Prefabricated Tensile Façade design and prototyping – P5

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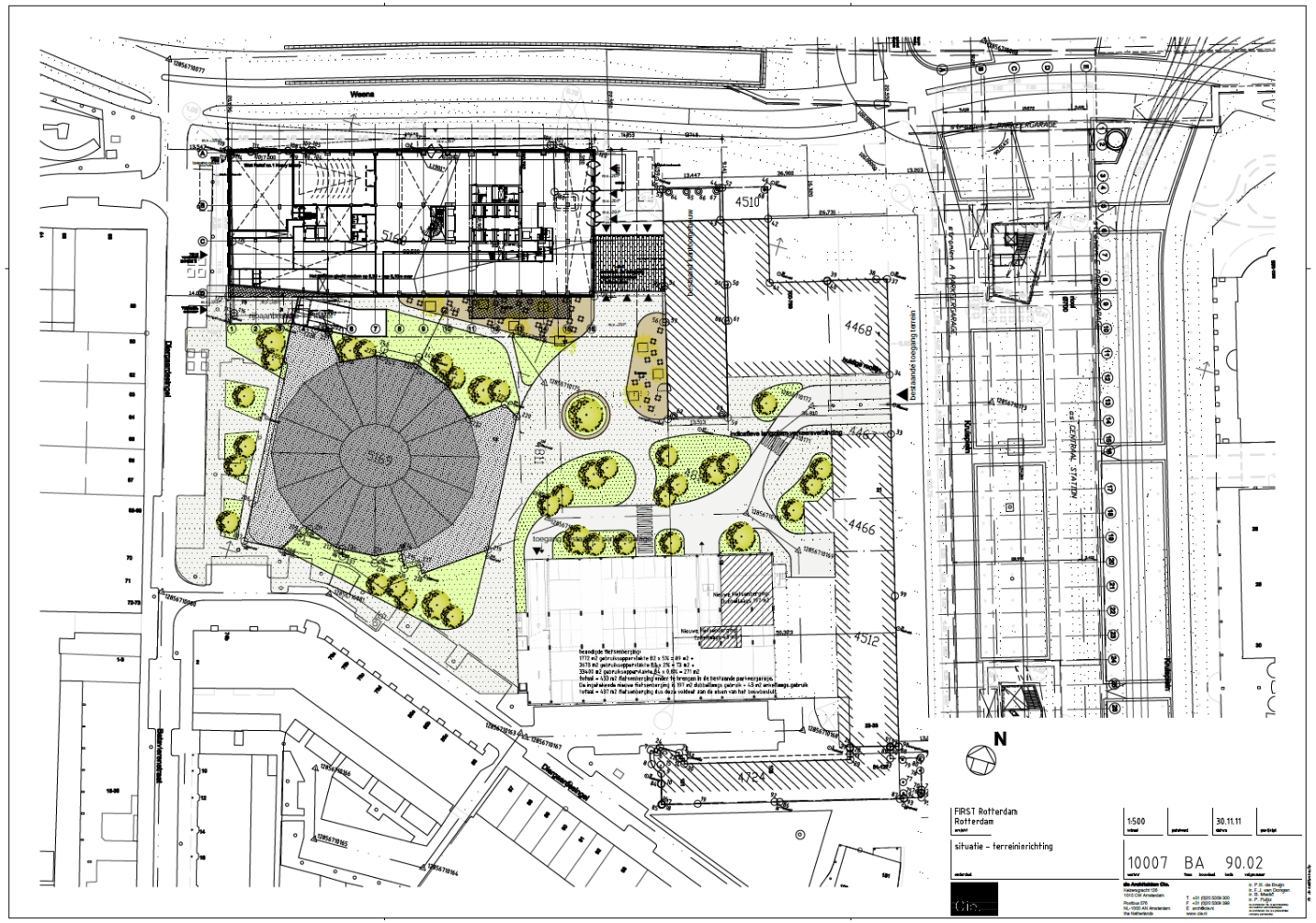
Mentor: Dr.ing. A. Luna Navarro

Second mentor: Prof.dr. M. Overend

External advisor: J. Montali

First Rotterdam Polished Concrete Prefabricated Panels (Loveld)

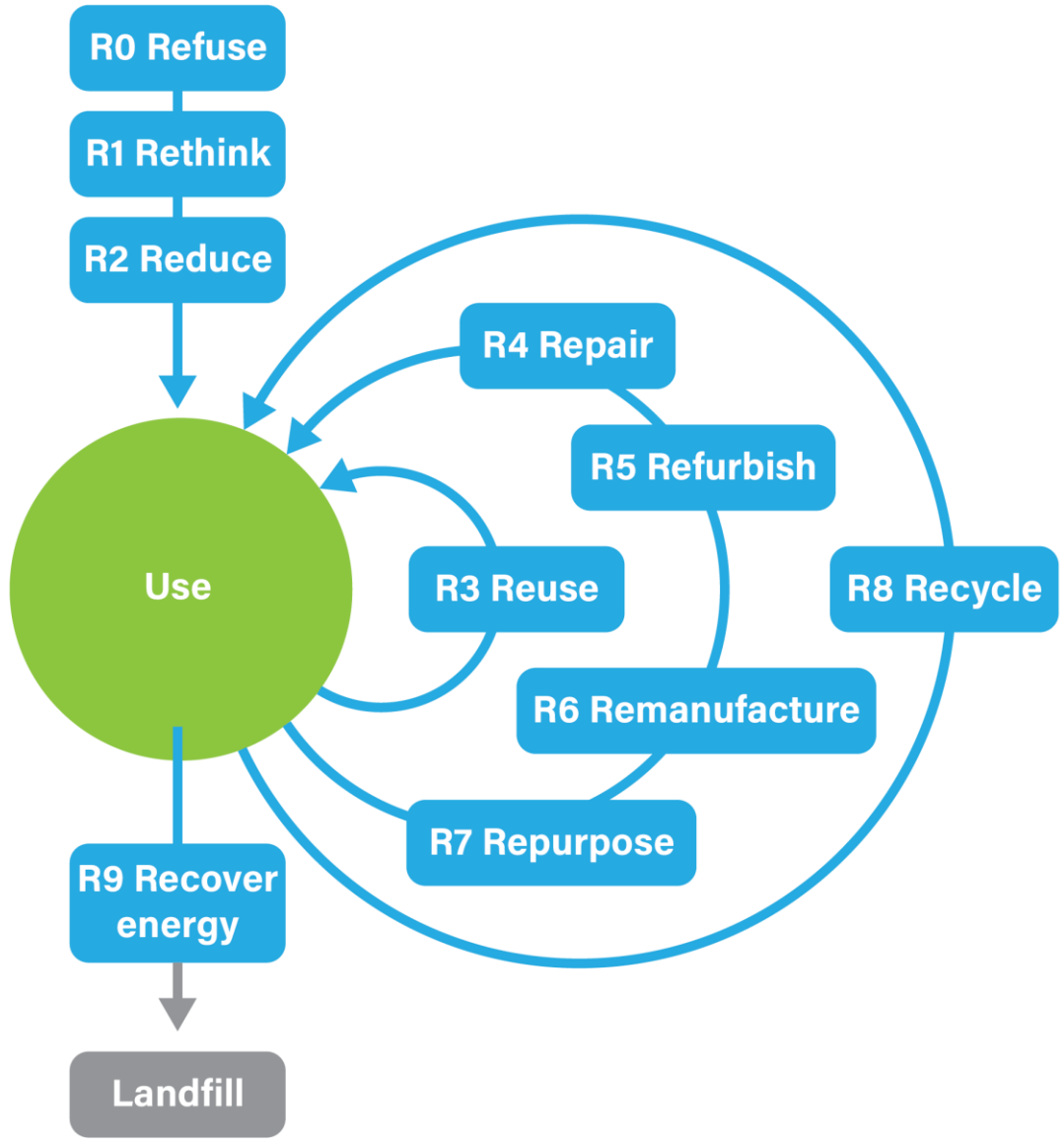


Left image: 10007-20120315-BOUWAANVRAAG (De Architecten Cie)


Rabobank
NaturaDutilh
ROBECO

Left image: Lecture FIRST Rotterdam (RoyalHaskoningDHV)

Right image: Techknowledge Facade Design Presentation (Shrotria Shashvat)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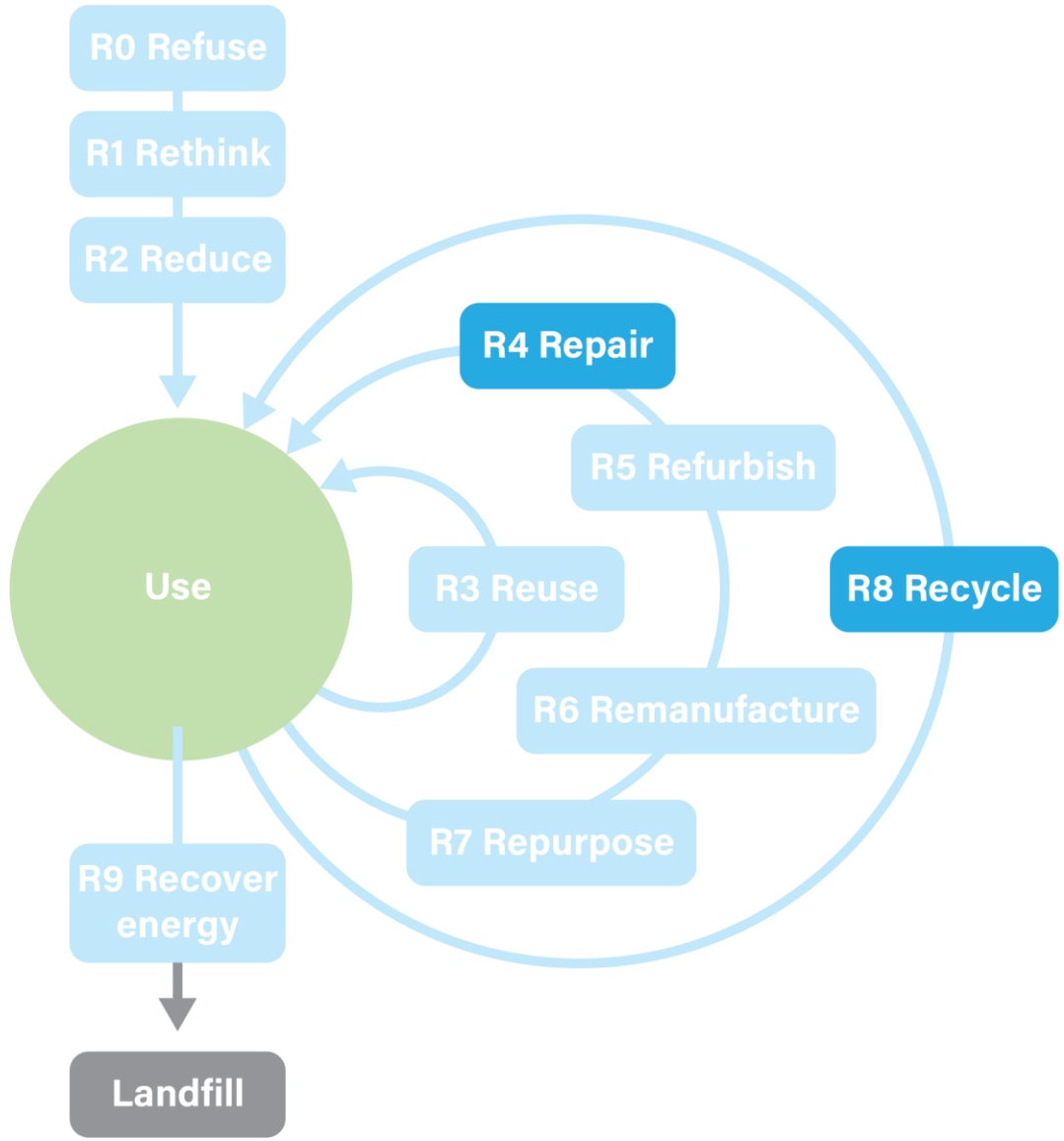
R1 Rethink
R2 Reduce
R4 Repair
R5 Refurbish
Use
R3 Reuse
R8 Recycle
R6 Remanufacture
R7 Repurpose
R9 Recover energy
Landfill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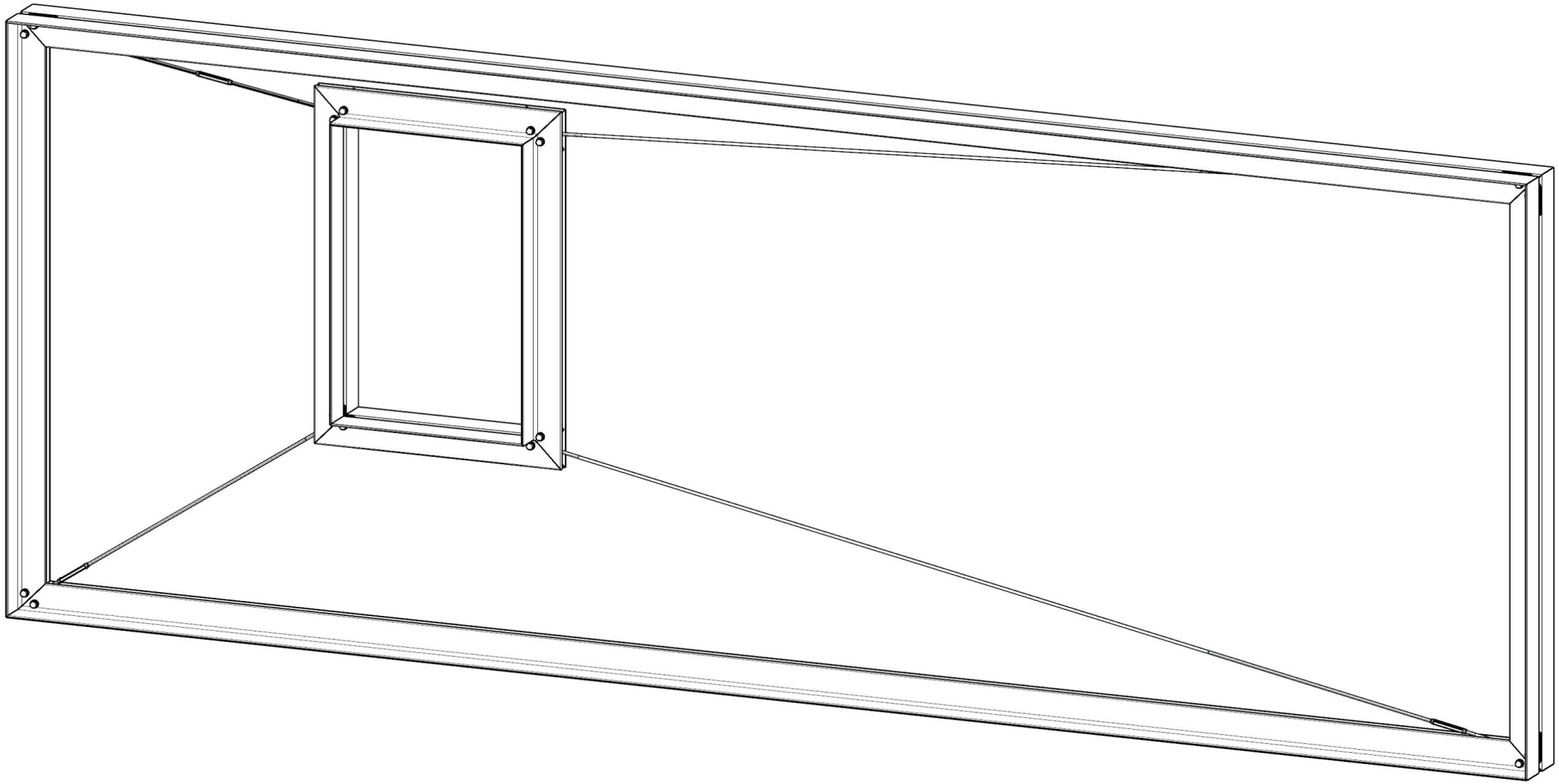
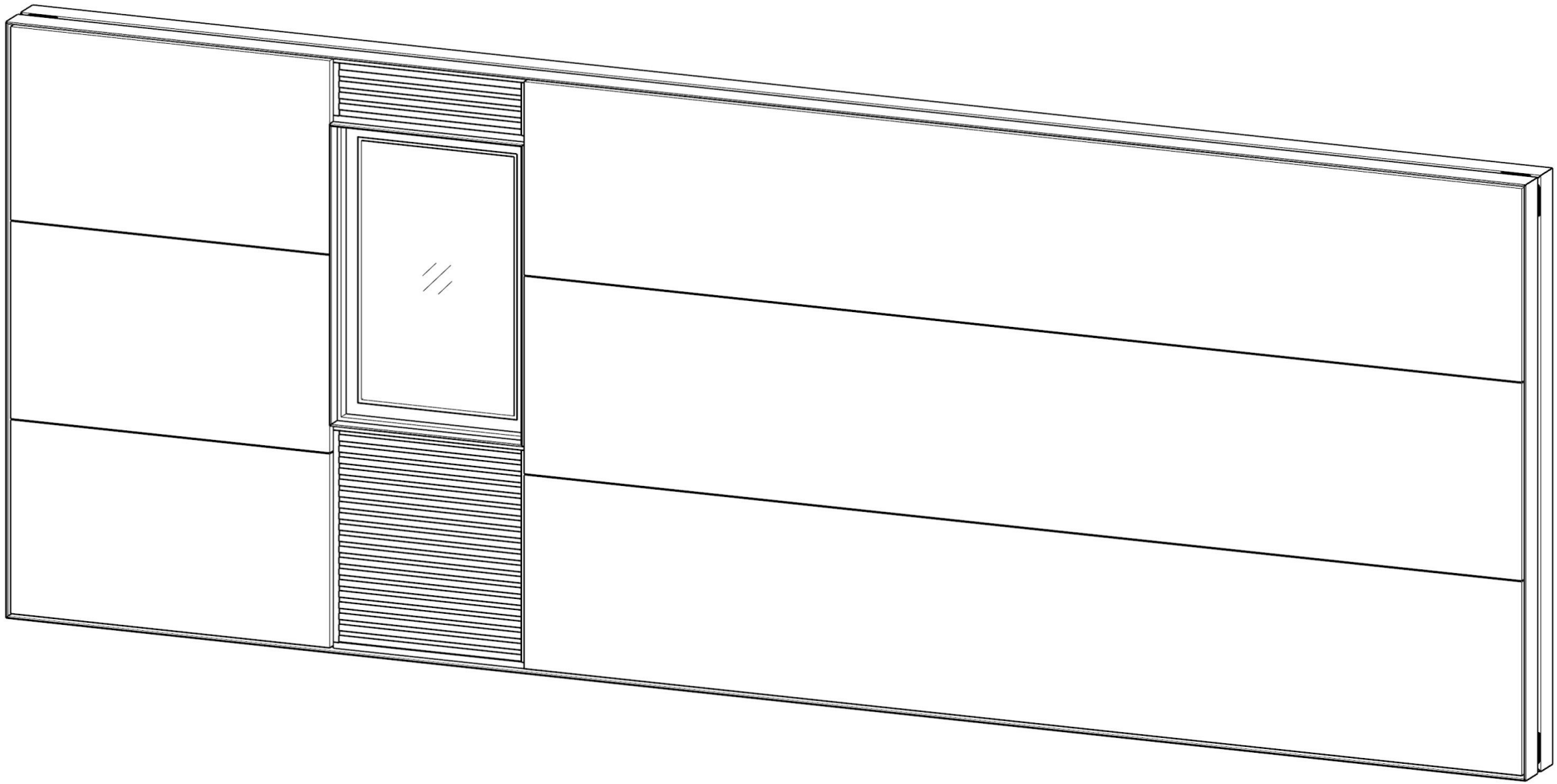
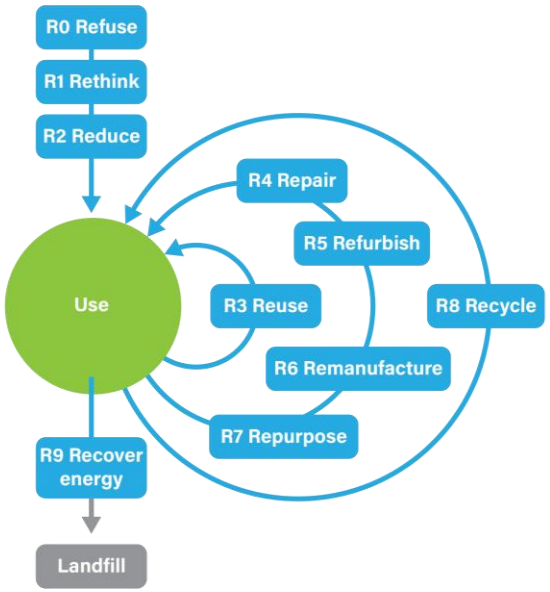


Tensile based facade panel (J. Montali, 2021)

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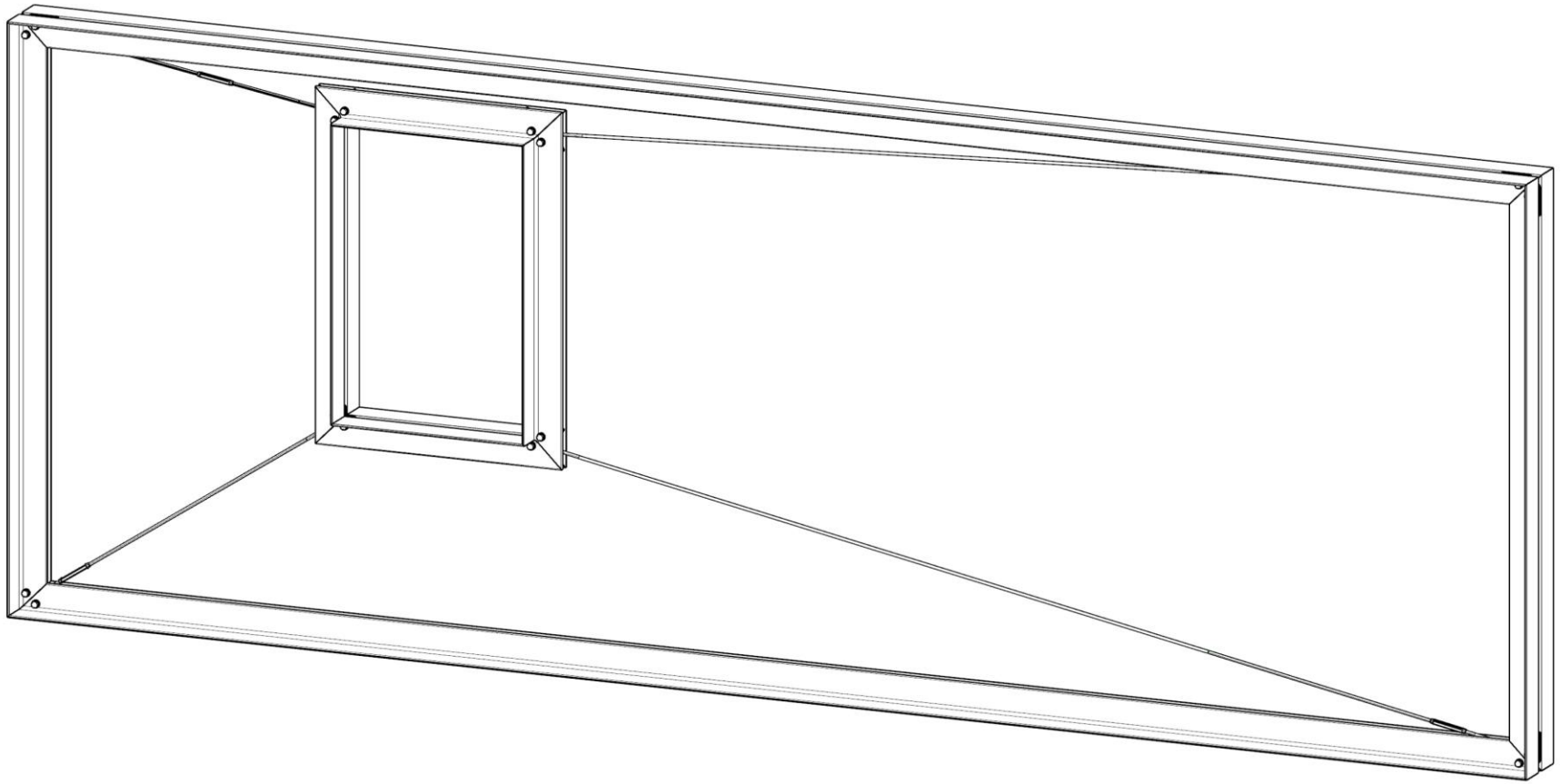

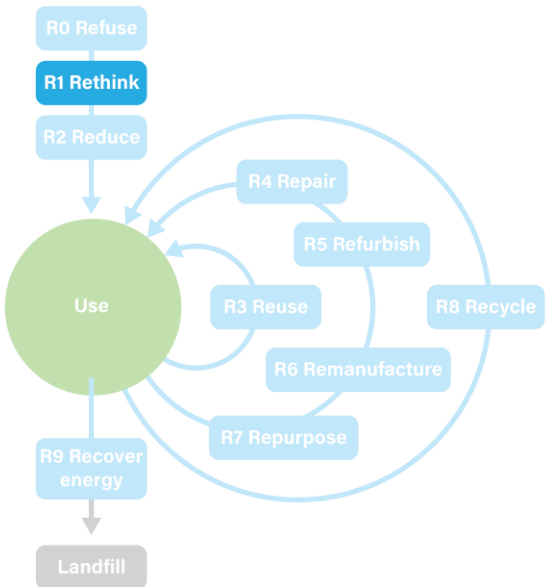
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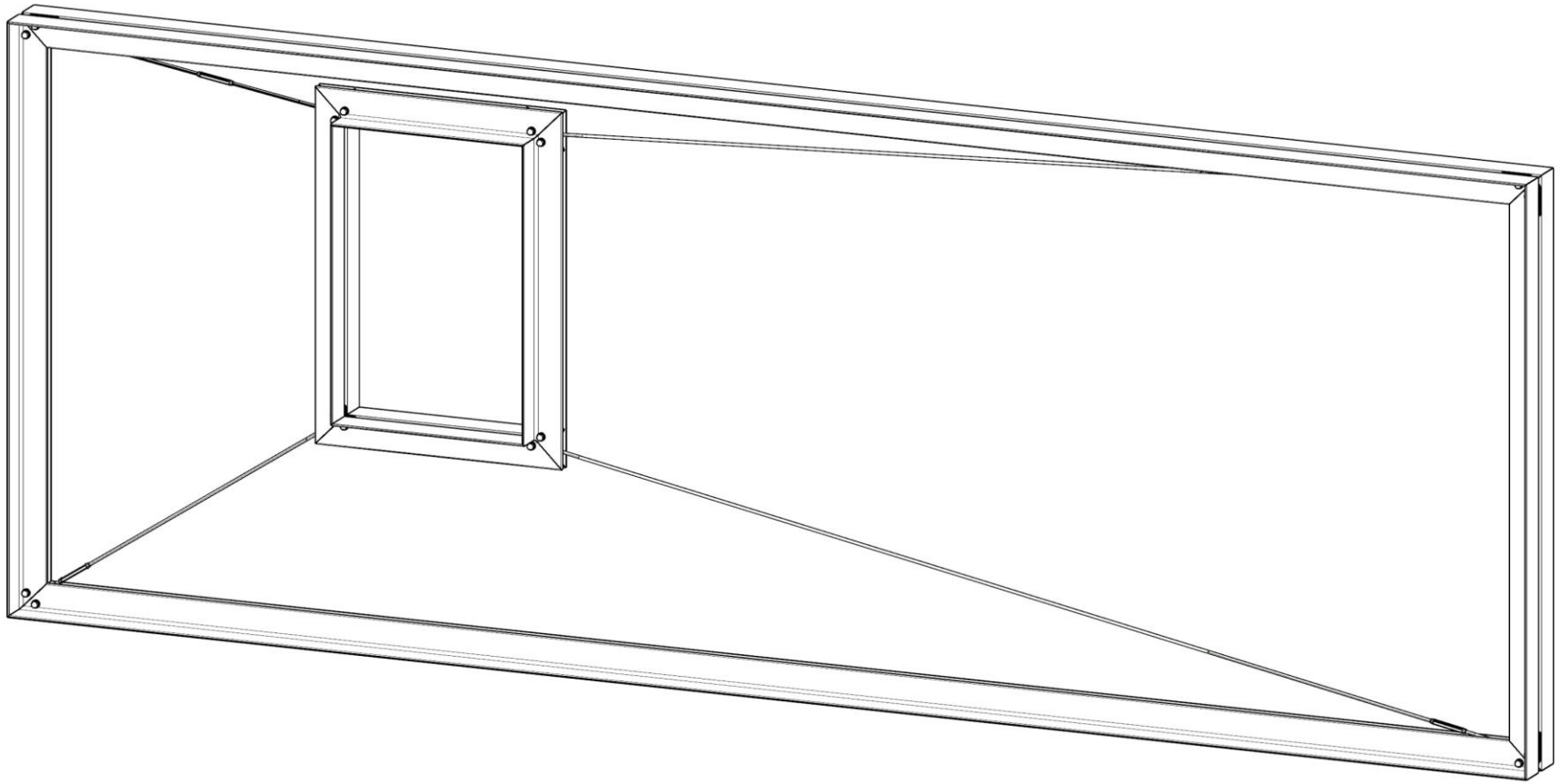

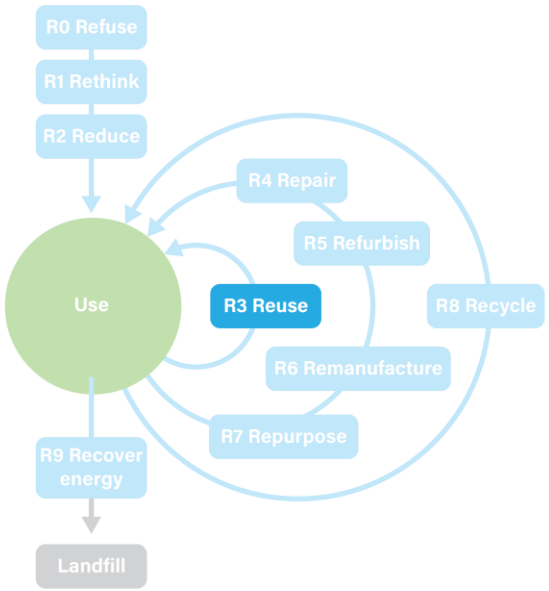
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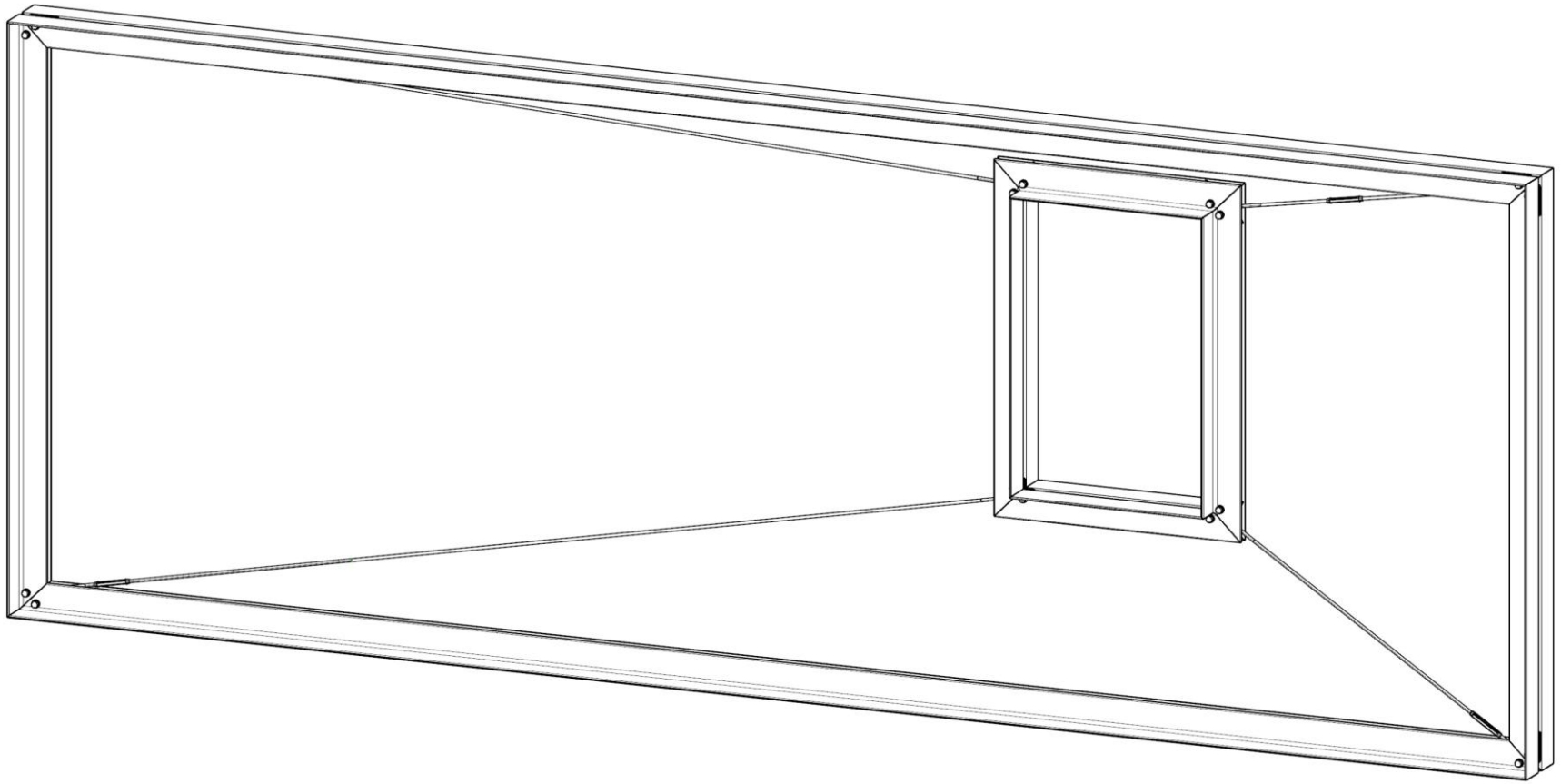

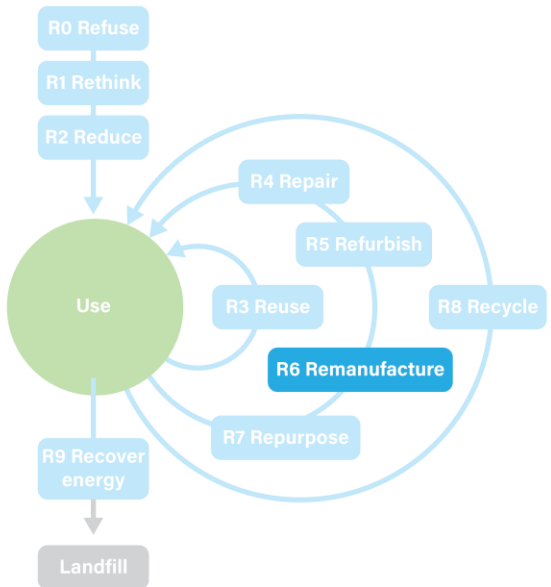
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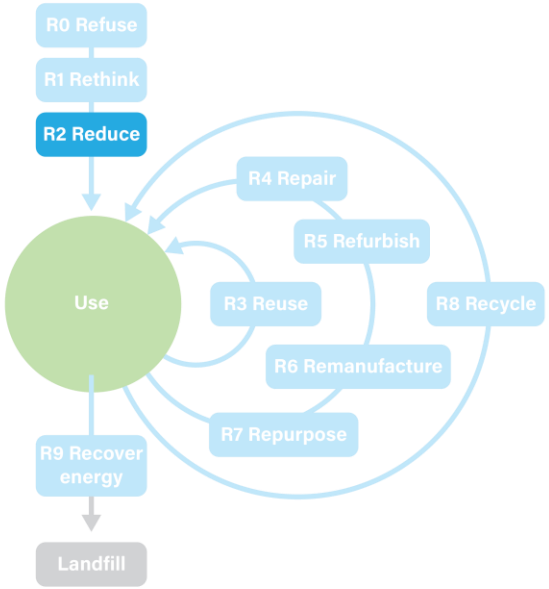
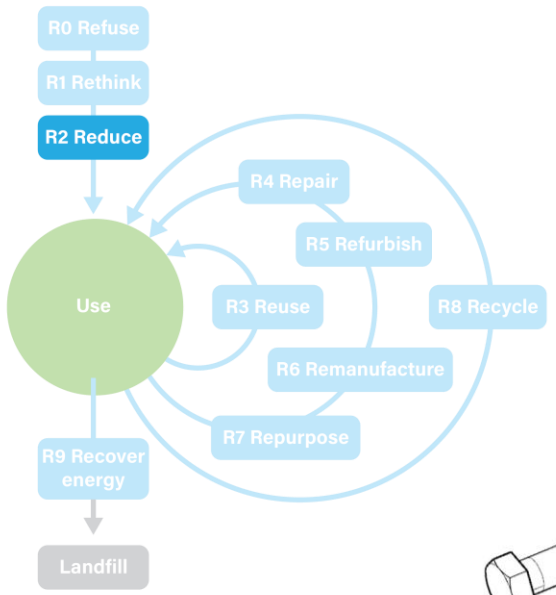


“The combination of the structural principle in which pure tension occurs in the cables with high-quality prestressing steel leads to a weight of the cable net including the knots of only **9 kg/m2**, with a span of 34x42 m. More traditional facade systems would require a steel use of **25 to 35 kg/m2**.”

Nationale staalprijs: Markthal (https://www.nationalestaalprijs.nl/project/gevel-winkel-en-appartementengebouw-markthal)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RQ: ‘How can the principle of a tensile based system be utilized to create a more effective prefabricated facade solution?’

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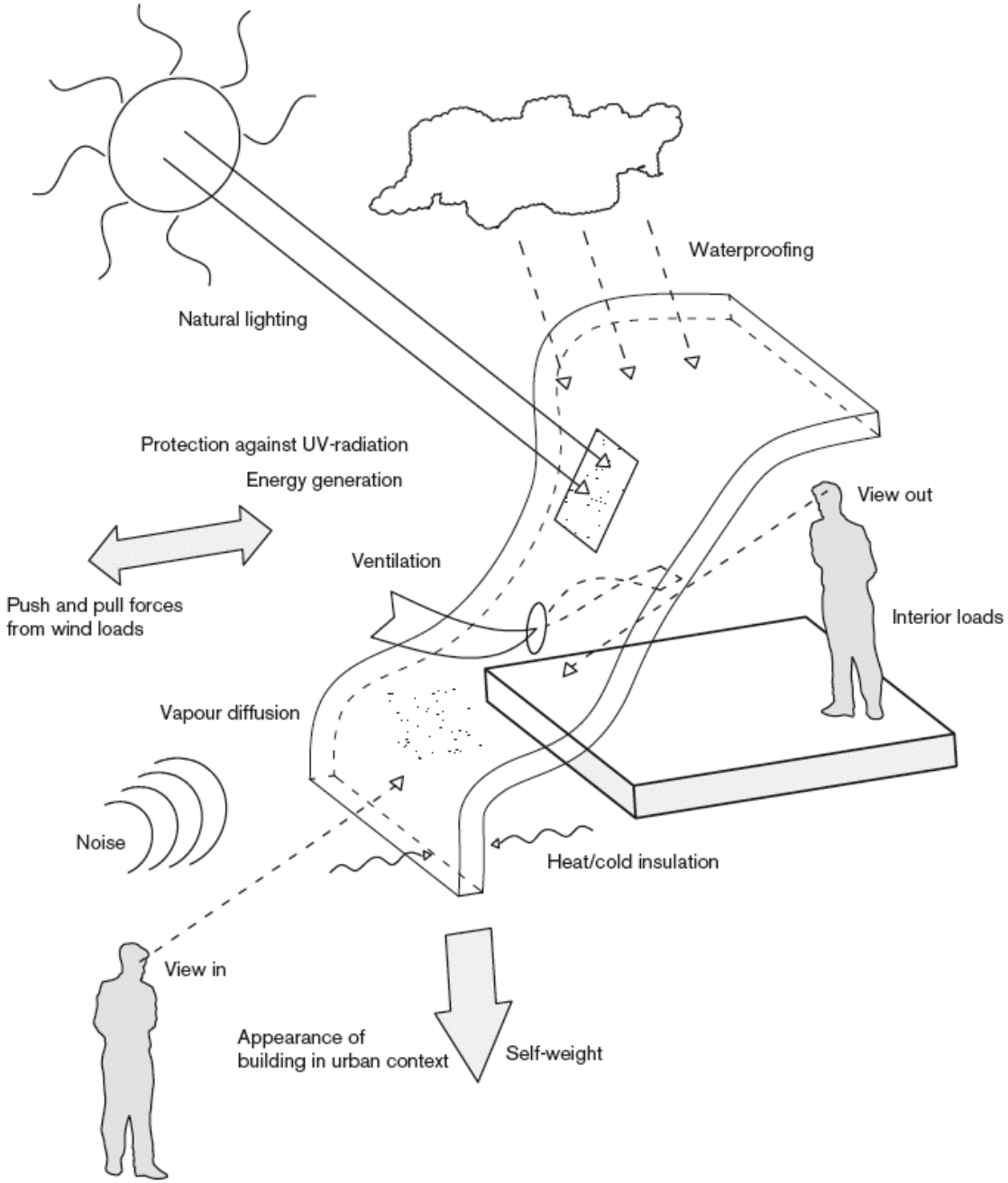
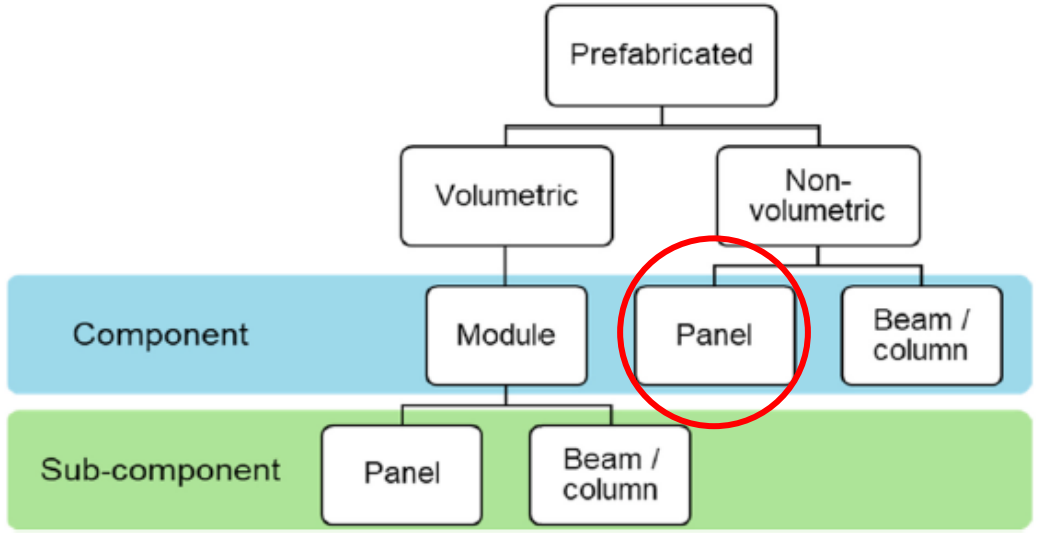
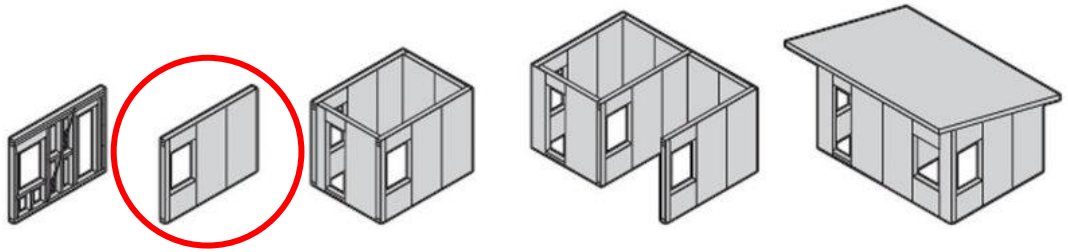


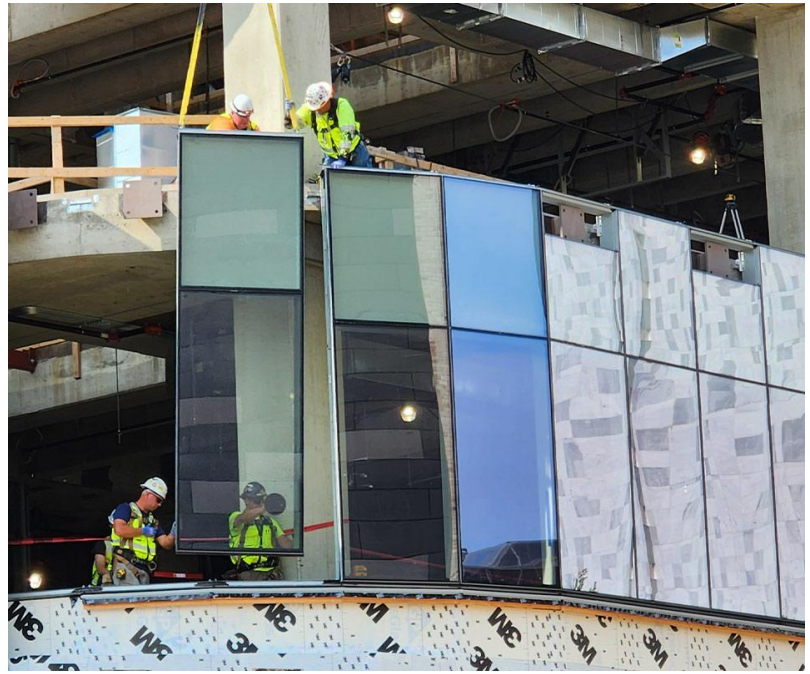
Facade design criteria (Knaack, 2007)

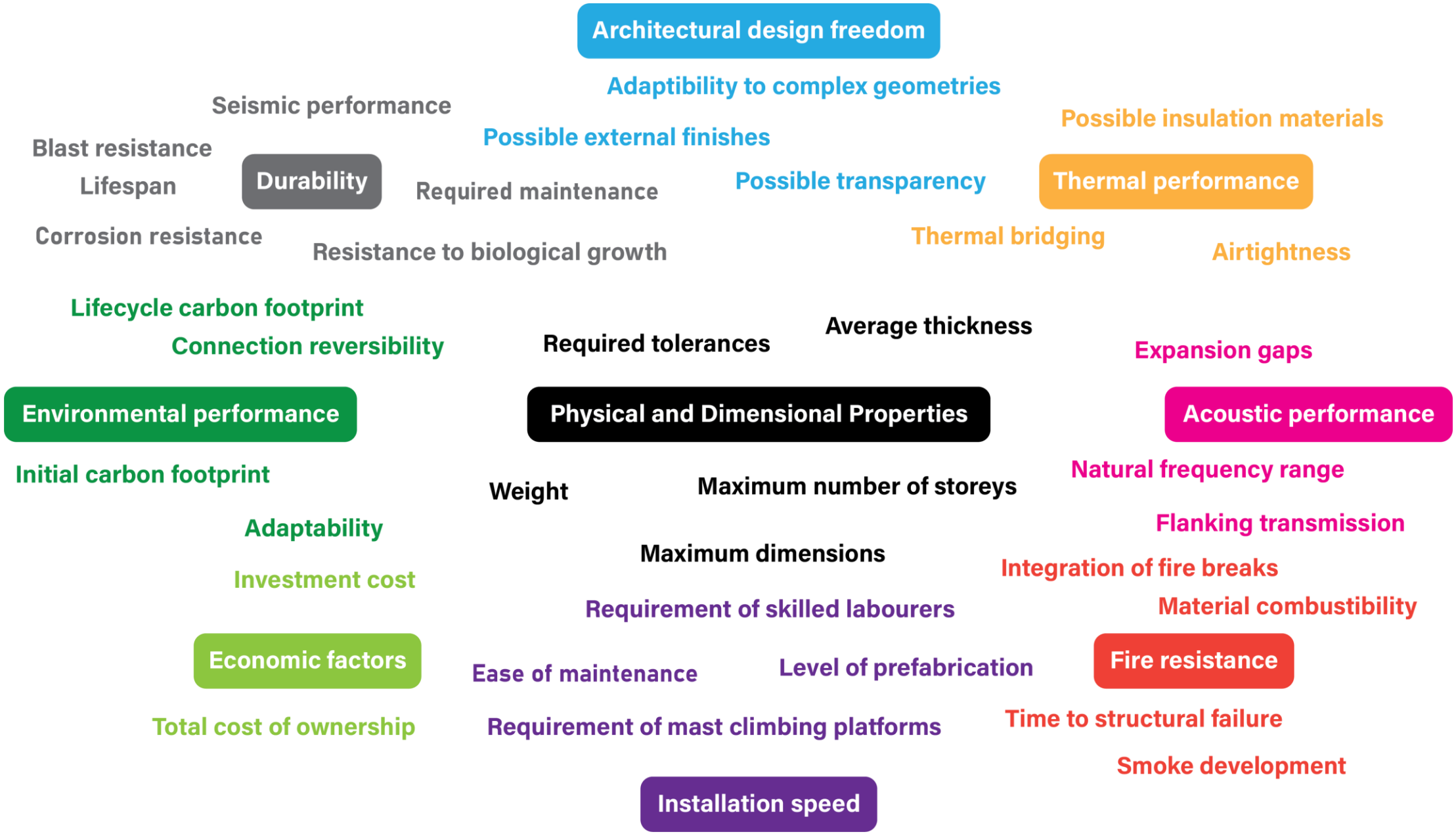




Top: Levels of prefabrication (Sah, T. et al, 2024)

Bottom: Types of prefabrication (Moradibistouni M., 2017)




Architectural design freedom
Adaptibility to complex geometries
Seismic performance
Possible insulation materials
Possible external finishes
Blast resistance
Durability
Lifespan
Required maintenance
Possible transparency
Thermal performance
Corrosion resistance
Thermal bridging
Resistance to biological growth
Airtightness
Lifecycle carbon footprint
Average thickness
Connection reversibility
Required tolerances
Expansion gaps
Environmental performance
Physical and Dimensional Properties
Acoustic performance
Initial carbon footprint
Natural frequency range
Weight
Maximum number of storeys
Adaptability
Flanking transmission
Maximum dimensions
Investment cost
Integration of fire breaks
Requirement of skilled labourers
Material combustibility
Economic factors
Ease of maintenance
Level of prefabrication
Fire resistance
Total cost of ownership
Requirement of mast climbing platforms
Time to structural failure
Smoke development
Installation speed

Wall panel types	Function	Advantages	Disadvantages
Lightweight timber framed (LTF)	Load-bearing in low-rise and non-load-bearing in mid to high-rise buildings	Lightweight, easy to fabricate, cost-effective, renewable resource	Susceptible to mould and termite, low fire resistance, durability issues with exposure to moisture, low blast resistance
Light gauge steel framed (LSF)	Load-bearing in low to mid-rise and non-load-bearing in high-rise buildings	Easy fabrication, high strength-to-weight ratio, resistance to mould and termite, good fire resistance, low embodied carbon	Corrosion of steel studs, thermal bridging effect, low blast resistance
Structural insulated panel (SIP)	Load-bearing in low-rise and non-load-bearing in mid to high-rise buildings	High strength-to-weight ratio, high thermal insulation, economical, low embodied carbon	Low fire resistance, durability issues, low impact and blast resistance
Cross-laminated timber (CLT)	Load-bearing in low to mid-rise and non-load-bearing in high-rise buildings	High strength, thermal insulation, renewable resource	Durability issues, low fire resistance, high cost
Precast concrete sandwich panel (PCSP)	Load-bearing and non-load-bearing in low to high-rise buildings	High strength, durable, fire resistant, high thermal insulation, low maintenance cost, low operational carbon	Wet connection, corrosion of steel reinforcement
Prefabricated Tensile Façade Panel (PTFP)	?	?	?

Prefabricated wall panel types, (2024) Prefabricated concrete sandwich and other lightweight wall panels for sustainable building construction: State-of-the-art review
Authors: Tilak Prasad Saha, Andrew William Laceya, Hong Haob, Wensu Chena)

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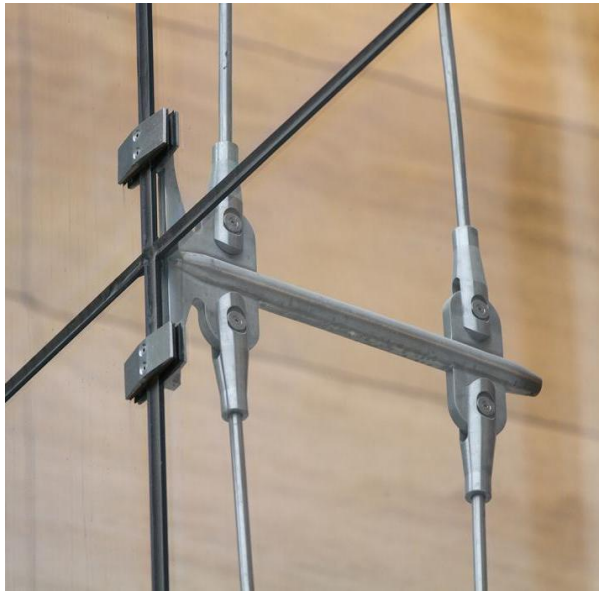
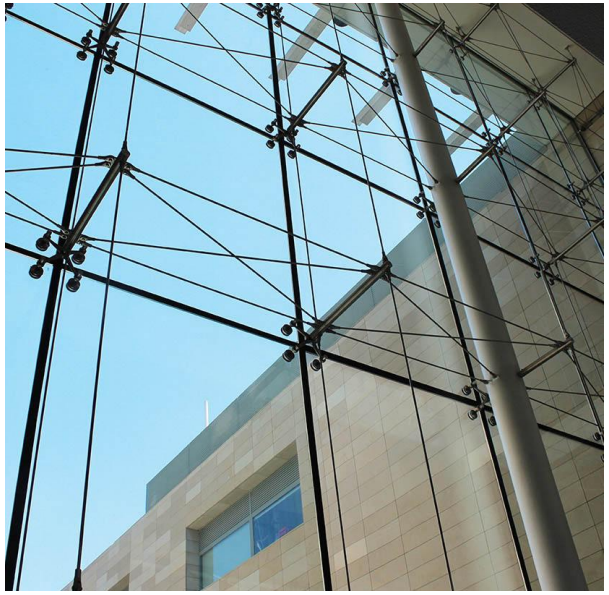
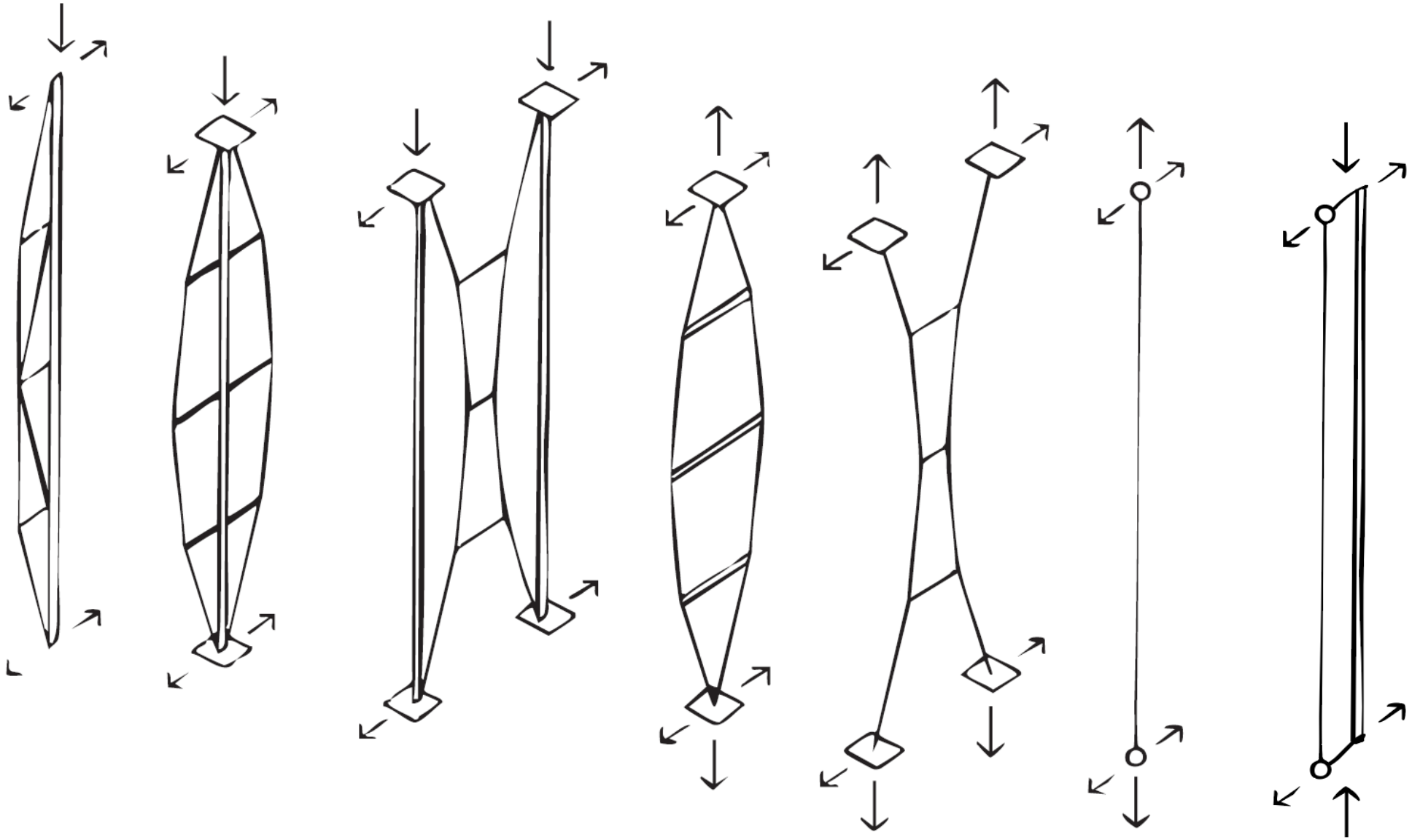
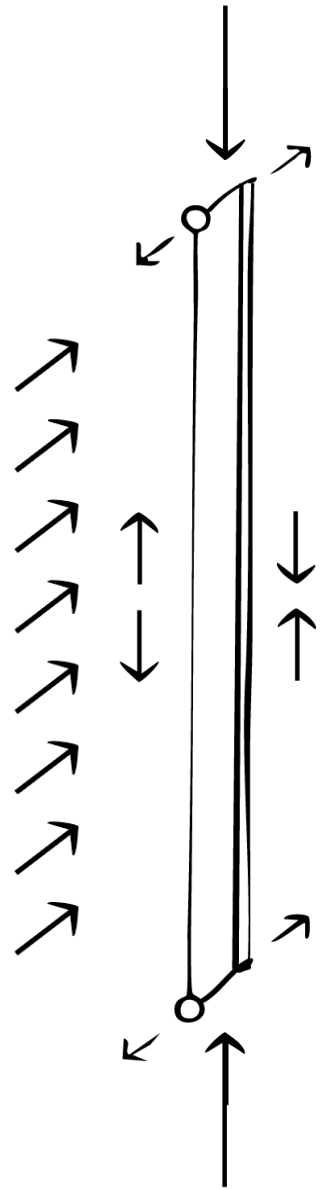


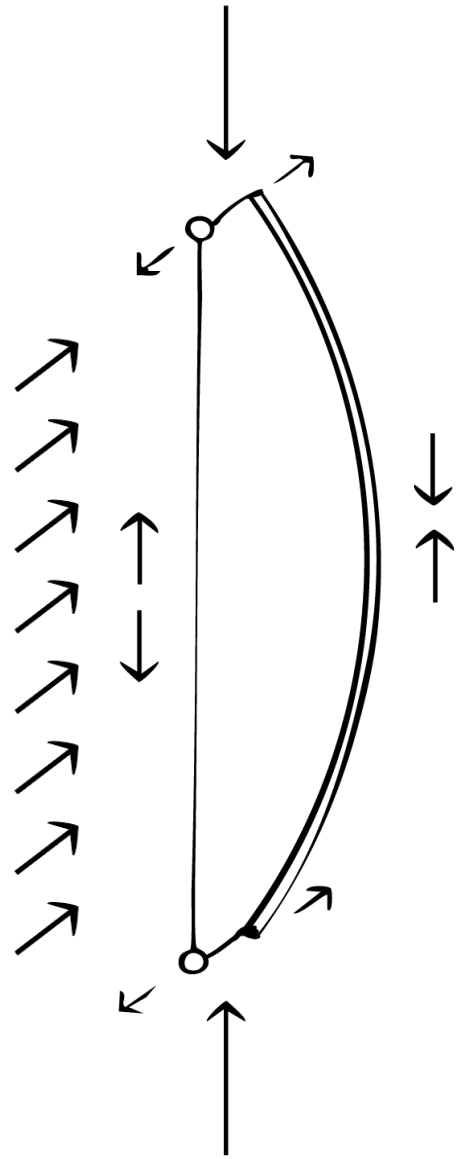


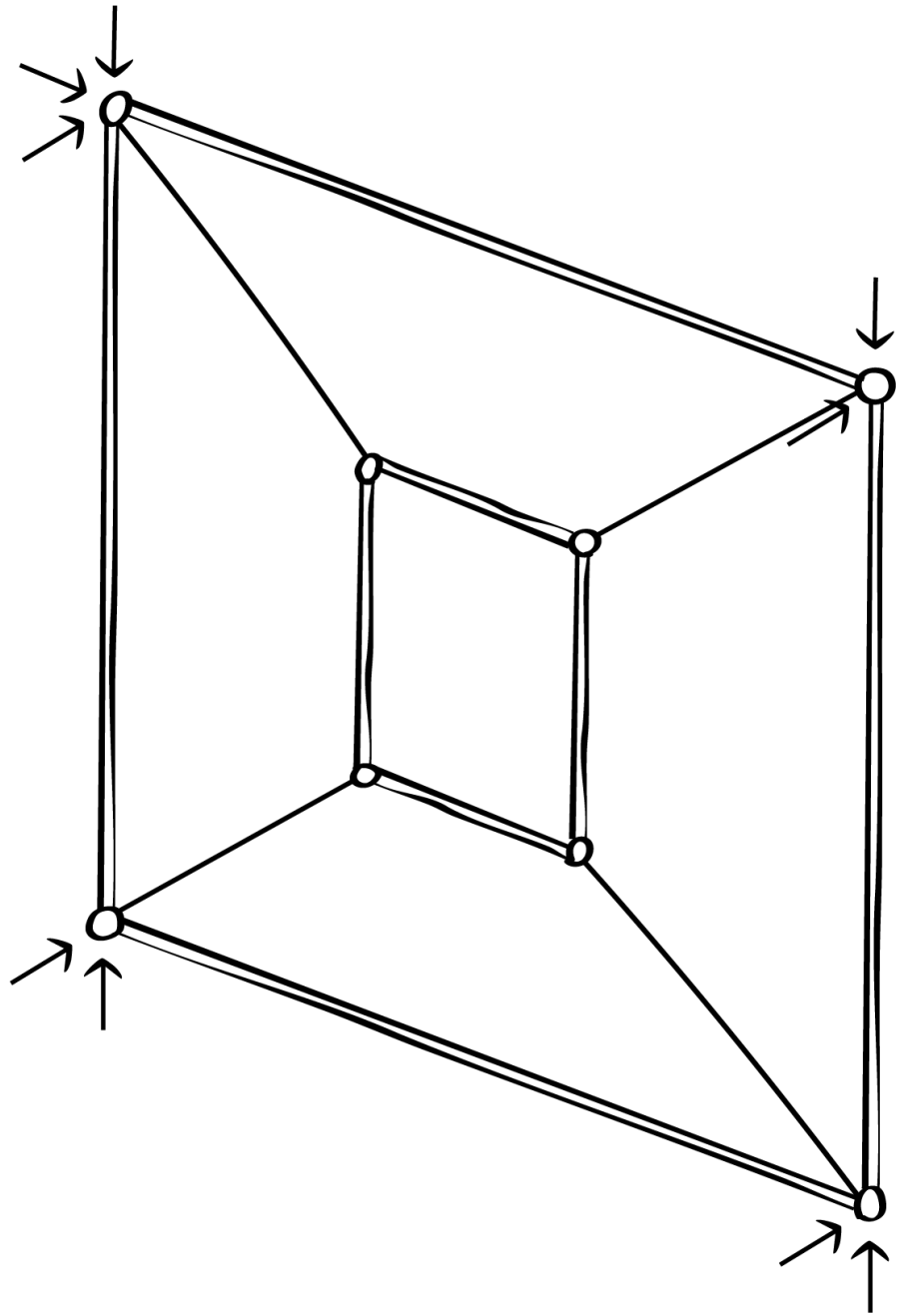
Bayer headquarter in Leverkusen (architect: Murphy/Jahn, Chicago, completion: 2002)

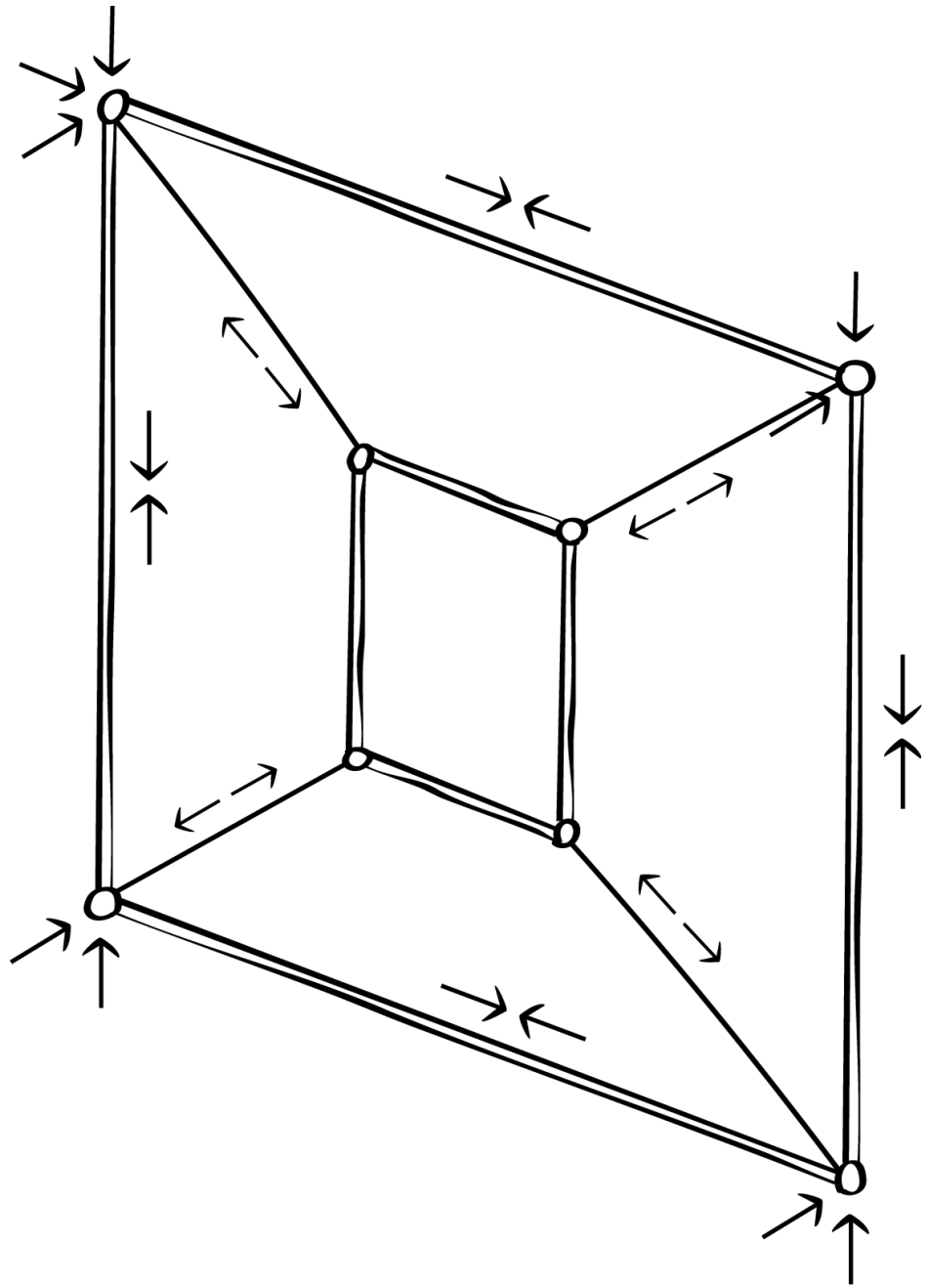


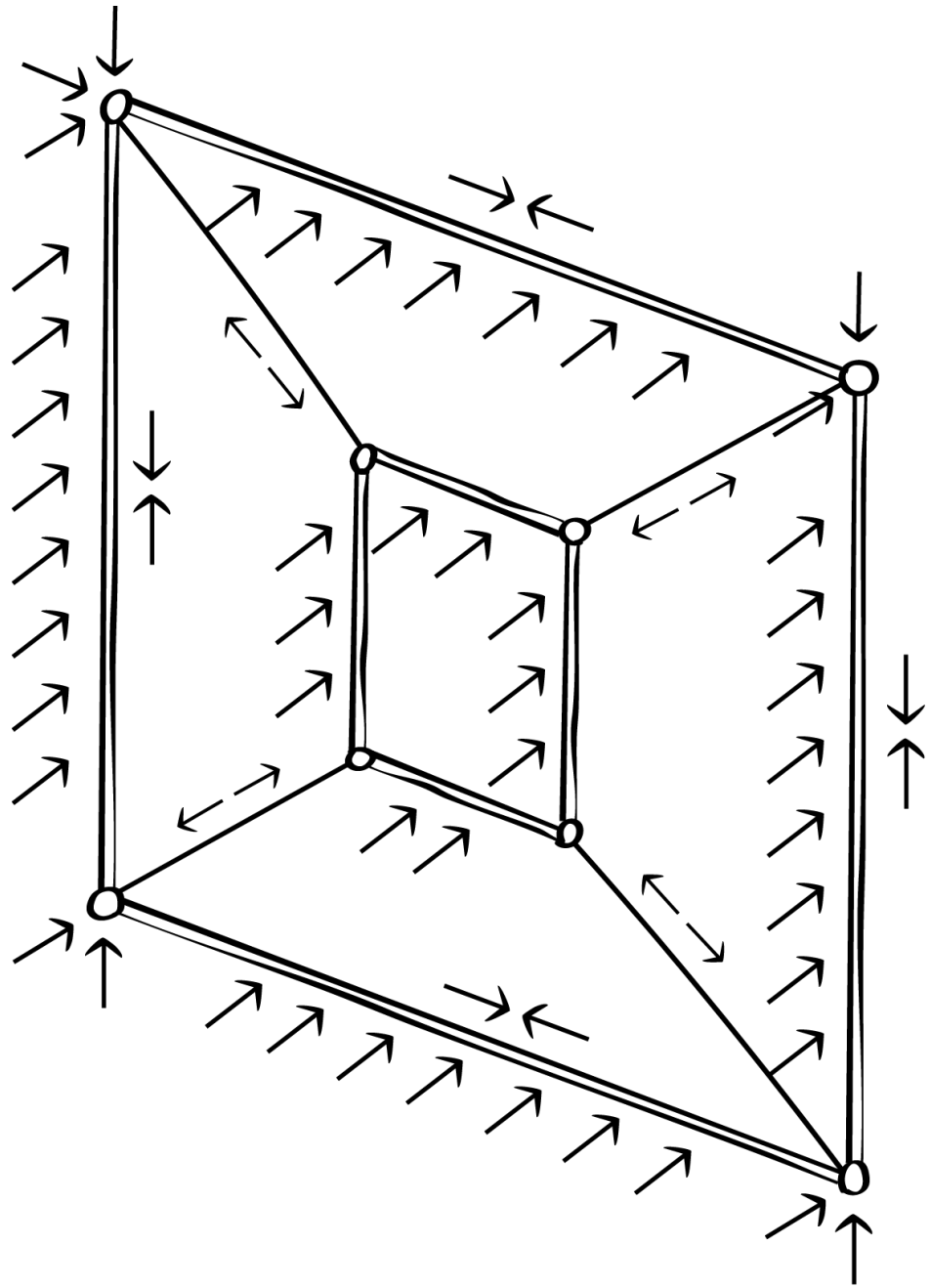
Principle primary structural systems of cable-stayed façades (W. Sobek et al.)

