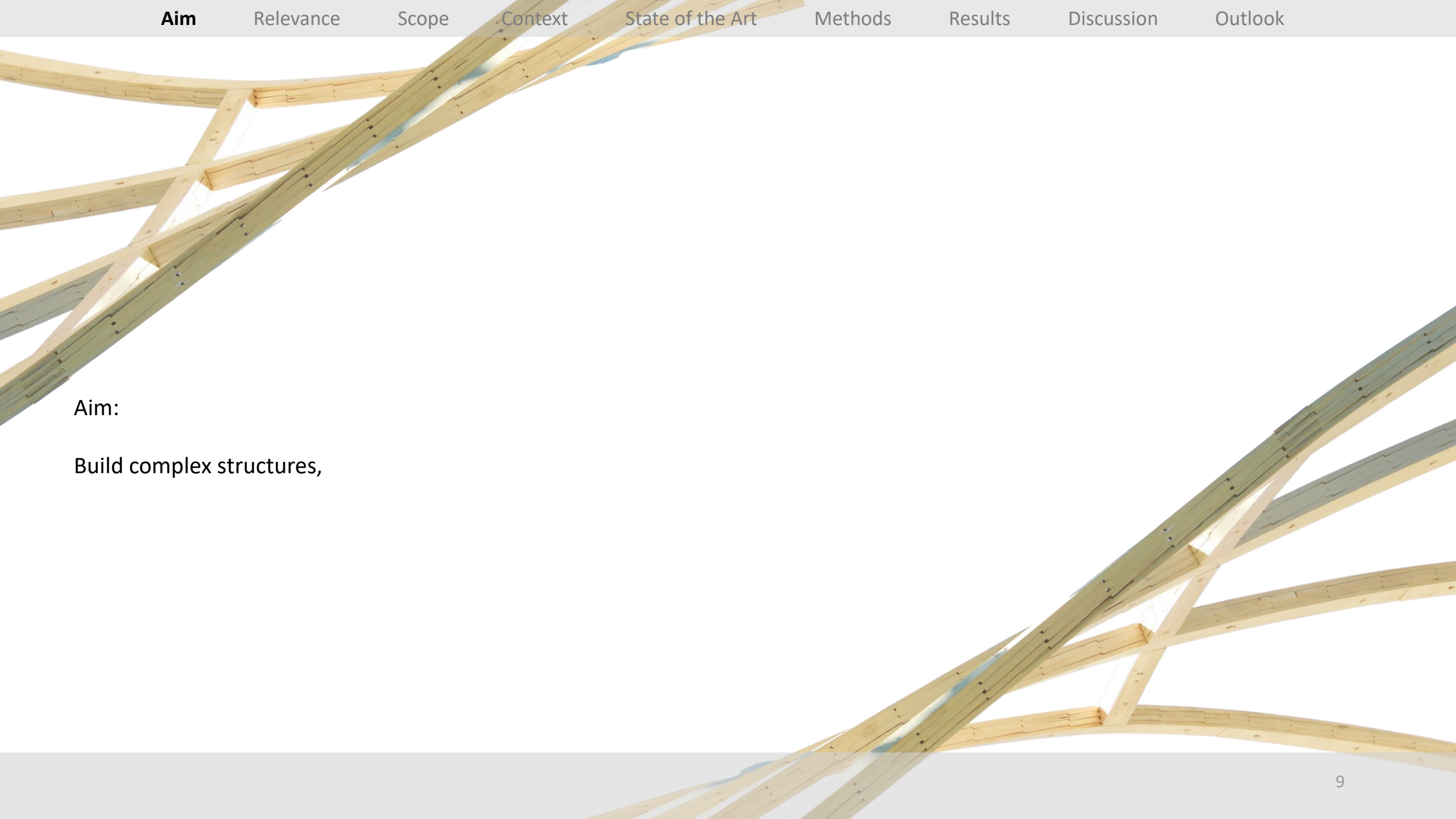
Principle of determined locking
by Hans Ulrich Grubenmann 1709 – 1783



00 Hans Ulrich Grubenmann swiss master carpenter 1709 – 1783, Portrait by Johann Jakob von Brunschwiler 1782

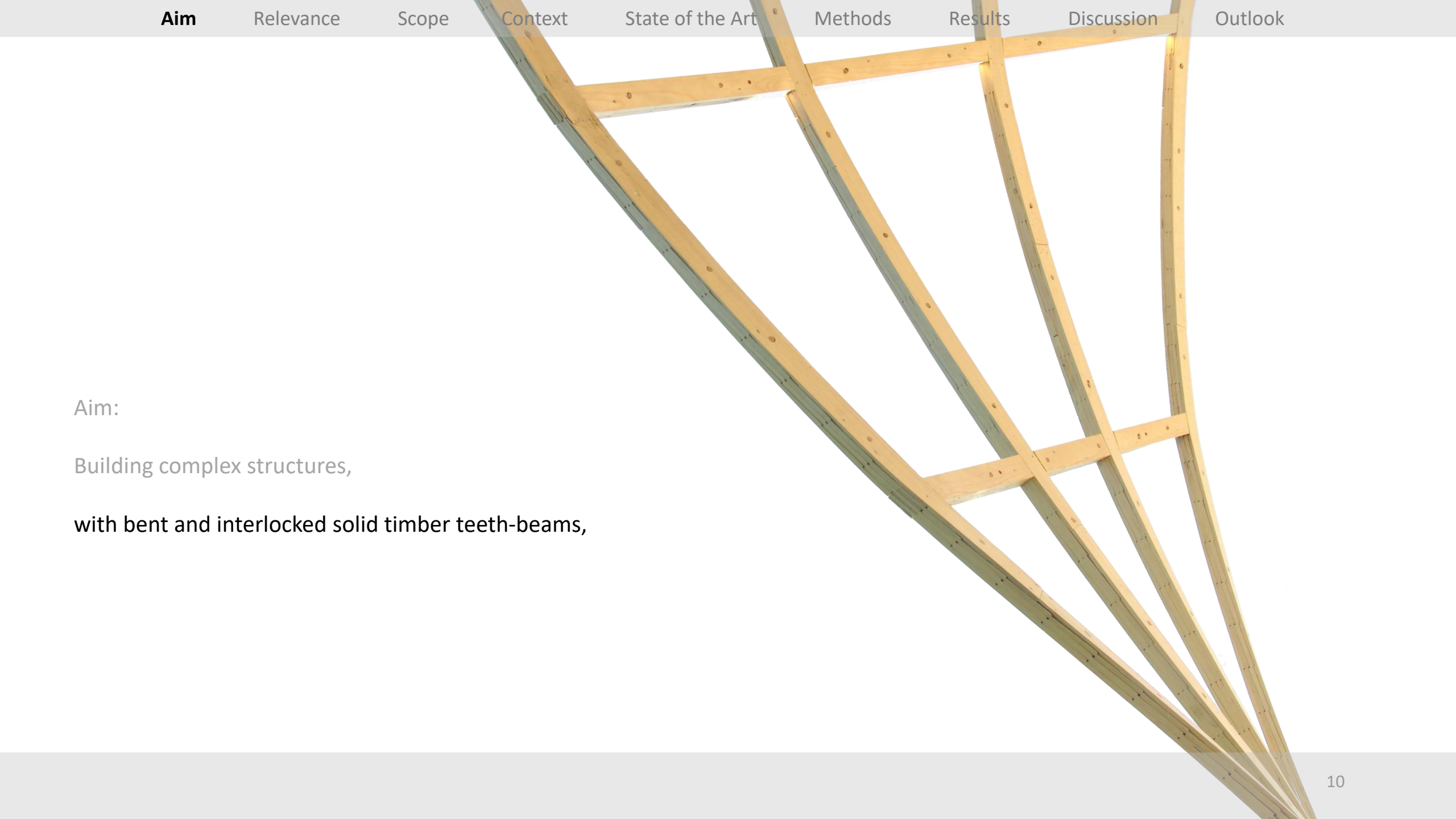



Cut straight
Transport straight
Bend to shape
Use
Reuse



Aim:

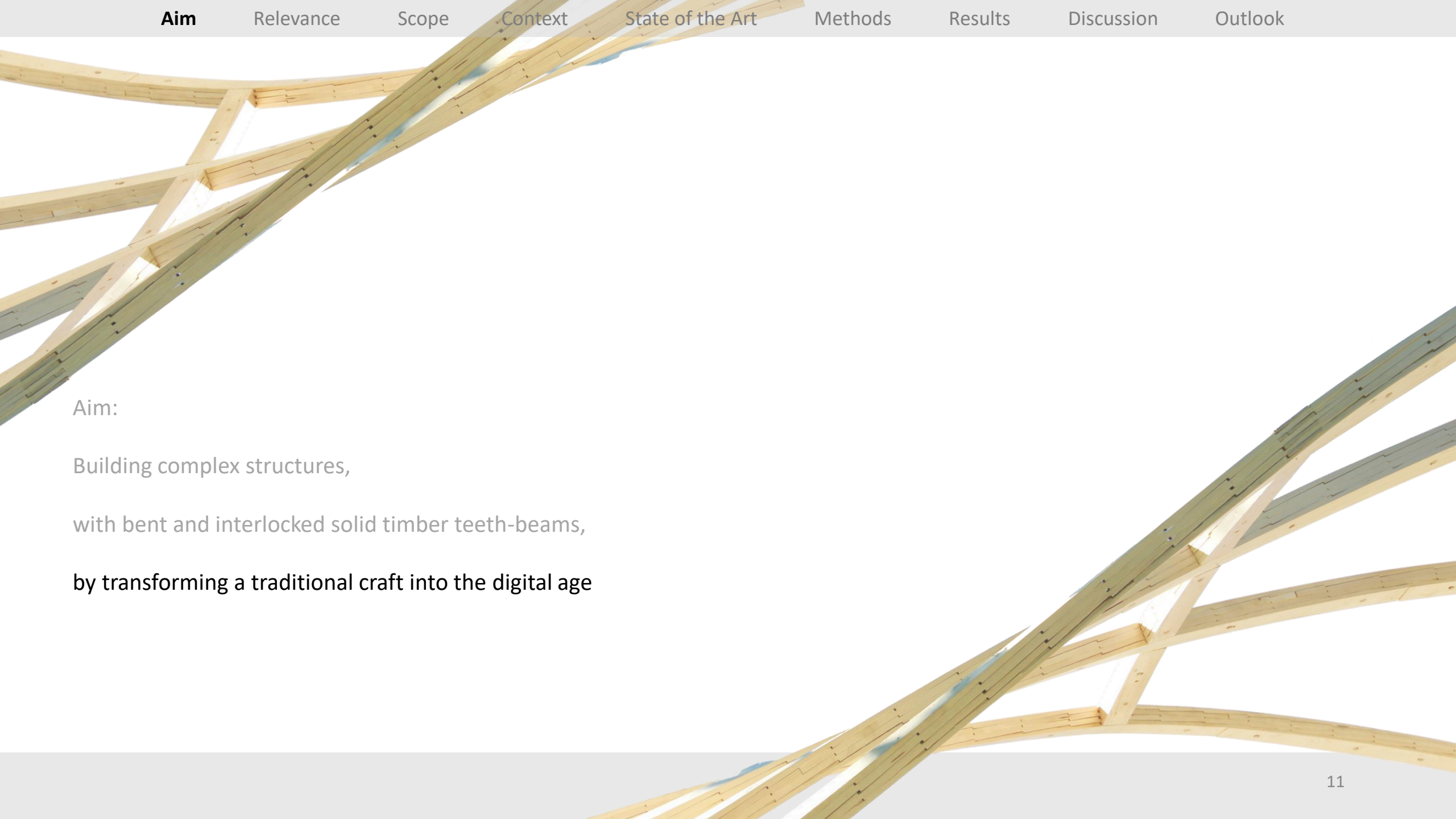
Build complex structures,



Aim:

Building complex structures,

with bent and interlocked solid timber teeth-beams,



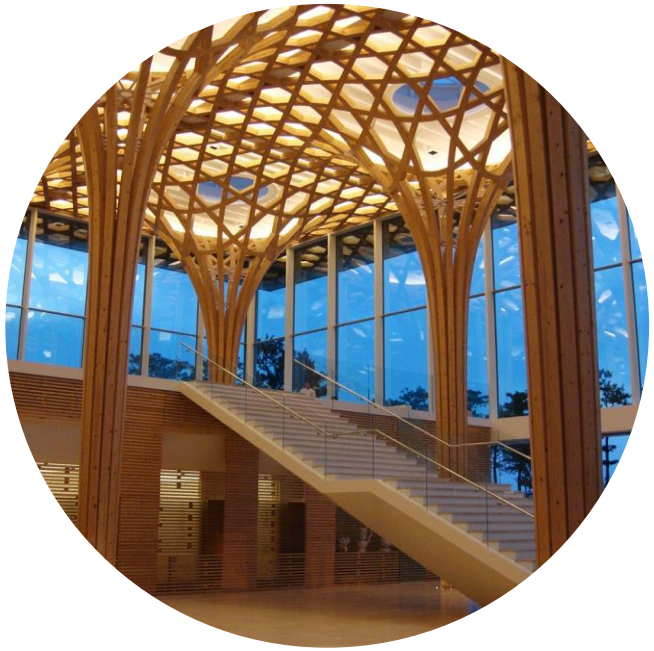
Aim:

Building complex structures,

with bent and interlocked solid timber teeth-beams,

by transforming a traditional craft into the digital age

01
For ecology



02
As design alternative

03
In contemporary carpentry

01 The Blue marble, Foto by NASA: taken on December 7, by the crew of the Apollo 17 spacecraft, 1972
02 As design alternative, The nine Bridges Country Club by Shigeru Ban and Blumer Lehman 2008, Image © Bluhmer Lehman
03 In contemporary carpentry, Krüsi CNC, Image © Krüsi Maschinenbau AG

For ecology – Building with wood

"In 2015 world leaders meeting in Paris agreed to move towards zero net greenhouse-gas emissions in the second half of this century"…

…"No other building material has environmental credentials as exciting and overlooked as wood."

05 The Economist, 2019

06 Demonstration for a cool future in Berlin

04 The Blue marble, Foto by NASA: taken on December 7, by the crew of the Apollo 17 spacecraft, 1972
05 From he newspaper the economist, on 05.01.2019
06 Climate Demonstration Berlin, Märkische Allgemeine 25. 01 2019

As design alternative

08 Freeform structure CLT

09 Glulam beam freeform structure

07 As design alternative, The nine Bridges Country Club by Shigeru Ban and Blumer Lehman 2008, Image © Bluhmer Lehman
08 Freeform Structure CLT, Elefantenhaus, Zürich 2014, Markus Schietsch Architekten, Image: Image © Walt + Galmarini AGW
09 Glulam beam freeform structure, The nine Bridges Country Club by Shigeru Ban and Blumer Lehman 2008, Image © Bluhmer Lehman

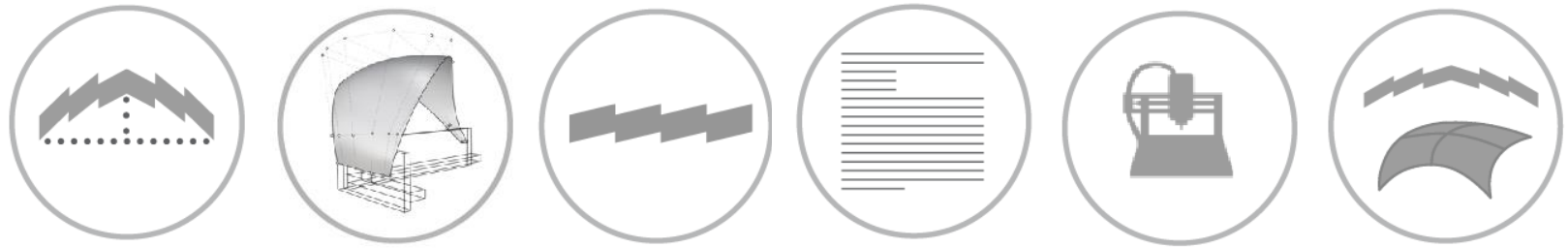
In contemporary carpentry

11 Curved glulam production, pressing

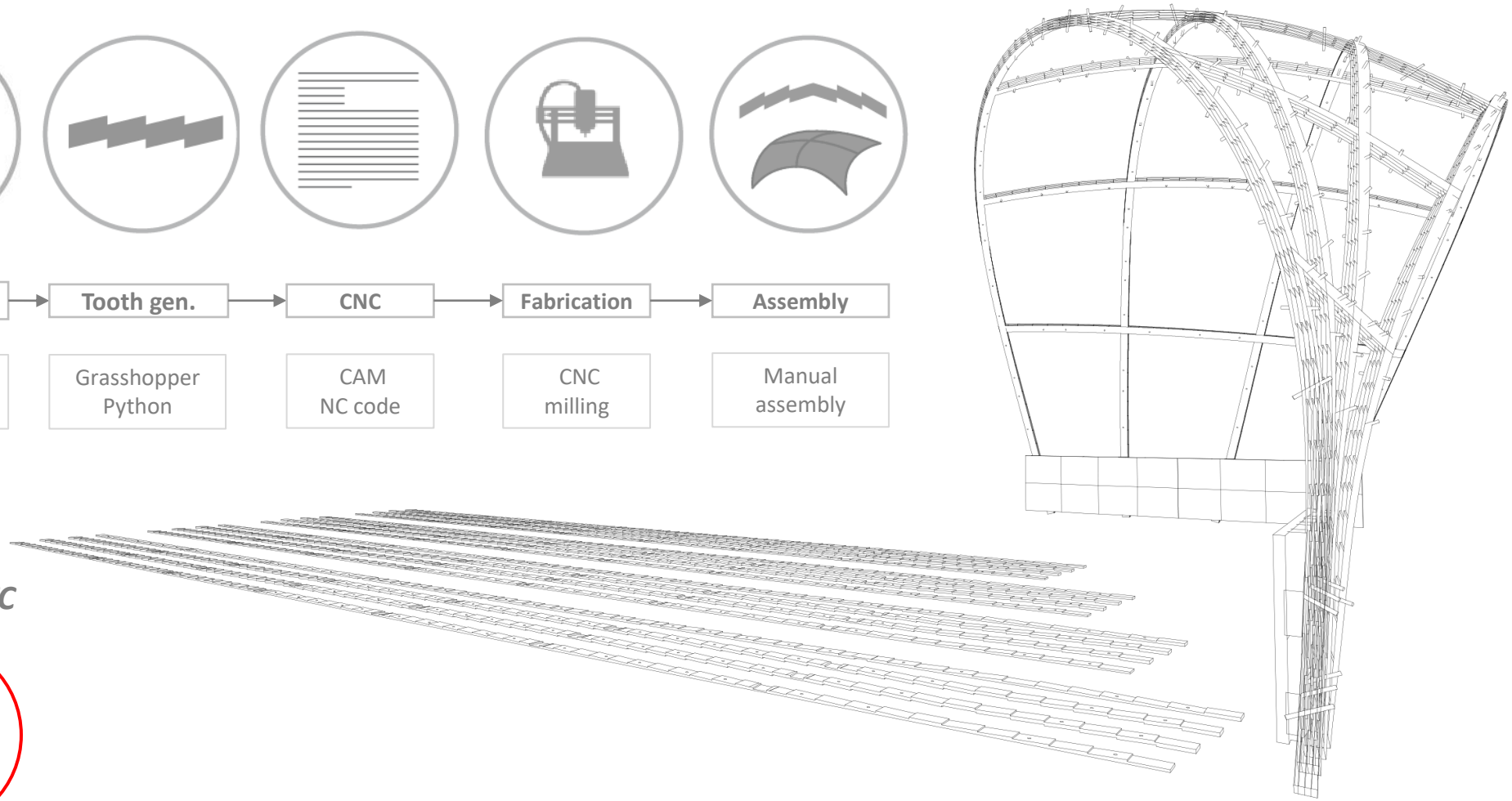
12 Advanced carpentry equipped with a CNC machine

10 In contemporary carpentry, Krüsi CNC, Image © Krüsi Maschinenbau AG
11 Curved glulam production, pressing, at JPF Ducret wood construction entrepreneur, Image © JPF-DUCRET SA
12 Advanced carpentry equipped with a CNC machine,Foto Miro Bannwart, 2019

