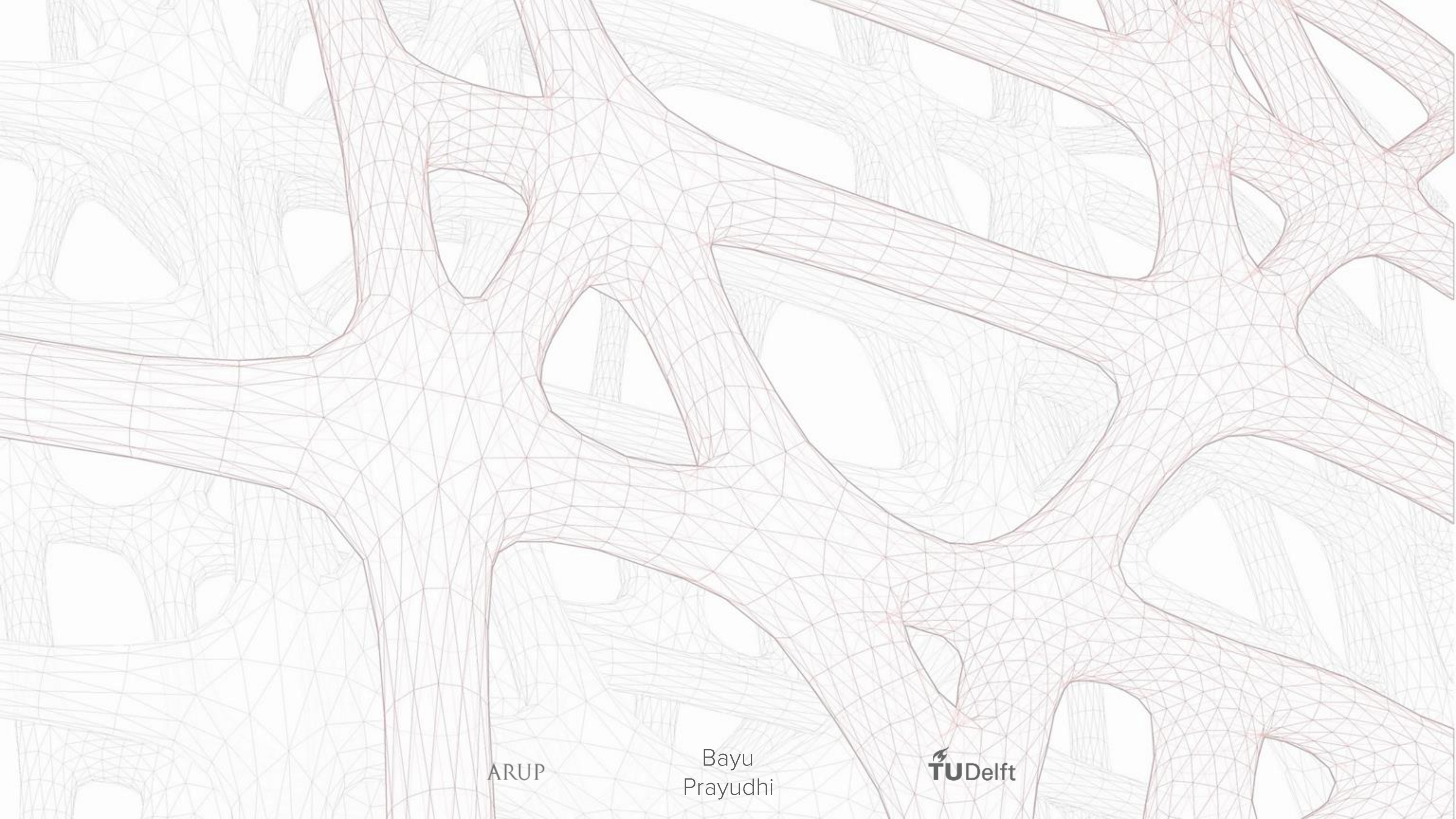
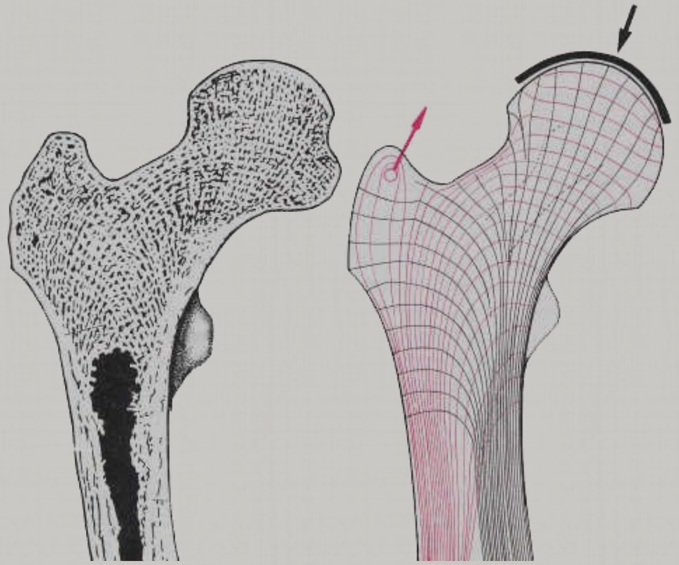


ARUP

Bayu
Prayudhi

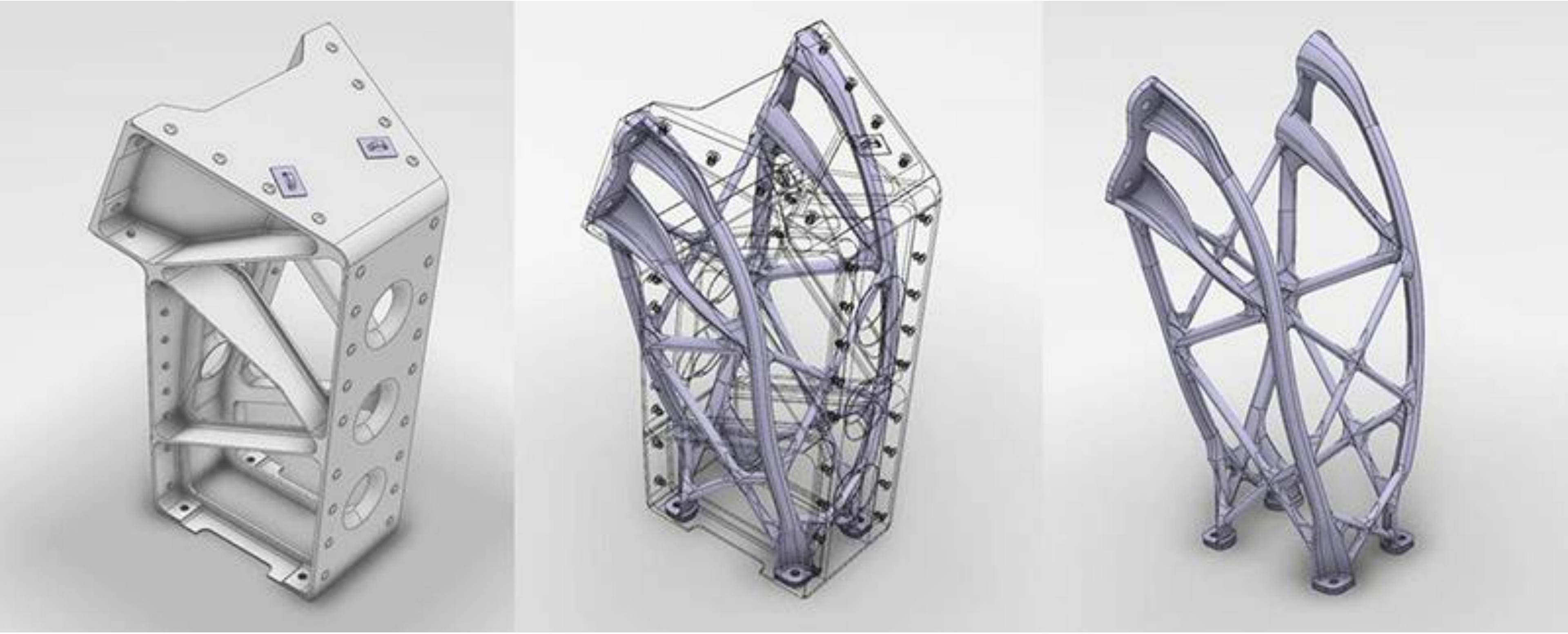
TU Delft



Wolff's law
Pawlyn, M. (2011)


steelfromchina.com

The optimization of material usage plays a necessary role in nature; the principle is **'materials are expensive and shape is cheap'** as opposed to current technology in our manufacturing industry, the opposite tend to be the case (Pawlyn, 2011).



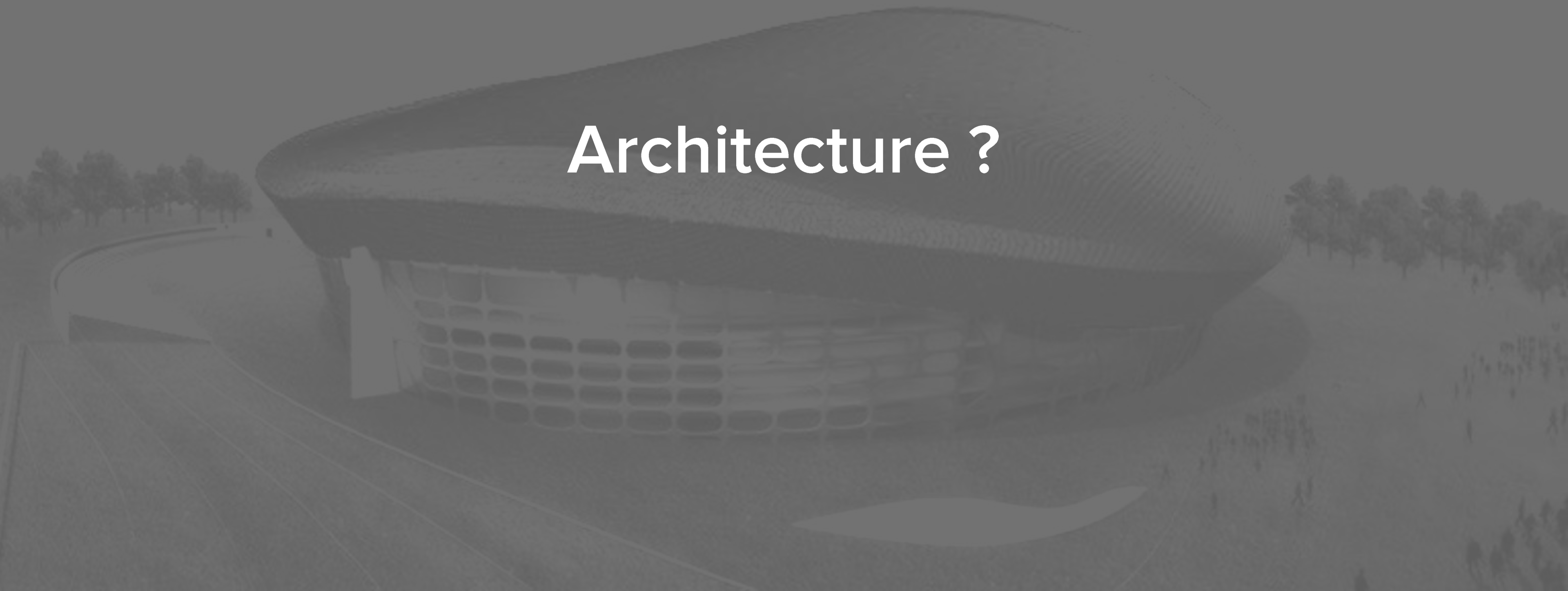
airbusdefenceandspace.com

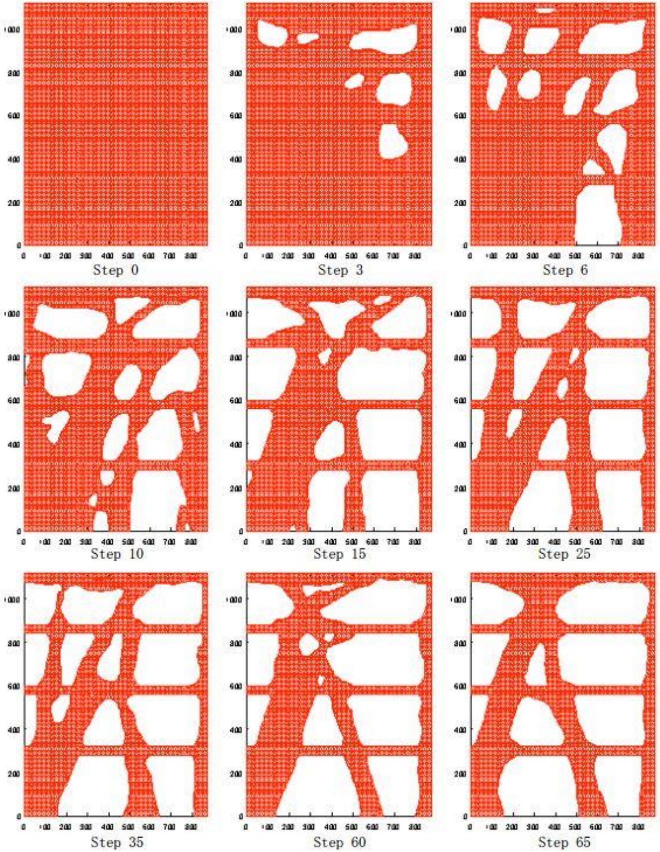
Jet Engine Bracket From Indonesia Wins 3D Printing Challenge

Dec 11, 2013 by Tomas Kellner

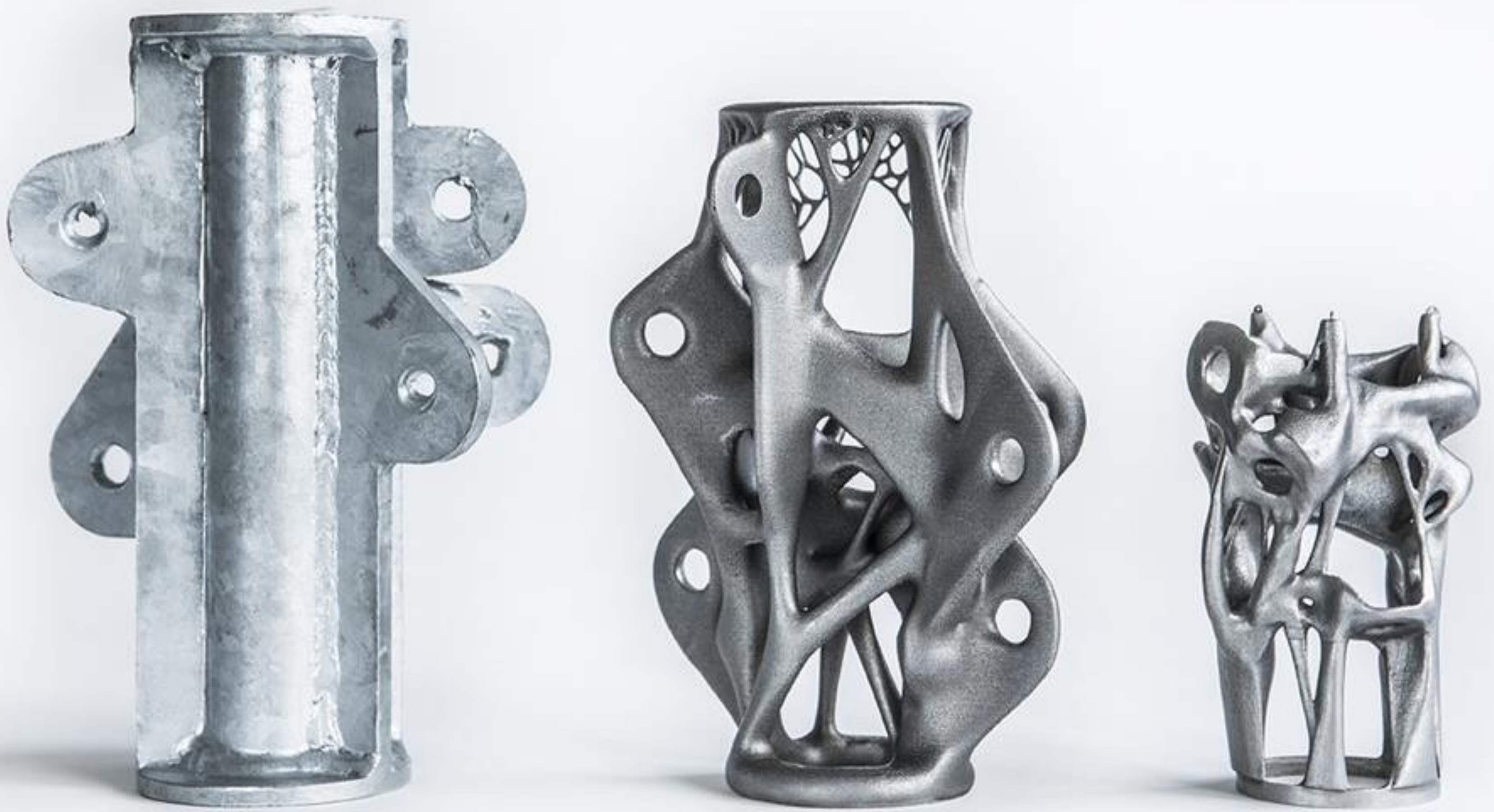
gereports.com

Architecture ?





Vlastic (2011) - evolo.us
Ohmori (2008)



arup.com


3F3D
FORM FOLLOWS FORCE
with 3D PRINTING

TOPOLOGY OPTIMIZATION FOR FREEFORM ENVELOPE DESIGN WITH ADDITIVE MANUFACTURING


TOPOLOGY OPTIMIZATION FOR FREEFORM ENVELOPE
DESIGN WITH ADDITIVE MANUFACTURING

design tool

TOPOLOGY OPTIMIZATION

fabrication method

ADDITIVE MANUFACTURING

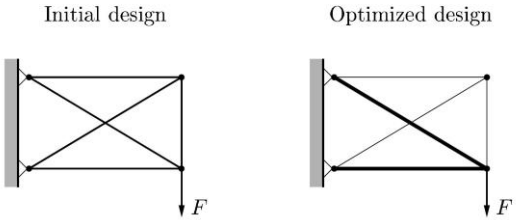
case study

FREEFORM ENVELOPE

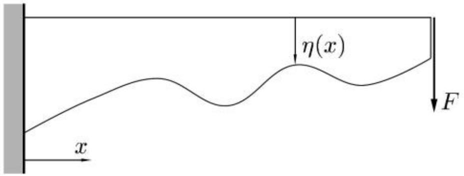
TOPOLOGY OPTIMIZATION

ADDITIVE MANUFACTURING

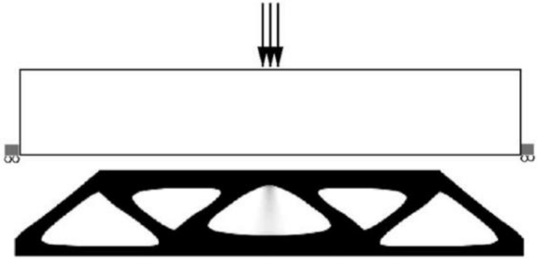
FREEFORM ENVELOPE



sizing optimization

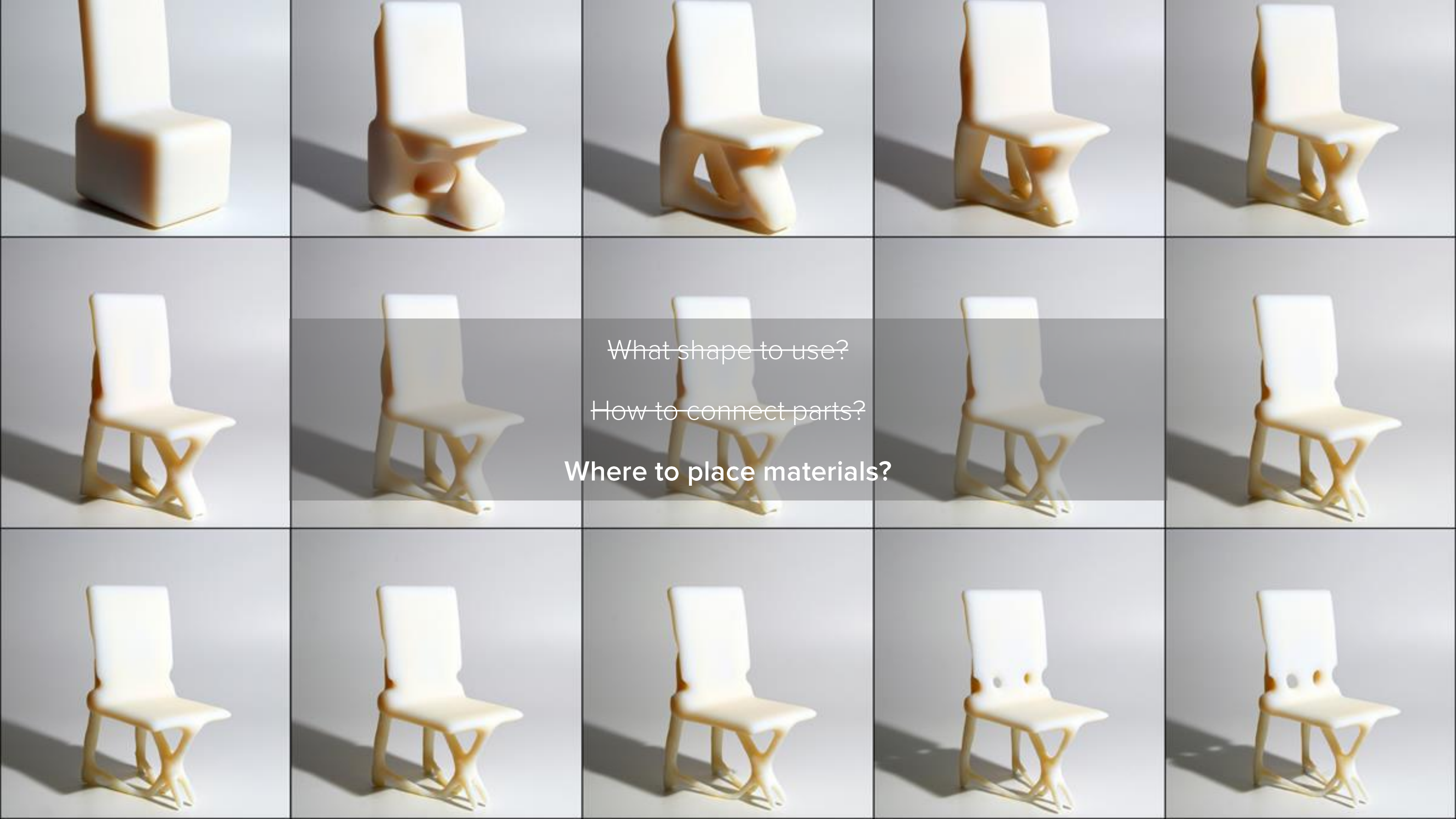


shape optimization



topology optimization

(Christensen & Klarbring, 2009)


~~What shape to use?~~
~~How to connect parts?~~
Where to place materials?