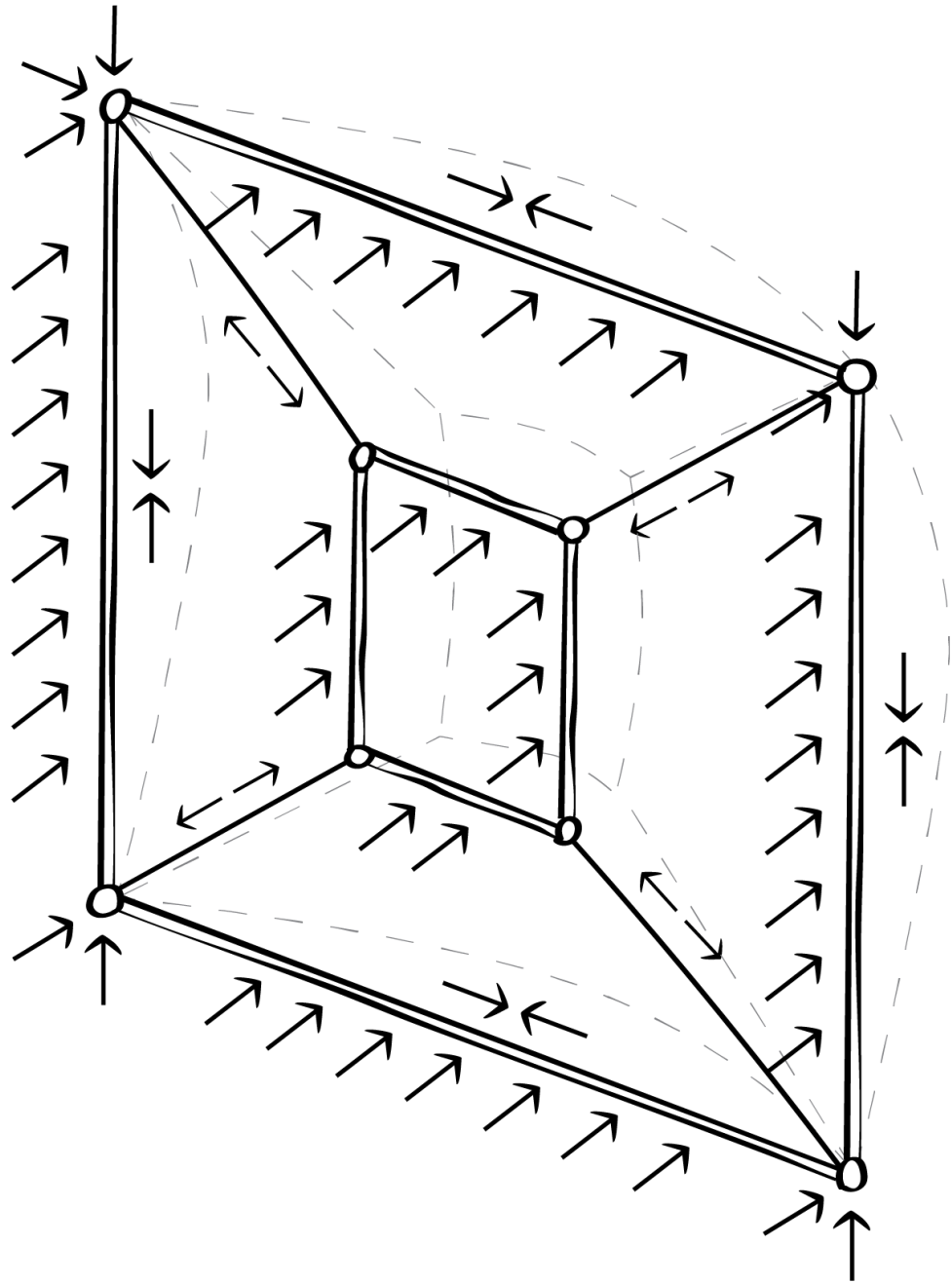


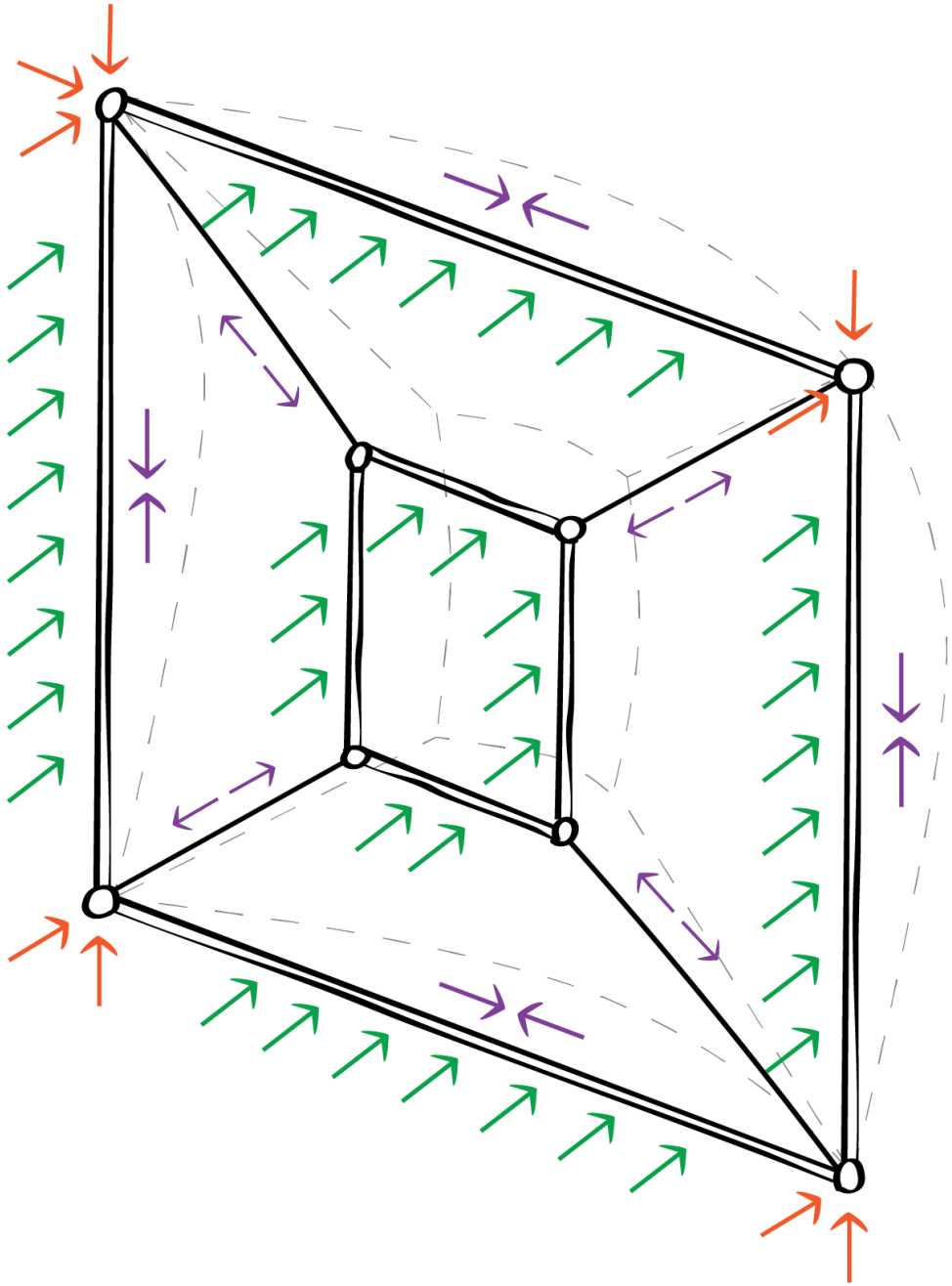






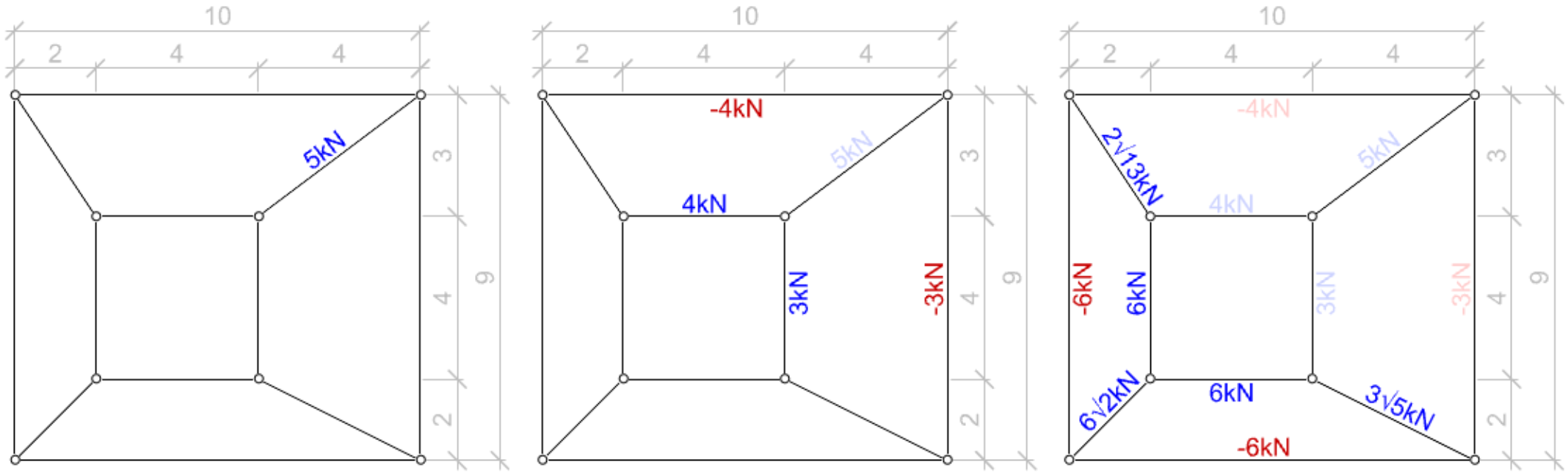






- Prestress
- Wind loads
- Panel configuration
- Other external loads and restraints

Prestress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9
-4kN
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4kN
3kN
-3kN
10
2
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9
-4kN
2√13kN
5kN
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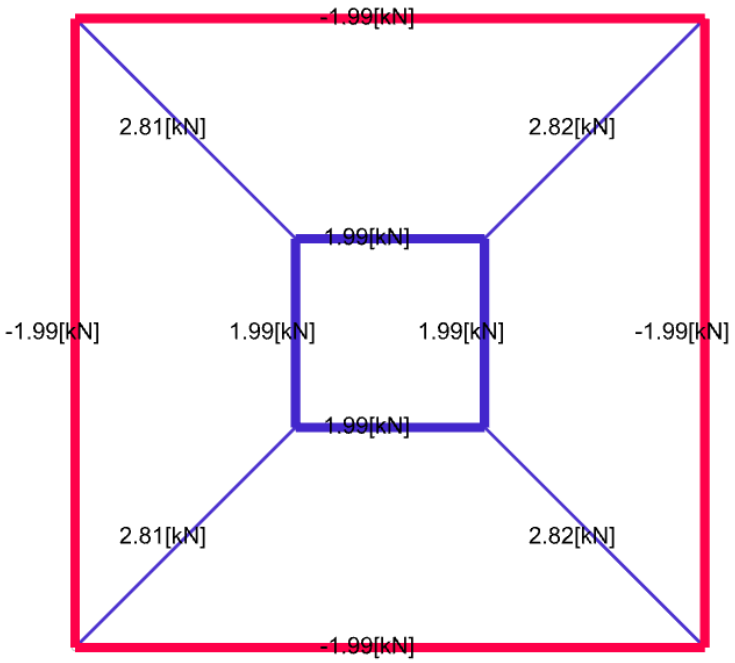
6√2kN
6kN
3√5kN
-6kN

Prestress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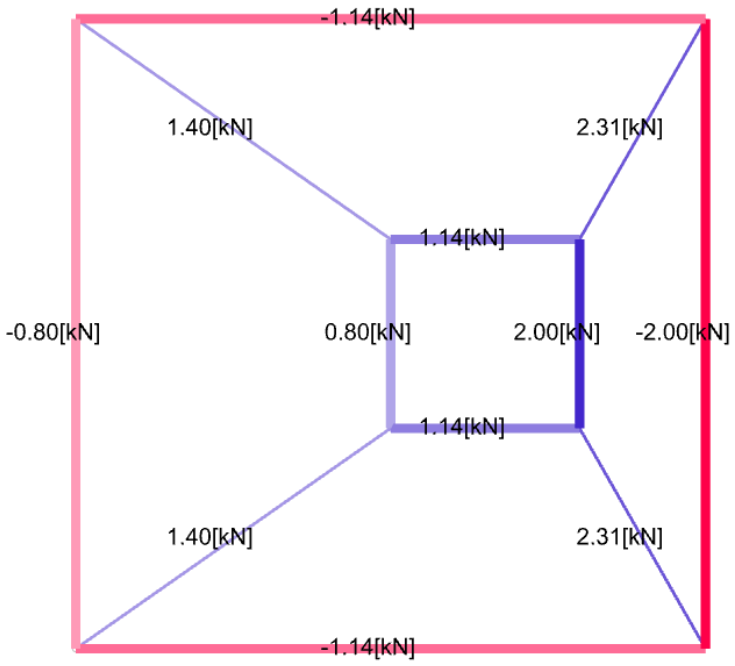
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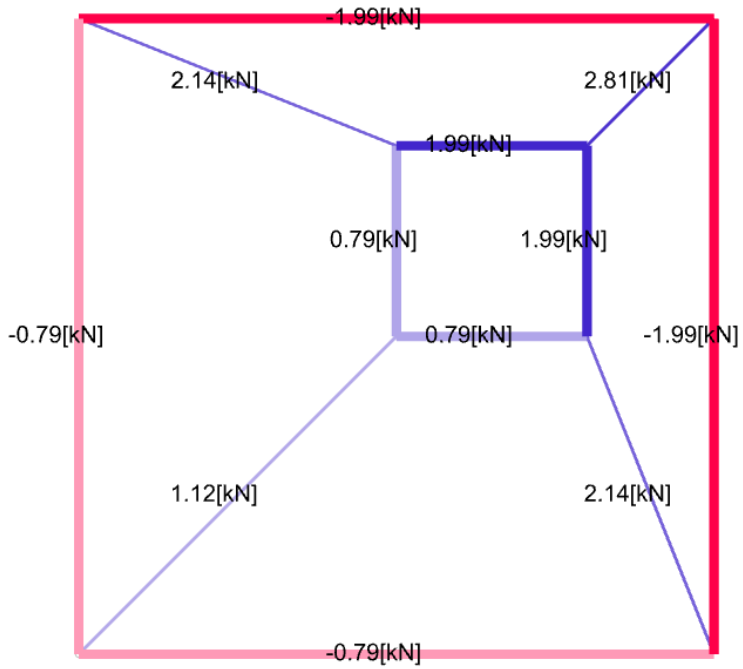
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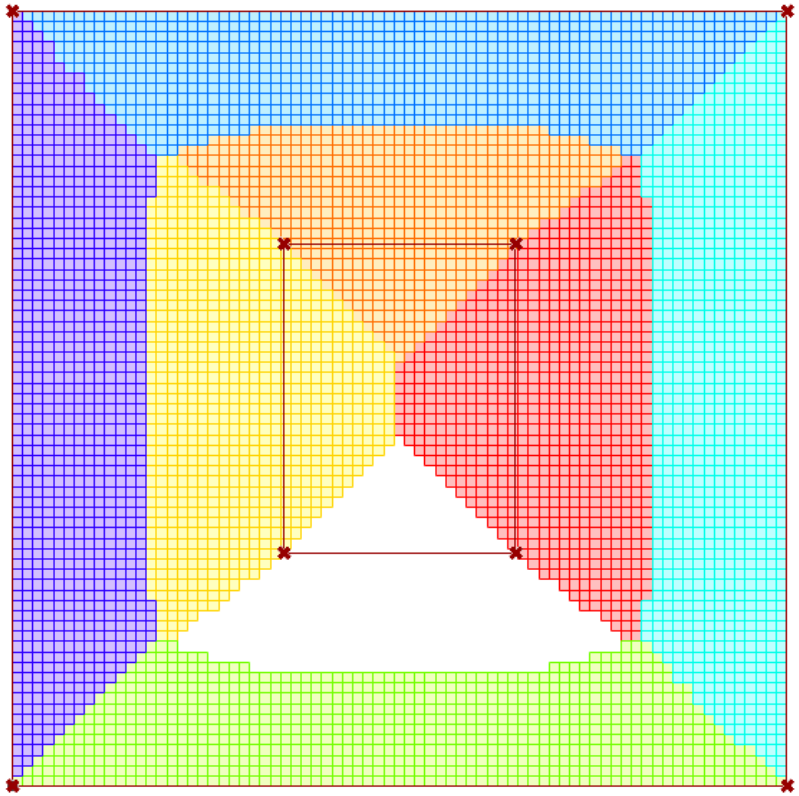
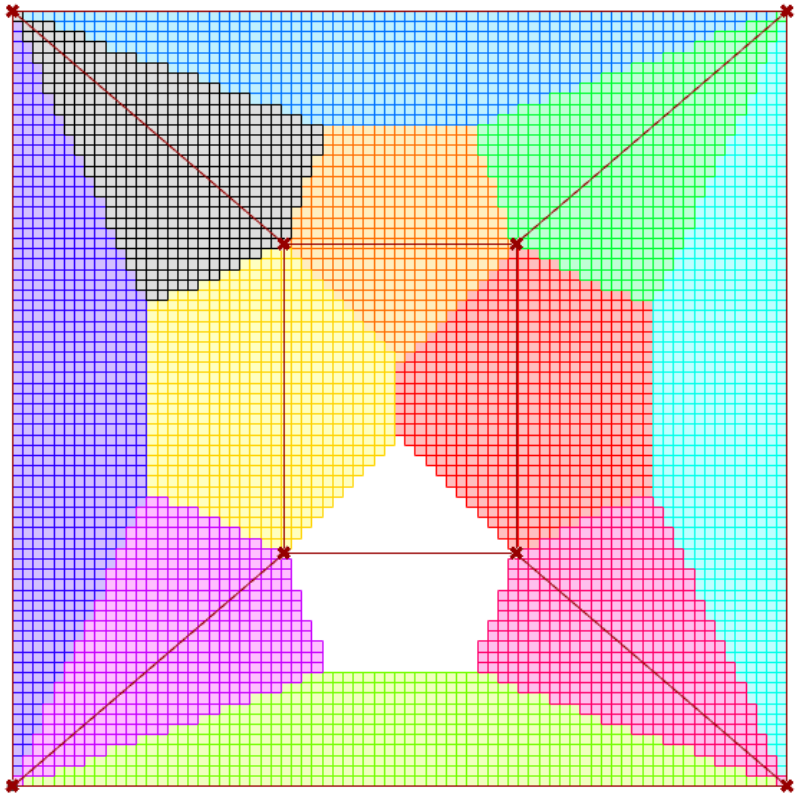
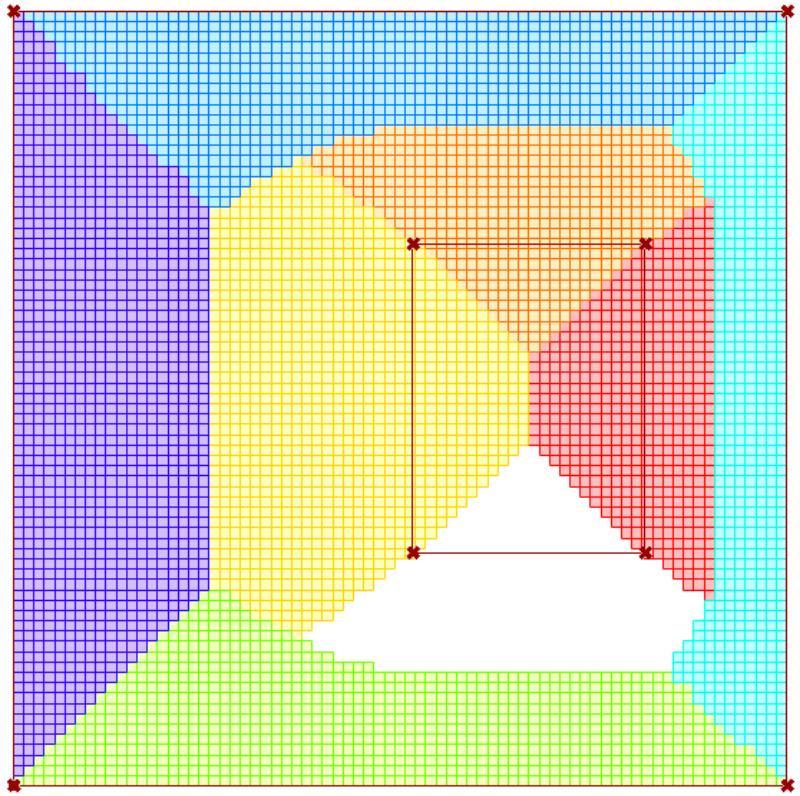
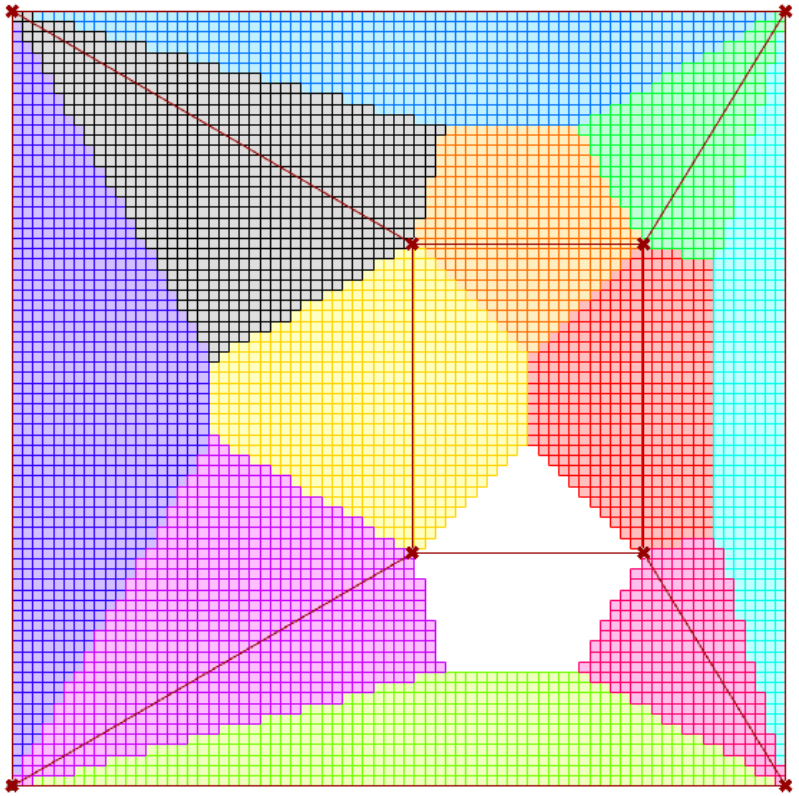
Wind loads



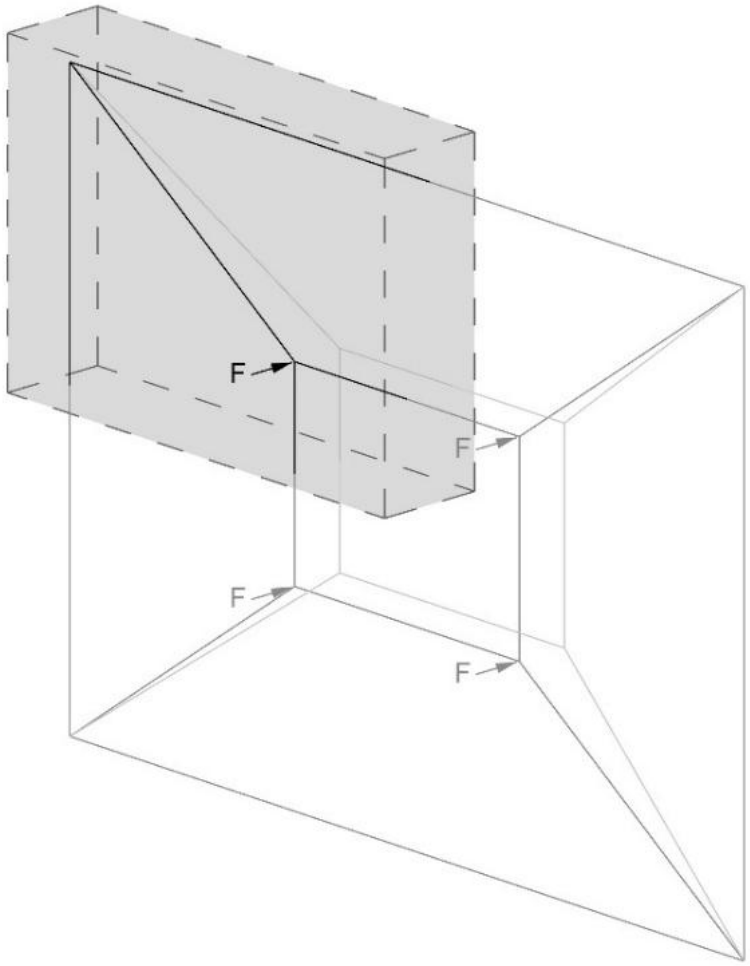


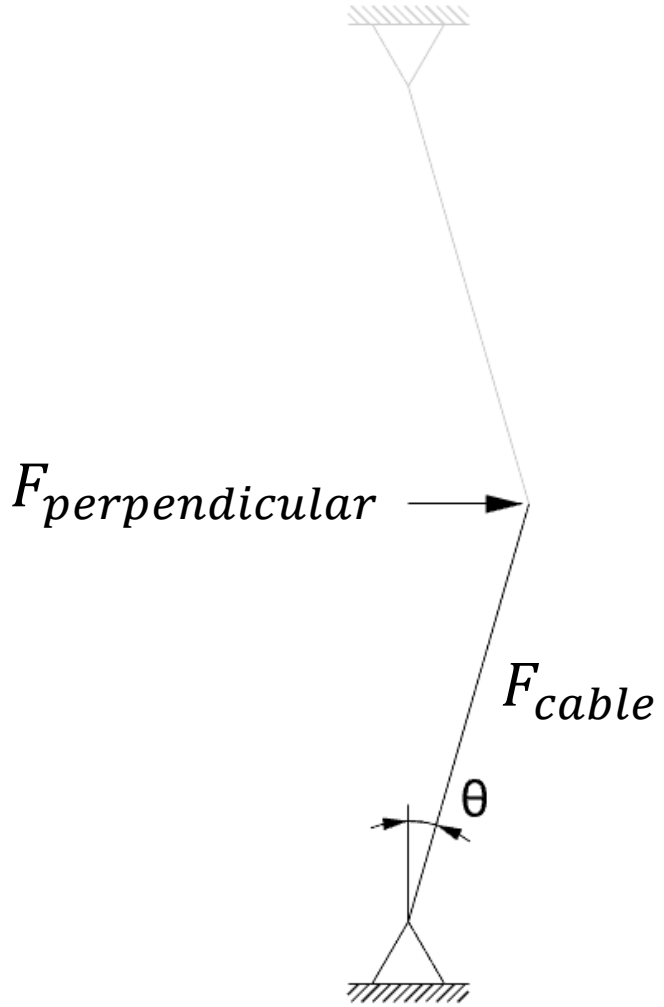
Wind loads



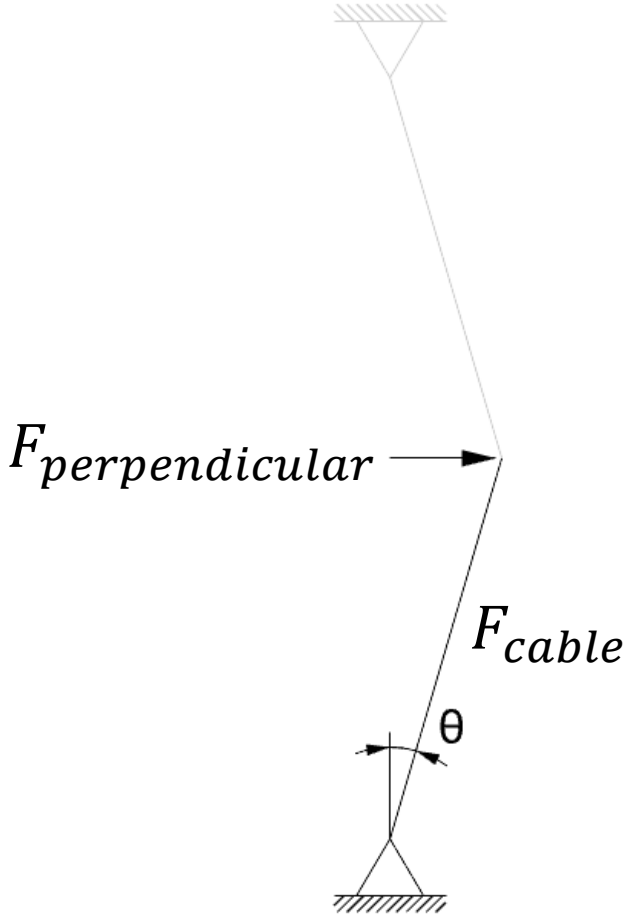


Prestress & Wind loads





$$F_{perpendicular} = \sin\theta \cdot F_{cable}$$



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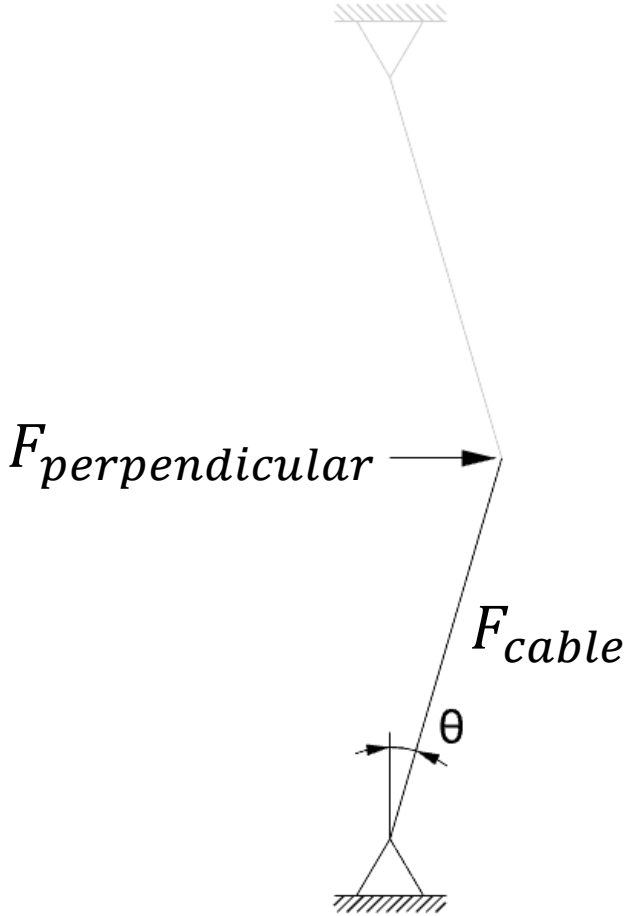
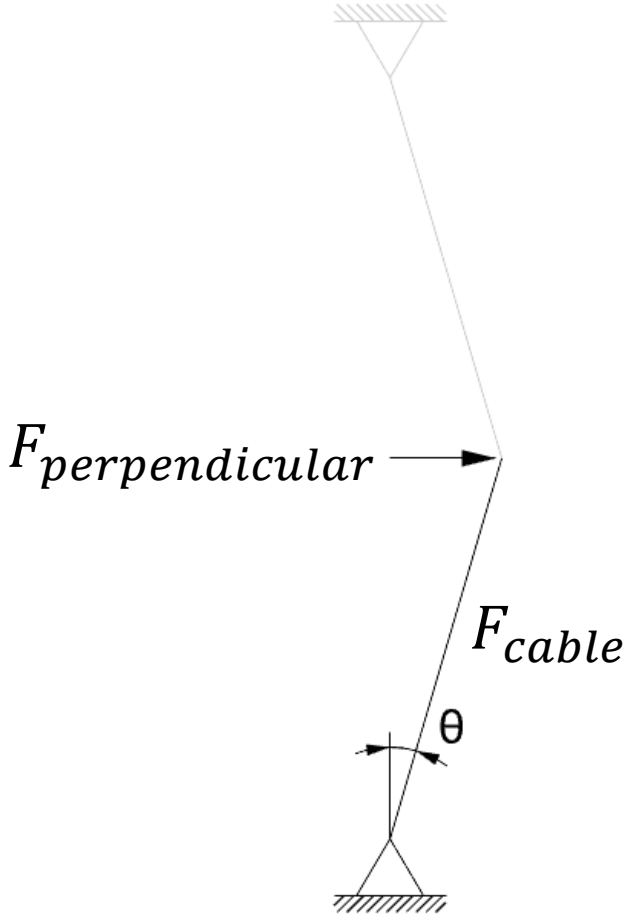
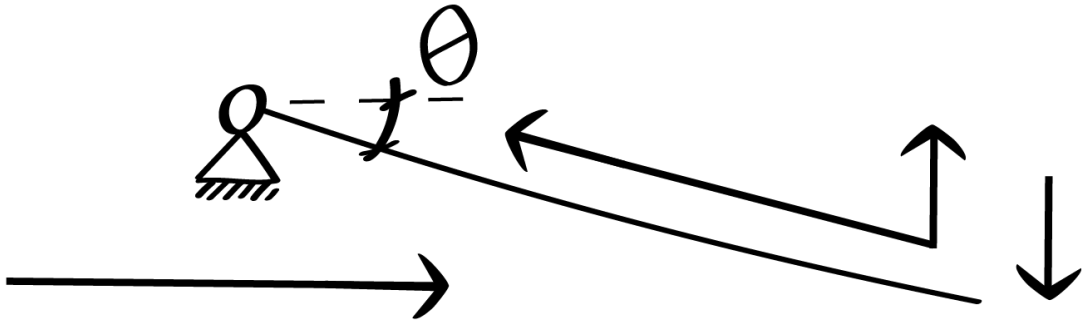
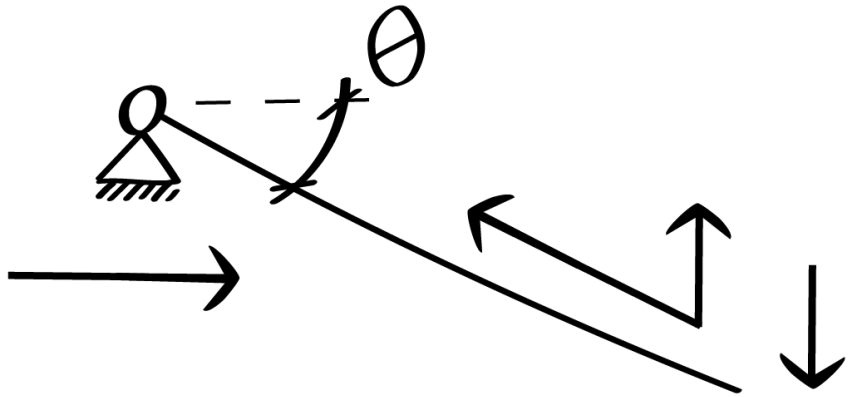


$$F_{perpendicular} = \sin\theta \cdot F_{pretension}$$

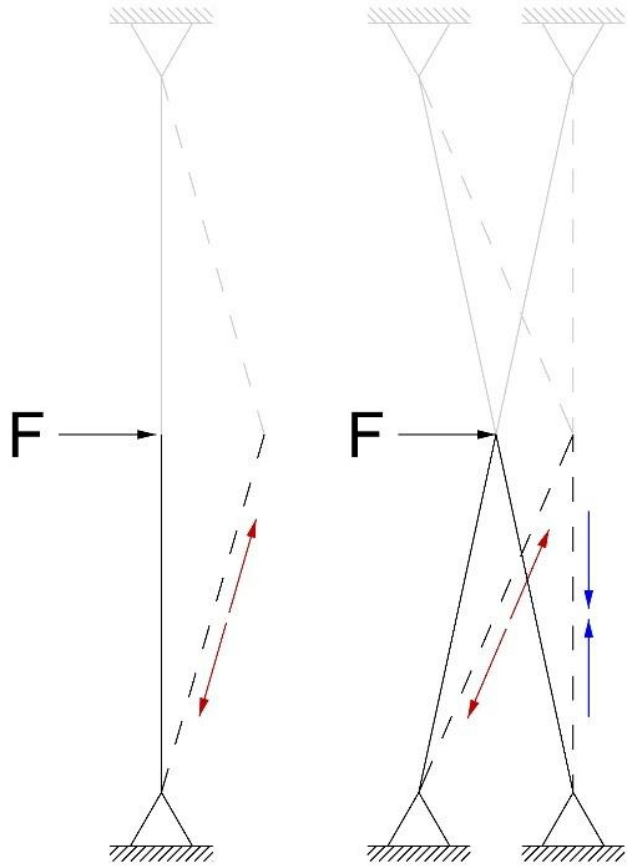


$$F_{perpendicular} = \sin\theta \cdot \left(F_{pretension} + \frac{\Delta L \cdot A \cdot E}{L} \right)$$

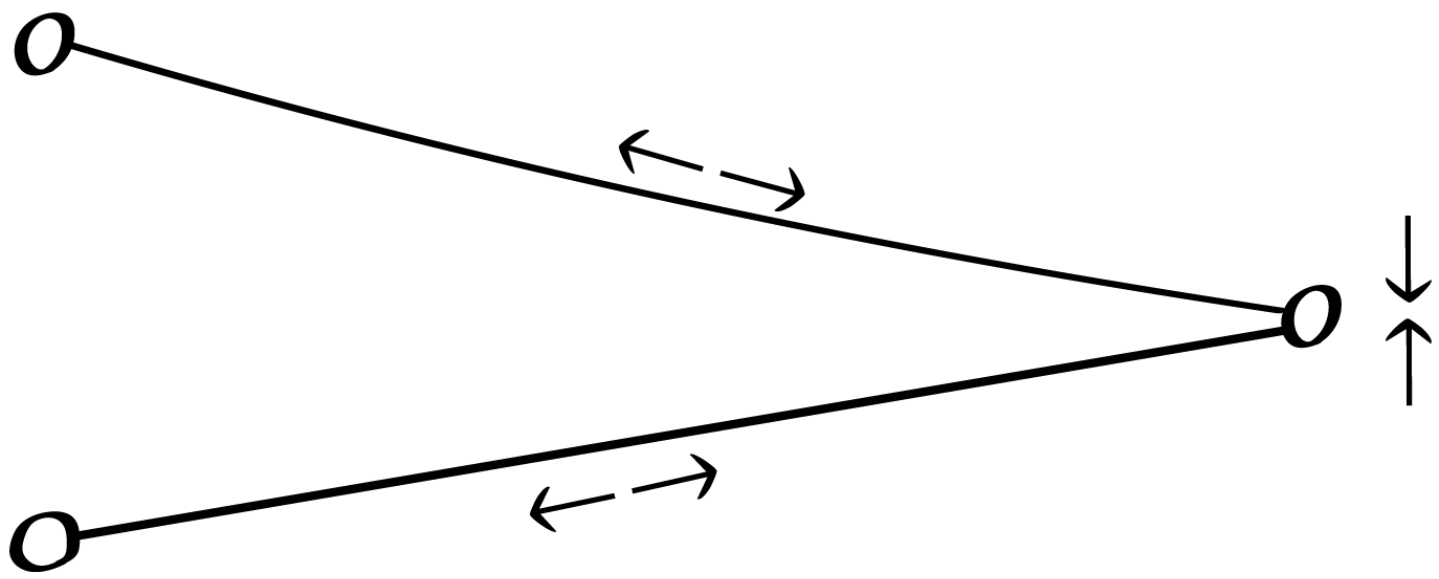




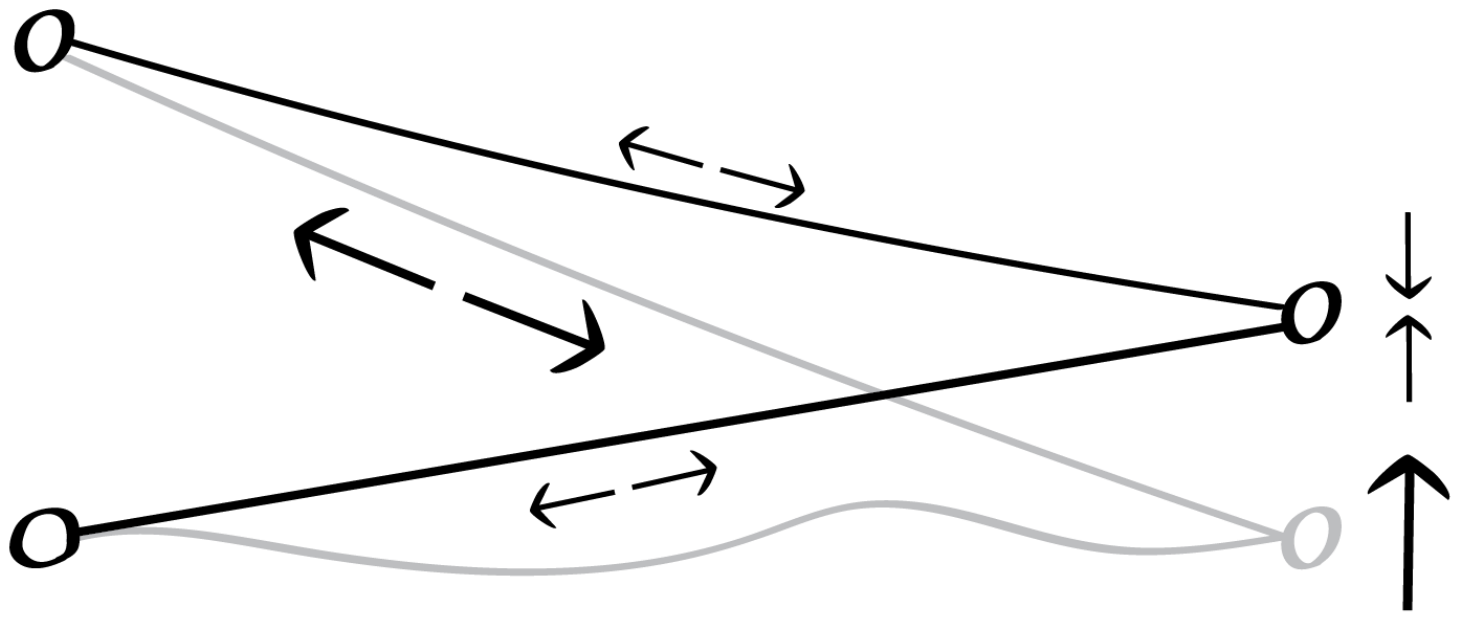
$$F_{perpendicular} = \sin\theta \cdot \left(F_{pretension} + \frac{\Delta L \cdot A \cdot E}{L} \right)$$



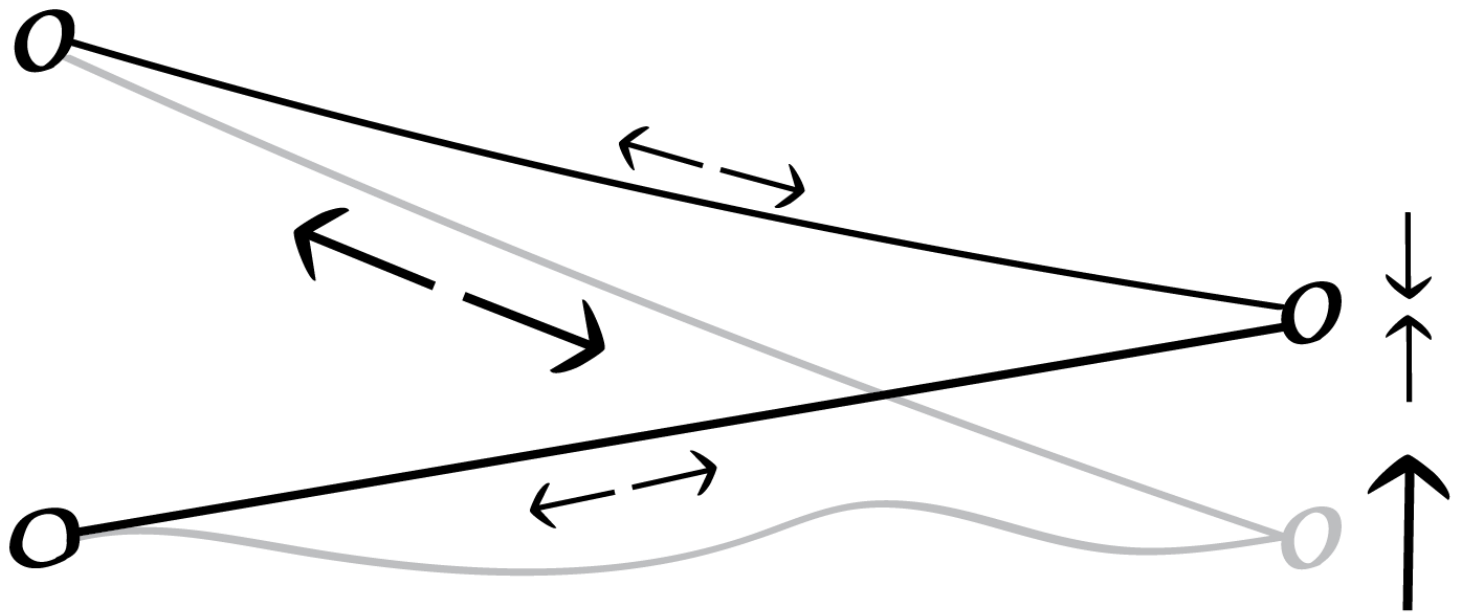
$$F_{perpendicular} = \sin\theta_{cable_1} \cdot F_{cable_1} - \sin\theta_{cable_2} \cdot F_{cable_2}$$



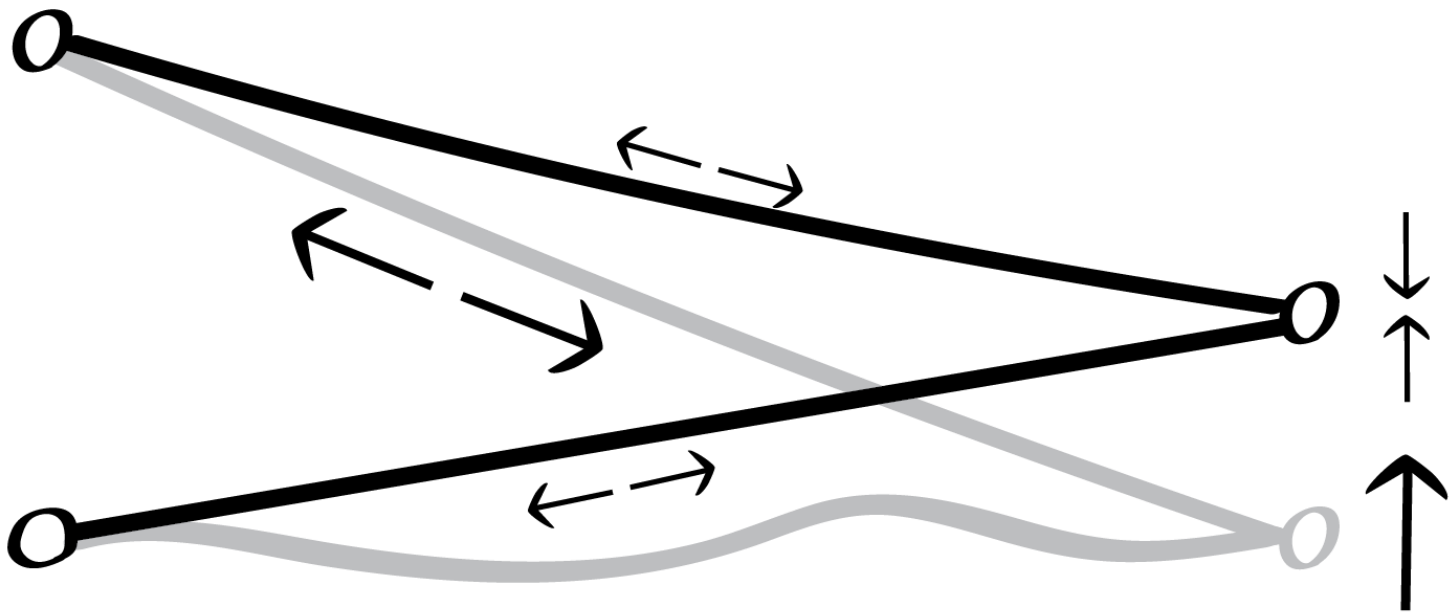
$$F_{perpendicular} = \sin\theta_{cable_1} \cdot F_{cable_1} - \sin\theta_{cable_2} \cdot F_{cable_2}$$



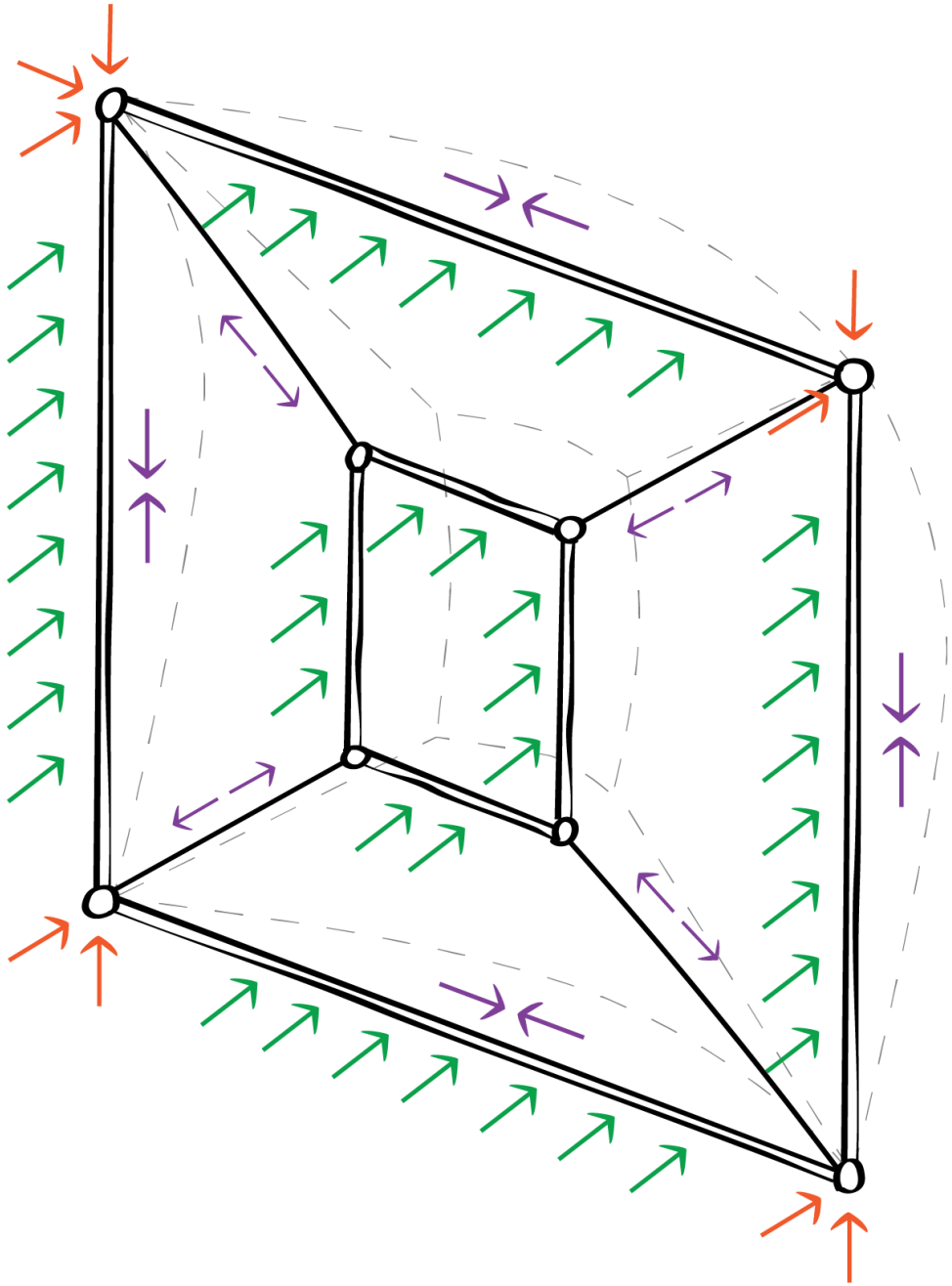
$$F_{perpendicular} = \sin\theta_{cable_1} \cdot F_{cable_1} - \sin\theta_{cable_2} \cdot 0$$



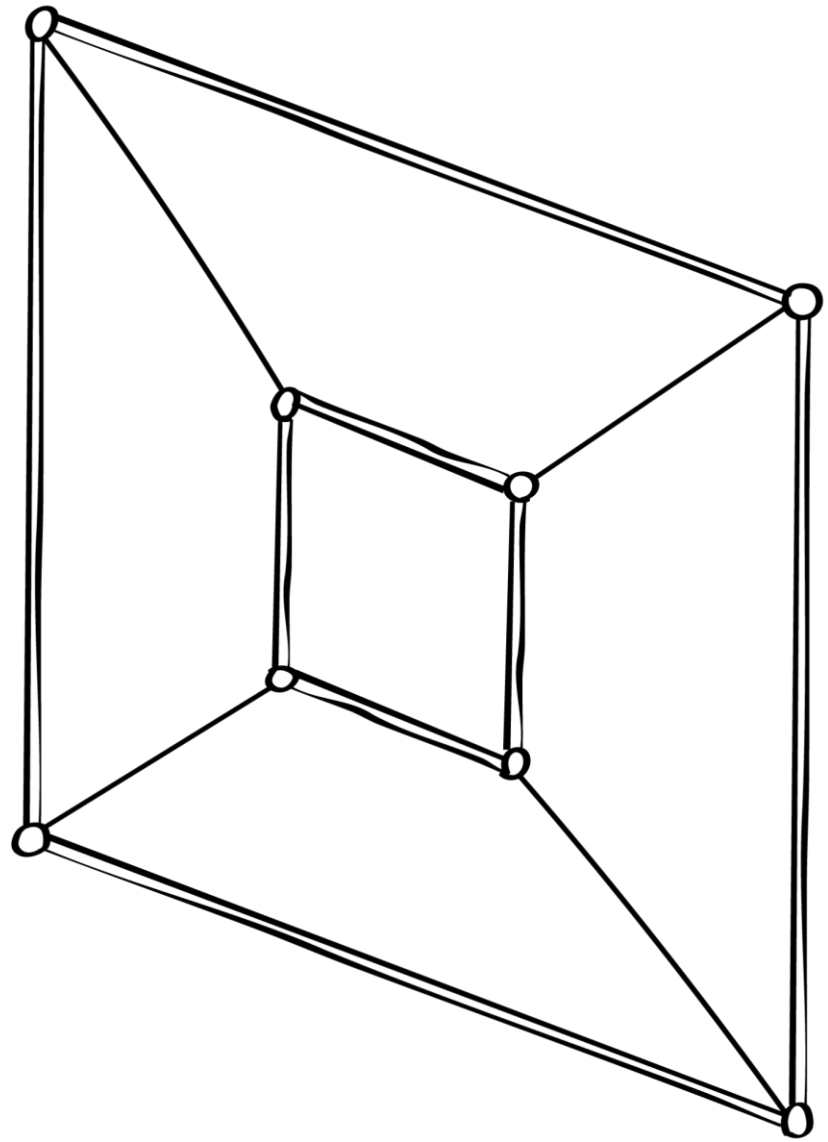
$$F_{pretension\ cable_2} = \frac{-\Delta L \cdot A \cdot E}{L}$$

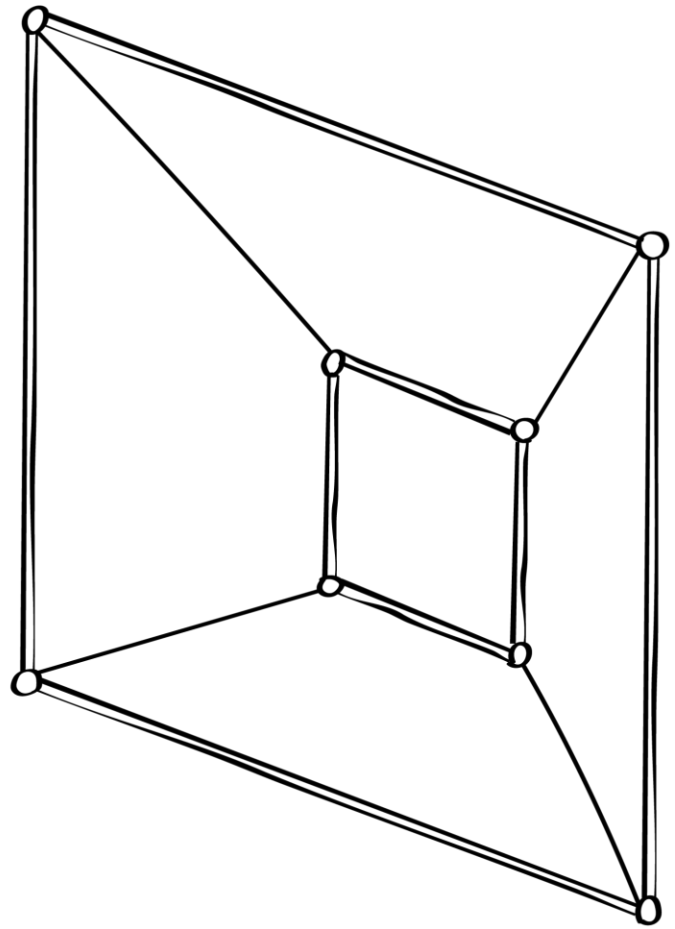


$$F_{pretension\ cable_2} = \frac{-\Delta L \cdot \boldsymbol{A} \cdot \boldsymbol{E}}{L}$$



- Prestress
- Wind loads
- **Panel configuration**
- Other external loads and restraints





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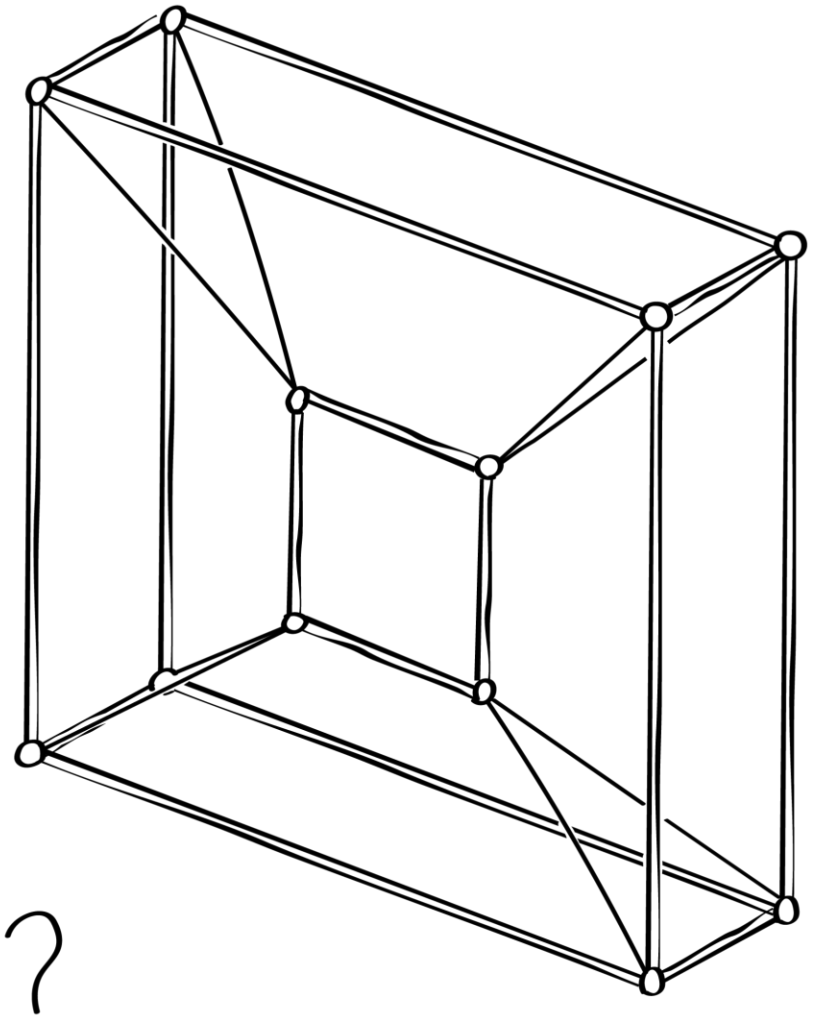
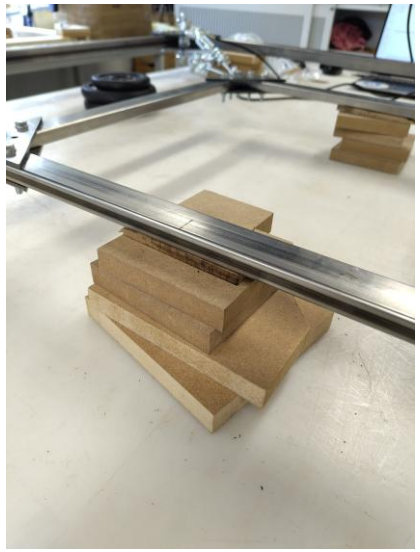
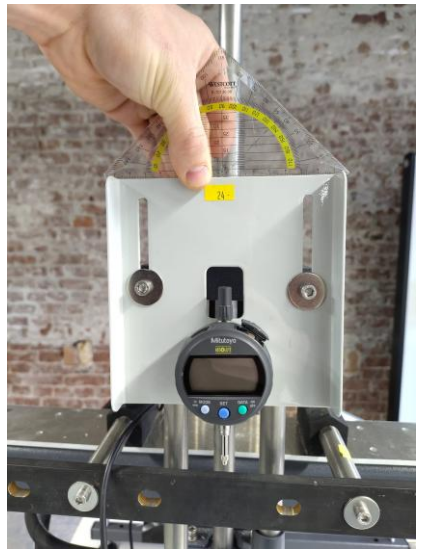
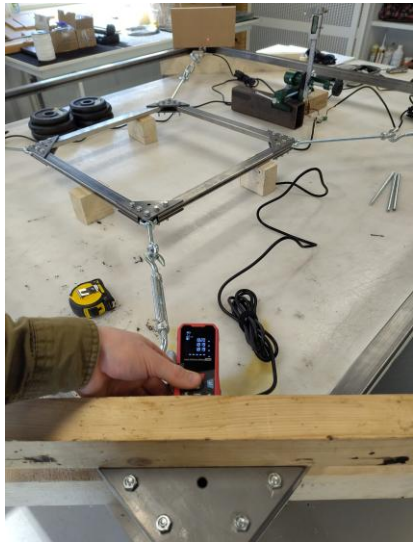


Prototyping!








