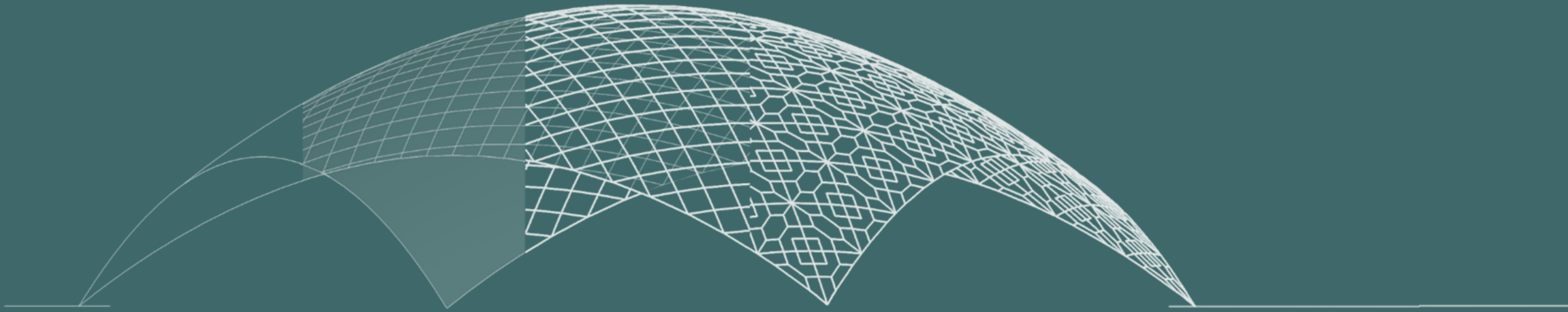
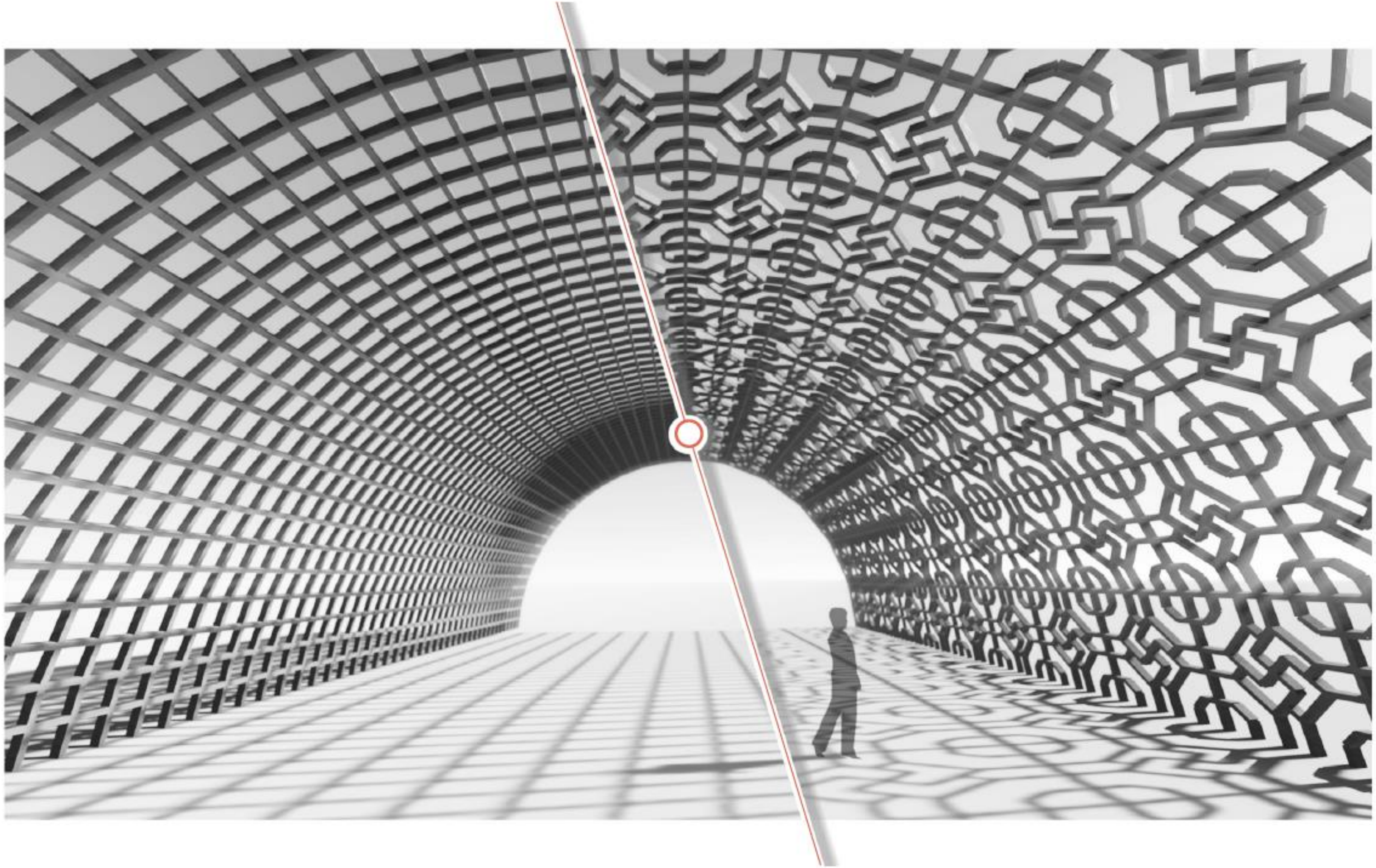