TO basic principle:

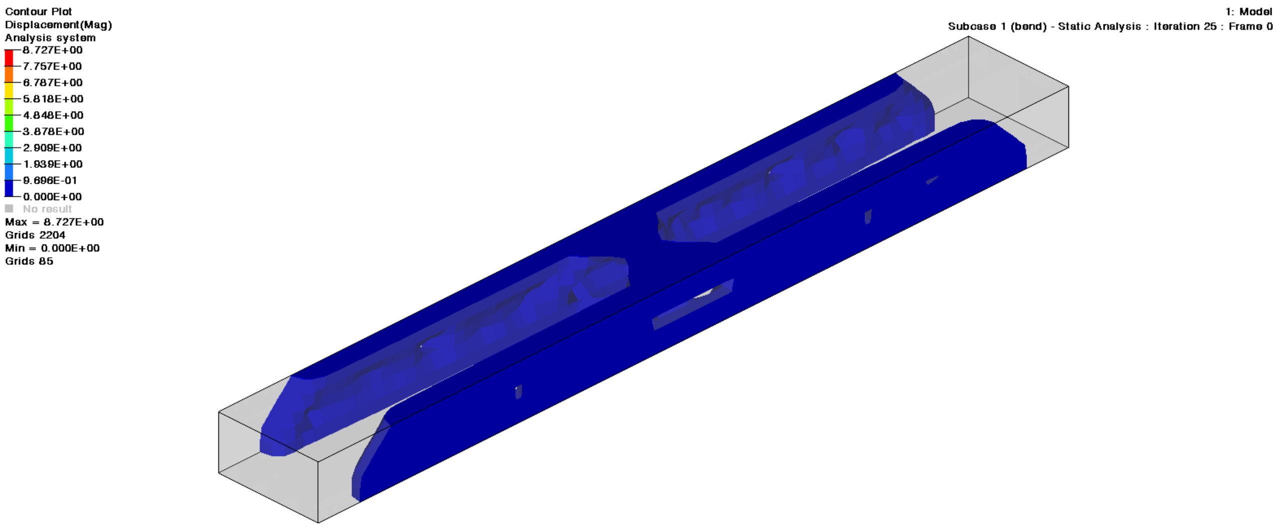
1. Define problem:

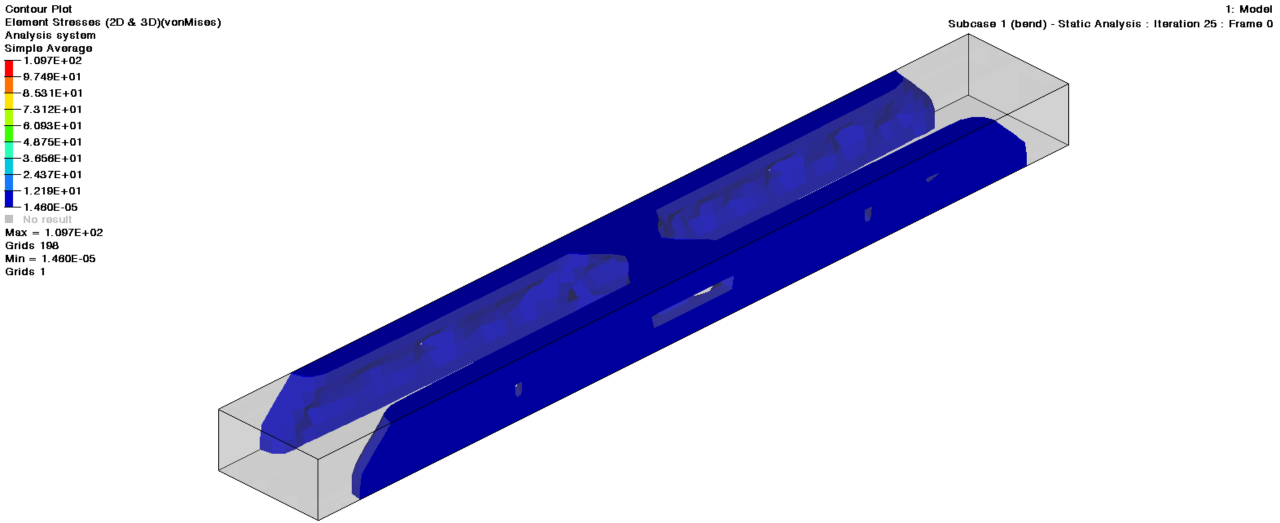
- Objective? Constraints?
- Domain? Boundary conditions?
- Loadcases?

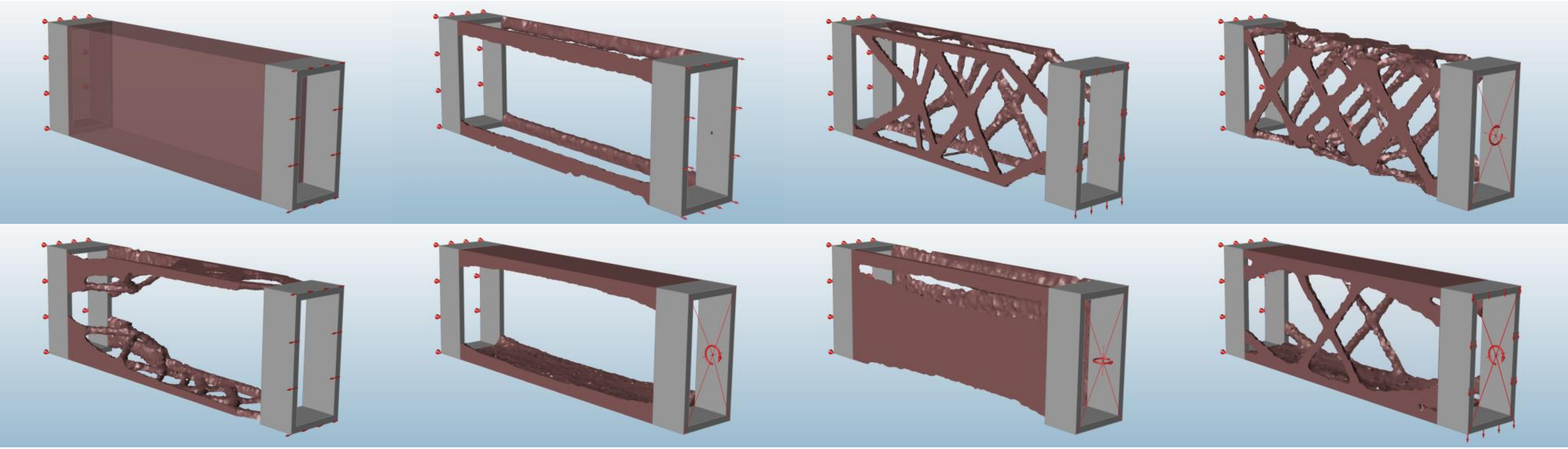
2. Discretize and parameterize material distribution

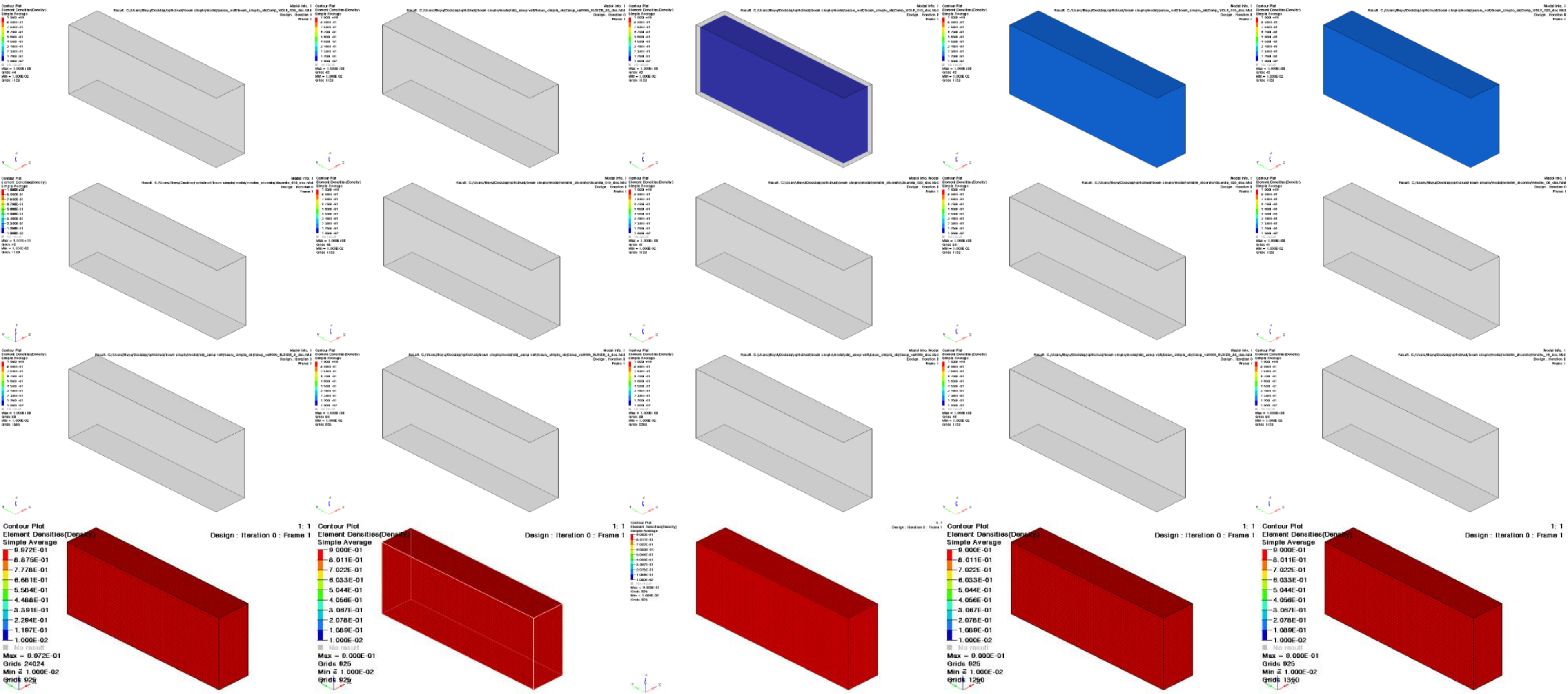
3. Optimize material distribution for best performance

4. Evaluate / fine-tune result (post-processing, shape optimization)





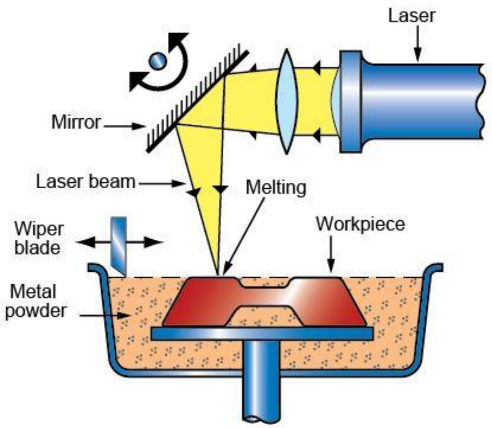



Contour Plot
Simple Average
Design : Iteration 0 : Frame 1
9.972E-01
8.875E-01
7.778E-01
6.681E-01
5.584E-01
4.488E-01
3.391E-01
2.294E-01
1.197E-01
1.000E-02
No result
Max = 9.972E-01
Grids 24024
Min = 1.000E-02
Contour Plot
Simple Average
Design : Iteration 0 : Frame 1
9.000E-01
8.011E-01
7.022E-01
6.033E-01
5.044E-01
4.056E-01
3.067E-01
2.078E-01
1.089E-01
1.000E-02
No result
Max = 9.000E-01
Grids 925
Min = 1.000E-02
Contour Plot
Simple Average
Design : Iteration 0 : Frame 1
9.000E-01
8.011E-01
7.022E-01
6.033E-01
5.044E-01
4.056E-01
3.067E-01
2.078E-01
1.089E-01
1.000E-02
No result
Max = 9.000E-01
Grids 925
Min = 1.000E-02
Contour Plot
Simple Average
Design : Iteration 0 : Frame 1
9.000E-01
8.011E-01
7.022E-01
6.033E-01
5.044E-01
4.056E-01
3.067E-01
2.078E-01
1.089E-01
1.000E-02
No result
Max = 9.000E-01
Grids 925
Min = 1.000E-02