UNIT
0.023
kg
ON
TARE
Max.5000g d=1g


UNIT
0.293
kg
ON
TARE
Max.5000g d=1g

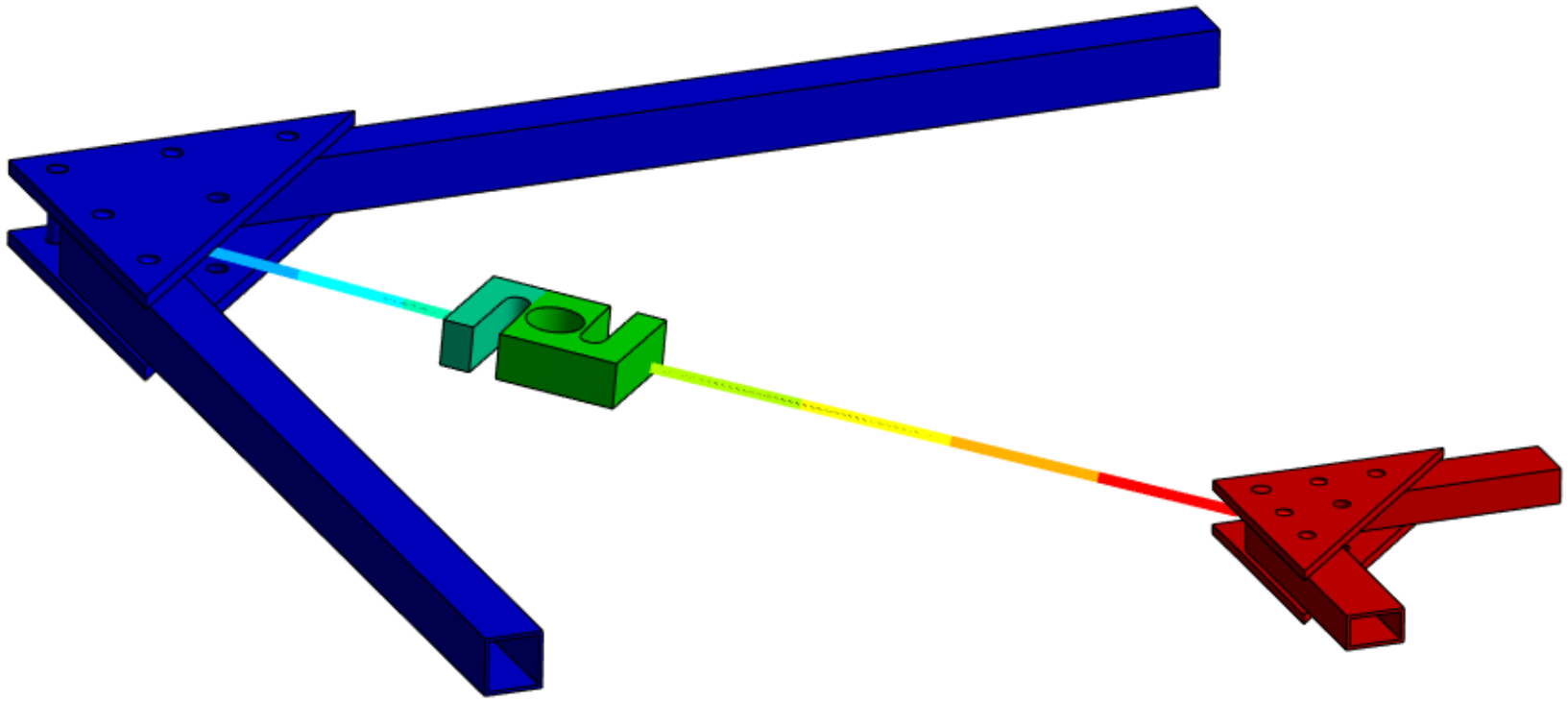

UNIT
0.407
kg
ON
TARE
Max.5000g d=1g


UNIT
0.176
kg
ON
TARE
Max.5000g d=1g

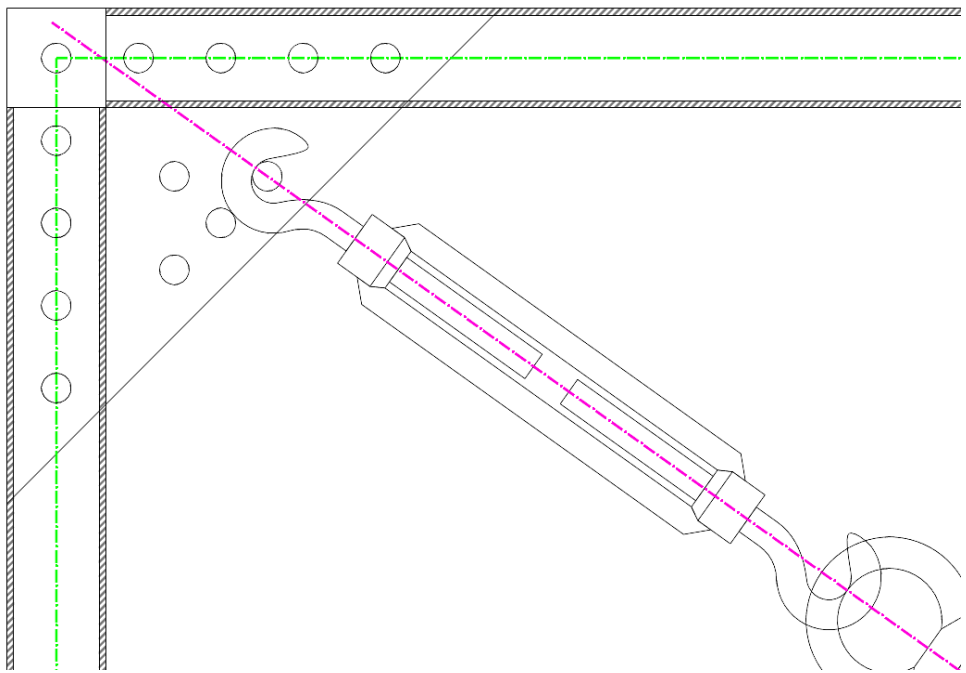

UNIT
0.133
kg
ON
TARE
Max.5000g d=1g

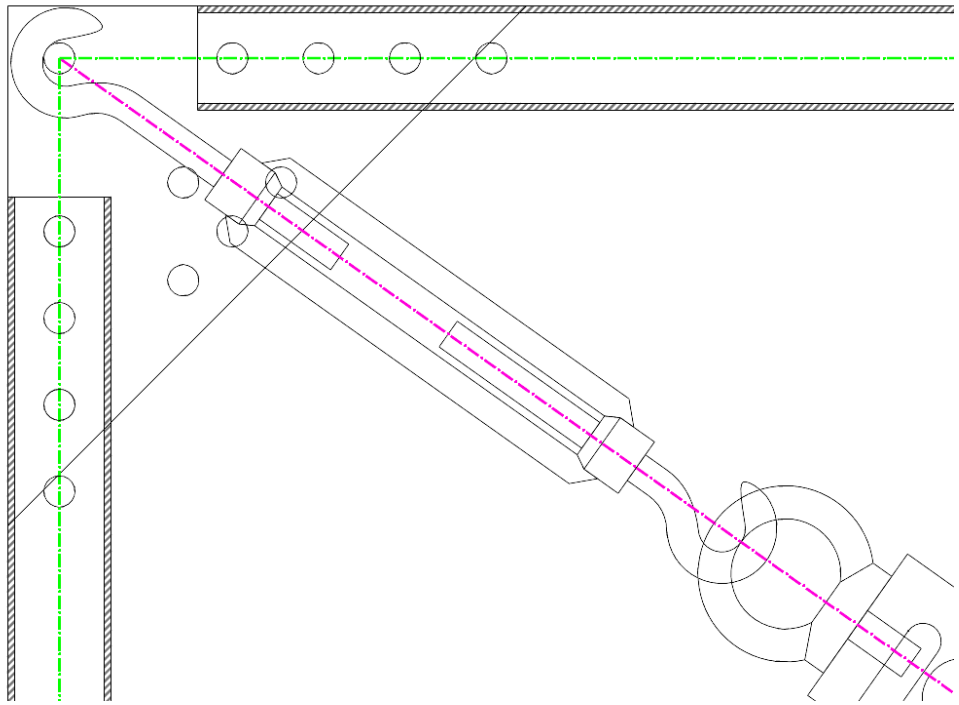
A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 2 s
19/03/2025 21:55

4,2449 Max
3,7766
3,3084
2,8401
2,3718
1,9035
1,4352
0,96696
0,49868
0,030404 Min



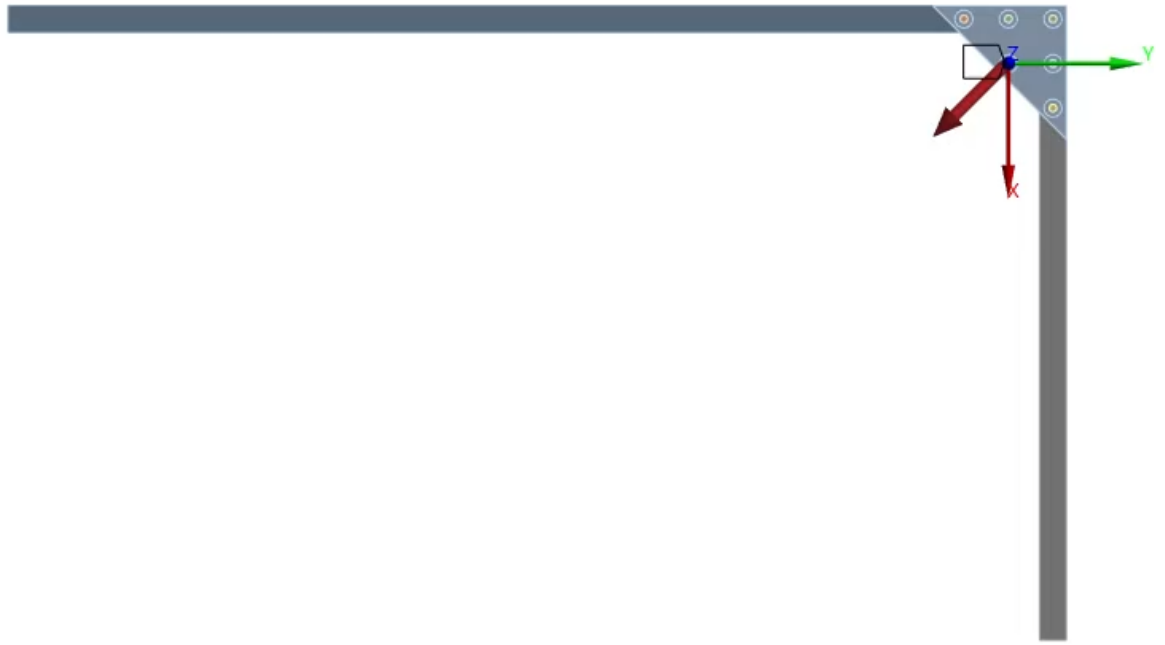
0,00 200,00 400,00 (mm)
100,00 300,00

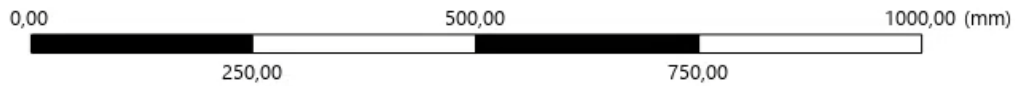




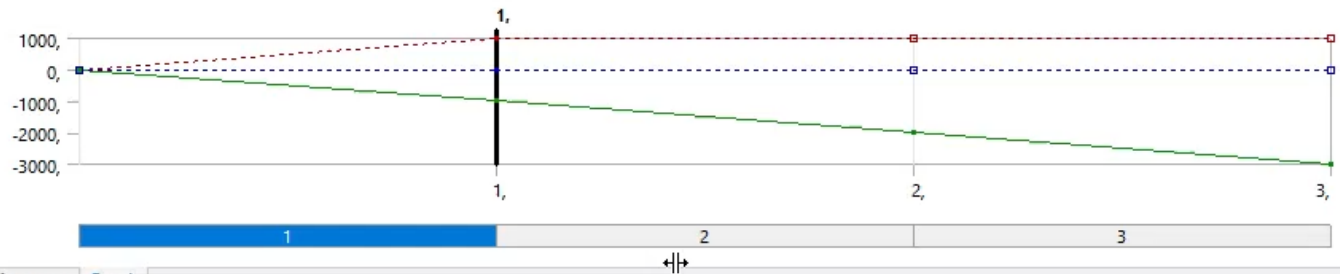
A: Static Structural
Force
Time: 1, s
19/03/2025 22:11

Force: 1414,2 N
Components: 1000,,-1000,,0,





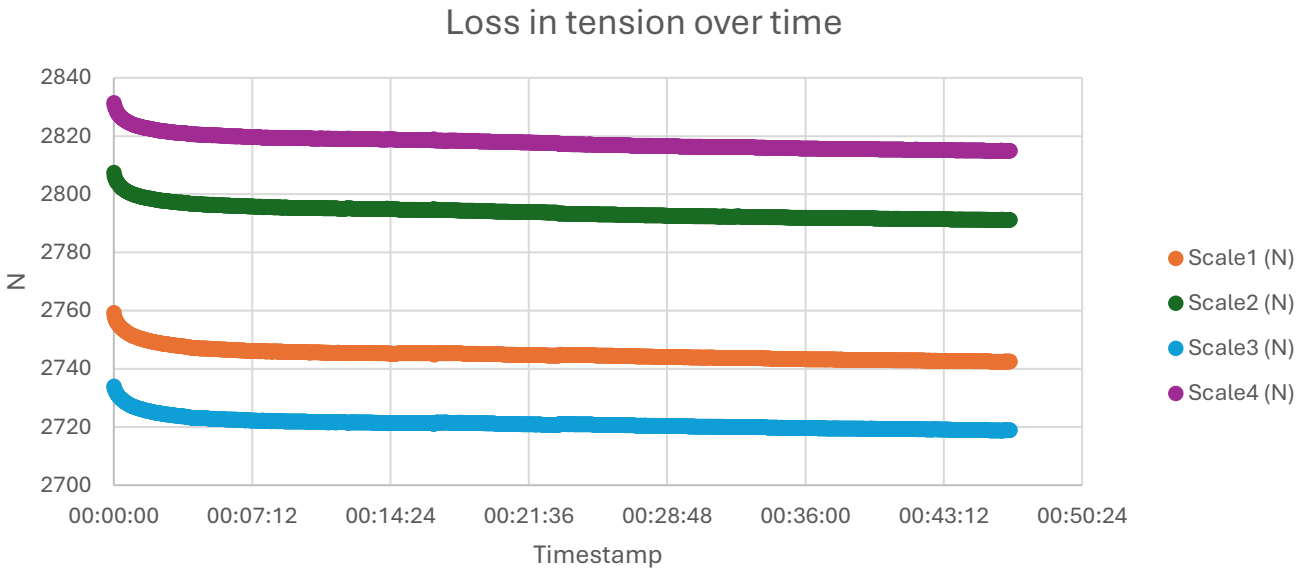
Graph

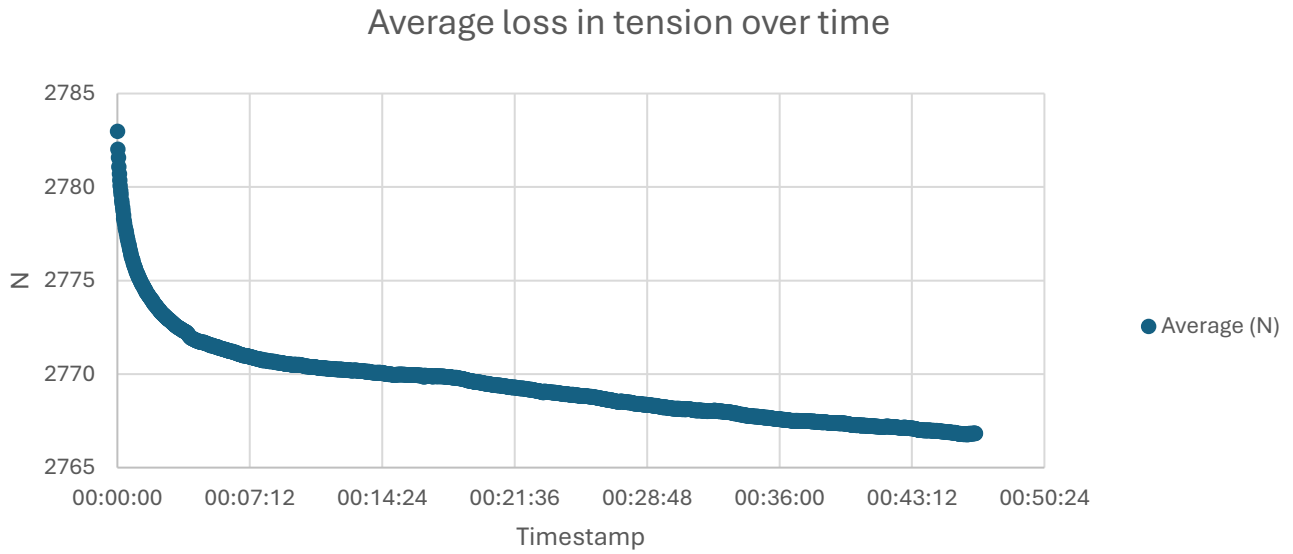


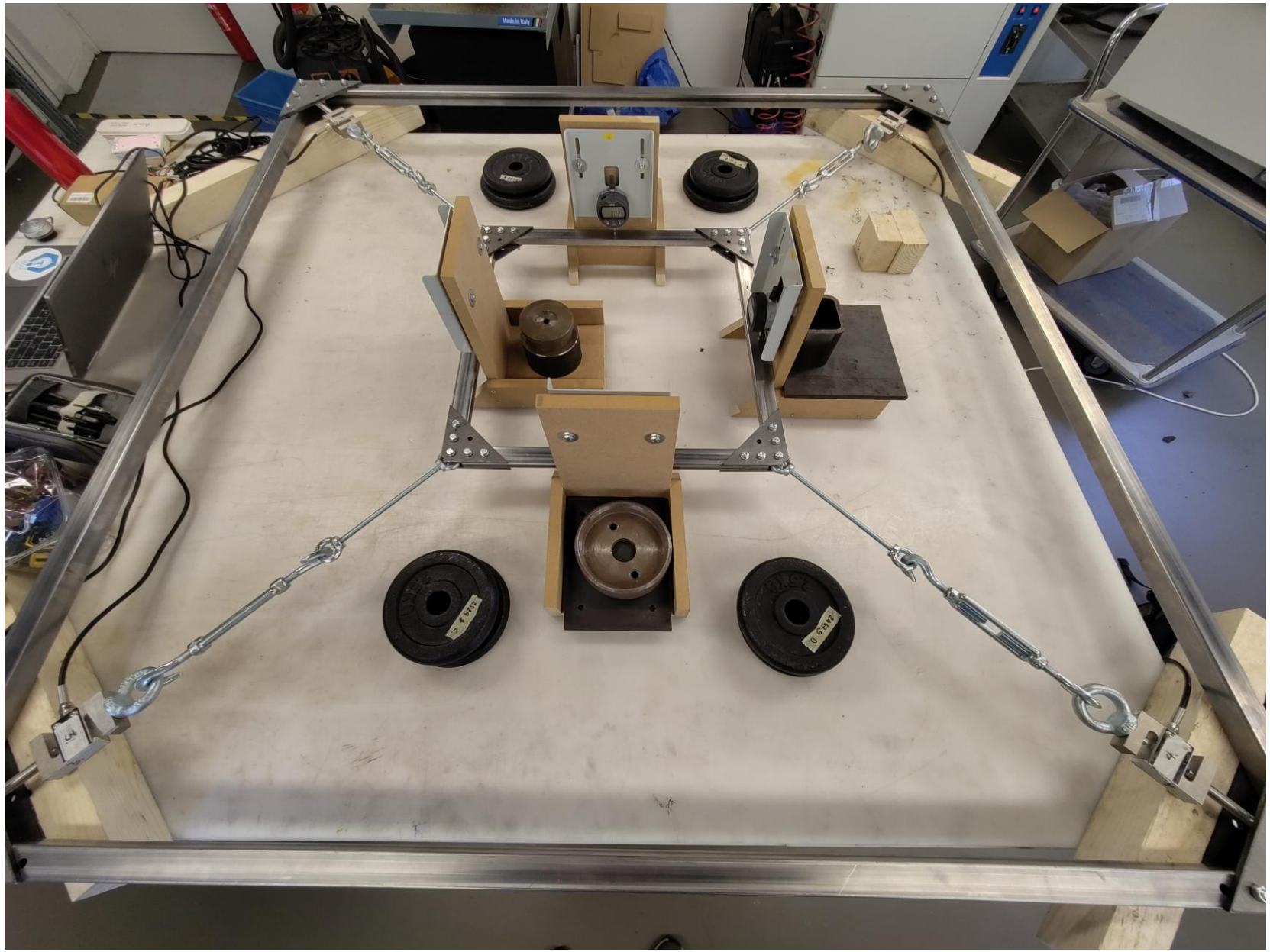
Messages Graph

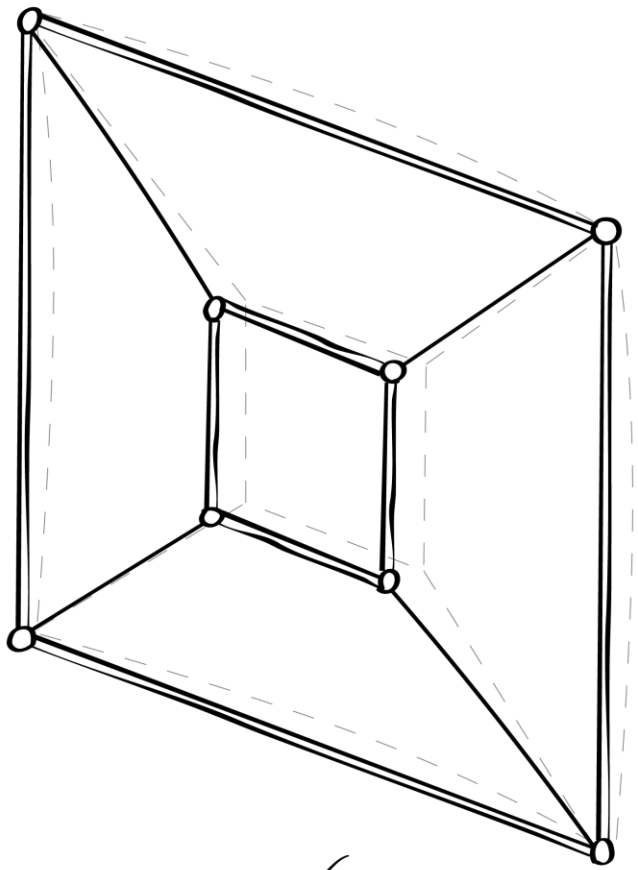
Tabular Data

	Steps	Time [s]	X [N]	Y [N]	Z [N]
1	1	0,	= 0,	0,	= 0,
2	1	1,	1000,	-1000,	0,
3	2	2,	= 1000,	-2000,	= 0,
4	3	3,	= 1000,	-3000,	= 0,
*					

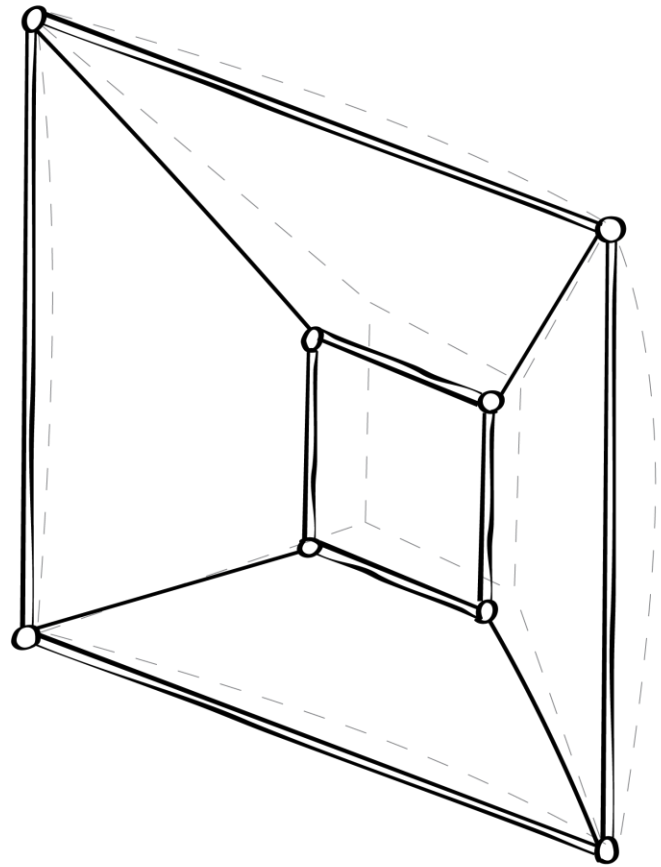

Loss in tension over time
2840
2820
2800
2780
2760
2740
2720
2700
N
00:00:00
00:07:12
00:14:24
00:21:36
00:28:48
00:36:00
00:43:12
00:50:24
Timestamp
Scale1 (N)
Scale2 (N)
Scale3 (N)
Scale4 (N)


Average loss in tension over time
2785
2780
2775
2770
2765
N
00:00:00
00:07:12
00:14:24
00:21:36
00:28:48
00:36:00
00:43:12
00:50:24
Timestamp
Average (N)





✓



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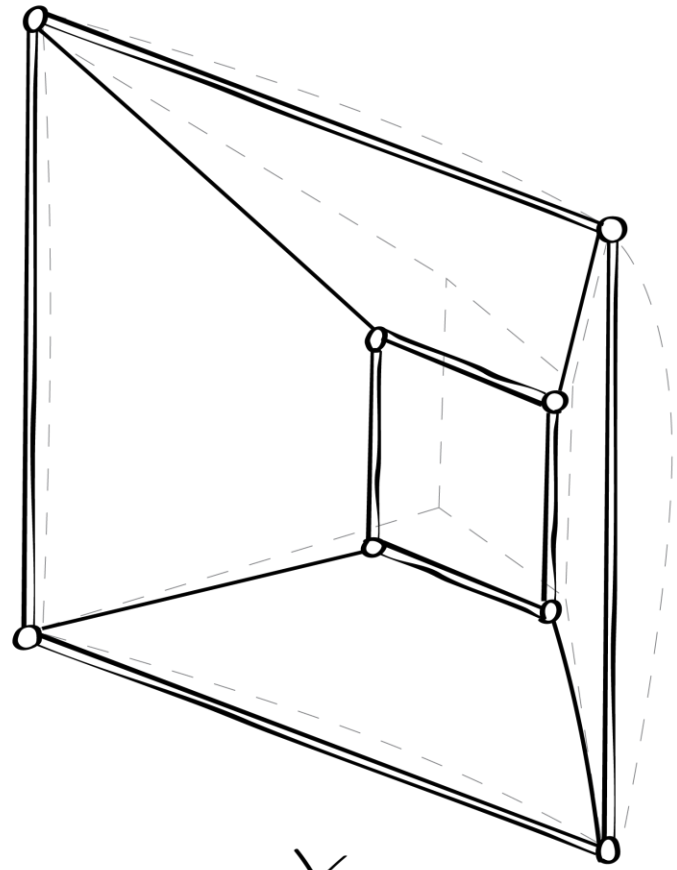
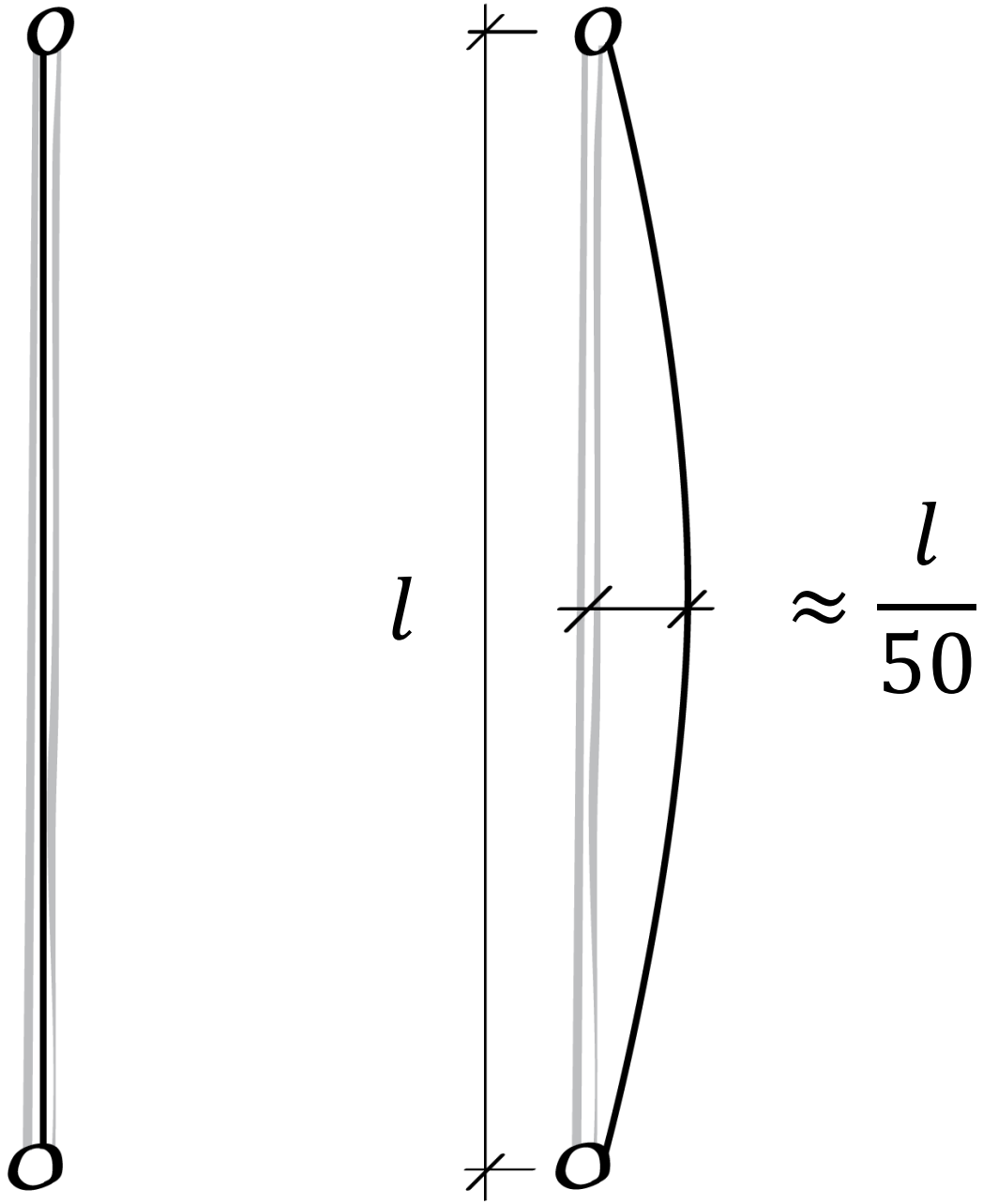
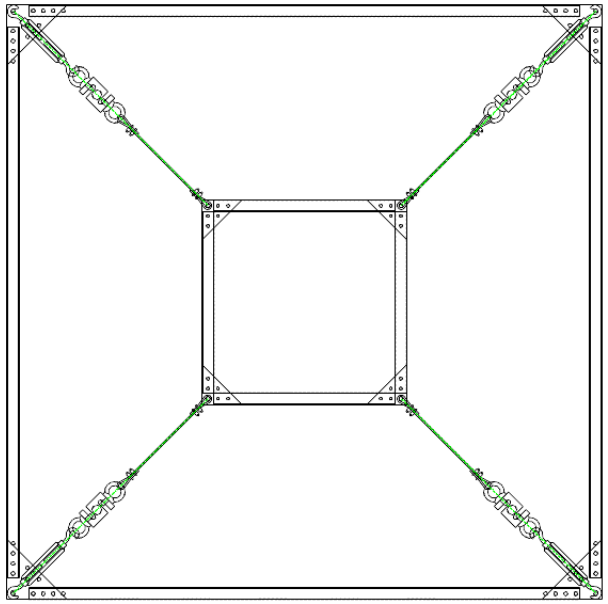
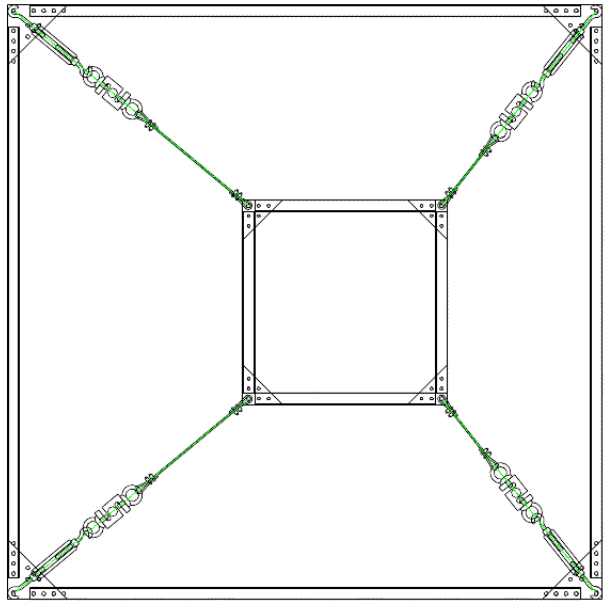
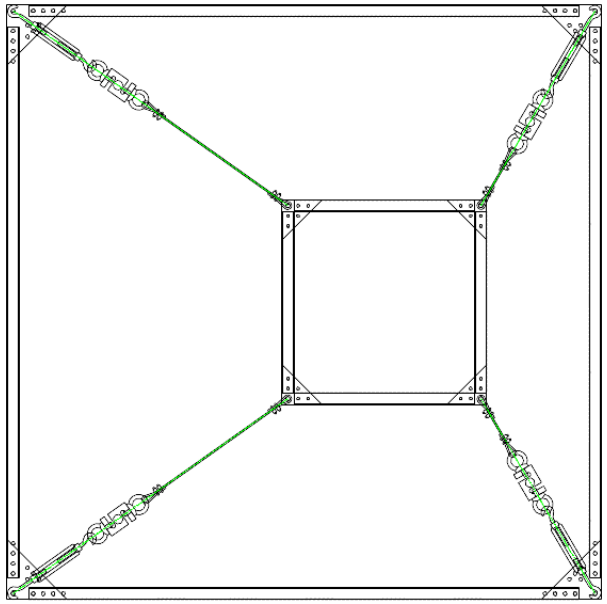


X

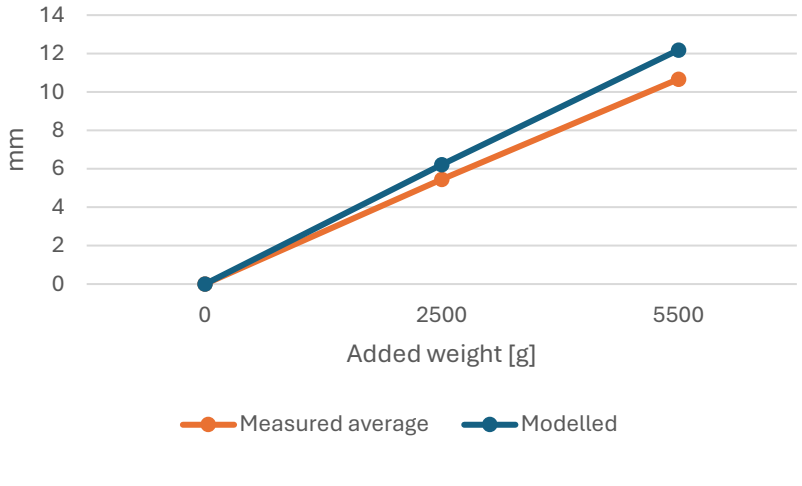

l
≈ l/50



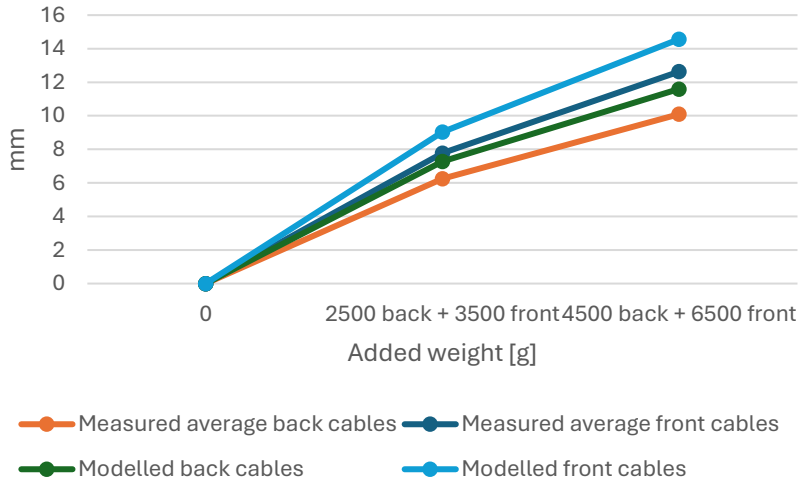




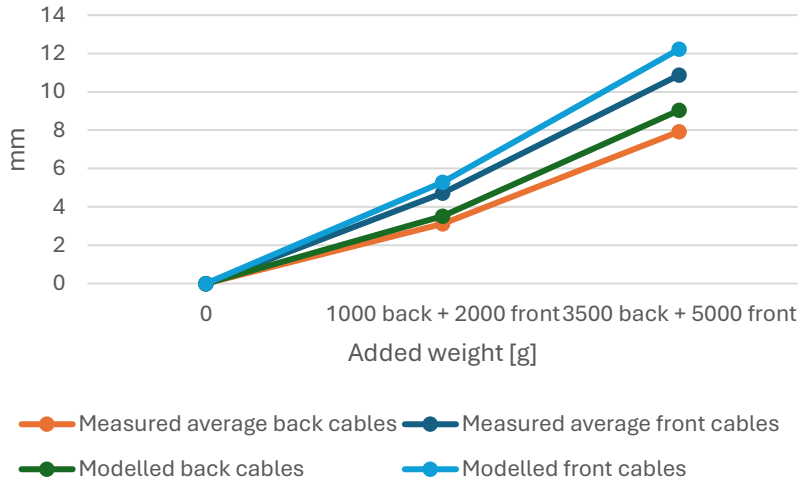
Measured against modelled displacement, no inner frame offset

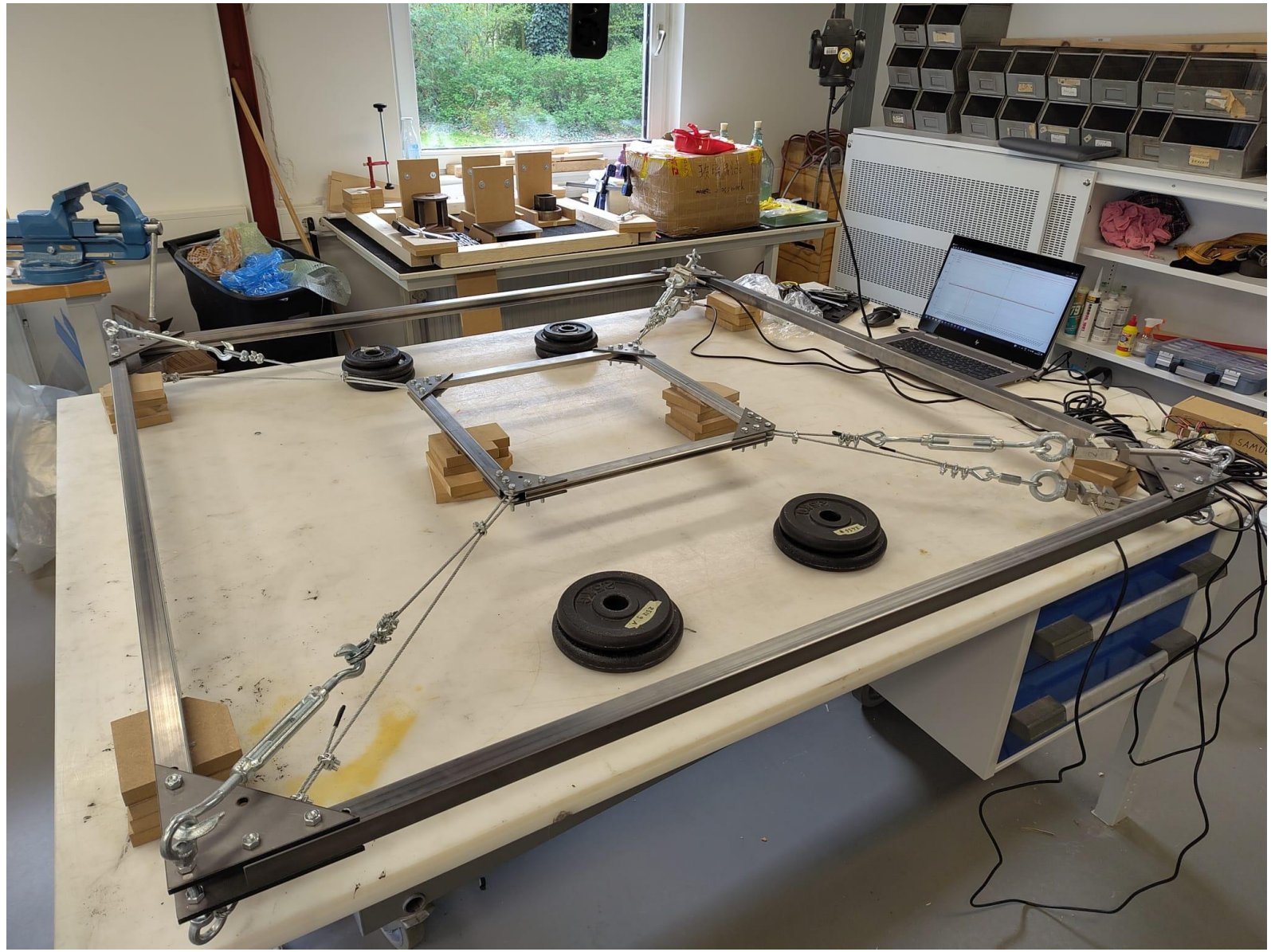


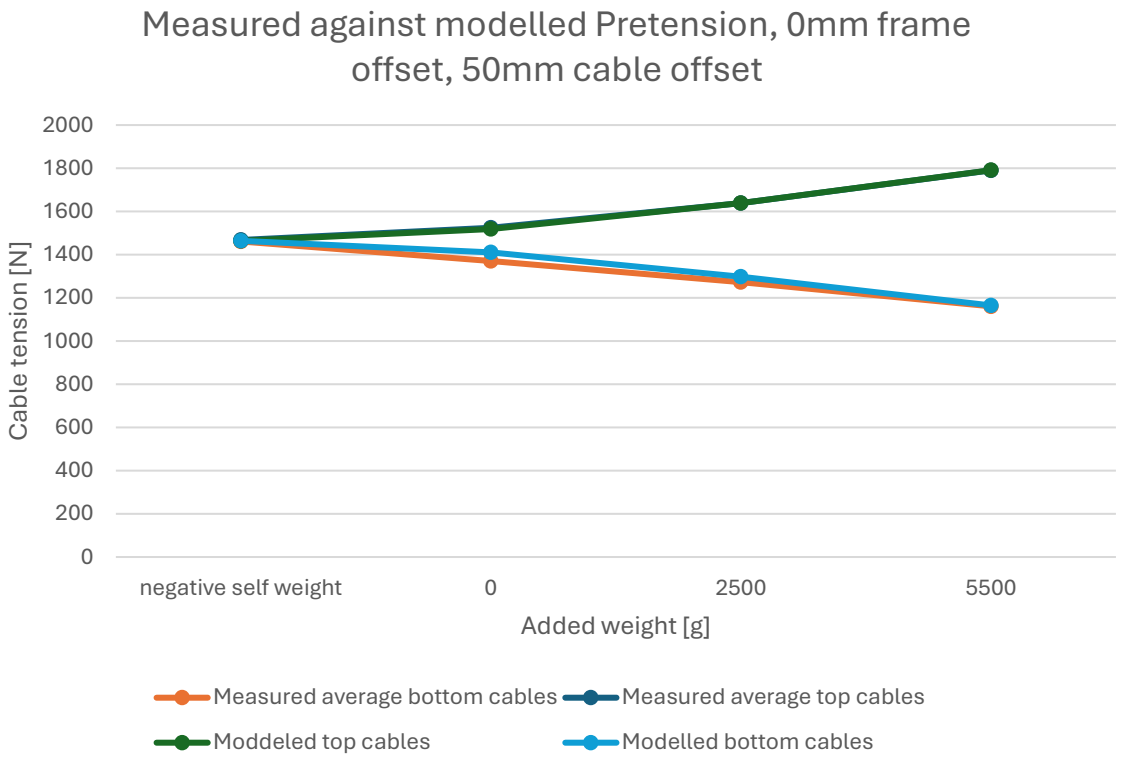
Measured against modelled Displacement, 72mm offset

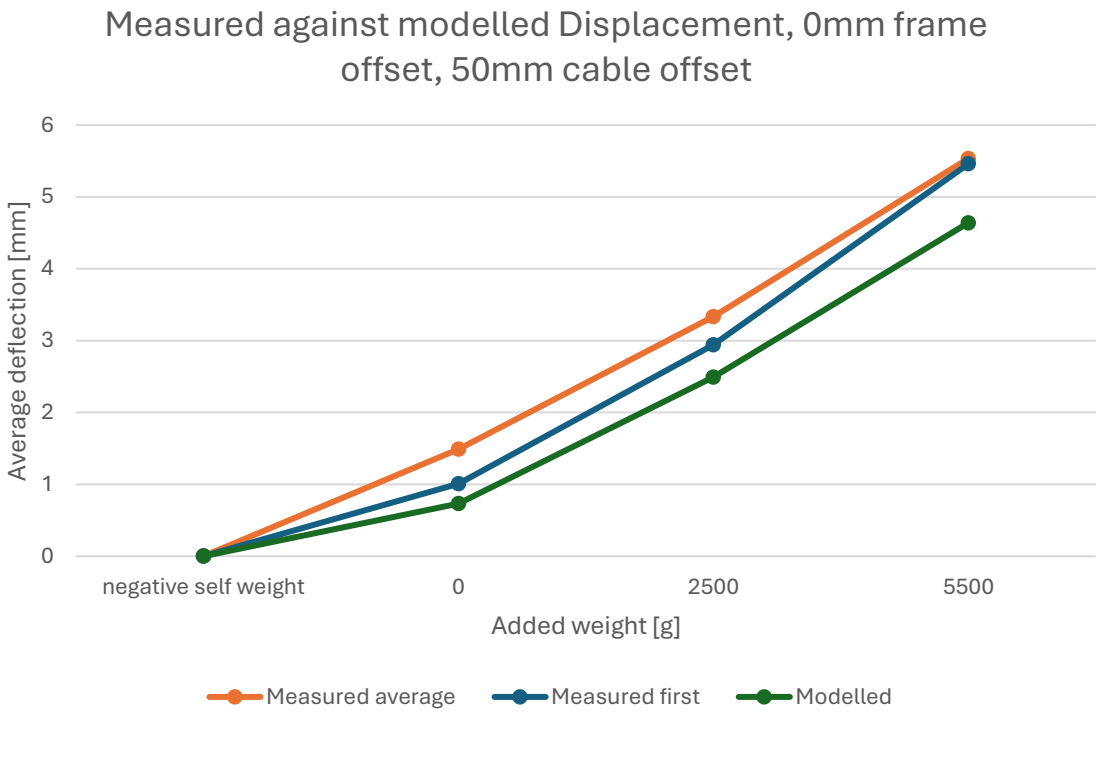


Measured against modelled Displacement, 123mm frame offset

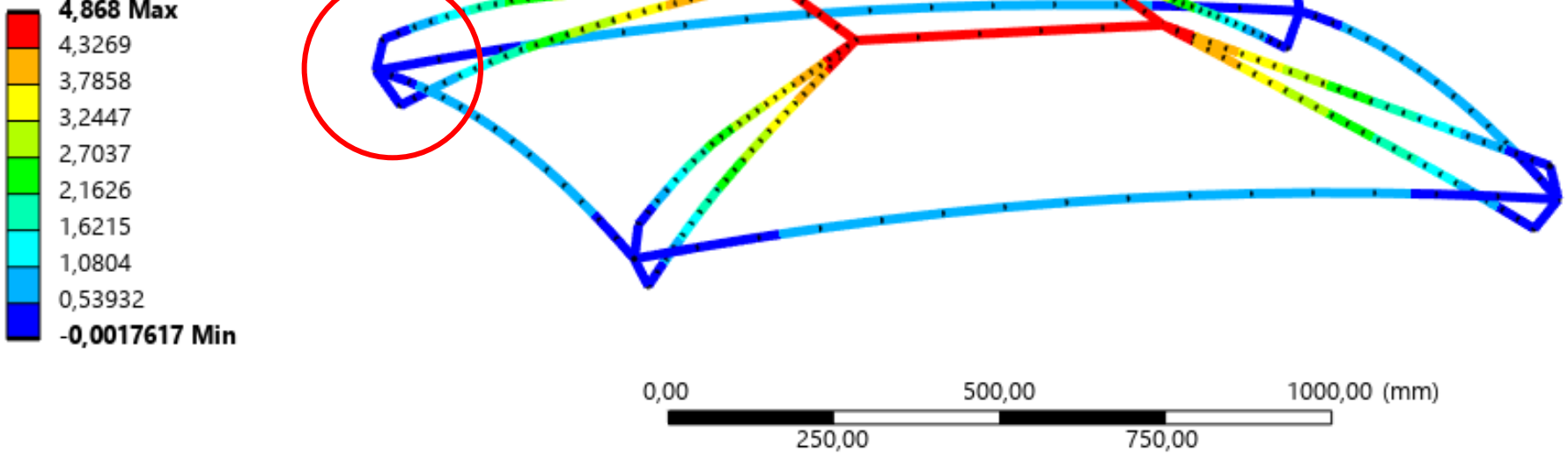


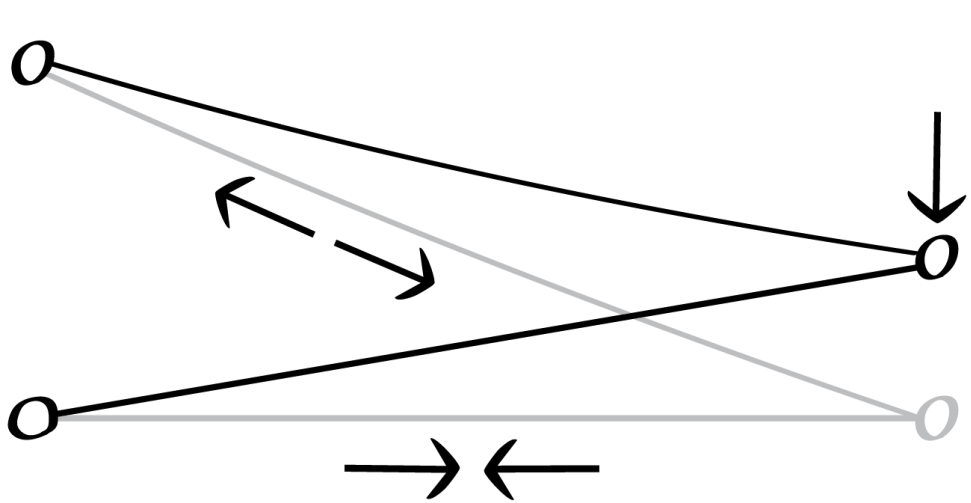


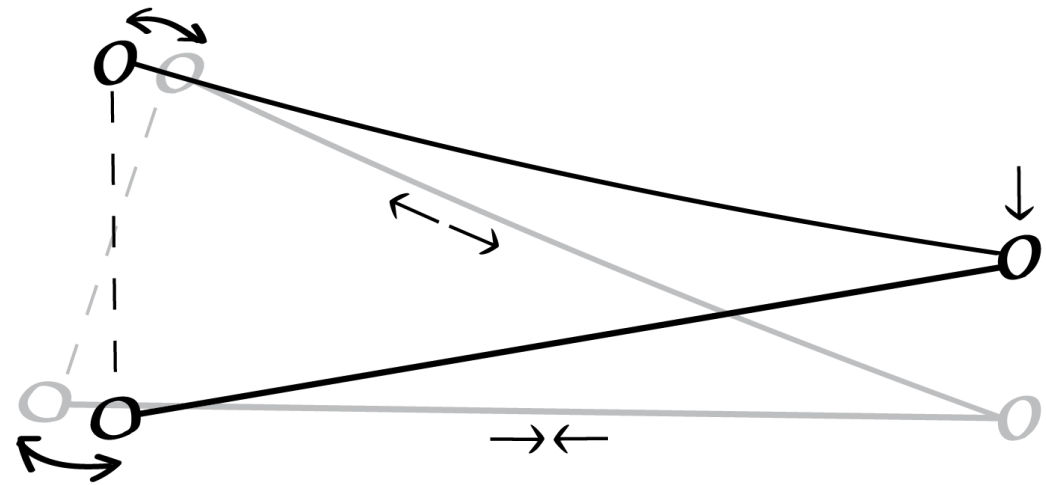

Measured against modelled Pretension, 0mm frame offset, 50mm cable offset
Cable tension [N]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
negative self weight
0
2500
5500
Added weight [g]
Measured average bottom cables
Measured average top cables
Moddeled top cables
Modelled bottom cables