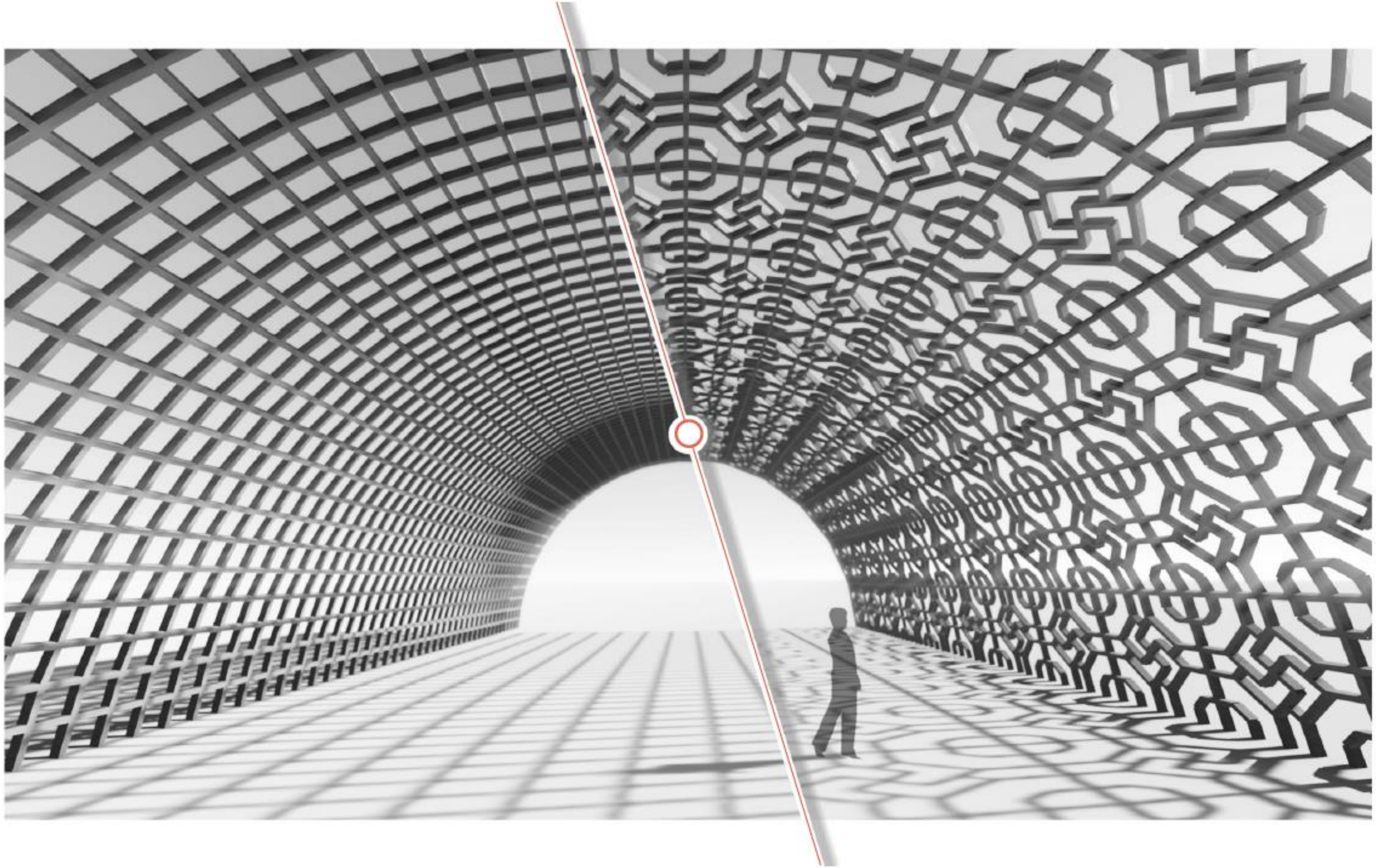