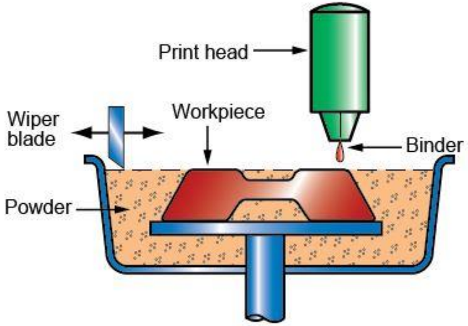
TOPOLOGY OPTIMIZATION

ADDITIVE MANUFACTURING

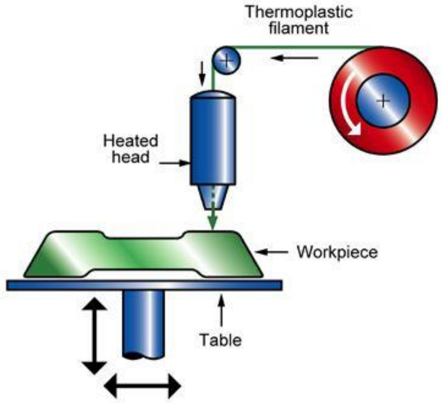
FREEFORM ENVELOPE



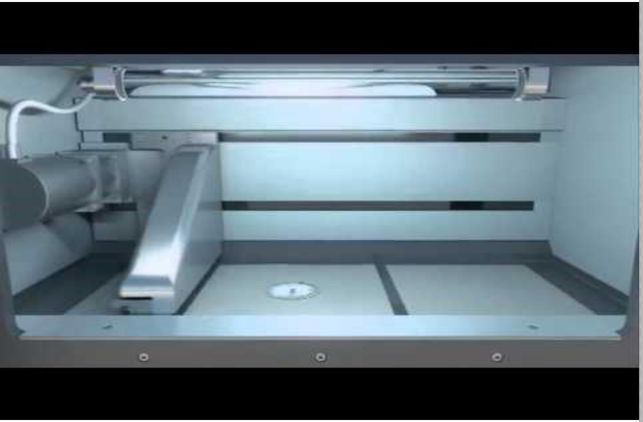
Direct metal laser sintering



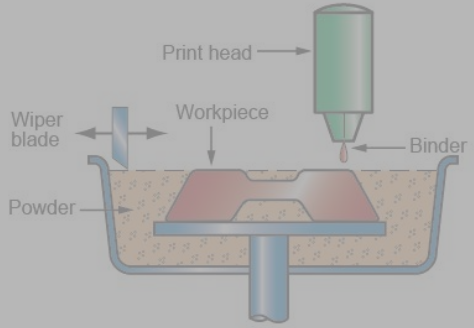
Binder jetting process



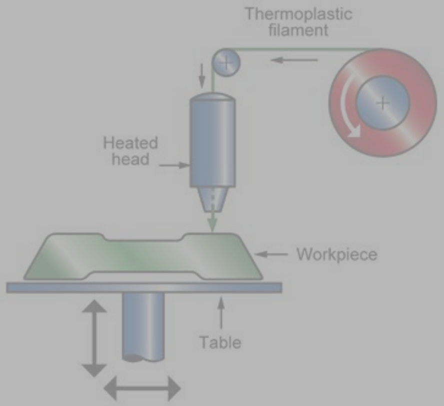
Fused deposition modeling



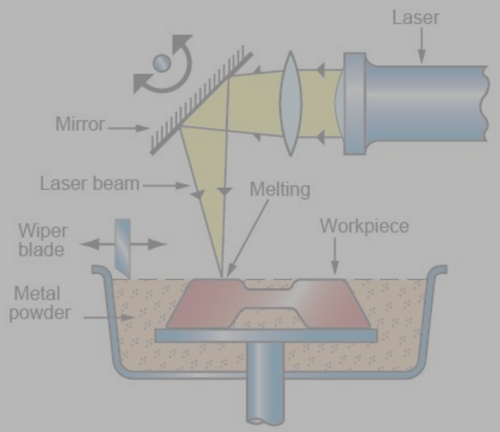
Direct metal laser sintering



Binder jetting process

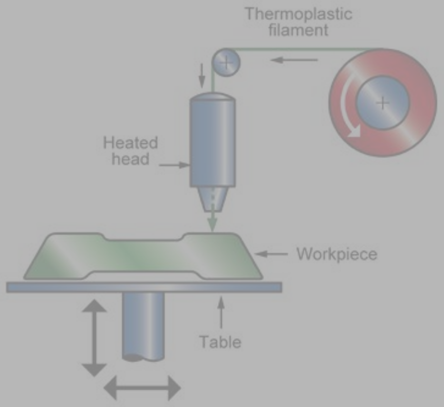


Fused deposition modeling

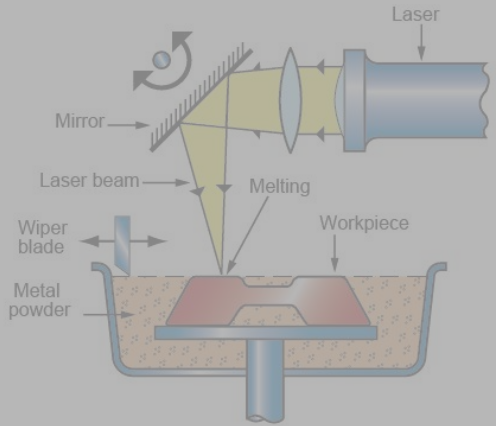


Direct metal laser sintering

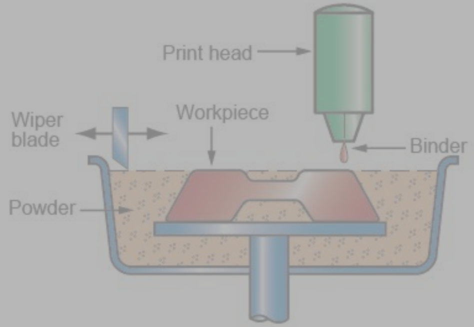
Binder jetting process



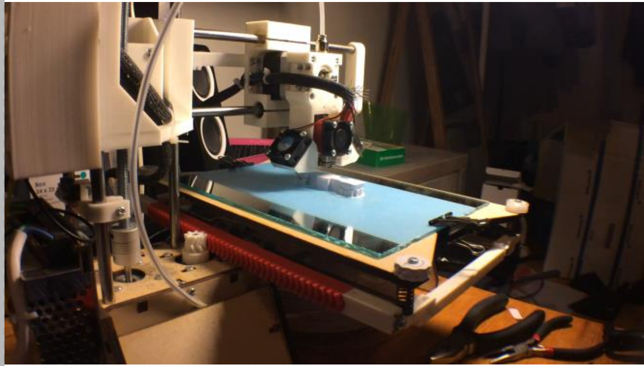
Fused deposition modeling



Direct metal laser sintering

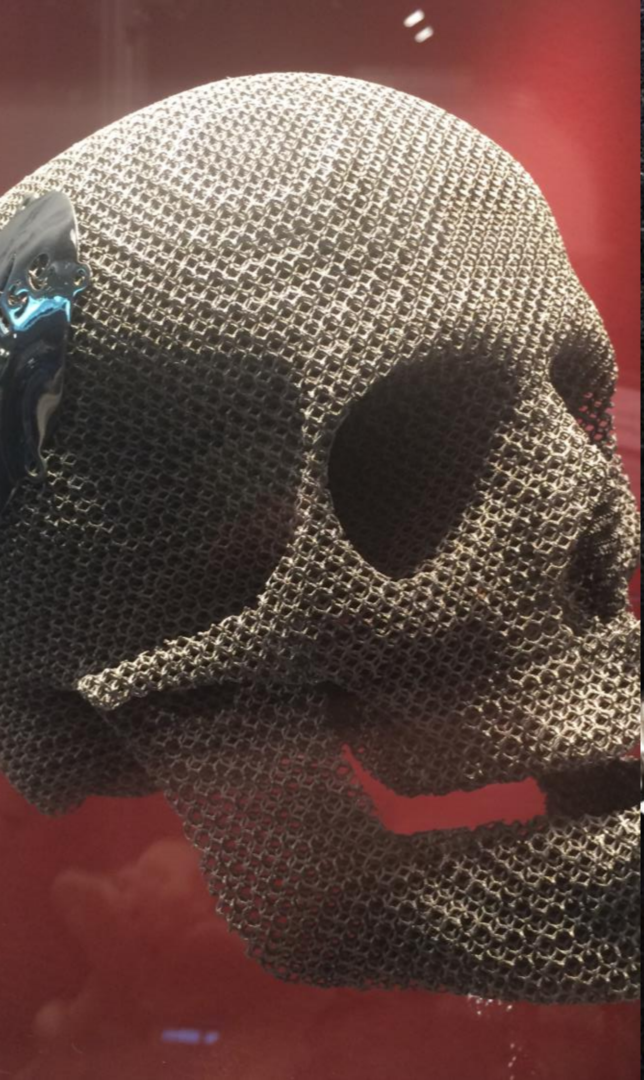


Binder jetting process

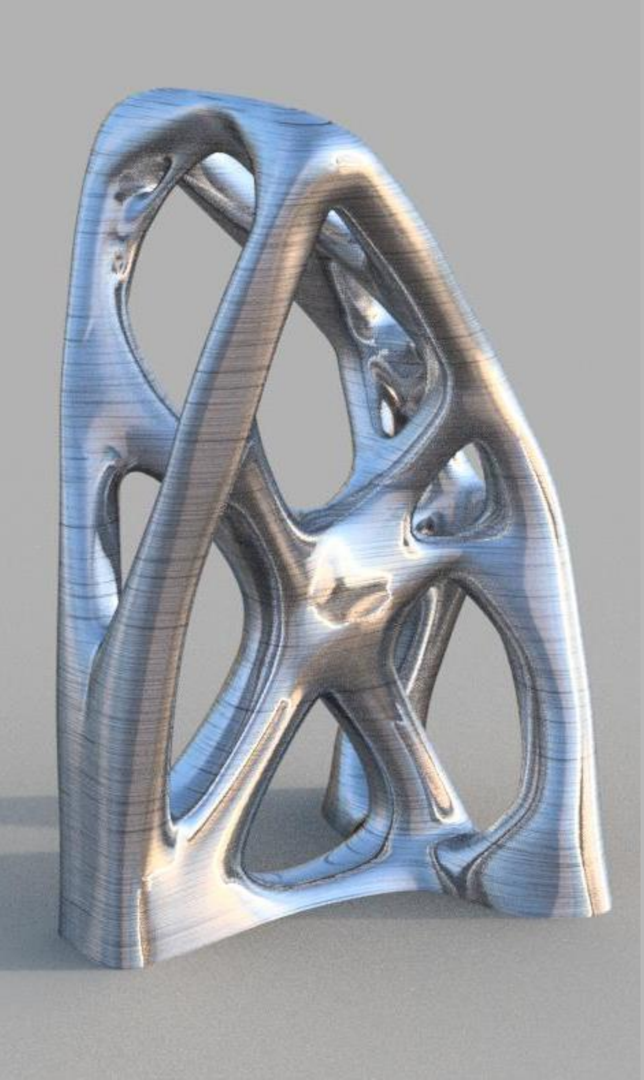


Fused deposition modeling

Metal Additive Manufacturing

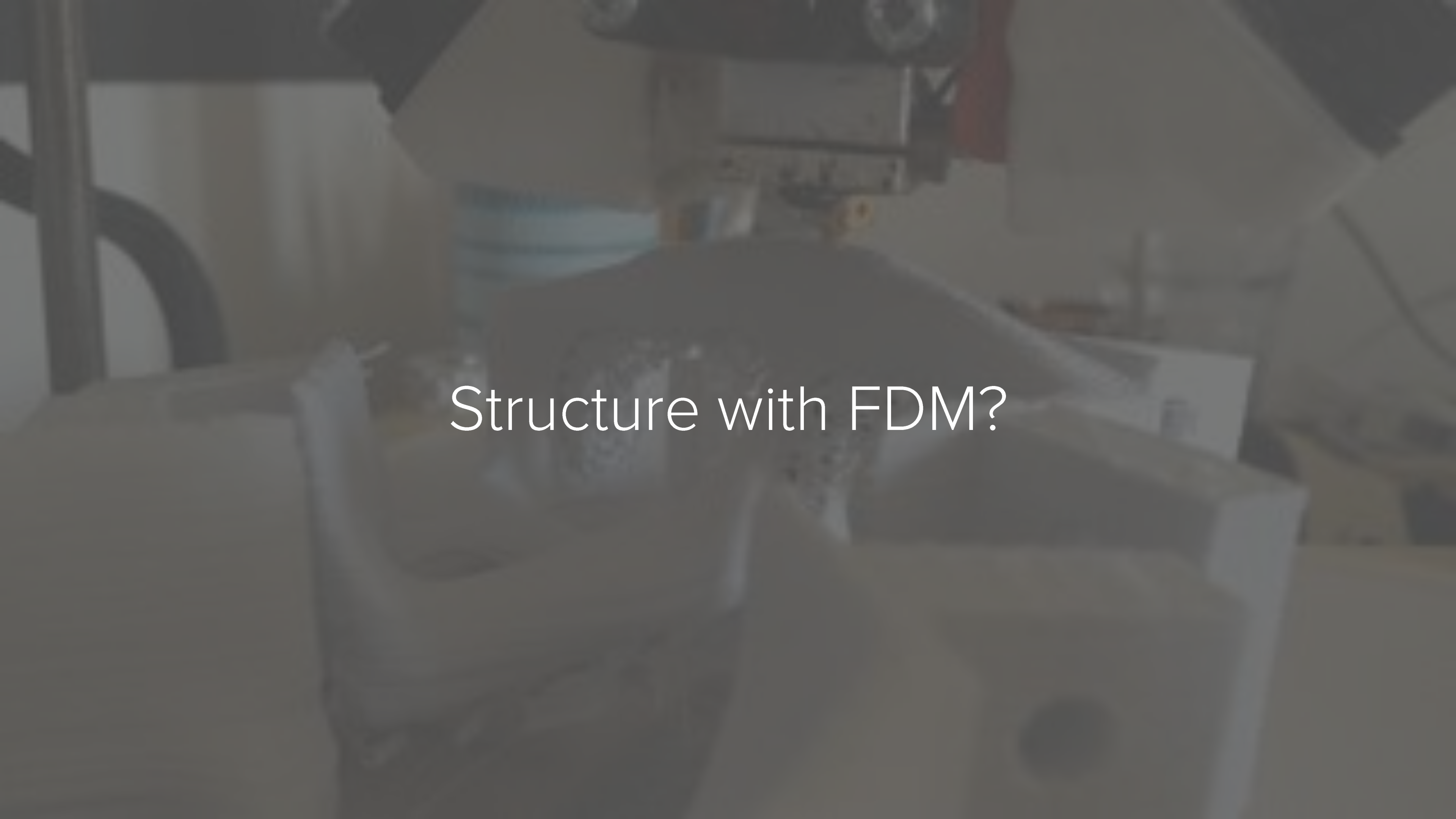


3dsystem ProX400
Build chamber 500x500x500
Resolution range : 10 µm – 100 µm



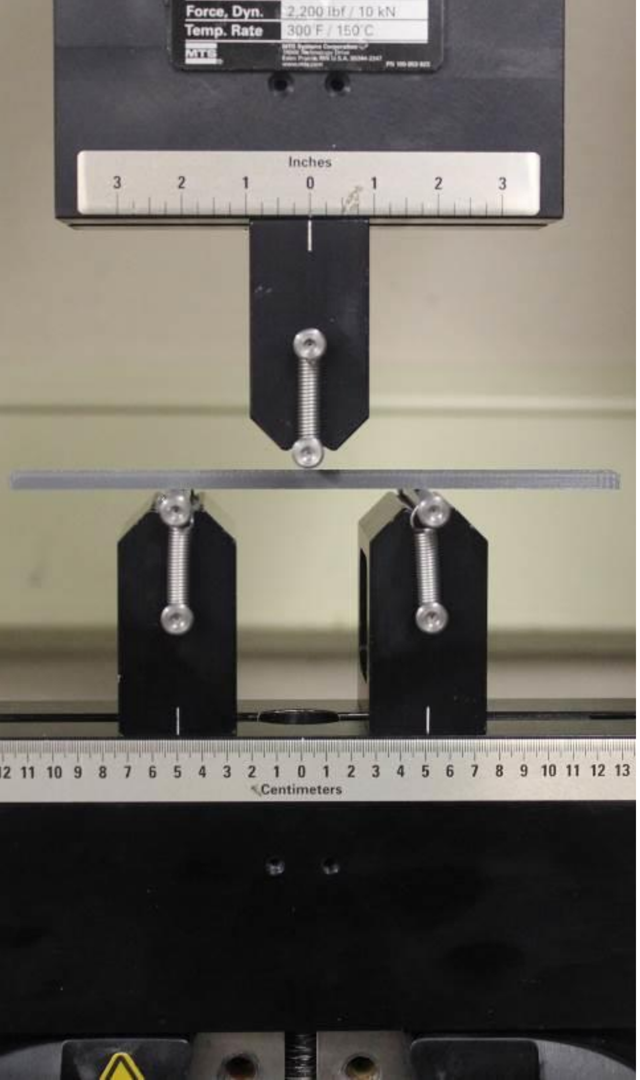
	Company	Country	Material	Ultimate Tensile Strength (MPa)	Price (EUR)
Binder jetting	Shapeways	NL	Stainless Steel 420 60% + Bronze 40%	682	229
	i.materialise	BE	Stainless Steel 420 60% + Bronze 40%	682	216
	ExOne	GER	Stainless Steel 420 60% + Bronze 40%	682	125
Direct Laser Melting	RapidObject	GER	Tool steel 1.2709	1100	757
	Stratasys	US	Stainless Steel 17-4 PH	980	1236
	Fit-Prototyping	GER	Stainless Steel 17-4 PH	980	930
	RapidObject	GER	Stainless steel 1.4542	930	924
	Stratasys	US	Stainless Steel 316L	675	1172
	Protolabs	UK	Stainless Steel 316L	675	1101
	Star-Prototype	CHN	Stainless Steel 316L	675	642
	Stratasys	US	Aluminum AlSi10Mg	400	1347
	Star-Prototype	CHN	Aluminum AlSi10Mg	400	1120
	Protolabs	UK	Aluminum AlSi10Mg	400	1044
	RapidObject	GER	Aluminum AlSi10Mg	400	428
	Fit-Prototyping	GER	Aluminum AlSi10Mg	400	350

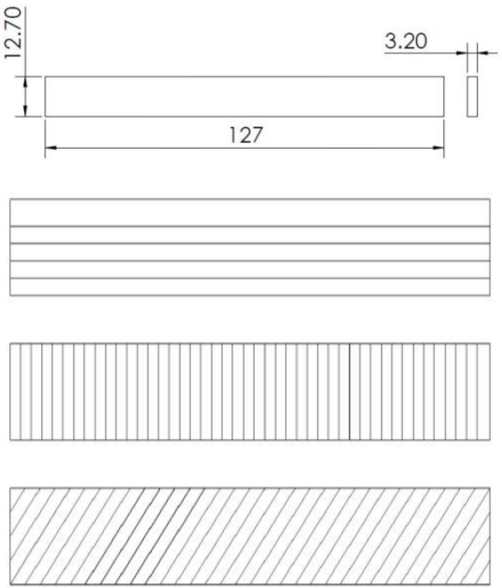
Structure with FDM?



Company	Country	Material	Ultimate Tensile Strength (MPa)
Markforged	US	Nylon + continuous carbon fibre	700
Arevolabs	US	PEEK (Polyetheretherketone) + milled carbon fibre	145
Indmatec	GER	PEEK (Polyetheretherketone)	98
Stratasys	GER	PEI (Polyetherimide)	81
Colorfabb	NL	Co-polyester + milled carbon fibre	76

Colorfabb.com





Raster Orientation (degrees)	Actual Width (mm)	Actual Thickness (mm)	Ultimate Stress (MPa)	Ultimate Strain (%)	Flexural Modulus (GPa)
0	12.63	3.34	99.34	6.64%	3.13
0	13.08	3.19	103.77	9.19%	3.17
0	13.08	3.09	100.90	13.29%	3.18
0	12.75	3.15	107.14	12.16%	3.48
0	12.76	3.23	99.87	11.82%	2.98
45	12.83	3.37	92.77	7.17%	2.98
45	12.69	3.36	92.29	7.48%	3.21
45	12.76	3.44	88.23	8.15%	2.93
45	13.10	3.34	89.43	8.81%	3.02
45	12.75	3.39	90.53	7.59%	2.78
90	12.74	3.38	85.77	4.73%	3.01
90	12.72	3.40	85.48	4.73%	2.88
90	12.77	3.33	87.32	4.75%	3.05
90	12.76	3.31	86.52	4.01%	3.00
90	12.67	3.37	85.59	4.30%	3.05

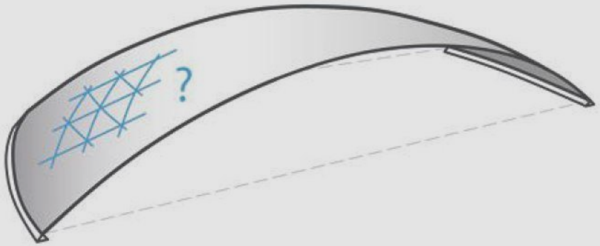
Raster Orientation (degrees)	Ultimate Stress (MPa)	Ultimate Strain (%)	Flexural Modulus of Elasticity (GPa)
0	102.203	0.106	3.187
45	90.649	0.078	2.985
90	86.136	0.045	3.000

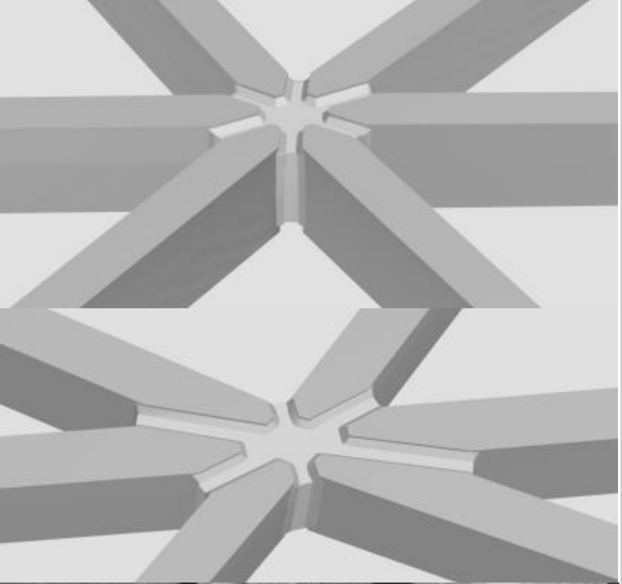
Letcher (2014)

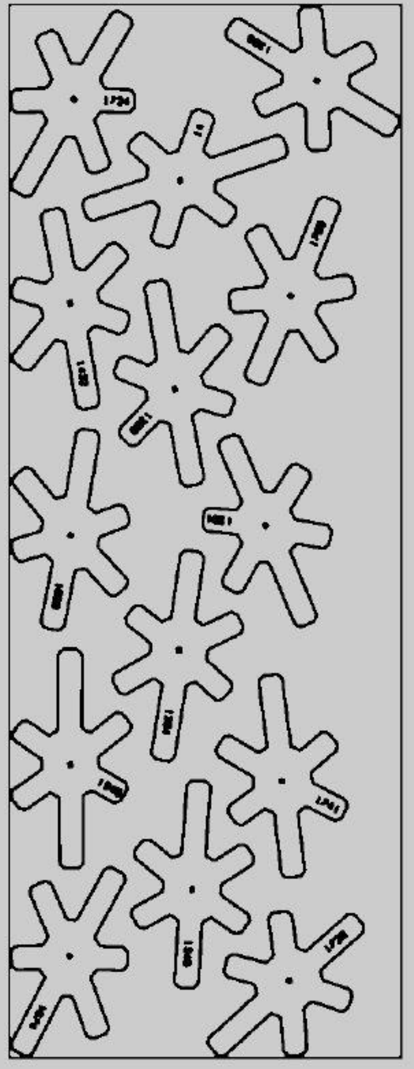
TOPOLOGY OPTIMIZATION

ADDITIVE MANUFACTURING

FREEFORM ENVELOPE







Sischka (2001)

Although triangulated surfaces can describe any freeform shape, employed in construction they are **economically less advantageous** than equivalent surface structures built of quadrilateral (four-sided) facets: Quadrangular mesh constructions require fewer machining operations on the glass, and fewer mullions (as they eliminate the diagonal mullion from one side of the triangle). (Schober, 2002)

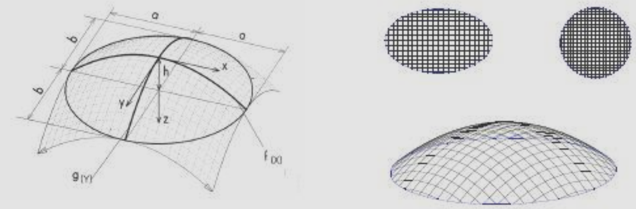


Figure 8. Translational surface covering an elliptical (top left) or circular plan

Figure 9. Joining of translational surfaces

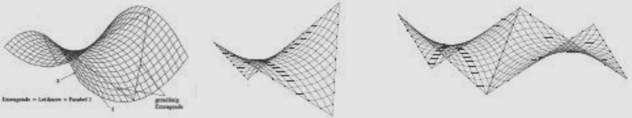


Figure 10. Hyperbolic paraboloid as translational surface (left) and joining possibilities (right)

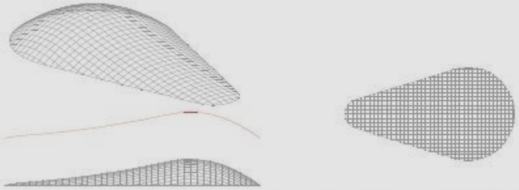
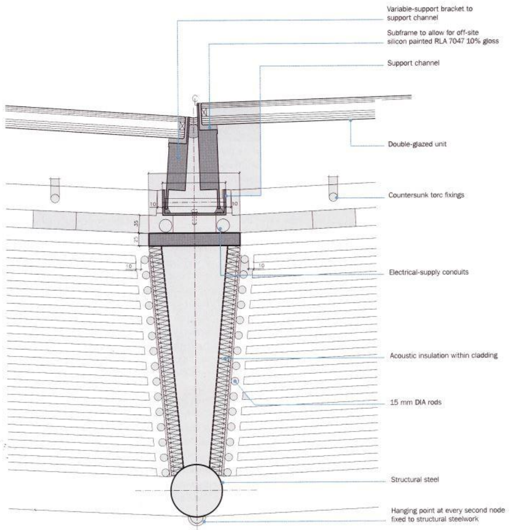
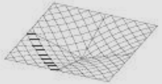


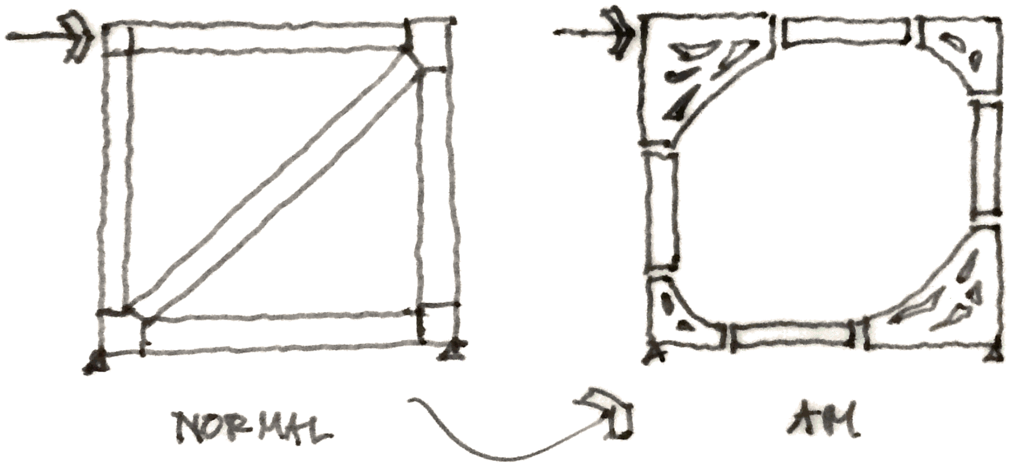
Figure 11. Translation surface covering two semi-circular plans connected with tangential edges.