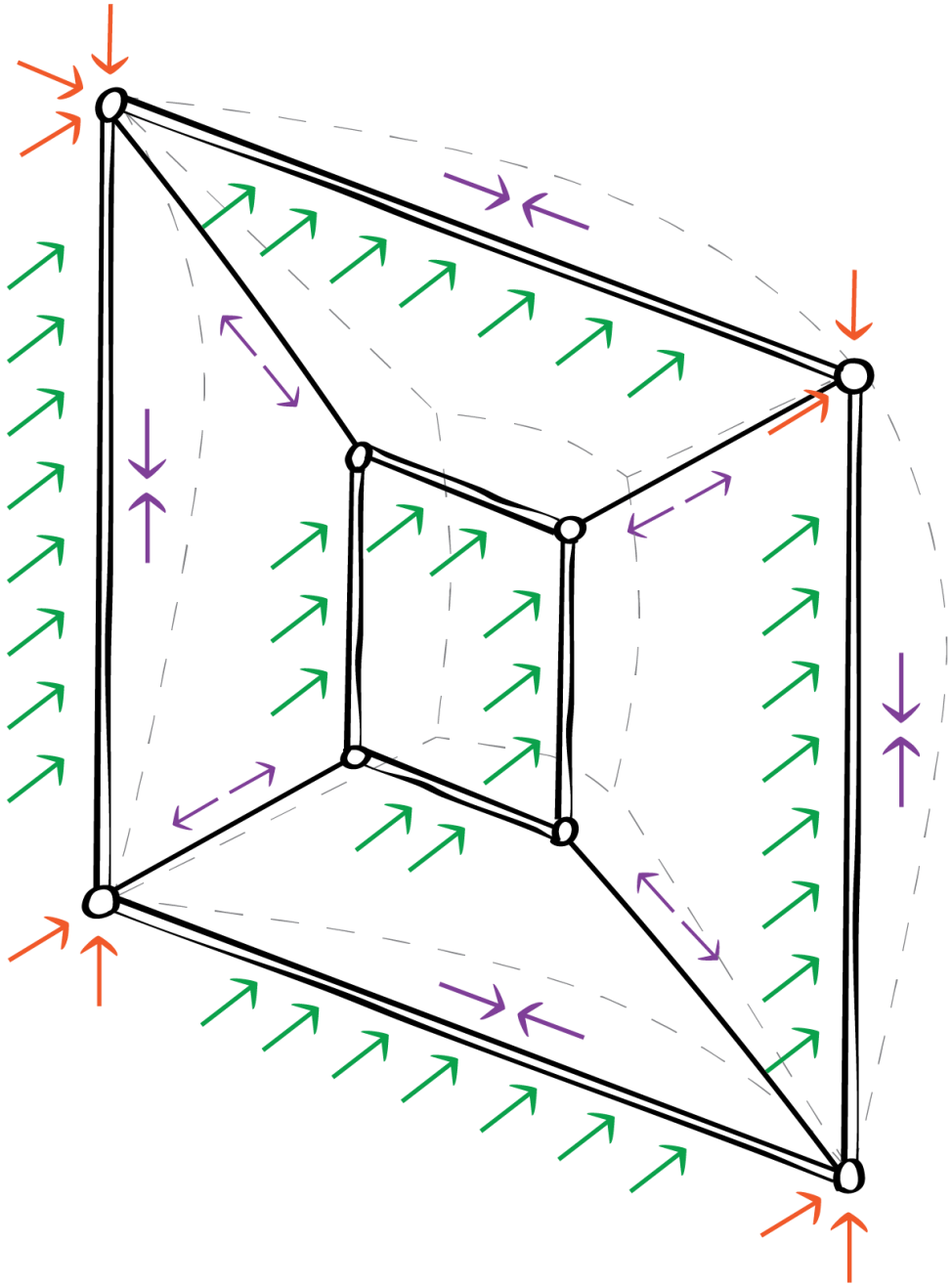

Measured against modelled Displacement, 0mm frame offset, 50mm cable offset
Average deflection [mm]
6
5
4
3
2
1
0
negative self weight
0
2500
5500
Added weight [g]
Measured average
Measured first
Modelled

G: Copy of 3D no offset more links
Directional Deformation
Type: Directional Deformation(Z Axis)
Unit: mm
Global Coordinate System
Time: 4 s
19/05/2025 13:34



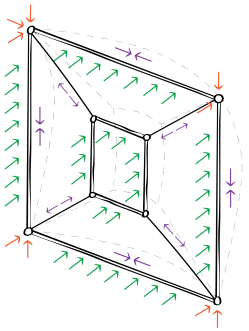


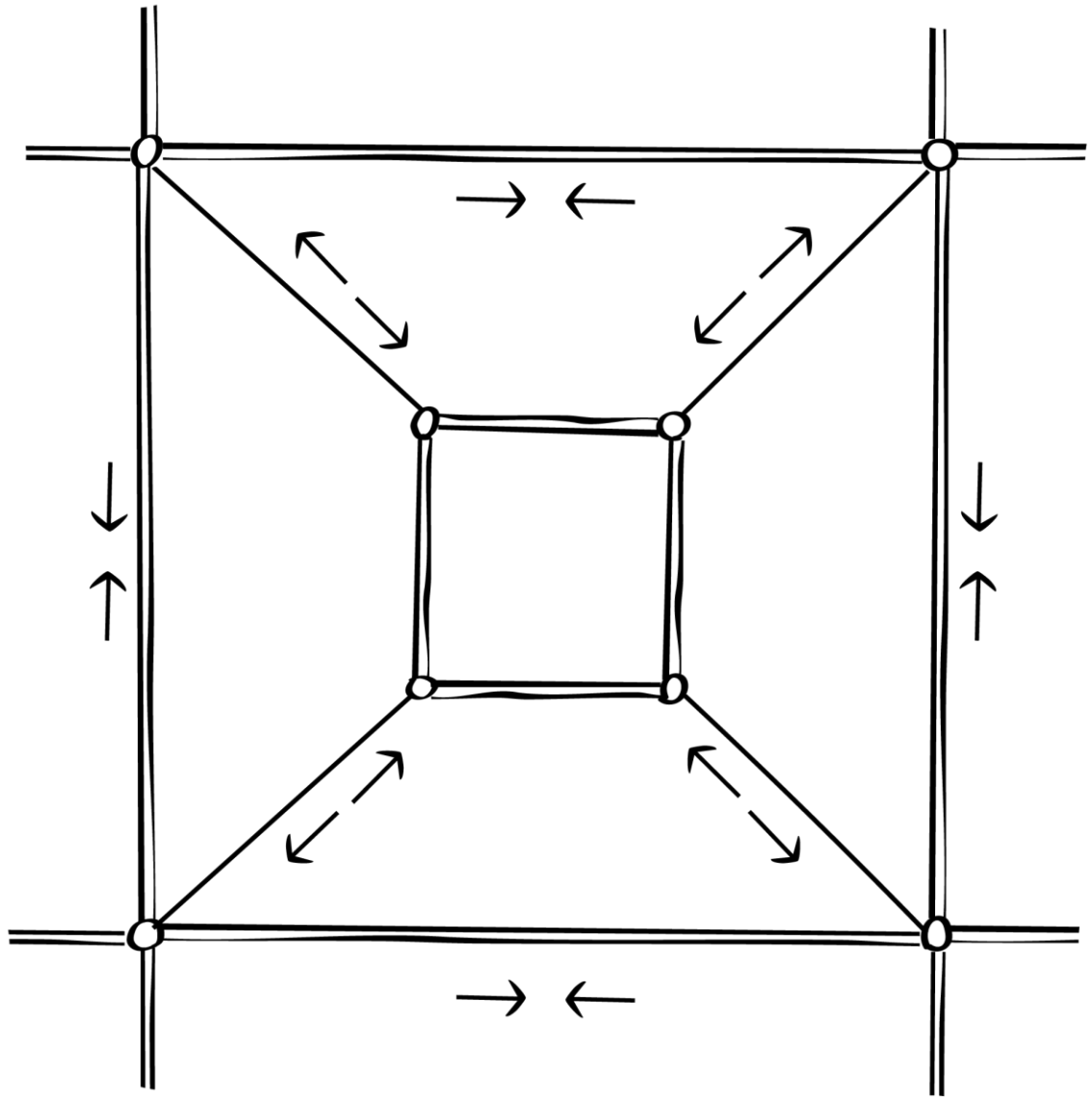


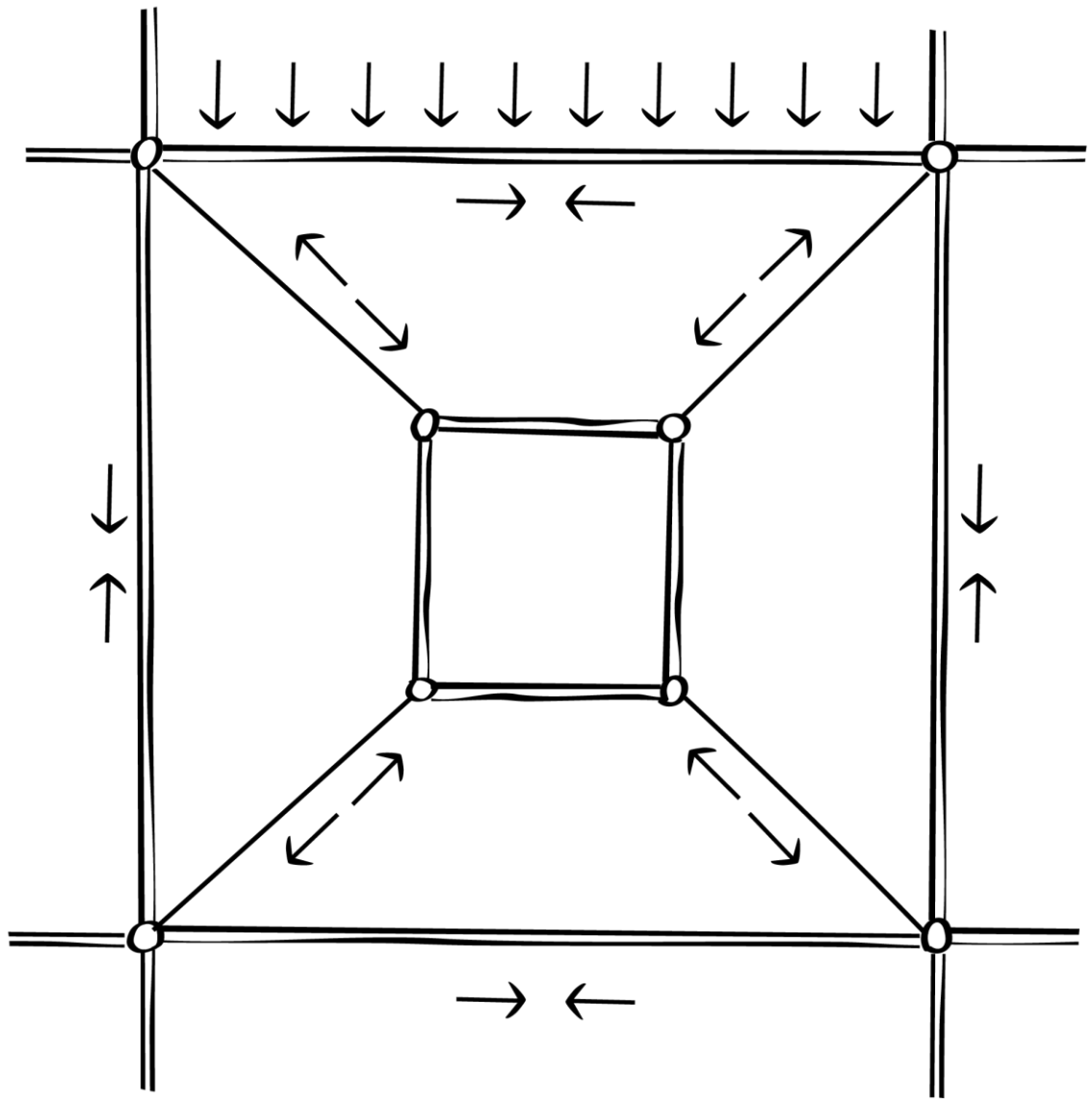


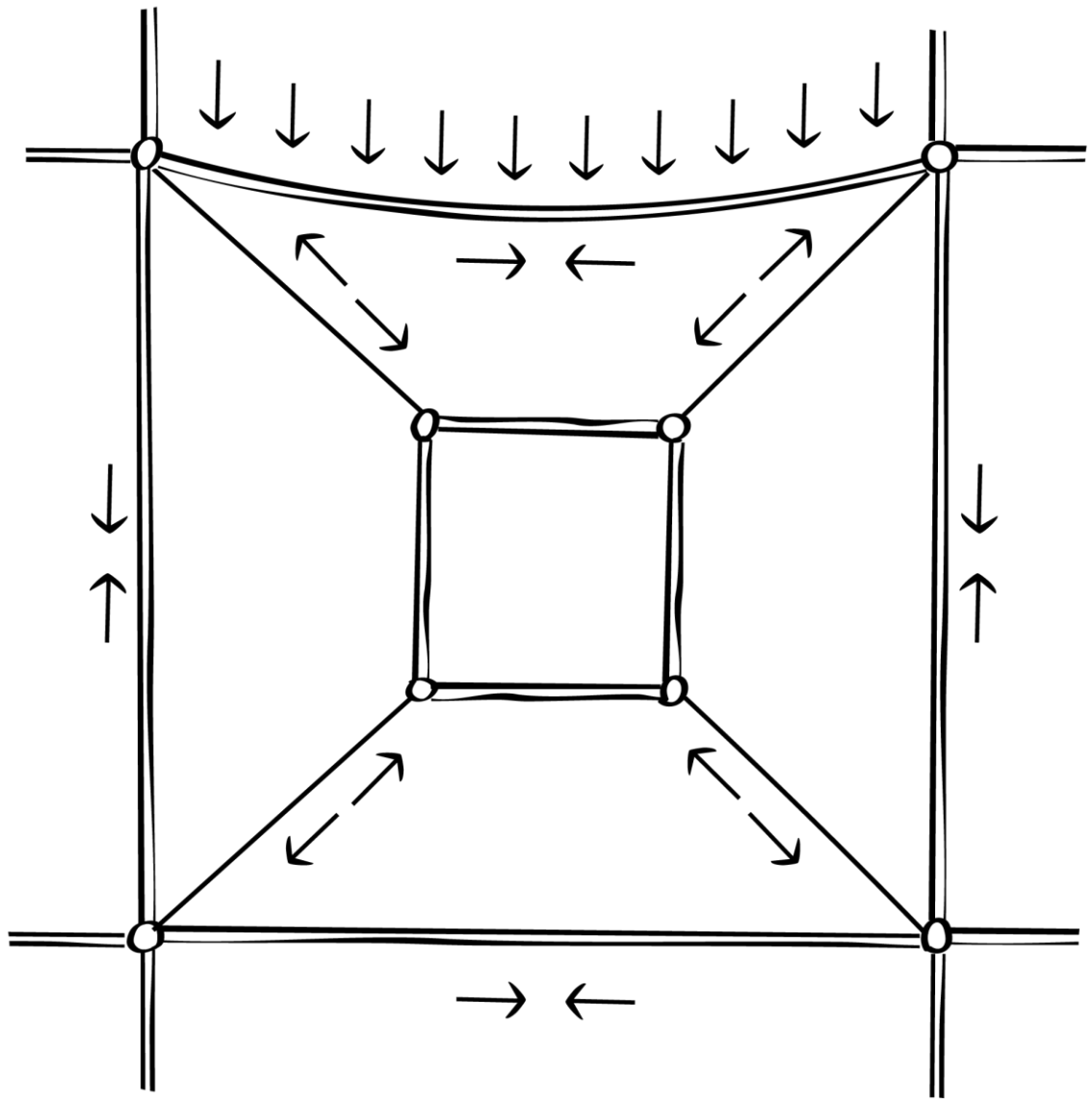
- Prestress
- Wind loads
- Panel configuration
- Other external loads and restraints

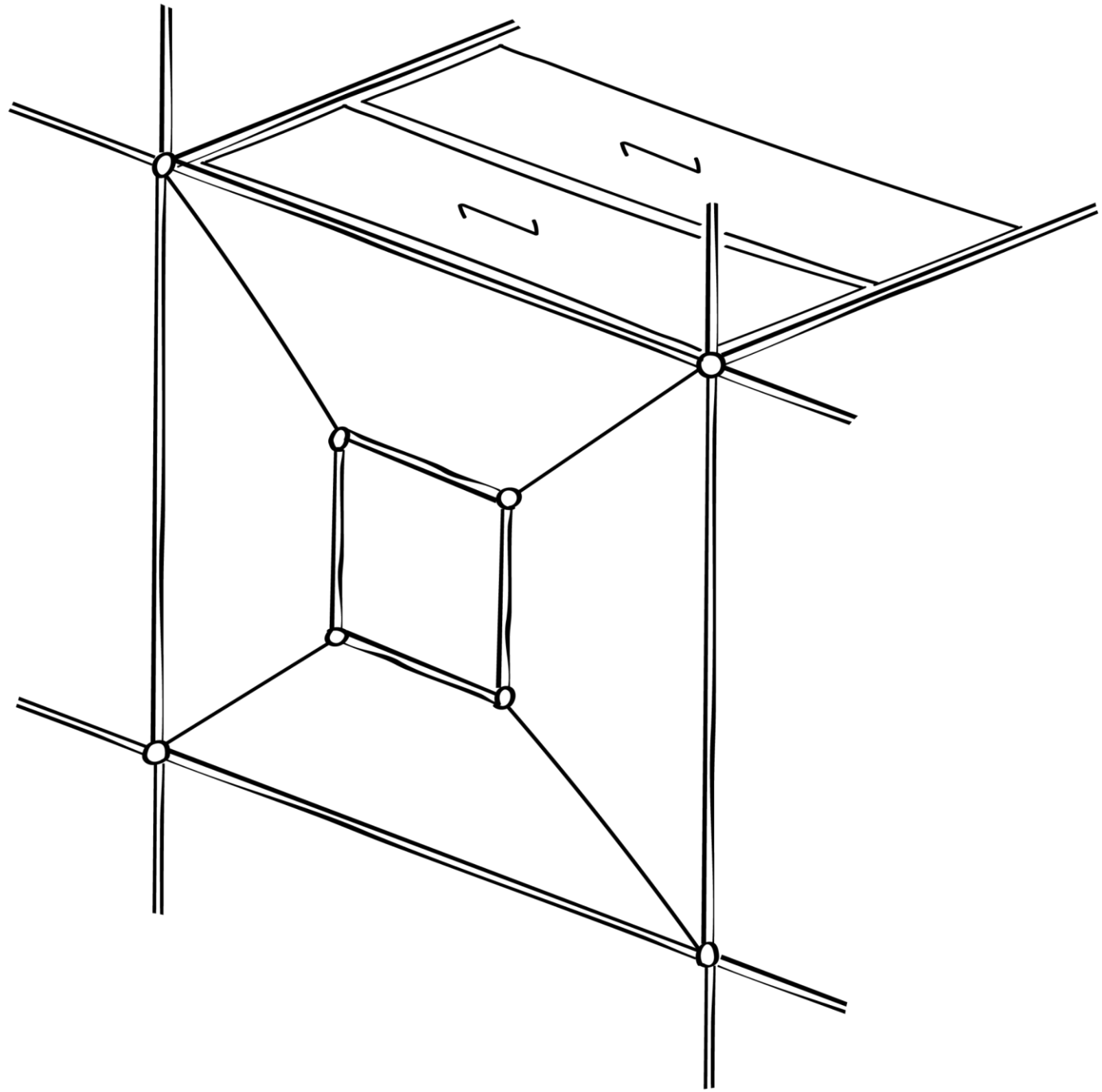
Other external loads and restraints

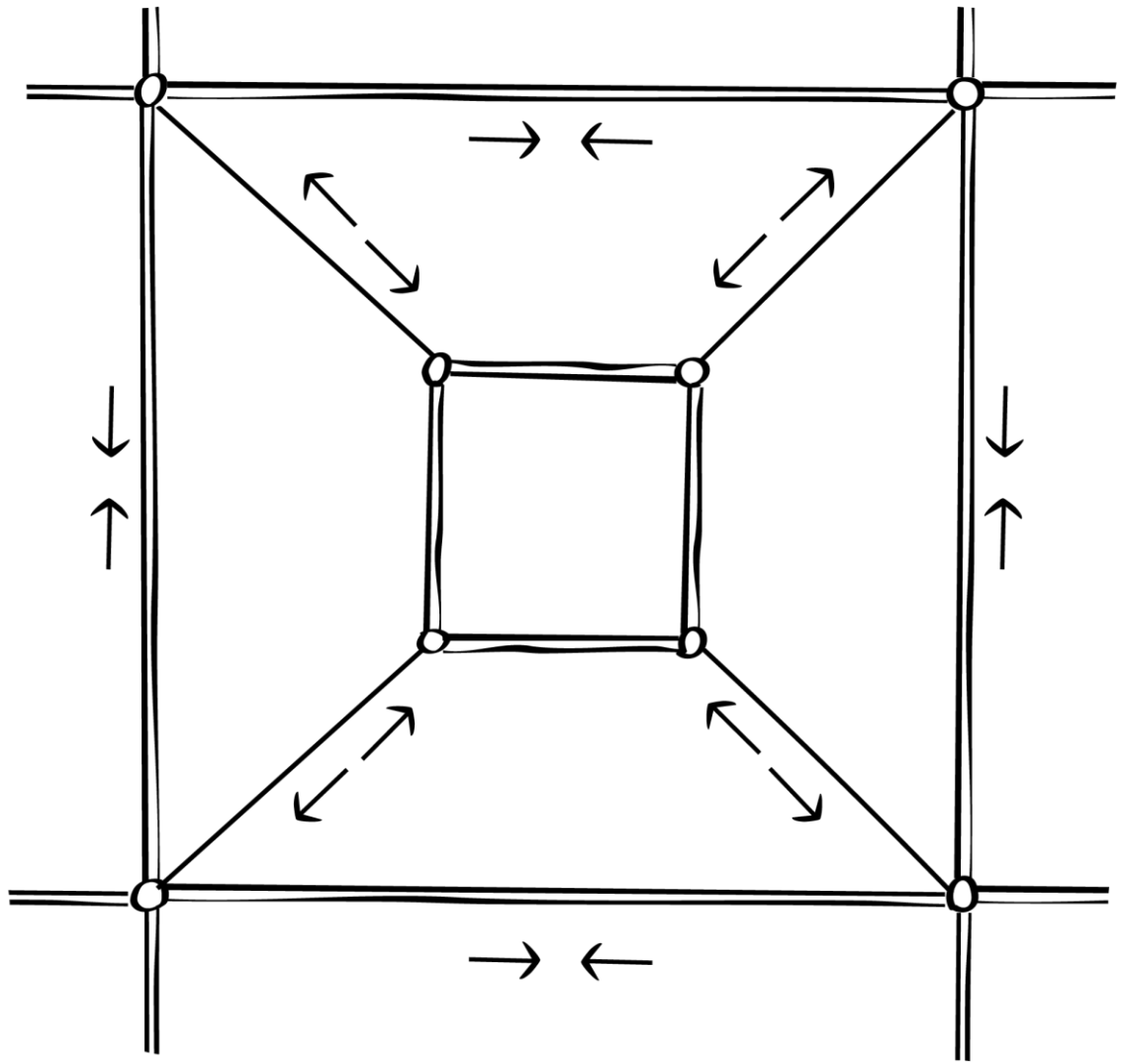


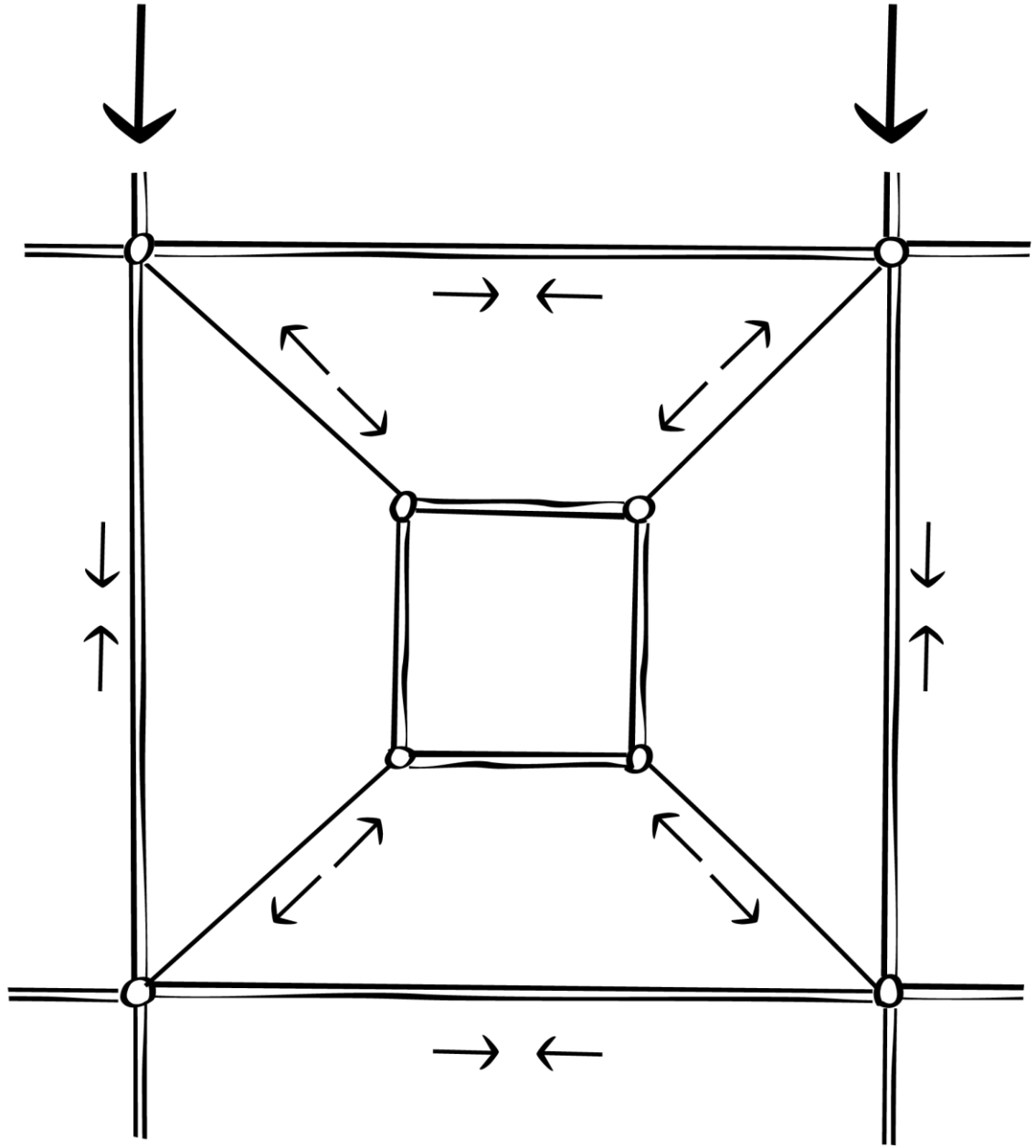


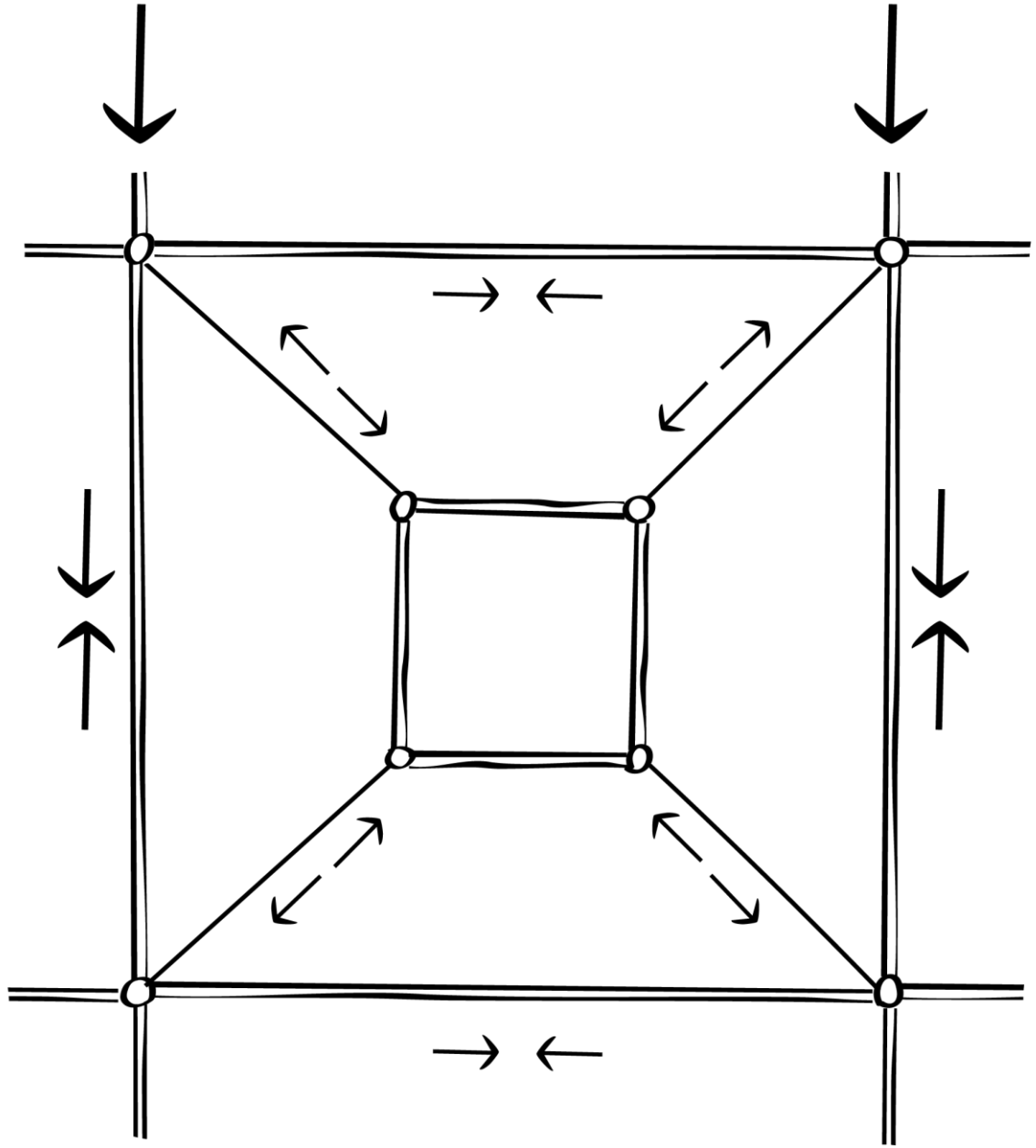


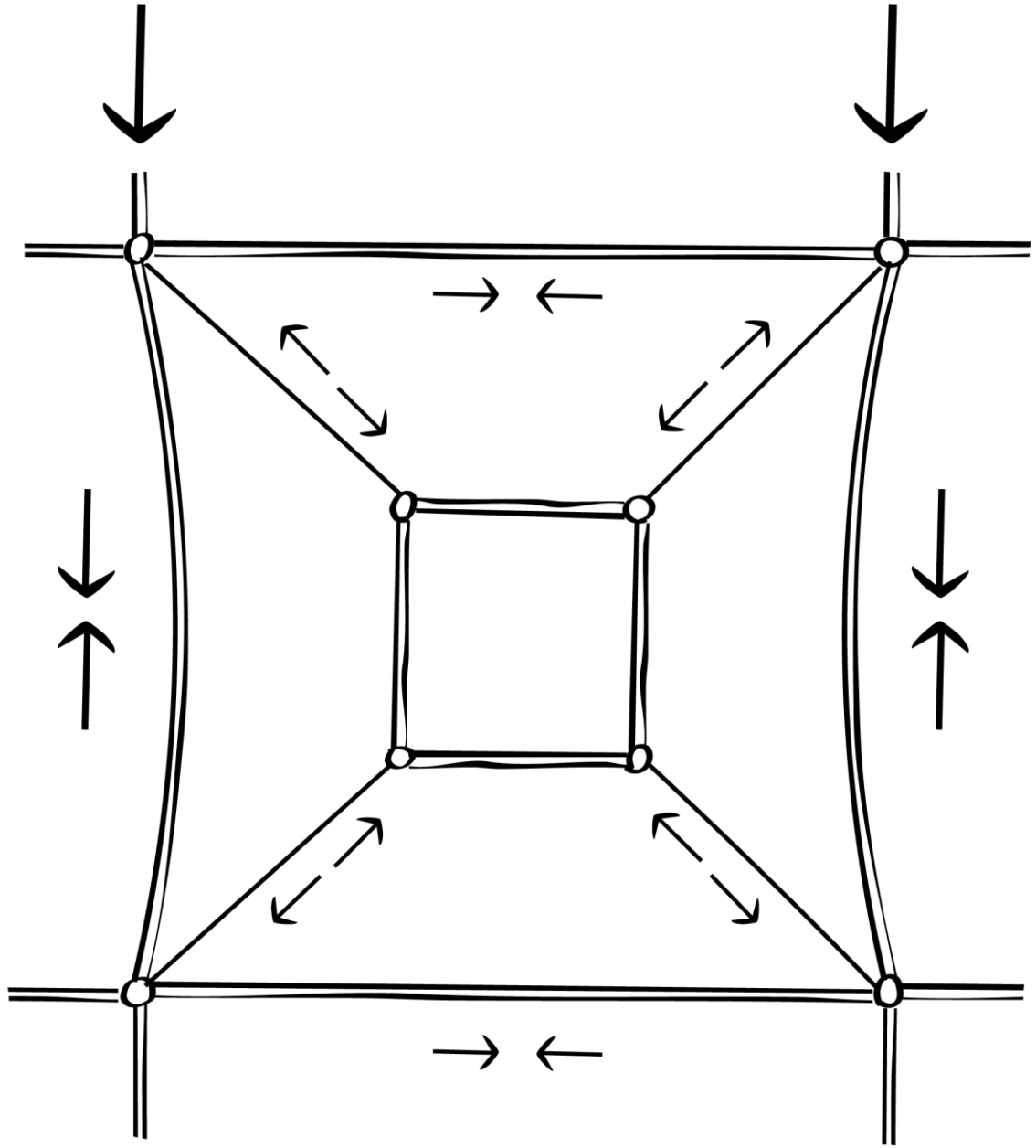


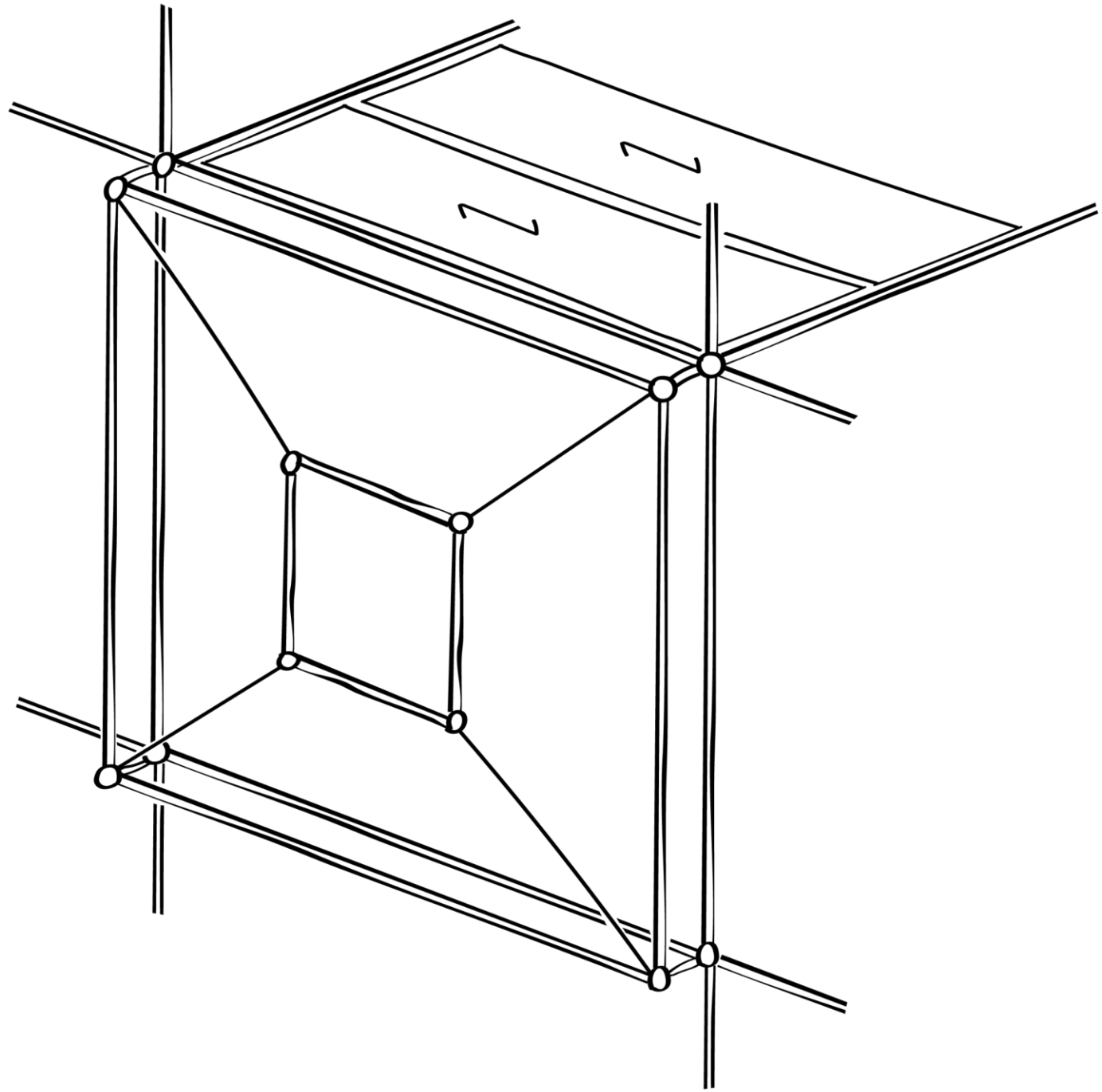

1
1

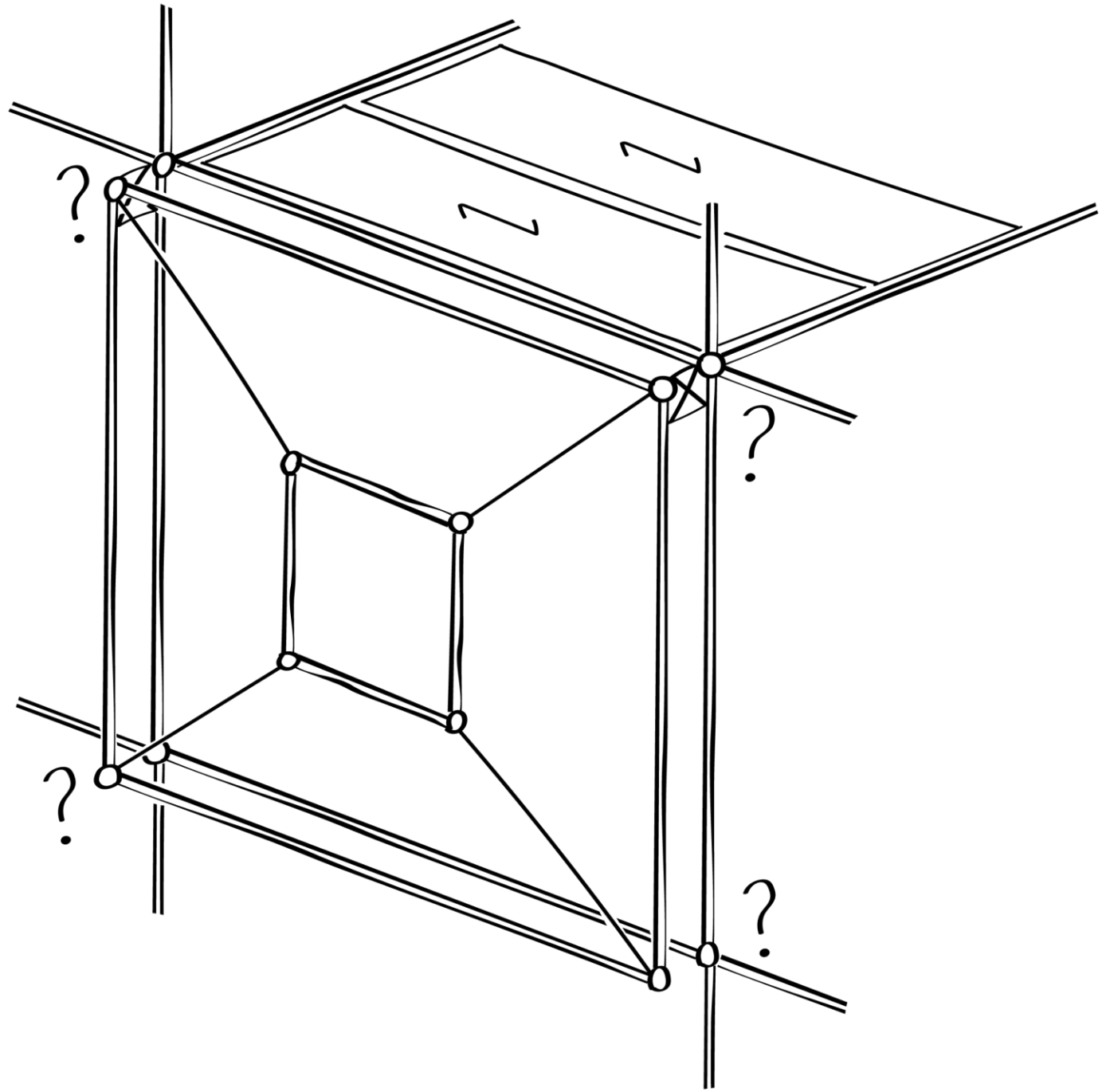




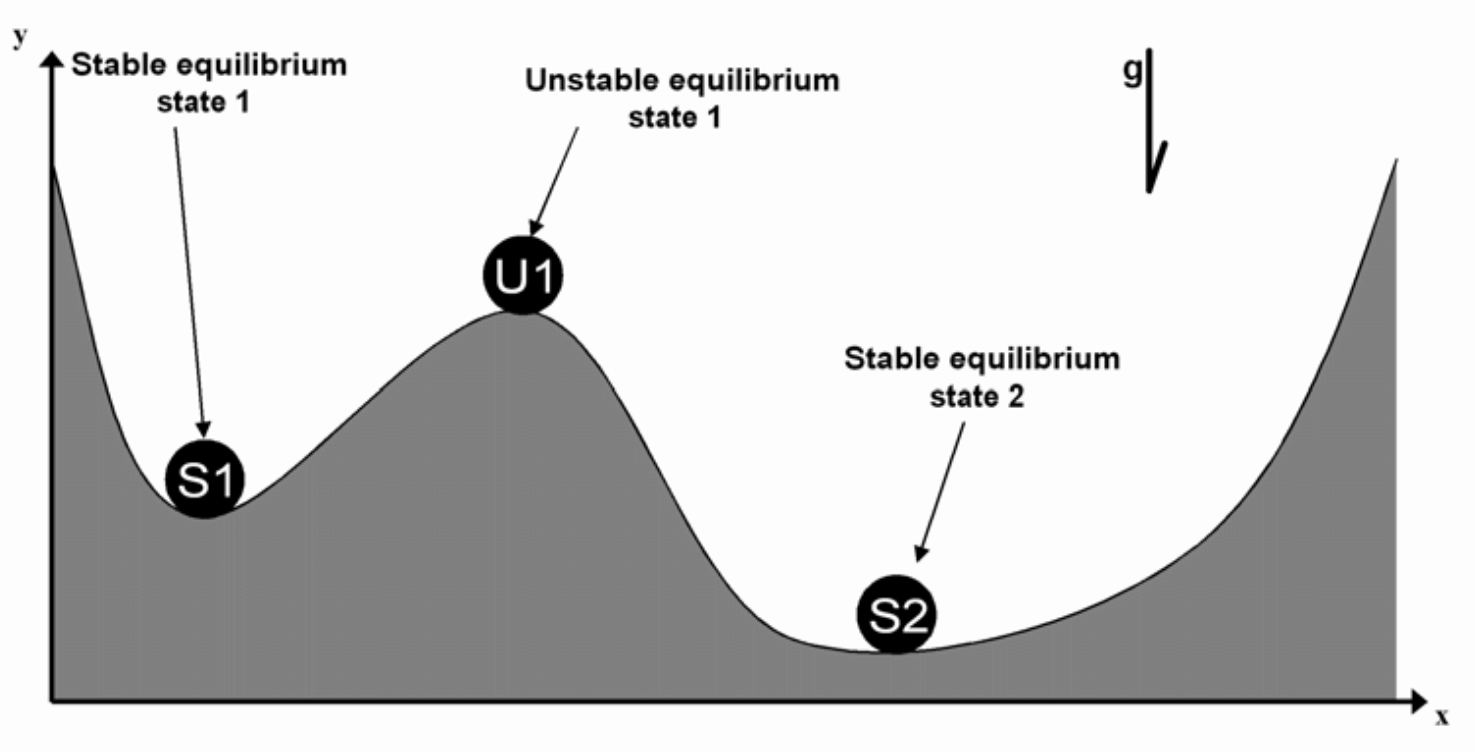




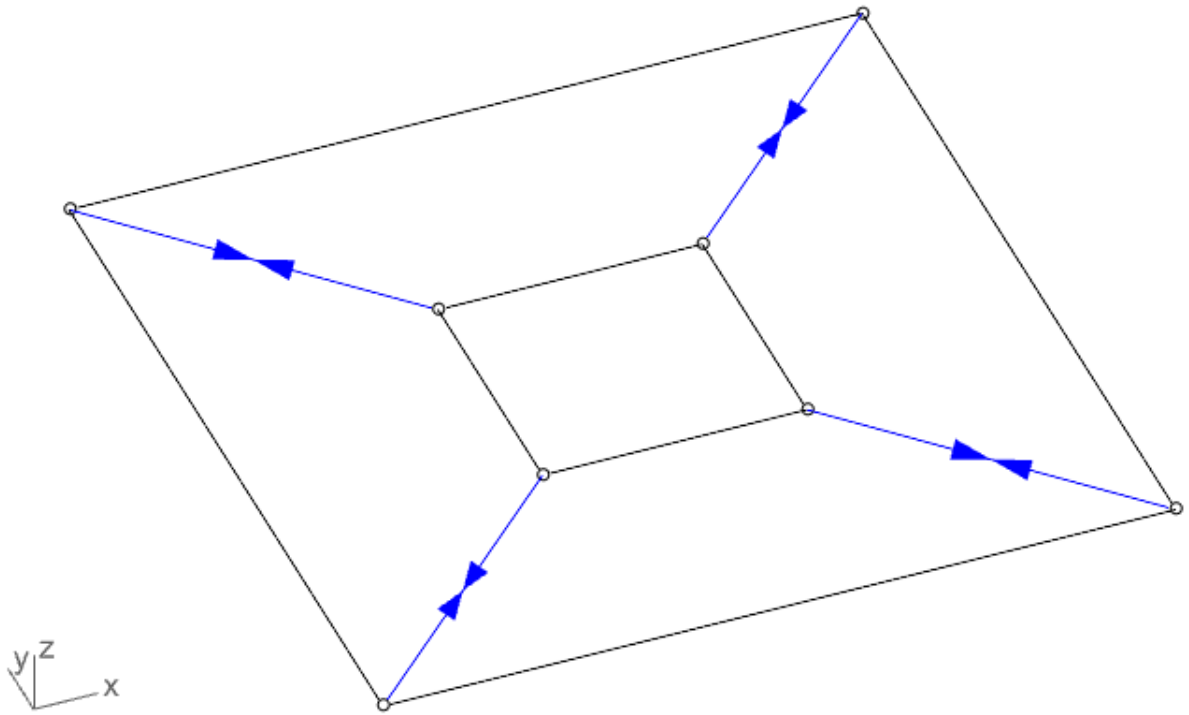


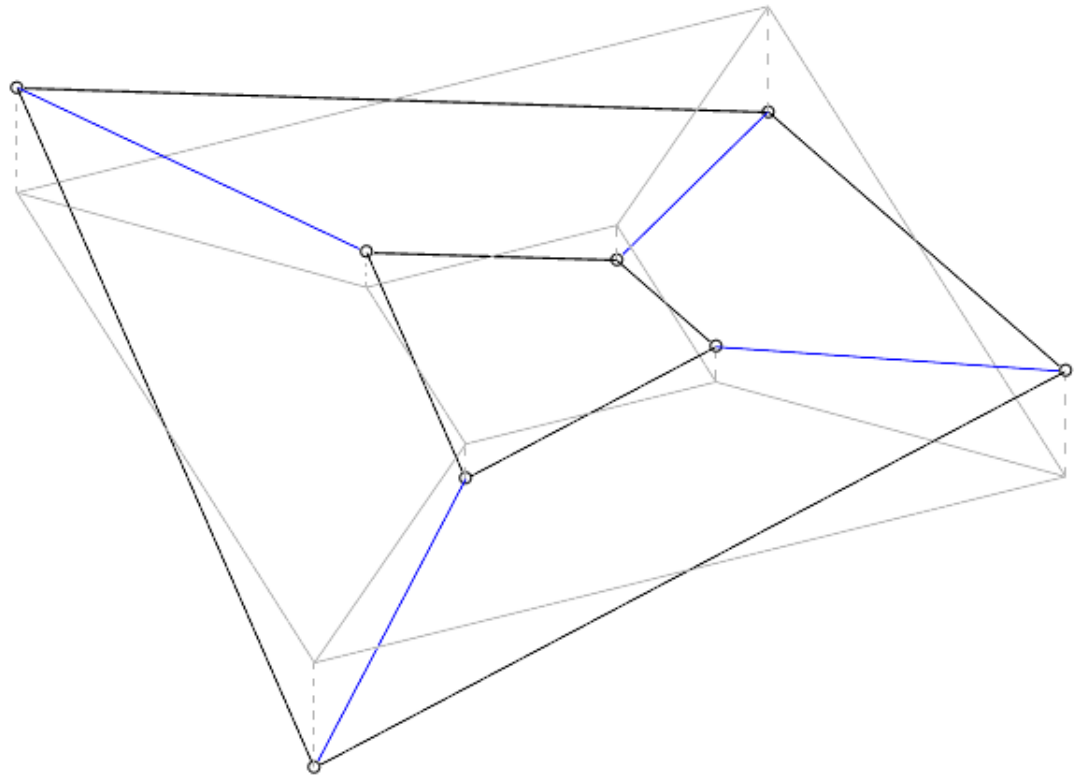

?
1
1
?
?
?

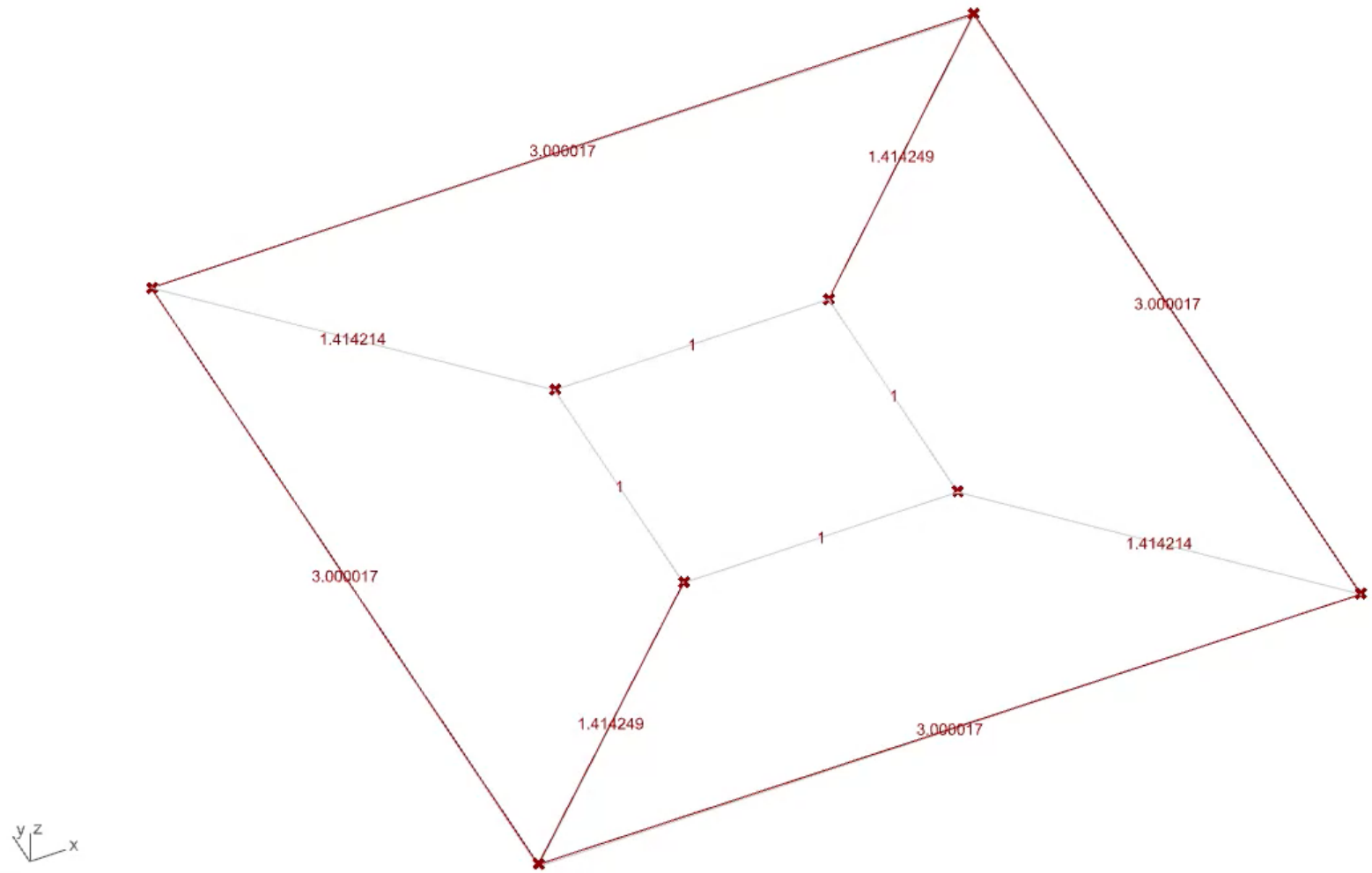
Stability

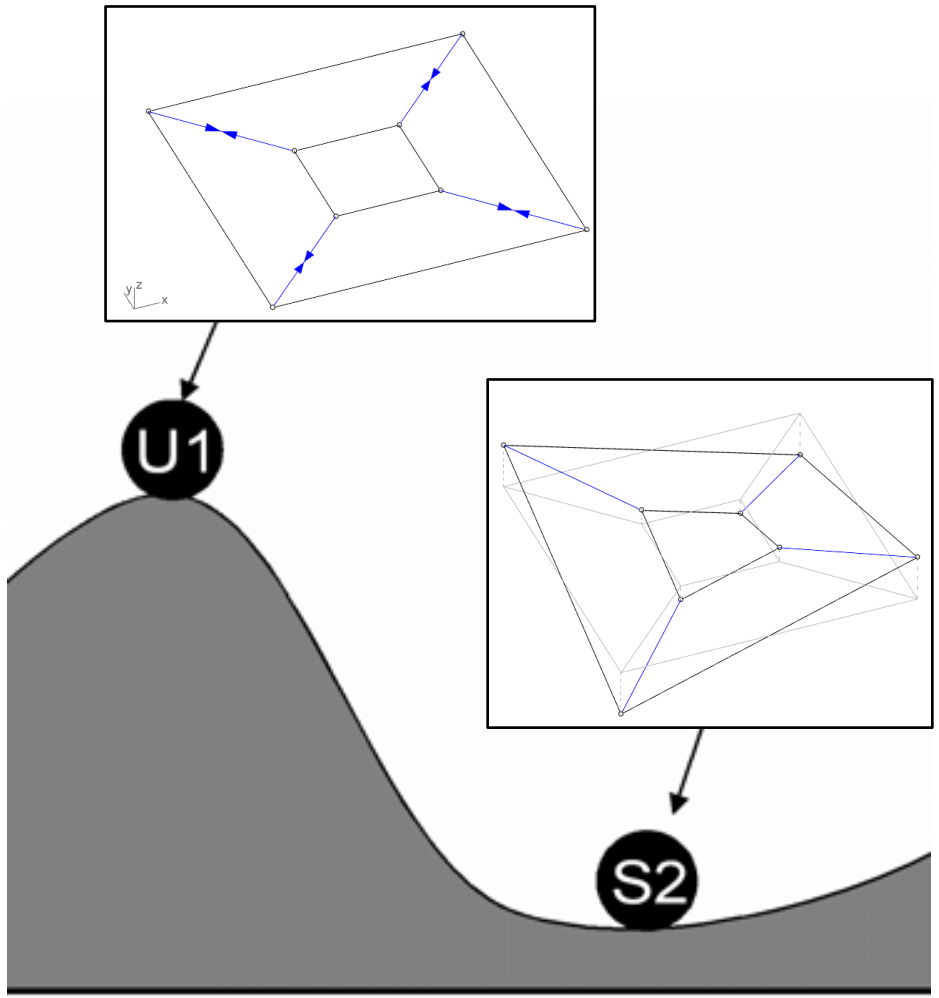


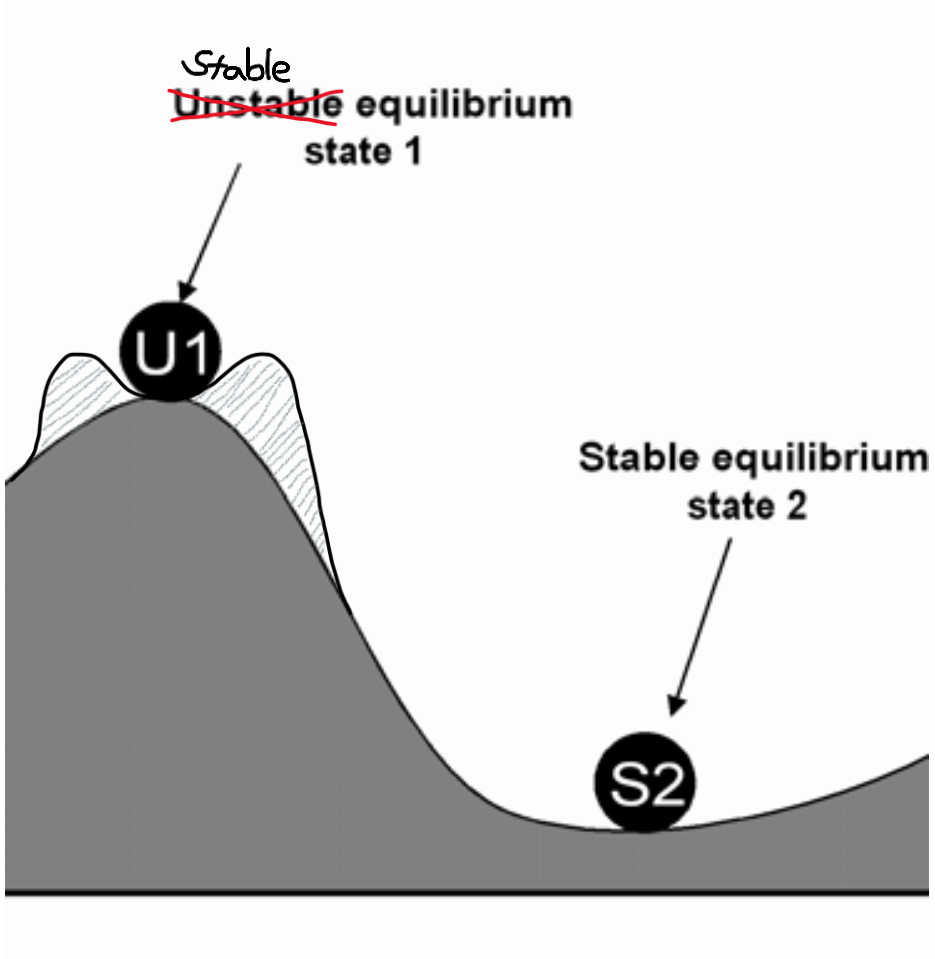
Ball on hill analogy (Carey King, https://www.researchgate.net/figure/Ball-on-hill-analogy_fig4_287068449)

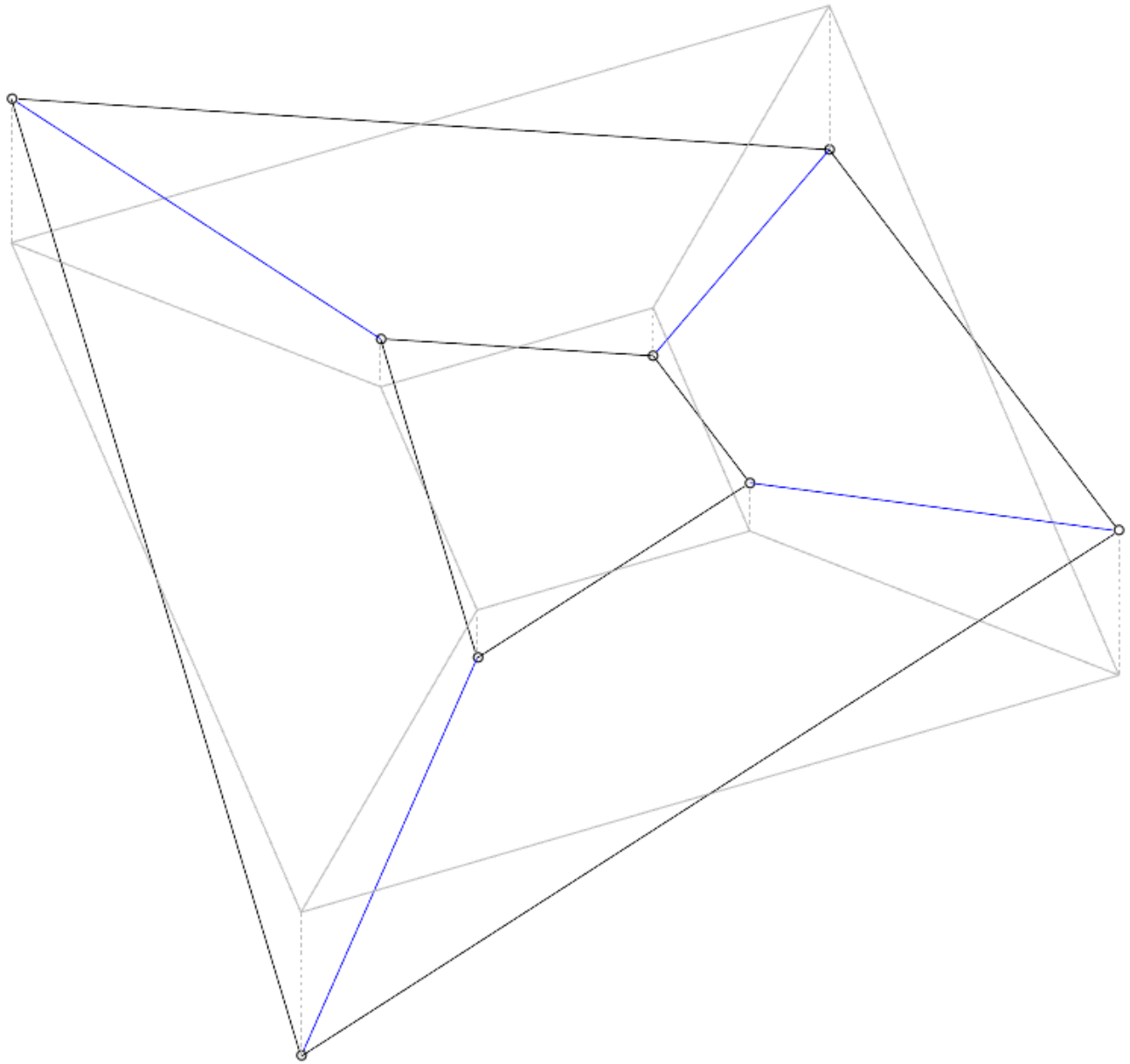

y
z
x

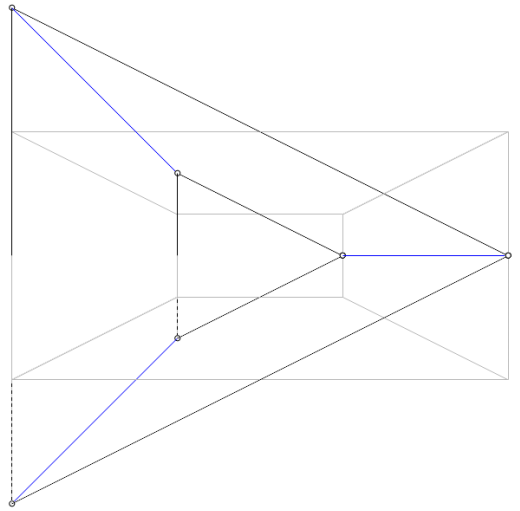


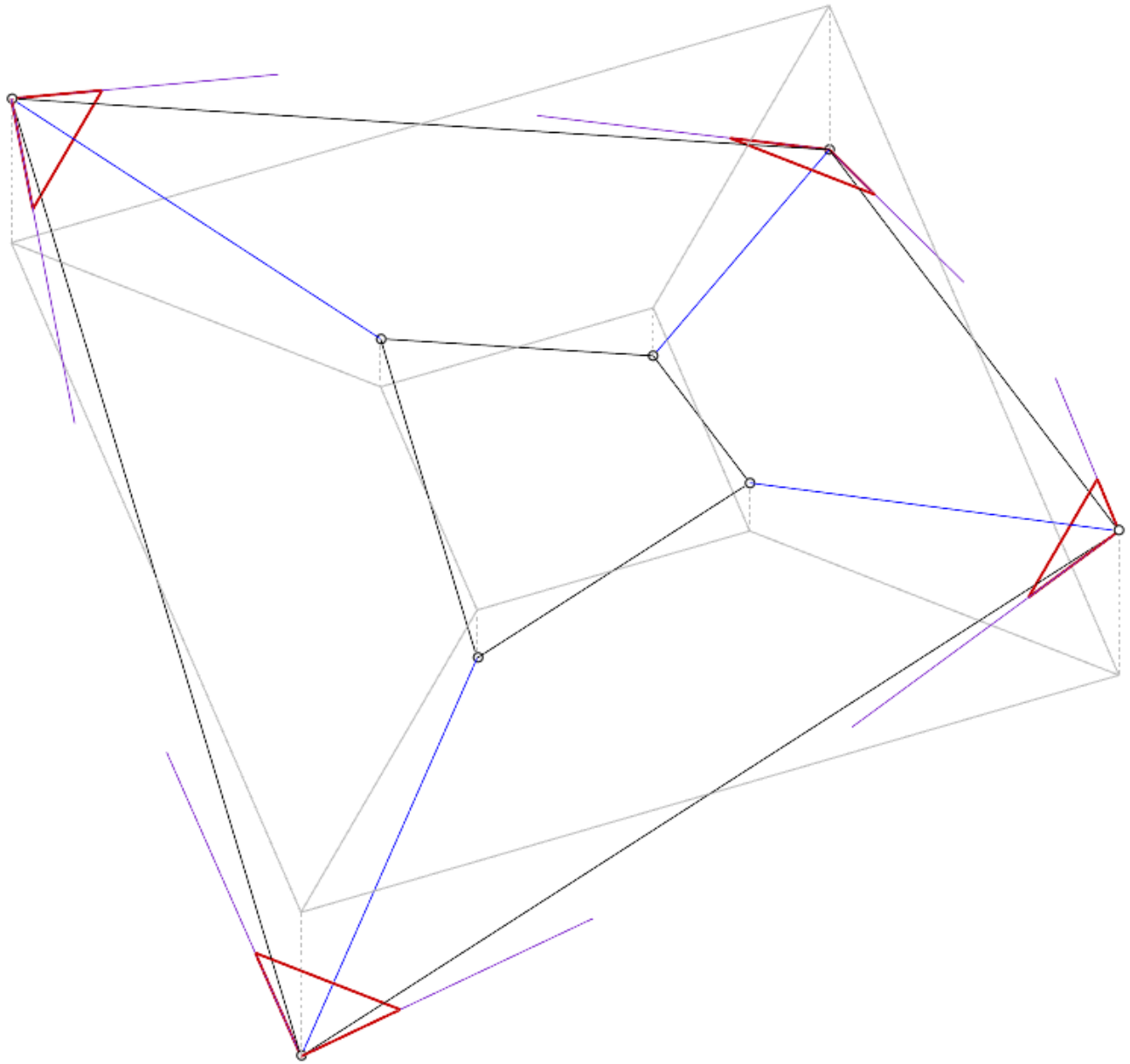

3.000017
1.414249
3.000017
1.414214
1
1
1
1
1.414214
3.000017
1.414249
3.000017
y
z
x