# Patterned grid-shell

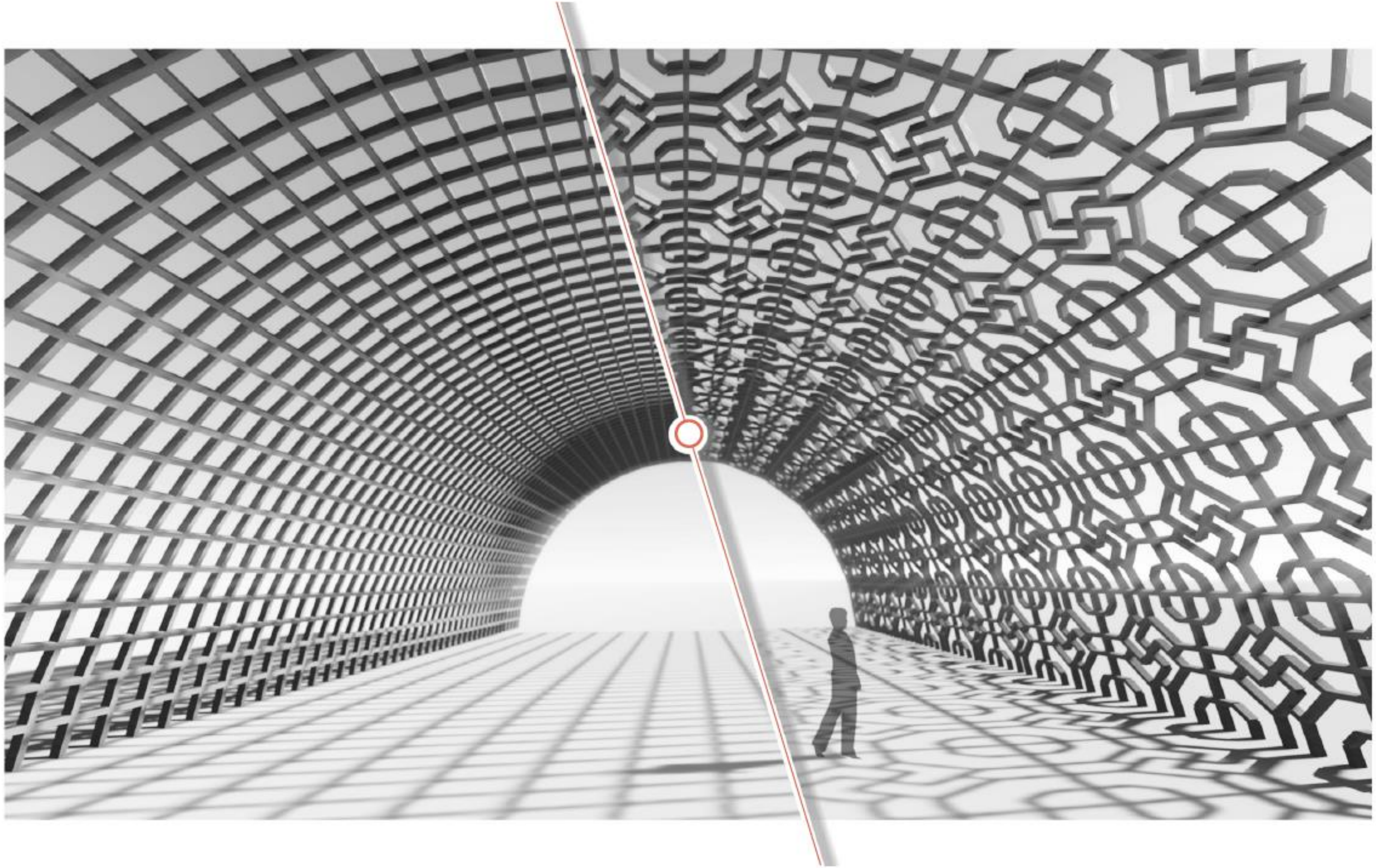
Designing a method to analyse and compare grid-shell influenced by traditional lattice patterns of north Asia.



*An attempt to embrace native design characteristics in contemporary architecture with the help of modern designing and simulation techniques*