B – CTC a purely geometrical approach



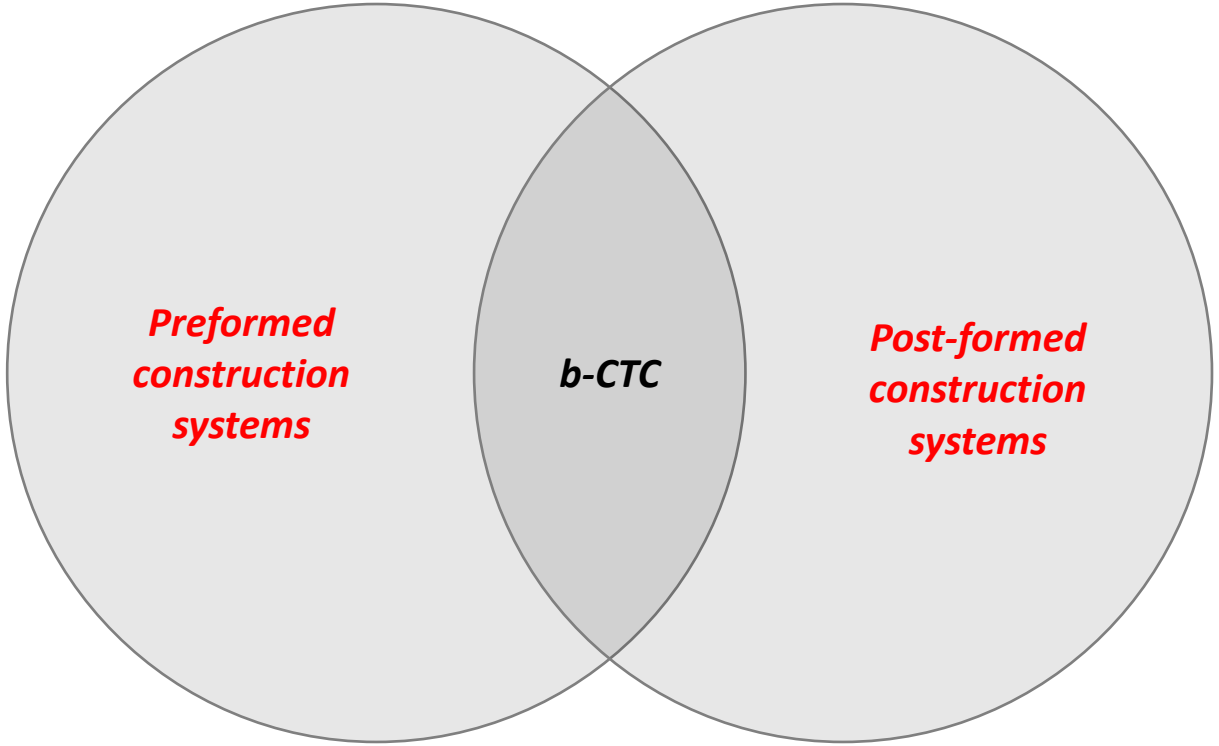
Bending tests	Shape design	Tooth gen.	CNC	Fabrication	Assembly
Physical tests	Nurb surface modelling	Grasshopper Python	CAM NC code	CNC milling	Manual assembly

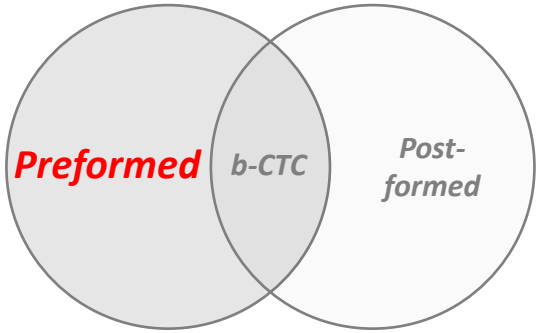


Geometry, from bent to straight

Beyond the scope of b - CTC

- **Structural analysis**
- **Skin, façade elements**

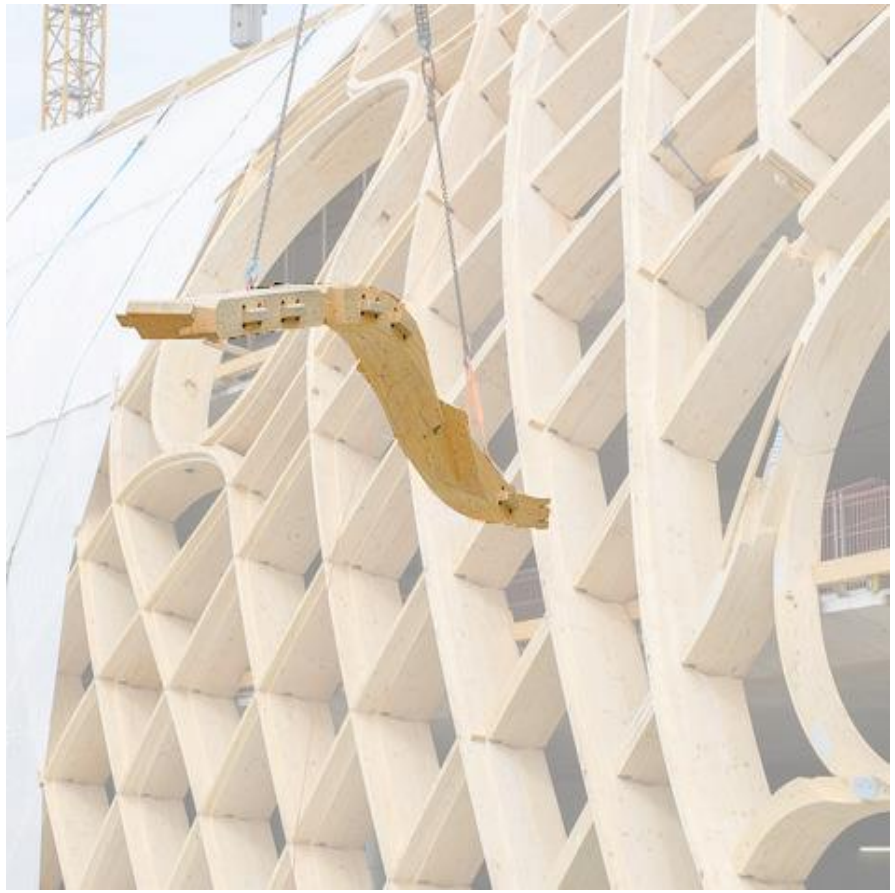

Preformed construction systems
b-CTC
Post-formed construction systems



Preformed advanced carpentry

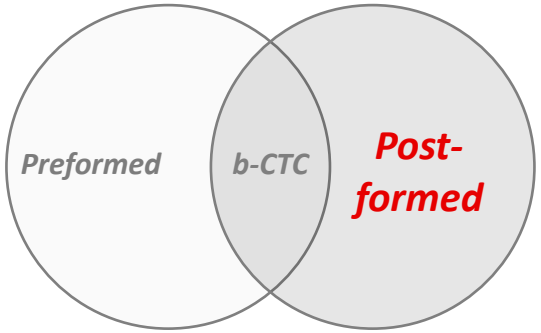
13 Preformed hygroscopic building elements

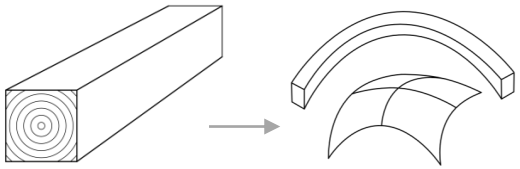
14 Construction from hygroscopic preformed elements



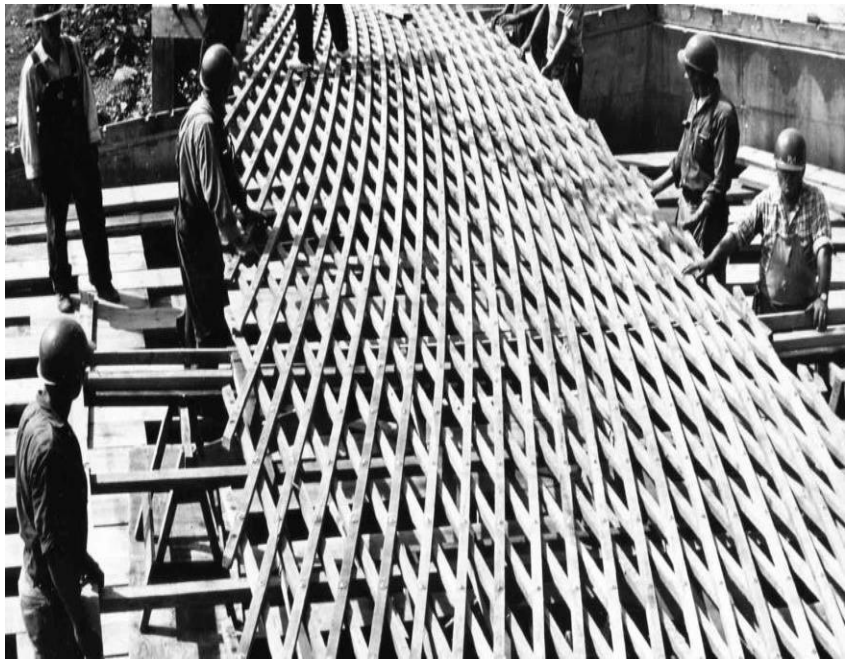
15 Complex construction from preformed glulam beams

13 Preformed hygroscopic building elements The Urbach Tower by ICD/ITKE, Foto © ICD/ITKE 2019
14 Construction from hygroscopic preformed elements, The Urbach Tower by ICD/ITKE, Photo © ICD/ITKE 2019
15 Complex construction from preformed glulam beams, Swatch center in Switzerland by Shigeru Ban and Blumer Lehmann, Image © Blumer Lehman





Post-formed Gridshells

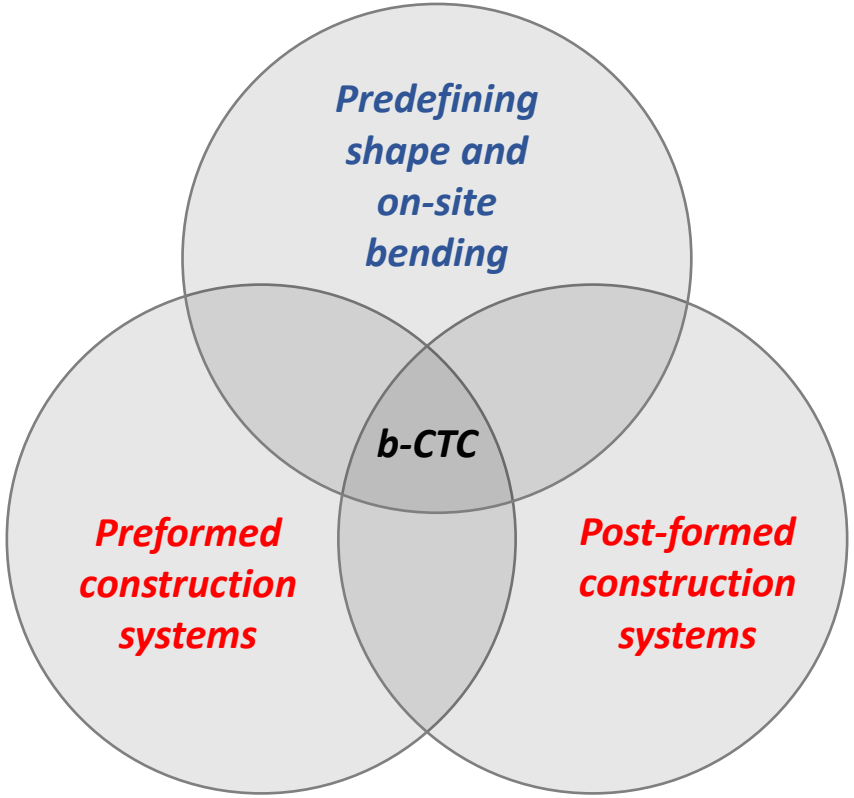


16 Grid shell construction, step 1: on site flat assembly

17 Grid shell construction, step 2: onsite forming process

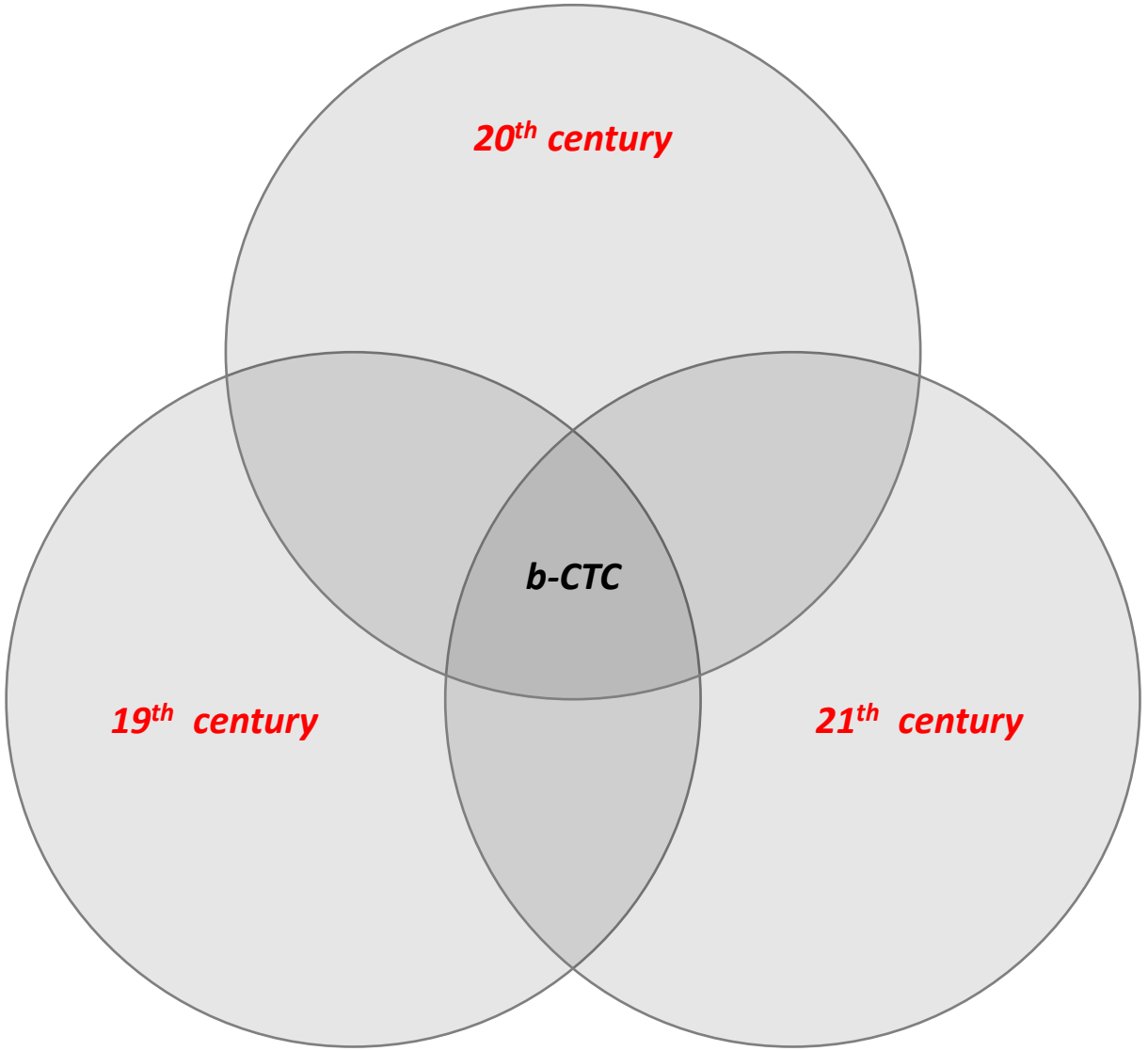
16 Grid shell construction, step 1: on site flat assembly, Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart.
17 Grid shell construction, step 2: onsite forming process, , Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart.

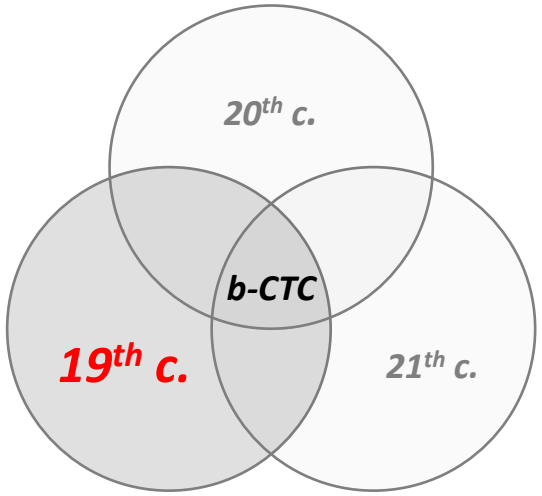
18
Complex construction from preformed glulam beams



19
Gridshell construction: on-site forming process

18 Complex construction from preformed glulam beams, Swatch center in Switzerland by Shigeru Ban and Blumer Lehmann, Image © Blumer Lehman
19 Grid shell construction: onsite forming process, , Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart


20th century
b-CTC
19th century
21th century



Teeth beams

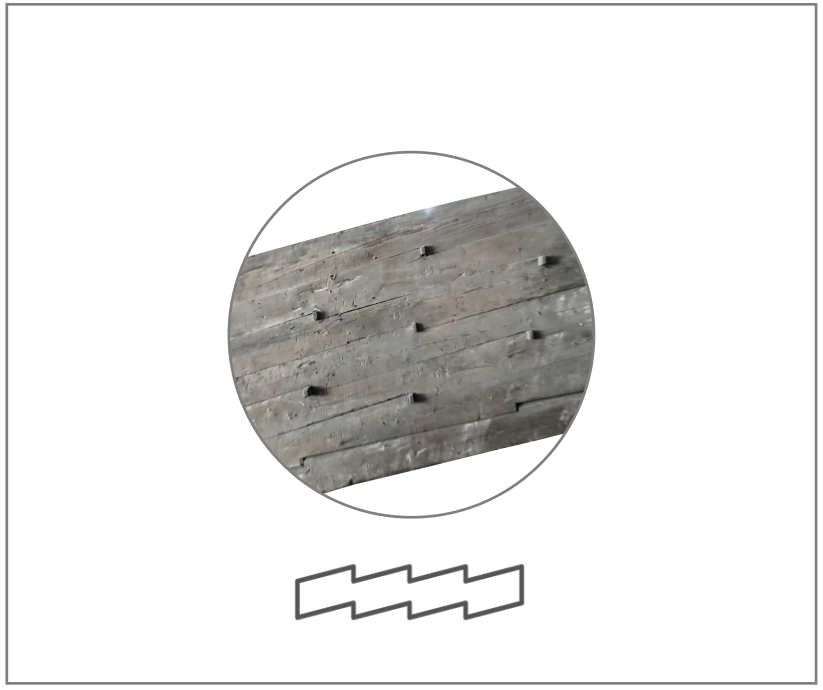
trusses

Wood joinery

Span: 60 m

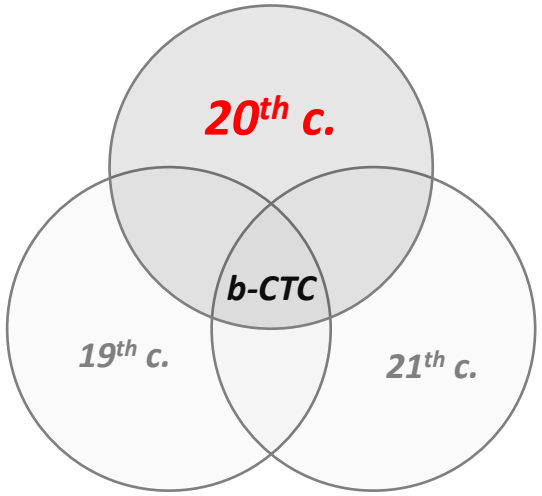
Teeth beam wood bridge

20 Wintersey teeth beam wood bridge in Switzerland Hasle Rüegsau, 1839



21 Interlocked teeth beams

20 Wintersey teeth beam woodbridge Switzerland Hasle Rüegsau 1839, Photo Miro Bannwart 2019
21 Interlocked teeth beams, Teeth-beam Woodbridge Switzerland 1839, Photo Miro Bannwart 2019