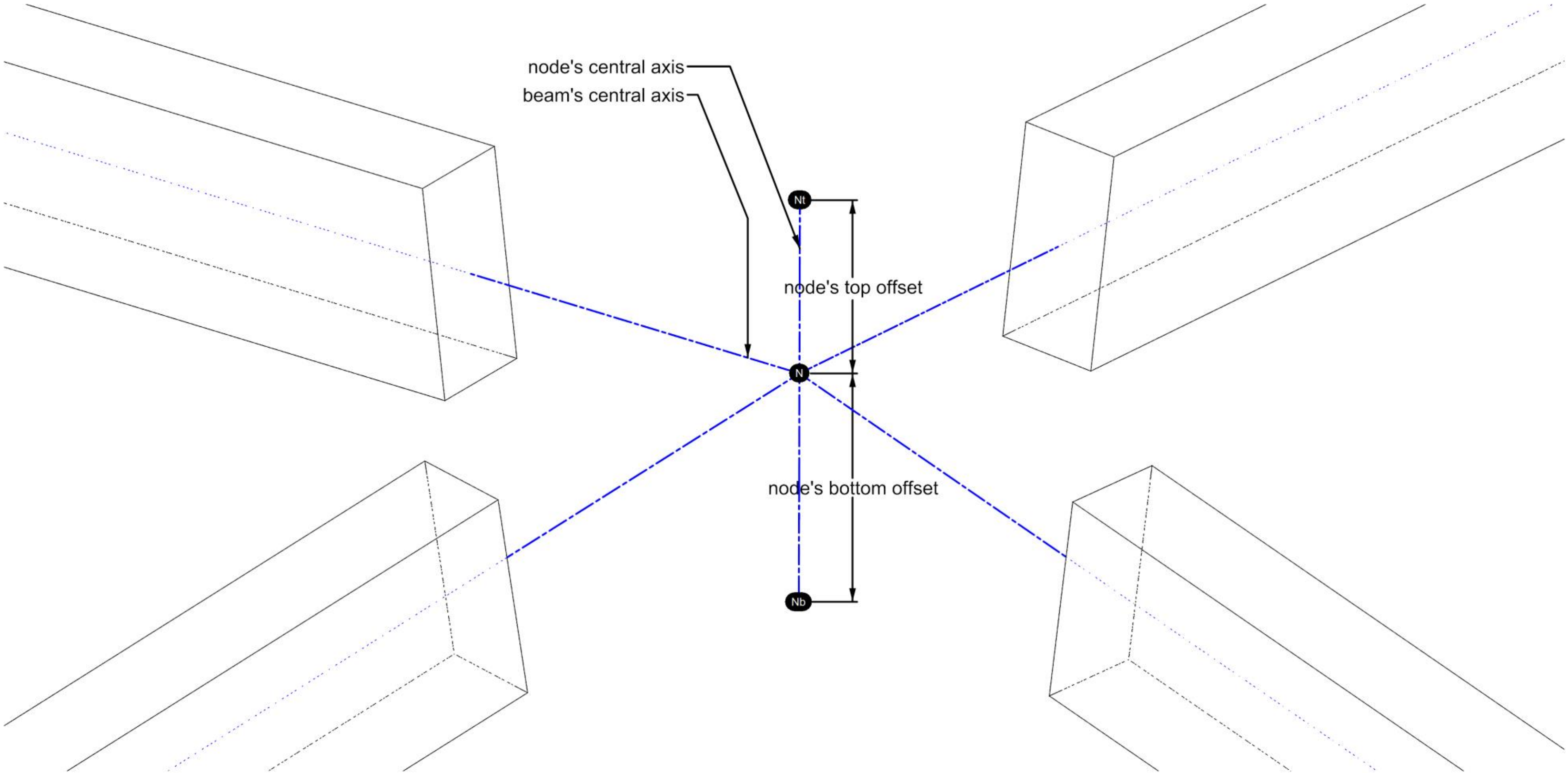




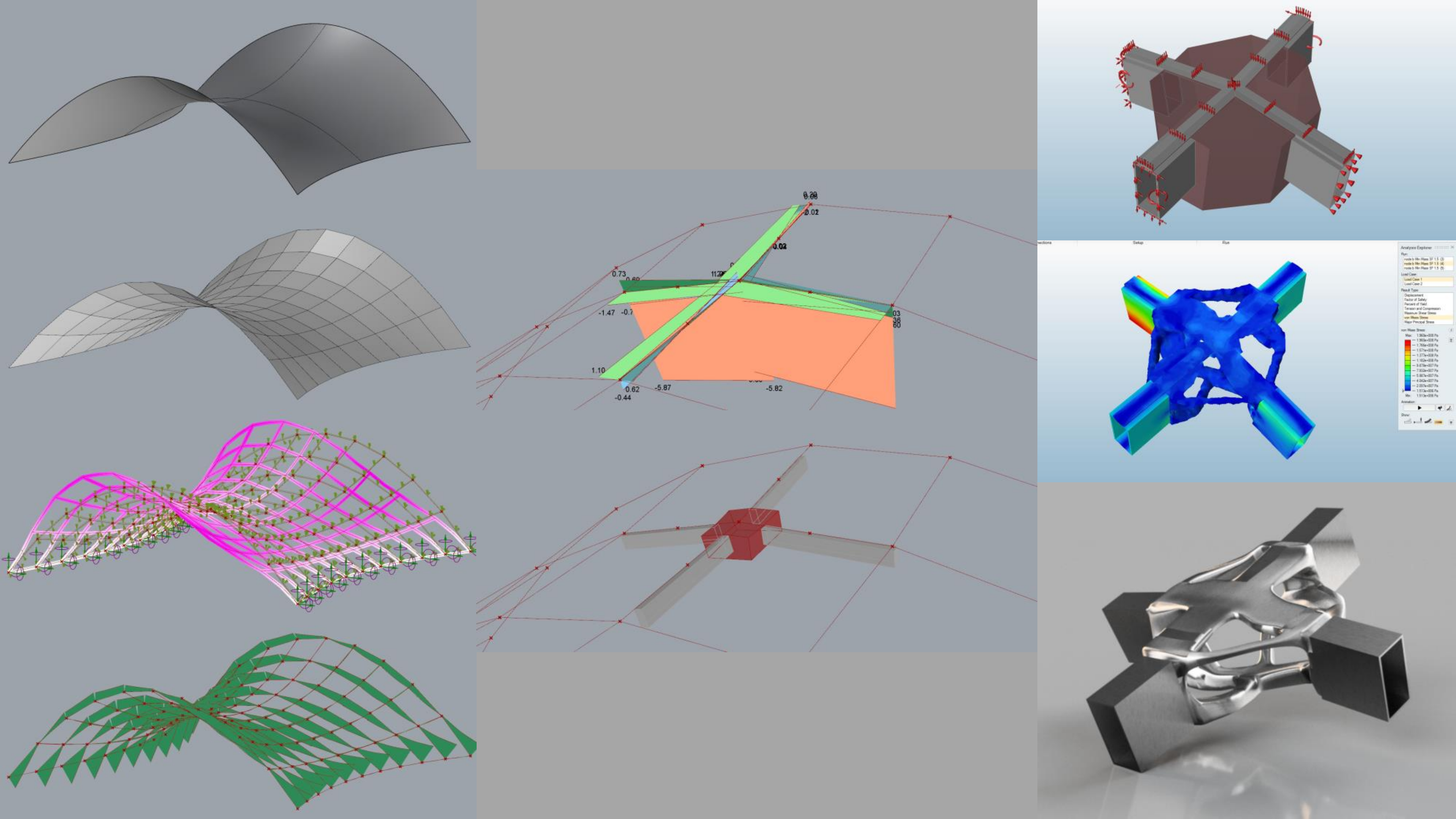
Schober (2005)
Fosterandpartner.com

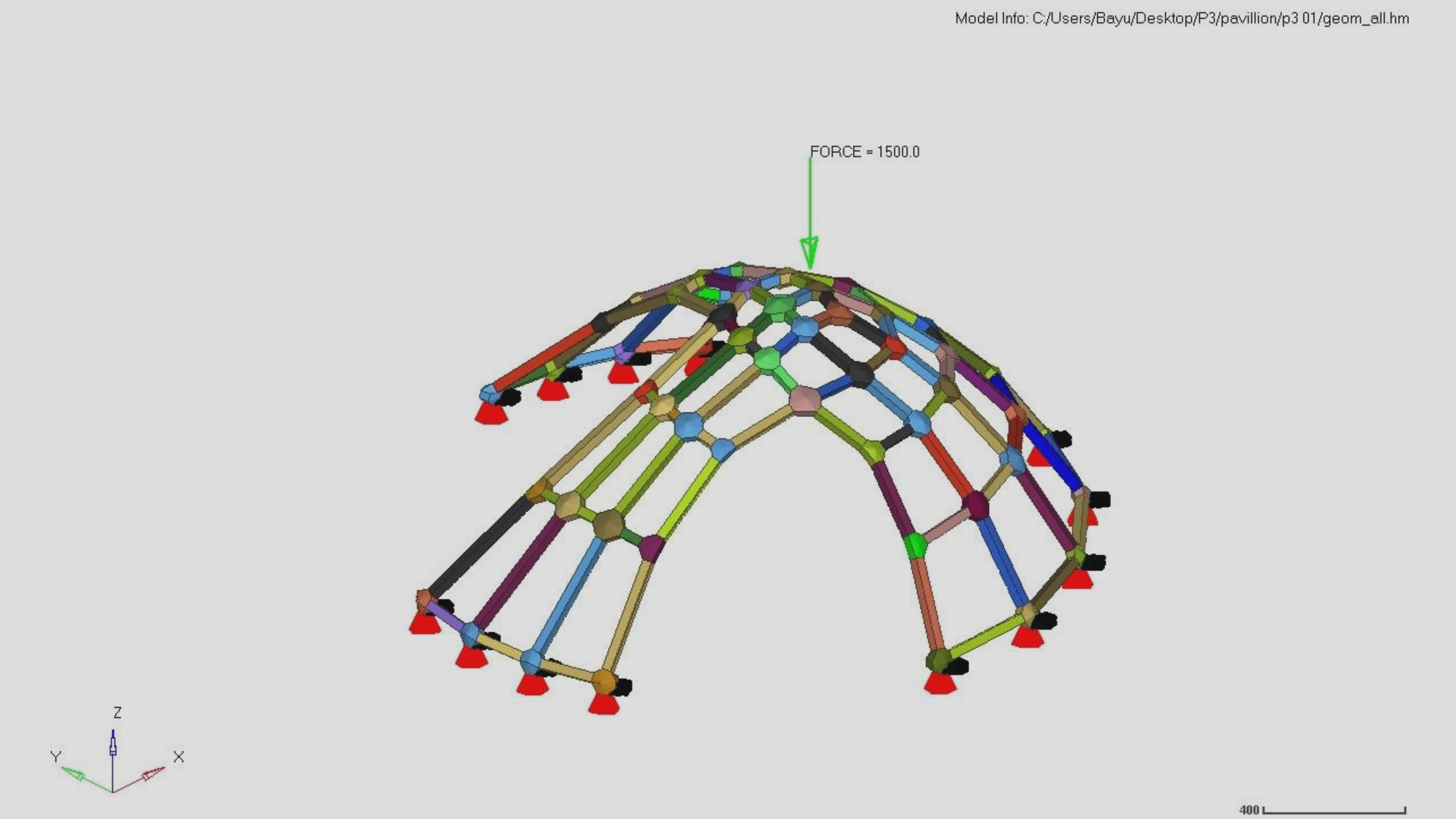
Design ideas

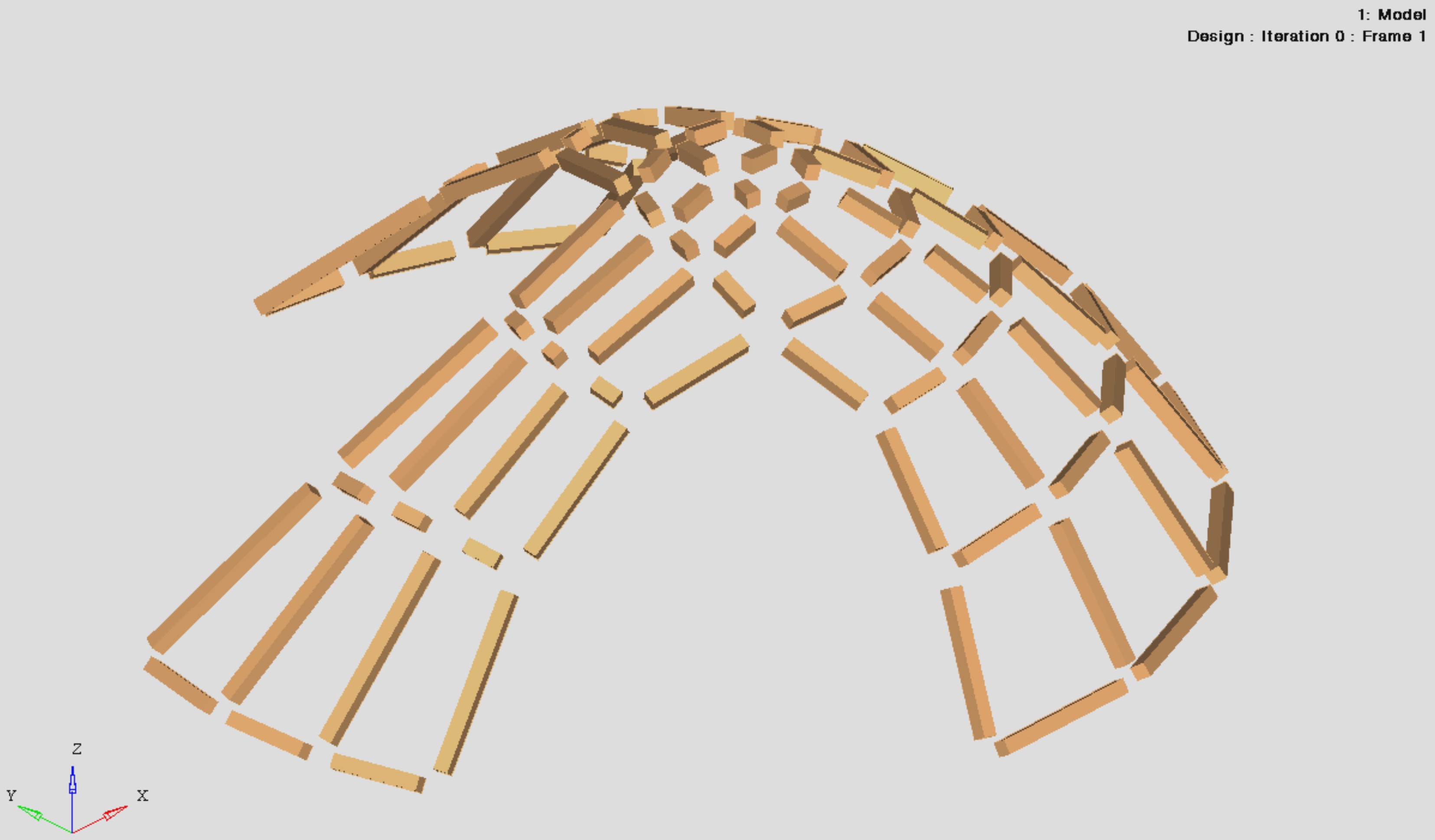

NORMAL
AM


node's central axis
beam's central axis
Nt
node's top offset
N
node's bottom offset
Nb

Localized Complexity

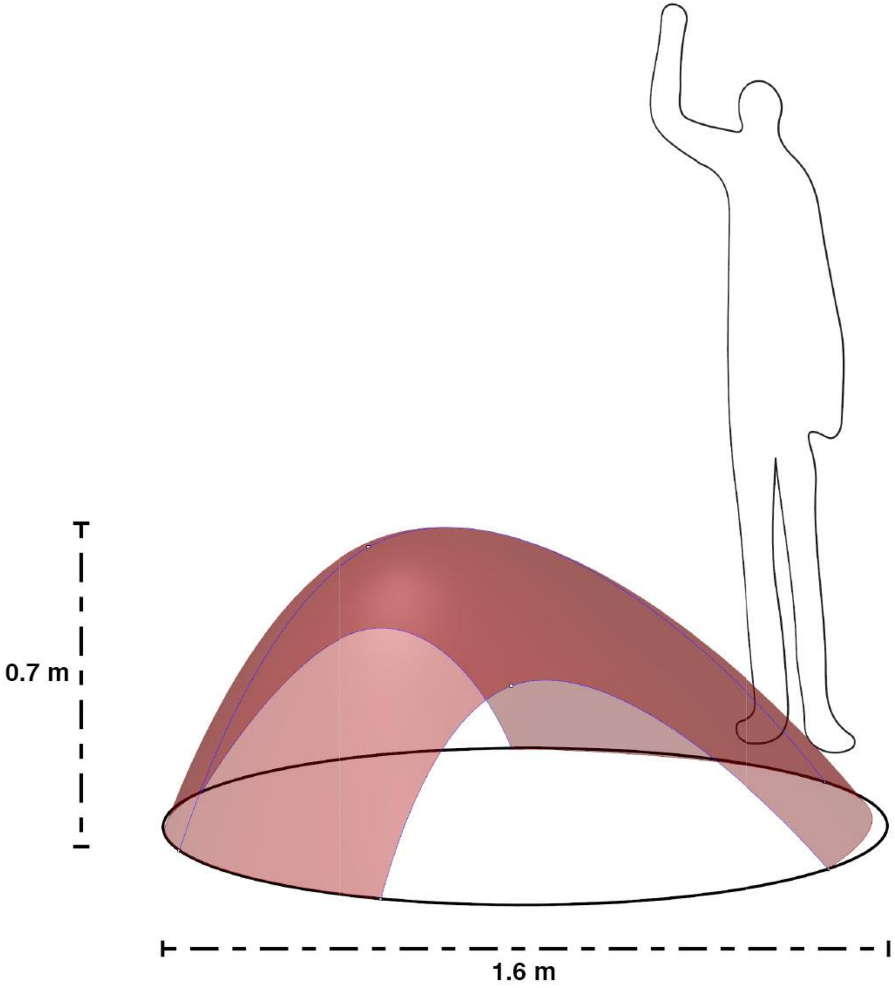

0.73
-1.47
1.10
0.62
-0.44
-5.87
-5.82
Setup
Run

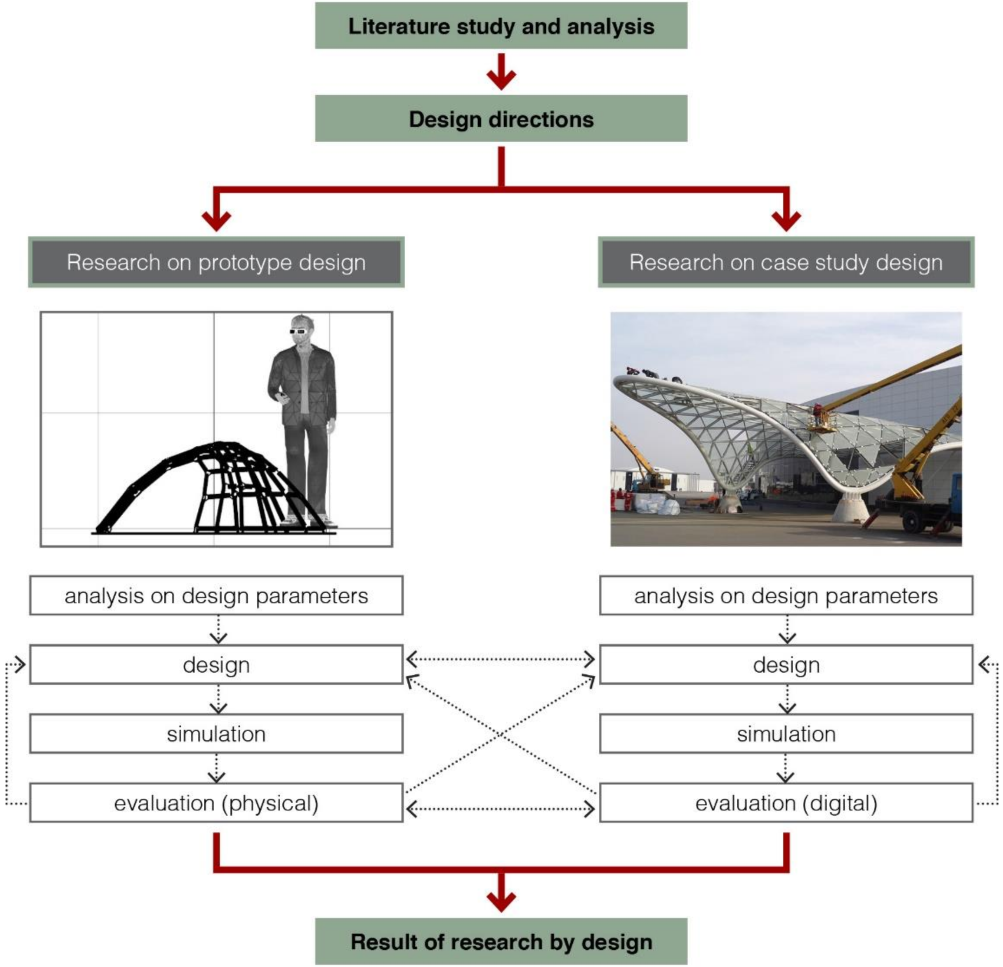

Model Info: C:/Users/Bayu/Desktop/P3/pavillion/p3 01/geom_all.hm
FORCE = 1500.0
Z
Y
X
400


1: Model
Design : Iteration 0 : Frame 1
Z
Y
X

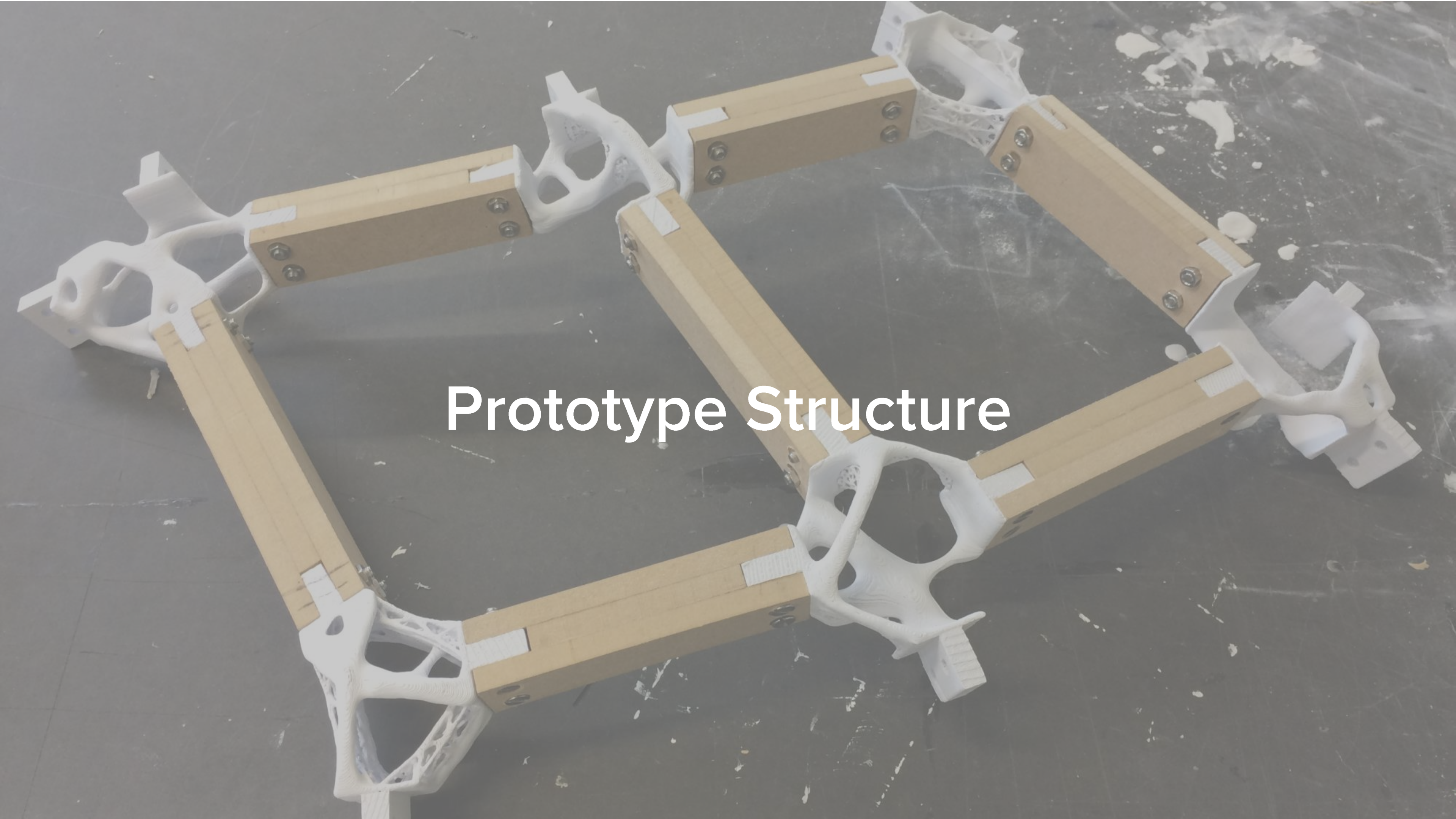
Global Calculation for Local Optimization

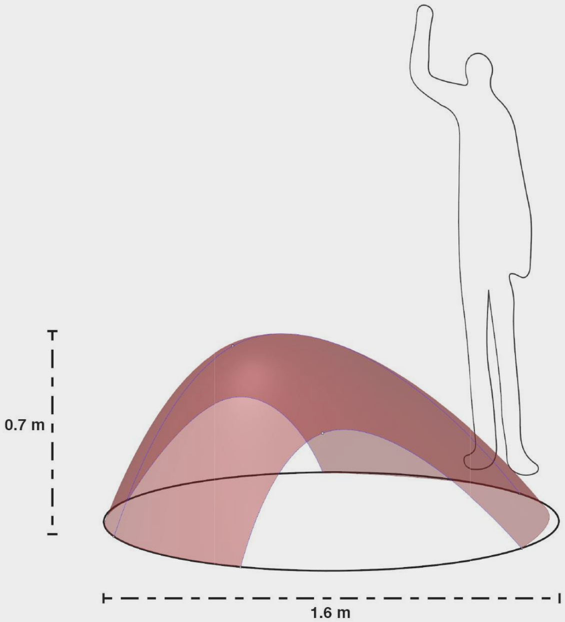

АГП 22

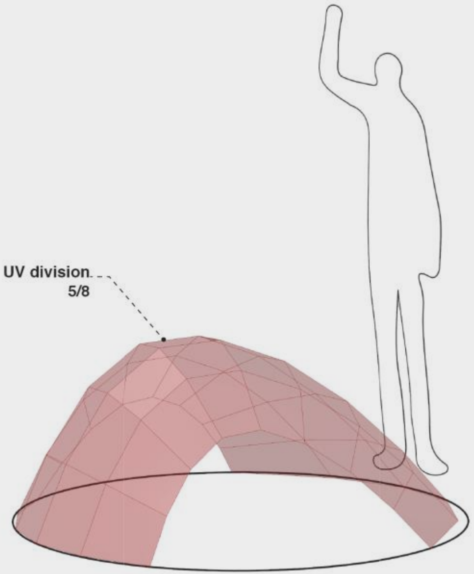

0.7 m
1.6 m

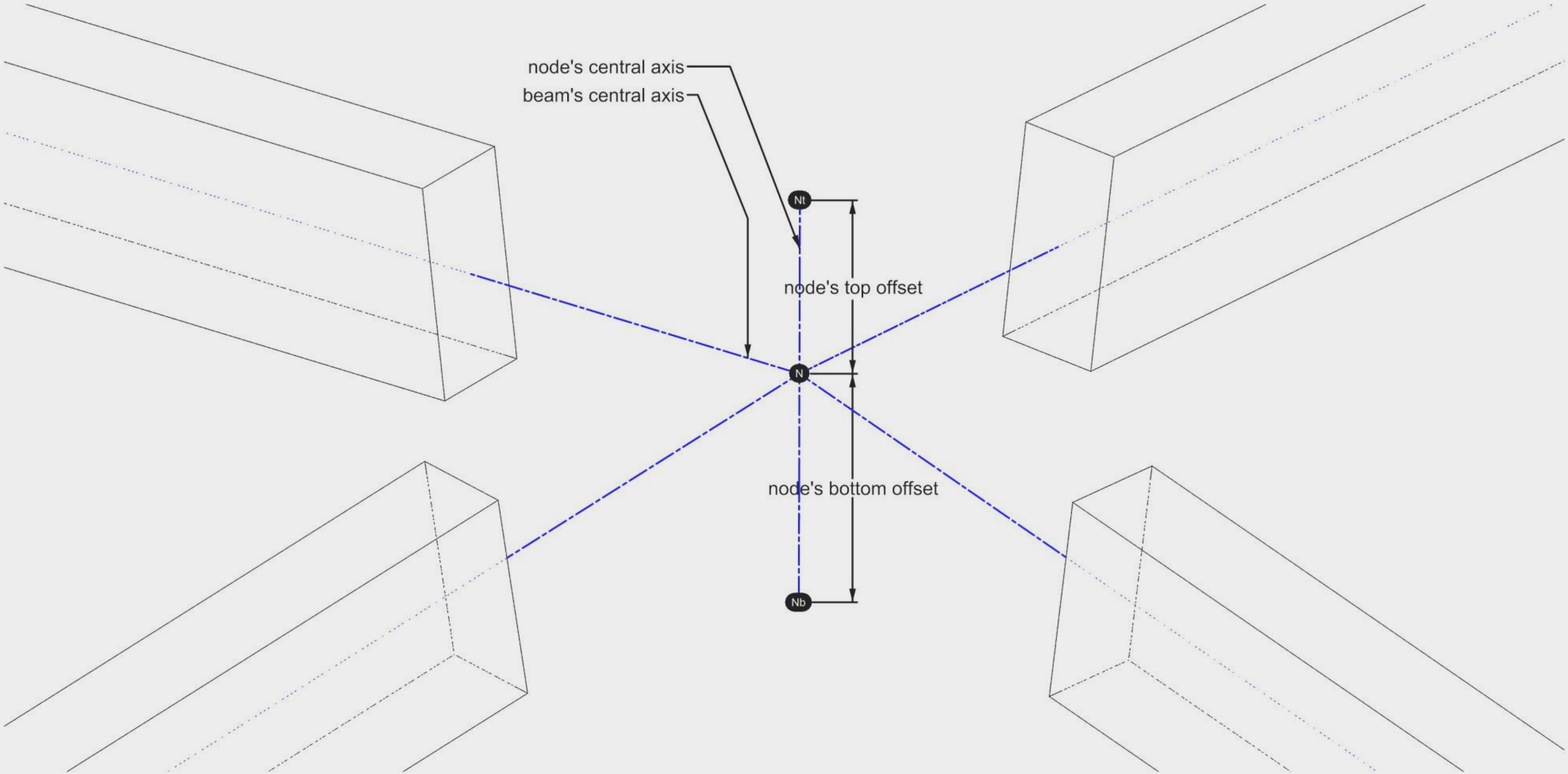

Literature study and analysis
Design directions
Research on prototype design
Research on case study design
analysis on design parameters
design
simulation
evaluation (physical)
analysis on design parameters
design
simulation
evaluation (digital)
Result of research by design