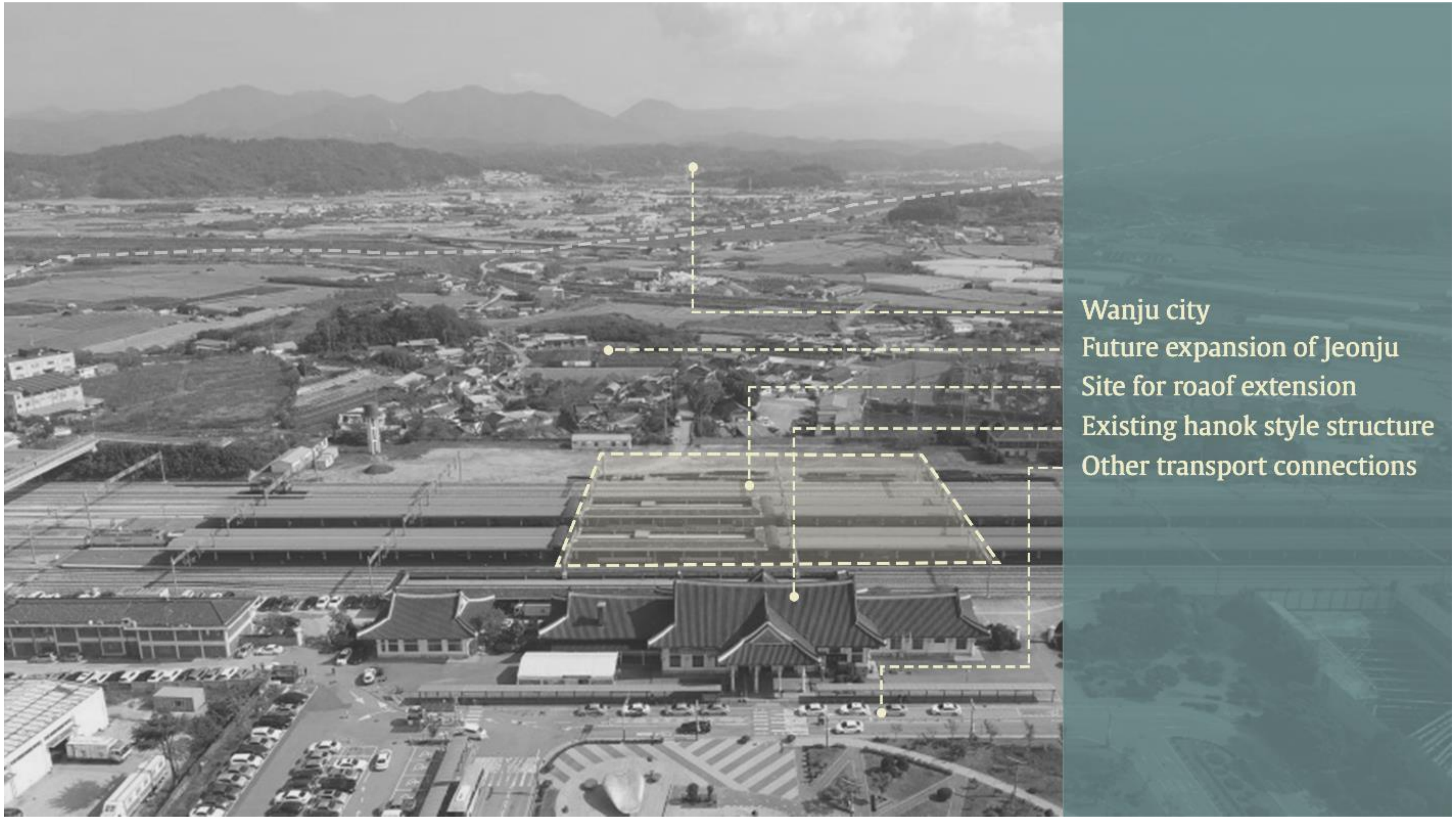
*An attempt to embrace native "**design characteristics**" in contemporary architecture with the help of modern designing and simulation techniques*



*An attempt to embrace native "**traditional art**" in contemporary architecture with the help of modern designing and simulation techniques*

[Project Scope, 2019]

Jeonju, train station, South Korea




Jeonju, train station, South Korea

[Jeonju Hanok Village, 2019]

[Jeonju travel blog , 2018]

[Jeonju travel blog , 2018]

[Jeonju travel blog , 2018]

# Jeonju Hanok village

### Form

[Pxhere, n.d.]

Hanok style shelter drives human vision to sky

### Colours

[Pxhere, n.d.]

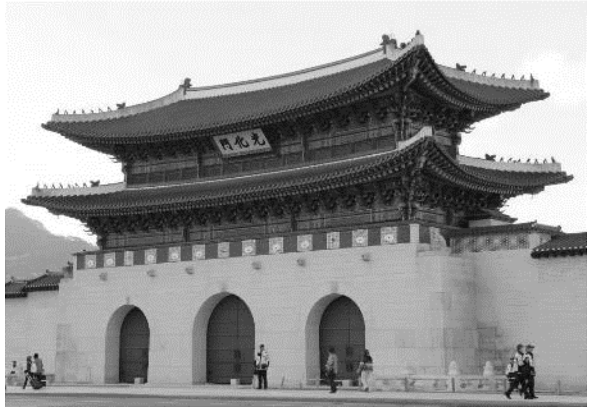
Colours highlights and distinguishes building elements

### Lattice

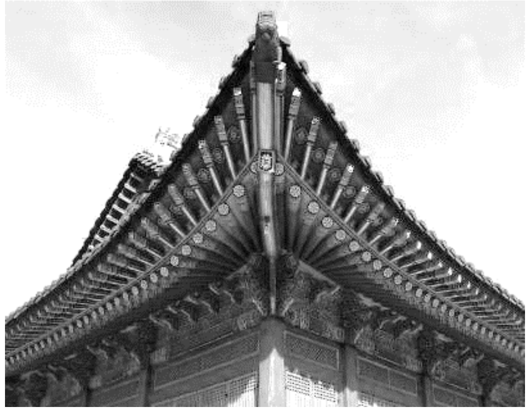
[Pxhere, n.d.]

Minimal space configuration dramatized with patterns of lattice frames of window

## Key design features



[Pxhere, n.d.]



[Pxhere, n.d.]

### Lattice

[Pxhere, n.d.]

Minimal space configuration dramatized with patterns of lattice frames of window

## Key design features

[CHANG, n.d.]