Span: 115 m

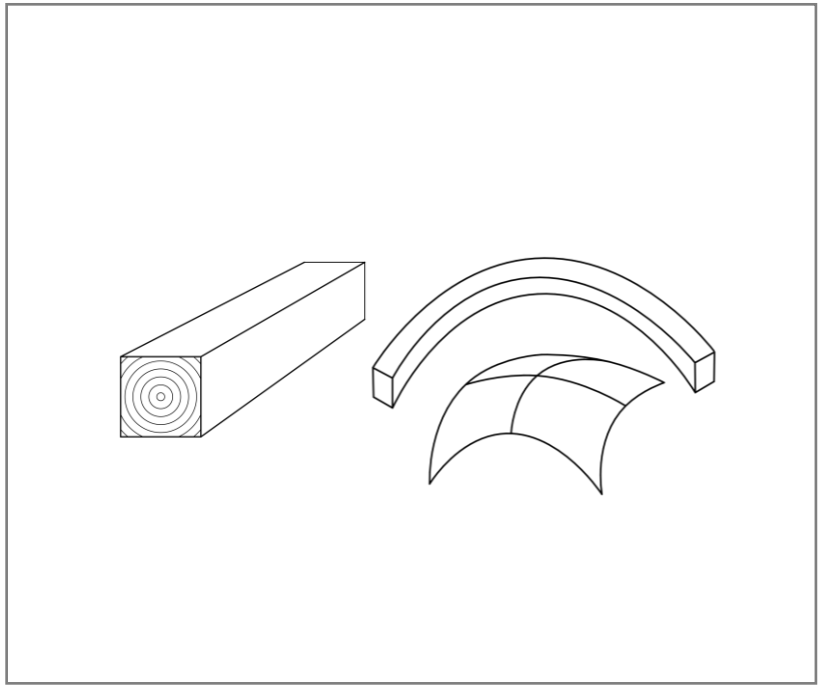
Height: 20 m

5 / 5 cm lamellas

4 Layers

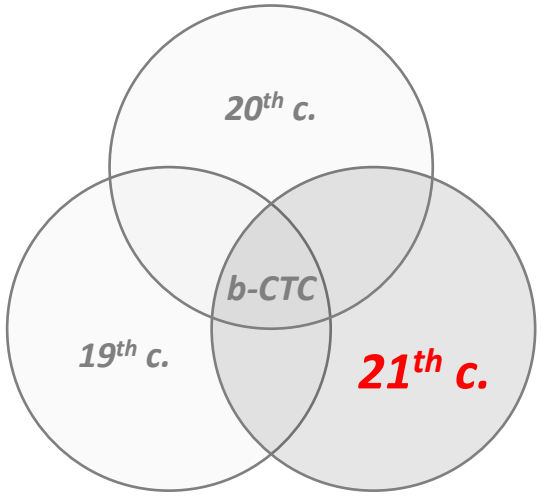
Multihalle

22 Multihalle in Mannheim by Frei Otto, 1975



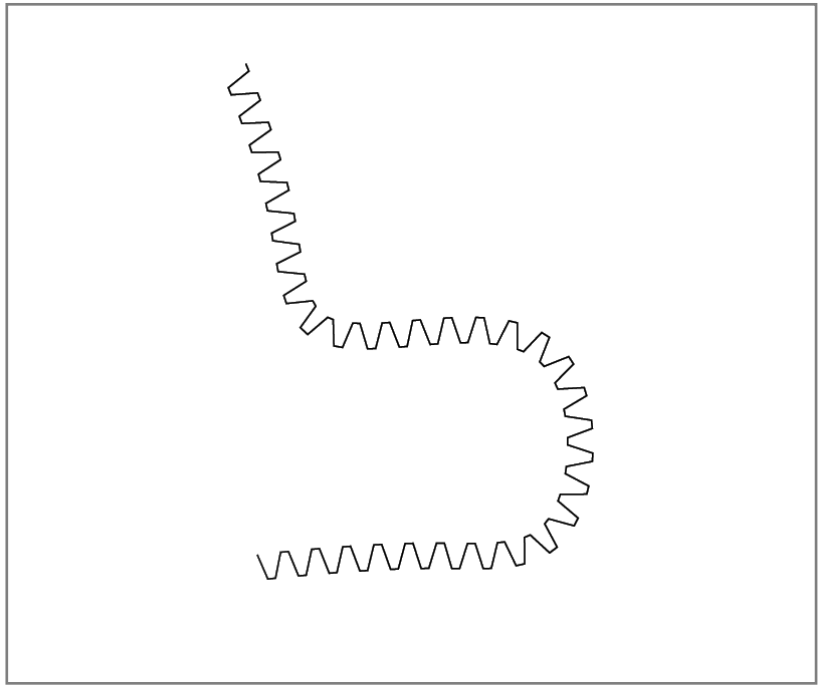
23 Lightweight construction in bent solid wood

22 Multihalle, Mannheim 1974/ 75 Frei Otto, Photo © by Verein Multihalle Mannheim, Daniel Lukac
23 Graphics Miro Bannwart 2019

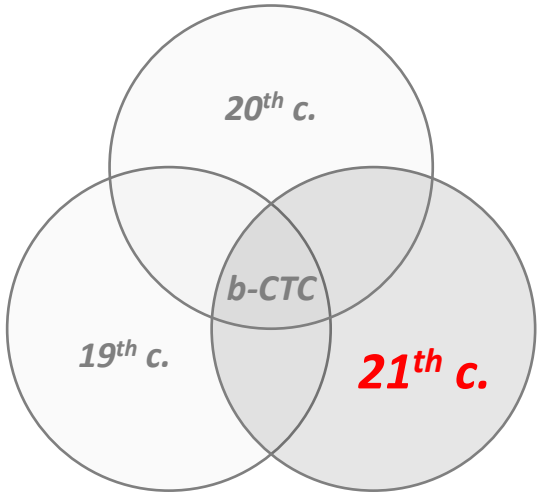


ZipShape chairs

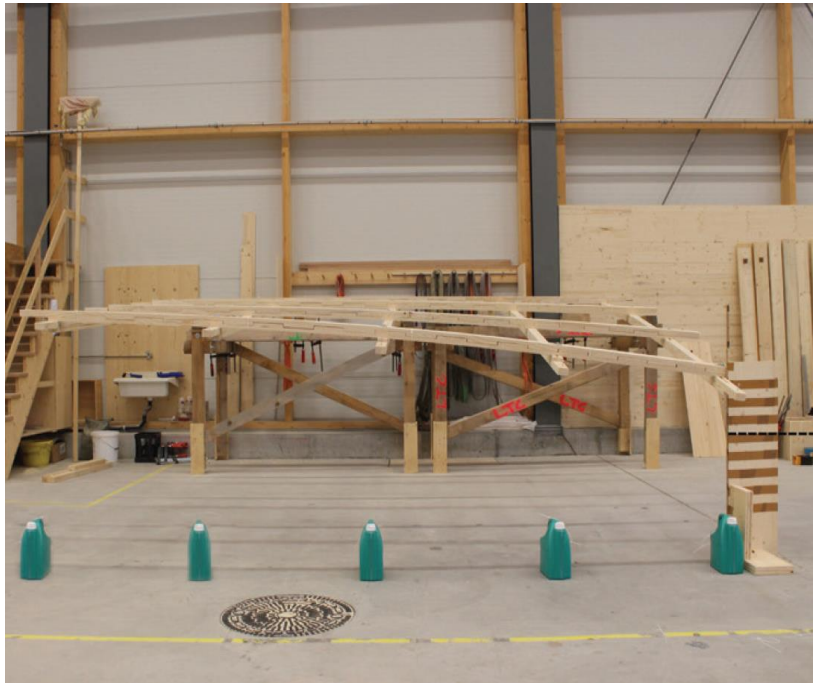
24 ZipShape chairs by Christoph Schindler



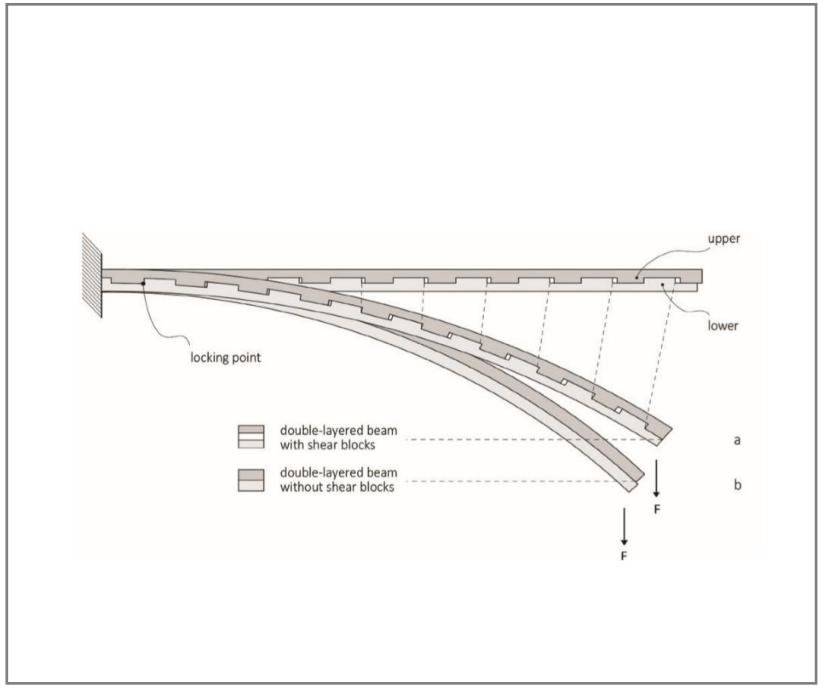
25 ZipShape principle



Novel bending-active system with controllable curvature-stiffness relation

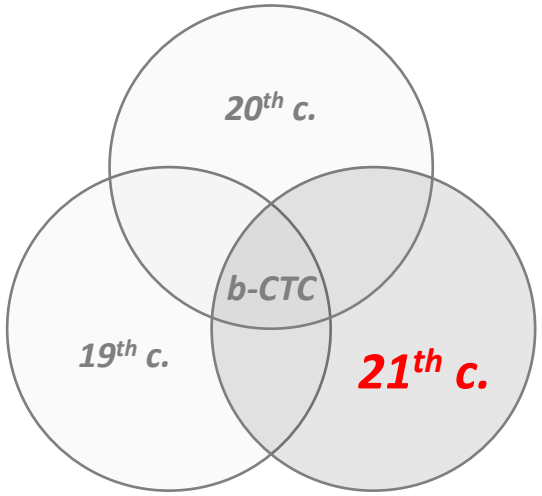


26 Self organized doubly curved gridshell by gravitational loads

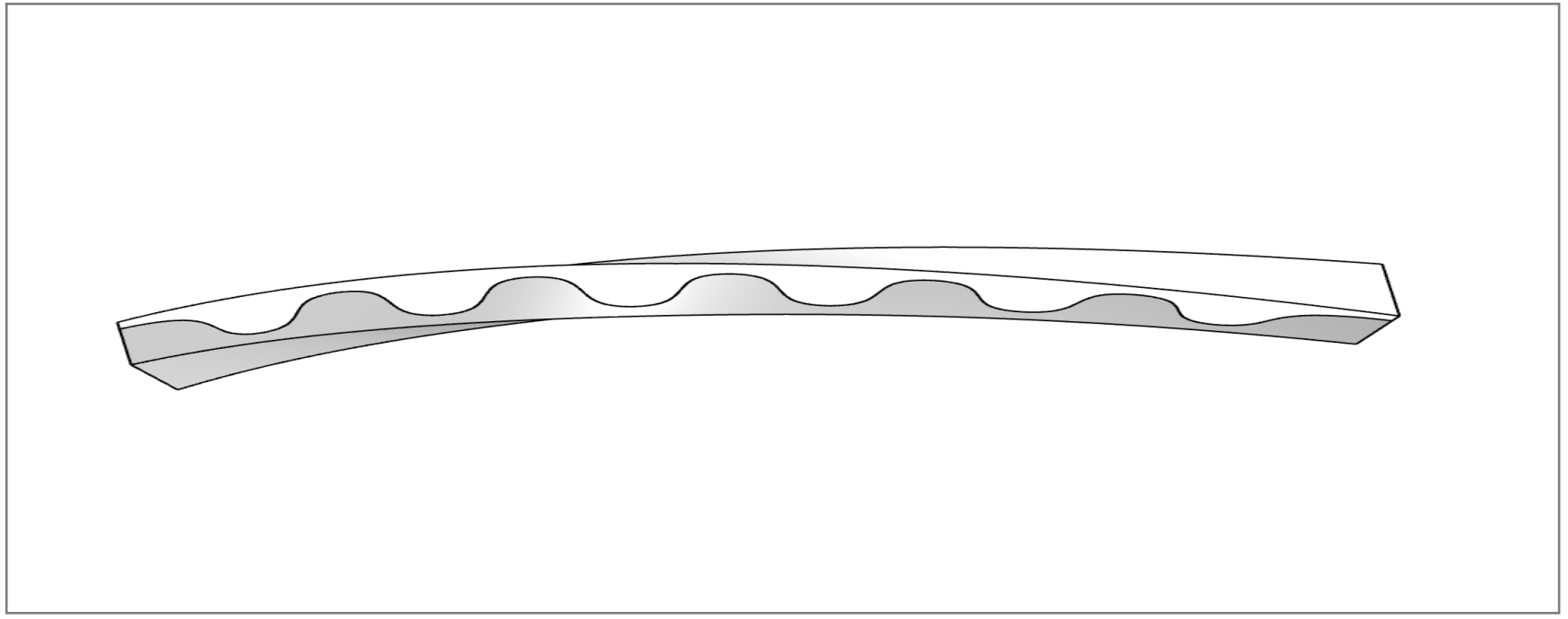


27 Cantilevering double layered element with shear blocks

26 Self-organized doubly curved gridshell by gravitational loads, Image from the publication: Novel bending-active system with controllable curvature-stiffnessrelation by © E. Baseta 2019
27 Cantilevering double layered linear element with shear blocks, Image from the publication: Novel bending-active system with controllable curvature-stiffnessrelation © by E. Baseta 2019

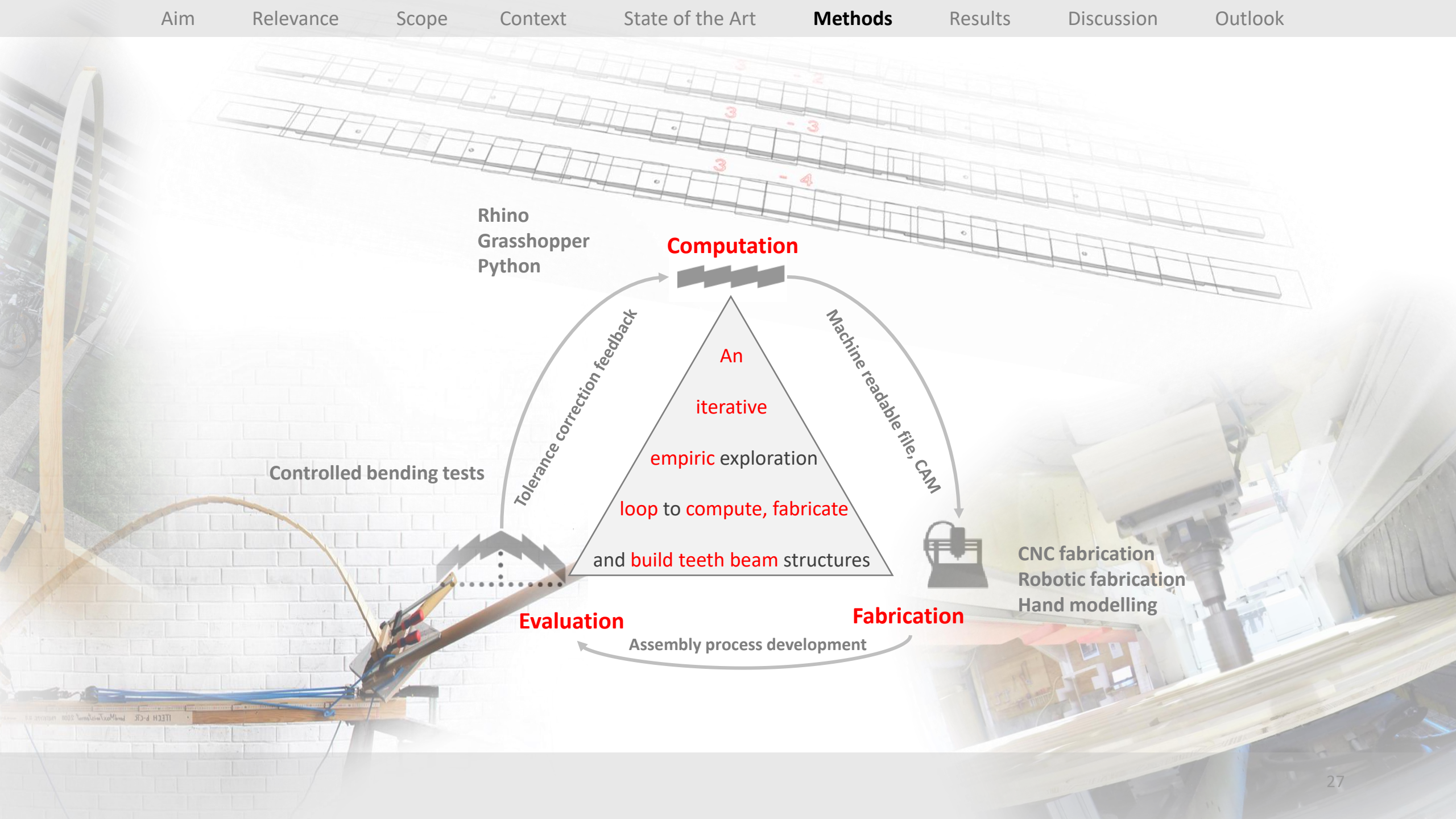


Zippered Wood



29 Project Zippered Wood, Principle

28 Project Zippered Wood,a collaboration of the University of British Columbia's HiLo Lab, the Uni-versity of Colorado, Denver's LoDo Lab, and HouMinn Practice Image © architecmagazin 2020
29 Project zippered Wood, Graphic by the Author

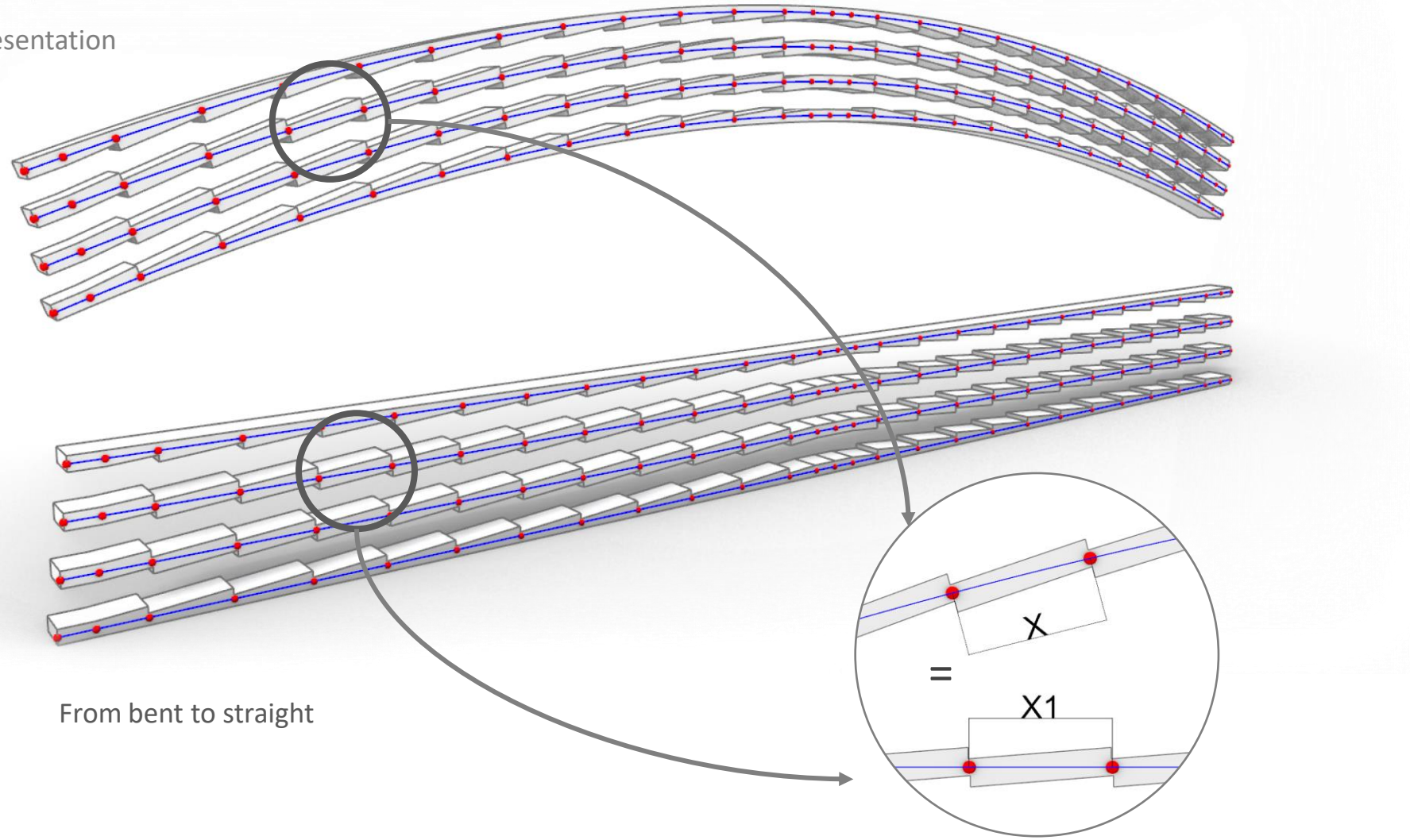

Rhino
Grasshopper
Python
Computation
Tolerance correction feedback
Machine readable file, CAM
An
iterative
empiric exploration
loop to compute, fabricate
and build teeth beam structures
Controlled bending tests
CNC fabrication
Robotic fabrication
Hand modelling
Evaluation
Fabrication
Assembly process development