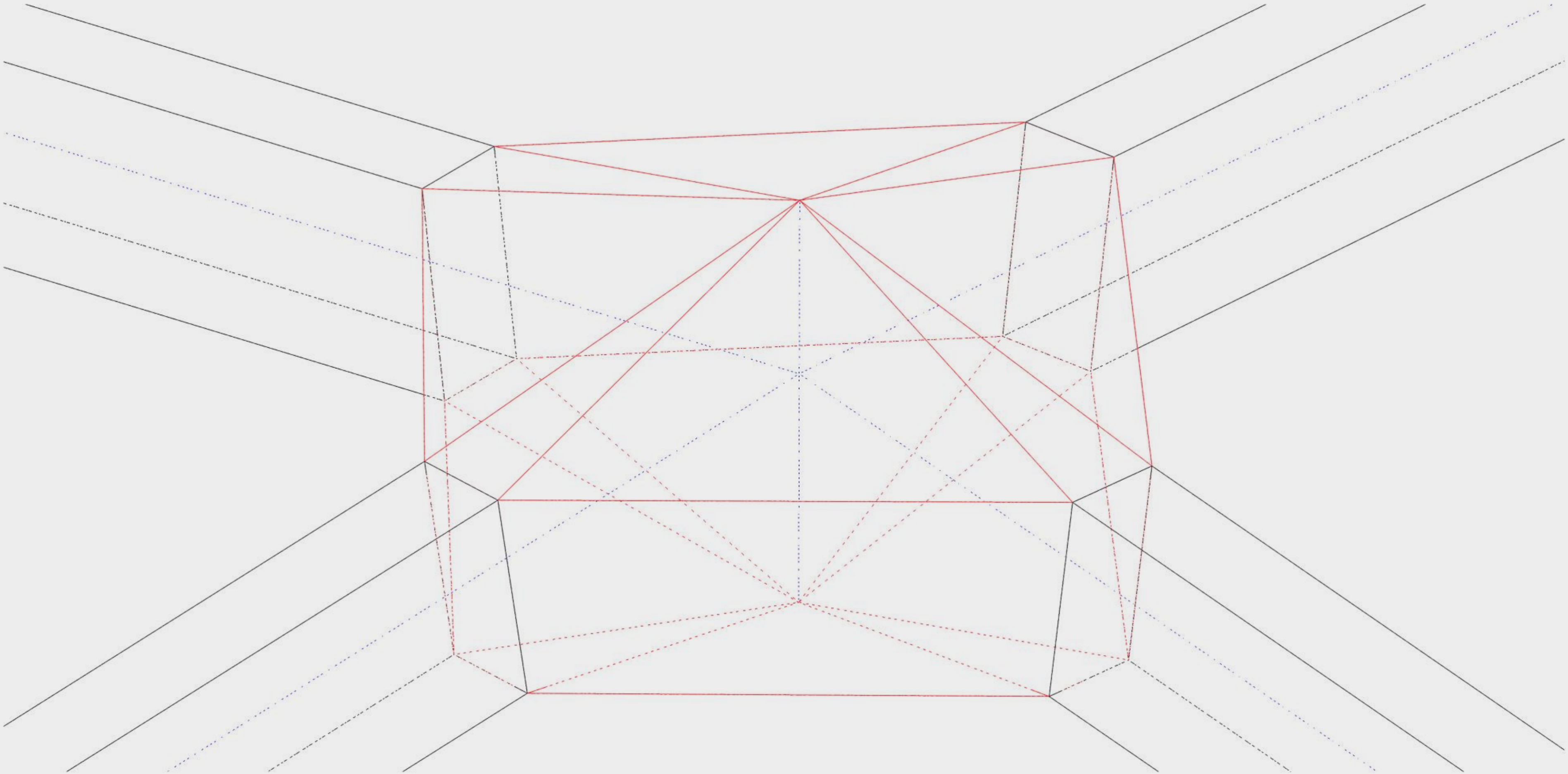
Prototype Structure

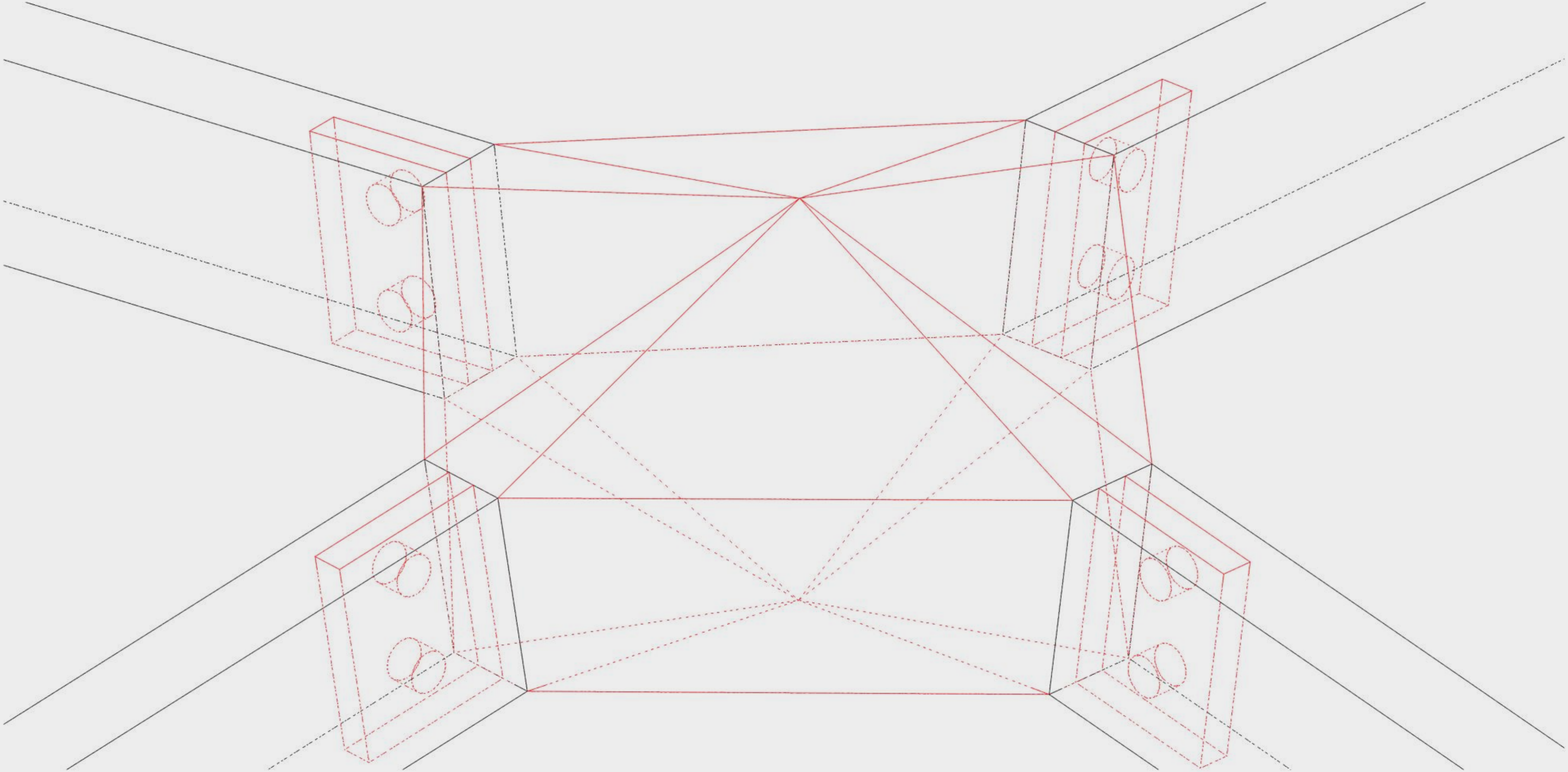


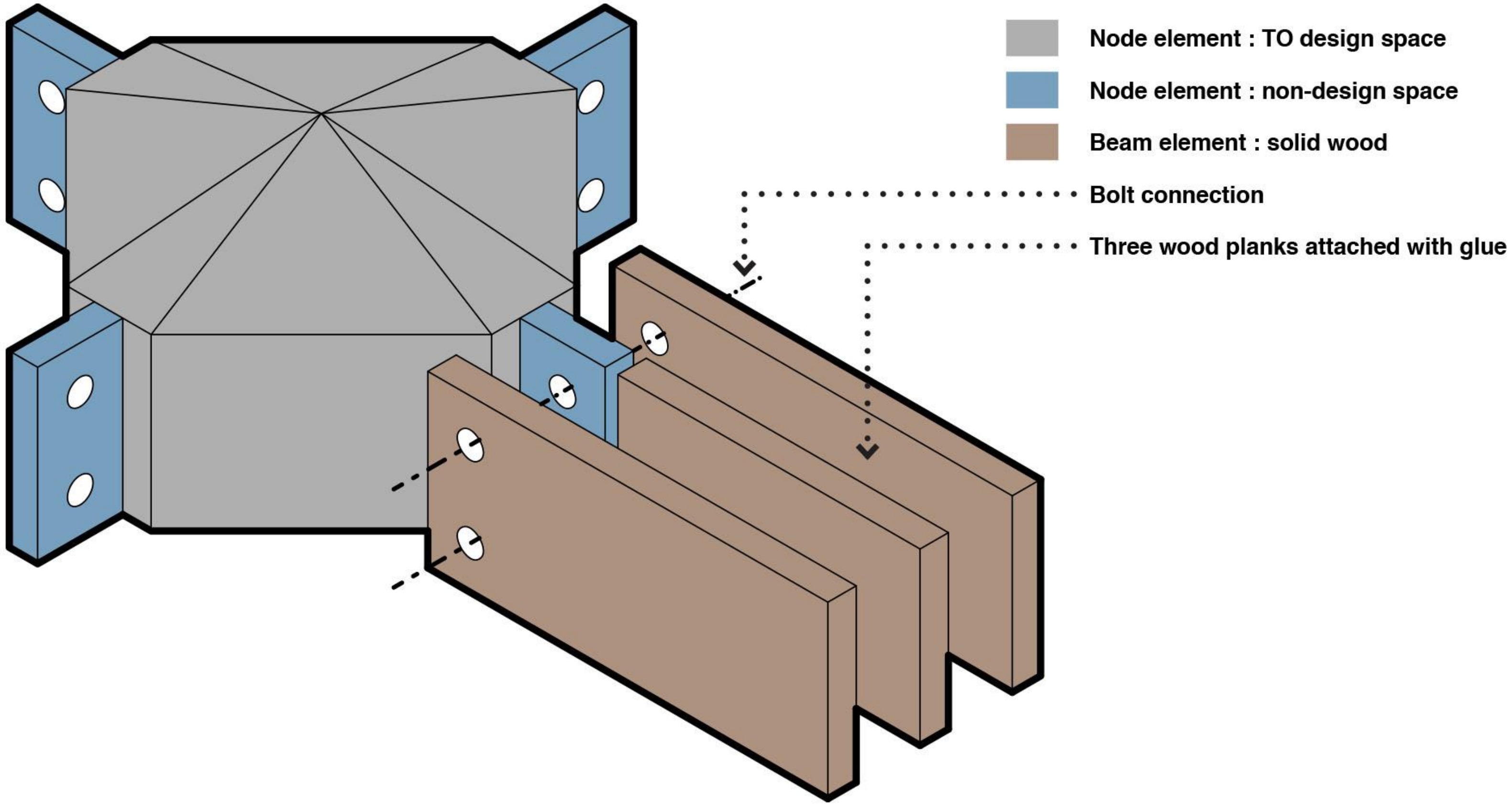

0.7 m
1.6 m


UV division
5/8

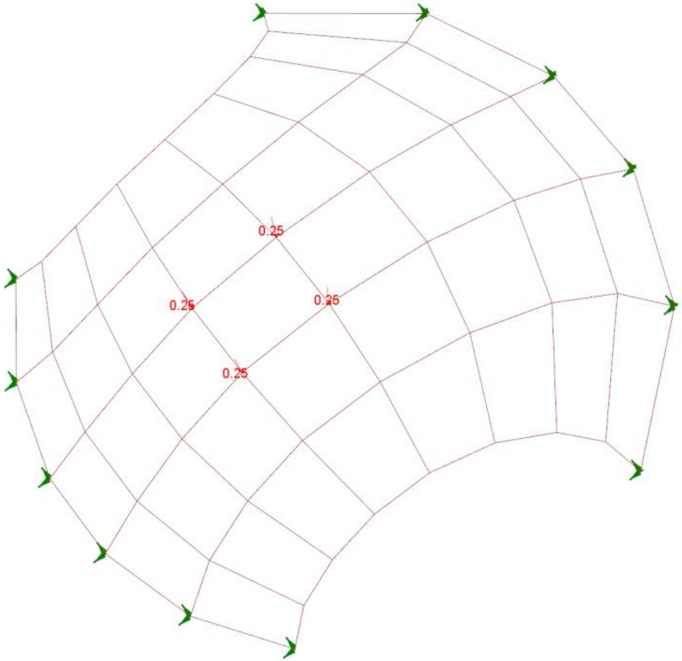

node's central axis
beam's central axis
Nt
node's top offset
N
node's bottom offset
Nb

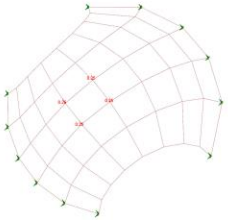




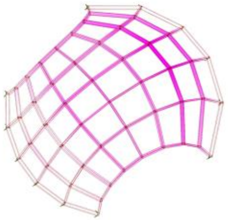


Node element : TO design space
Node element : non-design space
Beam element : solid wood
Bolt connection
Three wood planks attached with glue

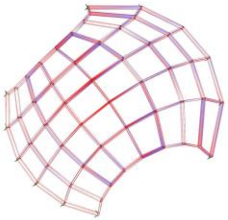

0.25
0.25
0.25
0.25



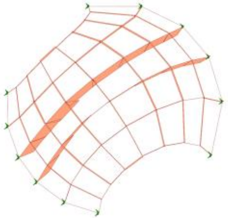
Loadcase and boundary conditions



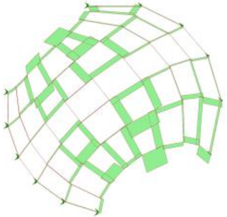
DIsplacement diagram



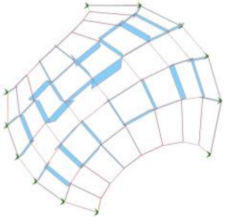
Beams utilization. Red: compression, Blue: tension



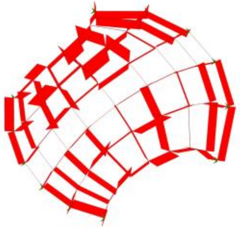
Nx: Normal (axial) forces on beam's local X-direction



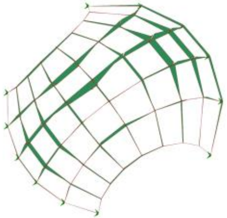
Vy: Shear forces on beam's local Y-direction (in plane shear)



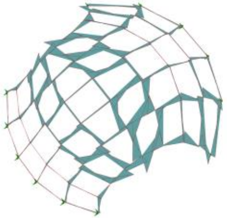
Vz: Shear forces on beam's local Z-direction (out of plane shear)



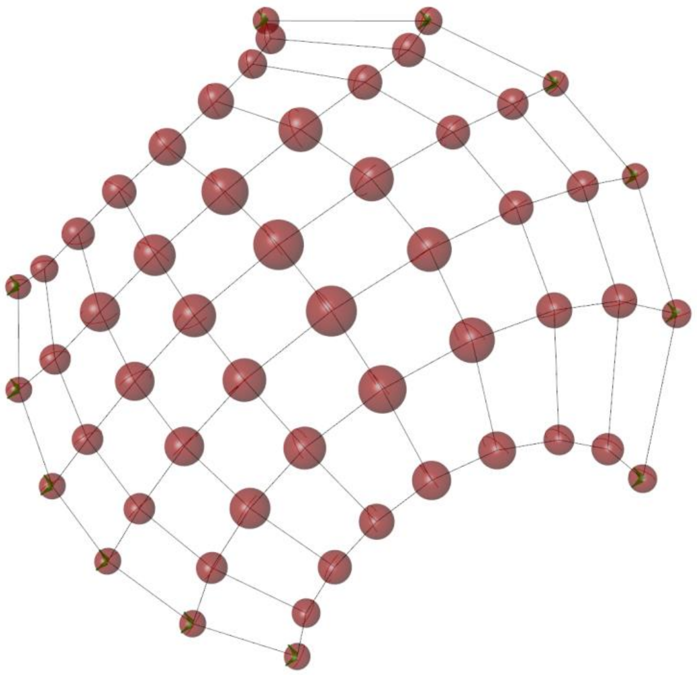
Mx: Torsional moment on beam's local X-axis

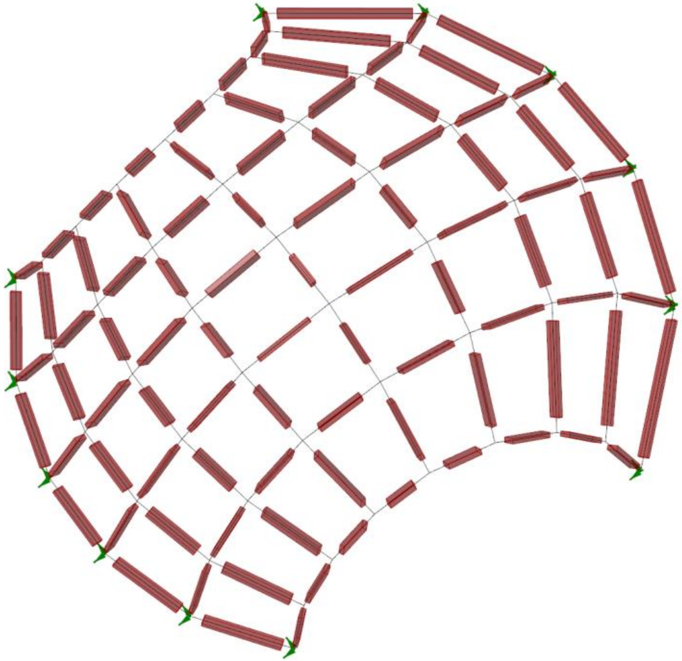


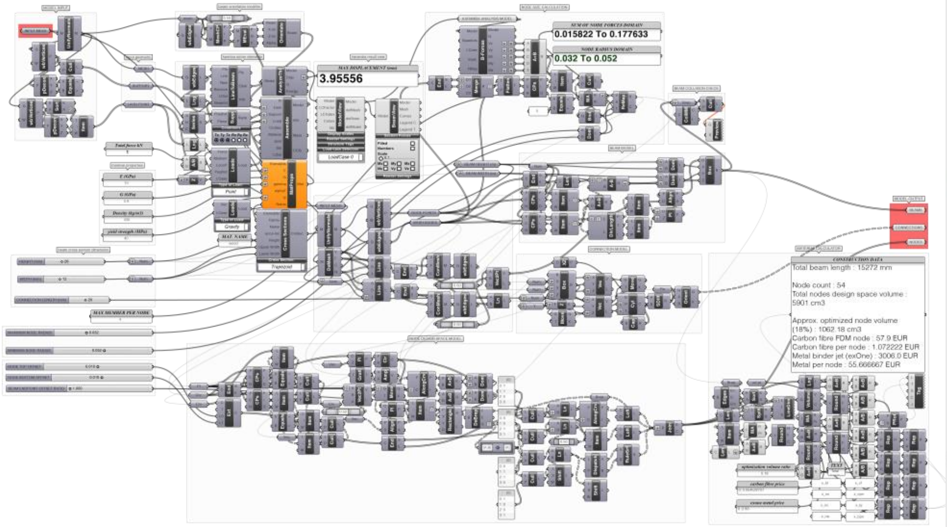
My: Bending moment on beam's local Y-axis (out of plane bending)