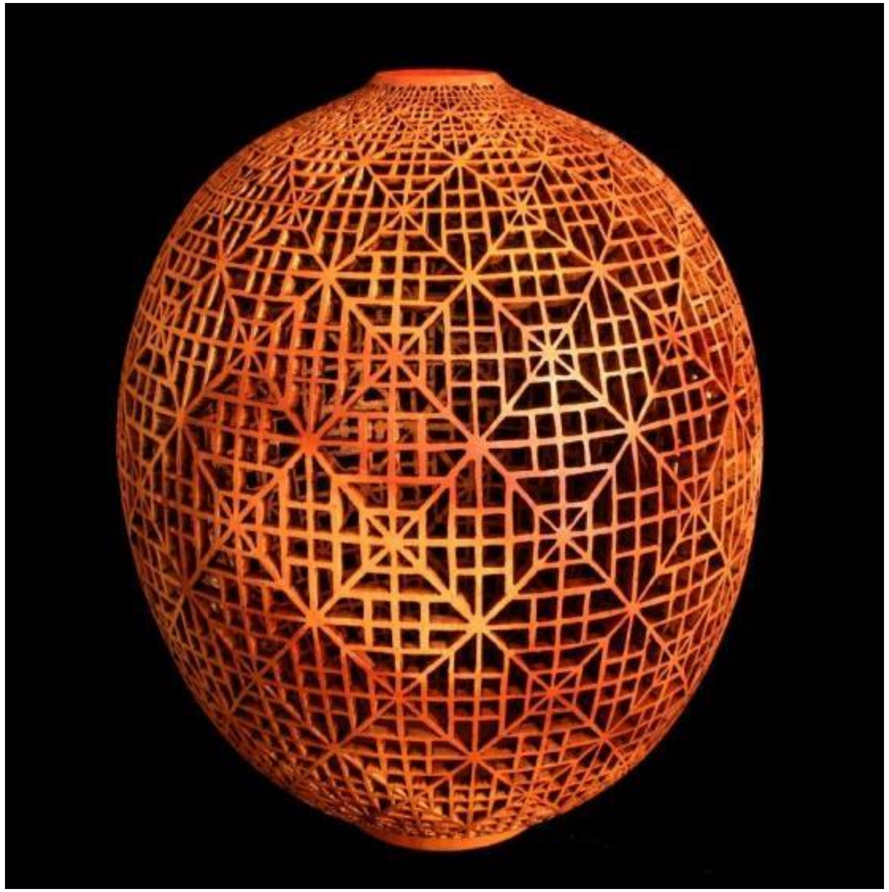
## Lattice

[Pxhere, n.d.]

Minimal space configuration dramatized with patterns of lattice frames of window

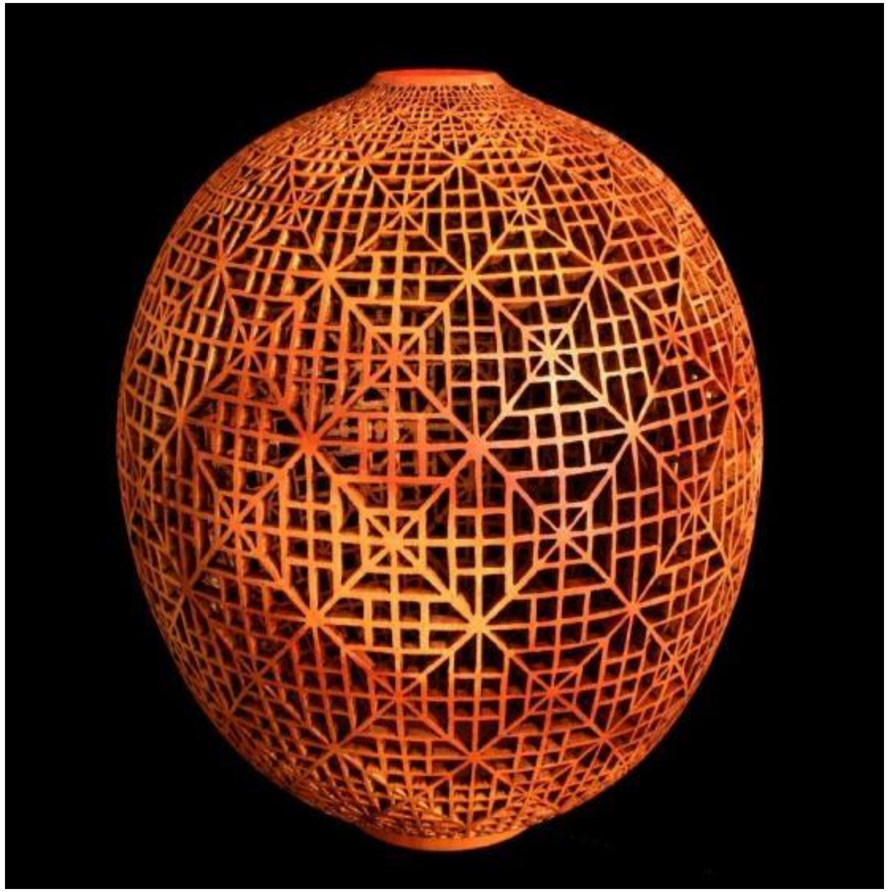
# Key design features

[Fennell, n.d.]



[Fennell, n.d.]