Results

The final prototype

Teeth system

Straight geometry representation

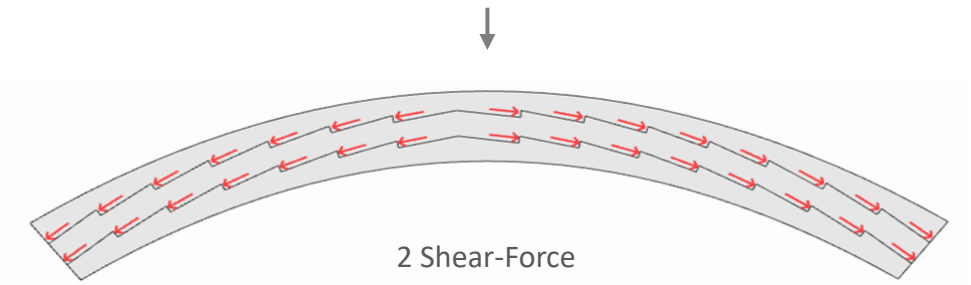


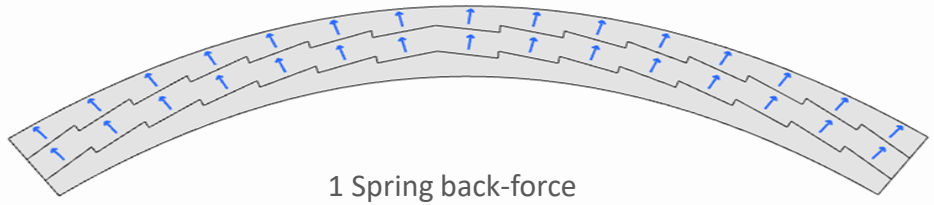
From bent to straight

Non-deforming middle line

Teeth system

Forces

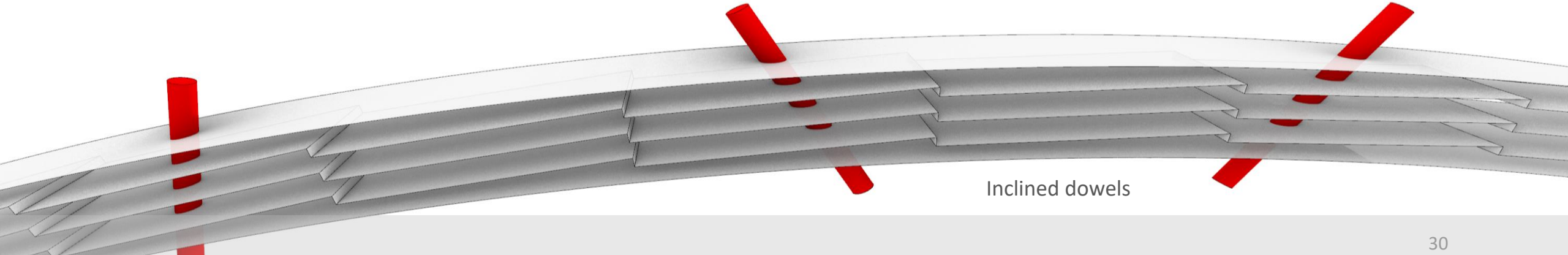




Glulam beam

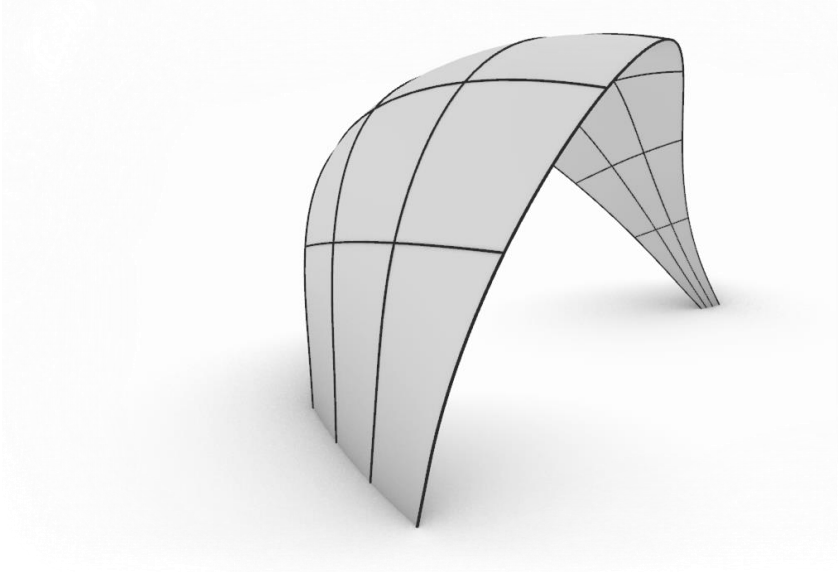
Conventional teeth beam

b-CTC



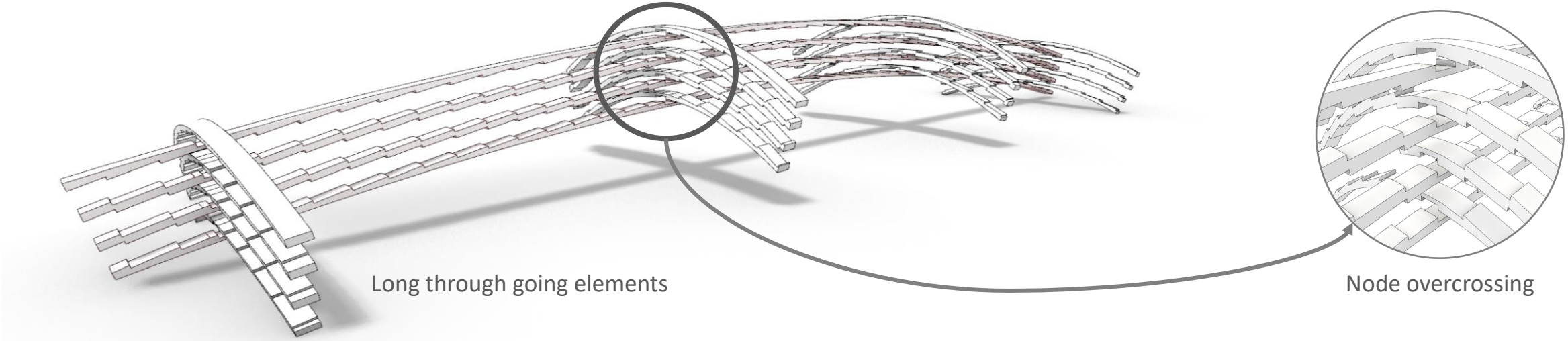
Teeth system

Discretization



Doubly curved design surface

28
Spruce forest, straight grown wood



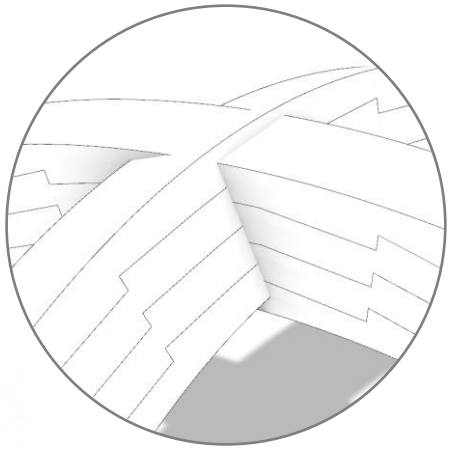
Long through going elements

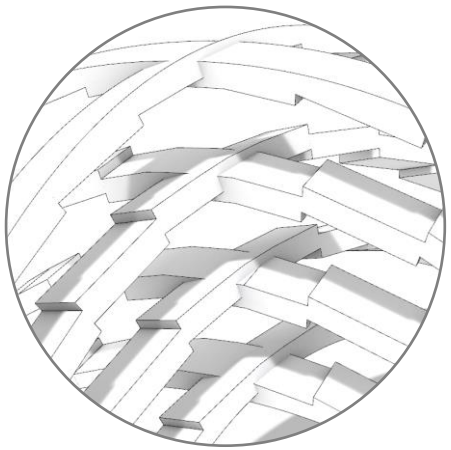
Node overcrossing

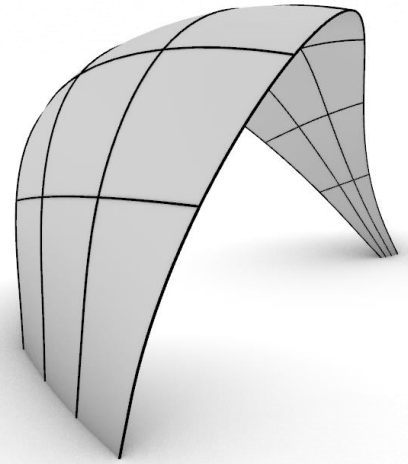
28 Spruce forest straight grown wood, Image © Urs Schäfer 2013