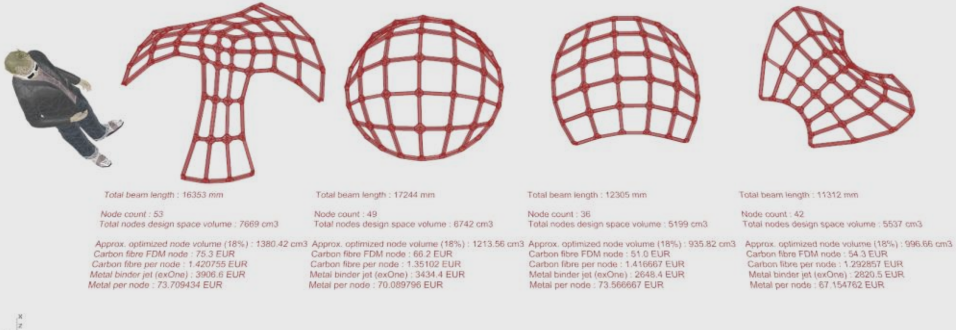


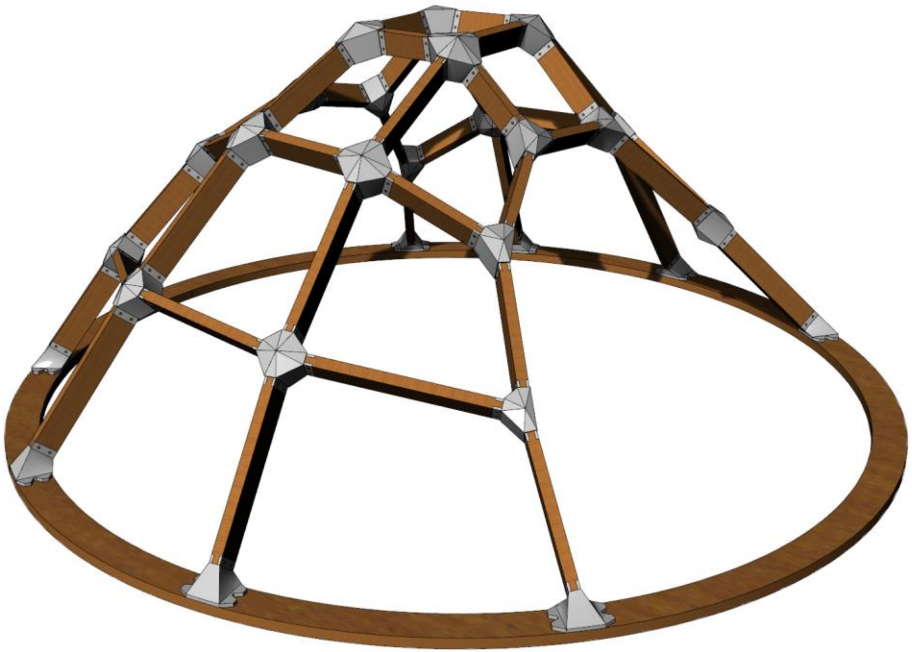
Mz: Bending moment on beam's local Z-axis (in plane bending)

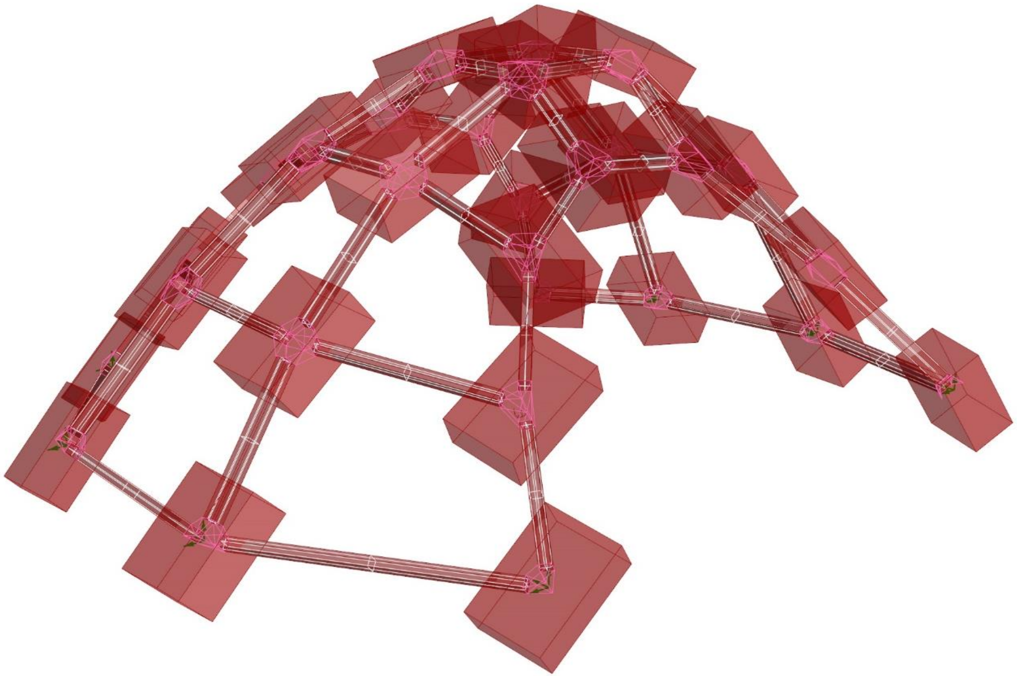


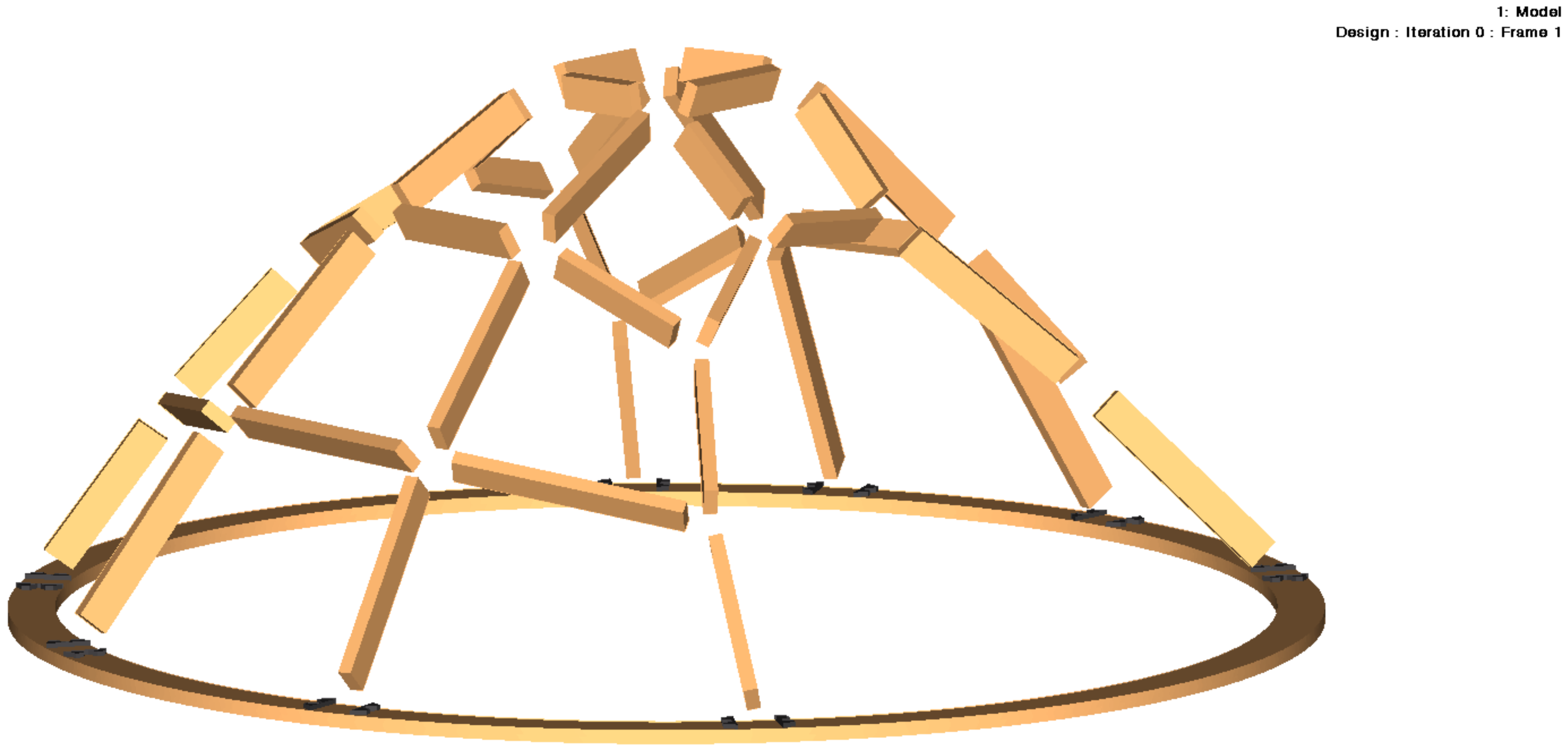



MAX DISPLACEMENT (mm)
3.95556
SUM OF NODE FORCES DOMAIN
0.015822 To 0.177633
NODE RADIUS DOMAIN
0.032 To 0.052
CONSTRUCTION DATA
Total beam length : 15272 mm
Node count : 54
Total nodes design space volume : 5901 cm3
Approx. optimized node volume (18%) : 1062.18 cm3
Carbon fibre FDM node : 57.9 EUR
Carbon fibre per node : 1.072222 EUR
Metal binder jet (exOne) : 3006.0 EUR
Metal per node : 55.666667 EUR

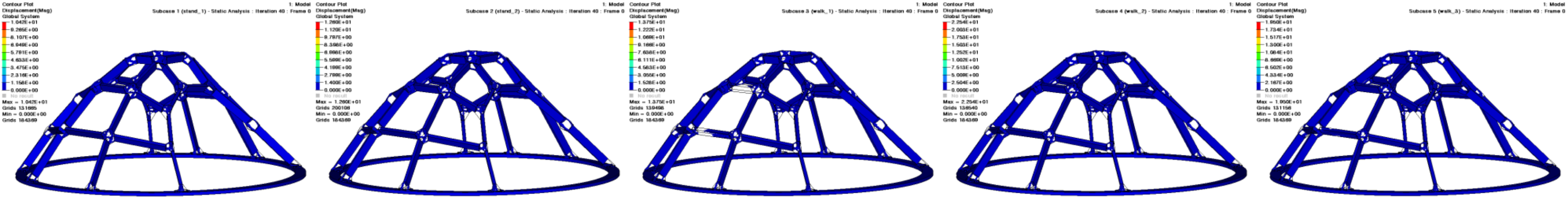

Total beam length : 16353 mm
Node count : 53
Total nodes design space volume : 7669 cm3
Approx. optimized node volume (18%) : 1380.42 cm3
Carbon fibre FDM node : 75.3 EUR
Carbon fibre per node : 1.420755 EUR
Metal binder jet (exOne) : 3906.6 EUR
Metal per node : 73.709434 EUR
Total beam length : 17244 mm
Node count : 49
Total nodes design space volume : 6742 cm3
Approx. optimized node volume (18%) : 1213.56 cm3
Carbon fibre FDM node : 66.2 EUR
Carbon fibre per node : 1.35102 EUR
Metal binder jet (exOne) : 3434.4 EUR
Metal per node : 70.089796 EUR
Total beam length : 12305 mm
Node count : 36
Total nodes design space volume : 5199 cm3
Approx. optimized node volume (18%) : 935.82 cm3
Carbon fibre FDM node : 51.0 EUR
Carbon fibre per node : 1.416667 EUR
Metal binder jet (exOne) : 2648.4 EUR
Metal per node : 73.566667 EUR
Total beam length : 11312 mm
Node count : 42
Total nodes design space volume : 5537 cm3
Approx. optimized node volume (18%) : 996.66 cm3
Carbon fibre FDM node : 54.3 EUR
Carbon fibre per node : 1.292857 EUR
Metal binder jet (exOne) : 2820.5 EUR
Metal per node : 67.154762 EUR



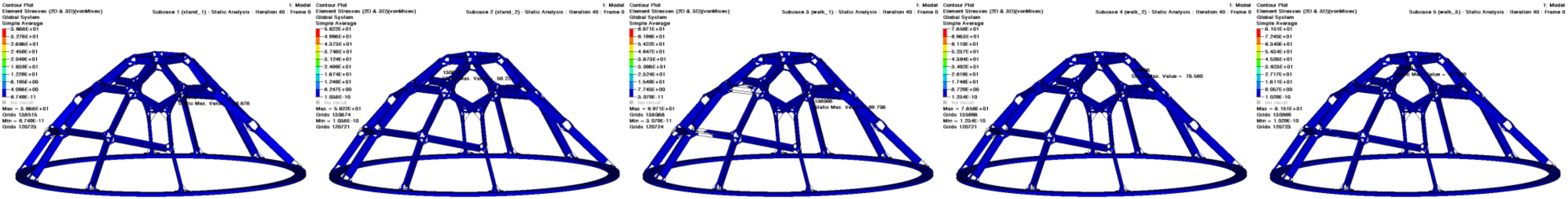


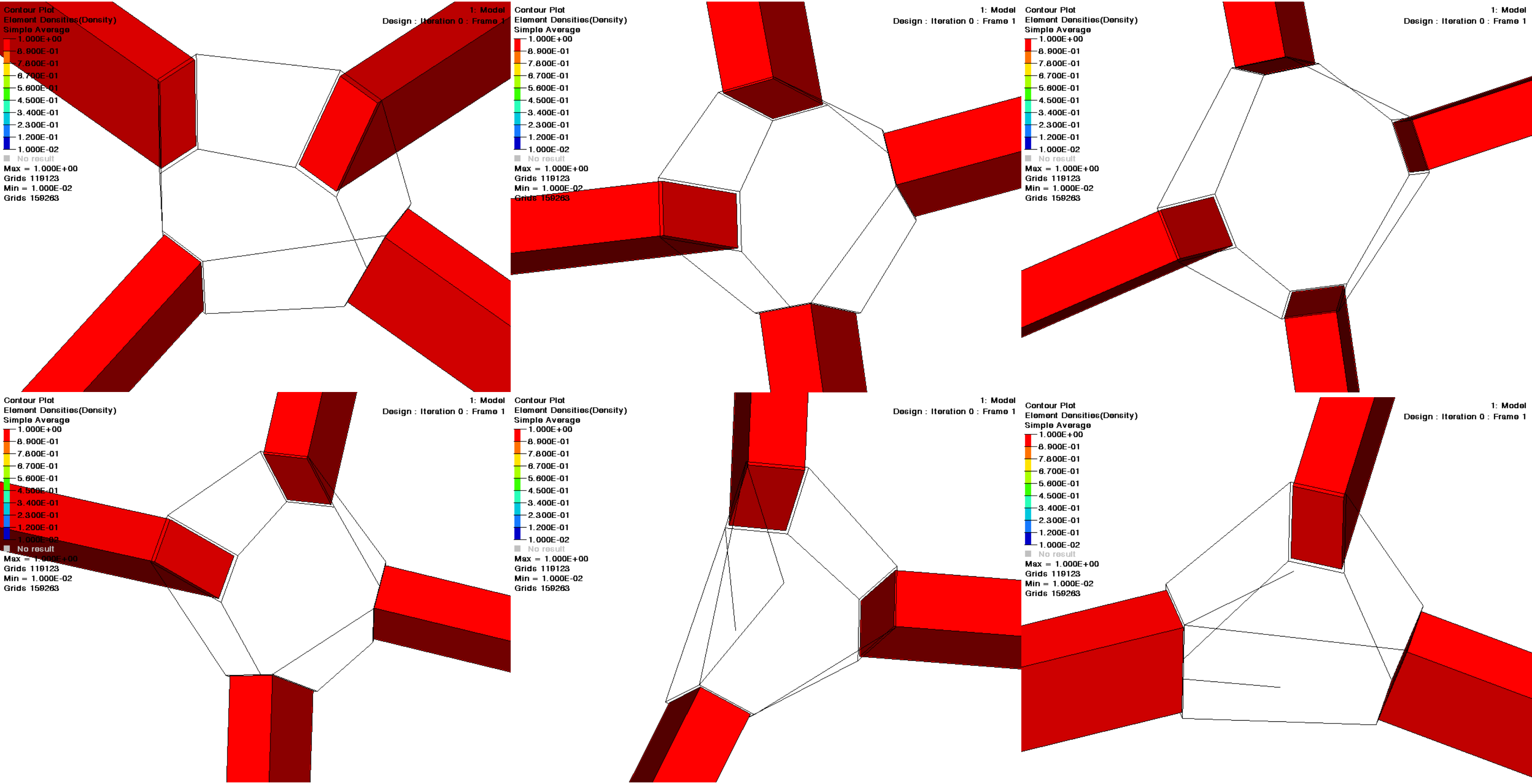

1: Model
Design : Iteration 0 : Frame 1

Displacement :

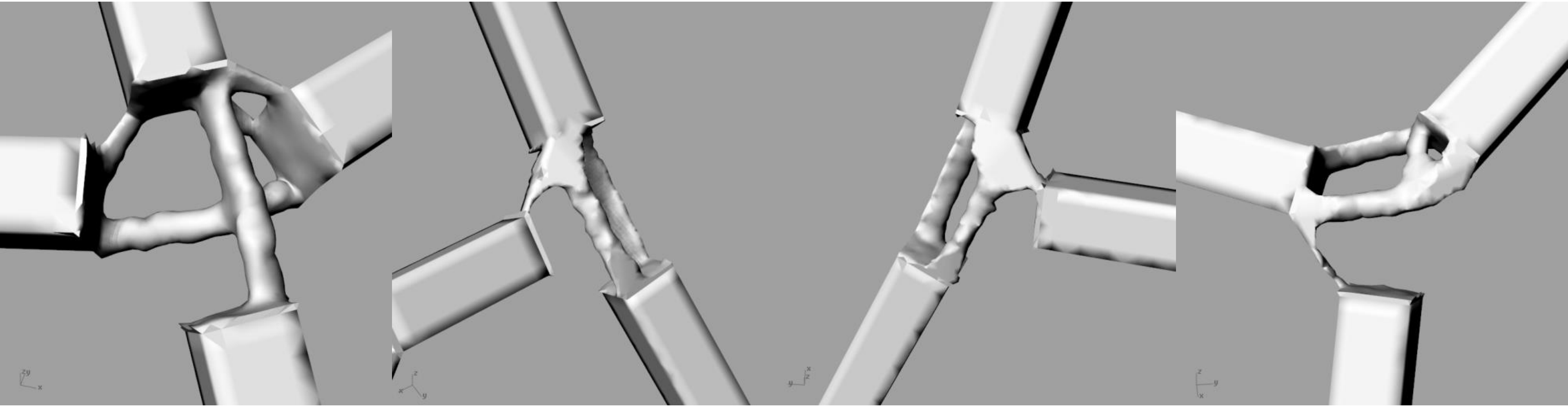


Von mises stresses

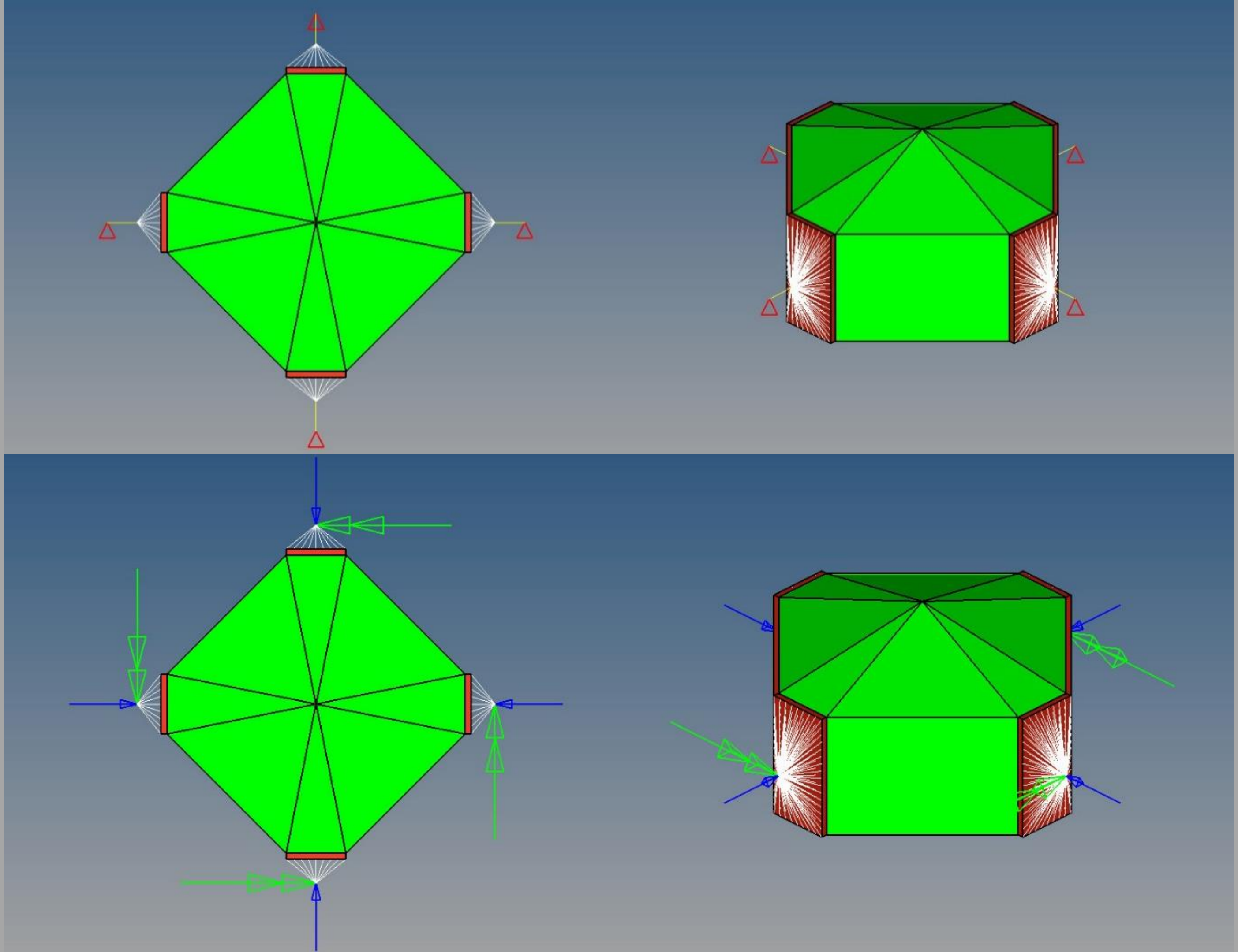


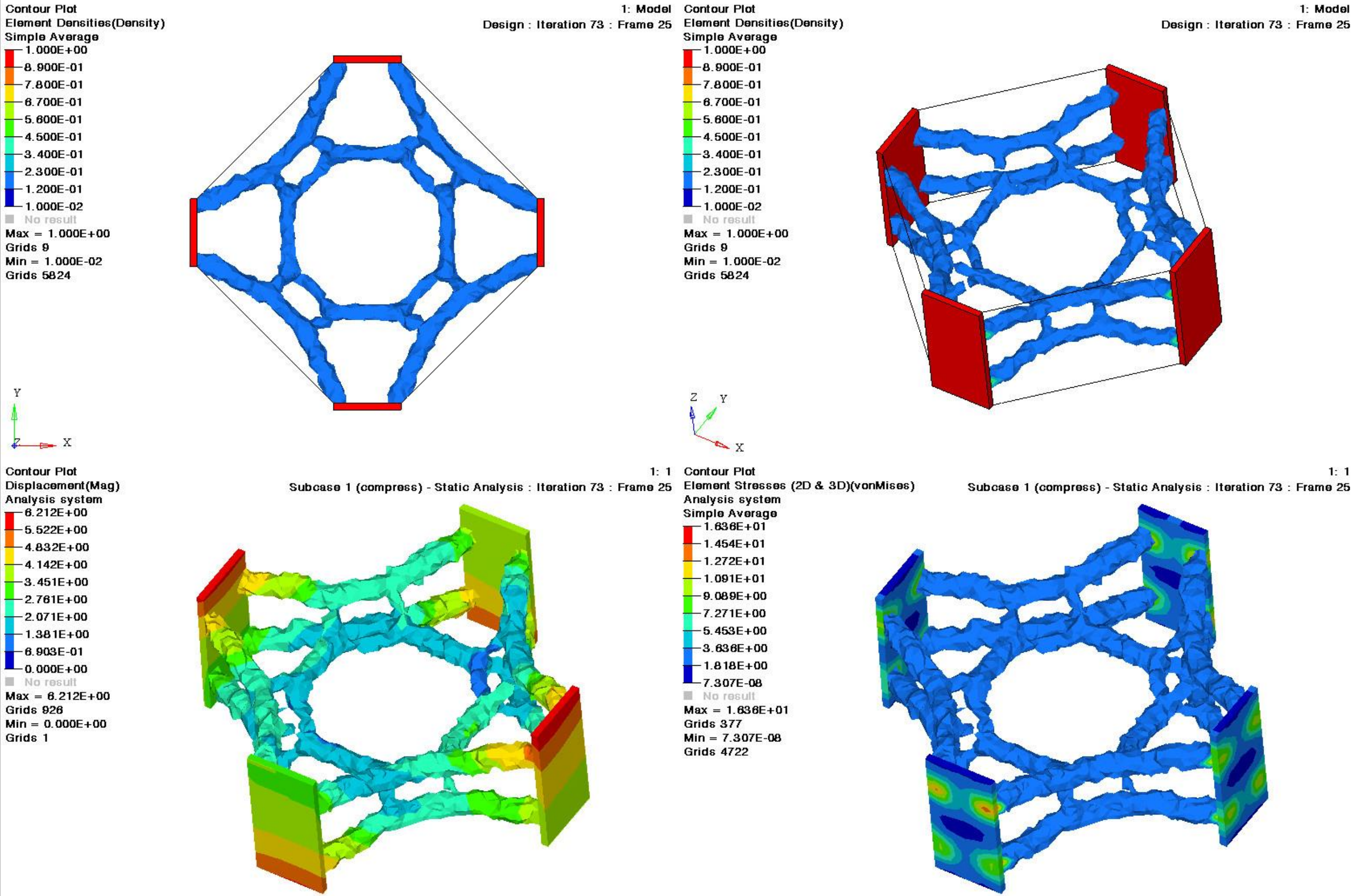


Contour Plot
Element Densities(Density)
Simple Average
1.000E+00
8.900E-01
7.800E-01
6.700E-01
5.600E-01
4.500E-01
3.400E-01
2.300E-01
1.200E-01
1.000E-02
No result
Max = 1.000E+00
Grids 119123
Min = 1.000E-02
Grids 159263
1: Model
Design : Iteration 0 : Frame 1