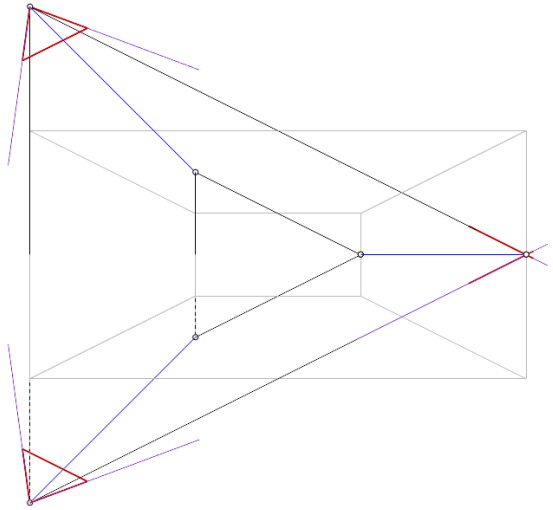

y
z
x
U1
S2

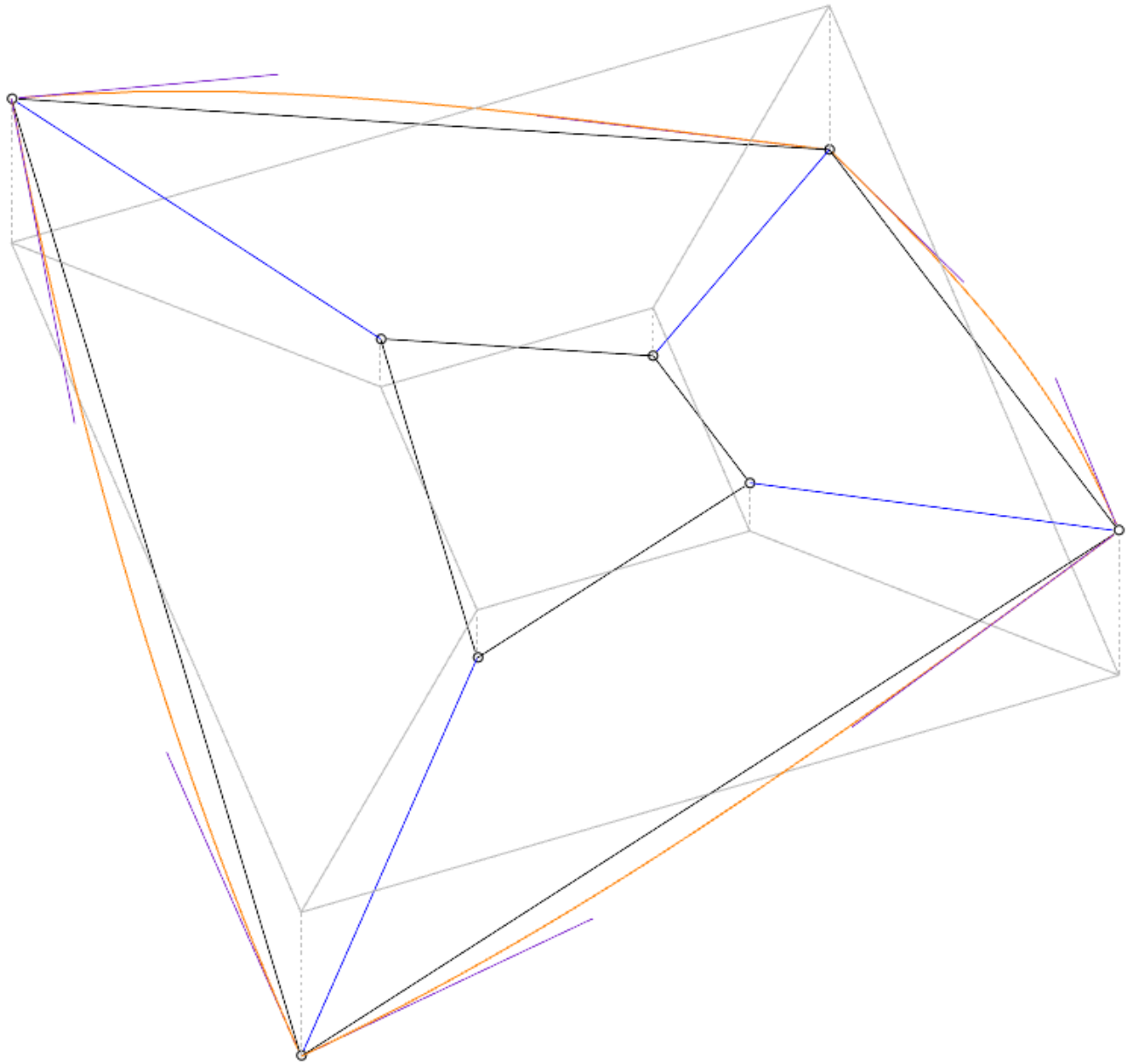

Stable
Unstable equilibrium
state 1
U1
Stable equilibrium
state 2
S2

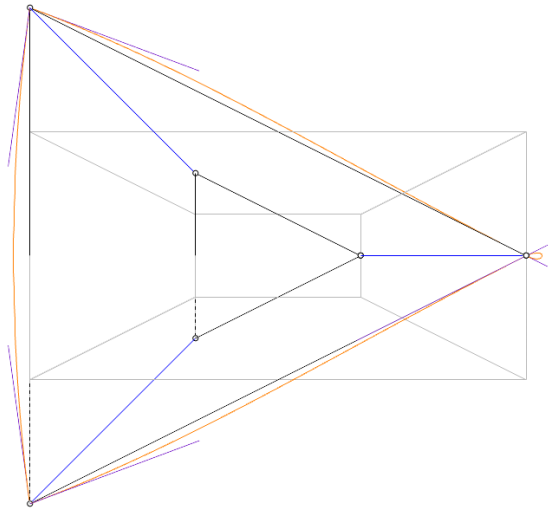


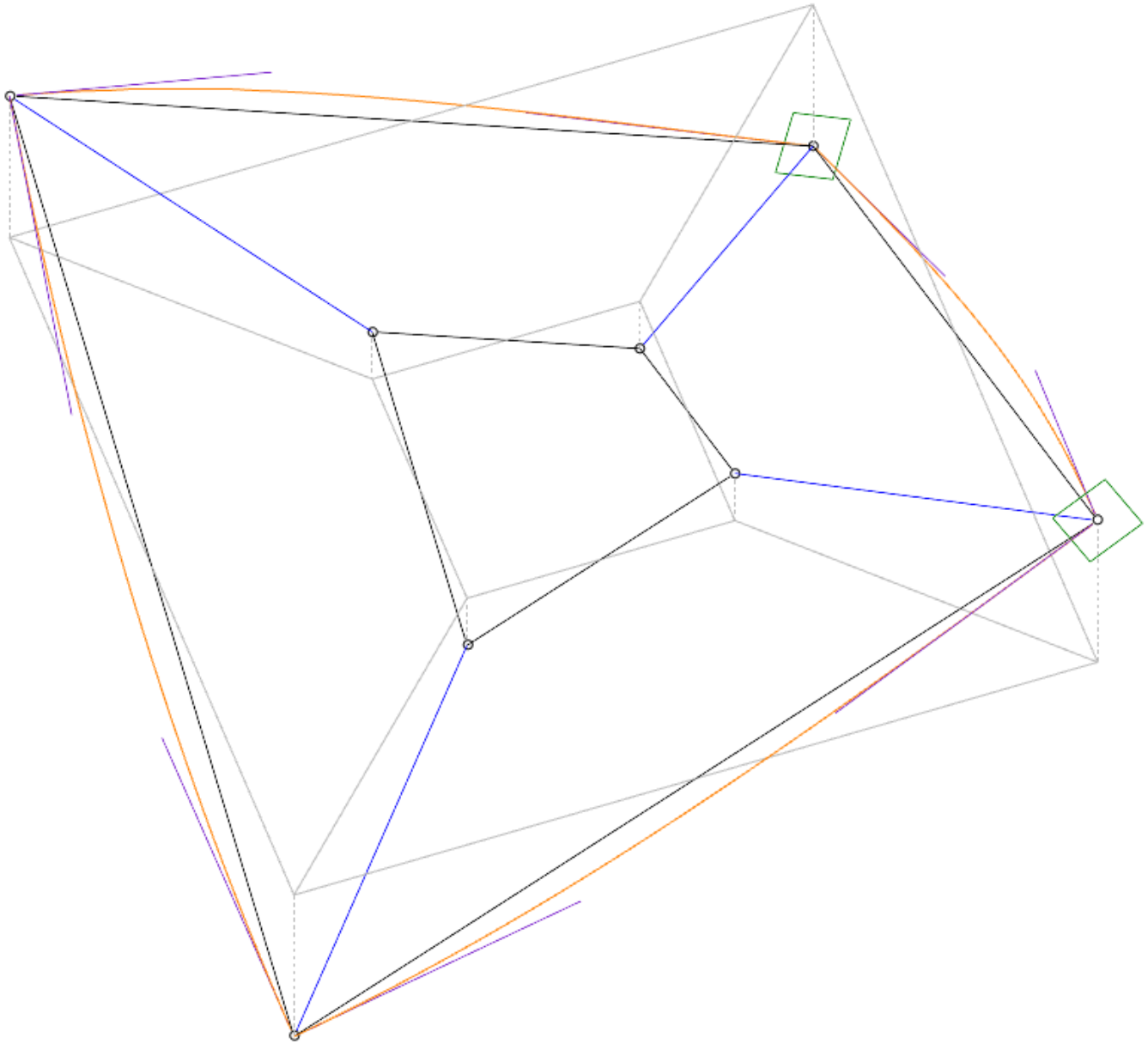


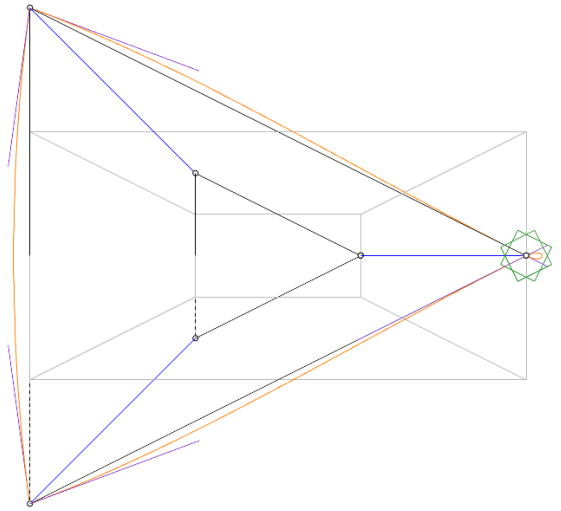


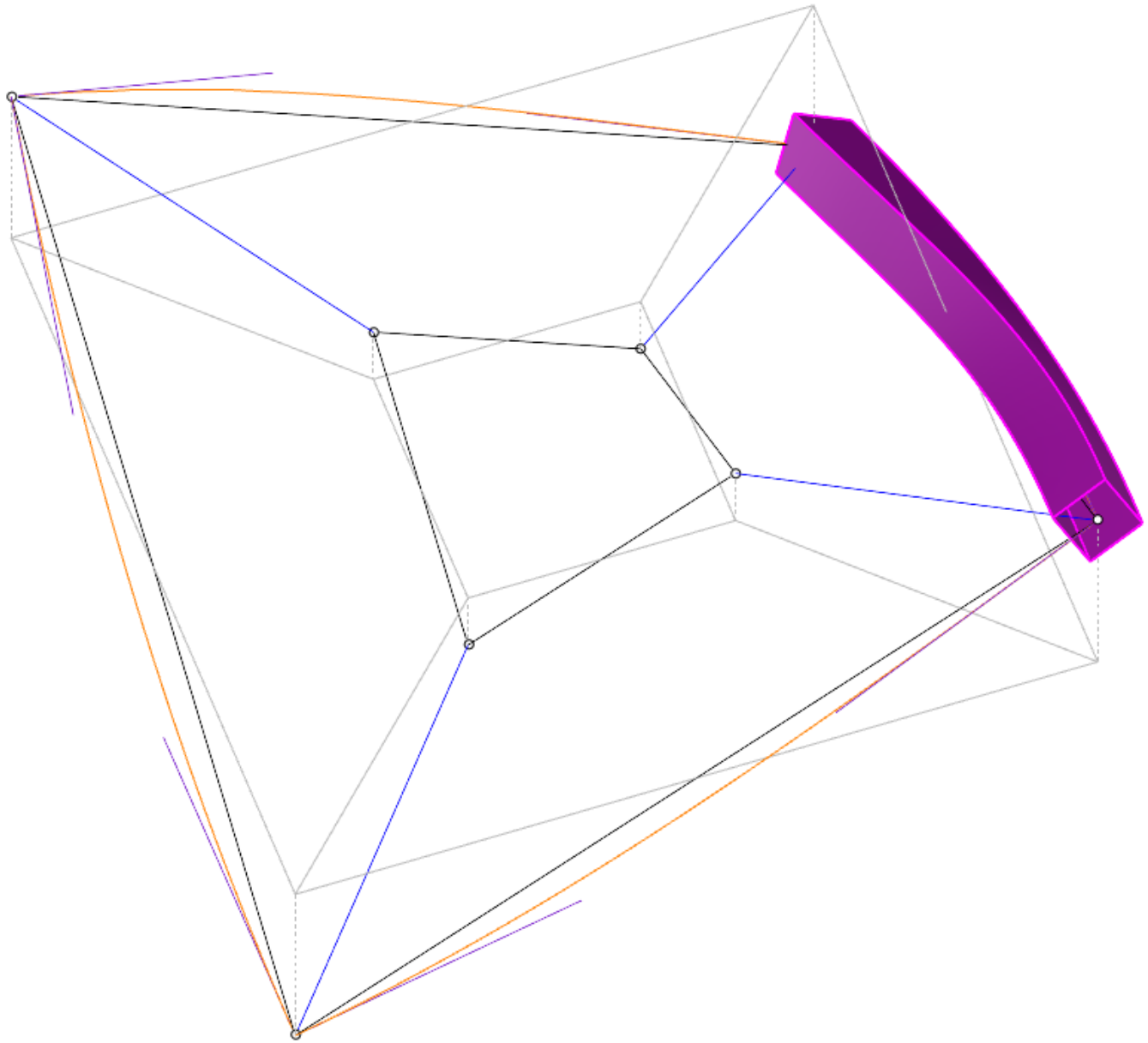


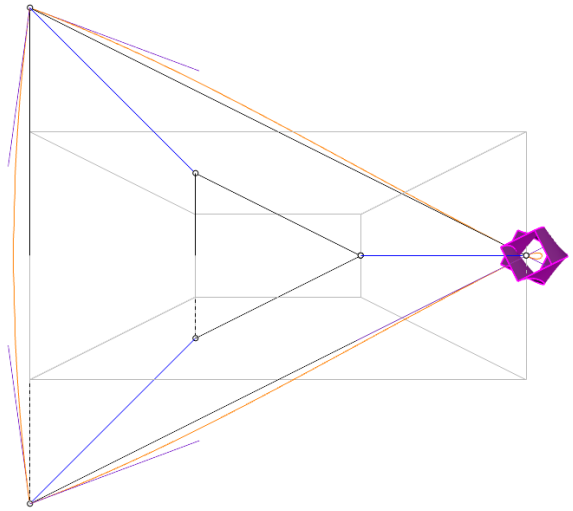


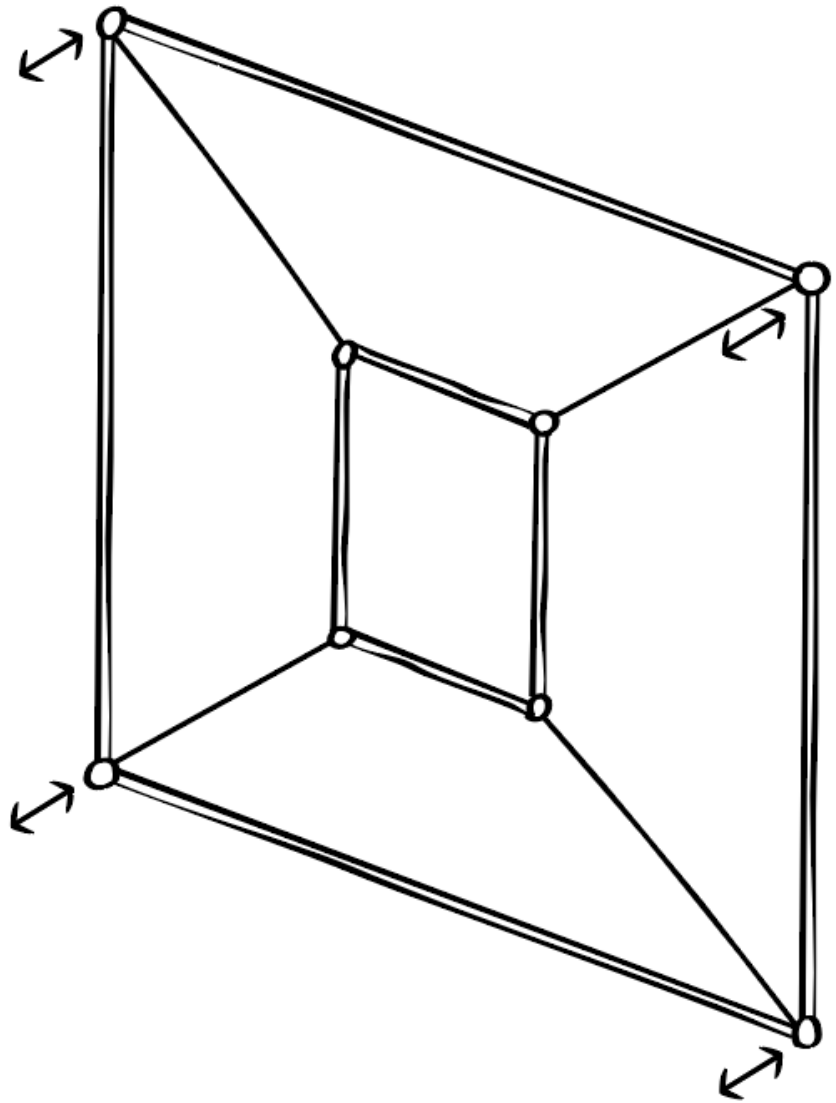


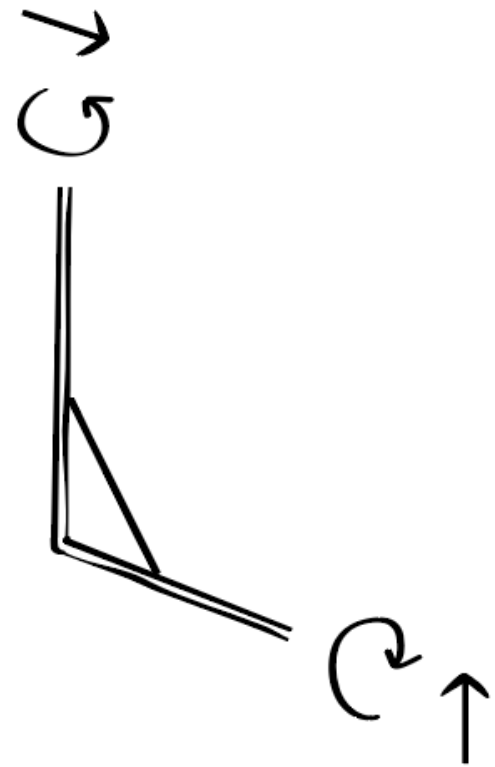


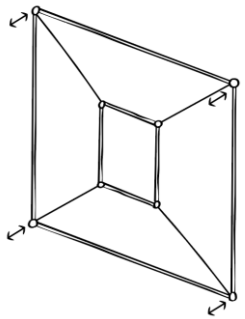


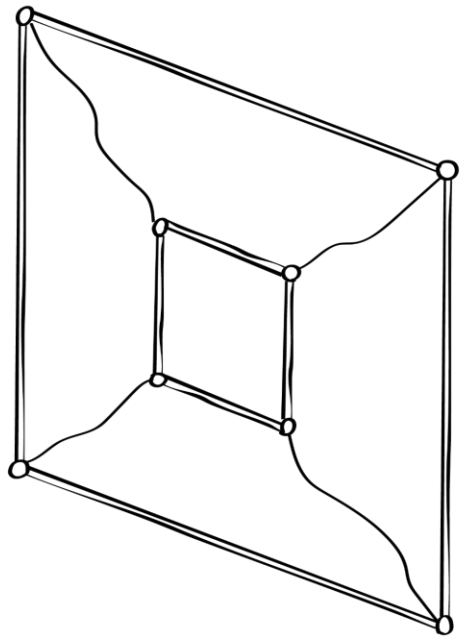


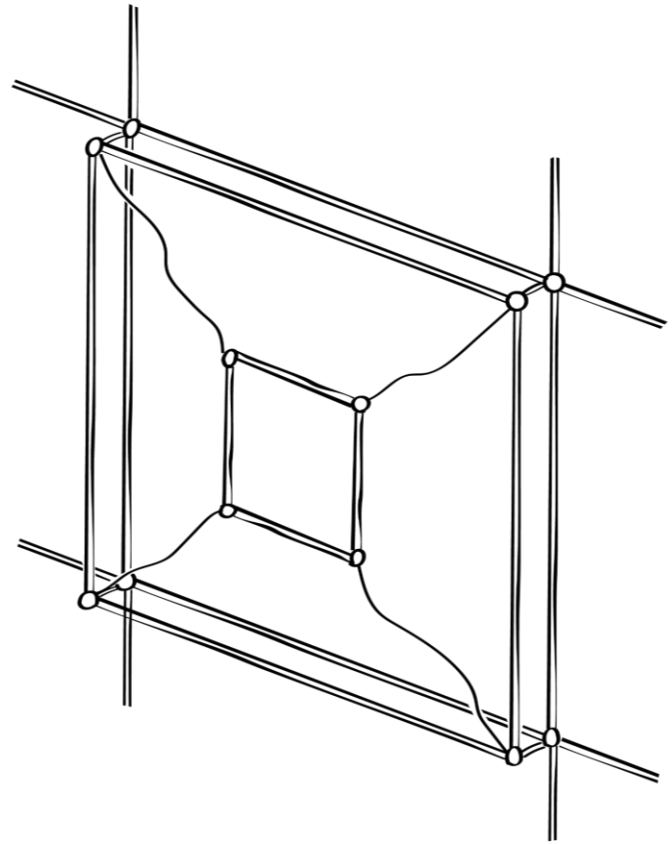


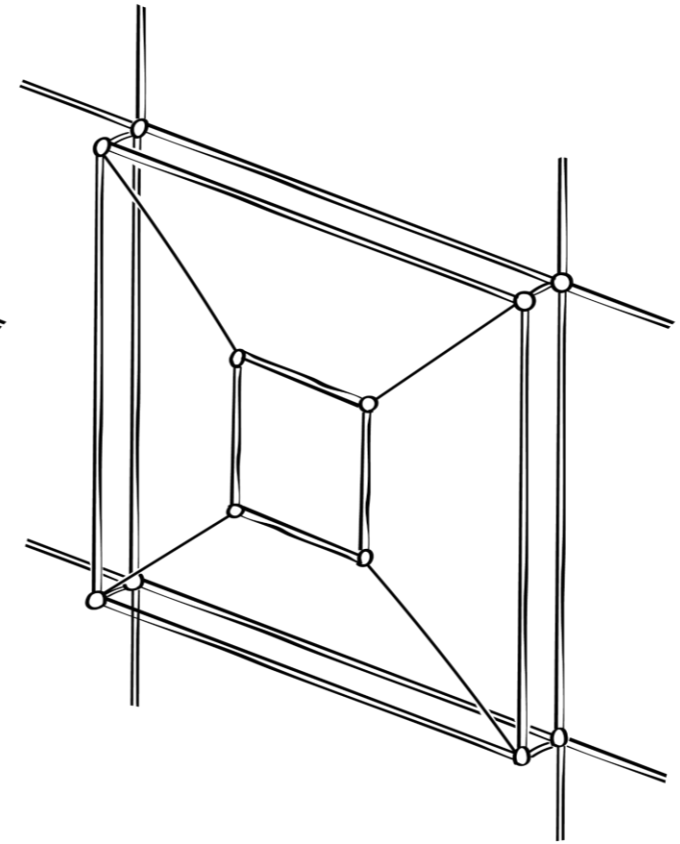


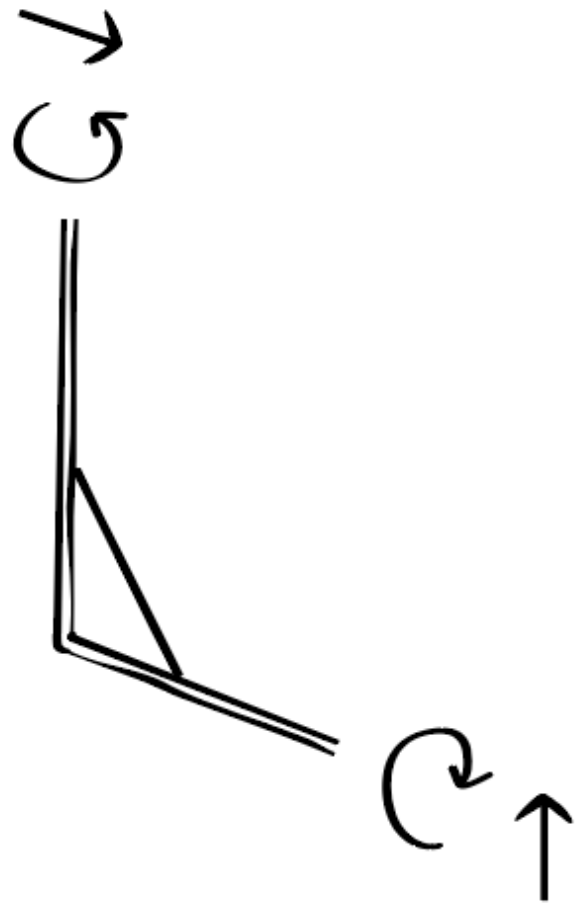


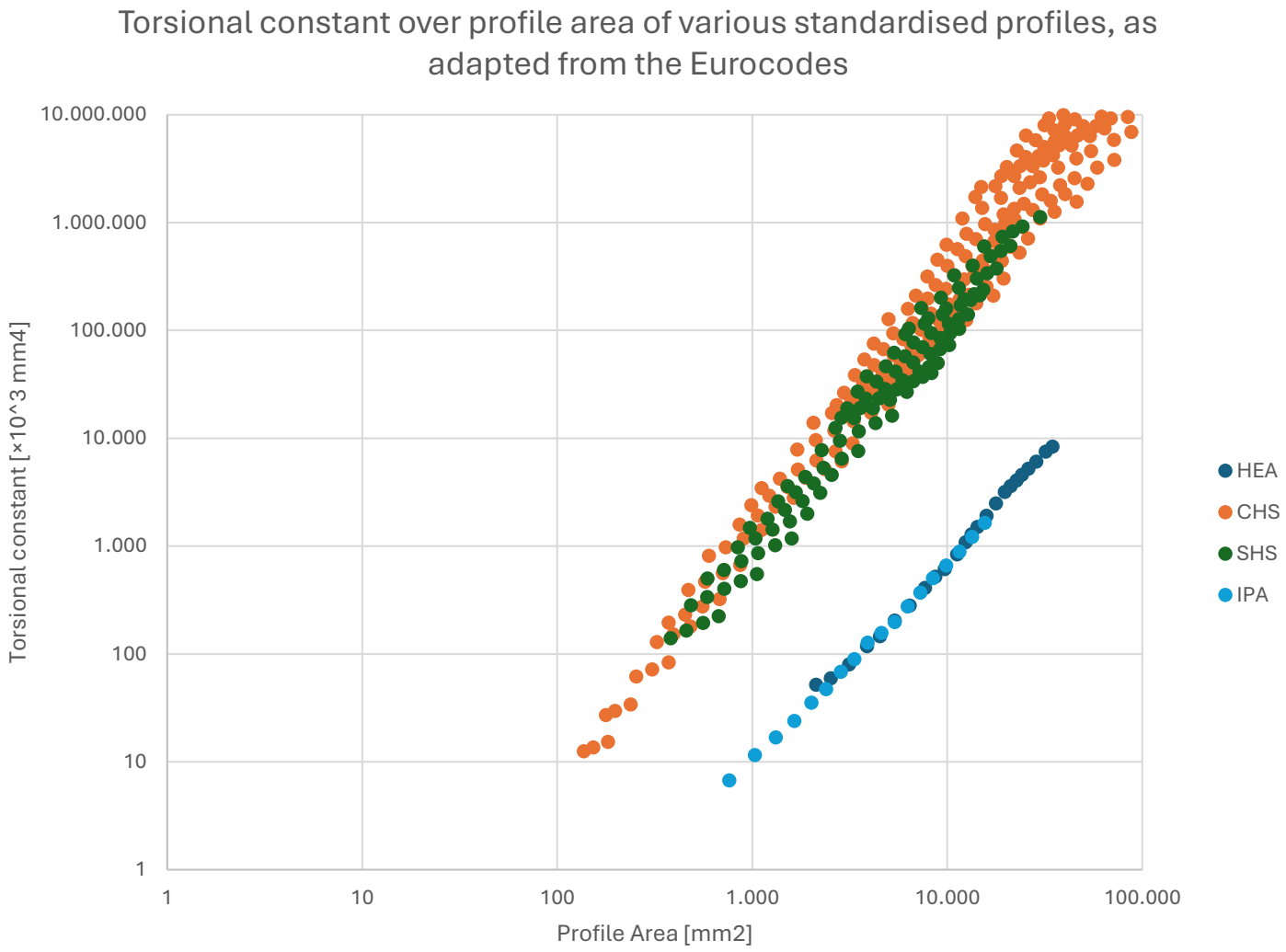


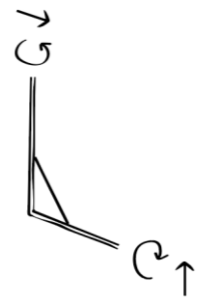


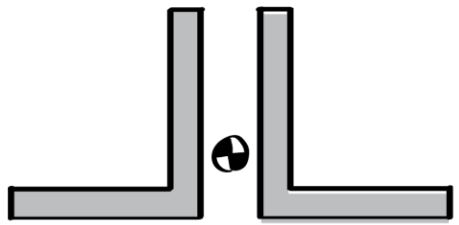


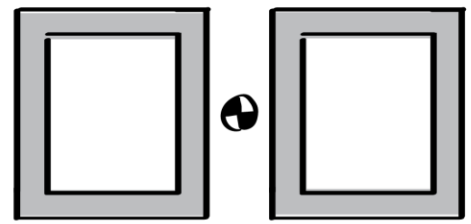


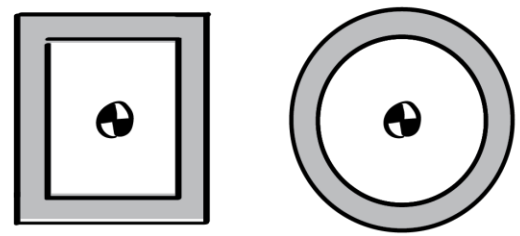


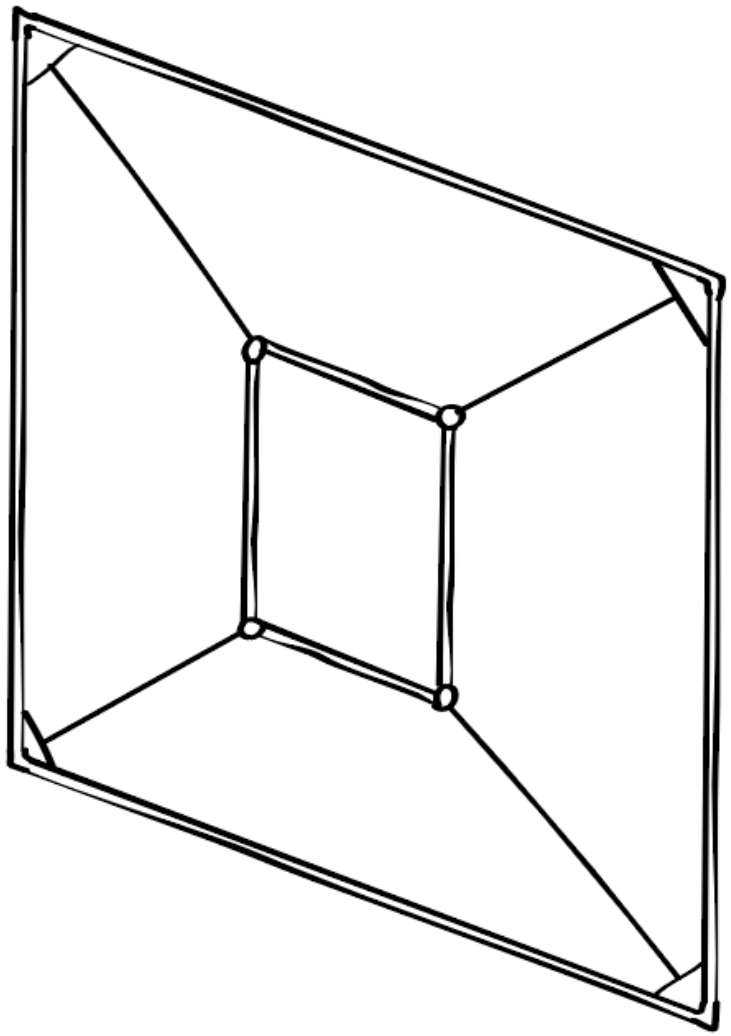

Torsional constant over profile area of various standardised profiles, as adapted from the Eurocodes
10.000.000
1.000.000
100.000
10.000
1.000
100
10
1
Torsional constant [×10^3 mm4]
1
10
100
1.000
10.000
100.000
Profile Area [mm2]
HEA
CHS
SHS
IPA

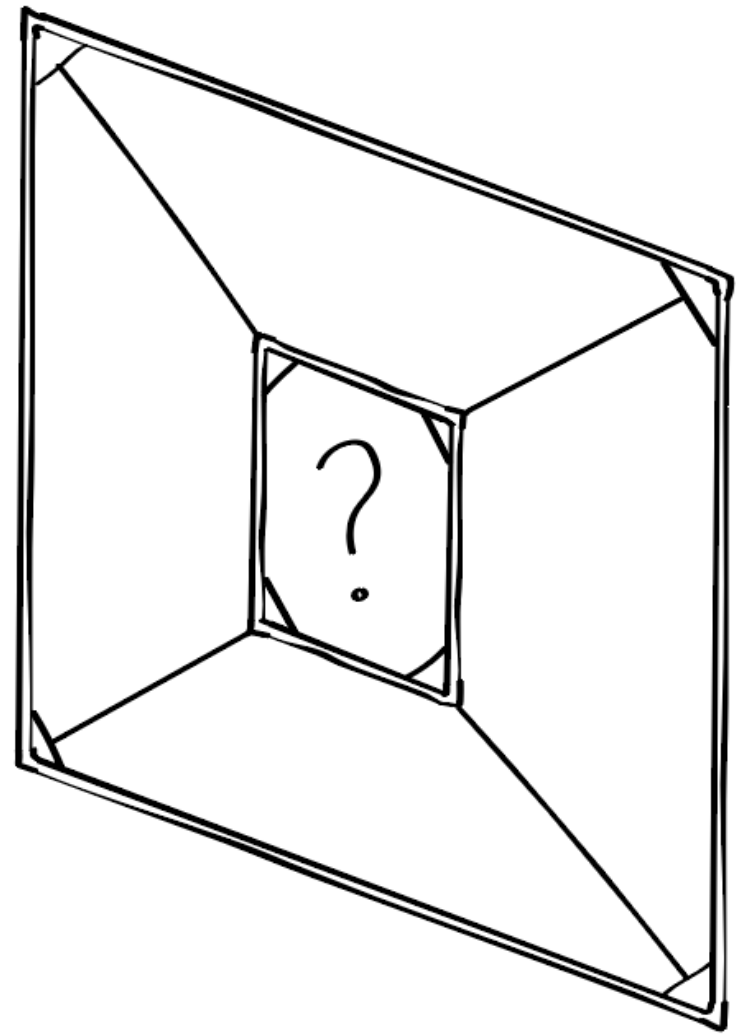


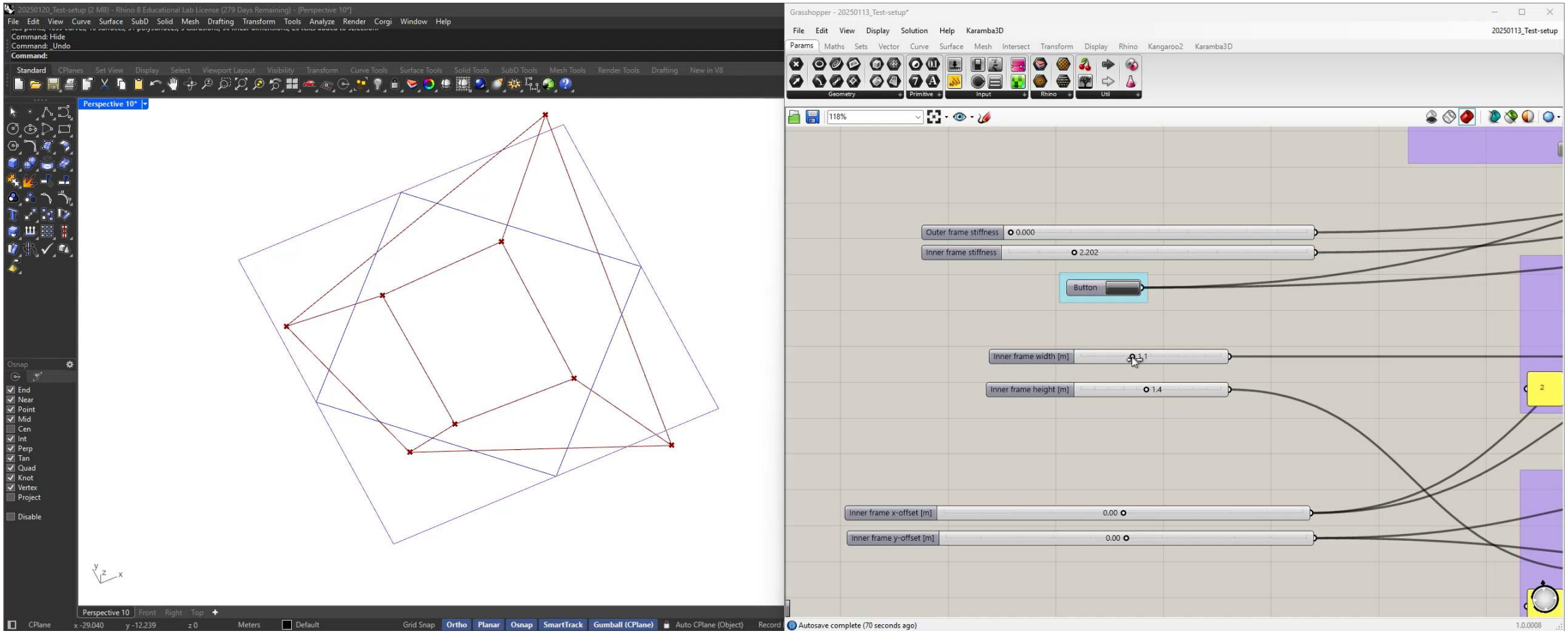


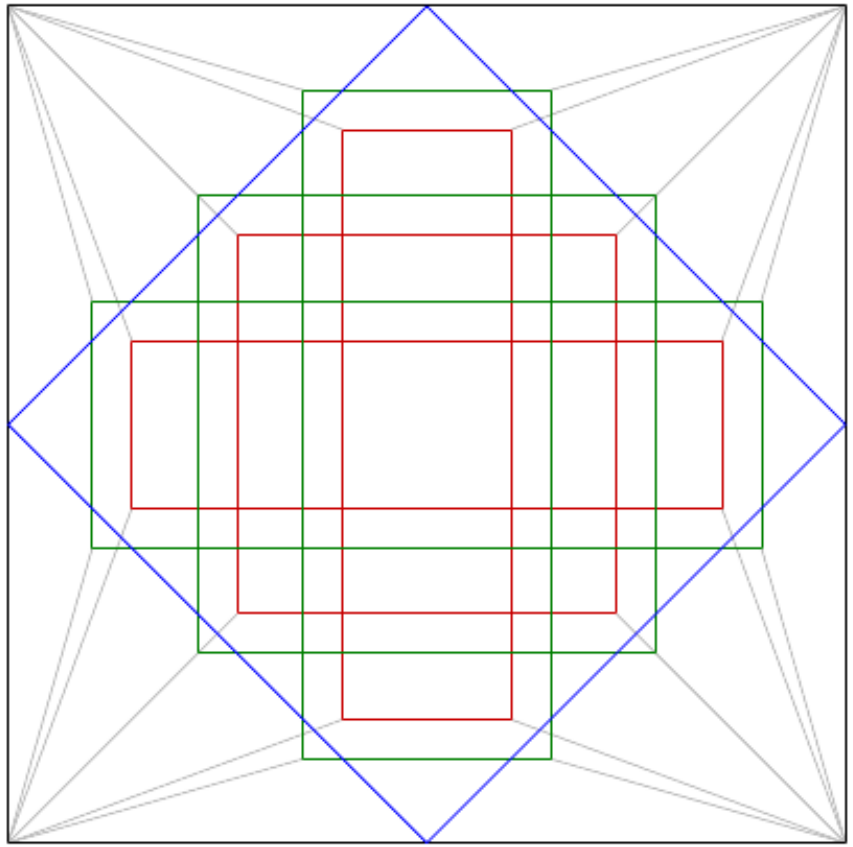


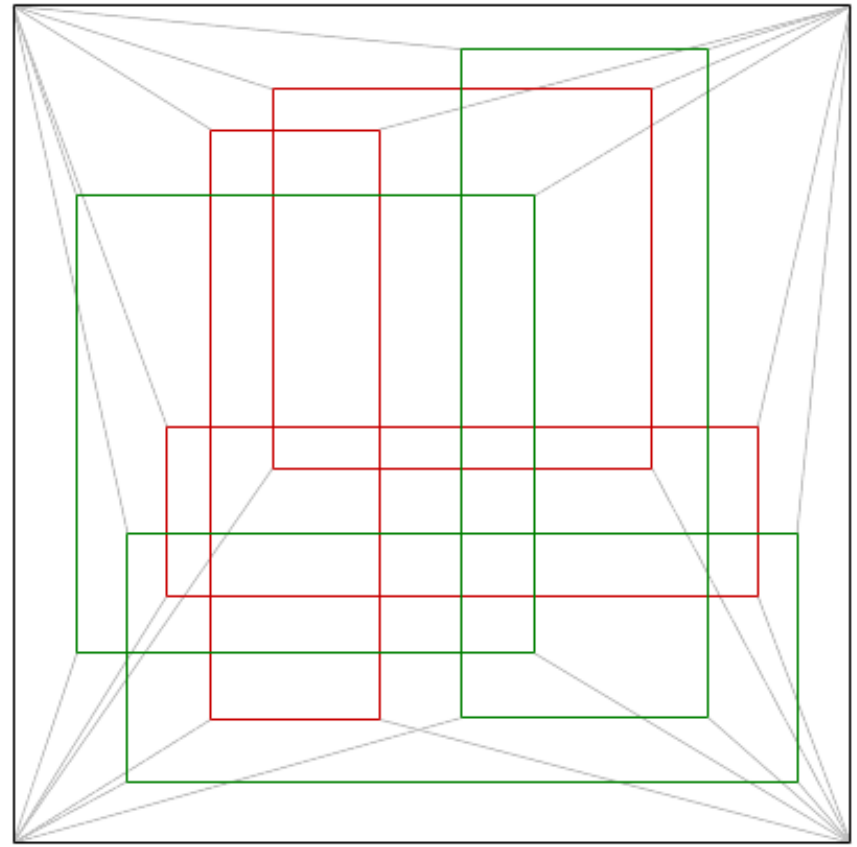


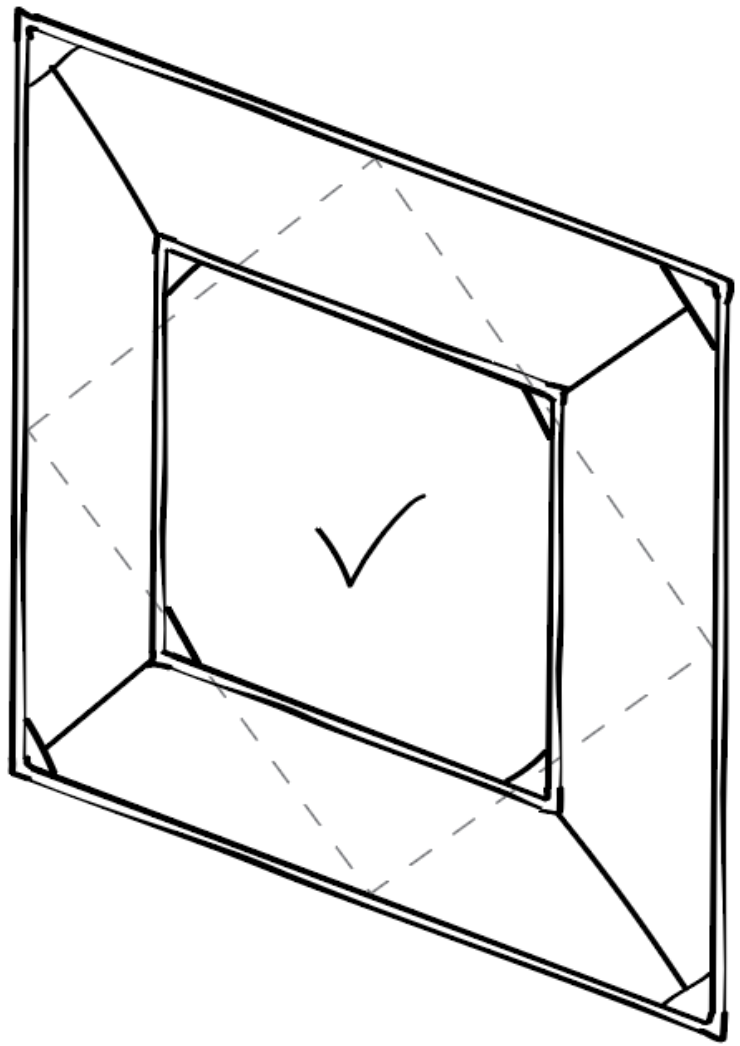


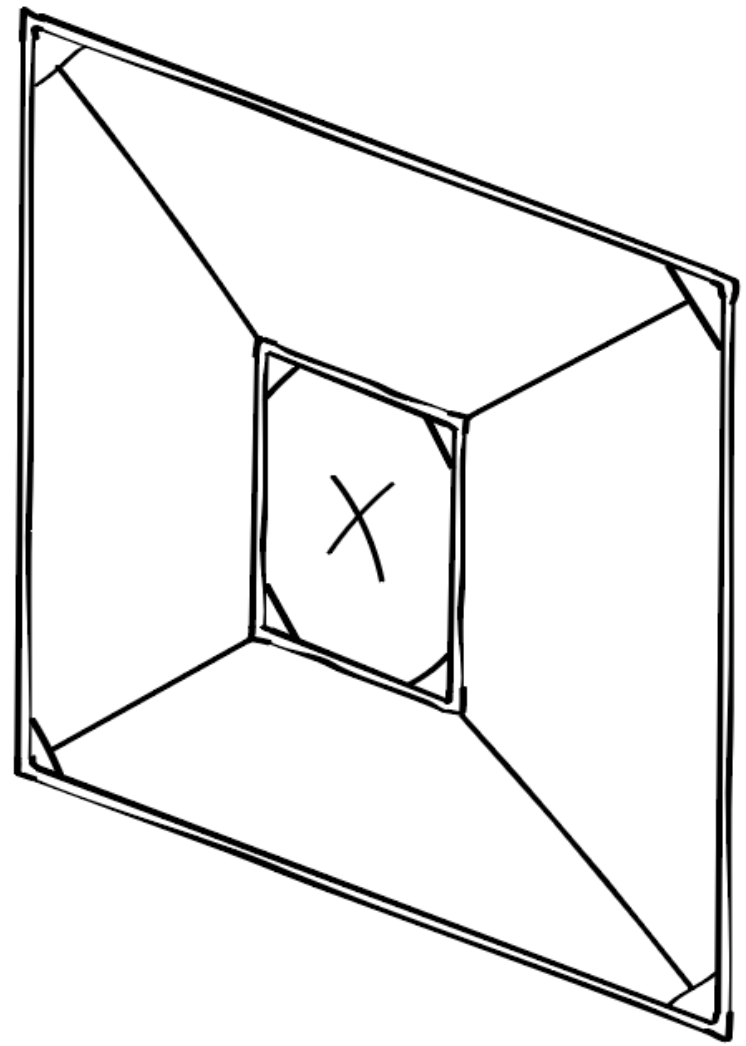


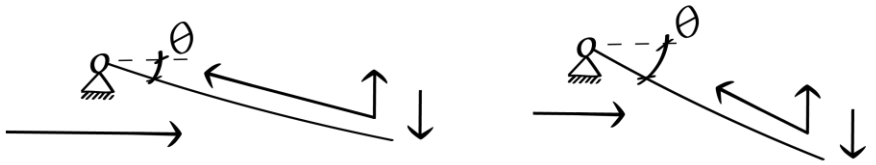

20250120_Test-setup (2 MB) - Rhino 8 Educational Lab License (279 Days Remaining) - [Perspective 10*]
File Edit View Curve Surface SubD Solid Mesh Drafting Transform Tools Analyze Render Corgi Window Help
Command: Hide
Command: _Undo
Command:
Standard CPlanes Set View Display Select Viewport Layout Visibility Transform Curve Tools Surface Tools Solid Tools SubD Tools Mesh Tools Render Tools Drafting New in V8
Perspective 10*
Osnap
End
Near
Point
Mid
Cen
Int
Perp
Tan
Quad
Knot
Vertex
Project
Disable
Perspective 10 Front Right Top
CPlane x -29.040 y -12.239 z 0 Meters Default Grid Snap Ortho Planar Osnap SmartTrack Gumball (CPlane) Auto CPlane (Object) Record
Grasshopper - 20250113_Test-setup*
File Edit View Display Solution Help Karamba3D
20250113_Test-setup
Params Maths Sets Vector Curve Surface Mesh Intersect Transform Display Rhino Kangaroo2 Karamba3D
Geometry Primitive Input Rhino Util
118%
Outer frame stiffness 0.000
Inner frame stiffness 2.202
Button
Inner frame width [m] 1.1
Inner frame height [m] 1.4
2
Inner frame x-offset [m] 0.00
Inner frame y-offset [m] 0.00
Autosave complete (70 seconds ago)
1.0.0008