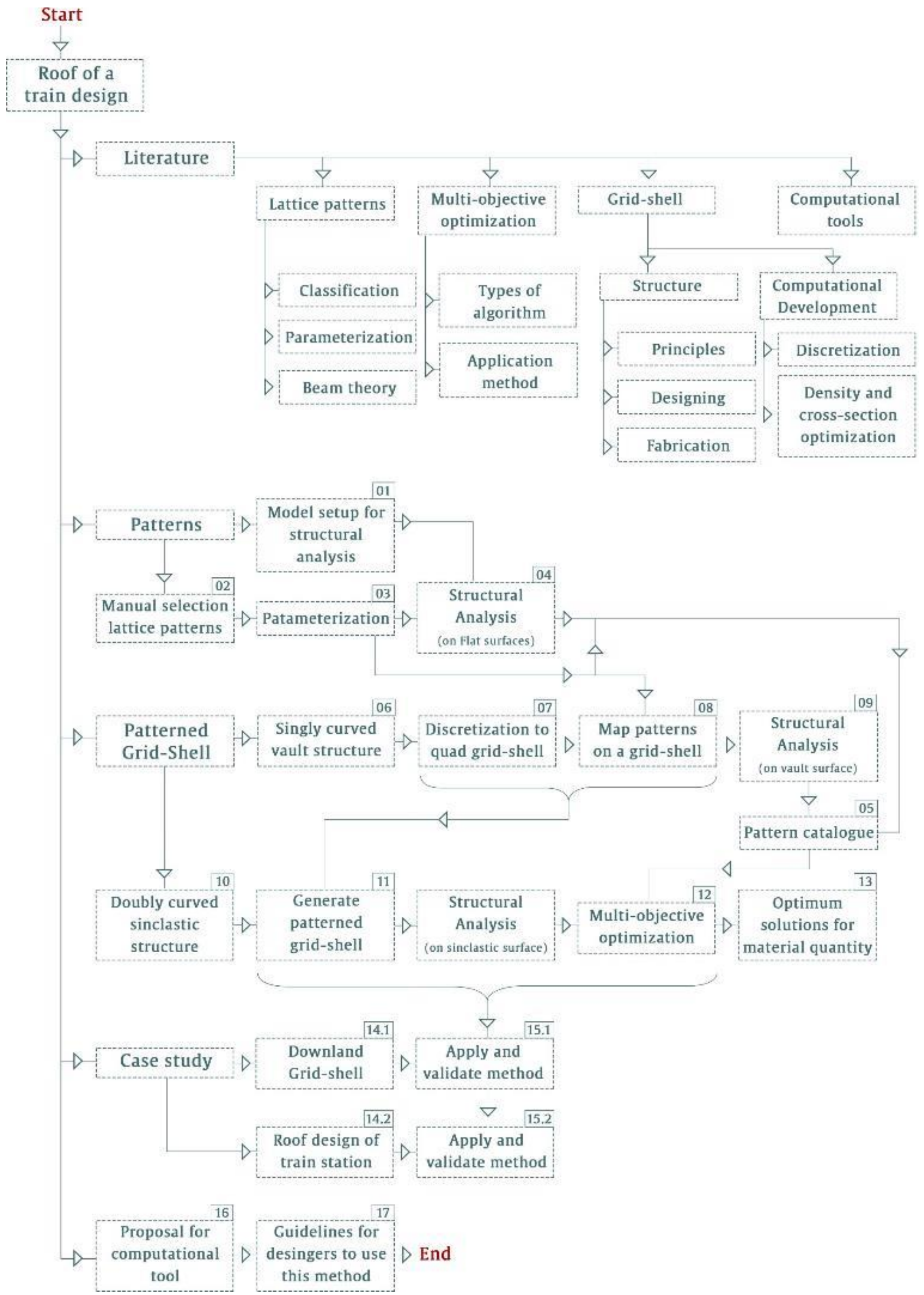
# Inspiration



[Fennell, n.d.]