Teeth system

Node complexity



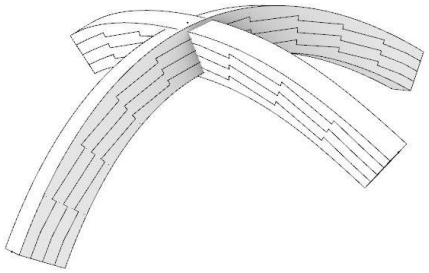


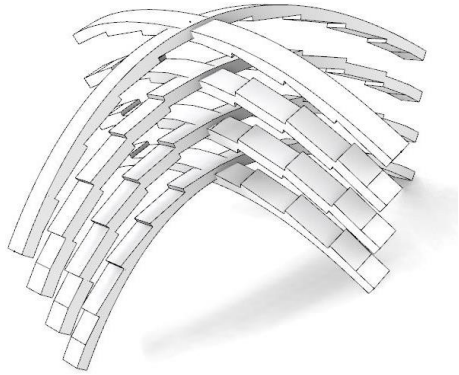


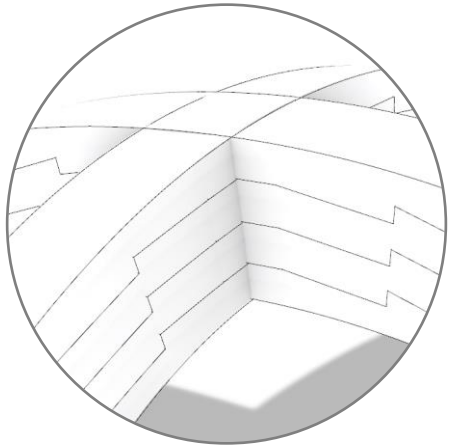
Doubly curved design surface

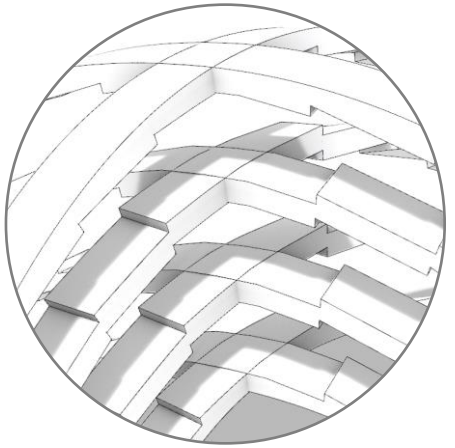
In plane single curved beams

The layers do not match



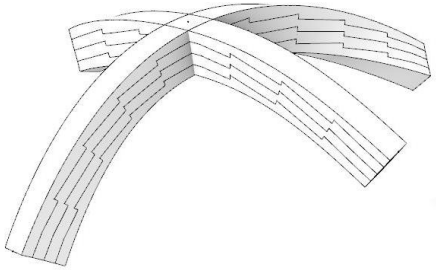


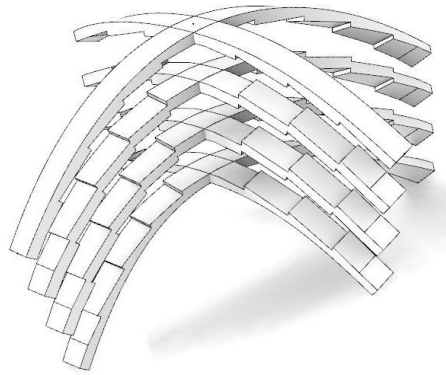




Out of plane twisted beams

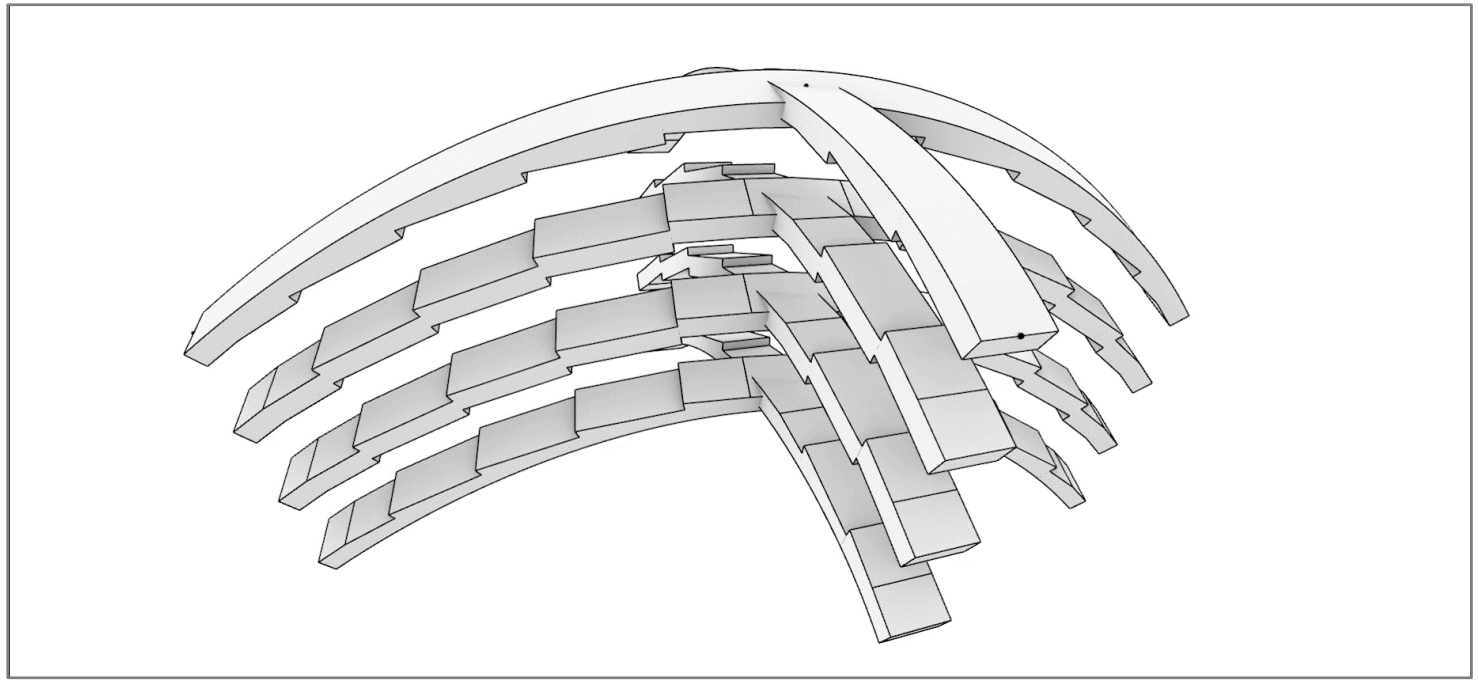
The layers do match



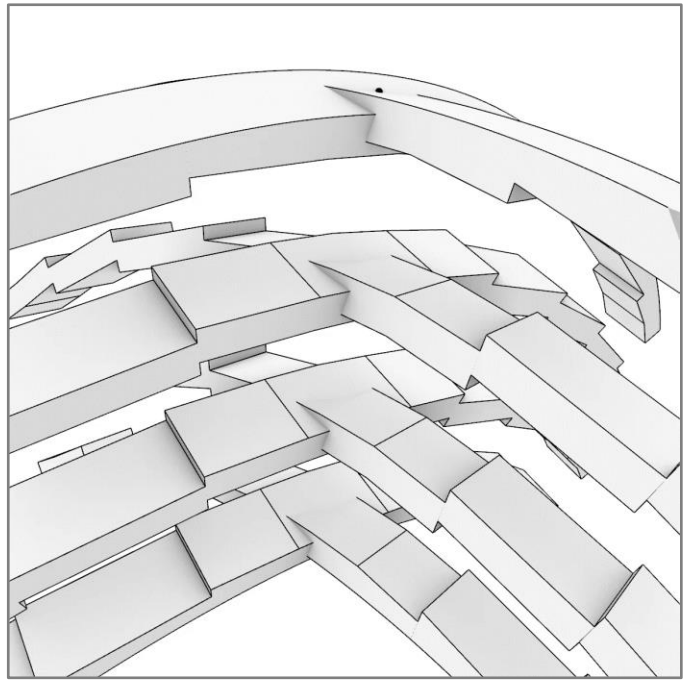


Teeth system

Node complexity



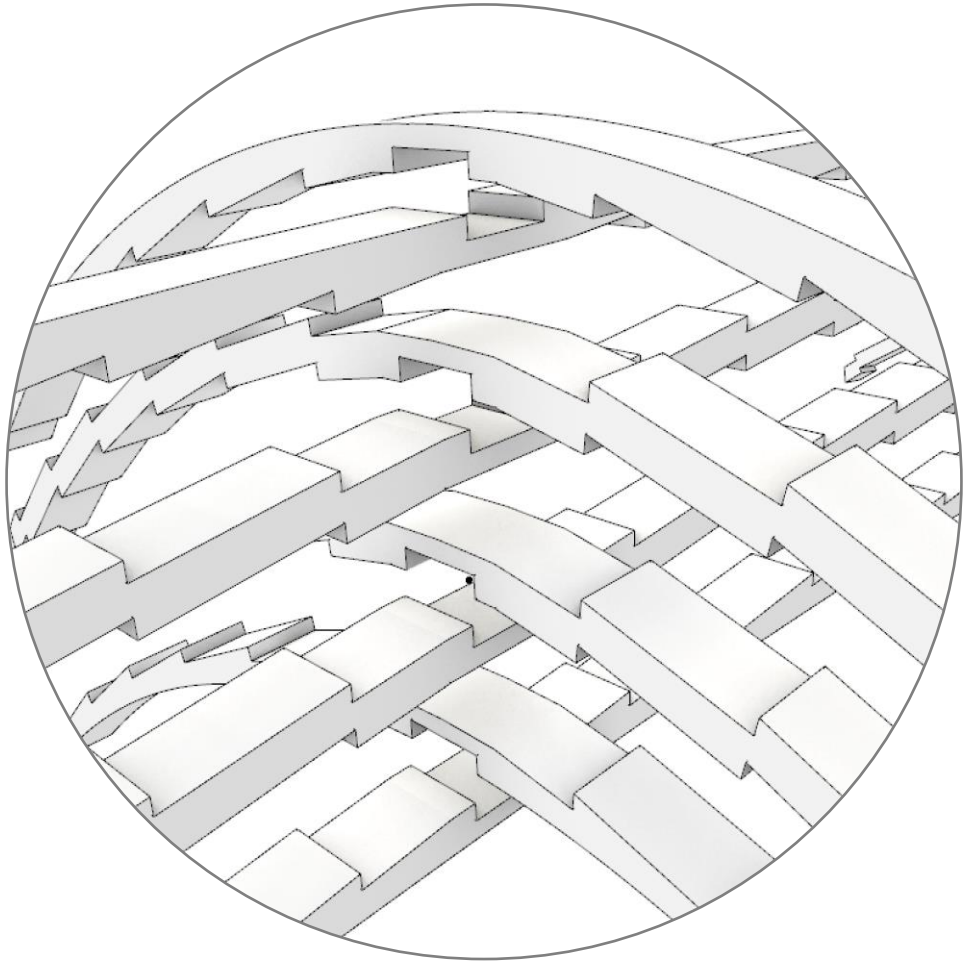
In plane beams to twisted beams



Intersection detail

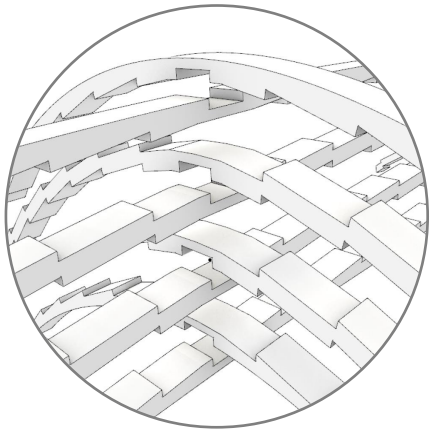
Teeth system

Node complexity

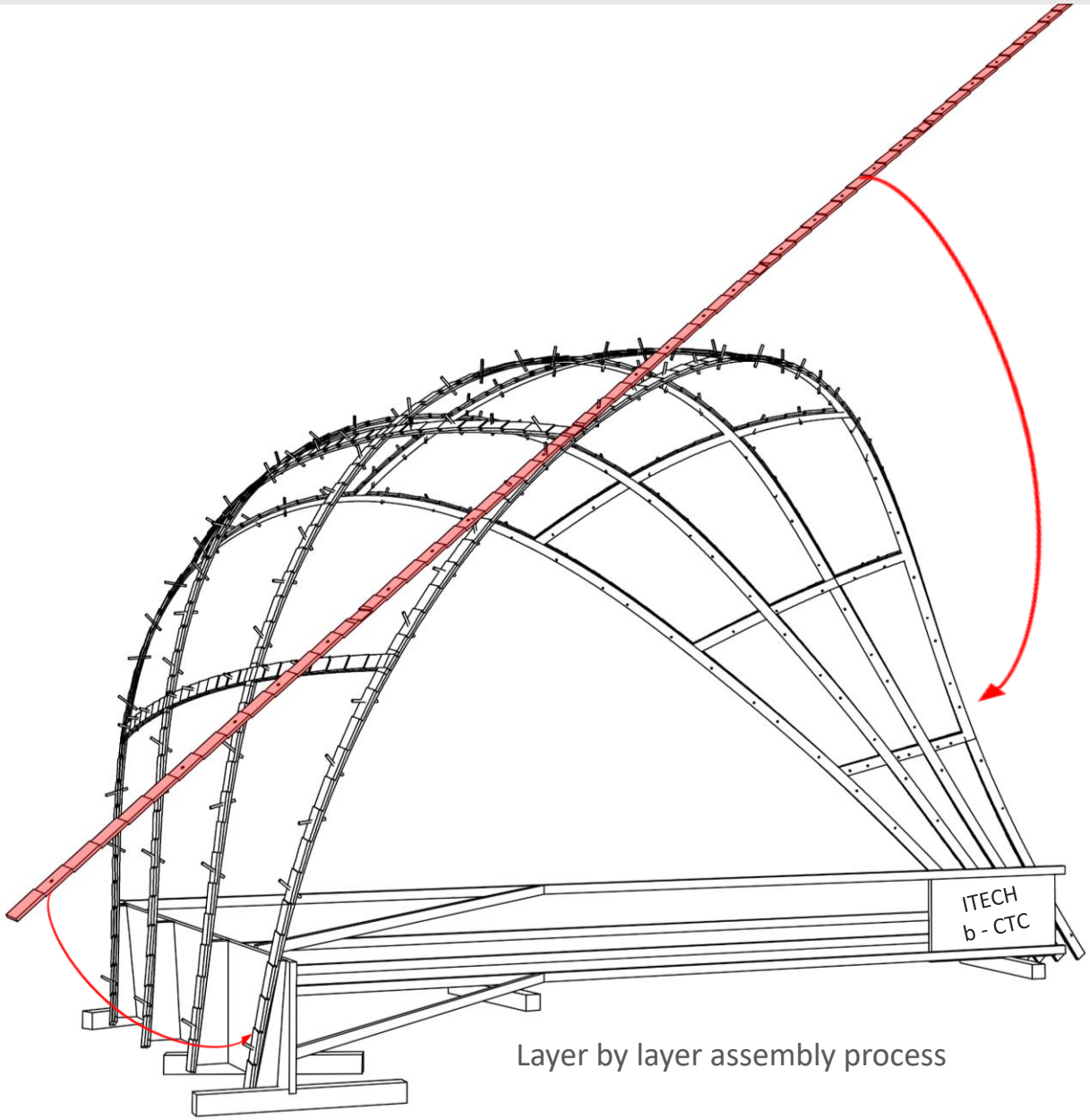


Fabricable node geometry

Teeth system
Assembly



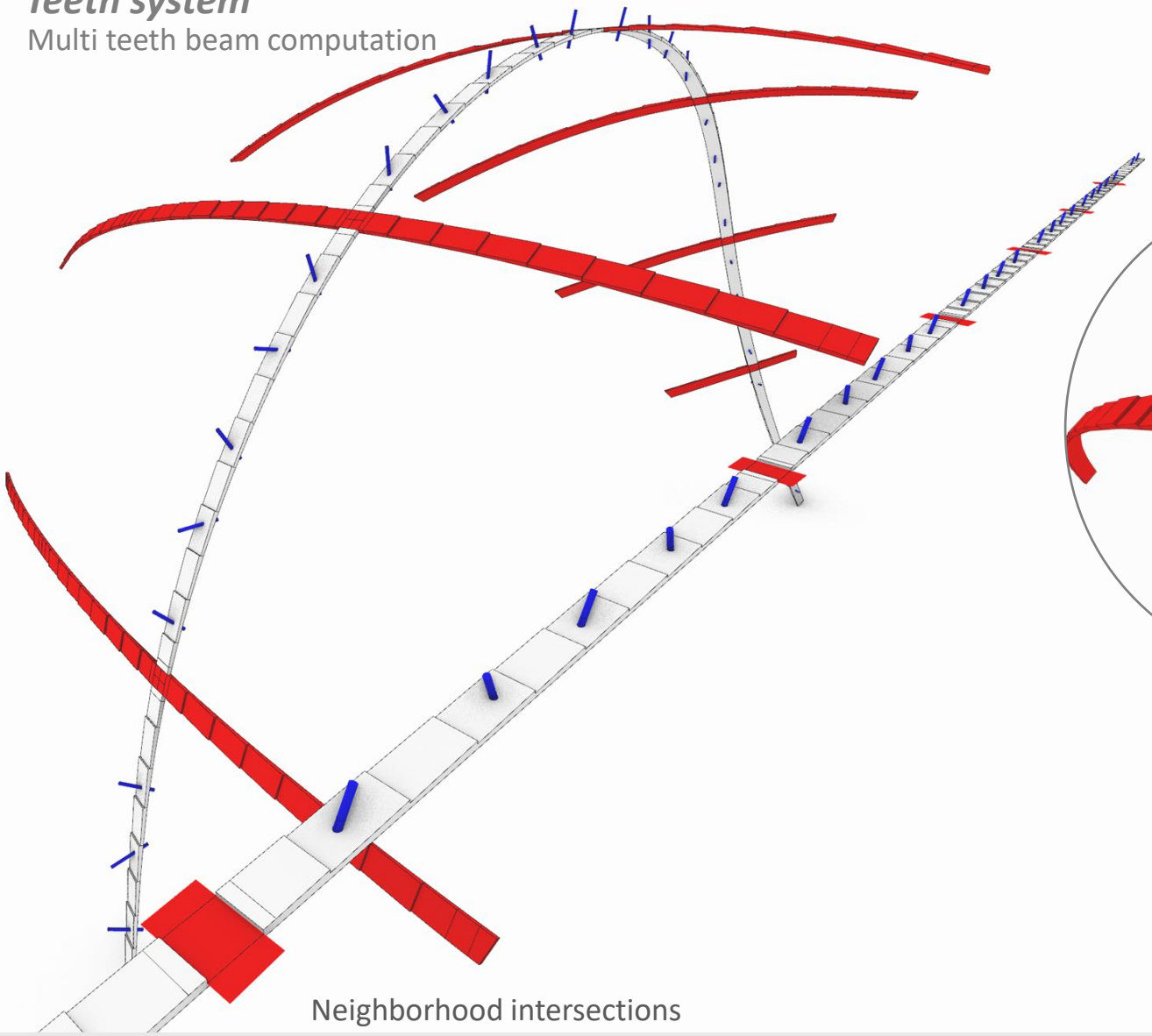
Node overcrossing



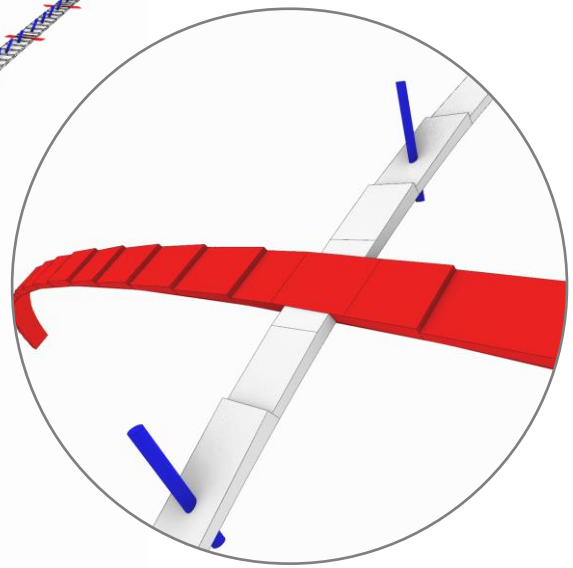
Layer by layer assembly process

Teeth system

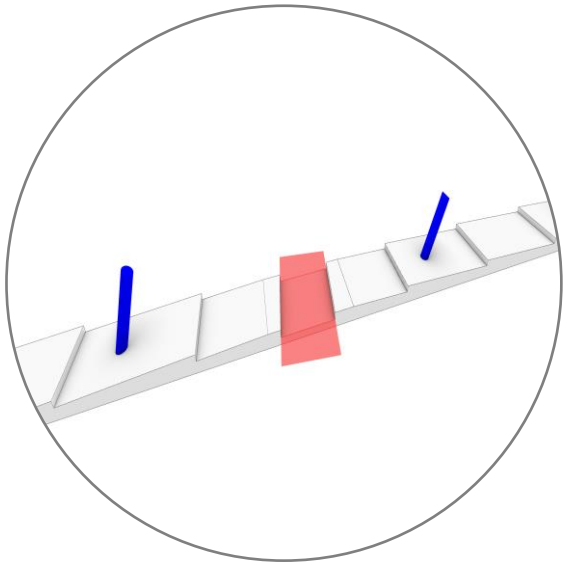
Multi teeth beam computation



Neighborhood intersections



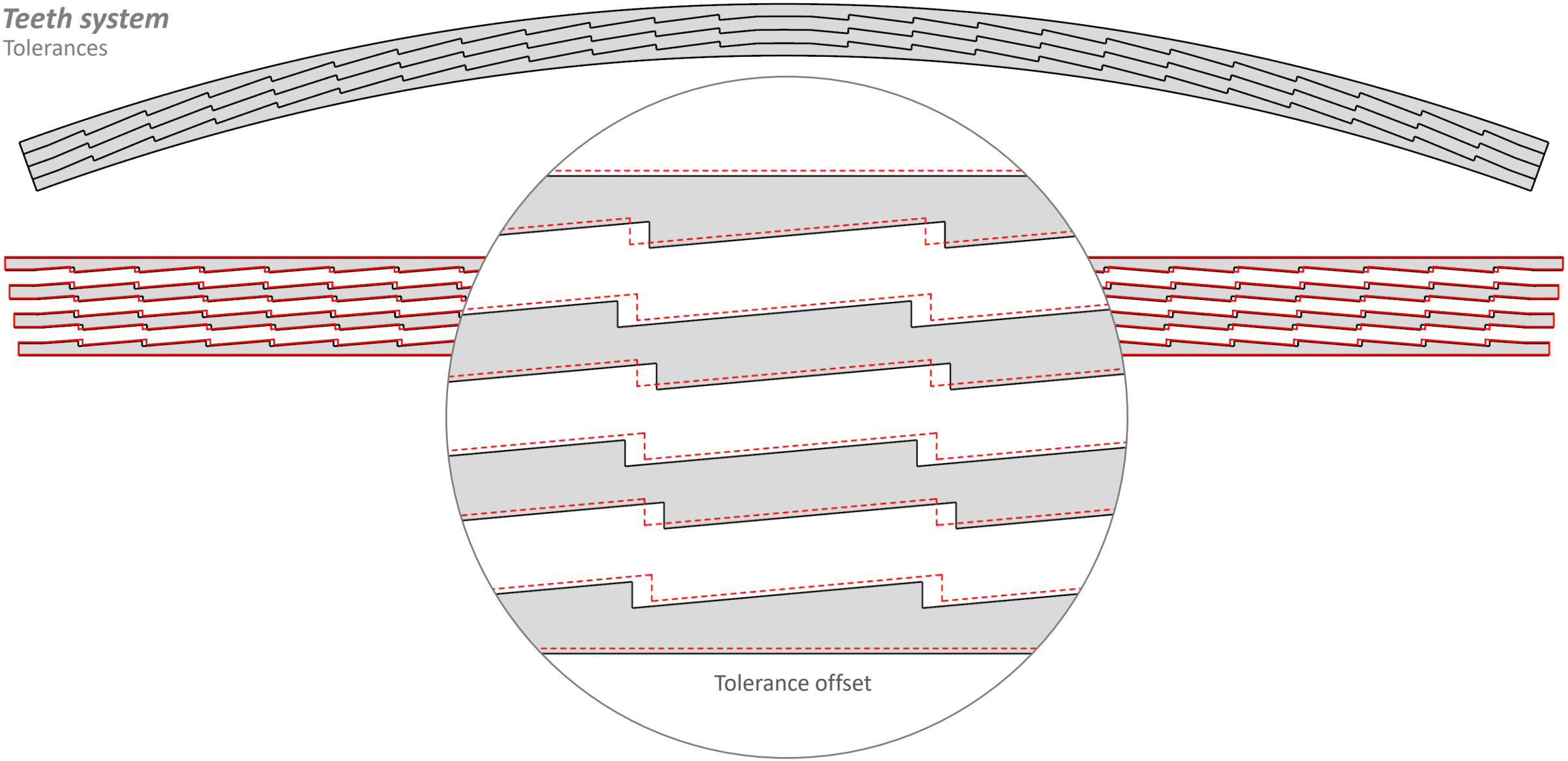
Intersection, bent



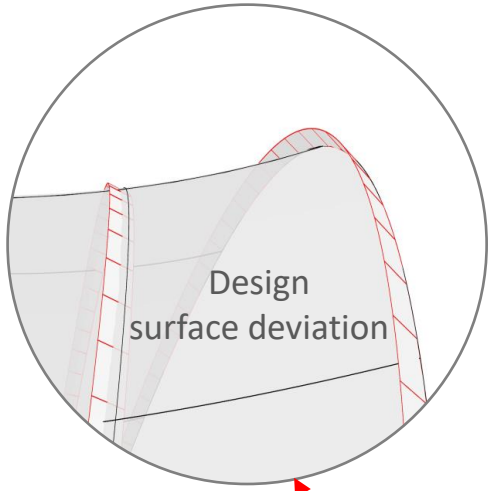
Intersection, straight

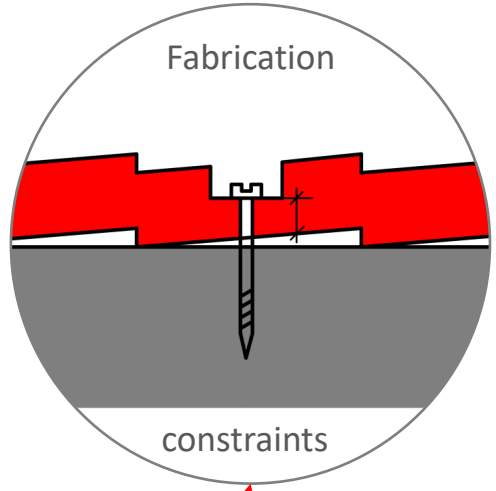
Teeth system

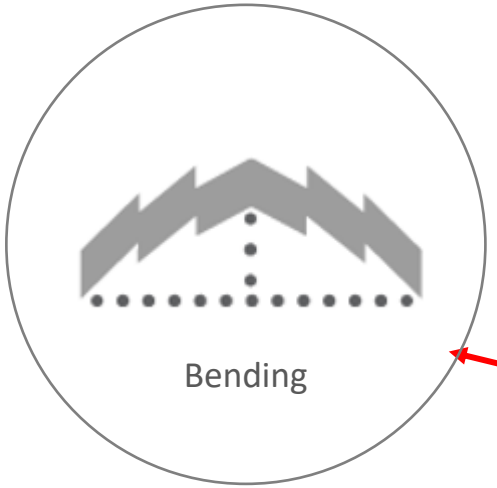
Tolerances



Limitations

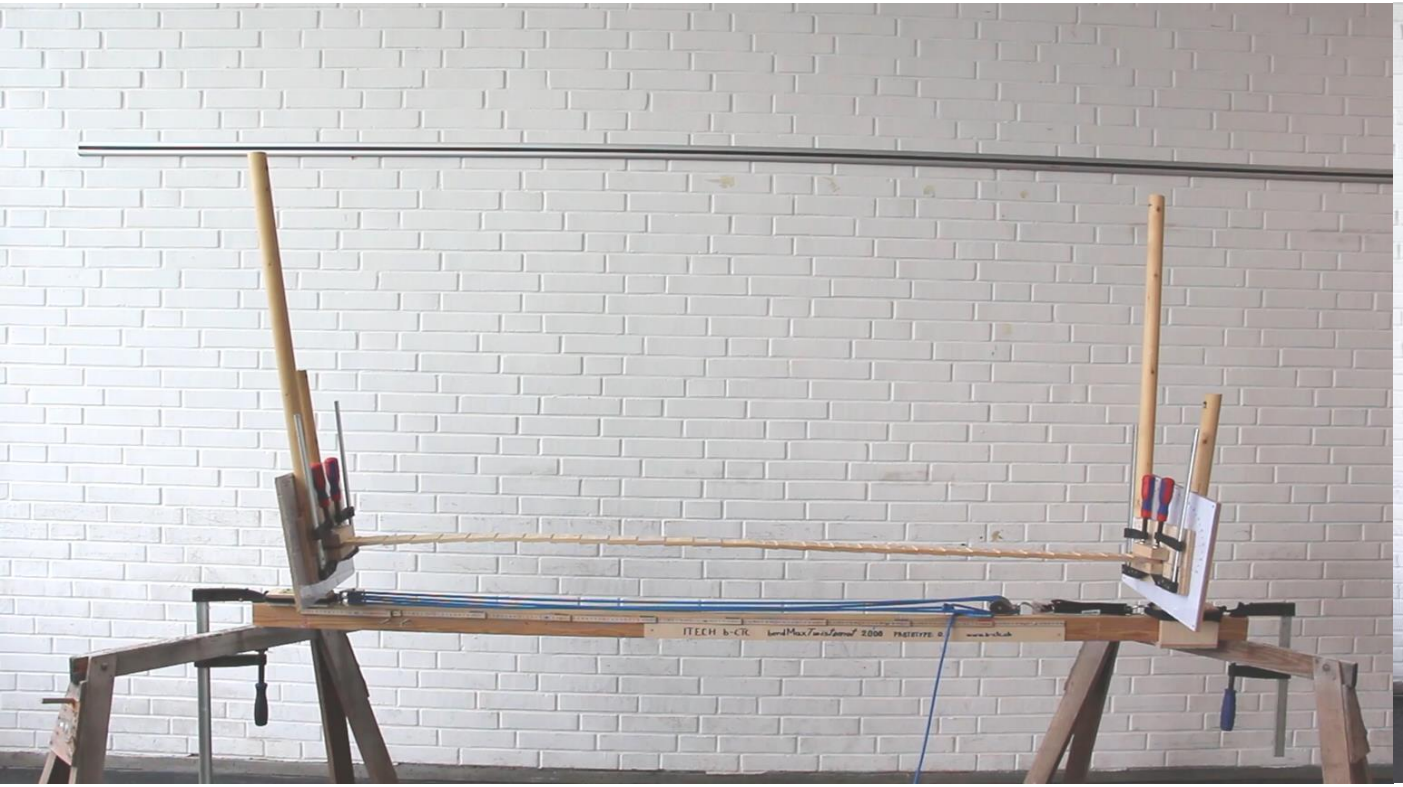






Limitations

Maximal bending and twisting

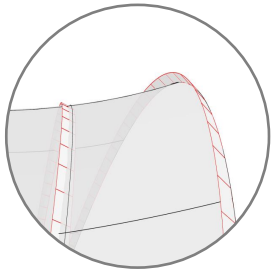


ITECH BendMax *TWISTOMAT*2000 PROTOTYPE 1.0

ITECH BendMax *TWISTOMAT*2000 PROTOTYPE 1.0

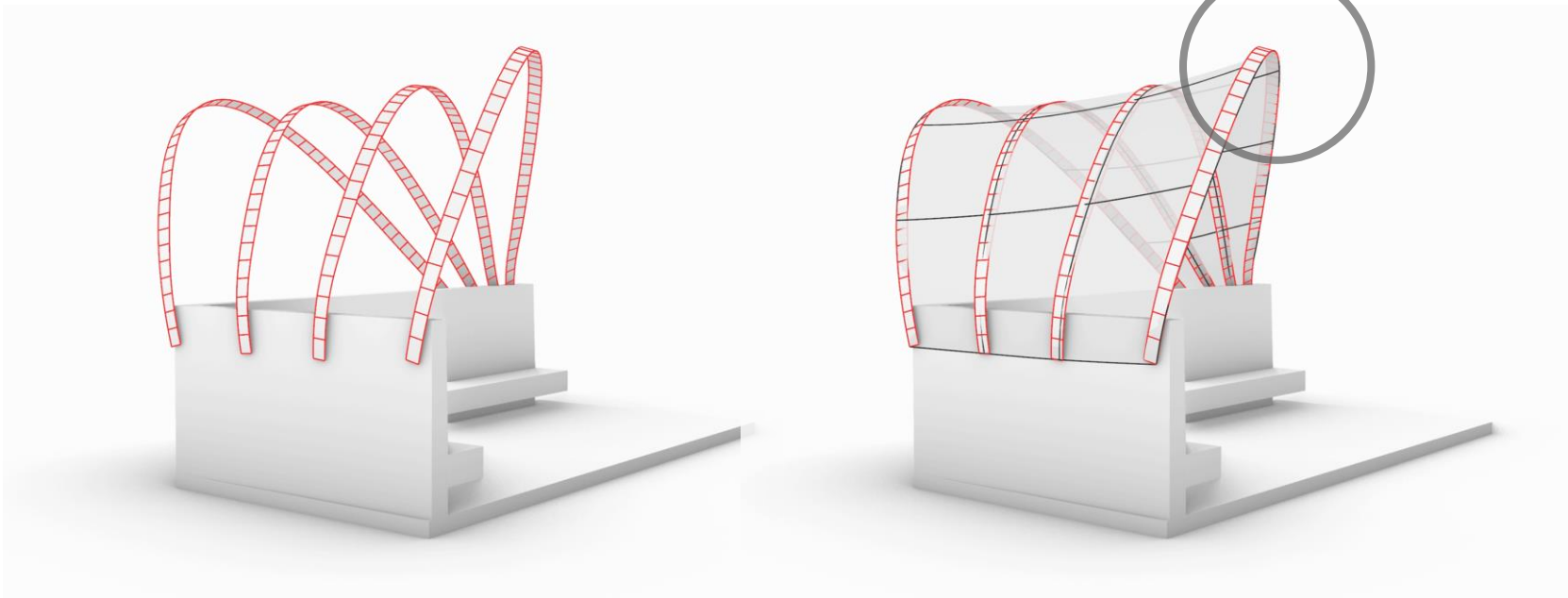
Teeth lamella 1000 mm / 60 mm / 7 mm

Torsion < 50 ° & Bending radius < 500 mm