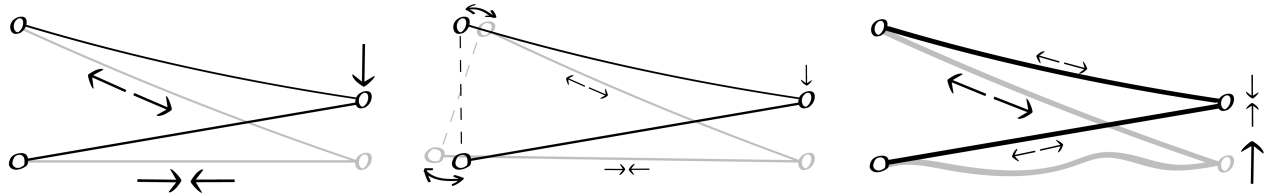


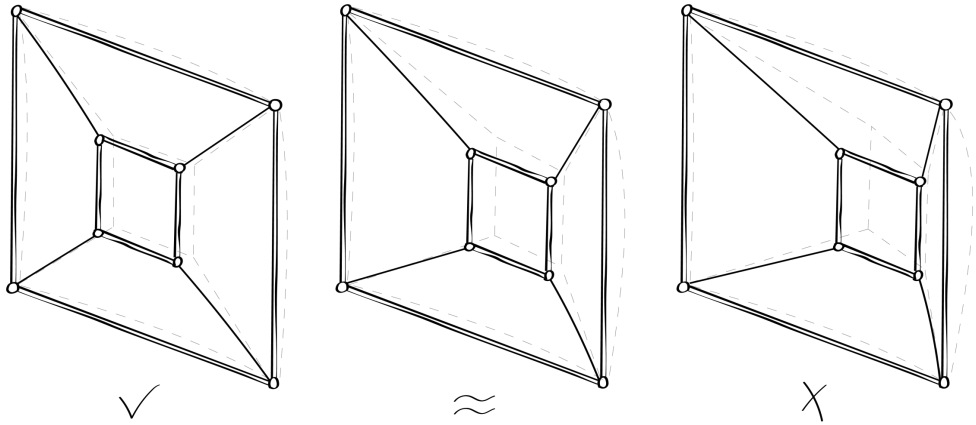


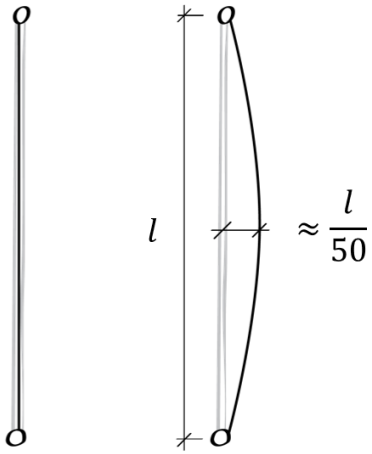


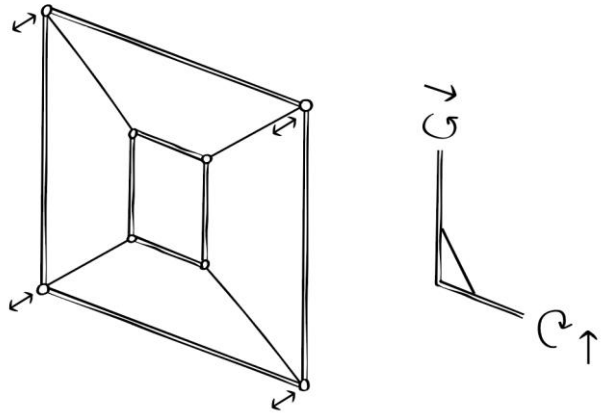


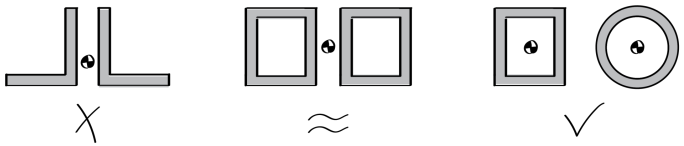

θ
θ

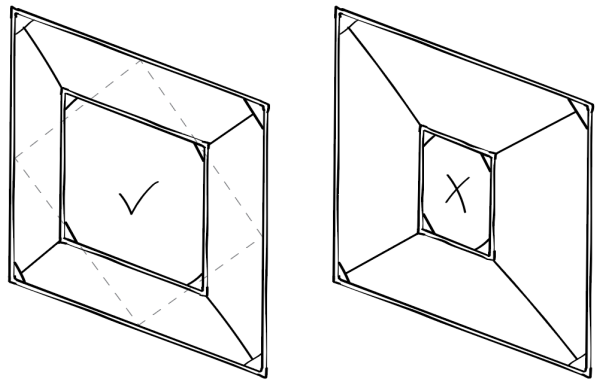


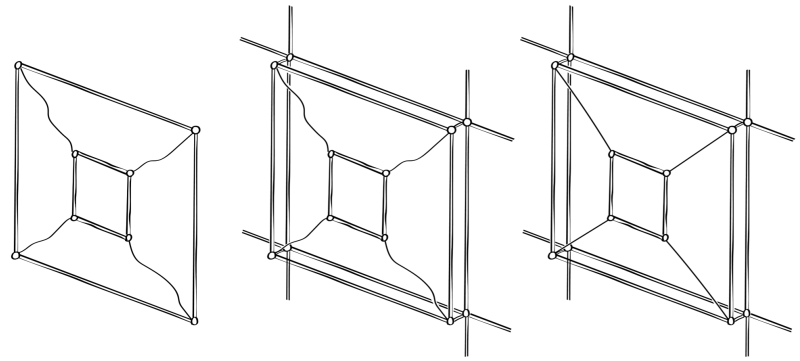


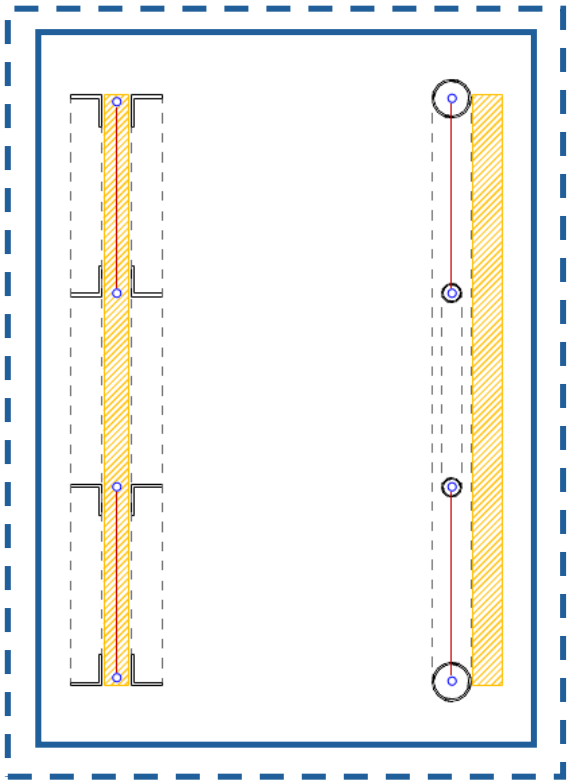

l
≈ l/50

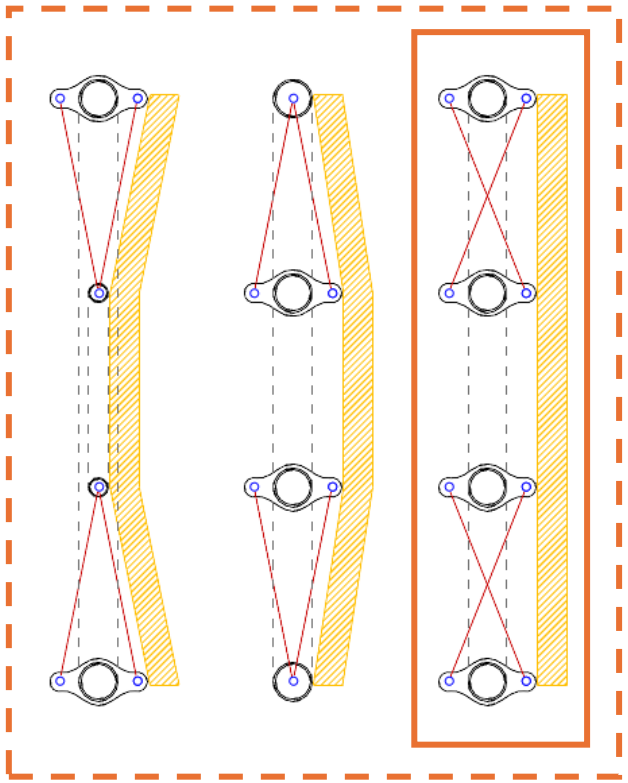


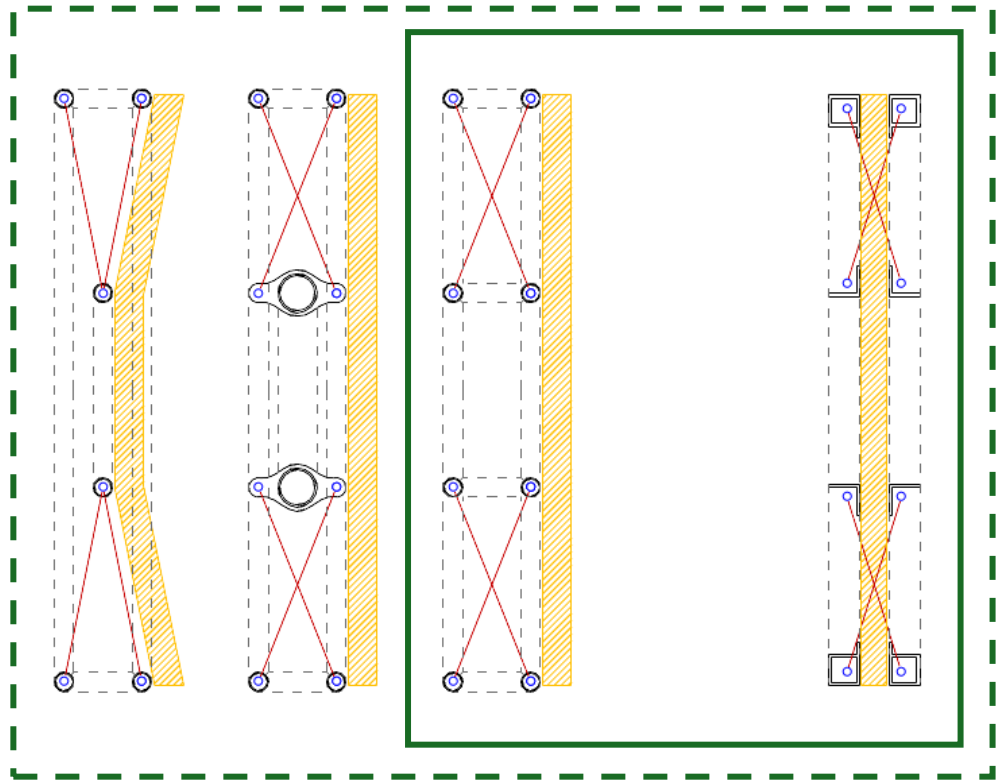


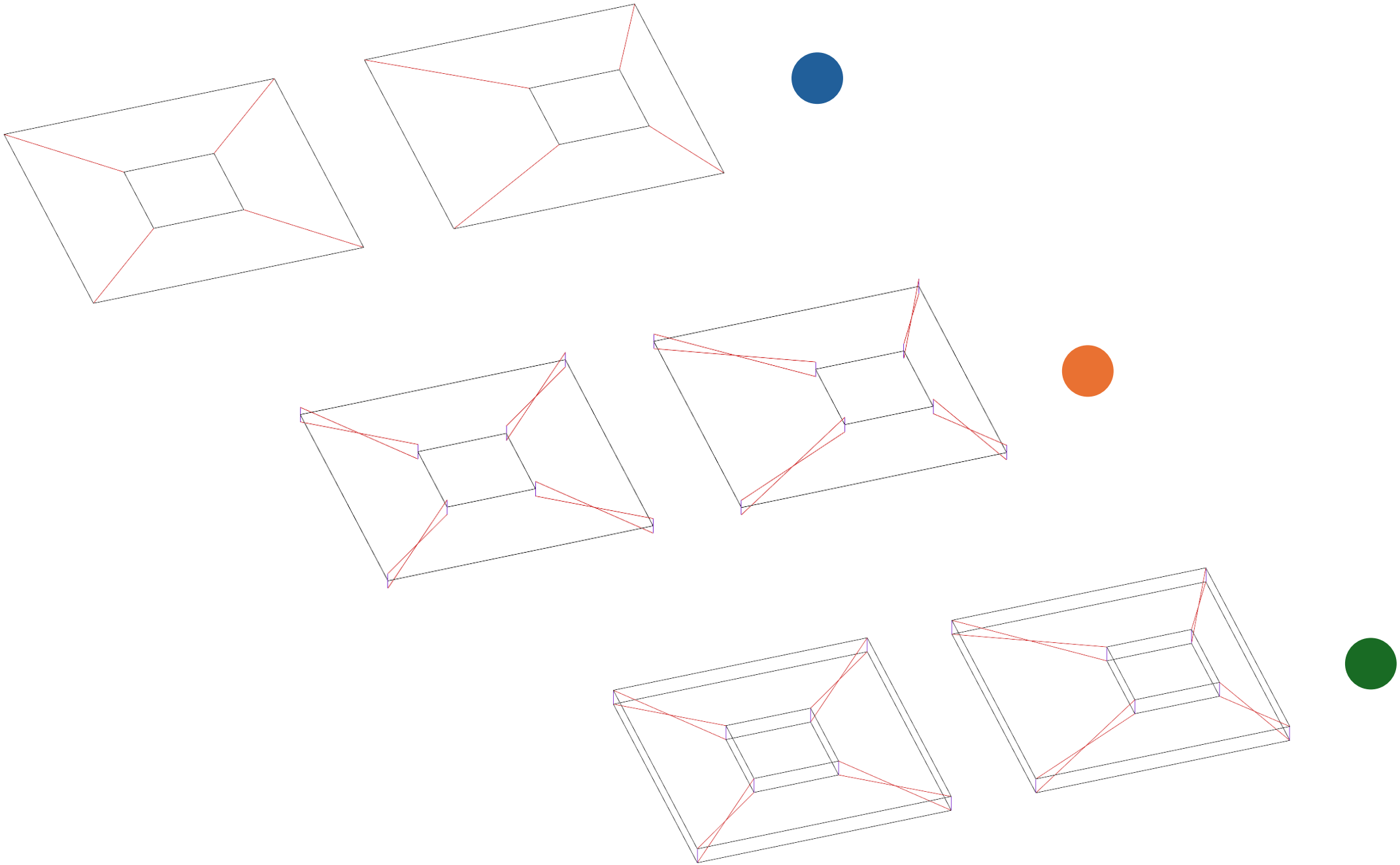




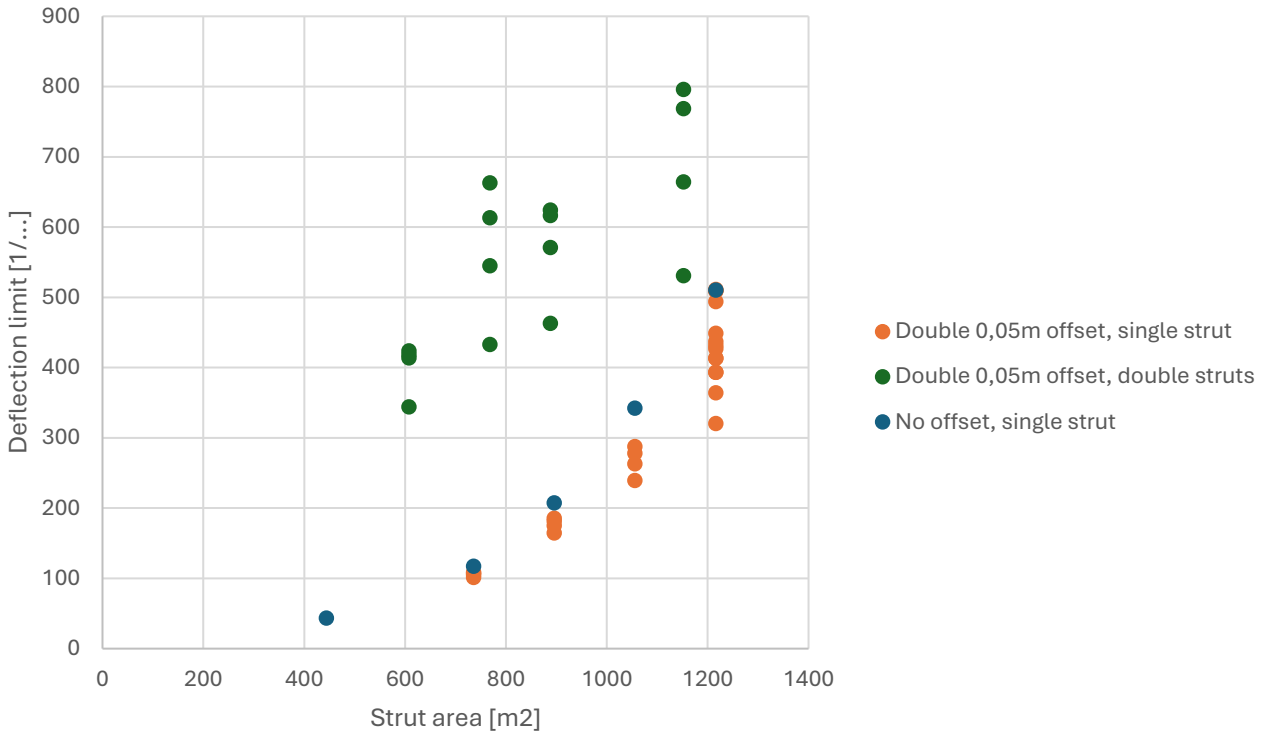


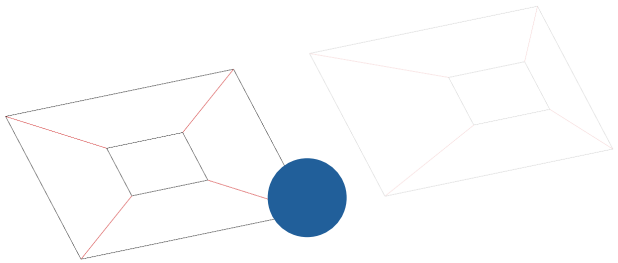


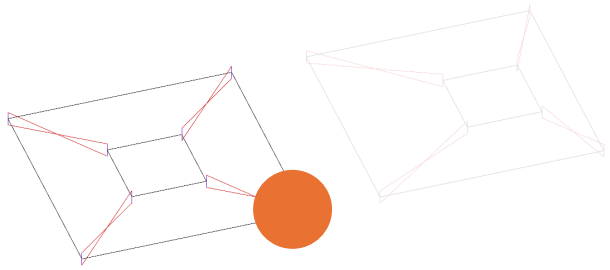


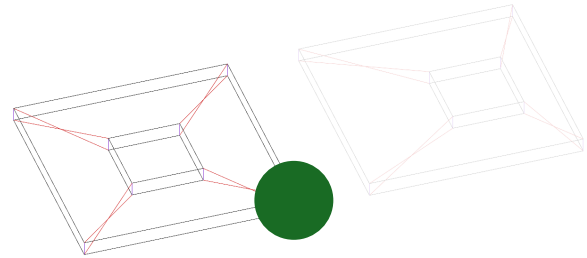


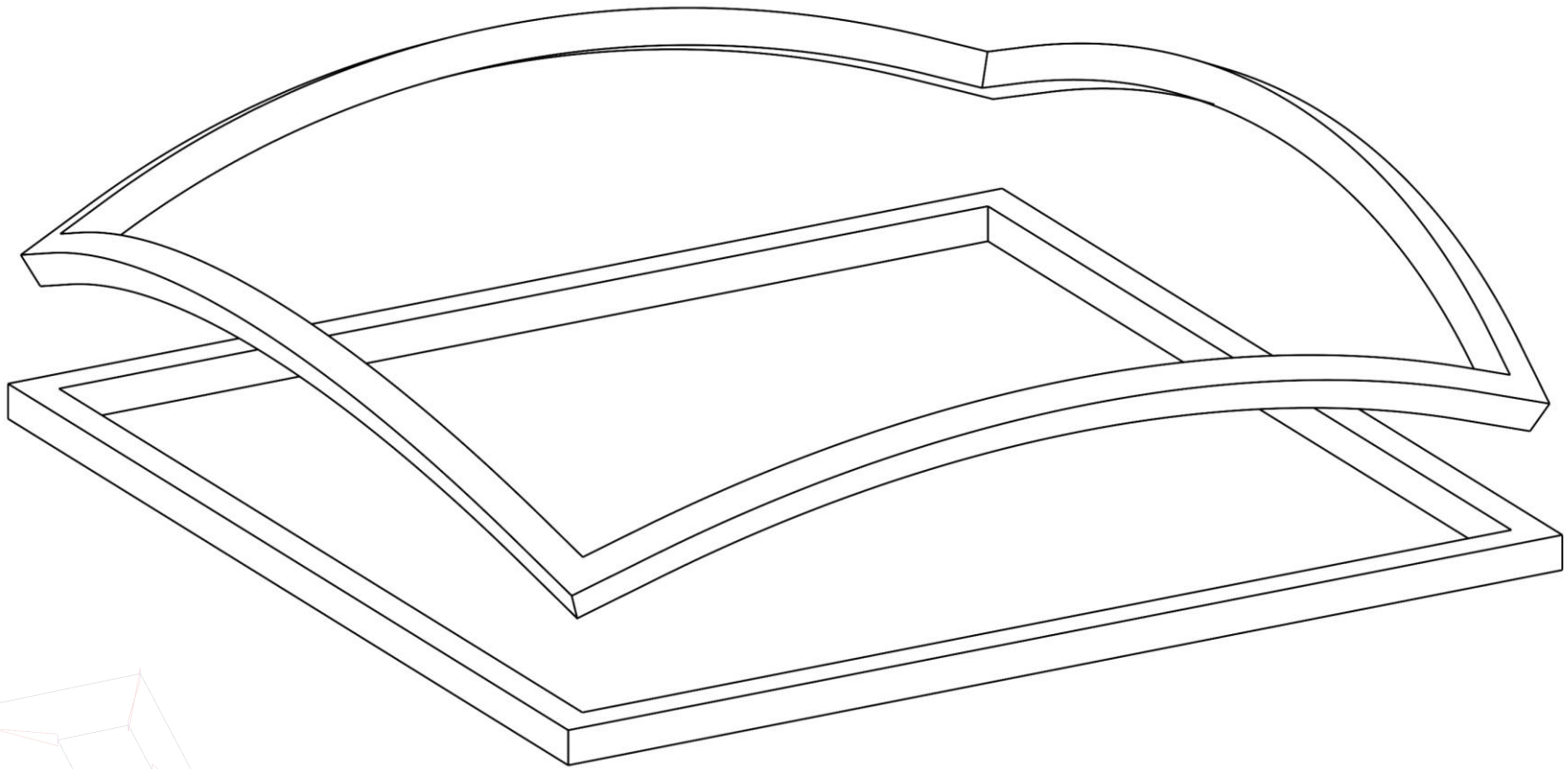
Deflection limit to strut area of various symmetrical configurations

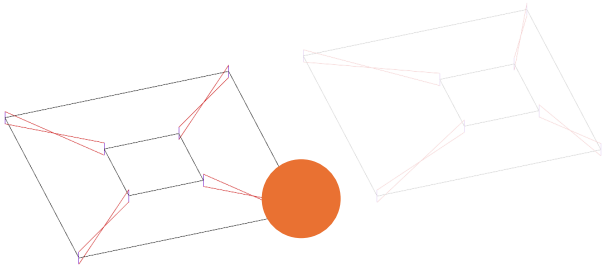




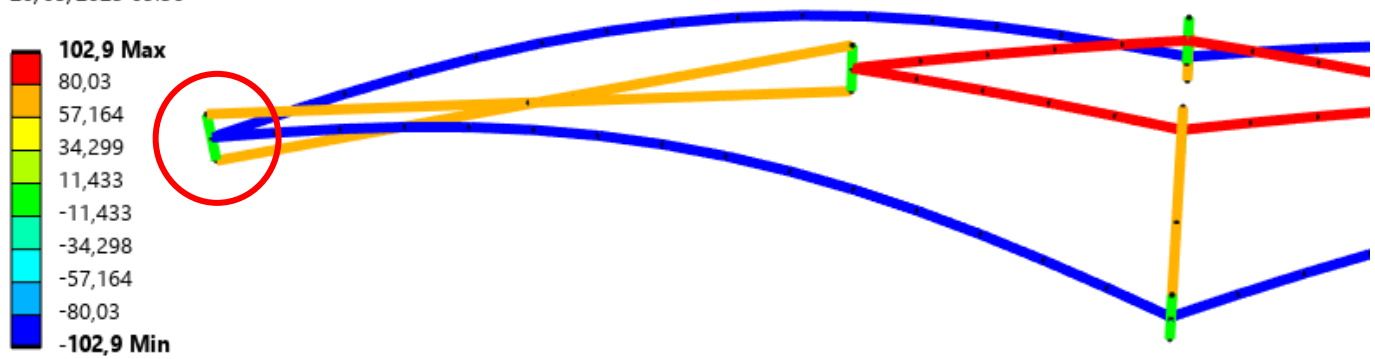


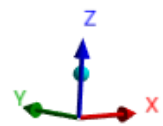


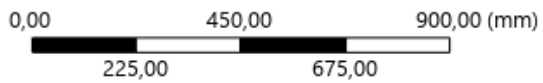


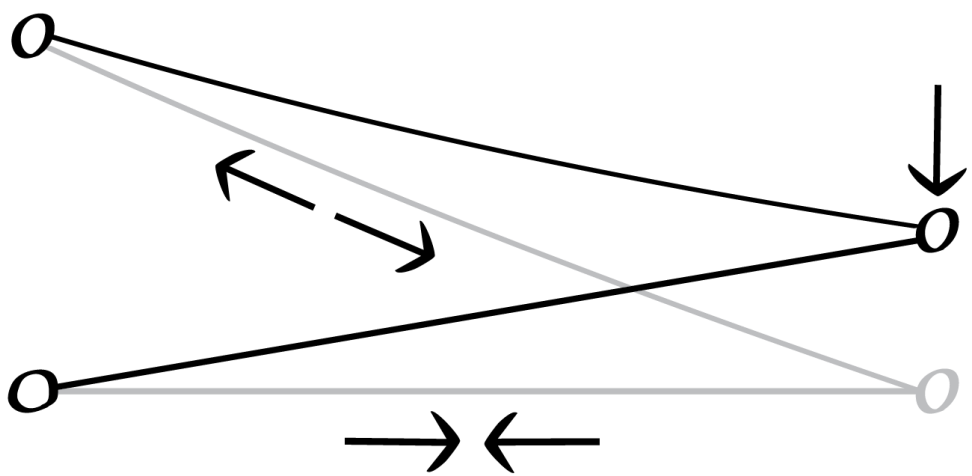


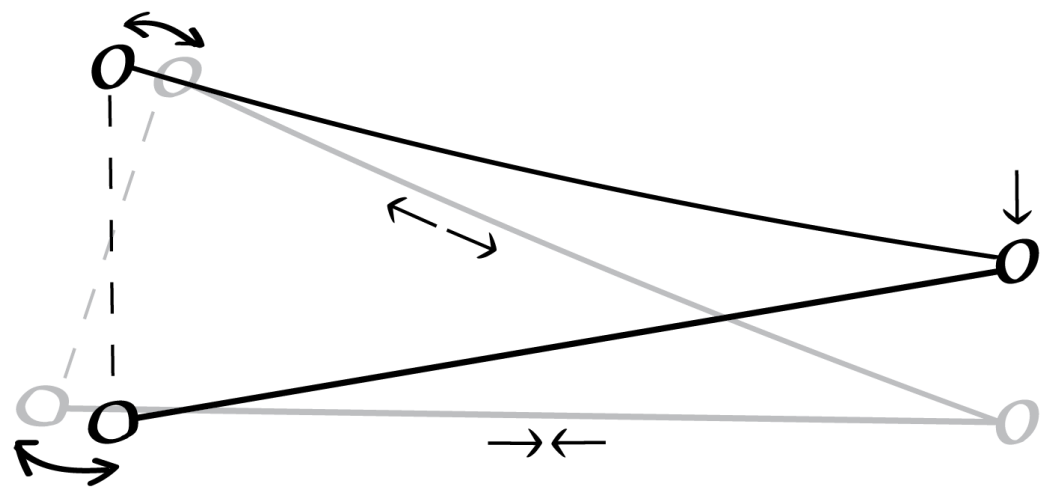
E: 3x3 1x1 double 0,05 offset with outer frame
Axial Force
Type: Directional Axial Force(X Axis) (Unaveraged)
Unit: kN
Solution Coordinate System
Time: 2000 ms
20/05/2025 09:36



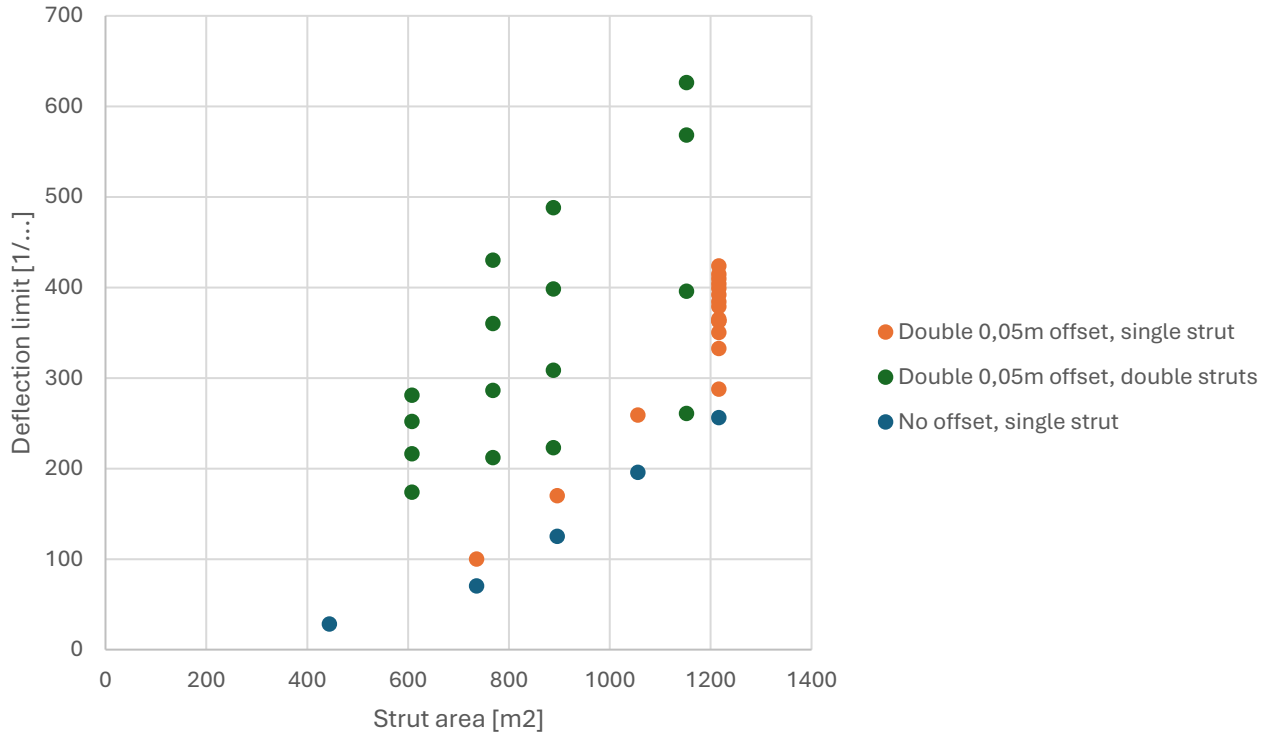


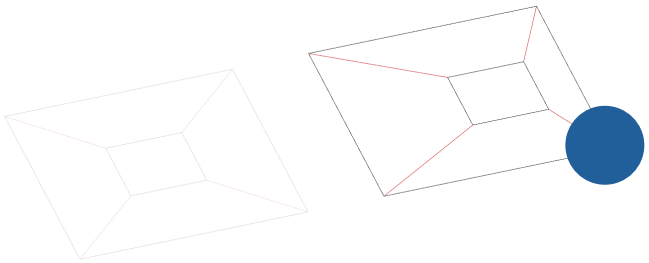


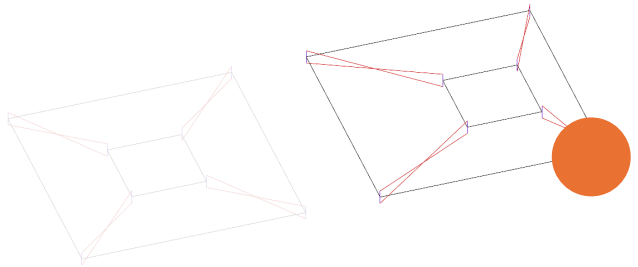


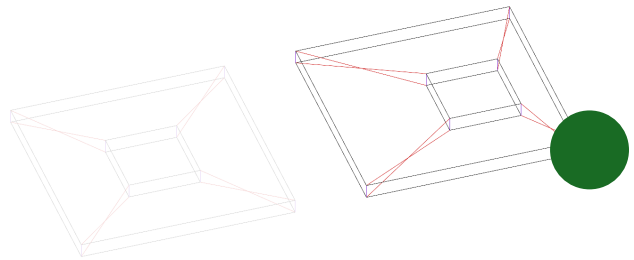


Deflection limit to strut area of various 0,5m offset configurations

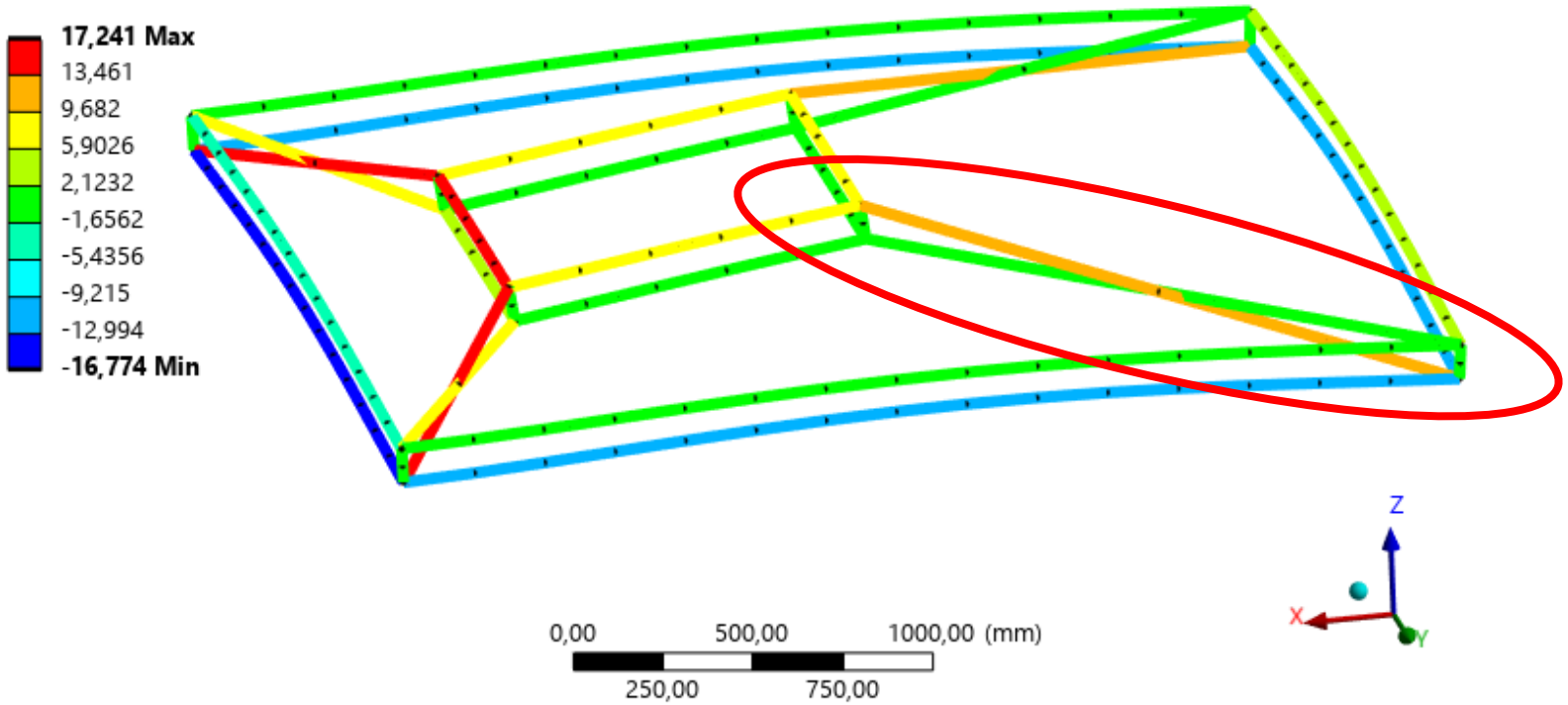




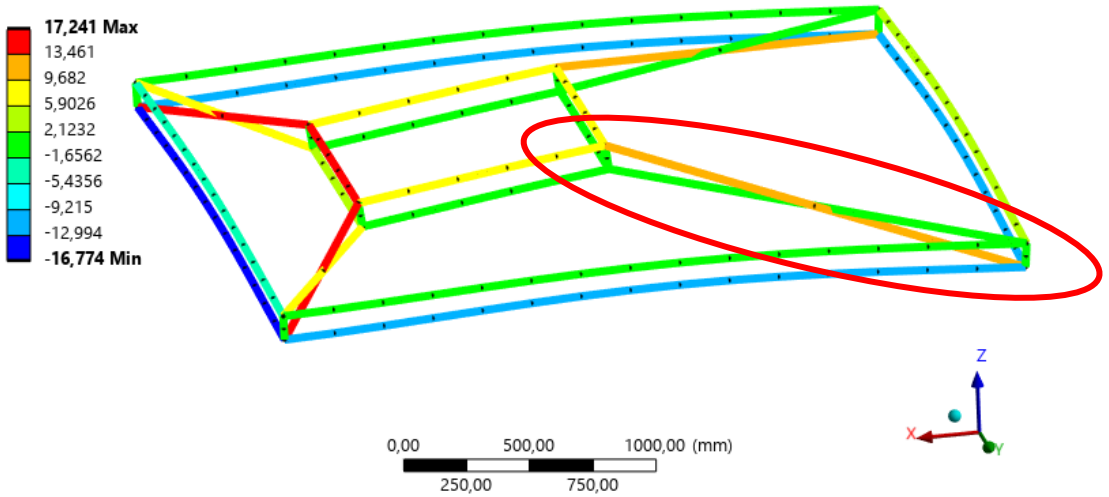


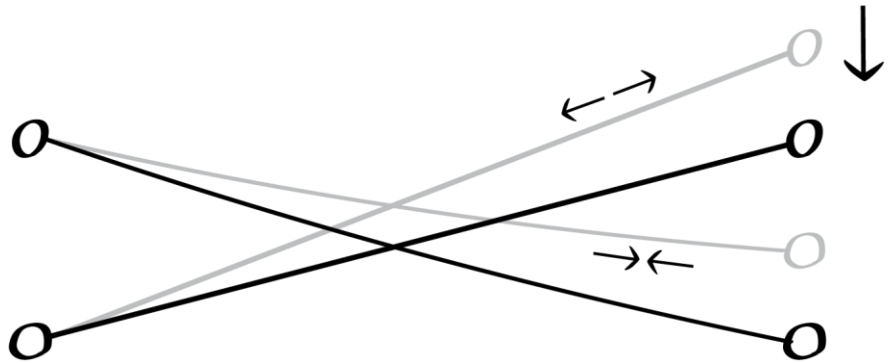


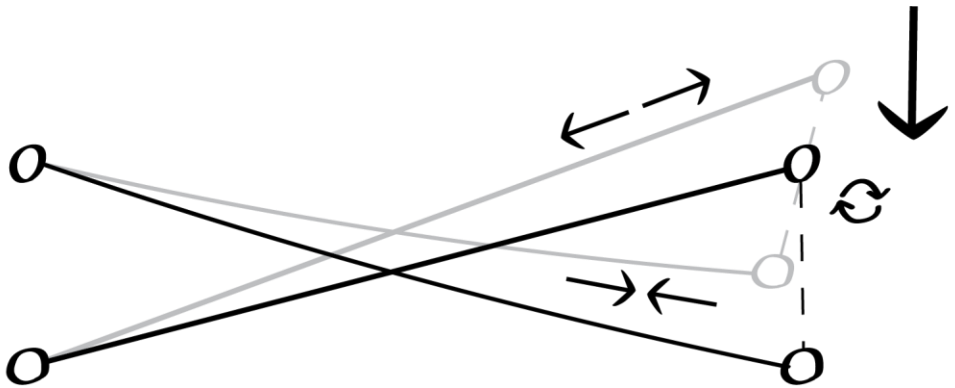
H: 3x3 1x1 double 0,05 offset with double outer frame, 0,5m off centre
Axial Force
Type: Directional Axial Force(X Axis) (Unaveraged)
Unit: kN
Solution Coordinate System
Time: 2000 ms
20/05/2025 09:51

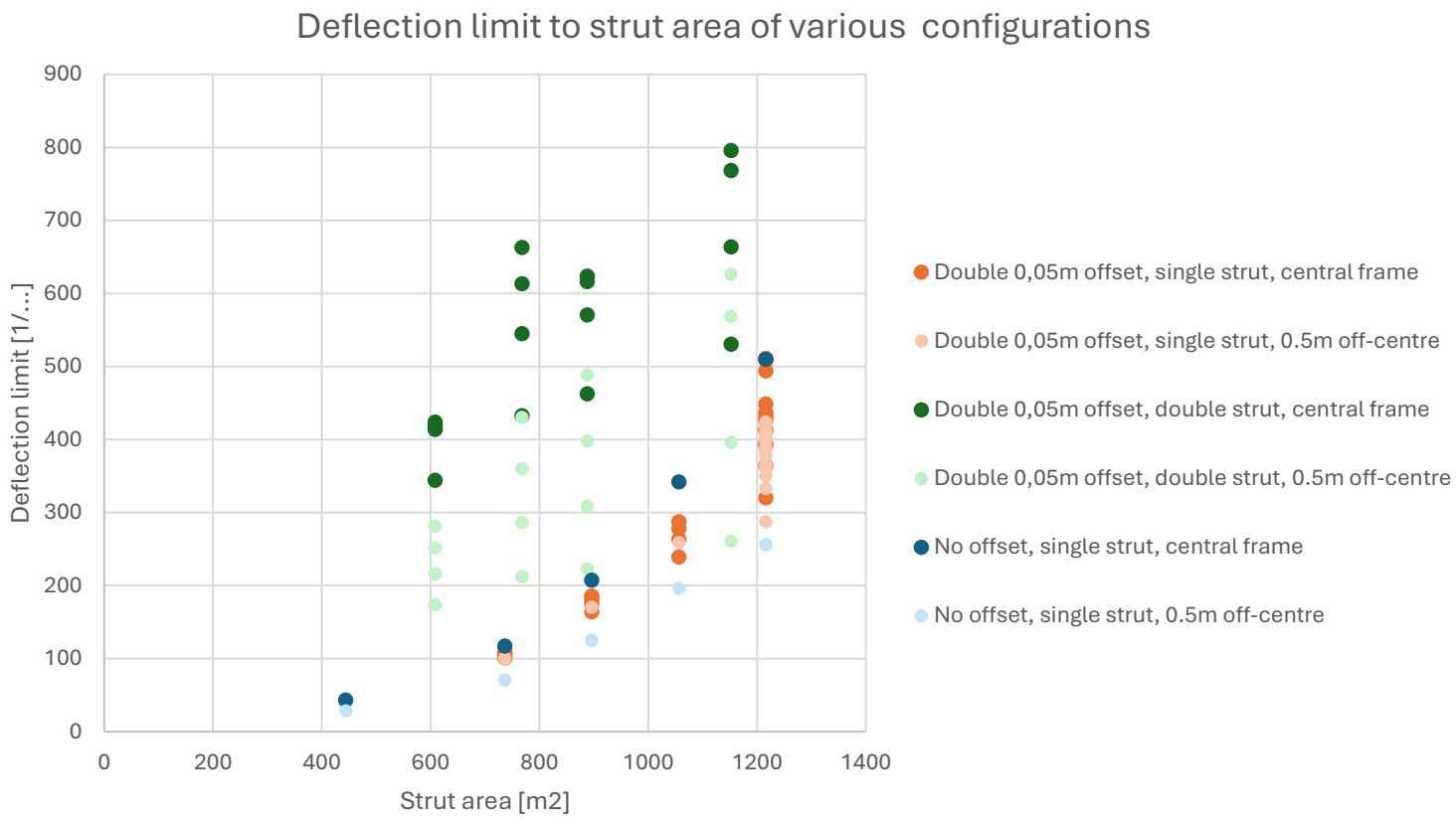


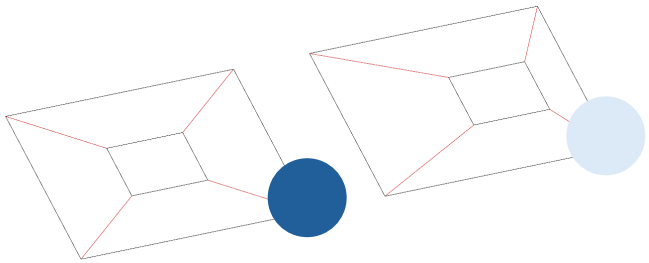
H: 3x3 1x1 double 0,05 offset with double outer frame, 0,5m off centre
Axial Force
Type: Directional Axial Force(X Axis) (Unaveraged)
Unit: kN
Solution Coordinate System
Time: 2000 ms
20/05/2025 09:51

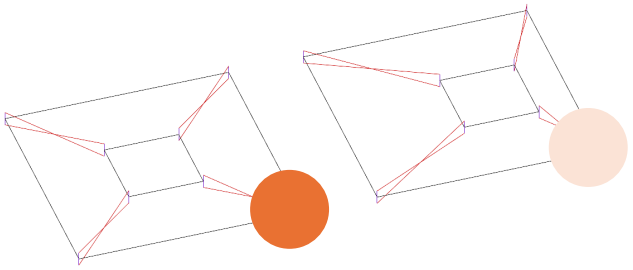


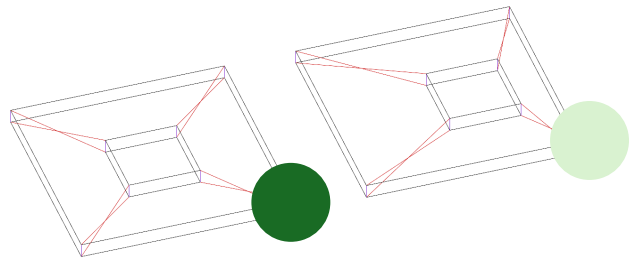


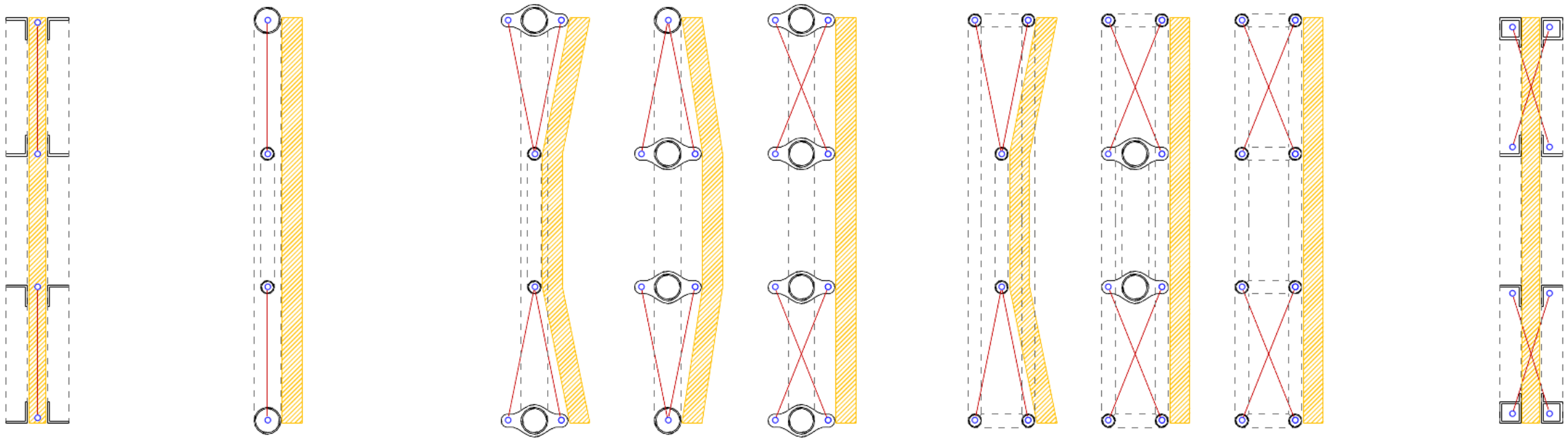


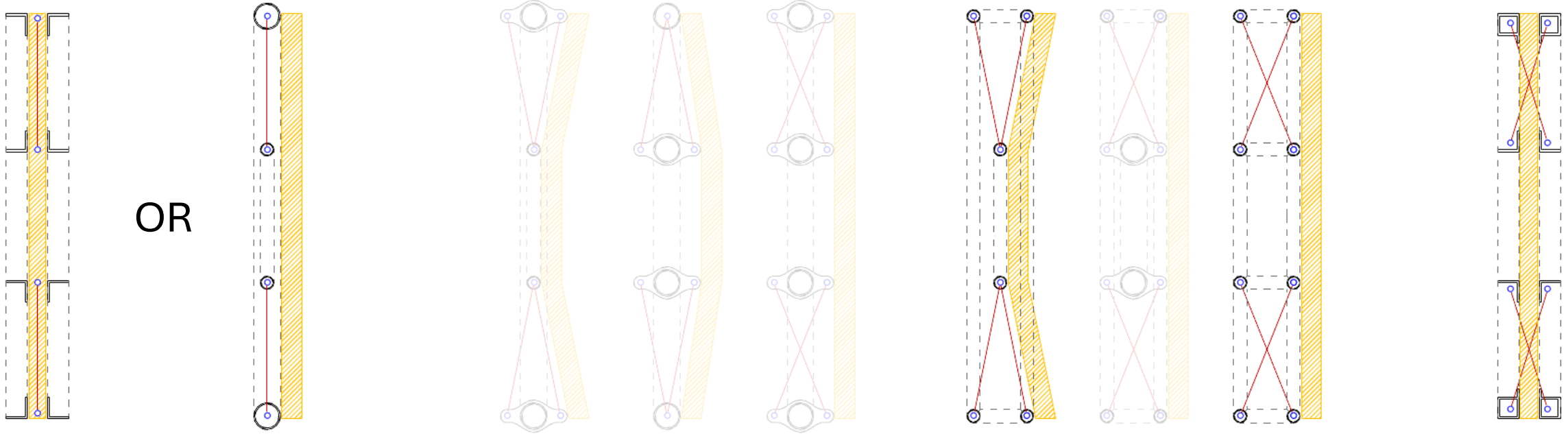

Deflection limit to strut area of various configurations
Deflection limit [1/...]
900
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
Strut area [m2]
Double 0,05m offset, single strut, central frame
Double 0,05m offset, single strut, 0.5m off-centre
Double 0,05m offset, double strut, central frame
Double 0,05m offset, double strut, 0.5m off-centre
No offset, single strut, central frame
No offset, single strut, 0.5m off-centre







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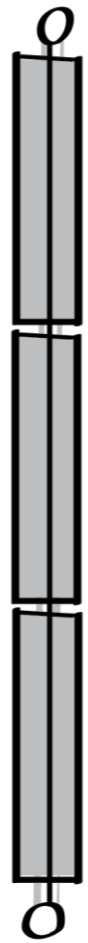

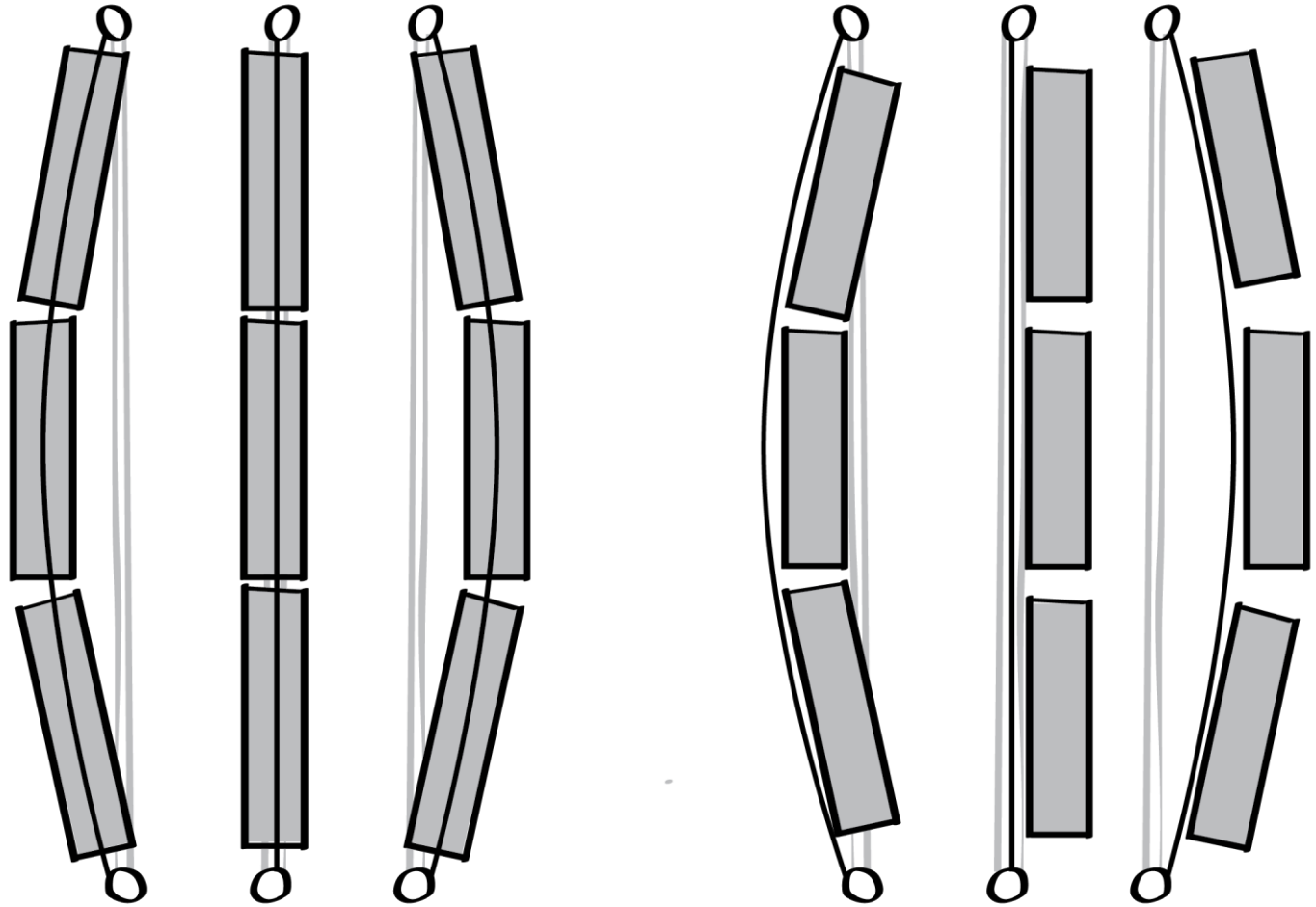

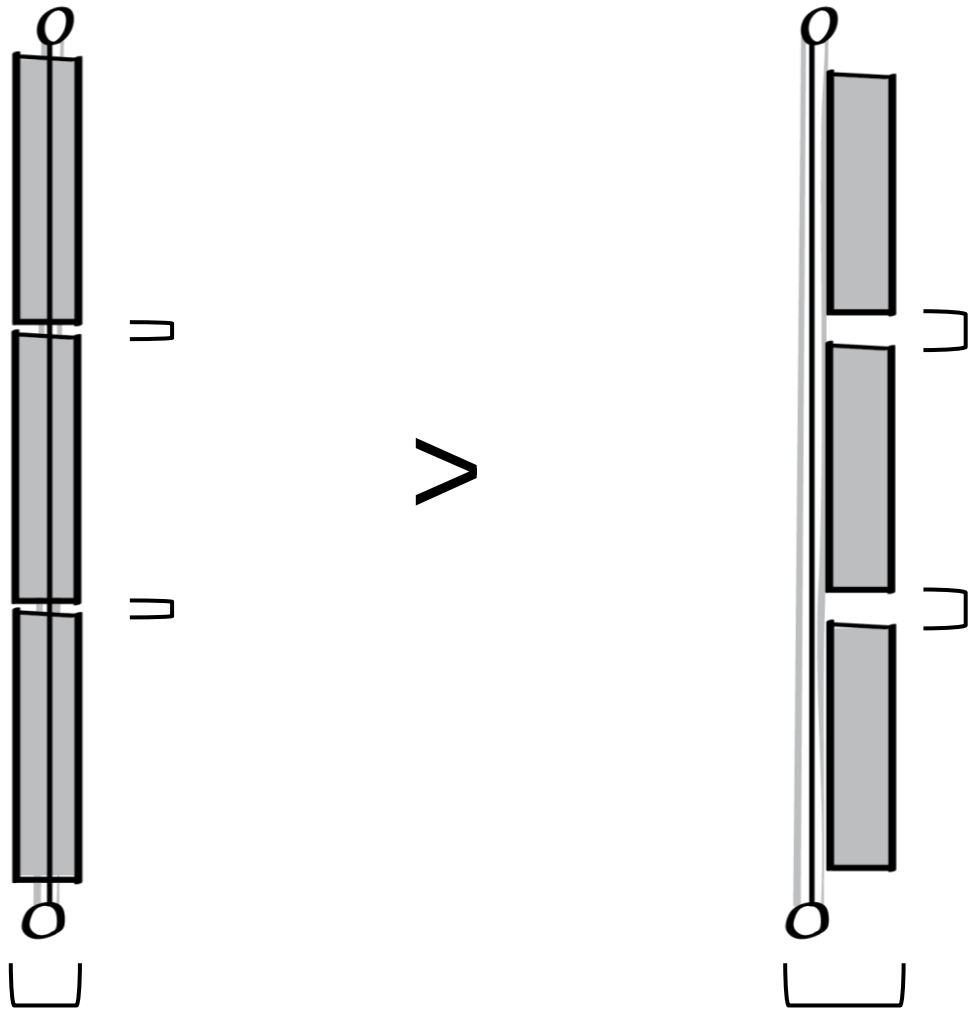

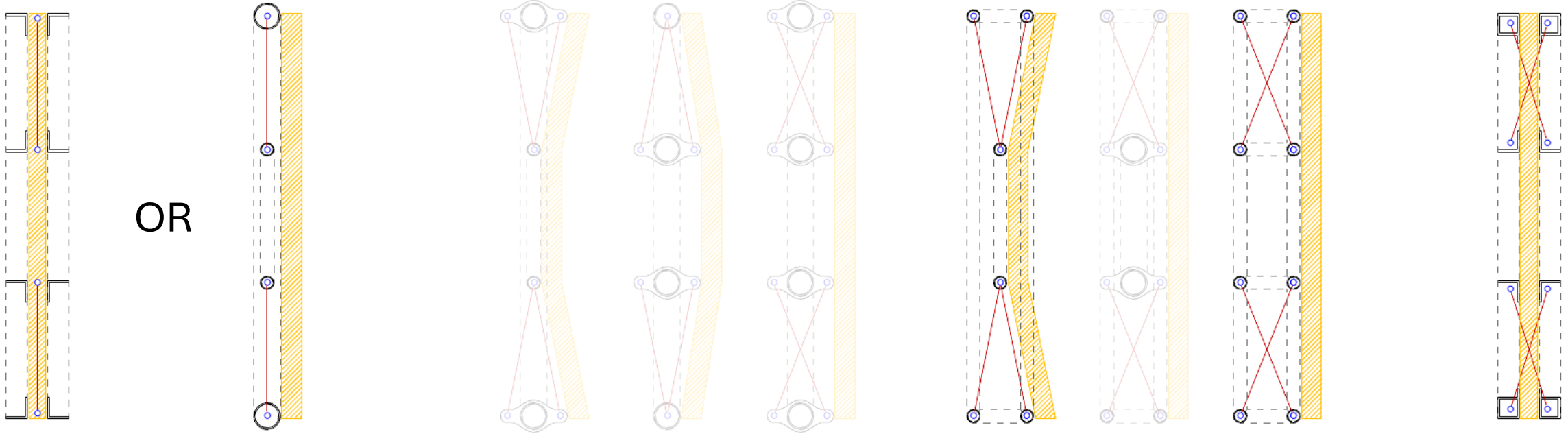
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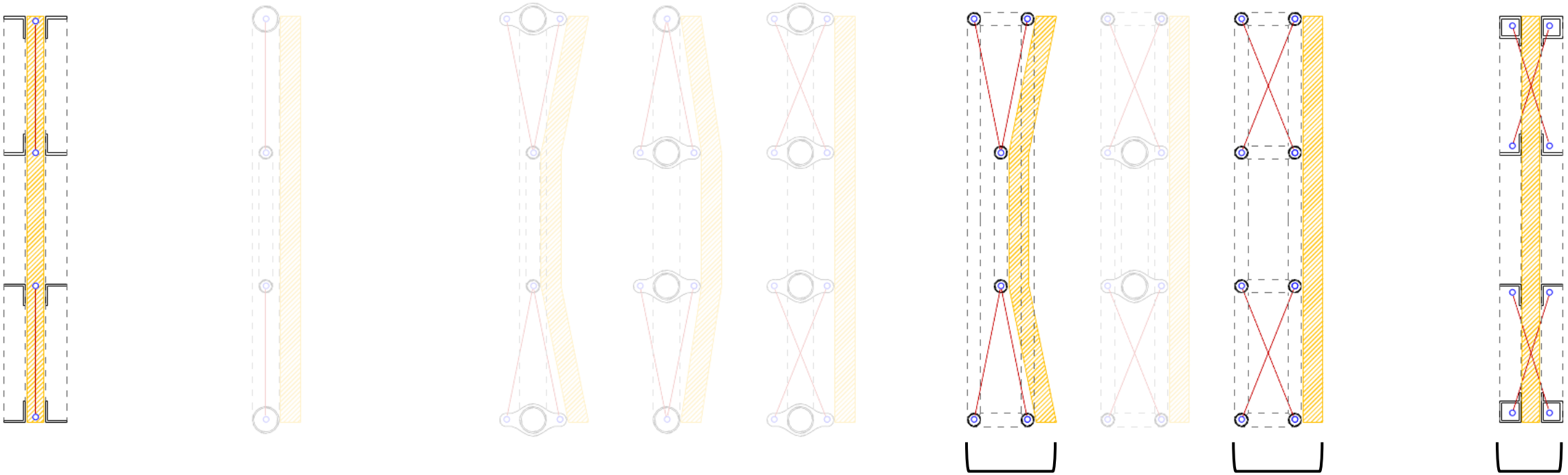