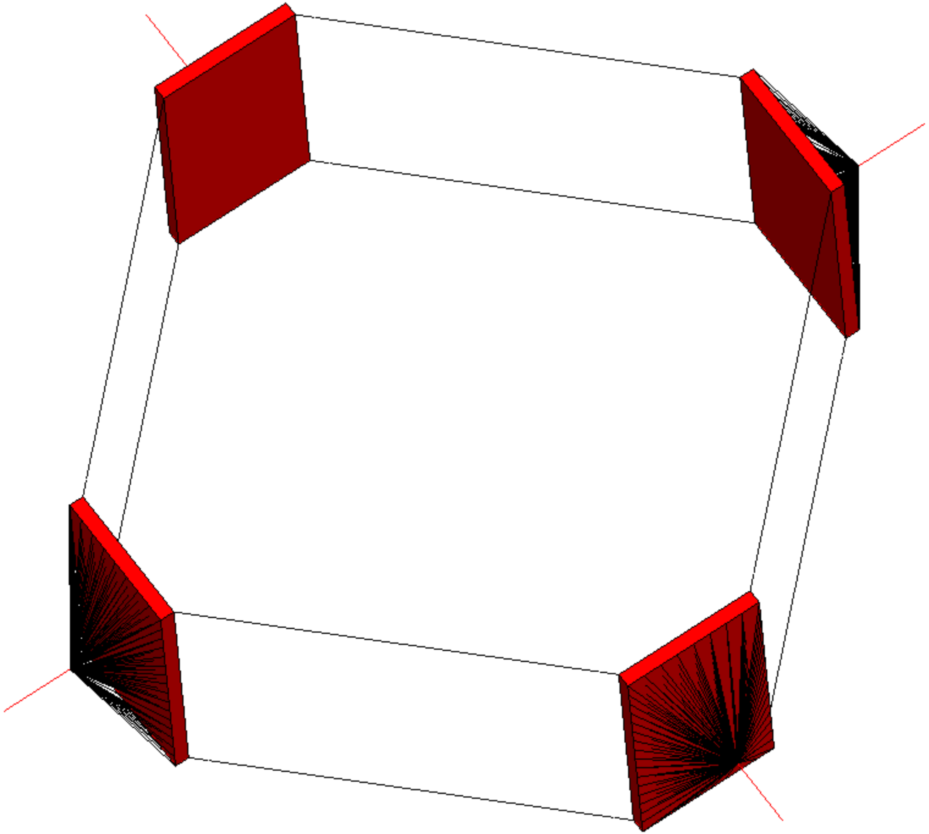


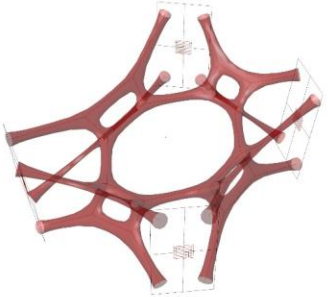
Generic design optimization

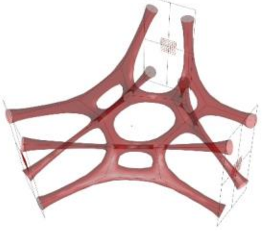


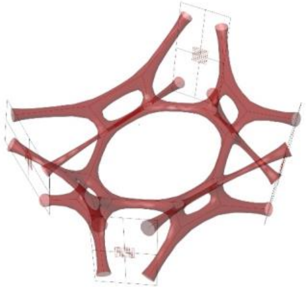


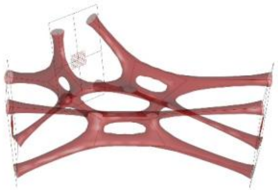
Contour Plot
Element Densities(Density)
Simple Average
1: Model
Design : Iteration 73 : Frame 25
1.000E+00
8.900E-01
7.800E-01
6.700E-01
5.600E-01
4.500E-01
3.400E-01
2.300E-01
1.200E-01
1.000E-02
No result
Max = 1.000E+00
Grids 9
Min = 1.000E-02
Grids 5824
Y
X
Contour Plot
Element Densities(Density)
Simple Average
1: Model
Design : Iteration 73 : Frame 25
1.000E+00
8.900E-01
7.800E-01
6.700E-01
5.600E-01
4.500E-01
3.400E-01
2.300E-01
1.200E-01
1.000E-02
No result
Max = 1.000E+00
Grids 9
Min = 1.000E-02
Grids 5824
Z
Y
X
Contour Plot
Displacement(Mag)
Analysis system
1: 1
Subcase 1 (compress) - Static Analysis : Iteration 73 : Frame 25
6.212E+00
5.522E+00
4.832E+00
4.142E+00
3.451E+00
2.761E+00
2.071E+00
1.381E+00
6.903E-01
0.000E+00
No result
Max = 6.212E+00
Grids 926
Min = 0.000E+00
Grids 1
Contour Plot
Element Stresses (2D & 3D)(vonMises)
Analysis system
Simple Average
1: 1
Subcase 1 (compress) - Static Analysis : Iteration 73 : Frame 25
1.636E+01
1.454E+01
1.272E+01
1.091E+01
9.089E+00
7.271E+00
5.453E+00
3.636E+00
1.818E+00
7.307E-08
No result
Max = 1.636E+01
Grids 377
Min = 7.307E-08
Grids 4722

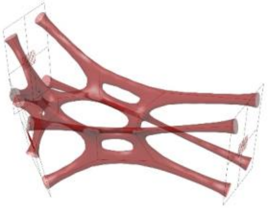


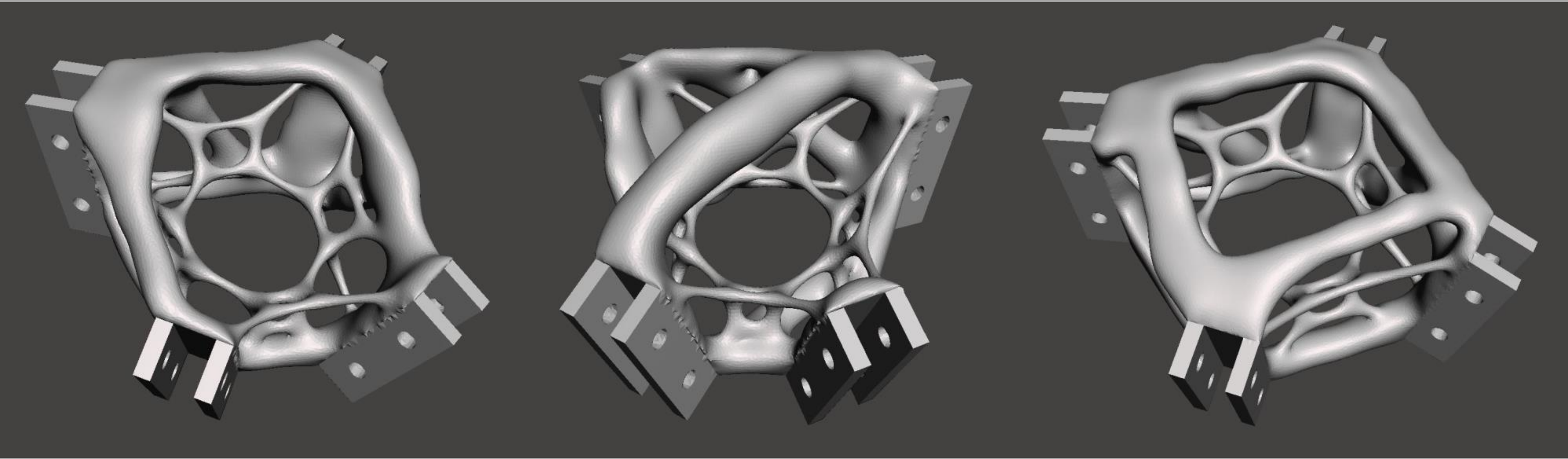


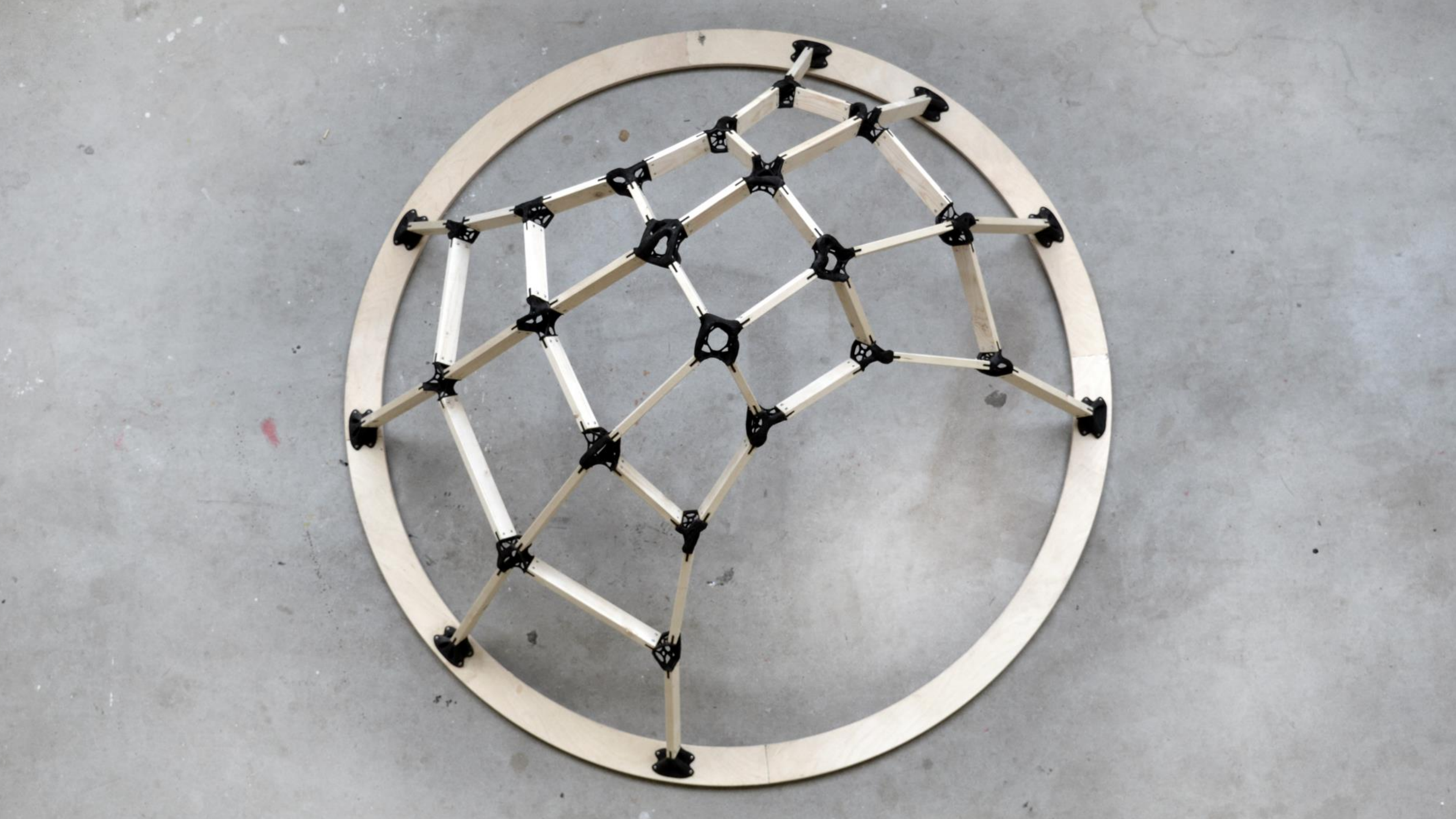






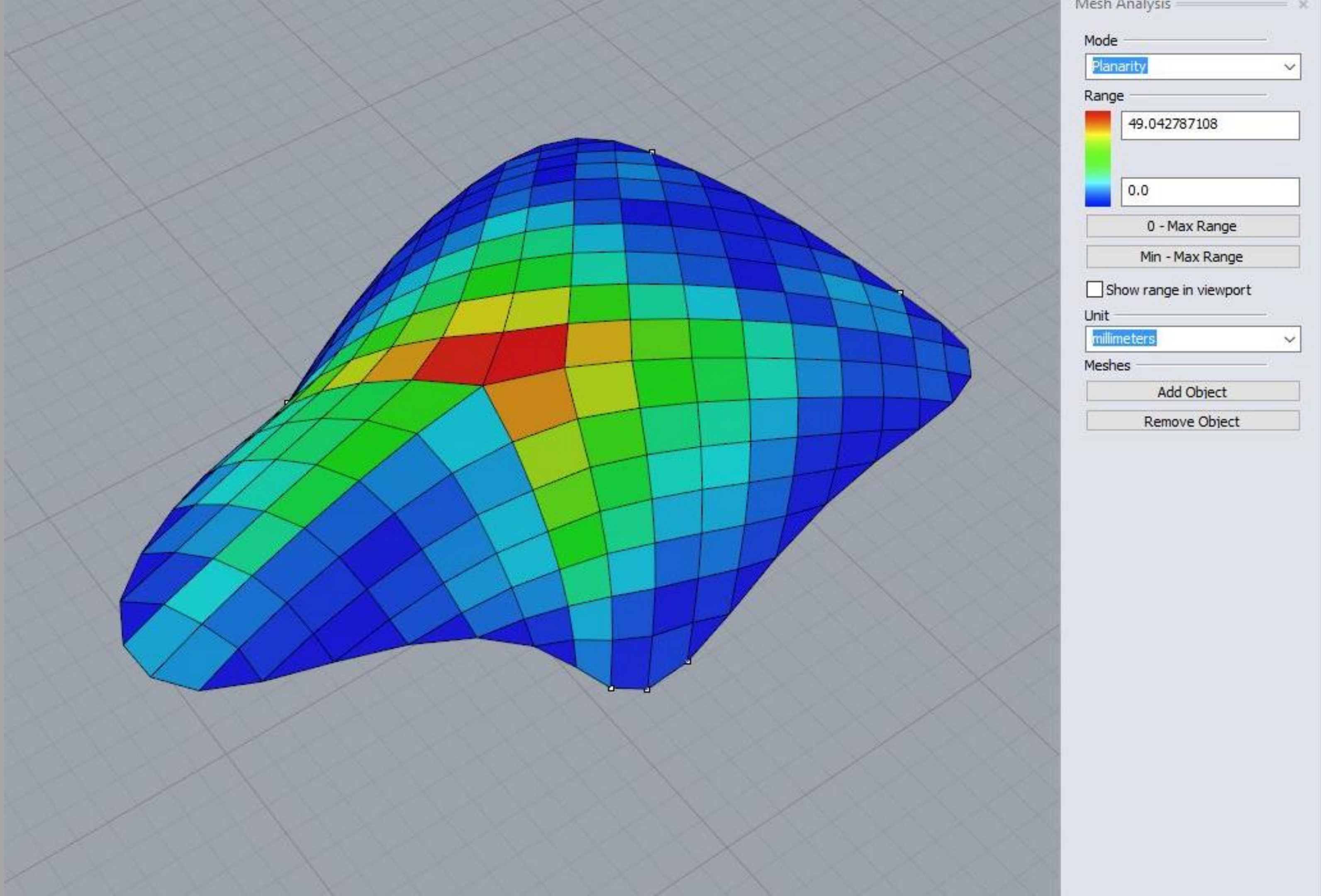






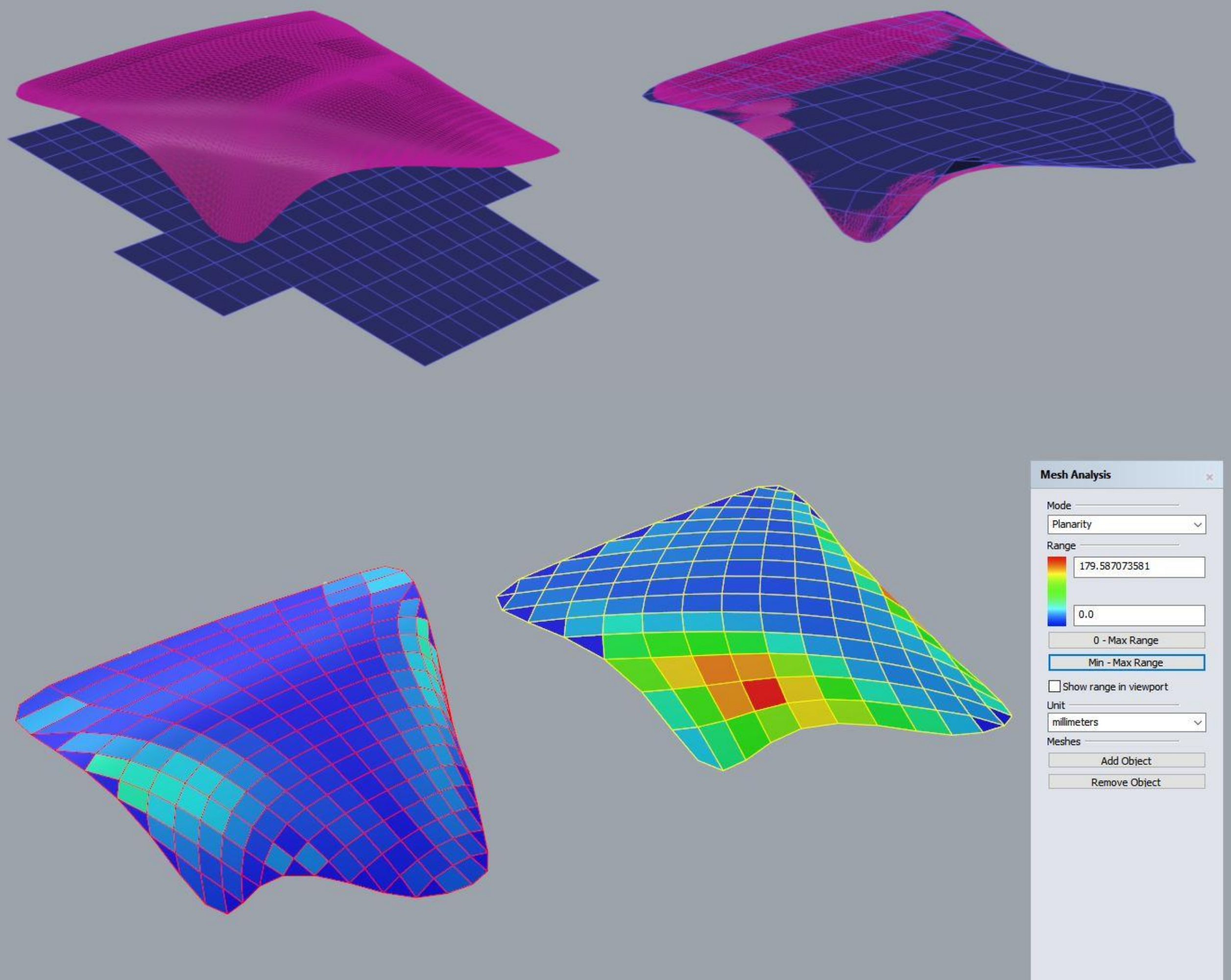
Case Study

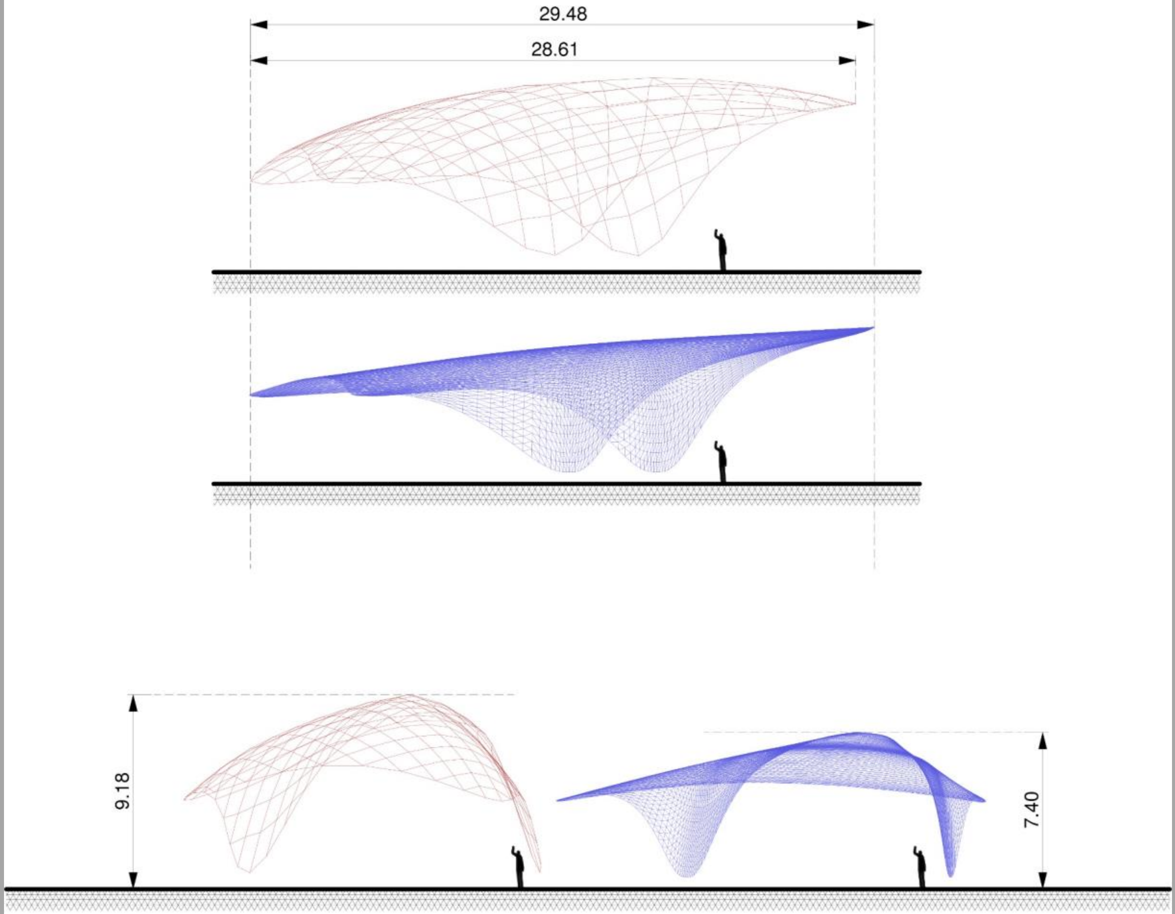

АГП 22


Mesh Analysis
Mode
Planarity
Range
49.042787108
0.0
0 - Max Range
Min - Max Range
Show range in viewport
Unit
millimeters
Meshes
Add Object
Remove Object