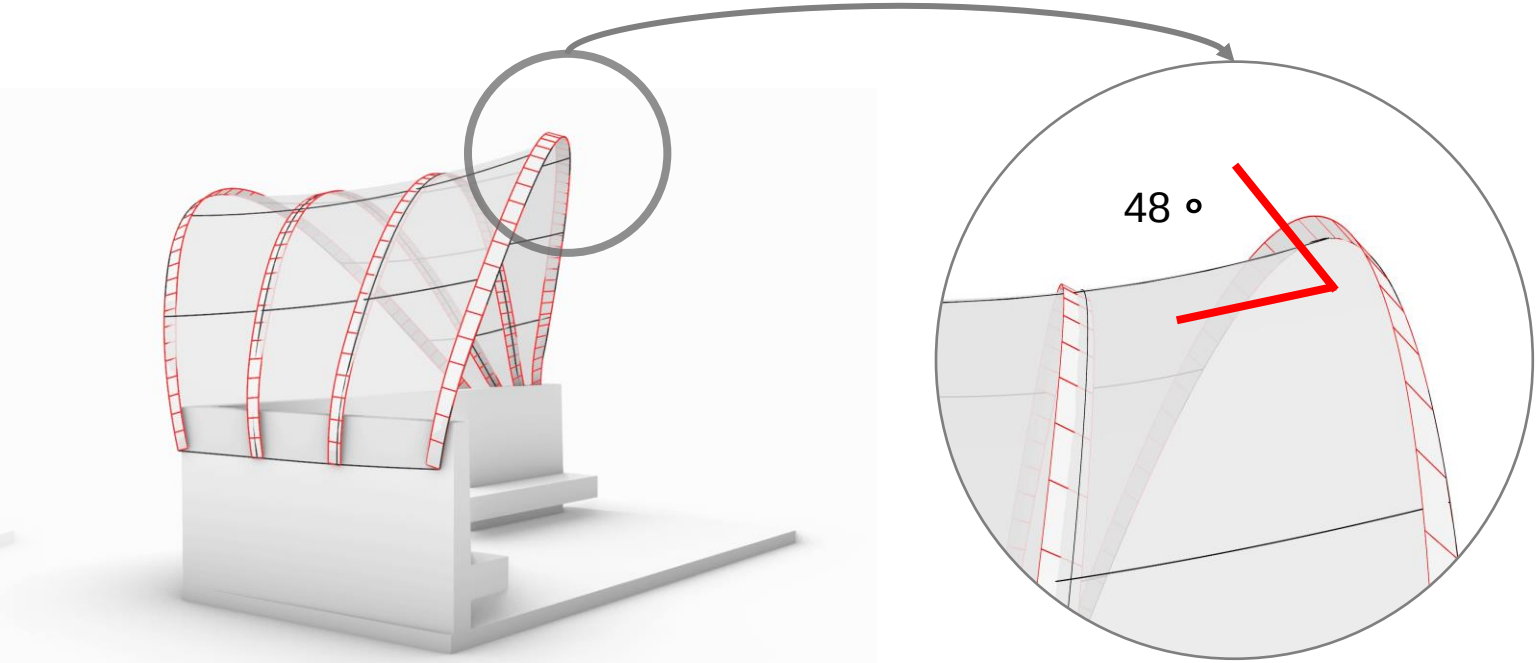


Limitations

Design surface deviation



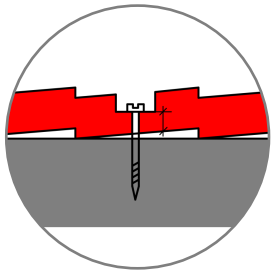
Single twisted teeth beam components



Single twisted teeth beam components in relation to the design surface

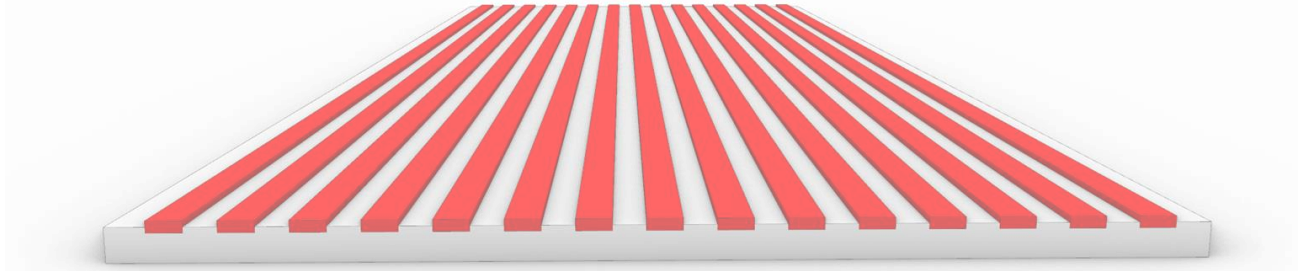
Design surface deviation

Teeth lamella 60 mm / 7 mm Additional torsion < 18 °



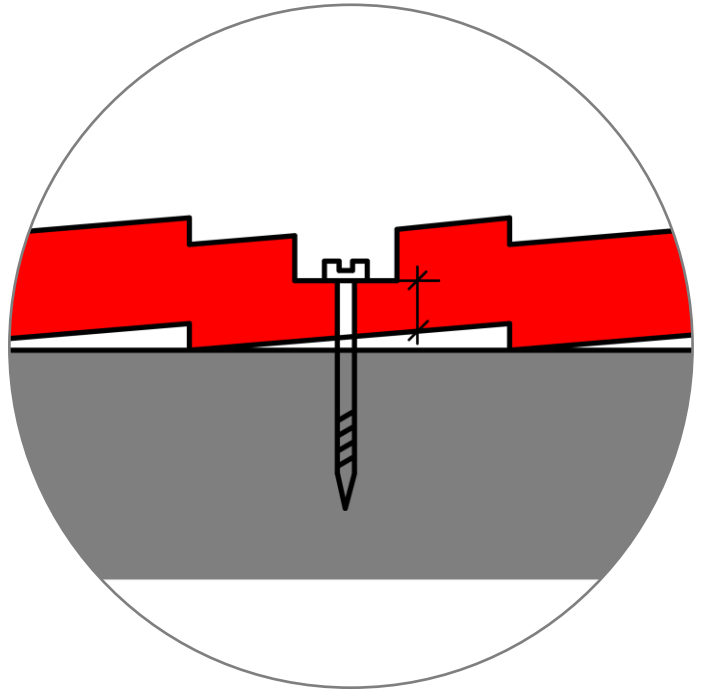
Limitations

Fabrication constraints



57 CNC table size, defining:

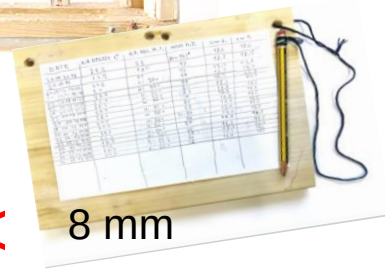
- Lamellas per table
- Max. lamella length



58 Minimal lamella thickness > 7 mm

Limitations

Water



ITECH Hygro*SIM* 3000 PROTOTYPE 1.0

Lamella 1400 mm / 32 mm / 18 mm : 3 Layers

Bending radius change < 14 mm

Change at the tips < 8 mm

The final prototype

Project partners

29 Zeughaus Teufen, wood construction Museum

30 Treppenbau.ch AG CNC - wood stairs manufacturer

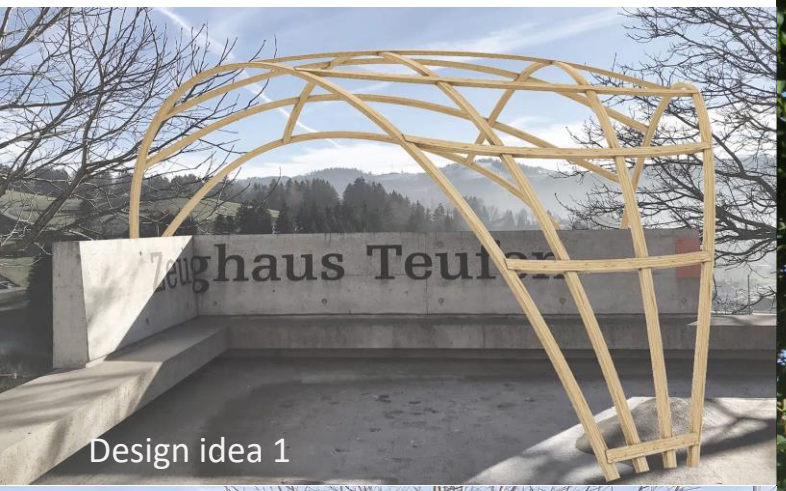
29 Zeughaus Teufen, Image © GIAN SALIS ARCHITEKT 2008
30 Treppenbau.ch AG CNC - wood stairs manufacturer, Photo Miro Bannwart 2019

The final prototype

Location in front of
the Zeughaus Teufen

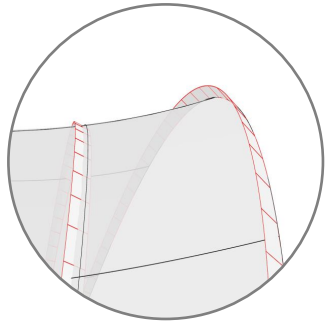
The final prototype

Shape design



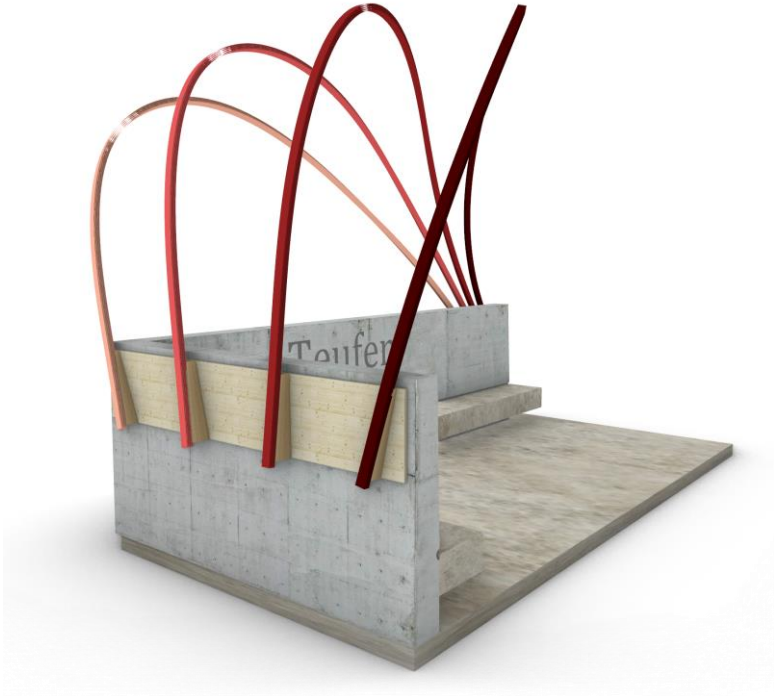
The final prototype

Shape design
- Increasing additional torsion



Additional torsion

Increasing additional torsion, top view



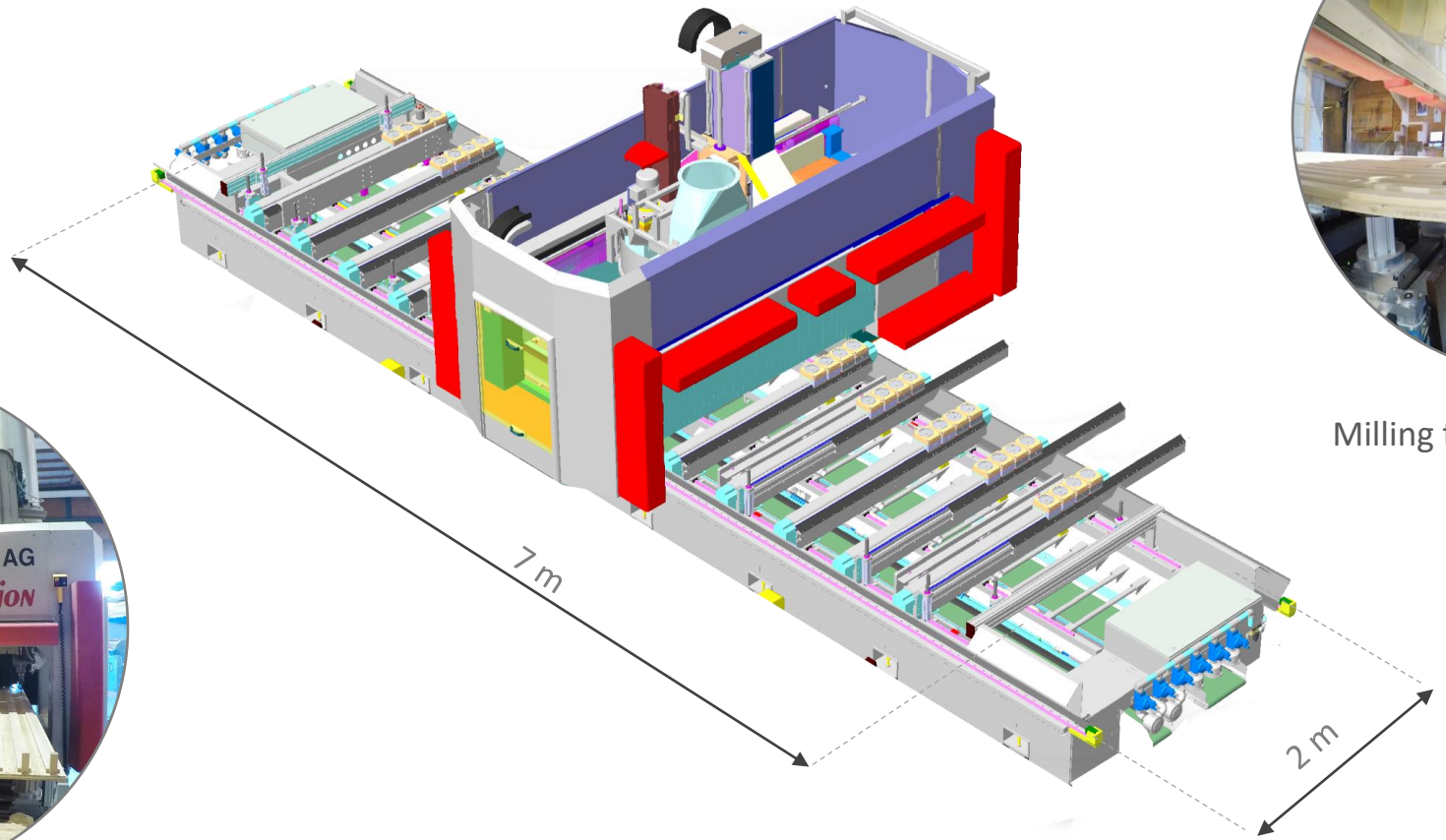
Increasing additional torsion, back view

Increasing additional torsion, physical confirmation model

The final prototype

Fabrication

Reichenbacher, CNC Vision 3



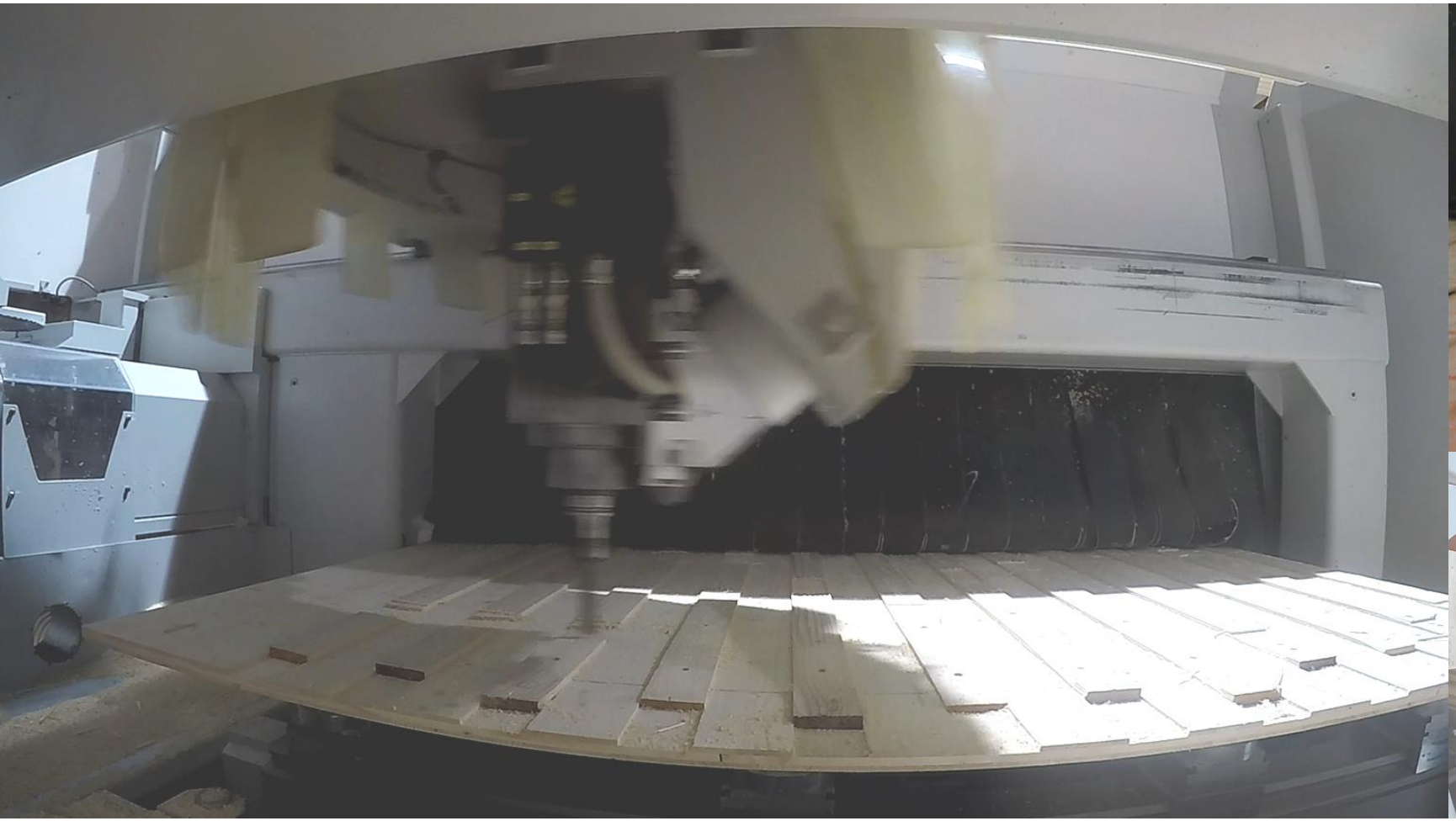
31 5-Axis CNC, Reichenbacher, Vision 3, model 4105