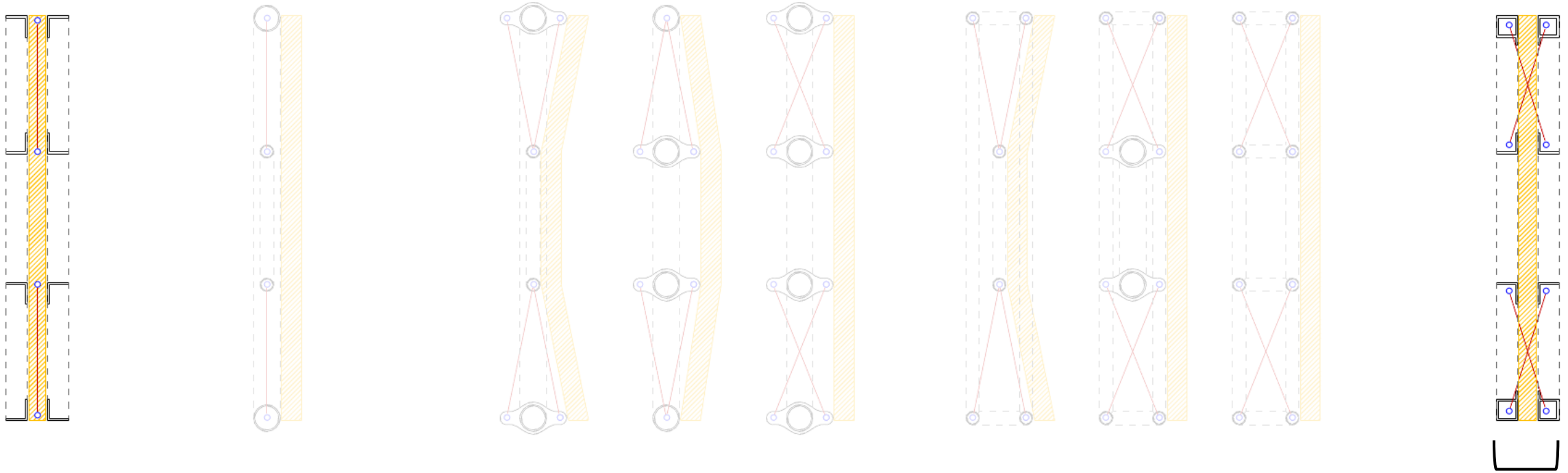

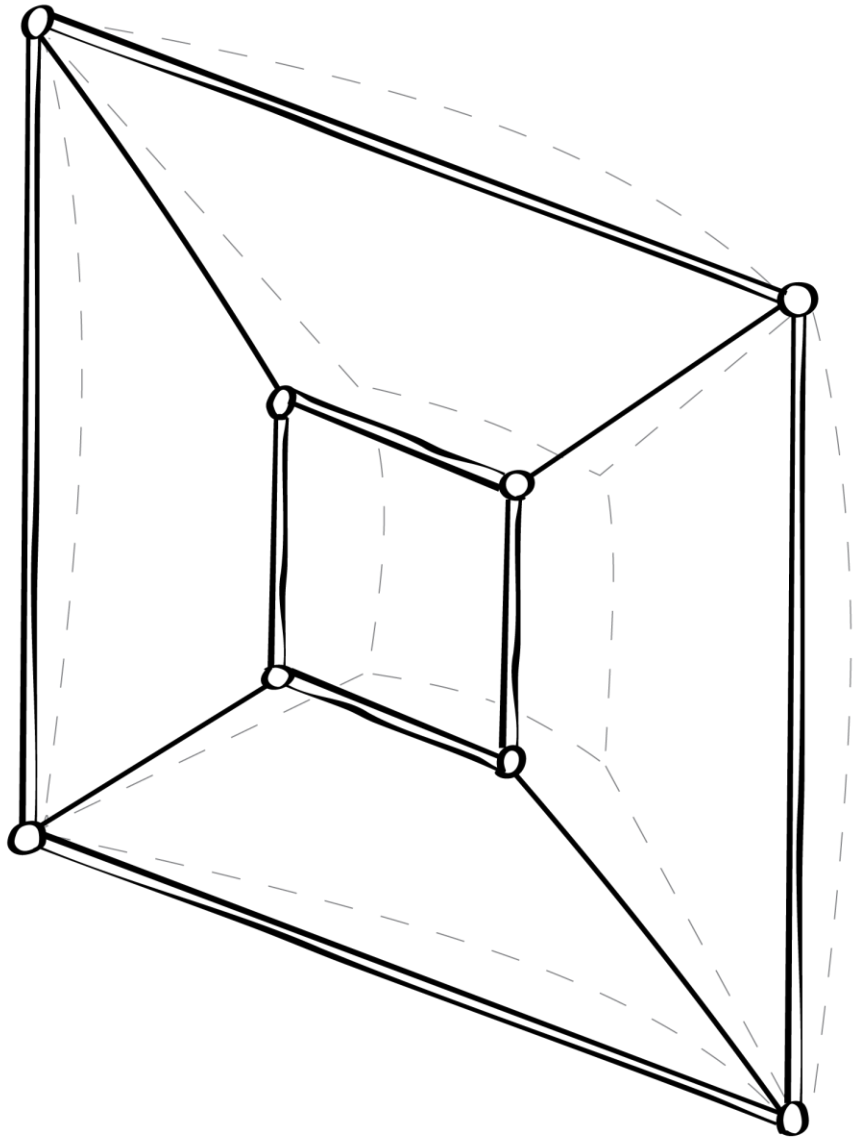

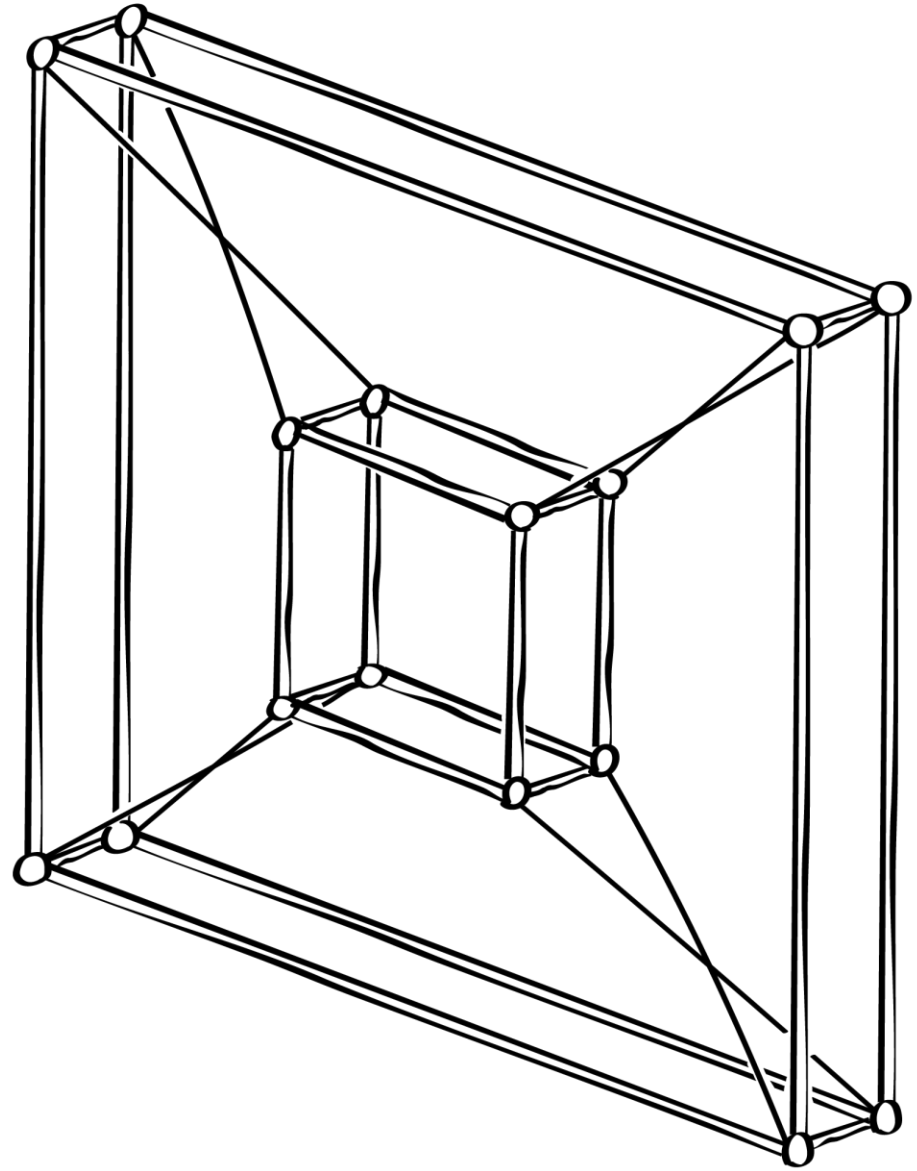

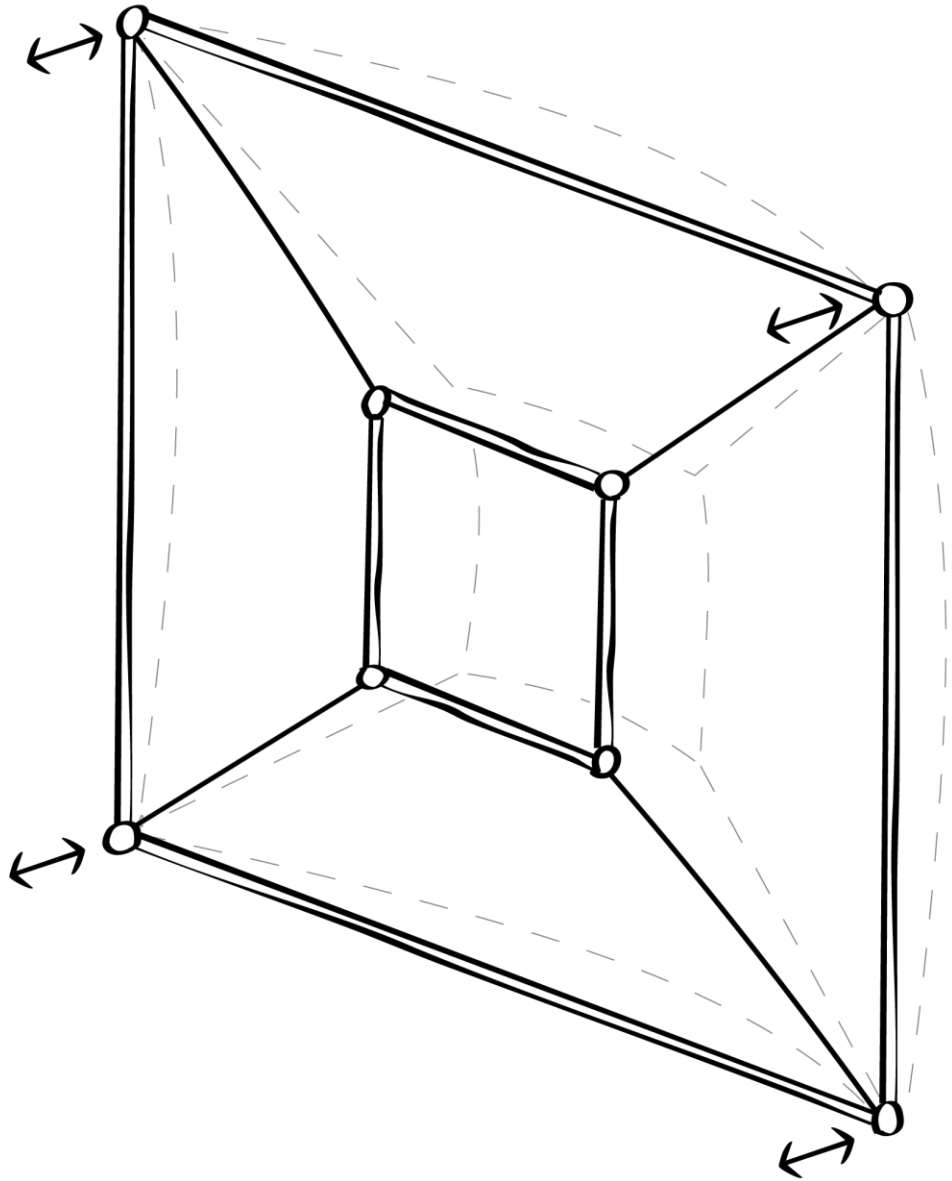

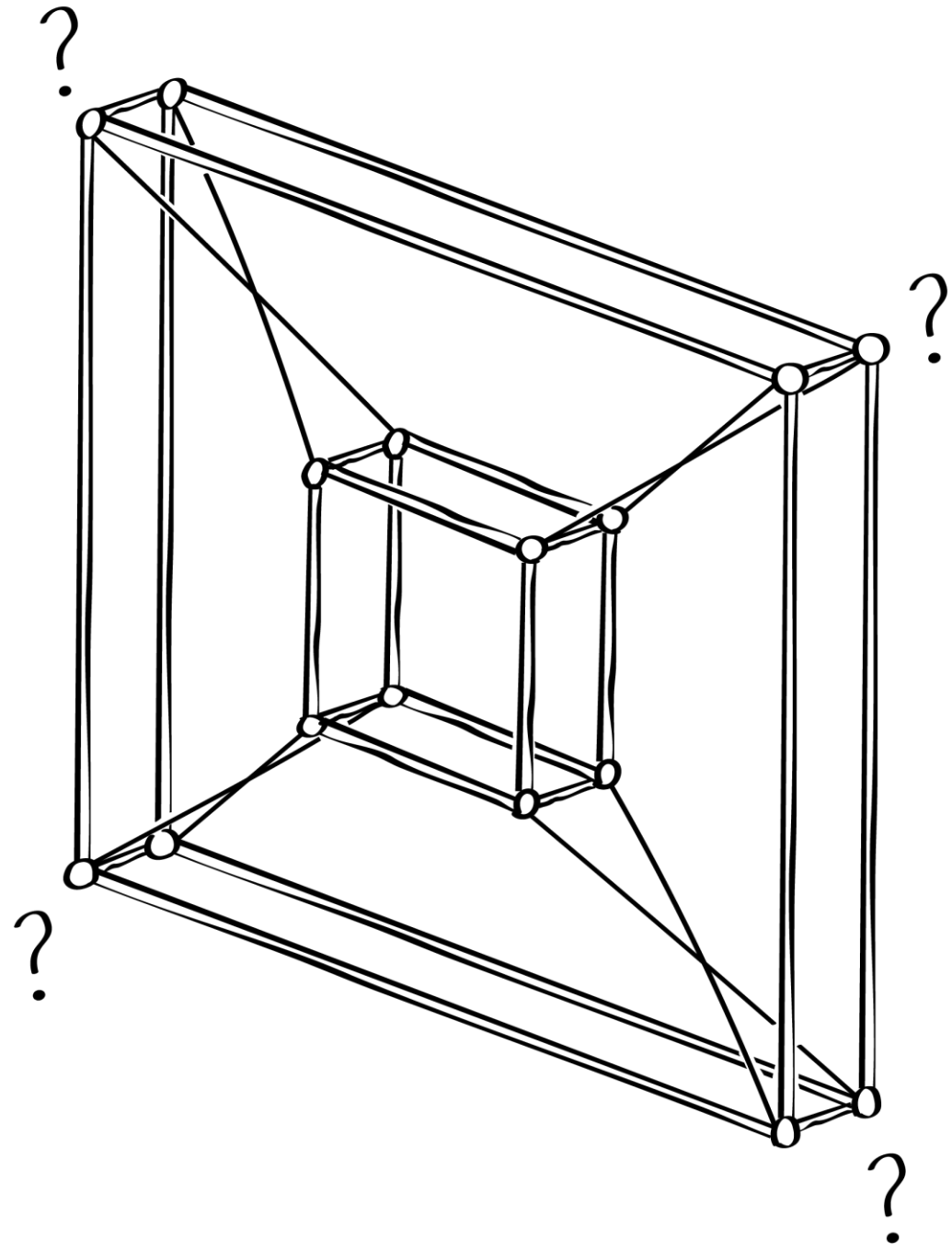

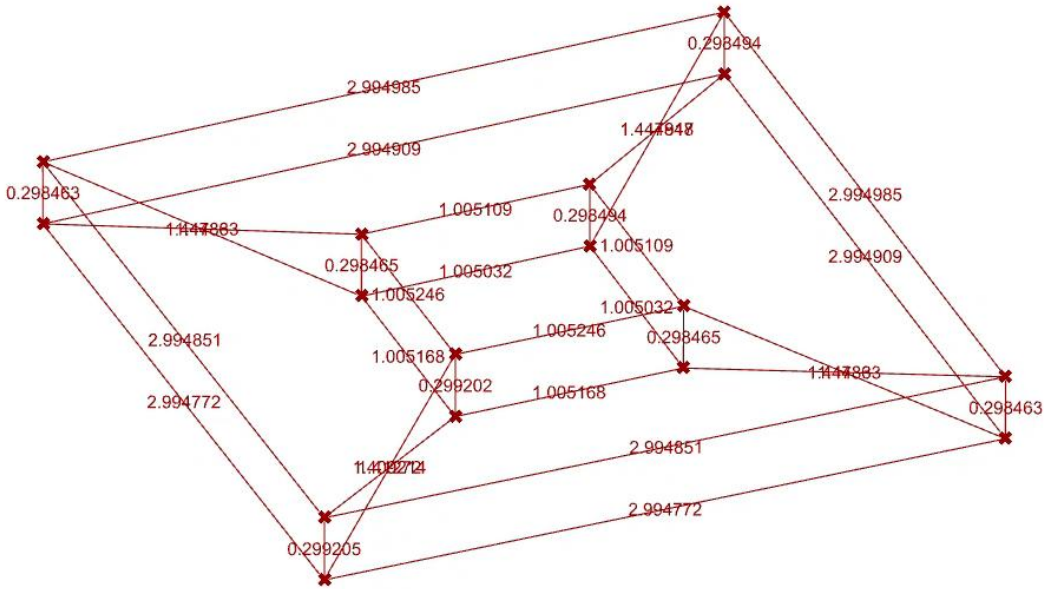
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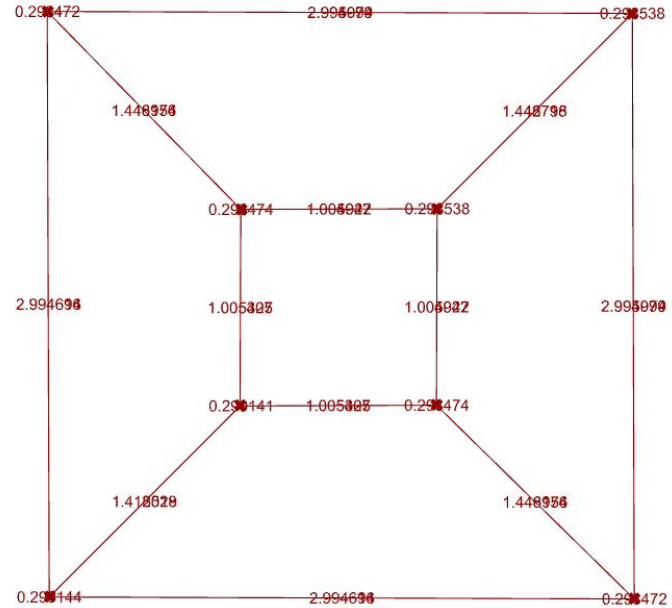

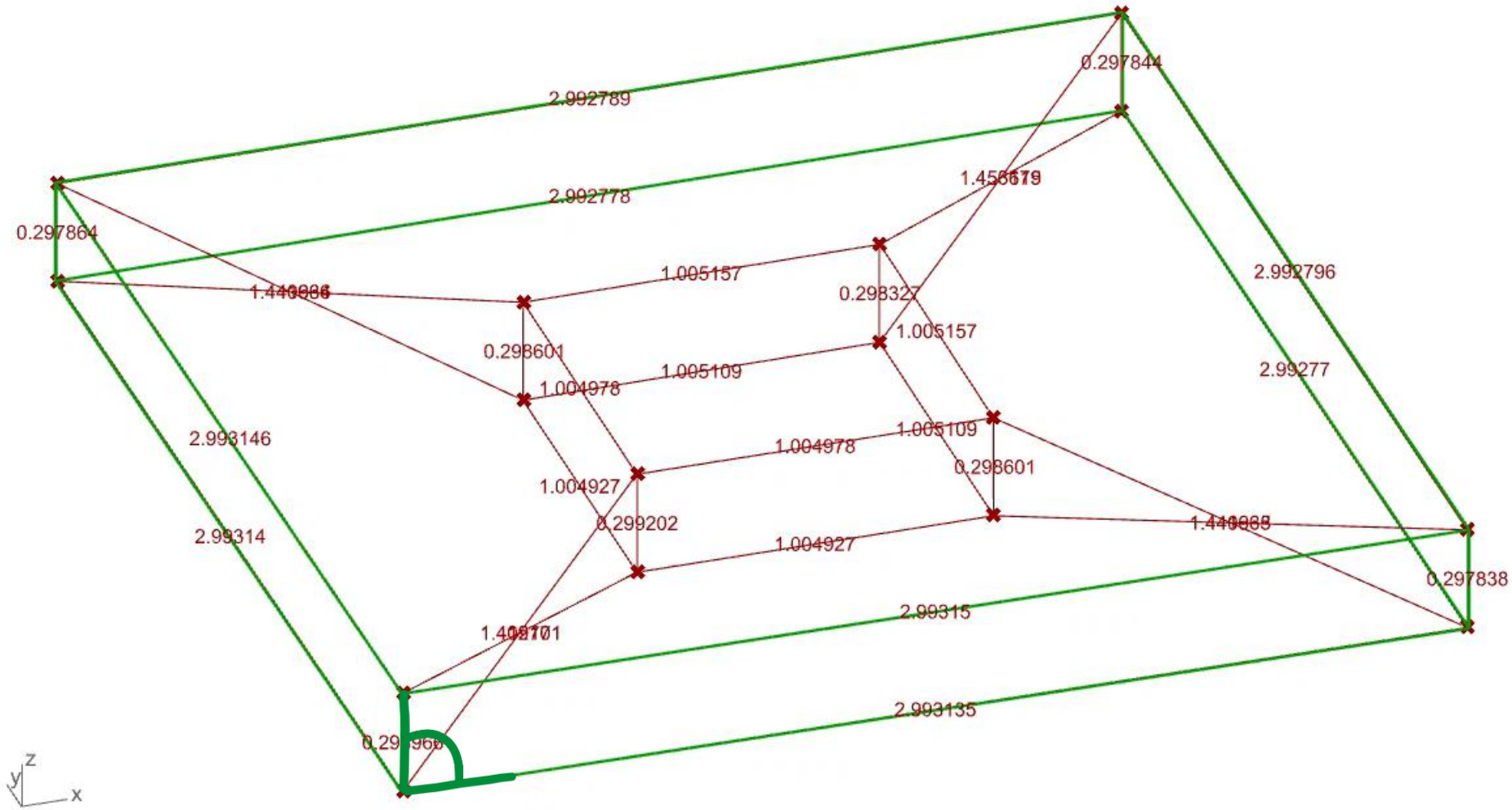
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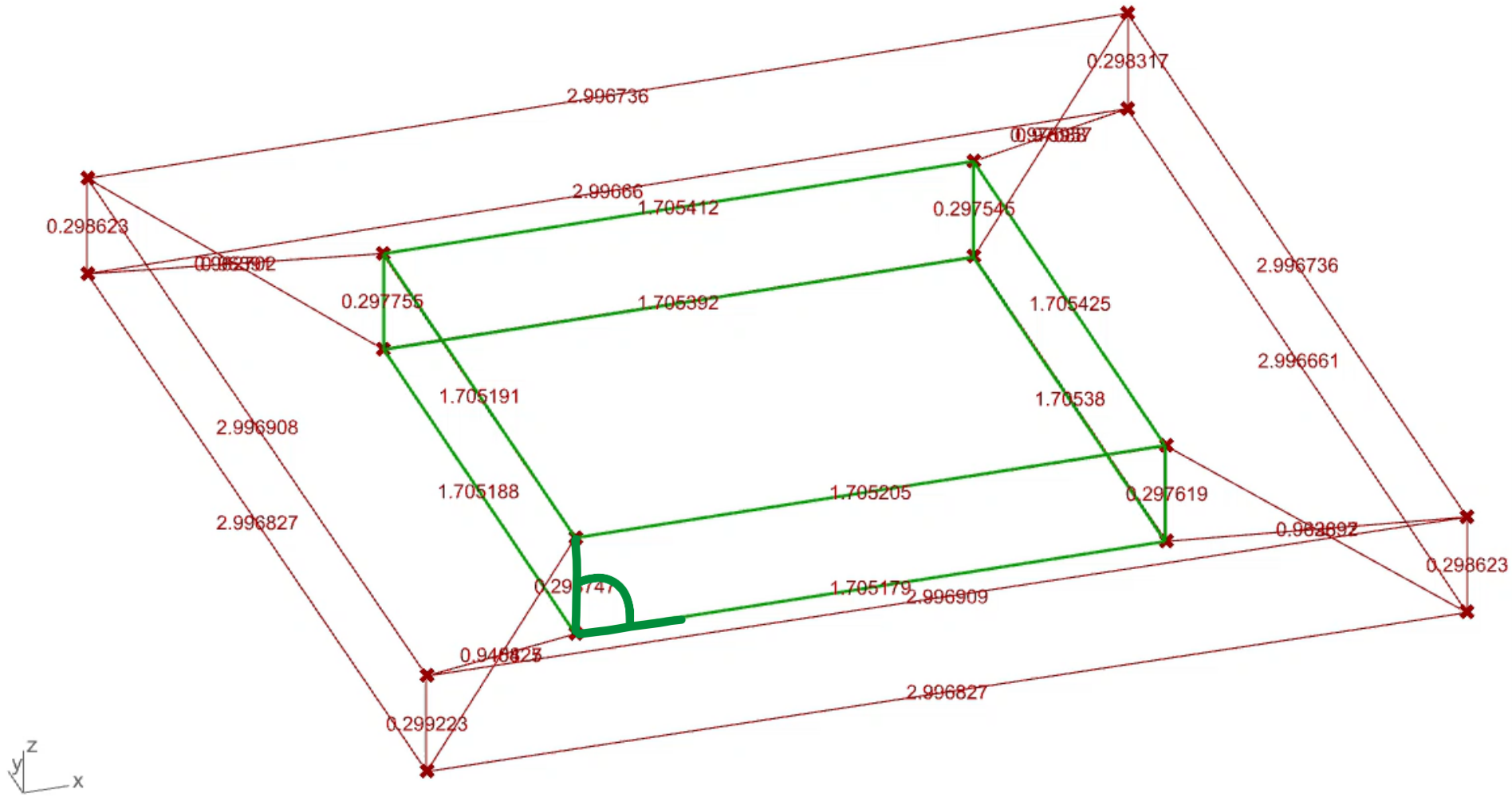
z
y
x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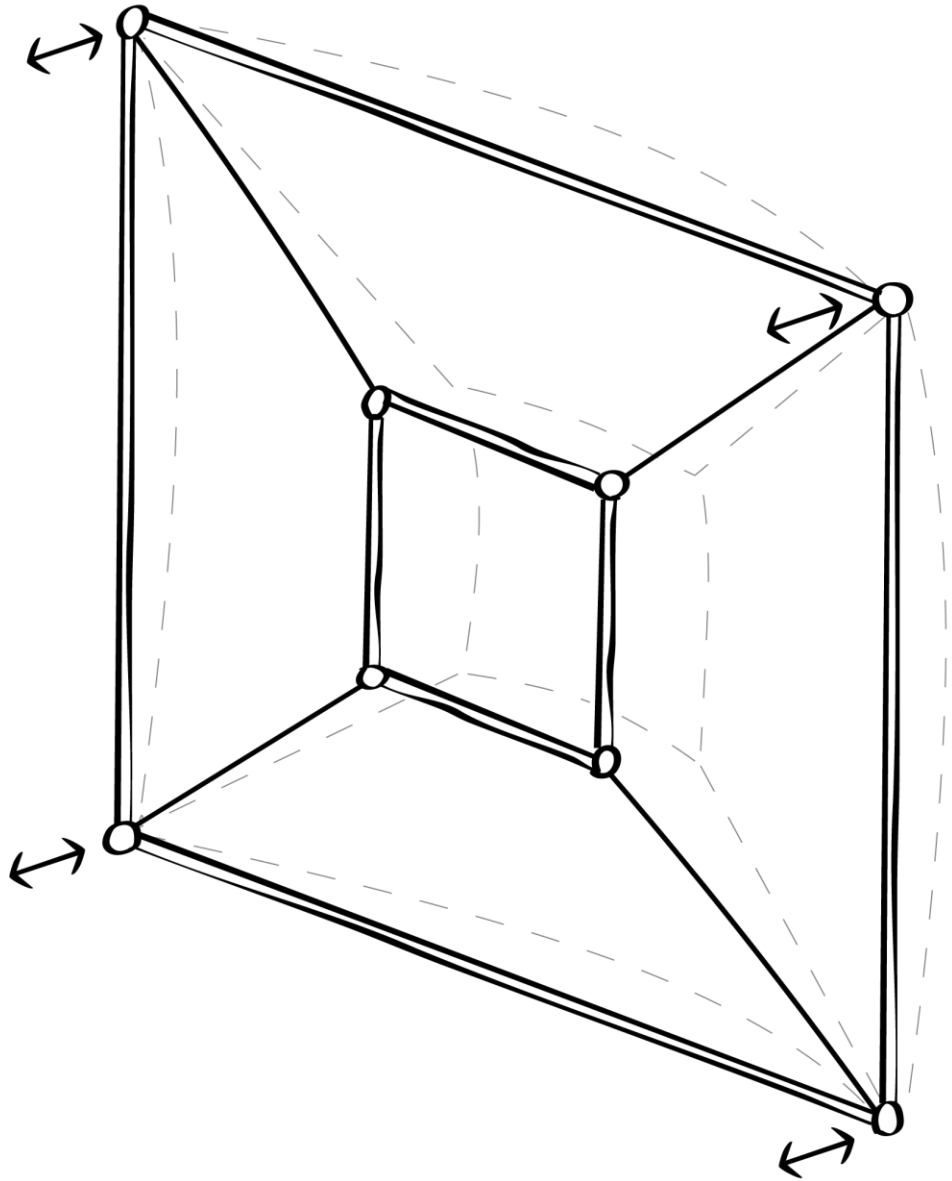
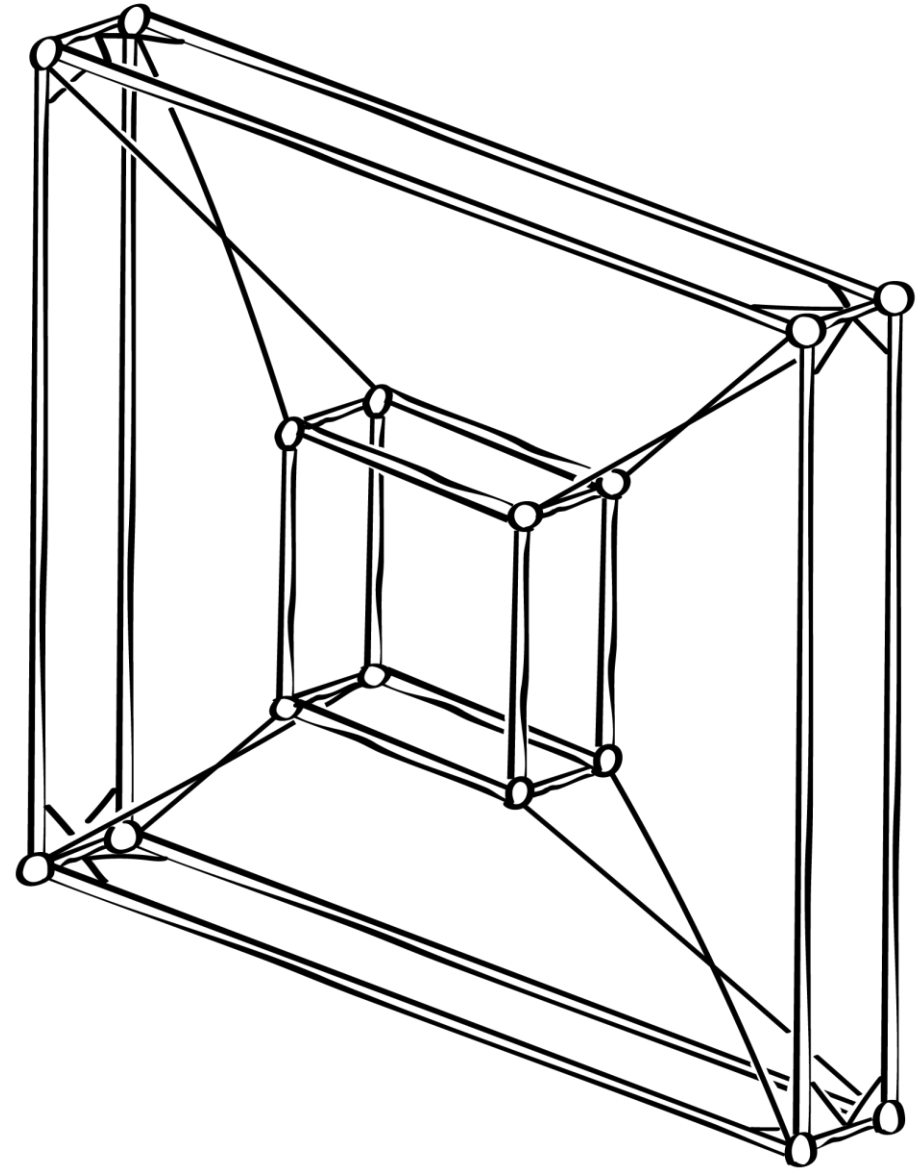
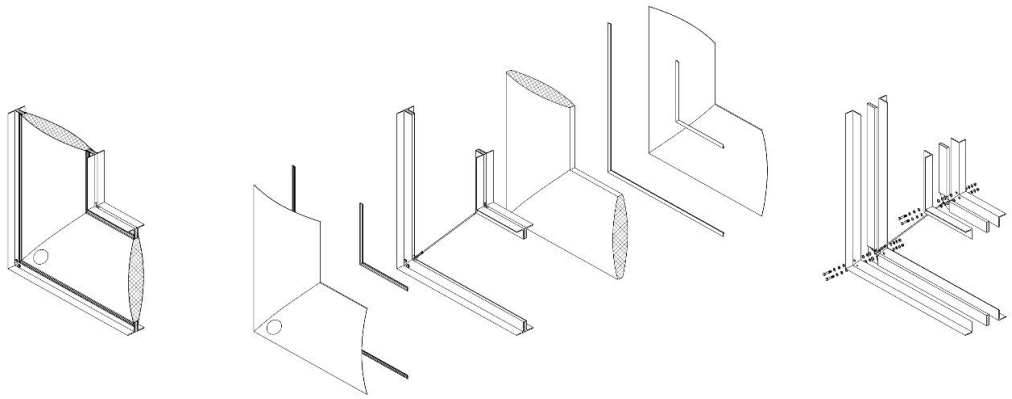
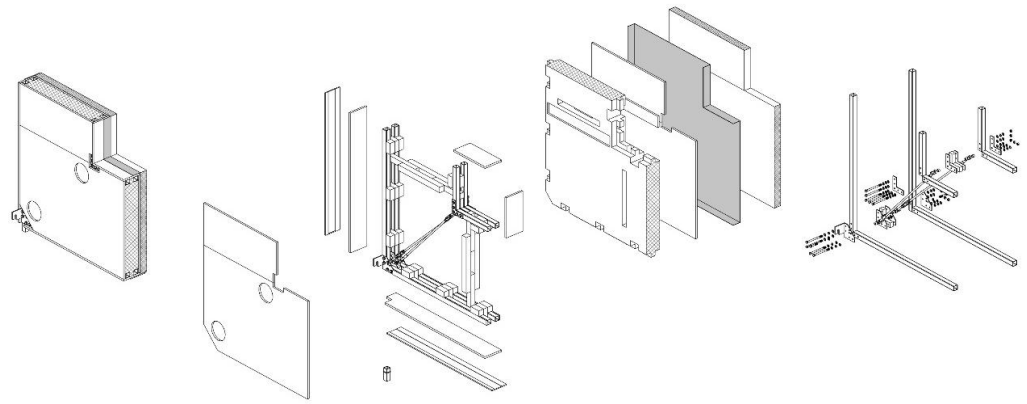
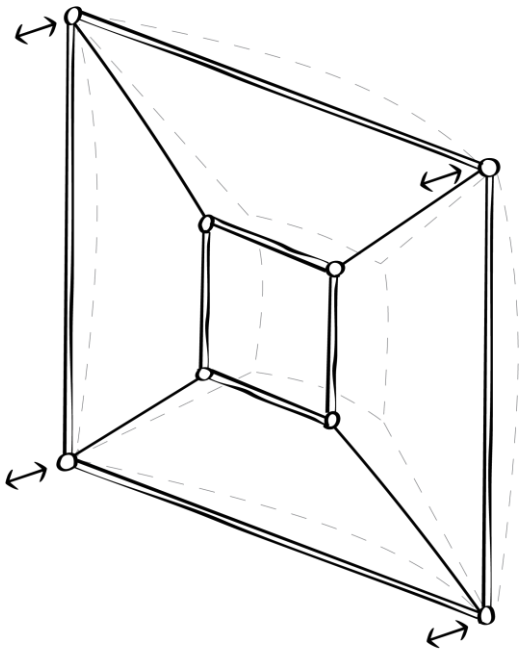
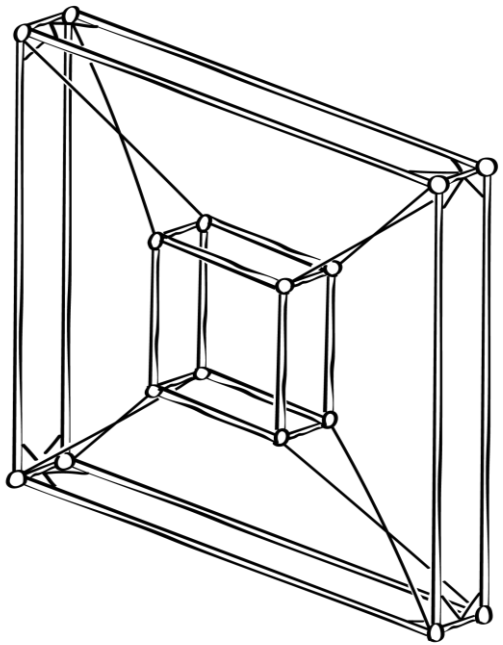


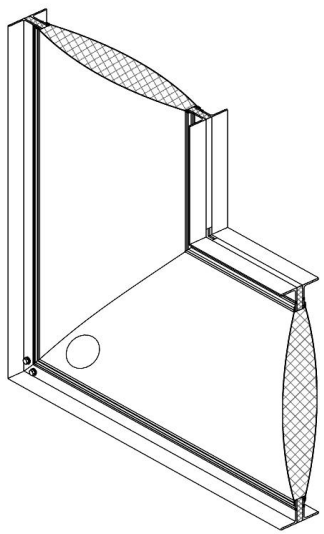


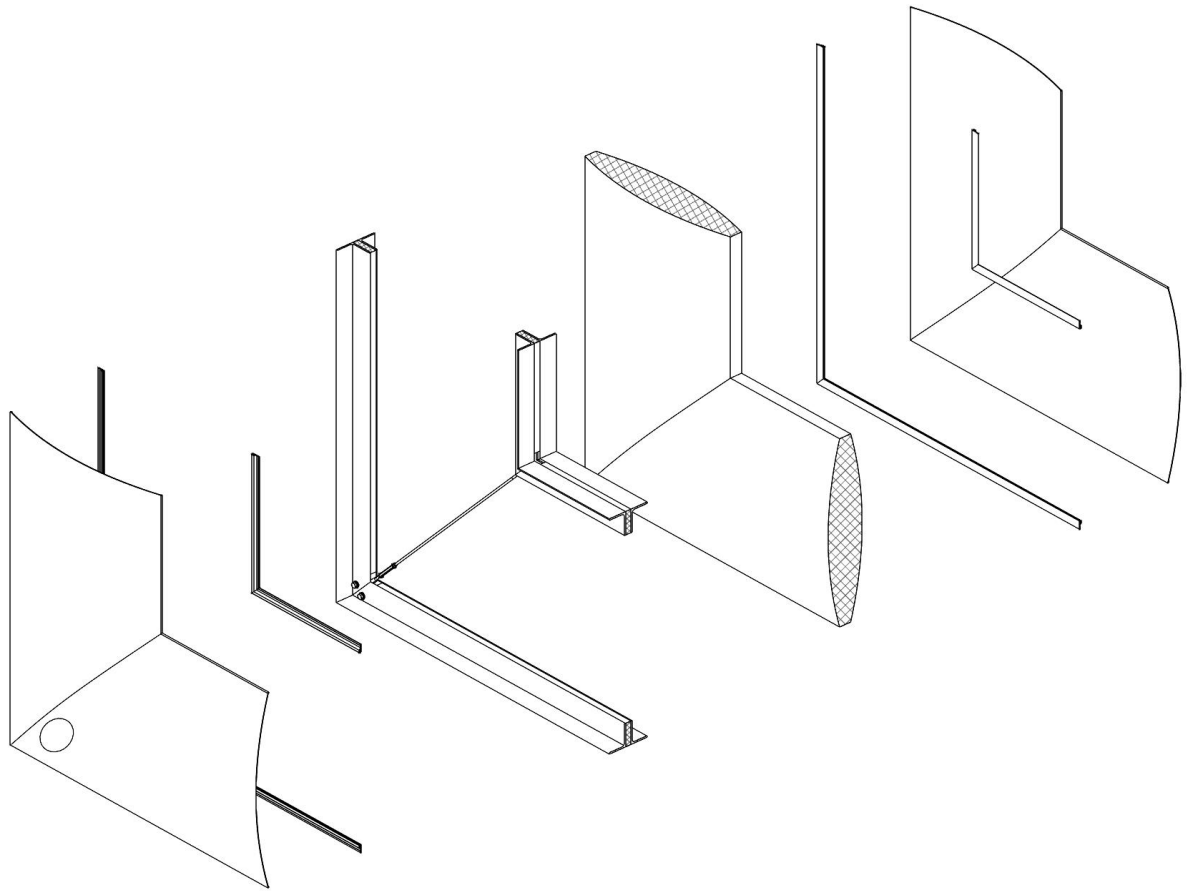


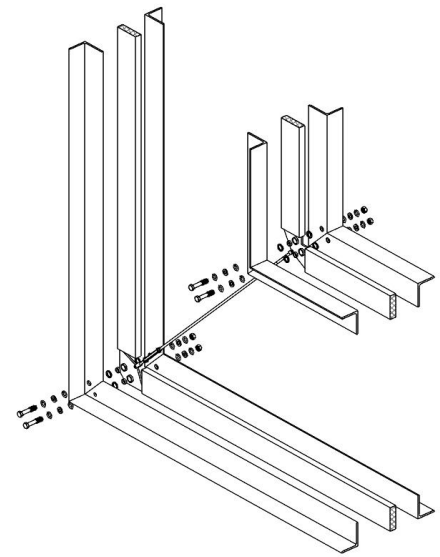


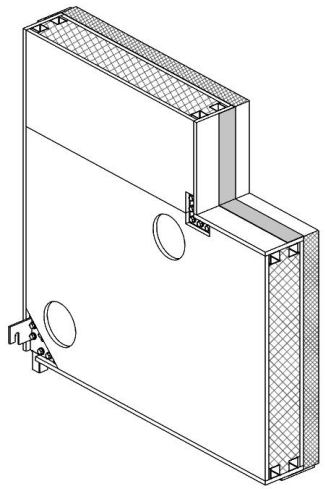


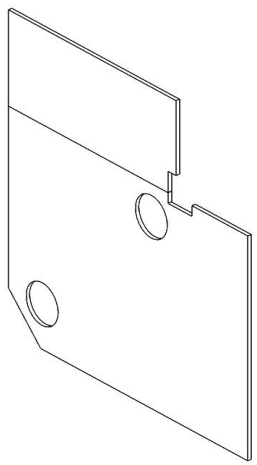


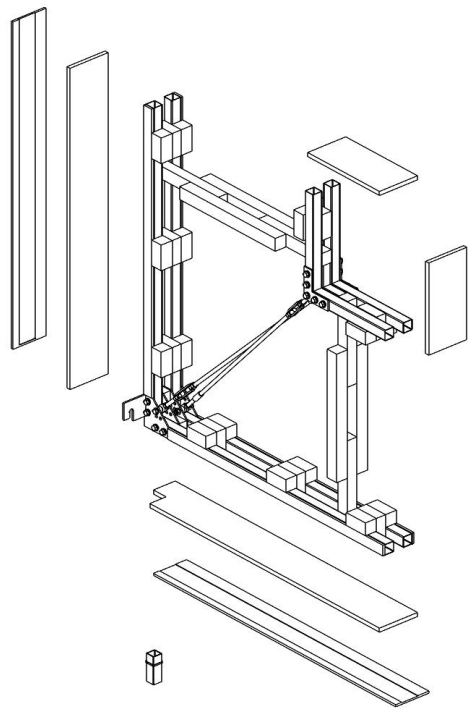


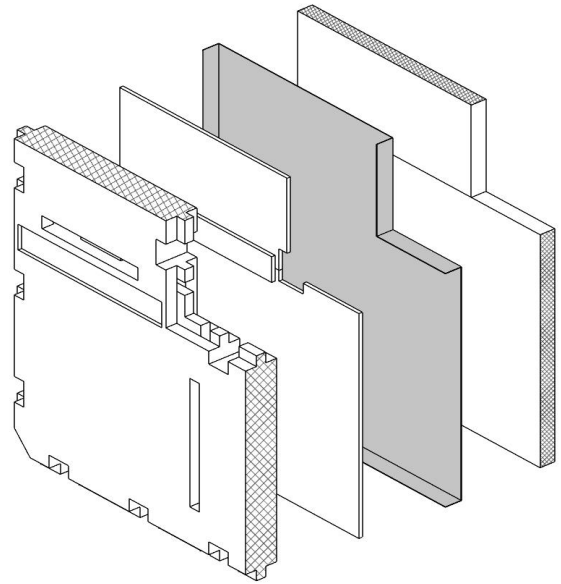


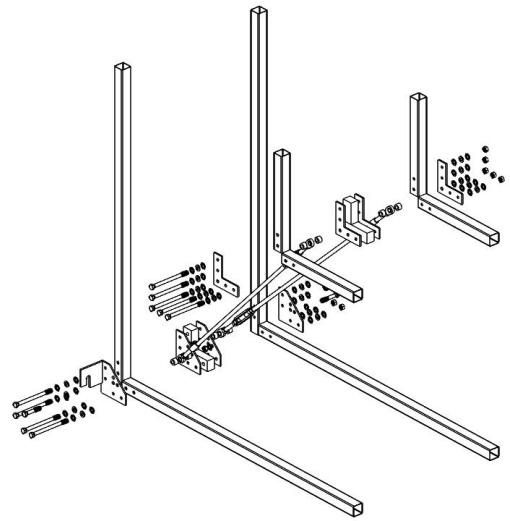


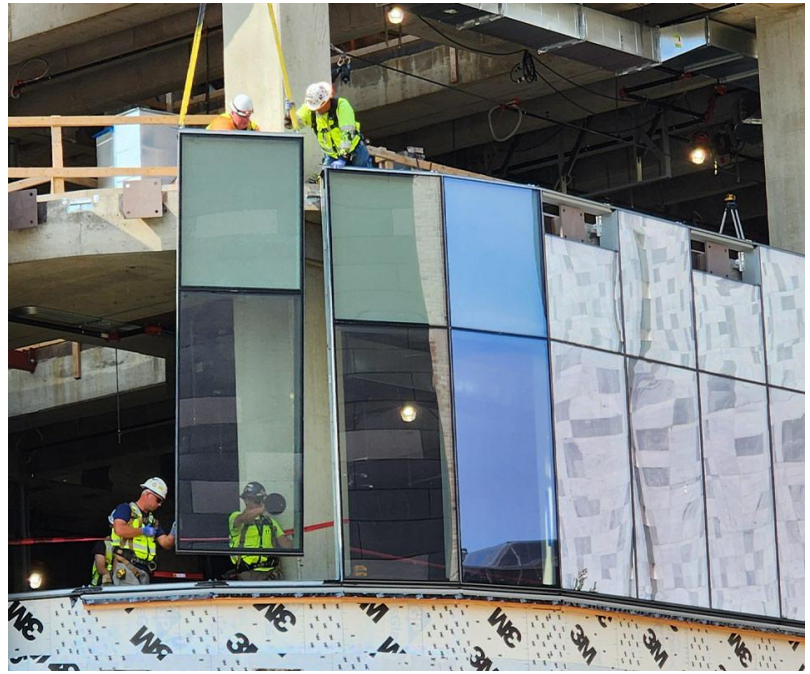


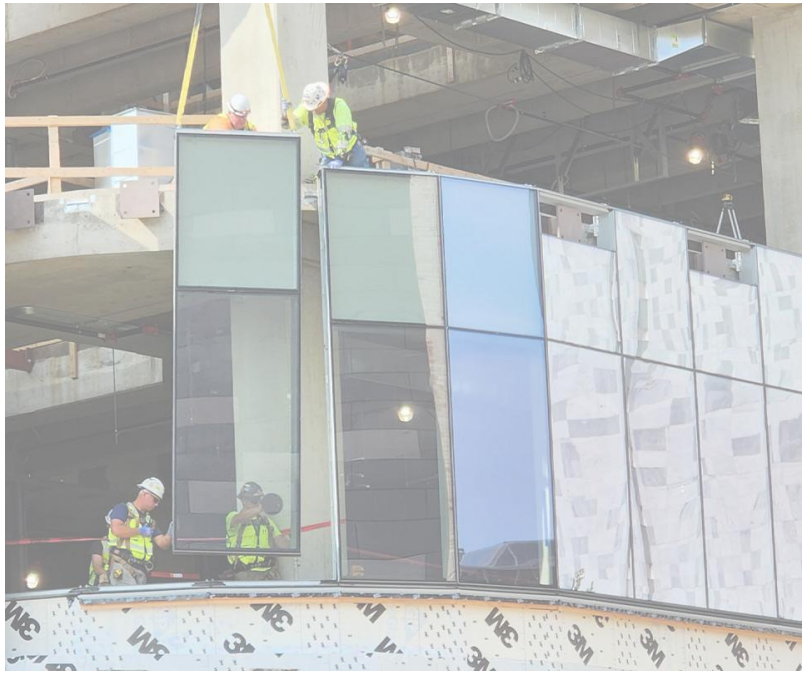


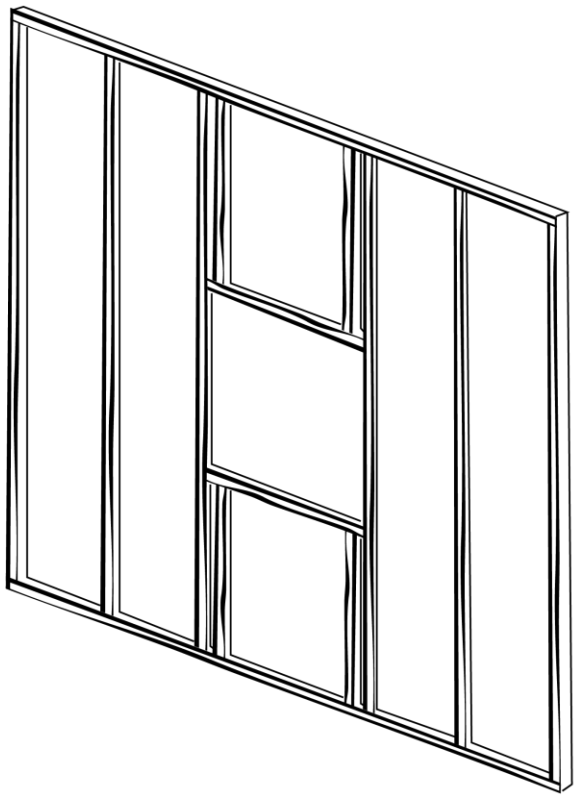


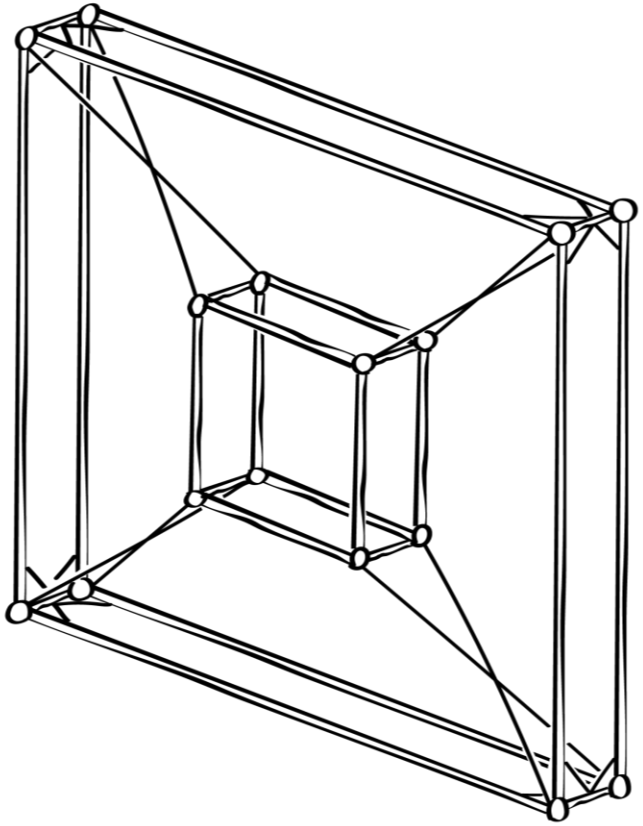


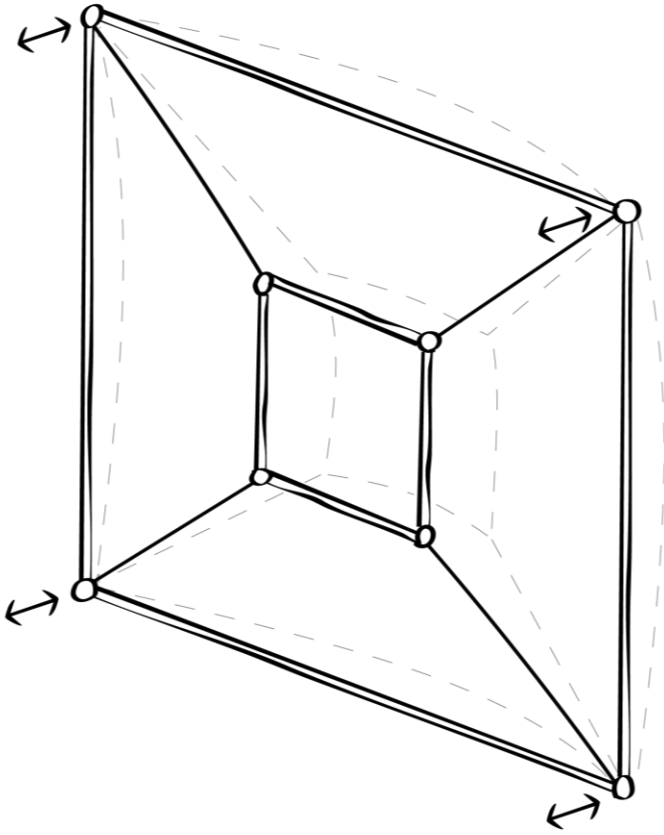




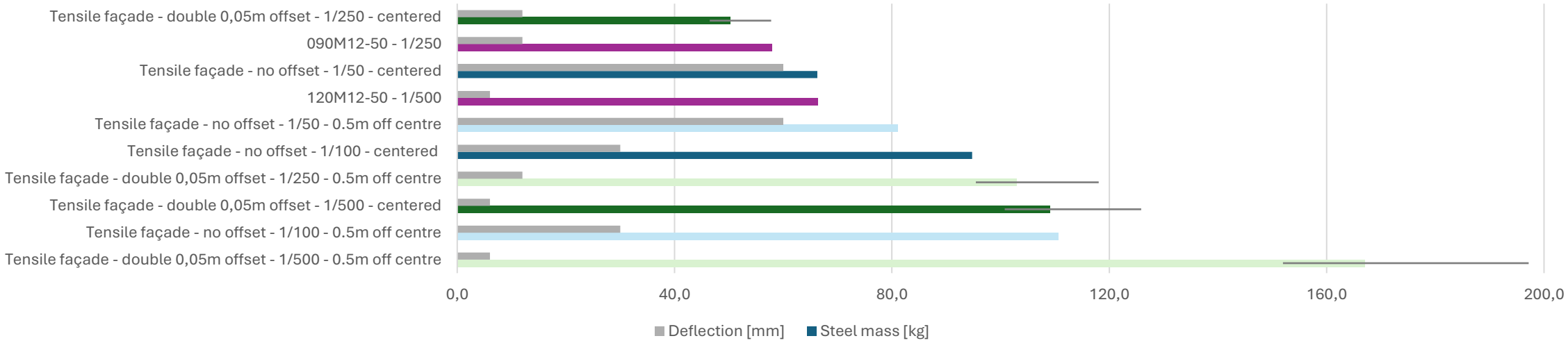




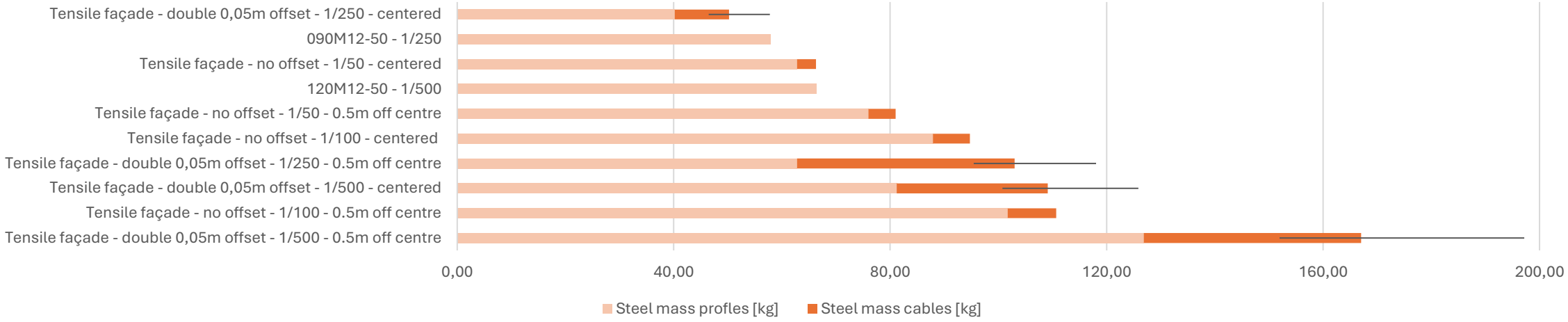


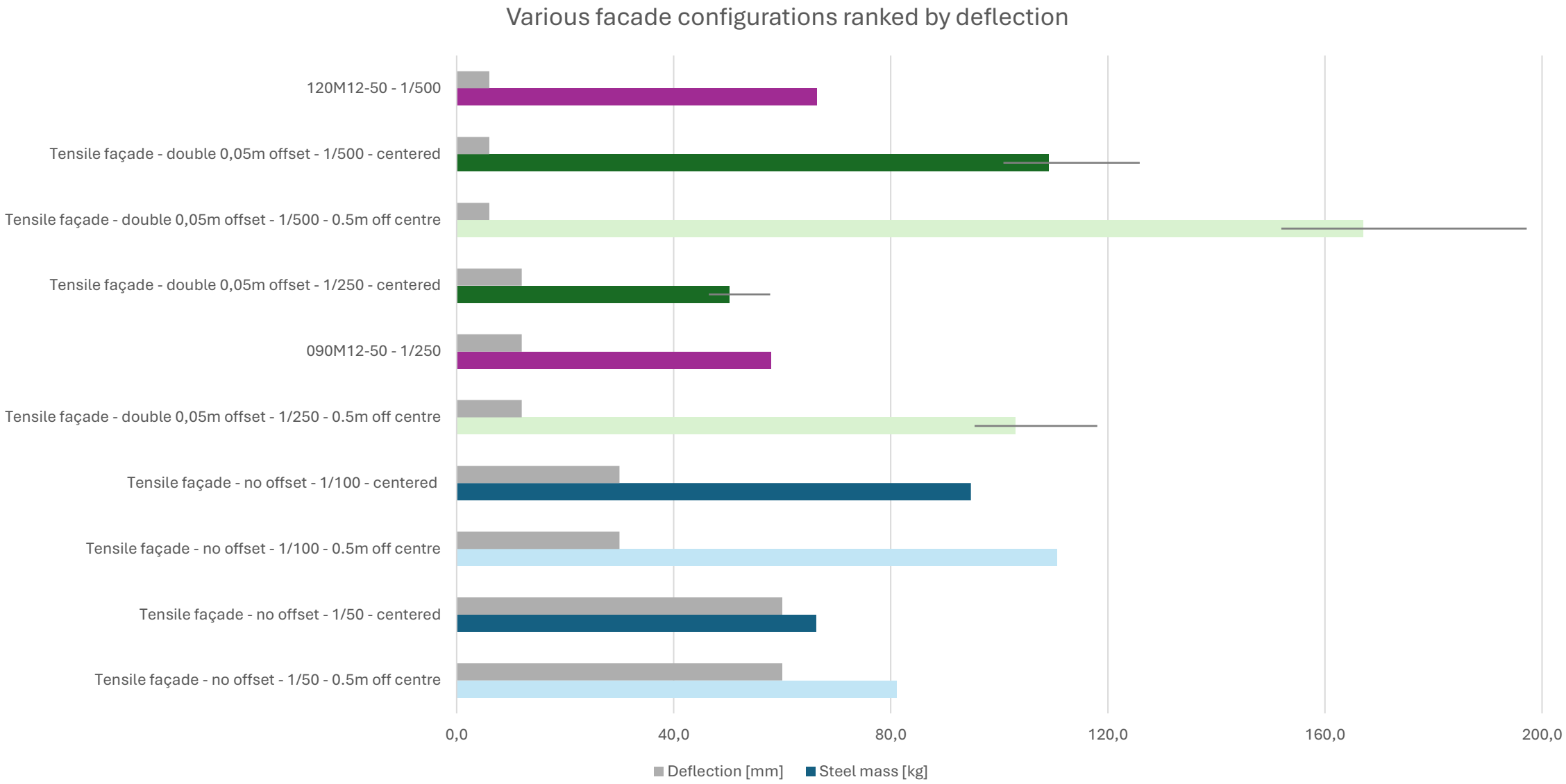


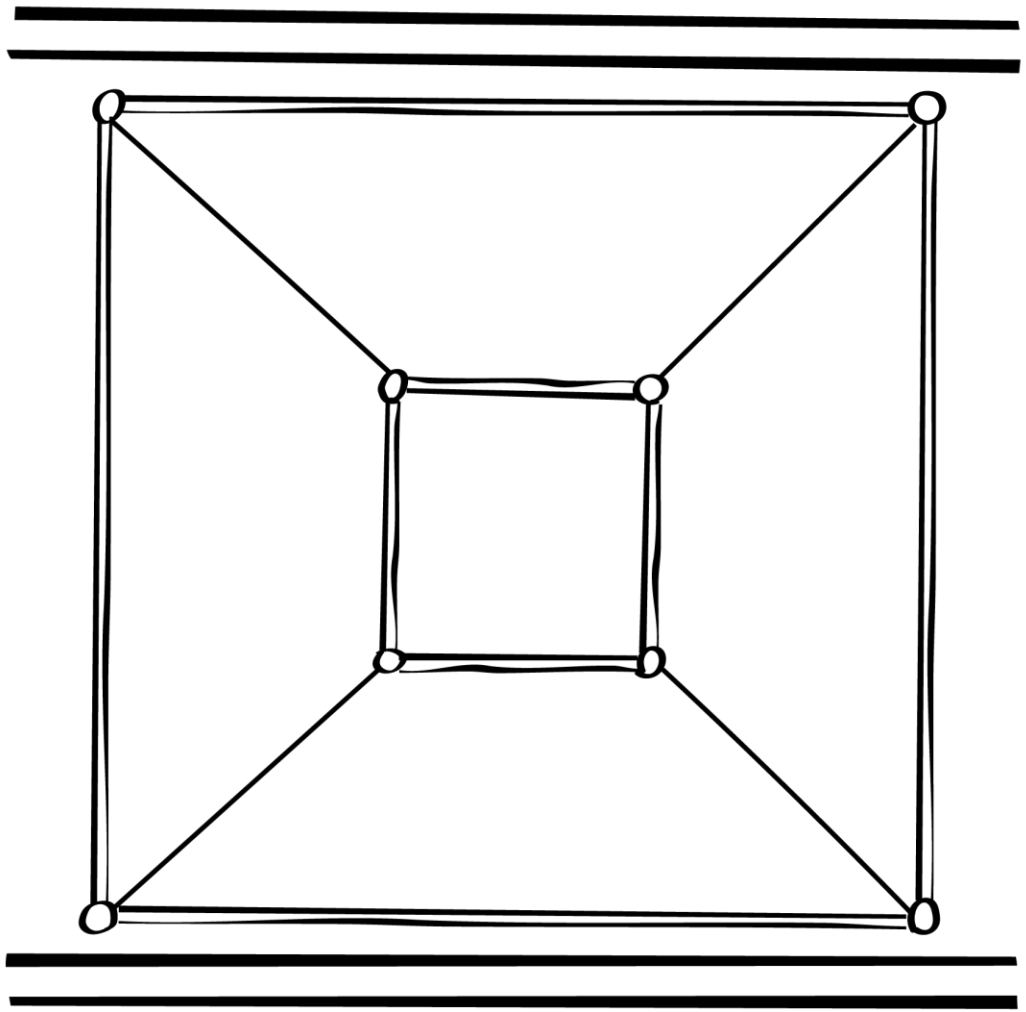
Various facade configurations ranked by steel material usage

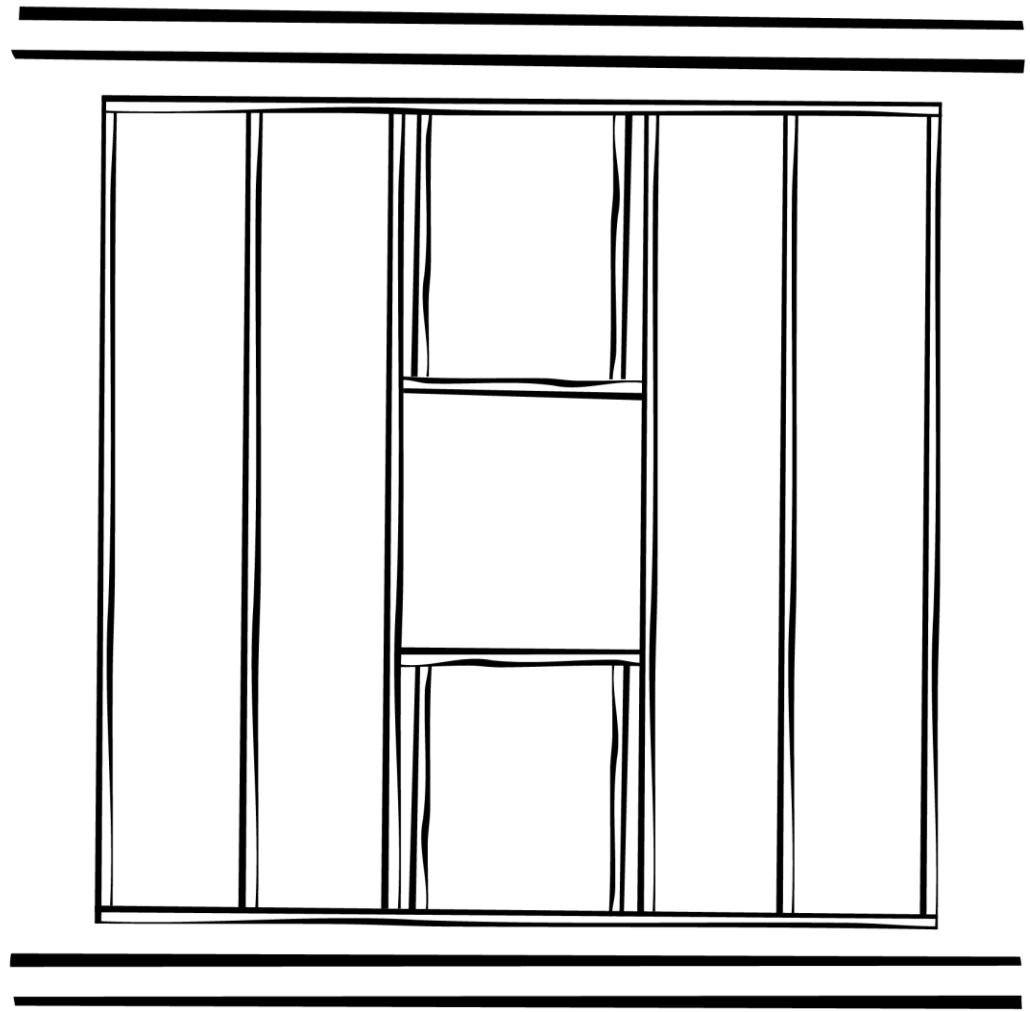


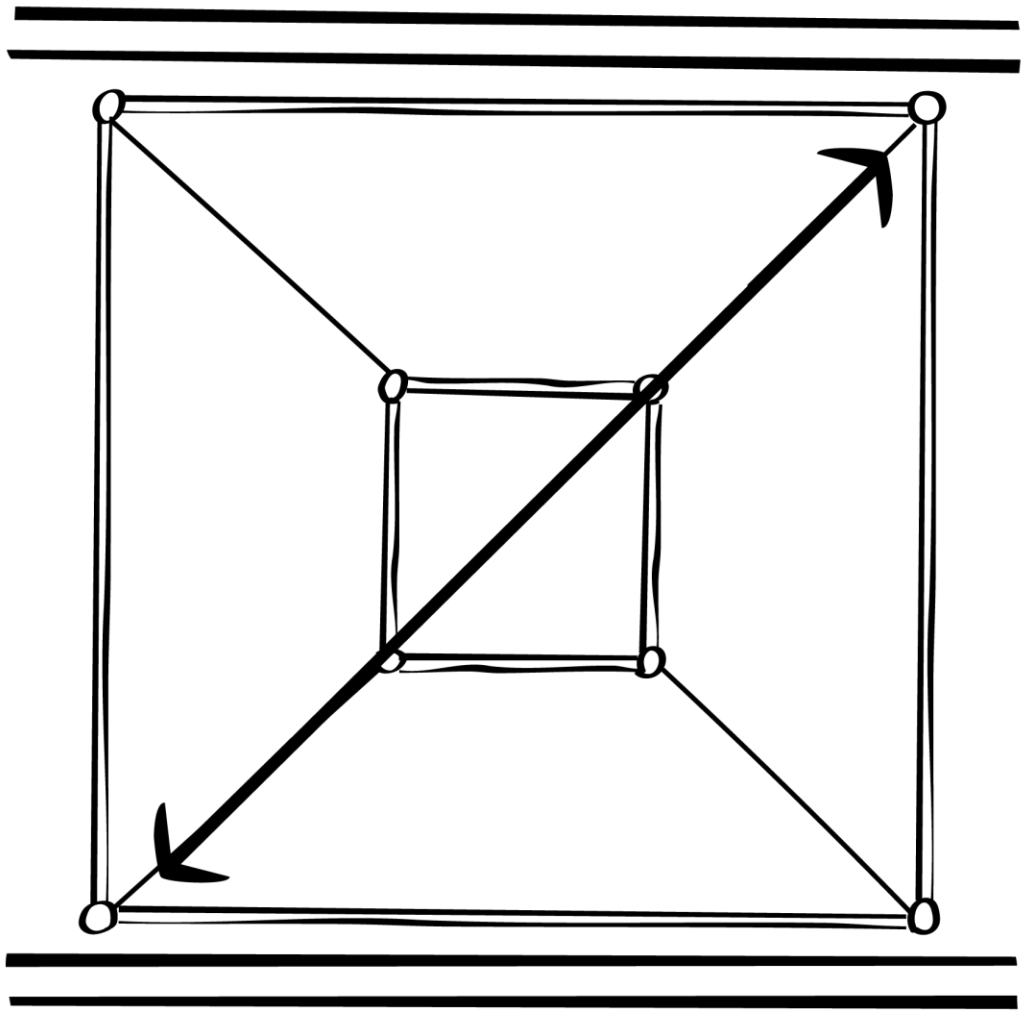
Profile to cable mass of various facade configurations