# Inspiration

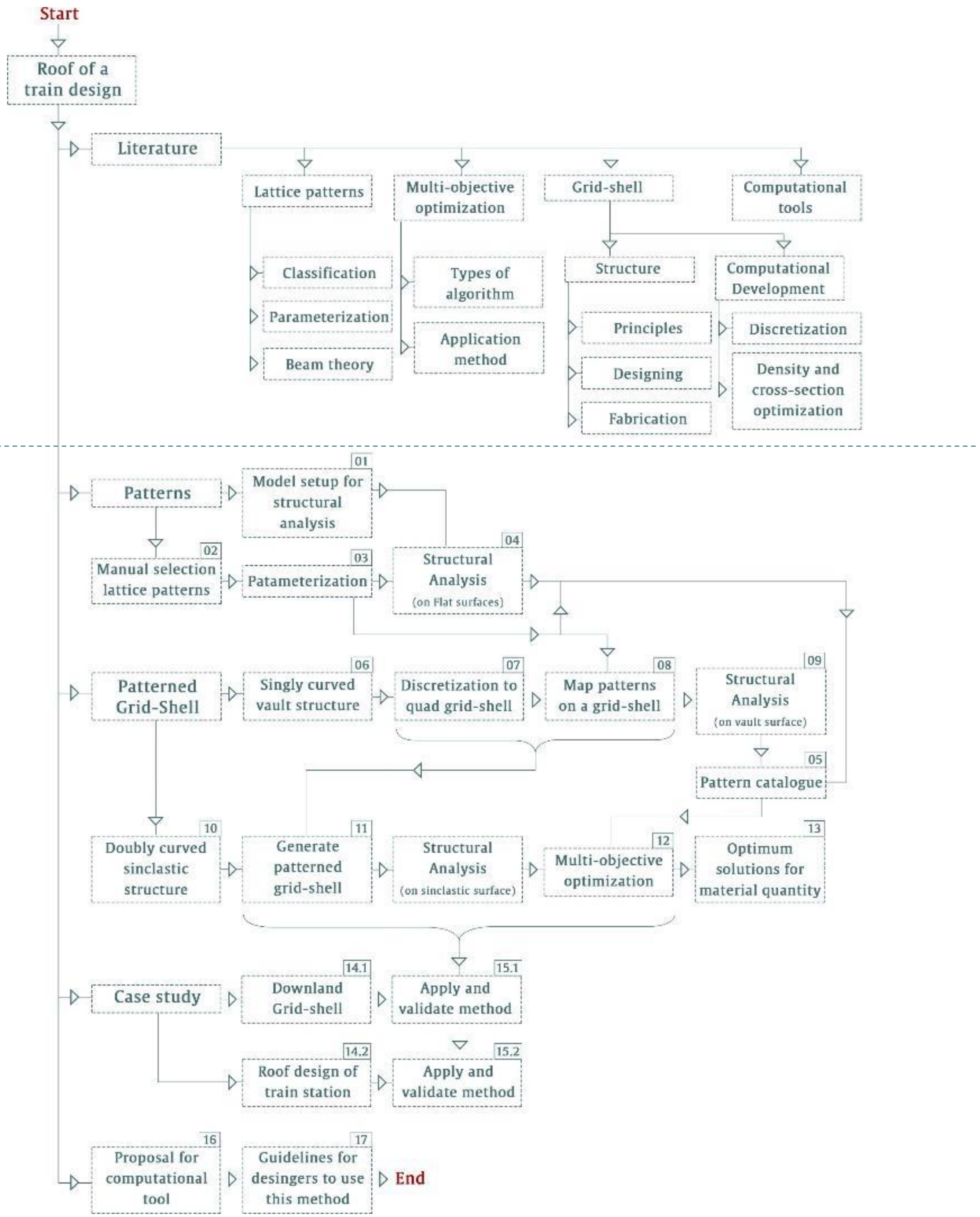
# Graduation plan

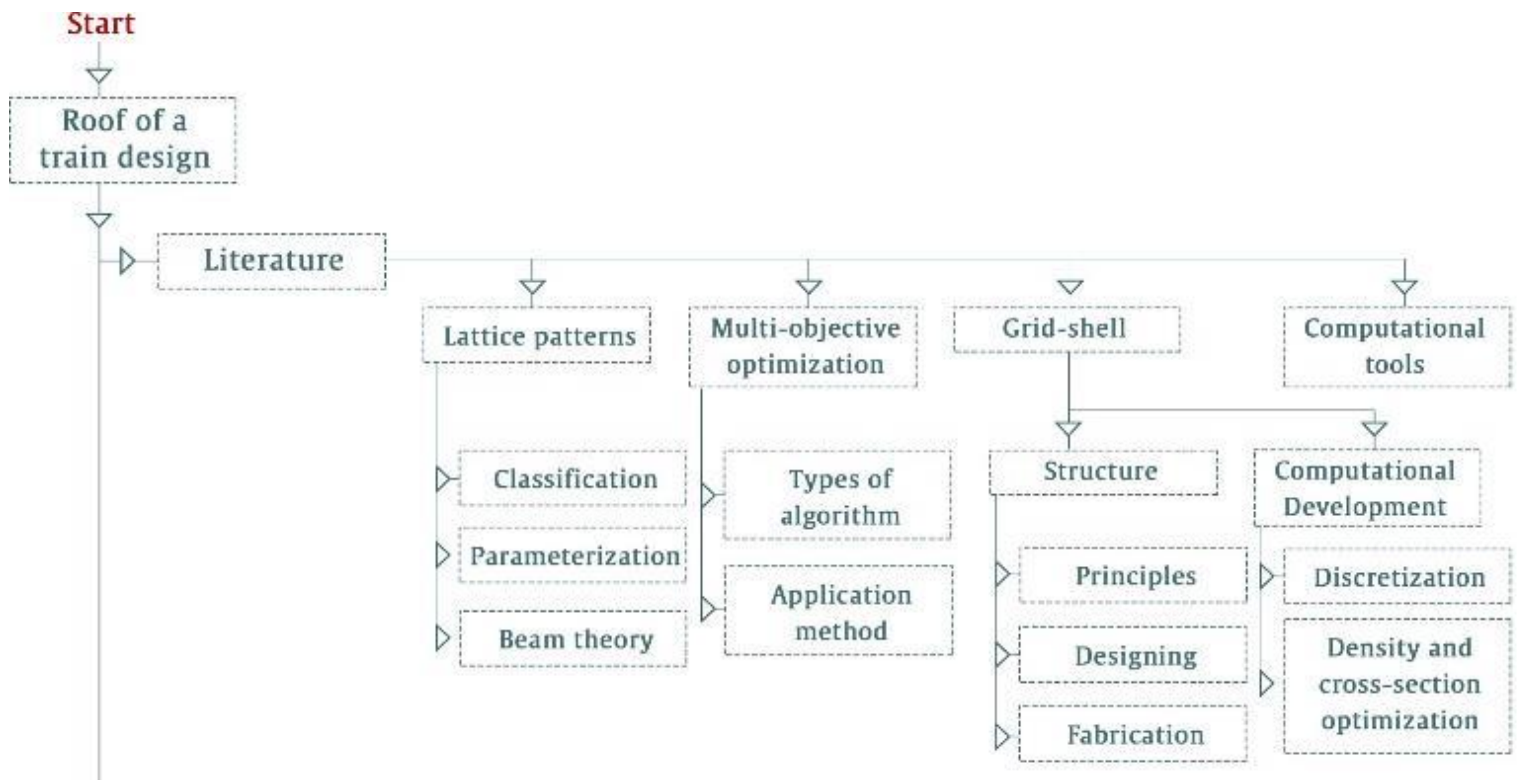


Start
Roof of a train design
Literature
Lattice patterns
Multi-objective optimization
Grid-shell
Computational tools
Classification
Parameterization
Beam theory
Types of algorithm
Application method
Structure
Computational Development
Principles
Designing
Fabrication
Discretization
Density and cross-section optimization
Patterns
01 Model setup for structural analysis
02 Manual selection lattice patterns
03 Patameterization
04 Structural Analysis (on Flat surfaces)
Patterned Grid-Shell
06 Singly curved vault structure
07 Discretization to quad grid-shell
08 Map patterns on a grid-shell
09 Structural Analysis (on vault surface)
05 Pattern catalogue
10 Doubly curved sinclastic structure
11 Generate patterned grid-shell
Structural Analysis (on sinclastic surface)
12 Multi-objective optimization
13 Optimum solutions for material quantity
Case study
14.1 Downland Grid-shell
15.1 Apply and validate method