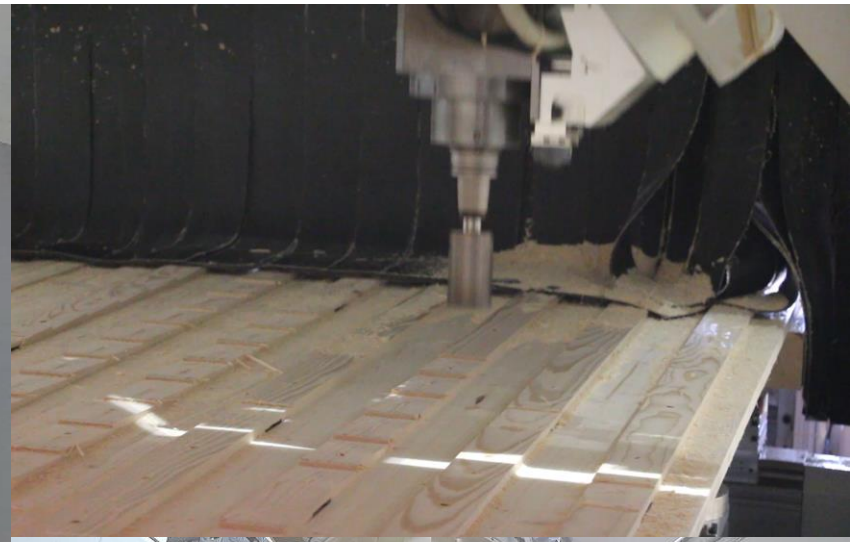
Milling tool: Diameter 10 cm

31 5-Axis CNC, graphic received from © Reichenbacher

The final prototype

Fabrication

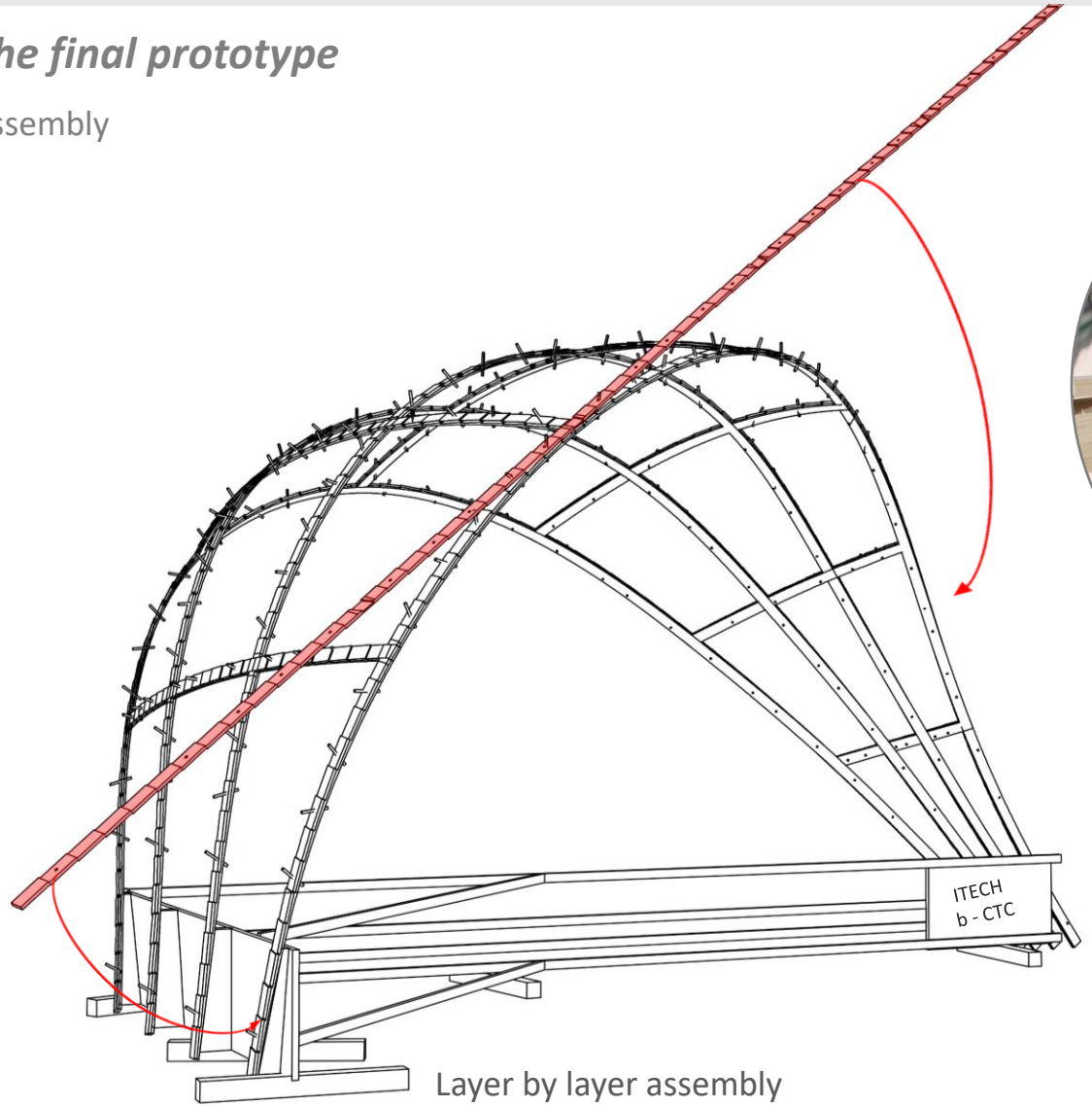




43 CNC Fabrication, machining time approx. 4 days

The final prototype

Assembly



Layer by layer assembly

Assembly with clamps

Assembly, front

The final prototype

Assembly

Assembly time approx. 4 days

The final prototype

Max. additional torsion

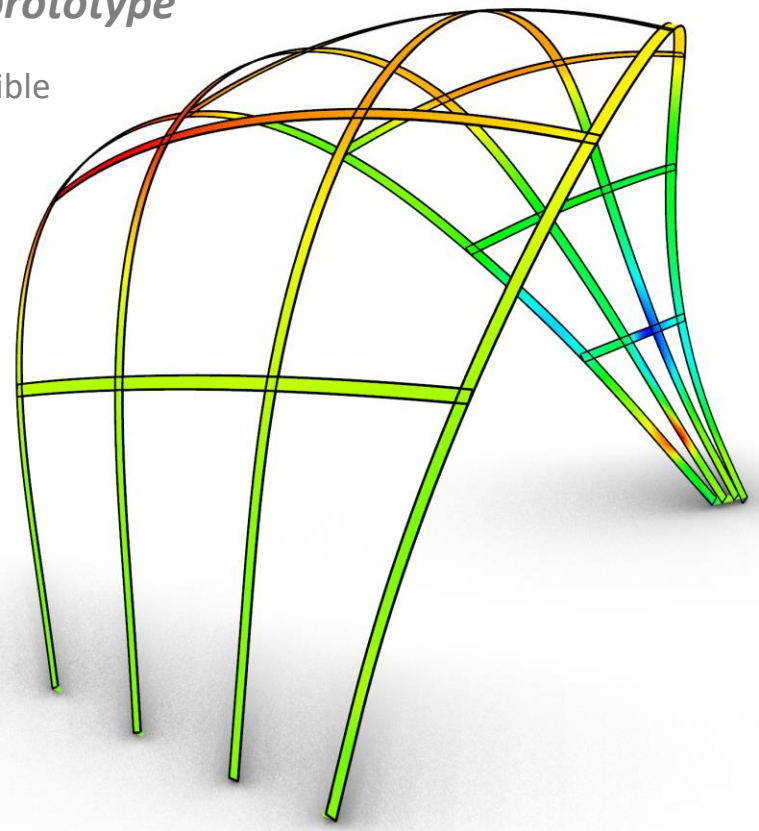
Location of max. additional requested torsion

Node during assembling

Assembled nodes

The final prototype

Dowels possible



Surface curvature analysis

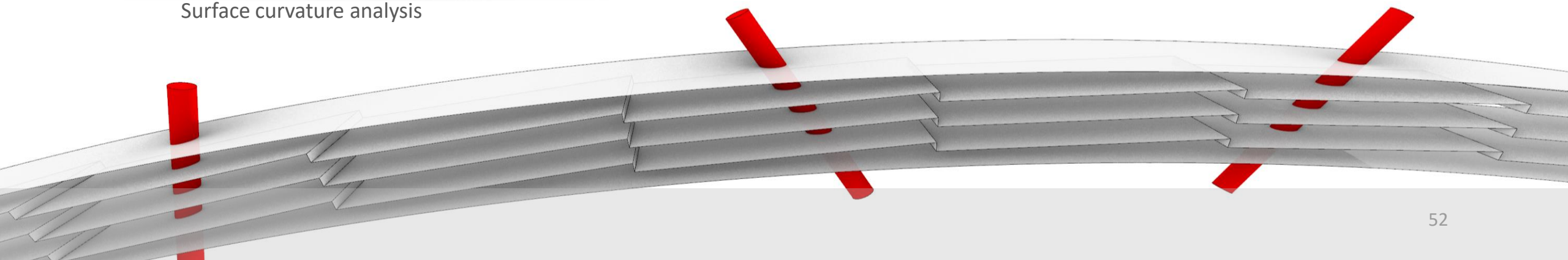
Screws

Dowels

Dowels possible

-1.7316e-07  1.7316e-07

Gaussian curvature



Structural point load test

The final prototype

Structural test

Structural height:	**46**	**mm**
Beam width:	**60**	**mm**
Layer count	**4**	
Lamella thickness	**16**	**mm**
Minimal layer depth	**7**	**mm**
Max. span:	**6**	**m**
Volume:	**0.14**	**m^3**
Weight	**62**	**kg**
Area	**19**	**m^2**
Kg / m^2	**3.2**	**Kg**
Structural test point load:	**0.7**	**kN**