Forces :

- Closeness to reference surface
- Closeness to boundary curve
- Planarize panels
- Equalize edges length
- Fairness curvature



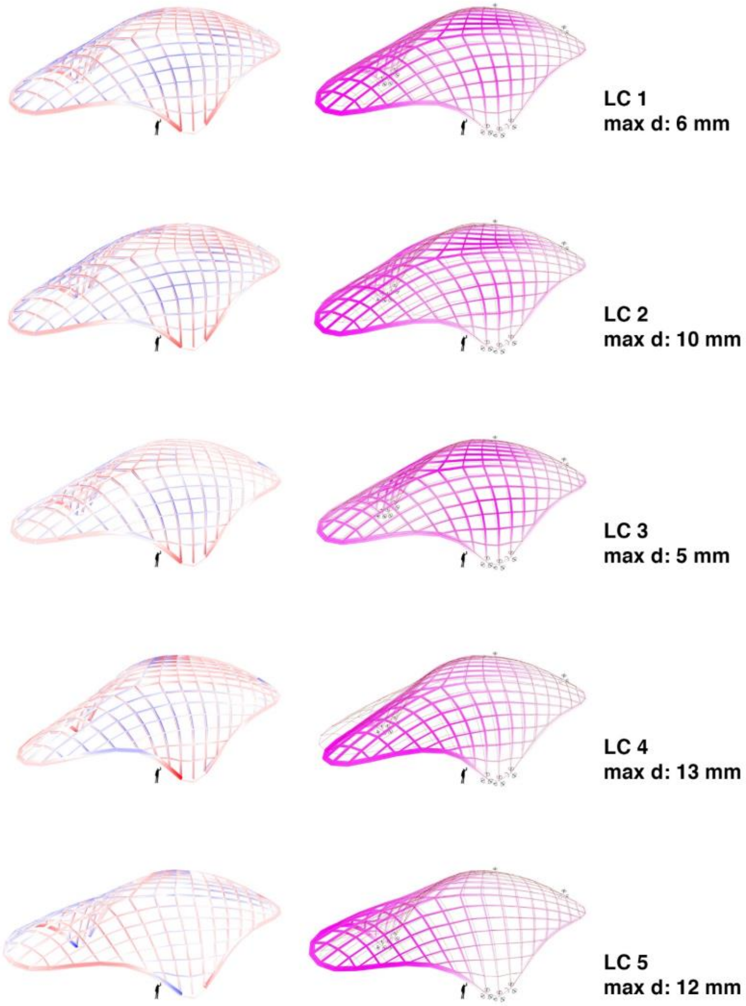

29.48
28.61
9.18
7.40

Loadcases:

LC1	: DL + LL	1.0
LC2	: DL + LL + Snow load	0.4
LC3	: DL + LL + Wind load (uplift)	0.8
LC4	: DL + LL + Lateral load (X)	0.4
LC5	: DL + LL + Lateral load (-X)	0.4

Beams:

RHS 200x100x8
CHS 400x10

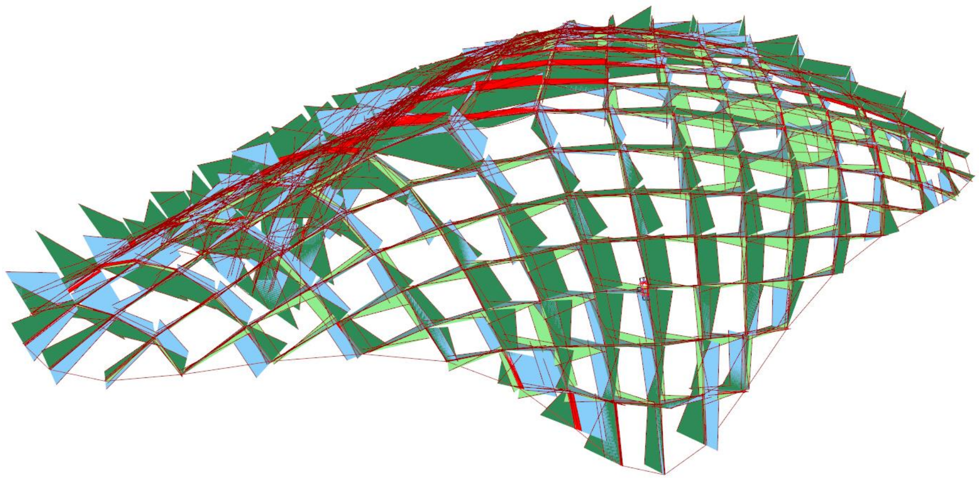


Loadcases:

LC1	: DL + LL	1.0
LC2	: DL + LL + Snow load	0.4
LC3	: DL + LL + Wind load (uplift)	0.8
LC4	: DL + LL + Lateral load (X)	0.4
LC5	: DL + LL + Lateral load (-X)	0.4

Beams:

RHS 200x100x8
CHS 400x10

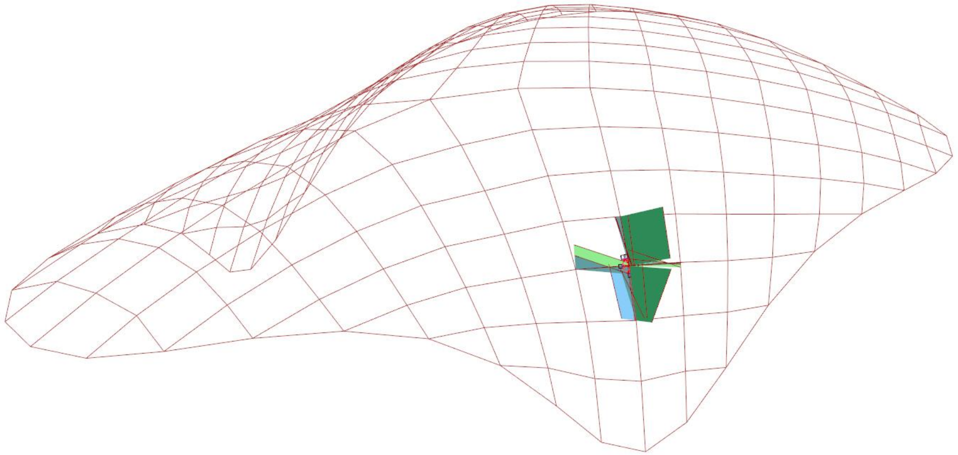


Loadcases:

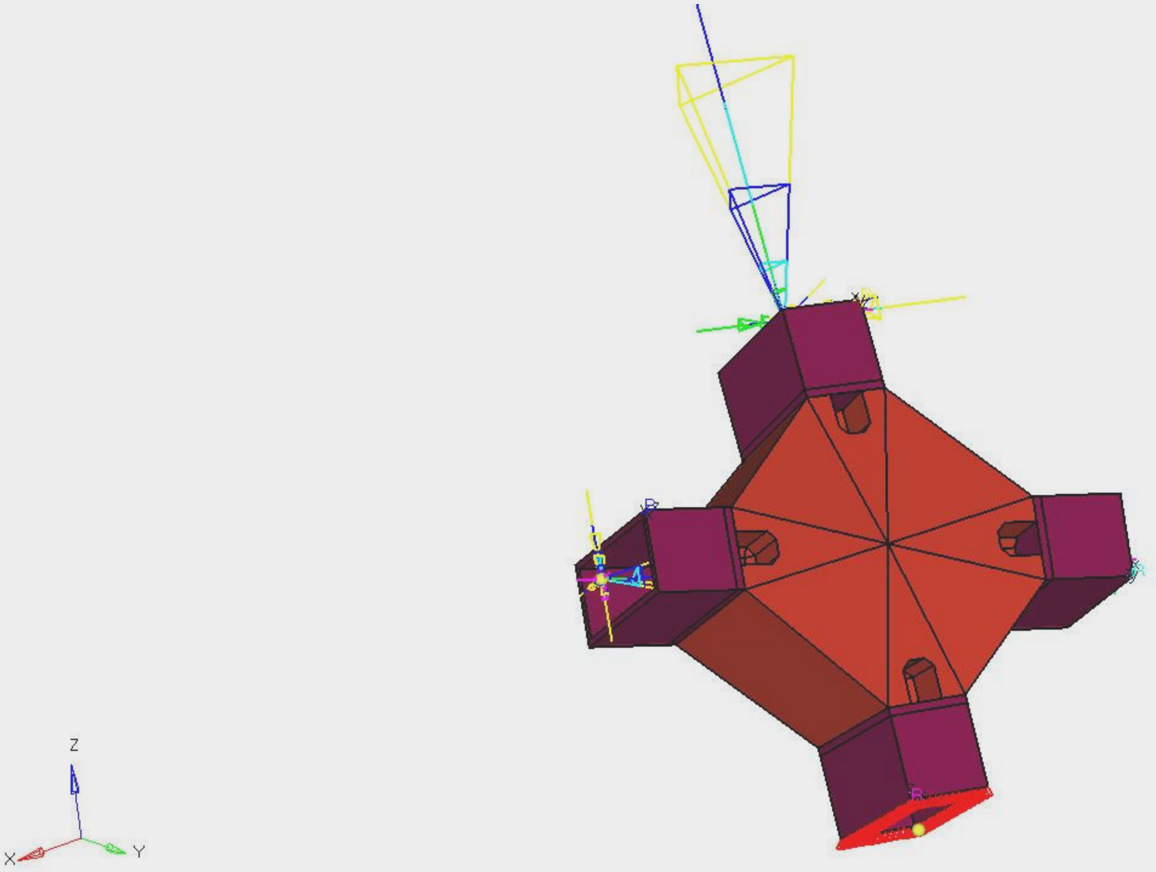
LC1	: DL + LL	1.0
LC2	: DL + LL + Snow load	0.4
LC3	: DL + LL + Wind load (uplift)	0.8
LC4	: DL + LL + Lateral load (X)	0.4
LC5	: DL + LL + Lateral load (-X)	0.4

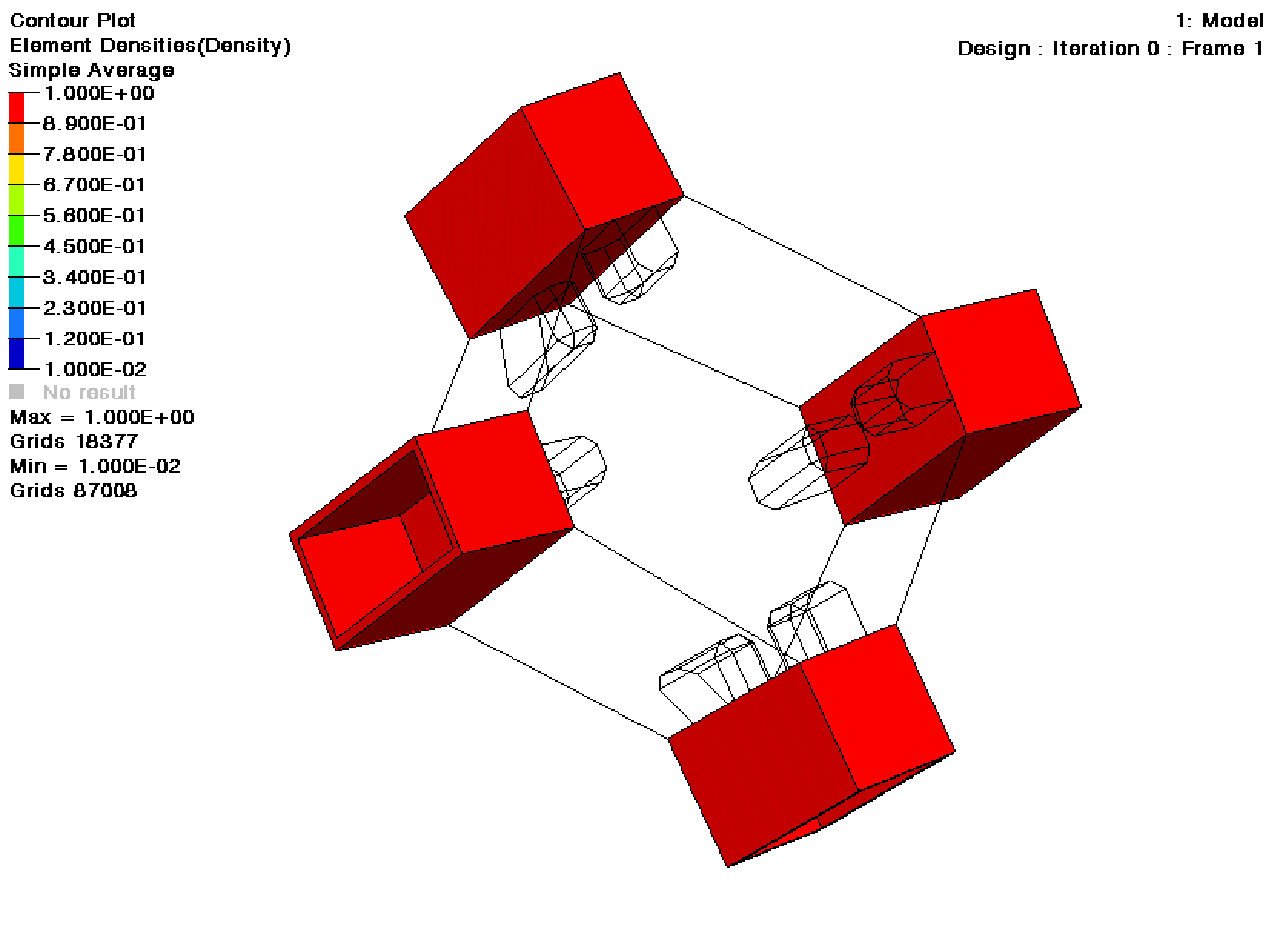
Beams:

RHS 200x100x8
CHS 400x10

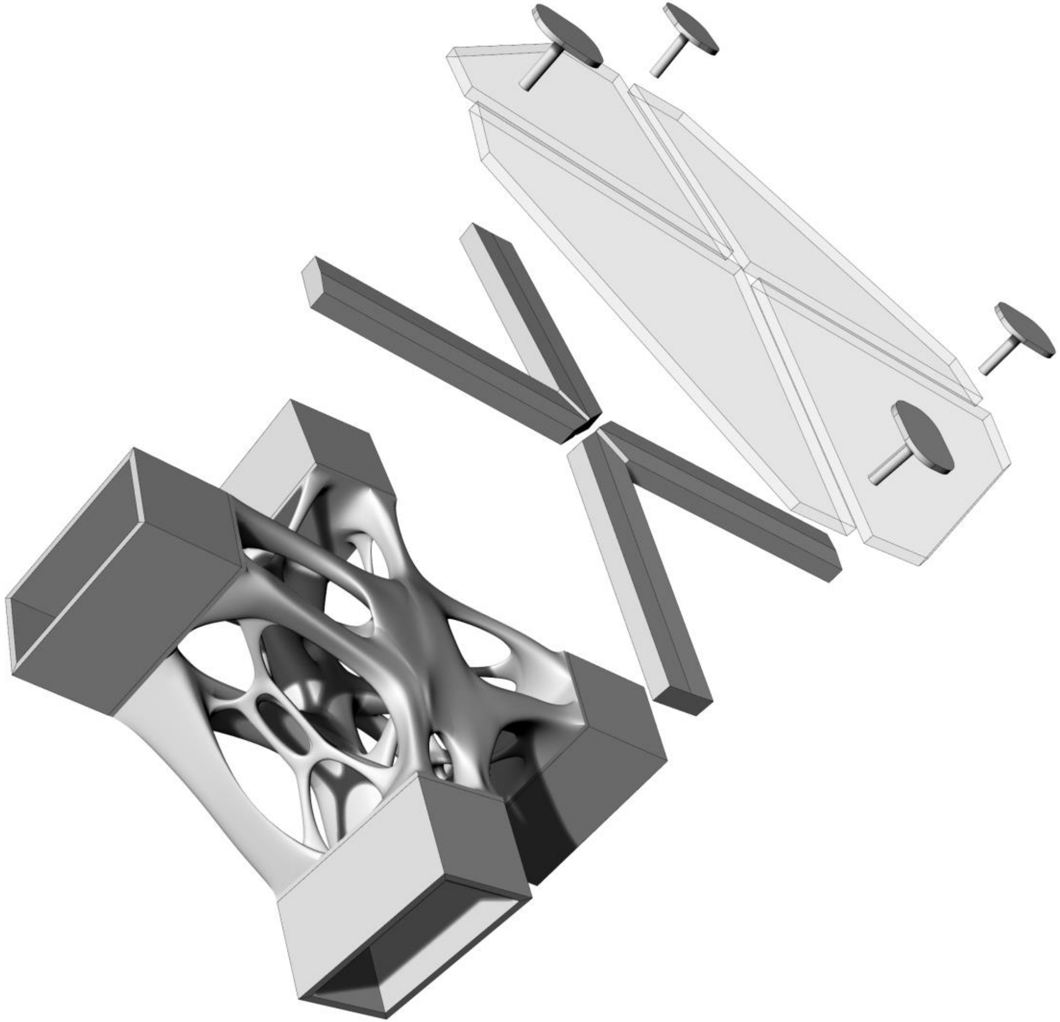


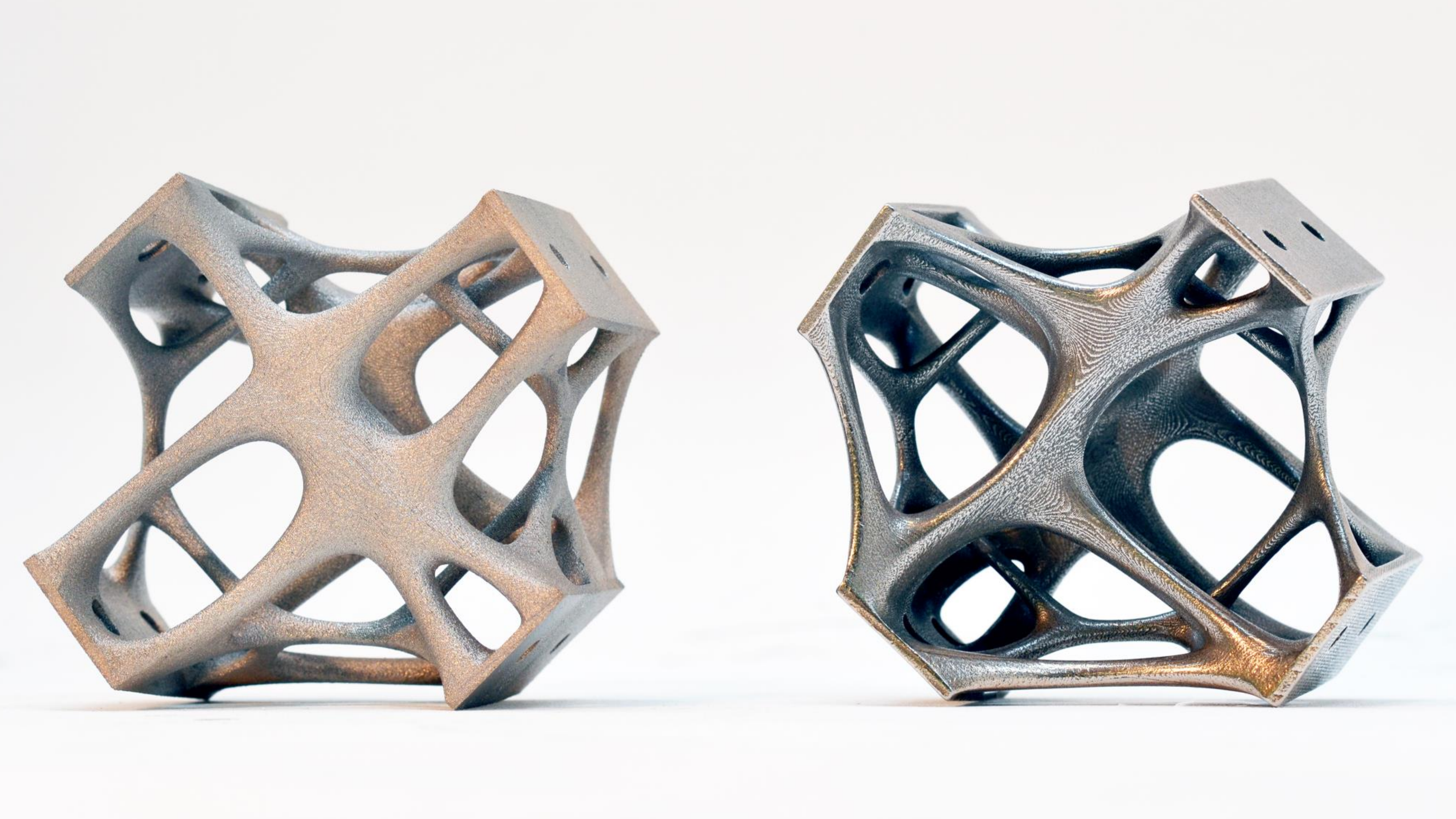
Model Info: C:/Users/Bayu/Desktop/p4/baku/baku.hm*





Contour Plot
Element Densities(Density)
Simple Average
1.000E+00
8.900E-01
7.800E-01
6.700E-01
5.600E-01
4.500E-01
3.400E-01
2.300E-01
1.200E-01
1.000E-02
No result
Max = 1.000E+00
Grids 18377
Min = 1.000E-02
Grids 87008
1: Model
Design : Iteration 0 : Frame 1





Further research

TO and AM in other architecture elements
Quad glazing assembly detail integration with AM
Extensive advanced structural analysis
Extensive physical test for AM materials
Extensive cost analysis

Conclusion

**AM as design tool :
Localized Complexity**

Conclusion

TO : designed by computer?

Thank you