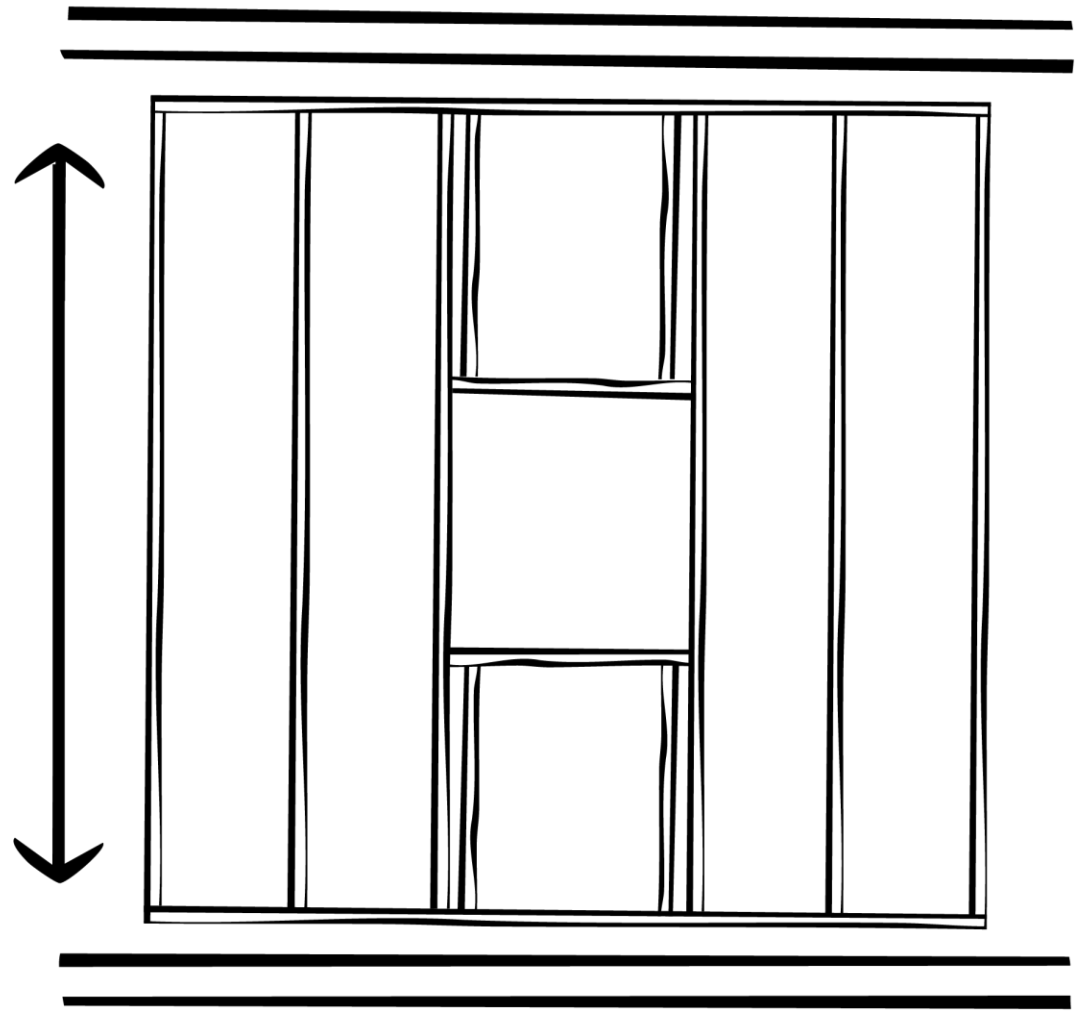


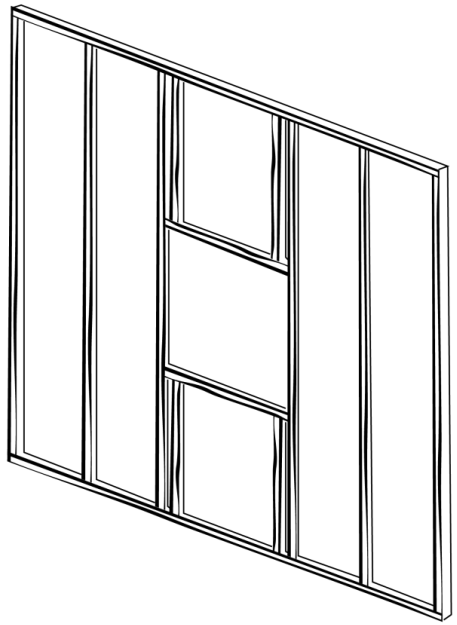

Various facade configurations ranked by deflection
120M12-50 - 1/500
Tensile façade - double 0,05m offset - 1/500 - centered
Tensile façade - double 0,05m offset - 1/500 - 0.5m off centre
Tensile façade - double 0,05m offset - 1/250 - centered
090M12-50 - 1/250
Tensile façade - double 0,05m offset - 1/250 - 0.5m off centre
Tensile façade - no offset - 1/100 - centered
Tensile façade - no offset - 1/100 - 0.5m off centre
Tensile façade - no offset - 1/50 - centered
Tensile façade - no offset - 1/50 - 0.5m off centre
0,0
40,0
80,0
120,0
160,0
200,0
Deflection [mm]
Steel mass [kg]



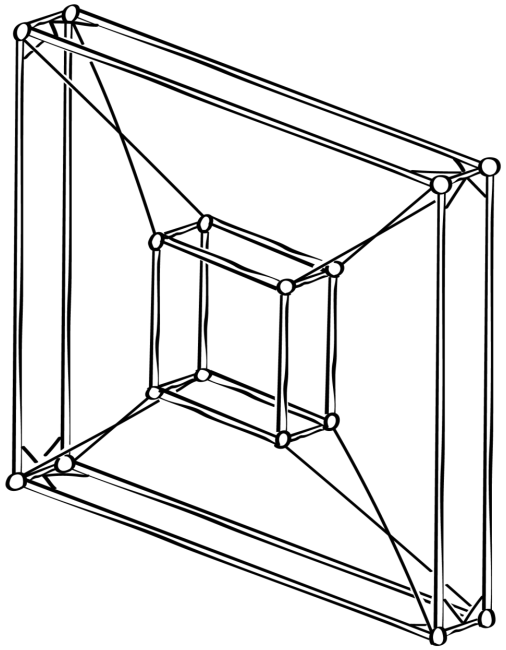




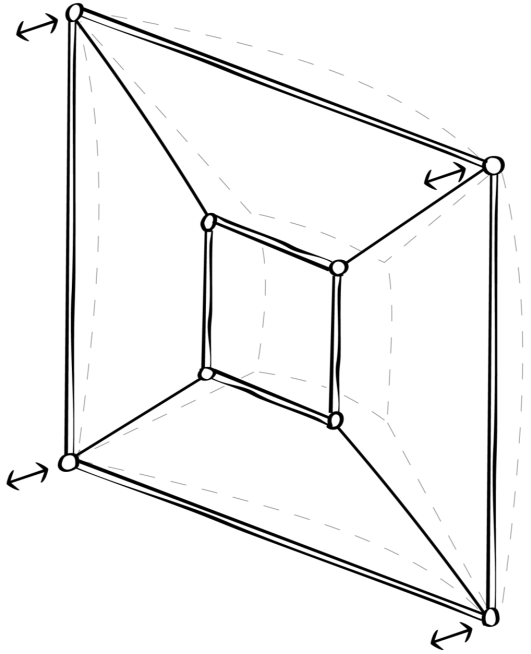




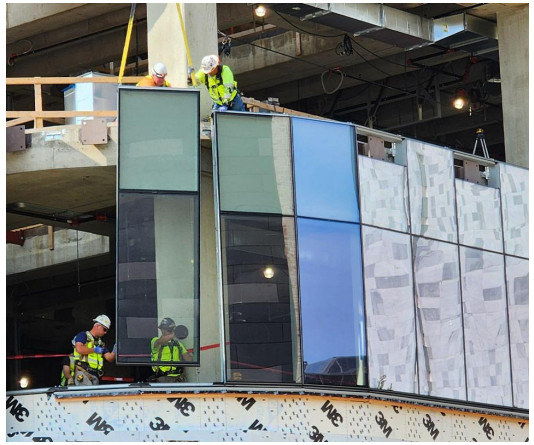
- Low out of plane deflections
- Low steel usage
- High configurability
- Low maintenance
- Easy to manufacture
- Easy to clad the panel
- No stability issues
- Prone to condensation issues
- Moderate thermal performance
- Moderate reusability
- Low to moderate shear resistance
- Continuous support required



- Low out of plane deflections
- Low to moderate steel usage
- Moderate configurability
- High maintenance
- Difficult to manufacture
- Moderate difficulty with cladding
- Moderate stability issues
- Highly prone to condensation issues
- Moderate thermal performance
- Potentially high reusability
- High shear resistance
- Few support points



- High out of plane deflections
- Low steel usage
- Low to moderate configurability
- High maintenance
- Moderately difficult to manufacture
- High difficulty with cladding
- High stability issues
- Prone to condensation issues
- Moderate to good thermal performance
- Potentially high reusability
- High shear resistance
- Few support points



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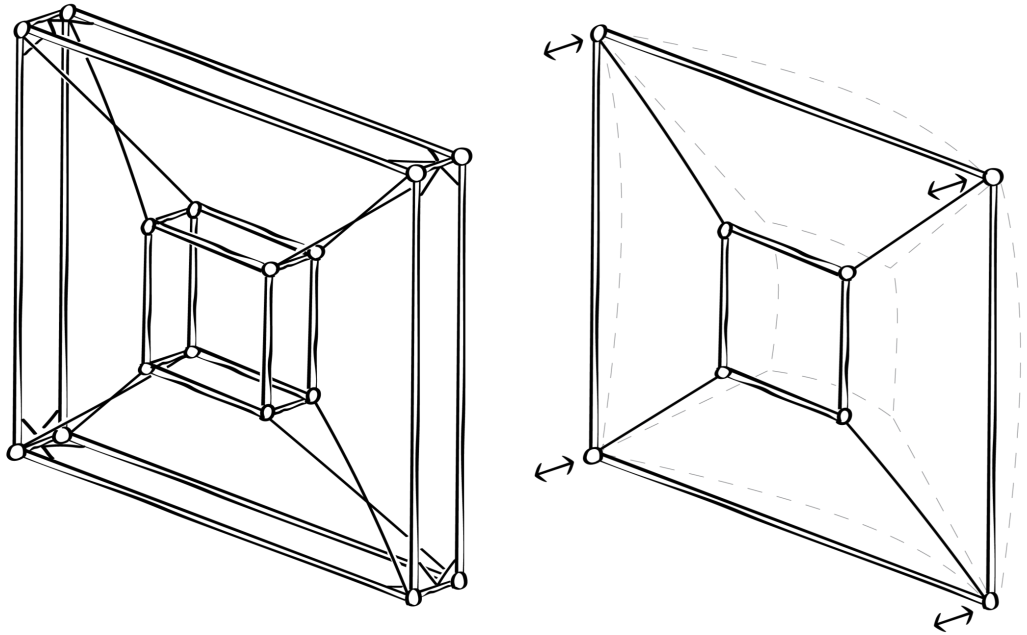

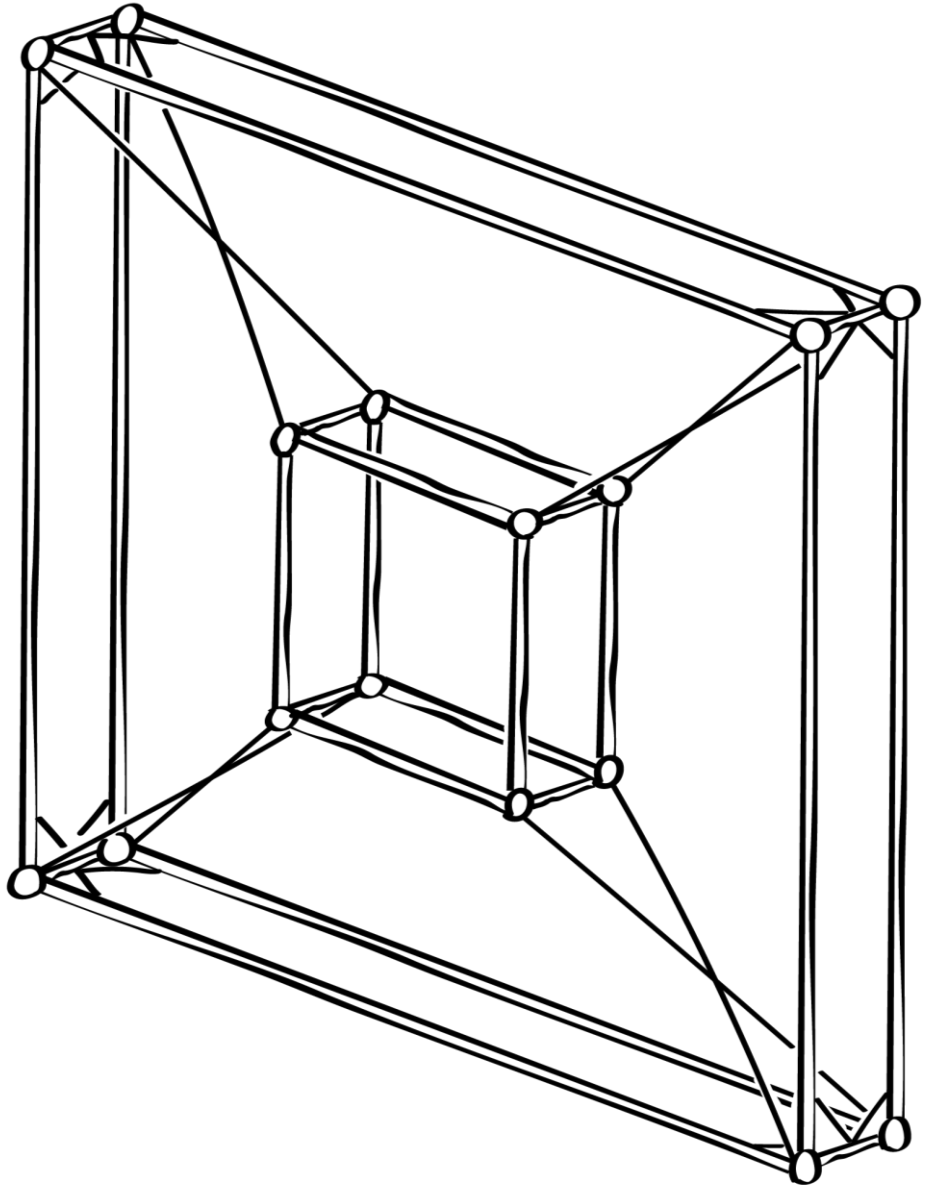

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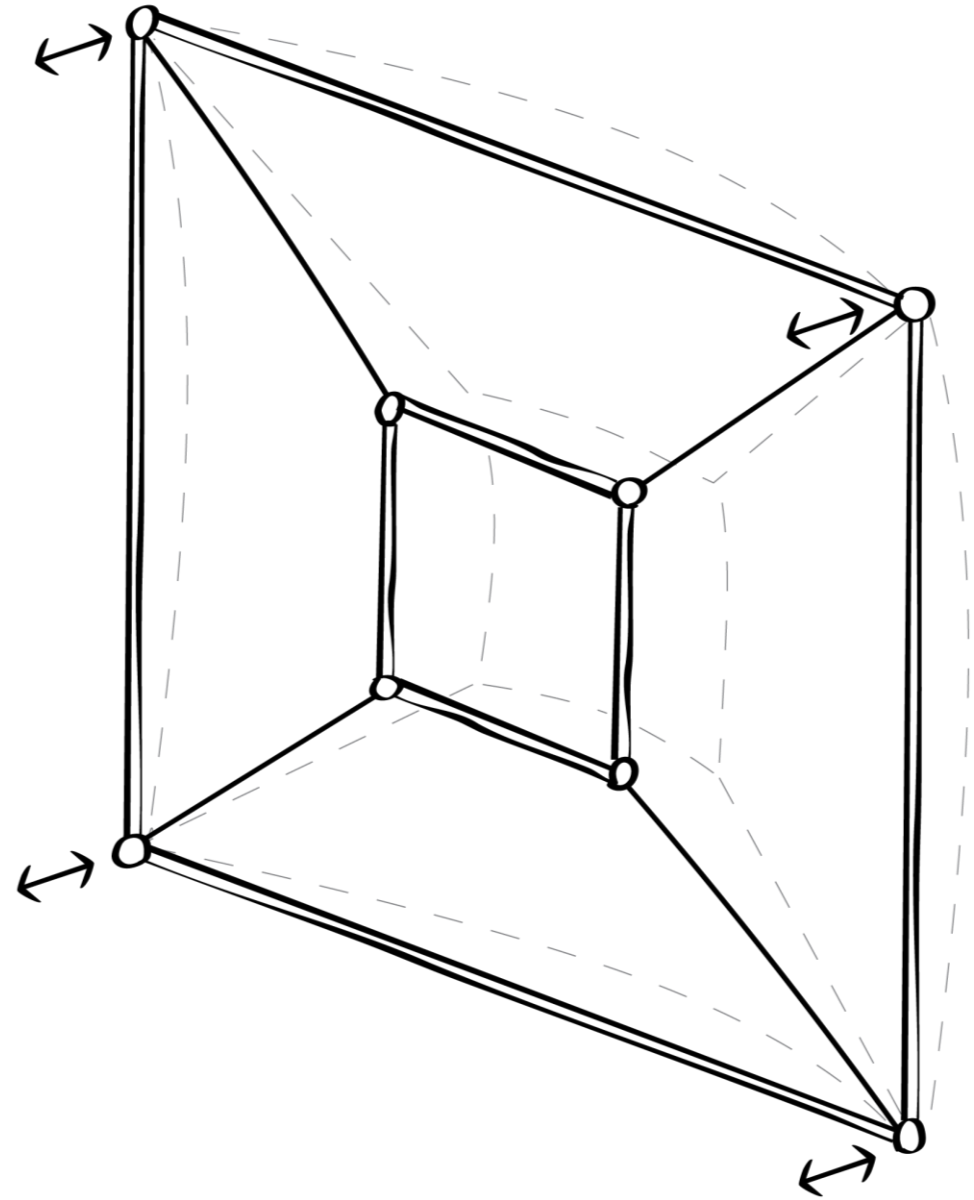
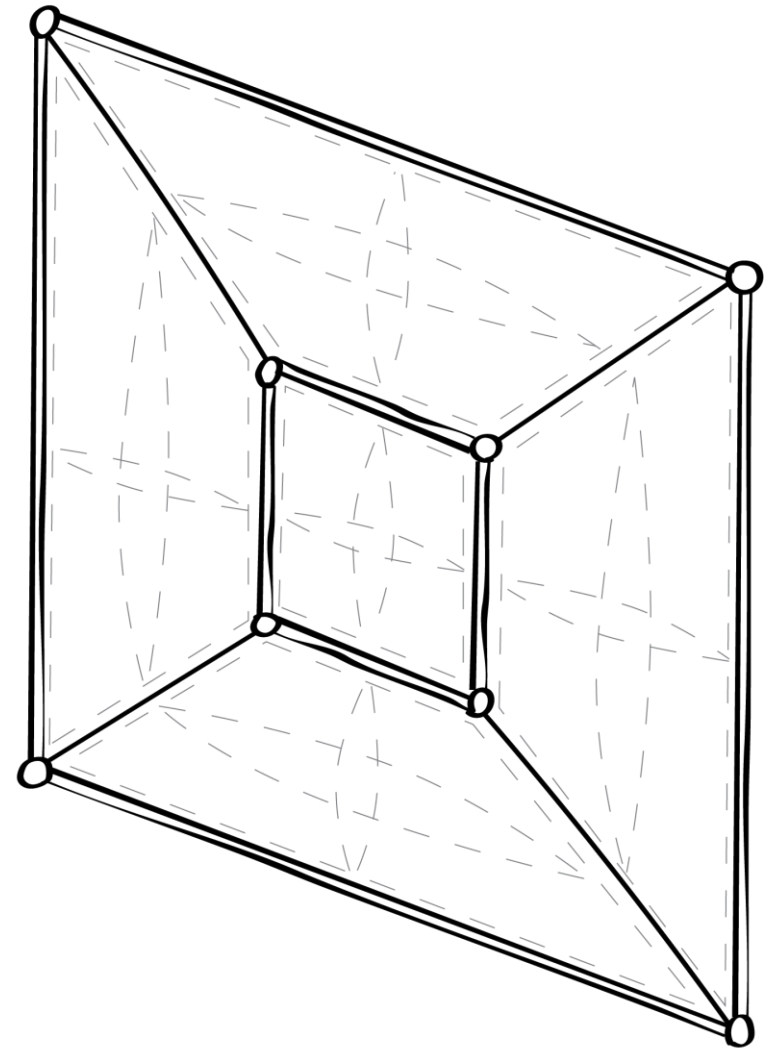
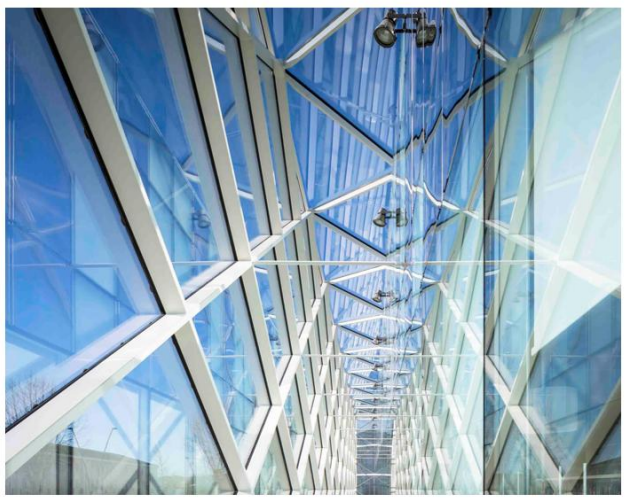
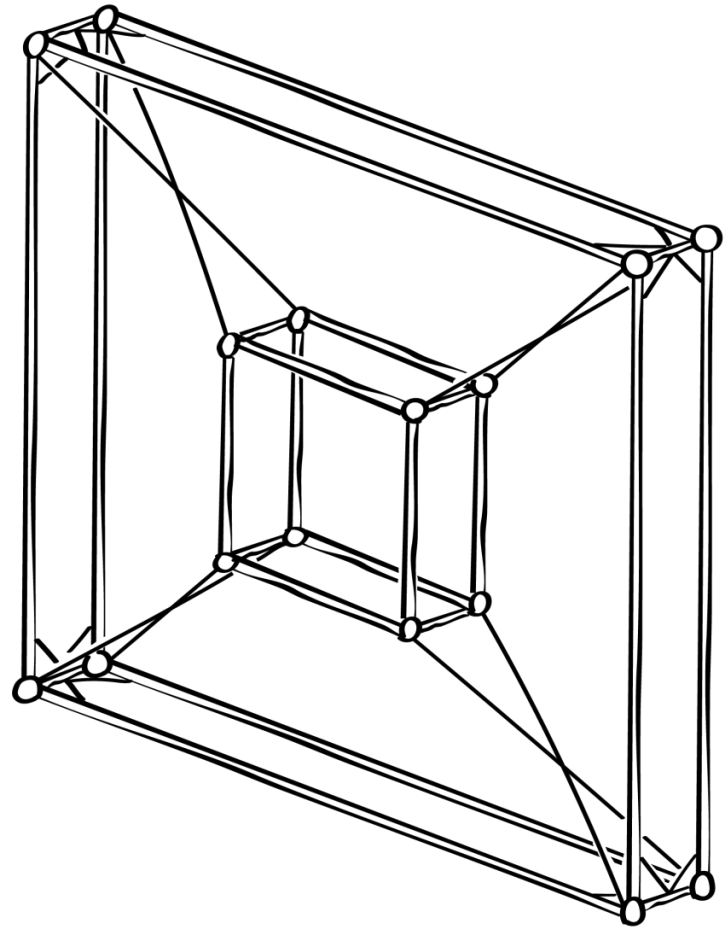
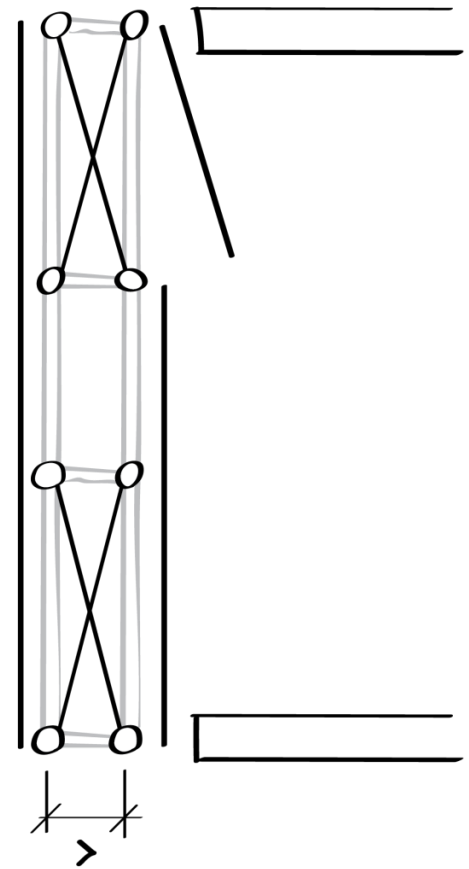
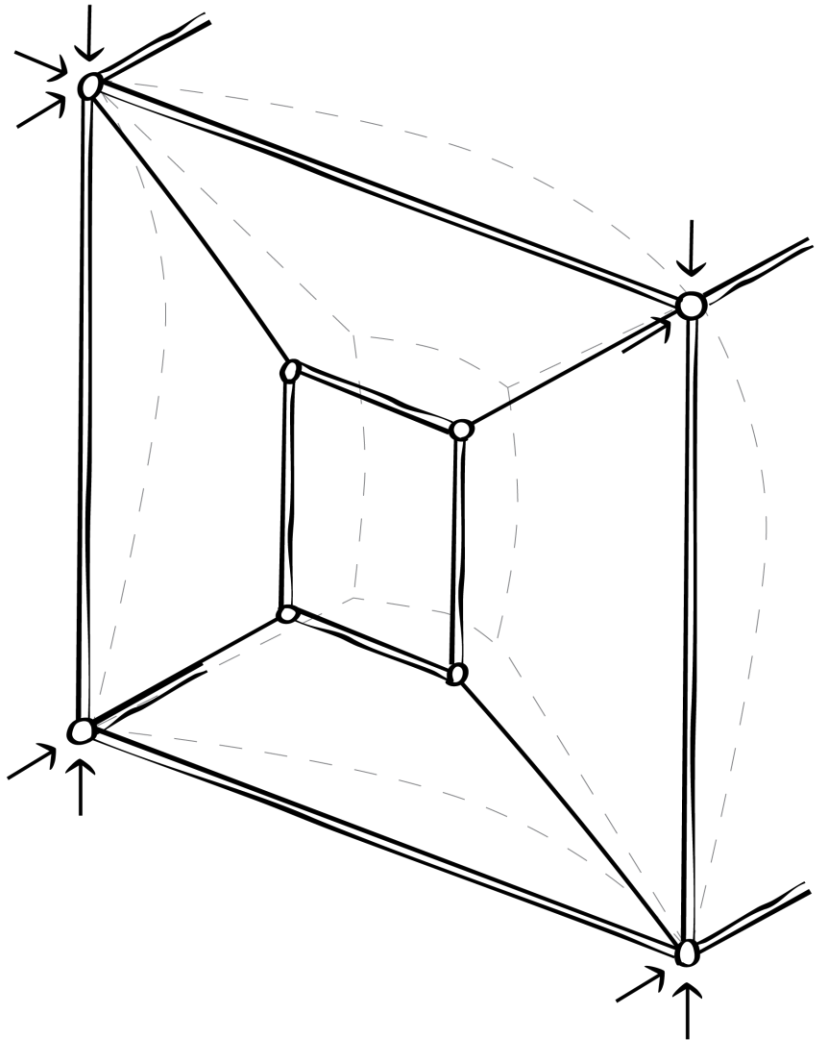


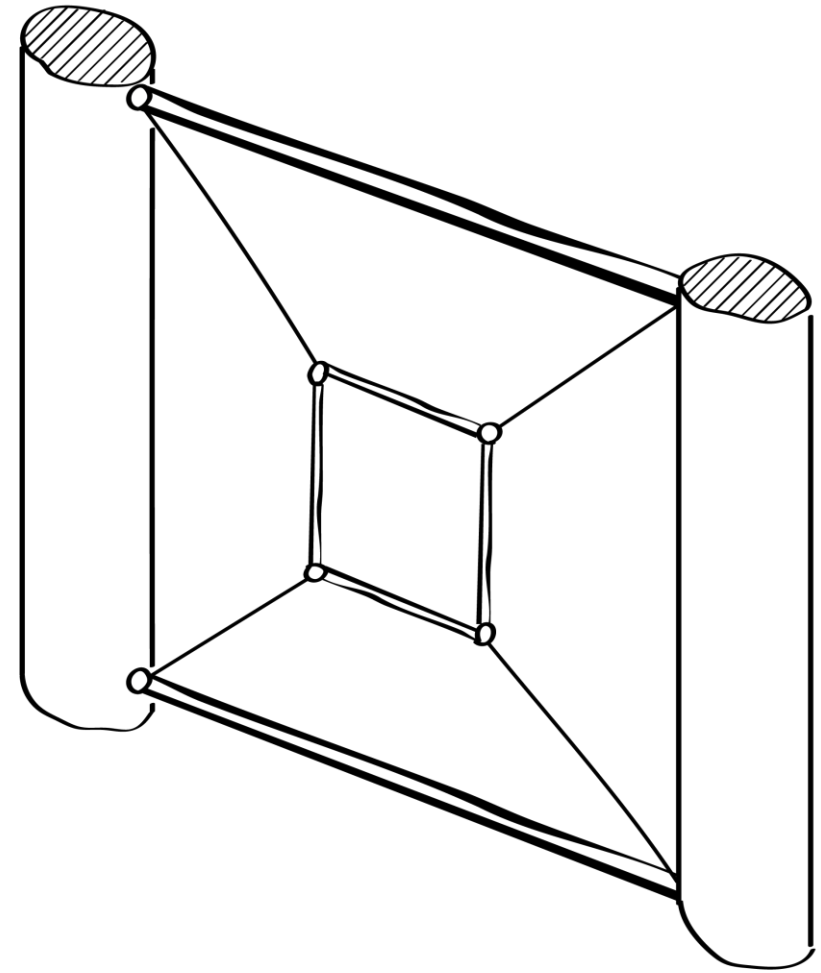




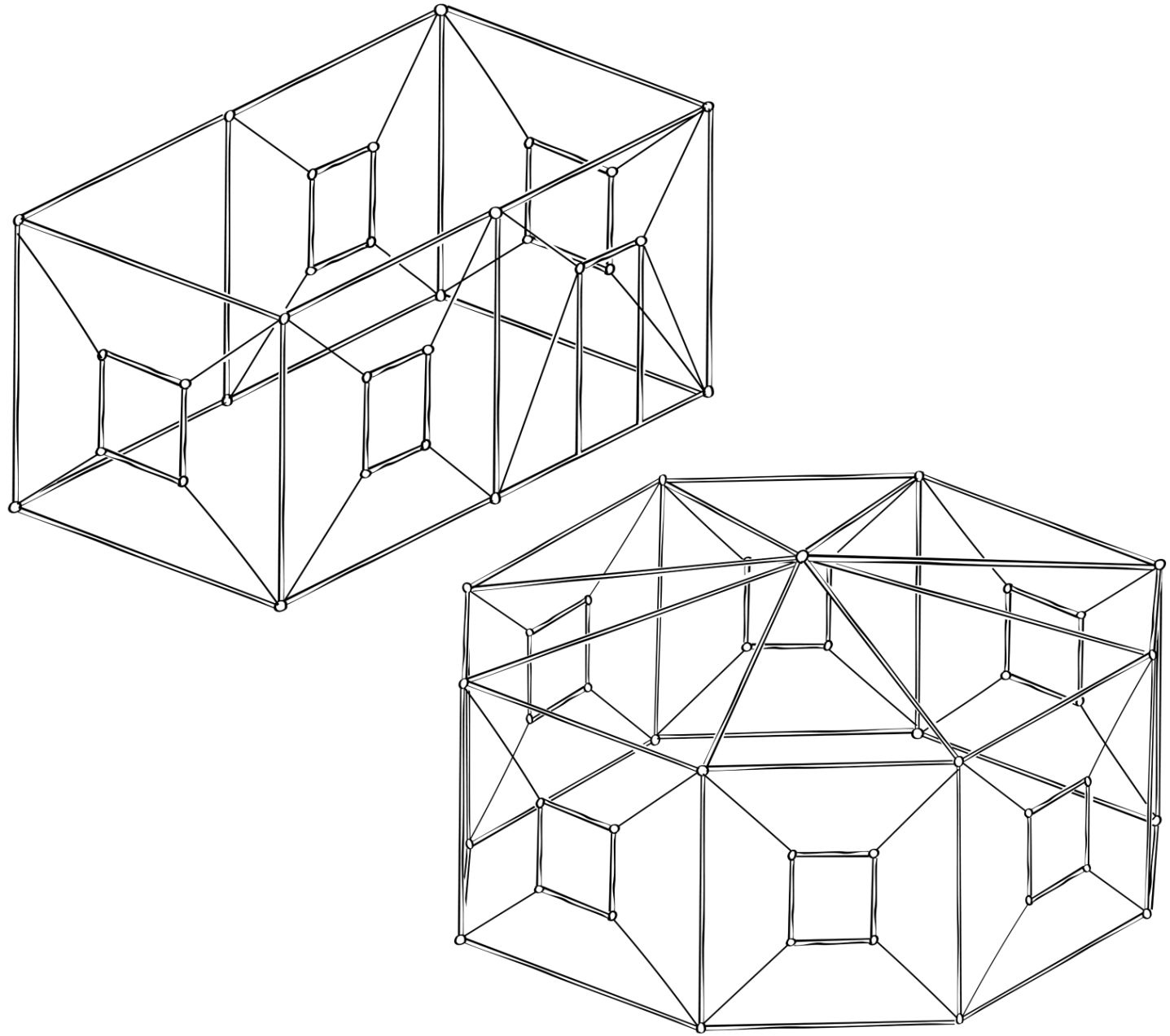


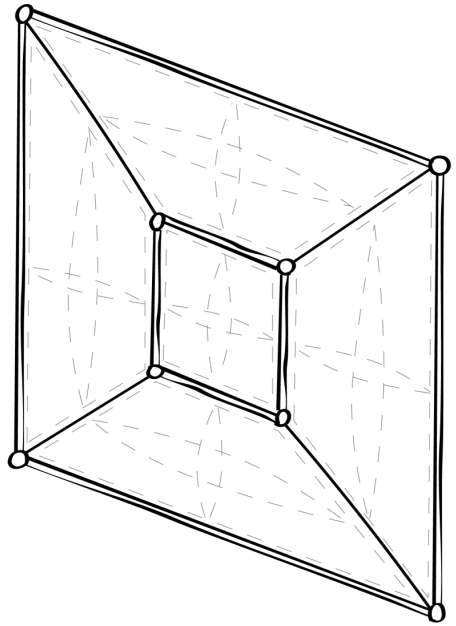


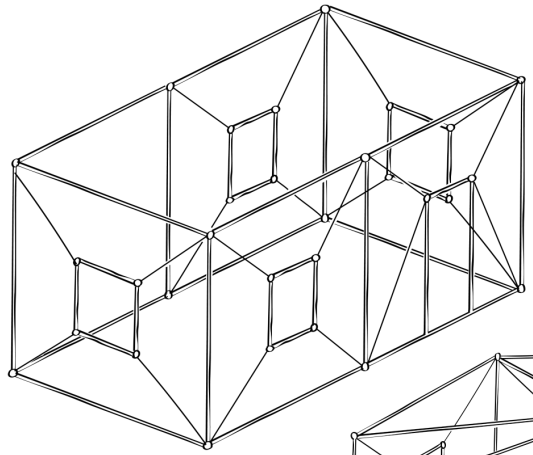


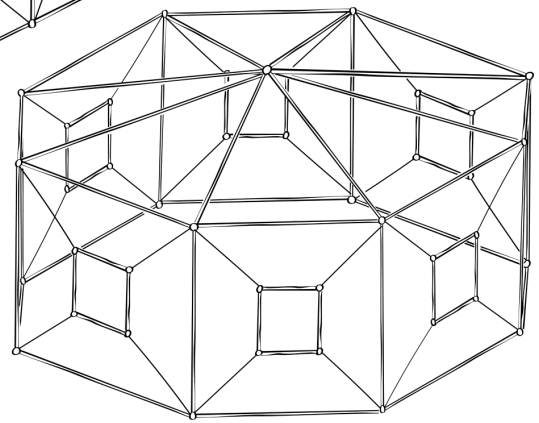


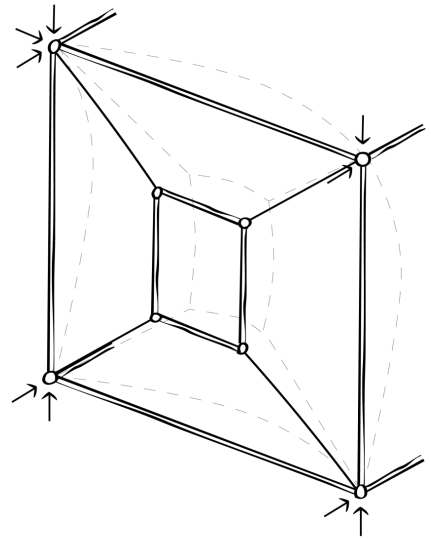

Overland(ish)
BASE CAMP

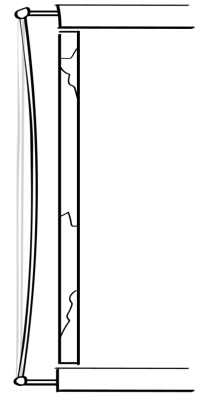


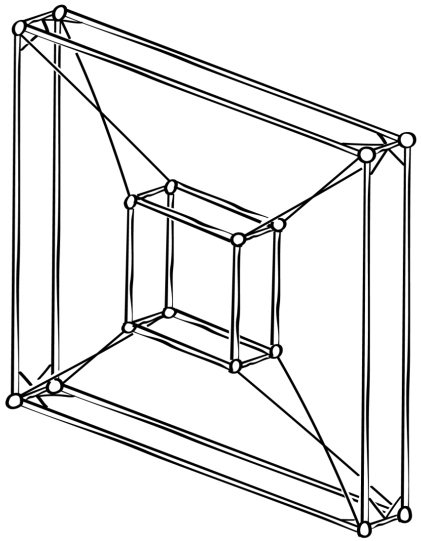


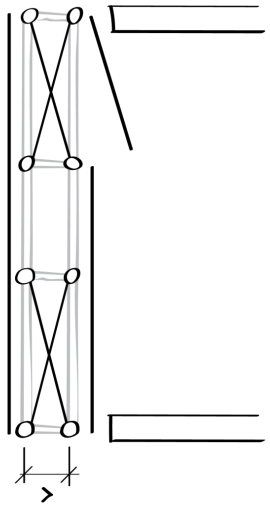


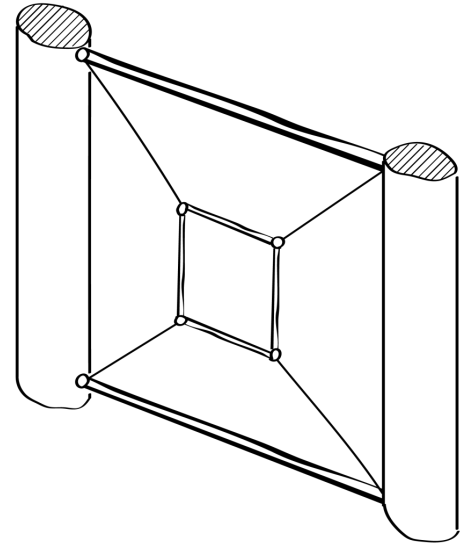


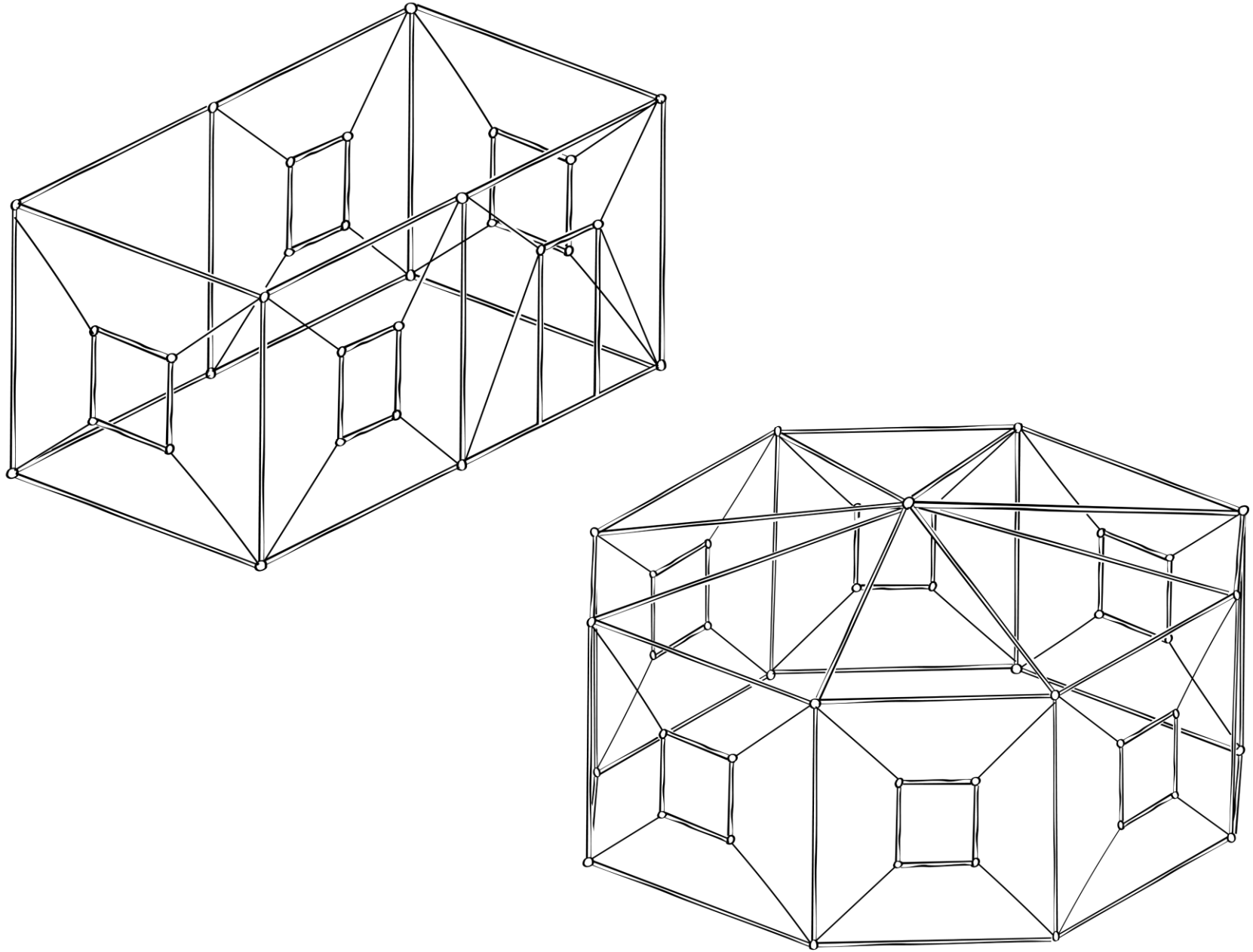


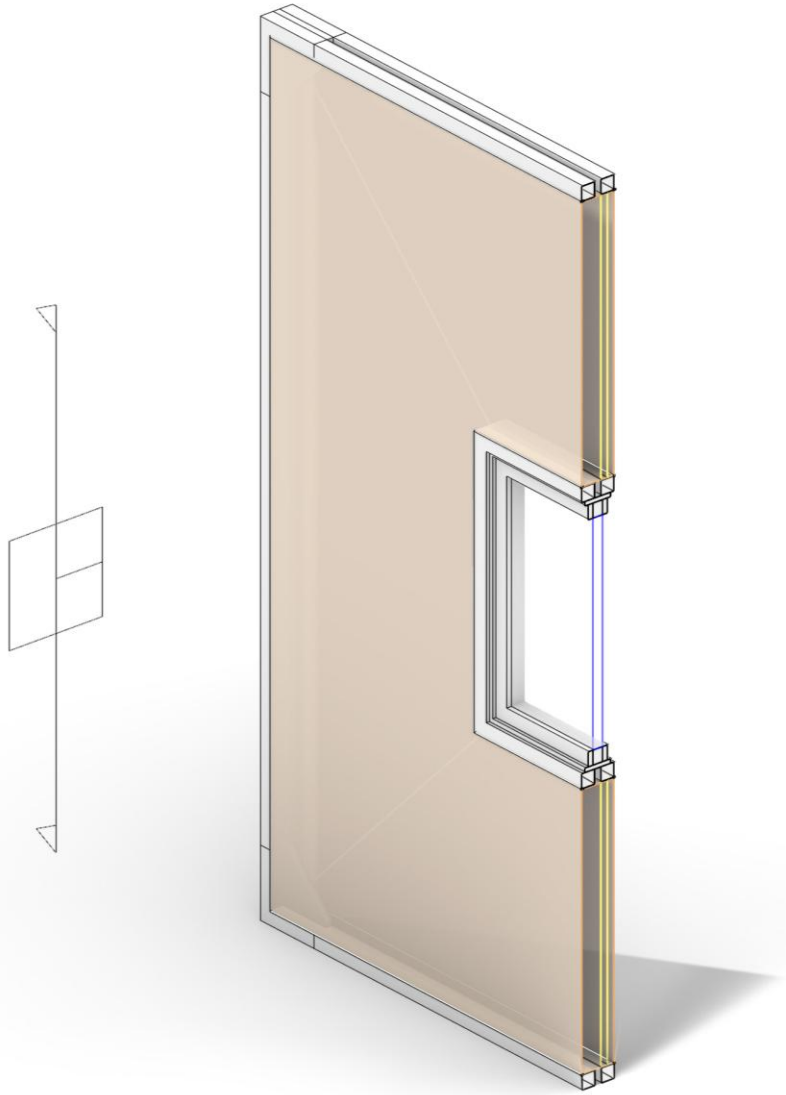


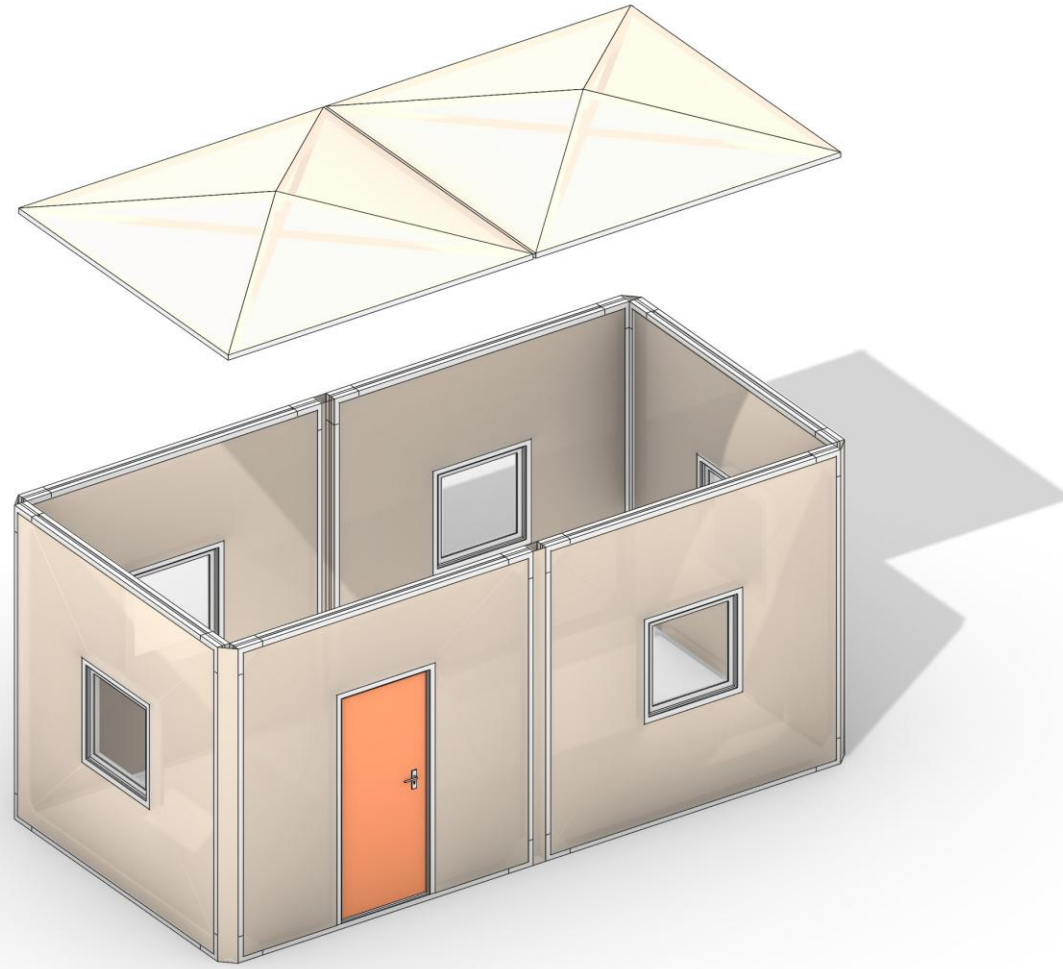


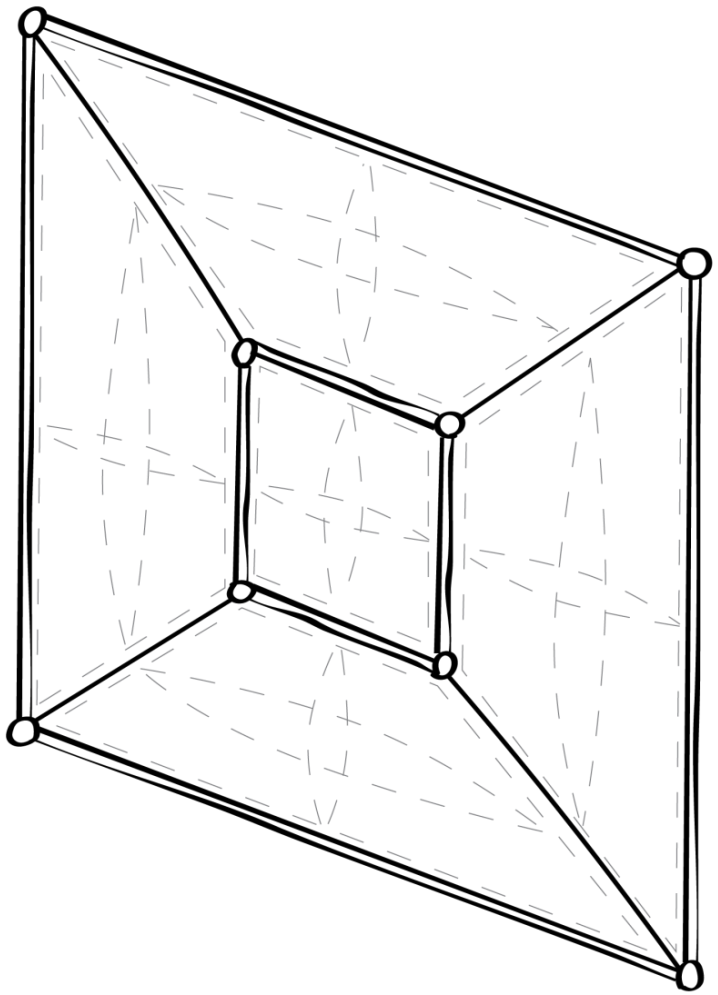


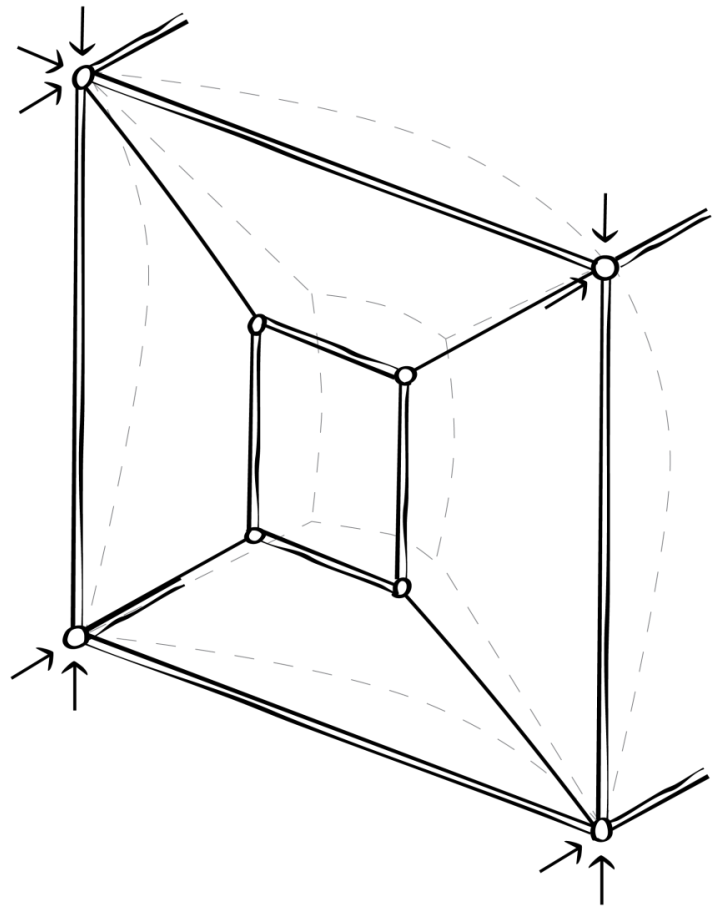


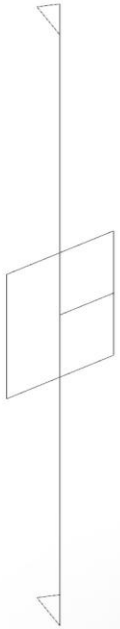


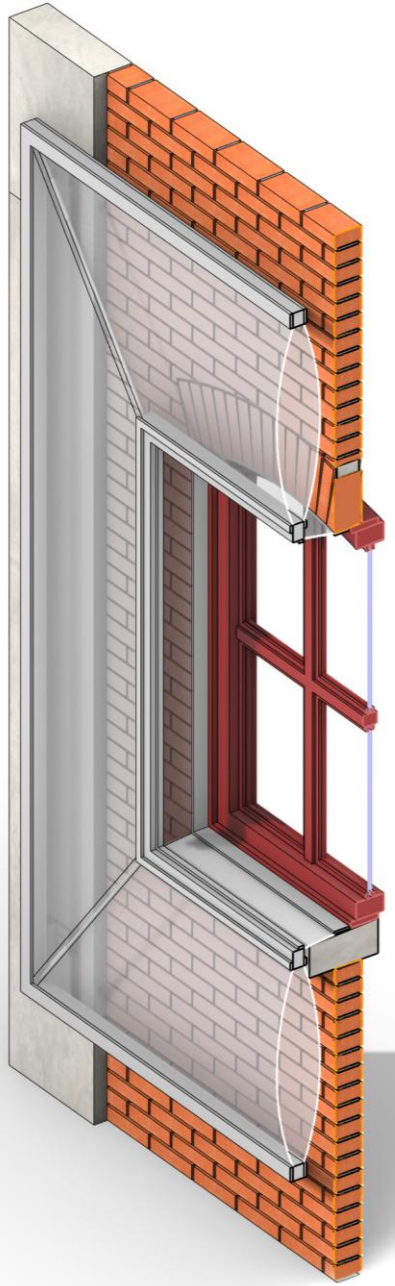


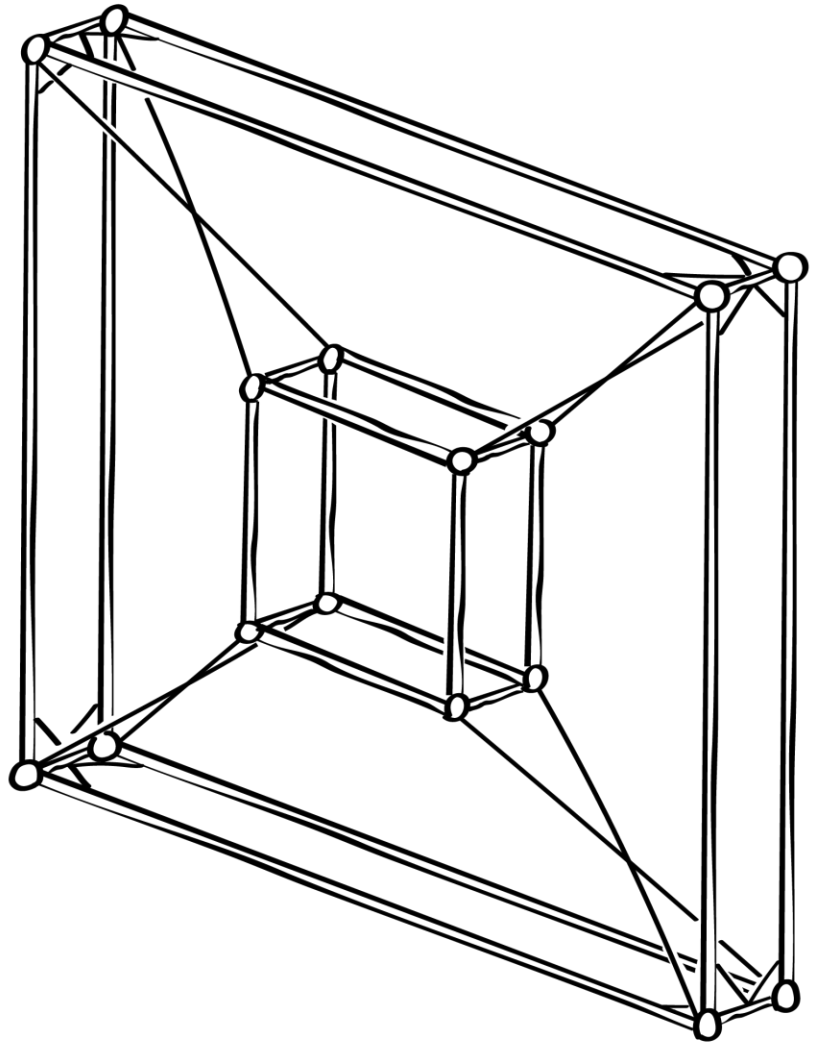


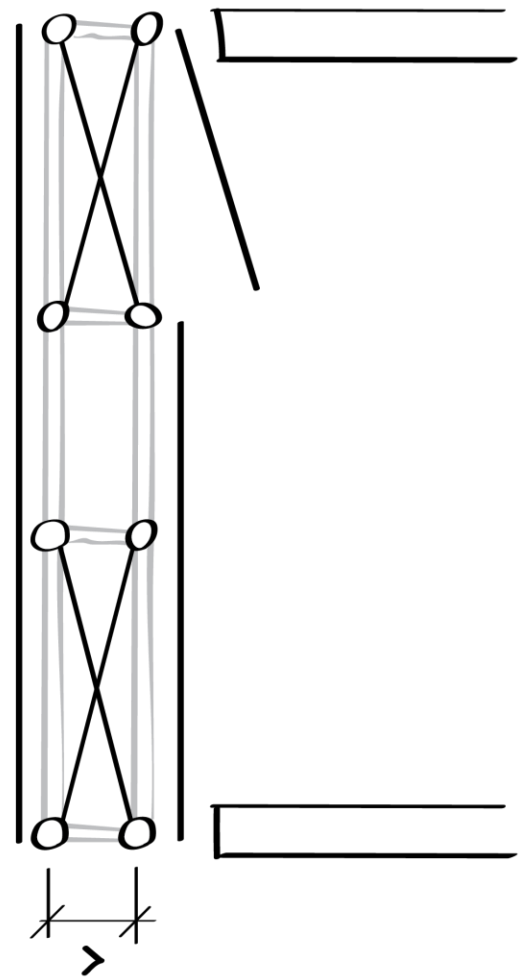


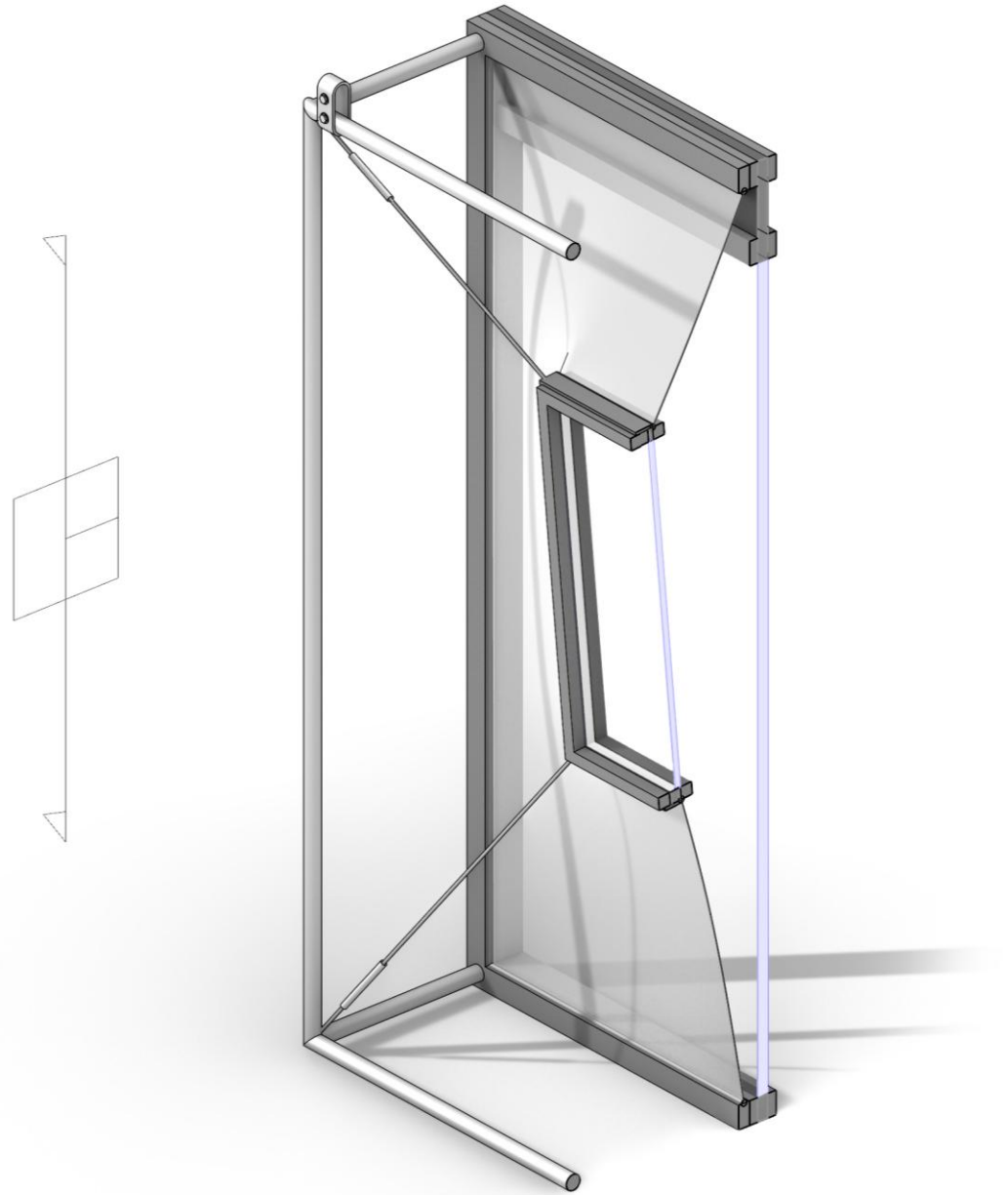












Thank you