Structural point load test

The final prototype

Accuracy

Fixation detail, front

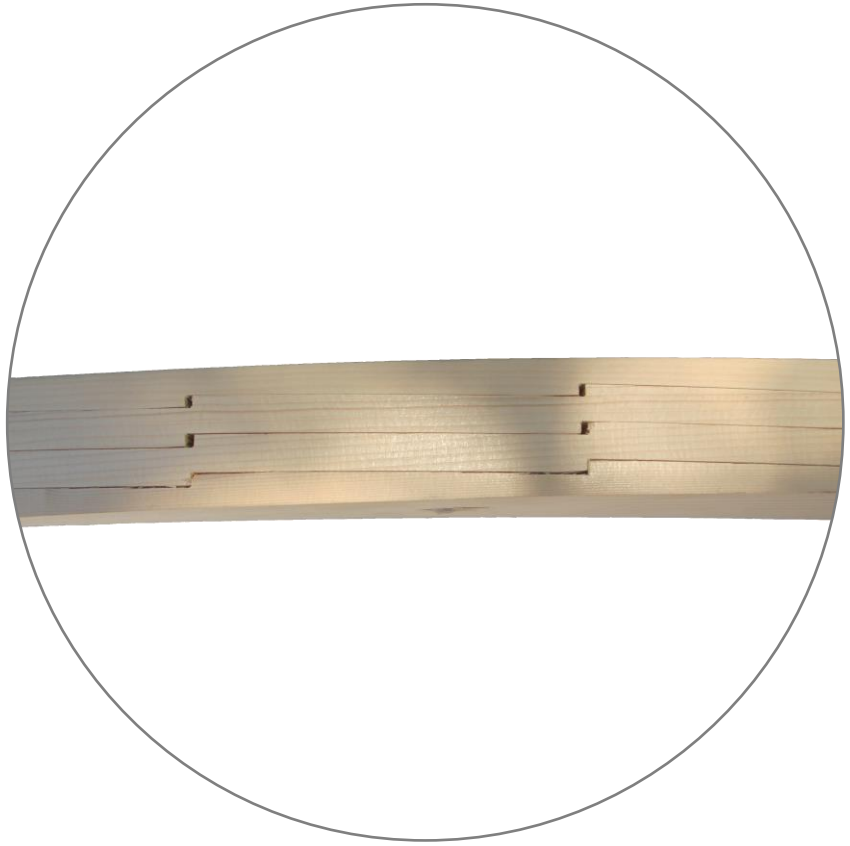
Fixation detail, back

Fixation detail, back

The final prototype

Teeth accuracy

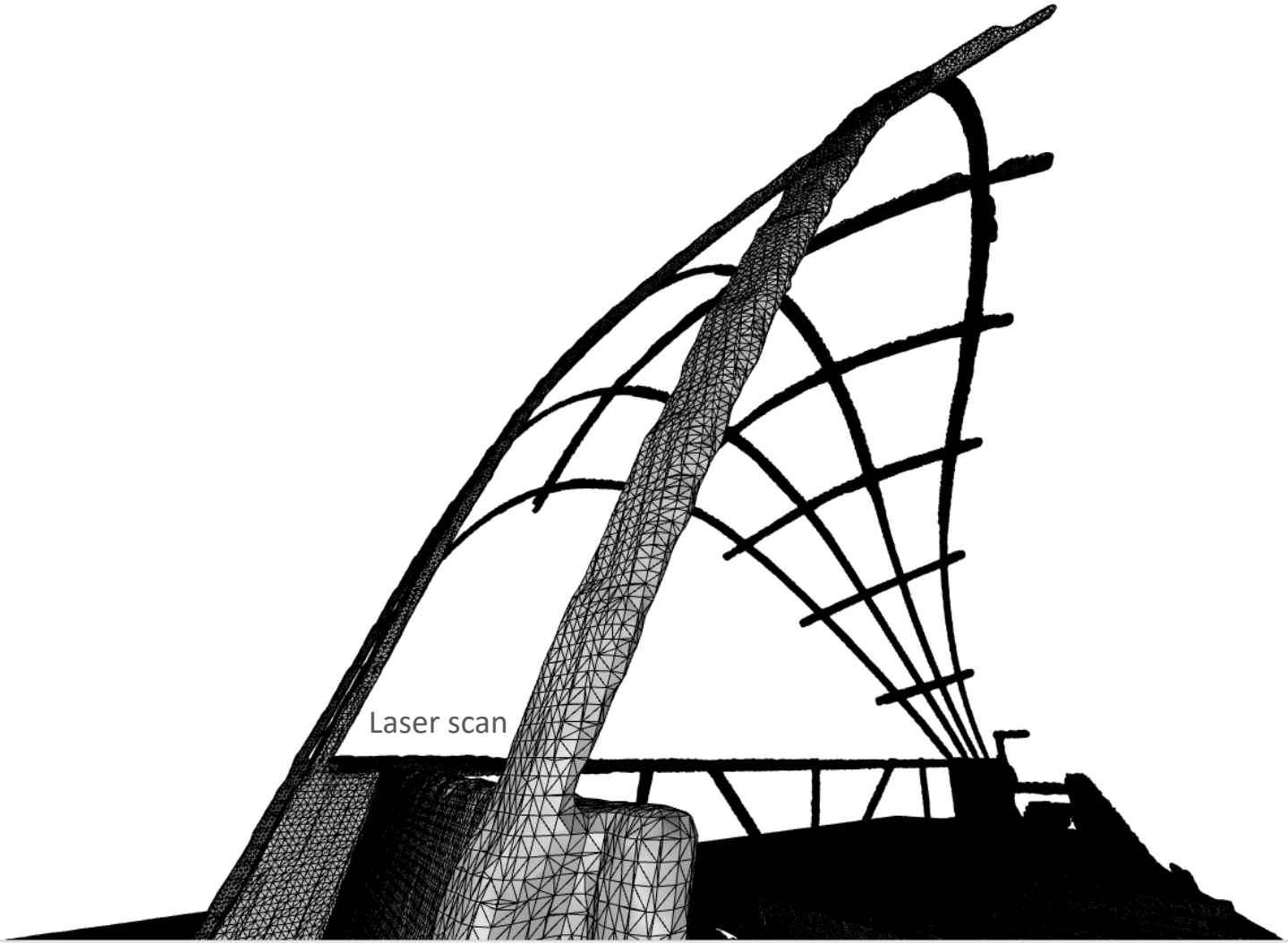
Teeth detail, full contact



Teeth detail, max. 2 mm gaps

The final prototype

Overall accuracy – a laser scanning attempt

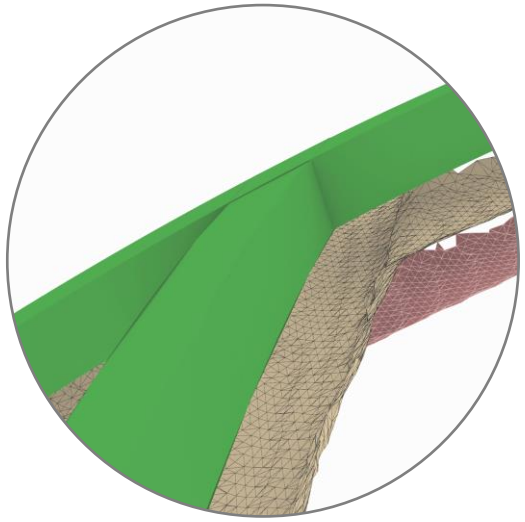


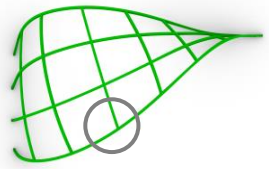
32 Faro laser scanner

32 Faro laser scanner, Photo © Faro

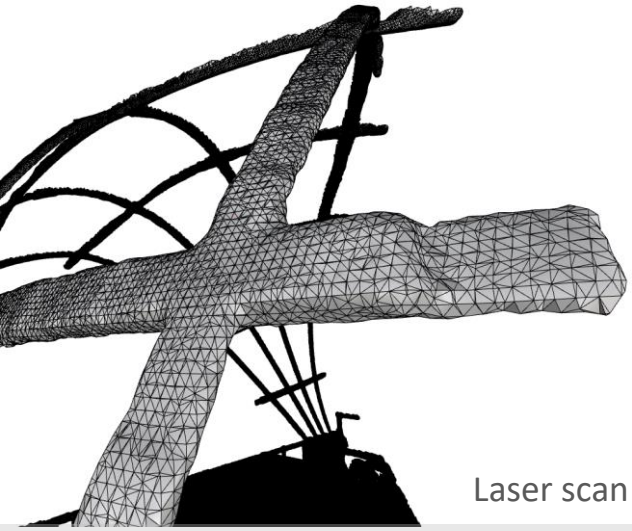
The final prototype

Overall accuracy –
a laser scanning attempt

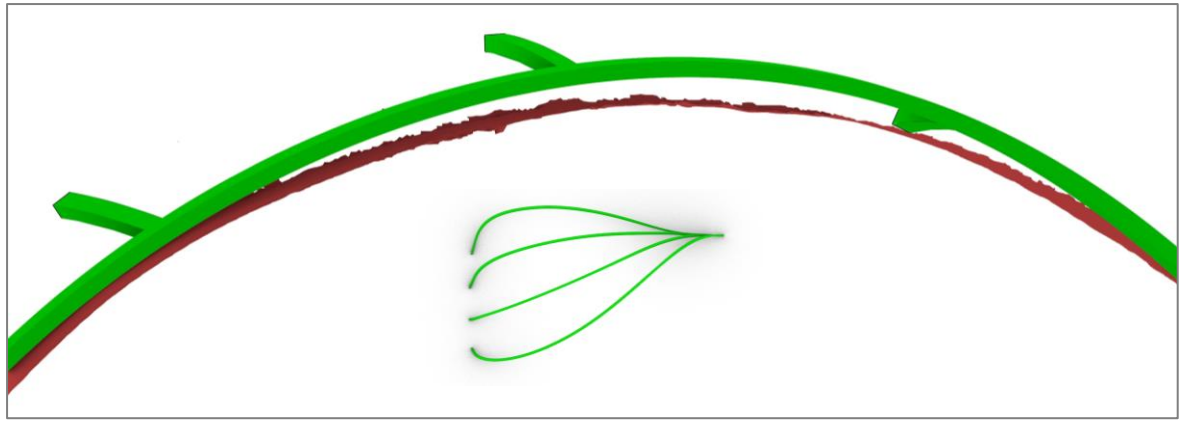




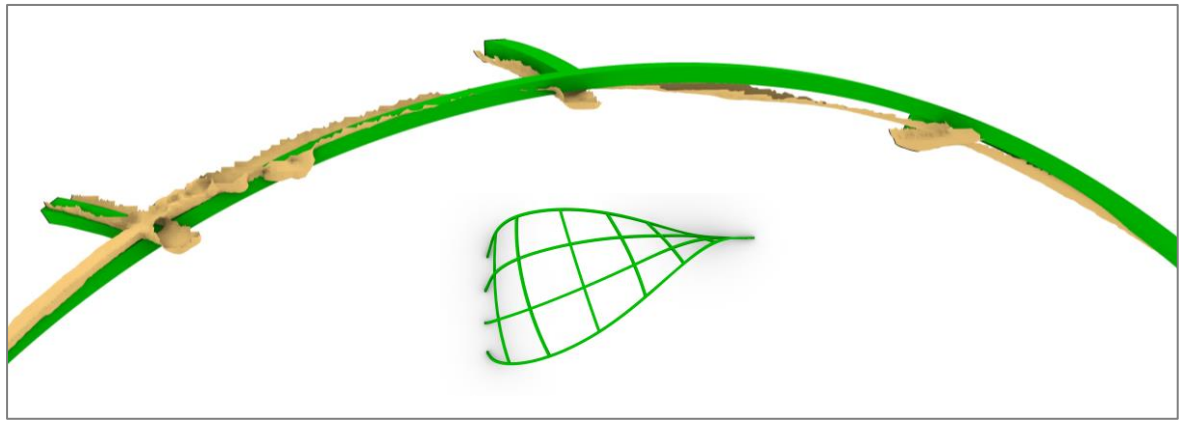
Scan 1 and 2



Laser scan

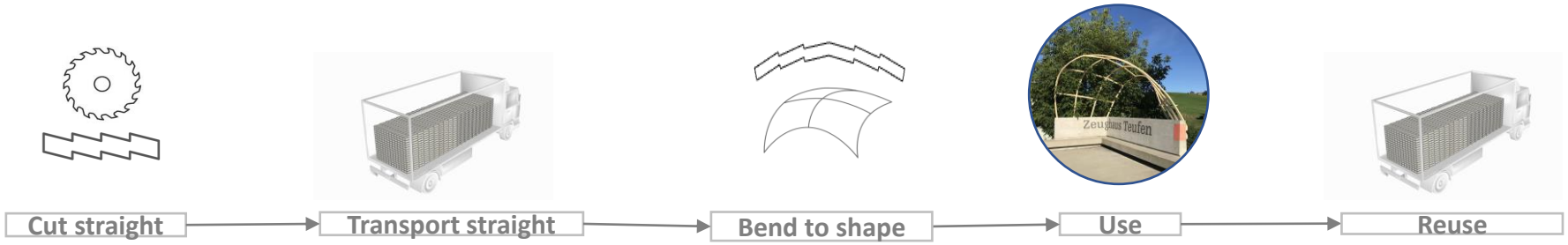


Laser scan 1: layer 1, longitudinal, max. deviation 14 cm



Laser scan 2: layer 1 longitudinal and layer 1 overcrossing, max. deviation 7 cm

- A working design to fabrication and assembly system for complex teeth beam structures



- An aesthetical value due to the use of solid lumber only…

…and due to the experience of forces due to the visibility of the teeth patterns

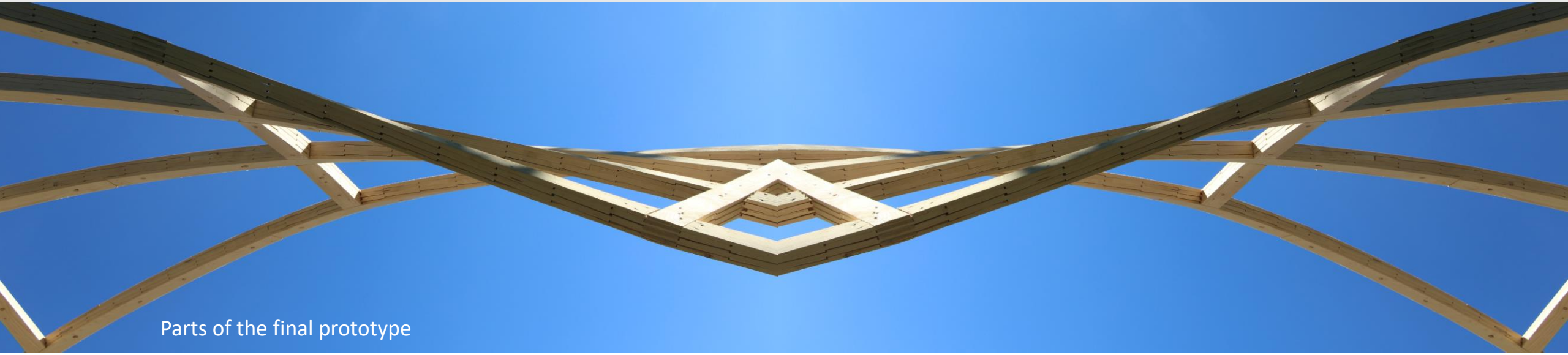
- ***A reduced and simplified production chain compared to glulam beams, feasible for every contemporary carpentry***

Glulam beams	Cut the three	Cut thin lamellas	Glue curved beams	Mill curved beams	Assembly
B - CTC	Cut the three	Cut medium lamellas	Mill flat lamellas	Assembly	

Parts of the final prototype

What could have worked better:

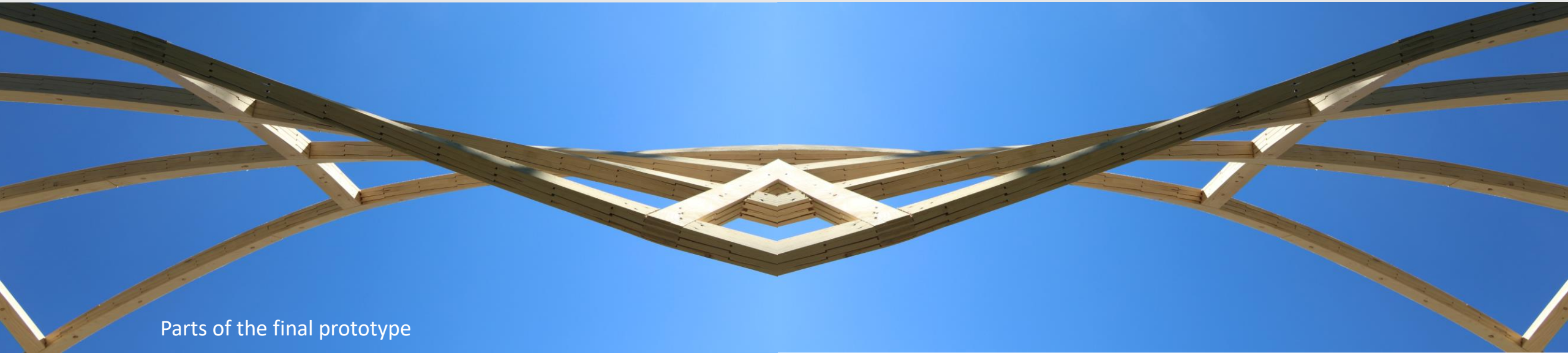
- Teeth accuracy
- Only wood connection with dowels



Parts of the final prototype

What would be interesting beyond:

- Conducting a detailed structural analysis
- Conducting breaking tests
- Comparing the structural performance of teeth beams to the structural performance glulam beams
- Developing b-CTC facade elements with natural materials



Parts of the final prototype

Within the next decade

- Application of b-CTC teeth beams in large-scale architectural projects

….In complex as well as in simpler shapes as an alternative for glulam beams

Thanks a lot to:

Adrian Scherrer from Treppenbau.ch AG for enabling the collaboration with Treppenbau.ch AG

Everybody from Treppenbau.CH AG for helping to make the final prototype pavilion possible

Pirmin Fischbacher from Innoholz for providing high quality swiss wood

Ulrich Vogt, **the curator of the Zeughaus Teufen** wood construction museum for enabling the prototype pavilion in front of the Zeughaus Teufen

The ITECH class 2019 for assisting through many discussions

Hans Jakob Wagner and Simon Bechert for guiding patiently this thesis

Katja Rinderspacher for organizing many ITECH and thesis issues

Professor Achim Menges and Professor Jan Knippers

for supervising my thesis

Image references:

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01 The Blue marble, Foto by NASA: taken on December 7, by the crew of the Apollo 17 spacecraft, 1972,https://upload.wikimedia.org/wikipedia/commons/4/43/The_Earth_seen_from_Apollo_17_with_transparent_background.png last visited on 07.10.2019 20:50h

02 As design alternative, The nine Bridges Country Club by Shigeru Ban and Blumer Lehman 2008, Image © Bluhmer Lehman Image from: https://www.lehmann-gruppe.ch/holzbau/referenz/haesley-nine-bridges-golf-resort.html last visited on 07.10.2019 20:50h

03 In contemporary carpentry, Krüsi CNC, Image © Krüsi Maschinenbau AG https://www.kruesi-ag.ch/ last visited on 18.10.2019 20:35h

04 The Blue marble, Foto by NASA: taken on December 7, by the crew of the Apollo 17 spacecraft, 1972,https://upload.wikimedia.org/wikipedia/commons/4/43/The_Earth_seen_from_Apollo_17_with_transparent_background.png last visited on 07.10.2019 20:50h

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08 Freeform Structure CLT, Elefantenhaus, Zürich 2014, Markus Schietsch Architekten, Image from Walt + Galmarini AG : https://momentum-magazin.de/de/elefantenhaus-zurich-erhalt-ingenieurbaupreis-2015/ last visited on 07.10.2019 20:50h

09 Glulam beam freeform structure, The nine Bridges Country Club by Shigeru Ban and Blumer Lehman 2008, Image © Bluhmer Lehman Image from: https://www.lehmann-gruppe.ch/holzbau/referenz/haesley-nine-bridges-golf-resort.html last visited on 07.10.2019 20:50h

10 In contemporary carpentry, Krüsi CNC, Image © Krüsi Maschinenbau AG https://www.kruesi-ag.ch/ last visited on 18.10.2019 20:35h

11 Glulam beam production at JPF Ducret wood construction entrepreneur, Image © JPF-DUCRET SA full link http://www.jpf-ducret.ch/de/brettschichtholz.html last visited on 07.10.2019 20:50h

12 Advanced carpentry equipped with a CNC Machine,Foto Miro Bannwart, 2019

13 Preformed hygroscopic building elements The Urbach Tower by ICD/ITKE, Foto © ICD/ITKE 2019, Institute for Computational Design and Construction, from https://icd.uni-stuttgart.de/?p=23336 last visited on 07.10.2019 20:50h

14 Construction from hygroscopic preformed elements, The Urbach Tower by ICD/ITKE, Foto © ICD/ITKE 2019, Institute for Computational Design and Construction, from https://icd.uni-stuttgart.de/?p=23336 last visited on 07.10.2019 20:50h

15 Complex construction from preformed glulam beams, Swatch center in Switzerland by Shigeru Ban and Blumer Lehmann, Image © Blumer Lehman AG, https://www.bauenmitholz.de/swatch-losgroesse-1/150/71582/ last visited on 18.10.2019. 20:52h

16 Grid shell construction, step 1: on site flat assembly, Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart. https://mai-nrw.de/vom-raumwunder-und-seinen-ingenieuren-die-multihalle-in-mannheim/#lightbox[group-57534]/0/ last visited on 18.10.2019. 20:54h

17 Grid shell construction, step 2: onsite forming process, , Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart. https://mai-nrw.de/vom-raumwunder-und-seinen-ingenieuren-die-multihalle-in-mannheim/ last visited on 18.10.2019. 20:55h

18 Complex construction from preformed glulam beams, Swatch center in Switzerland by Shigeru Ban and Blumer Lehmann, Image © Blumer Lehman AG, https://www.bauenmitholz.de/swatch-losgroesse-1/150/71582/ last visited on 18.10.2019. 20:52h

19 Grid shell construction, onsite forming process, , Foto: Archiv Institut für Leichte Flächentragwerk, Stuttgart. https://mai-nrw.de/vom-raumwunder-und-seinen-ingenieuren-die-multihalle-in-mannheim/ last visited on 18.10.2019. 20:55h

Image references:

20 Wintersey teeth beam woodbridge Switzerland Hasle Rüegsau 1839, Photo Miro Bannwart 2019
21 Interlocked teeth beams, Teeth-beam Woodbridge Switzerland 1839, Foto Miro Bannwart 2019
22 Multihalle, Mannheim 1974/ 75 Frei Otto, Foto by Verein Multihalle Mannheim, Daniel Lukac, https://www.visit-mannheim.de/Media/attraktionen/multihalle-mannheim last visited on 07.10.2019 20:50h
23 Graphics Miro Bannwart 2019
24 ZipShape chair by Christoph Schnindler in 2008, Image © Schindlersalmerón https://www.schindlersalmeron.com/workshops/zipshape last visited on 08.10.2019 20:49h
25 ZipShape principle, Graphic by © Marcel Abegglen, 2014
26 Self-organized doubly curved gridshell by gravitational loads, Image from the publication: Baseta, E., 2019,Novel bending-active system with controllable curvature-stiffness relation, ISSN 2309-0103 p.7
27 Cantilevering double layered linear element with shear blocks, Image from the publication: Baseta, E., 2019, Novel bending-active system with controllable curvature-stiffness relation, ISSN 2309-0103 p.6
28 Spruce forest straight grown wood, Image © Urs Schäfer 2013 Image © Urs Schäfer 2013: https://www.bielertagblatt.ch/mein-beitrag/fotowettbewerb/letzte-sonnenstrahlen-im-tannenwaldlast visited on 07.10.2019 20:50h
29 Zeughaus Teufen, Image © GIAN SALIS ARCHITEKT 2008 https://www.giansalis.ch/ZHT.html last visited on 07.10.2019 20:50
30 Treppenbau.ch AG CNC - wood stairs manufacturer, Photo Miro Bannwart 2019
31 5-Axis CNC, graphic received from © Reichenbacher
32 Faro laser scanner, Photo © Faro https://www.faro.com/de-de/produkte/bausektor-bim-cim/faro-focus/ last visited on 18.10.2019. 21:08

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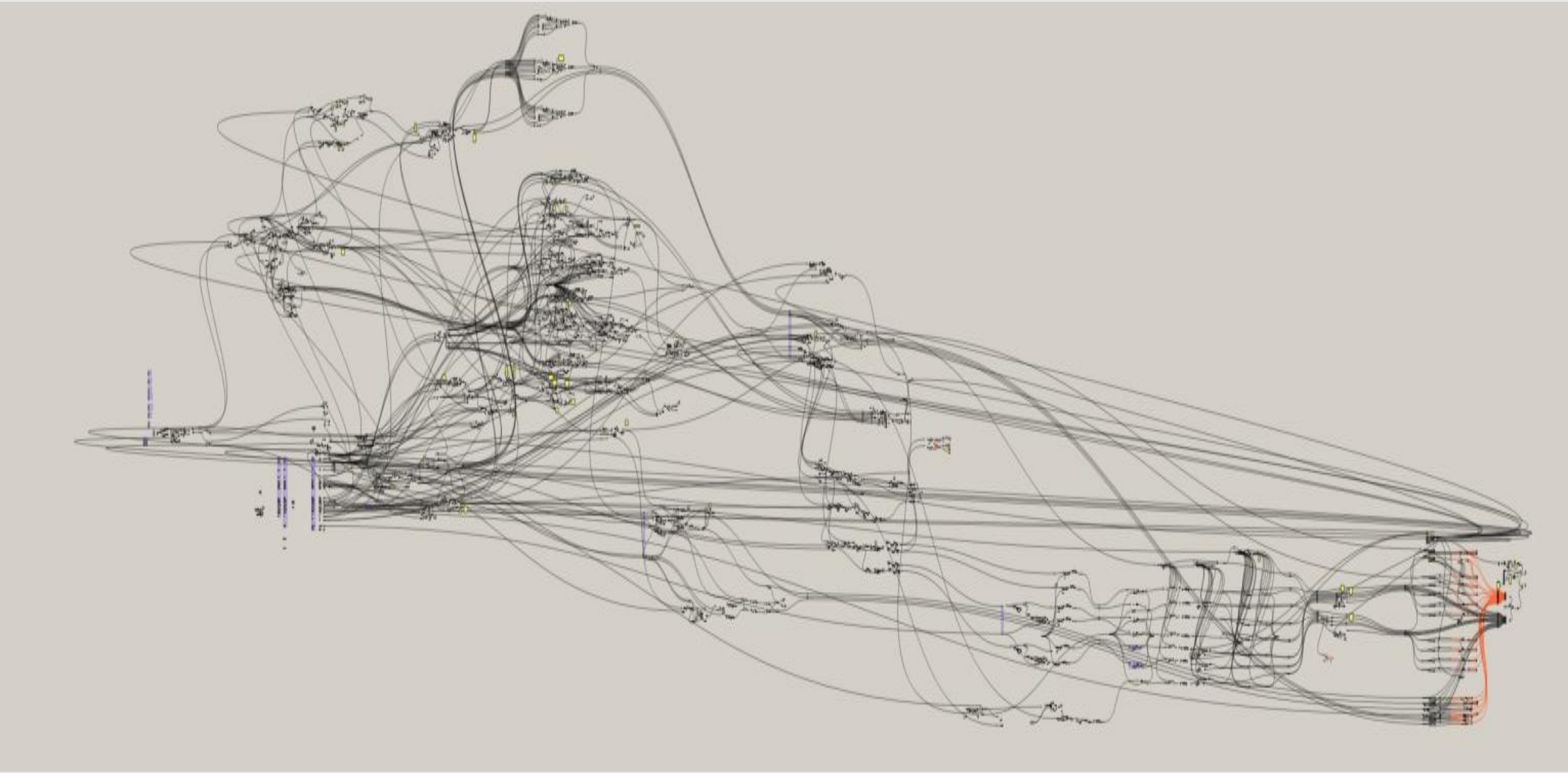
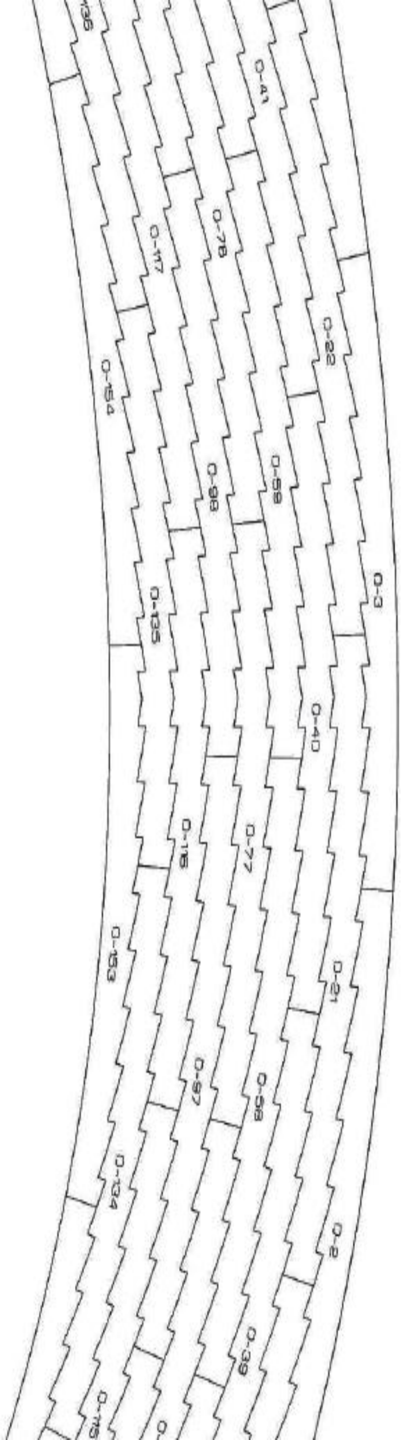
Thanks a lot

for your attention



Wintersey Zahnträger Holzbrücke in Hasle Rüegsau, Kanton Bern, 1839

Zahnträger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