14.2 Roof design of train station
15.2 Apply and validate method
16 Proposal for computational tool
17 Guidelines for desingers to use this method
End

Literature research

Project Development

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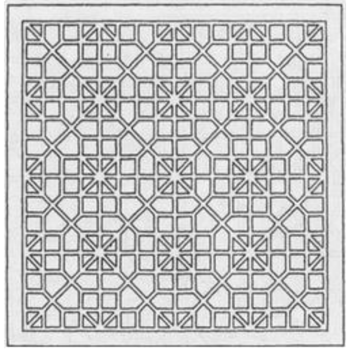
Density and cross-section optimization

## Chinese lattice designs:

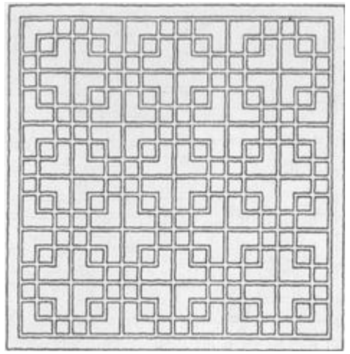
- 3000 years old art
- Evolved in China and North-East Asian plateau
- 300+ patterns collection
- Classified in 26 different types  based on geometry and symbolic values.

B. Octagon (B10a)



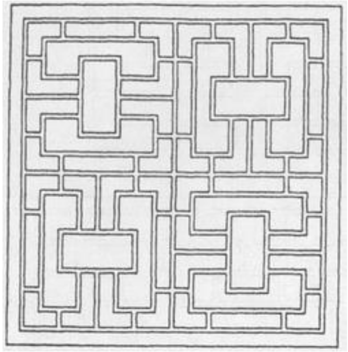
[Dye, 1974]

H. No Focus (H7a)



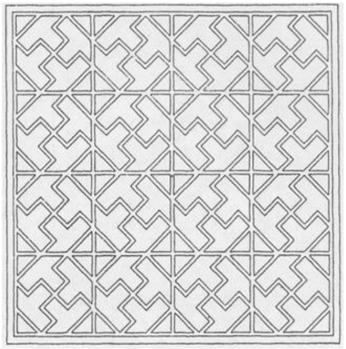
[Dye, 1974]

J. Presentation (J4a)



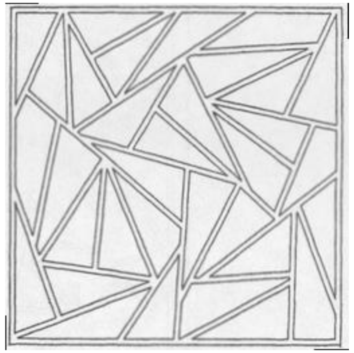
[Dye, 1974]

R. Like Swastika (R11a)



[Dye, 1974]

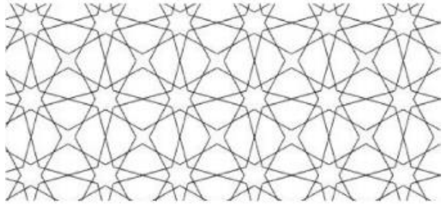
X. Rustic Ice-ray (X6b)



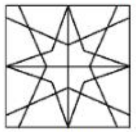
[Dye, 1974]

## Methods of parameterization

### 1. Find the smallest motif



Group of pattern

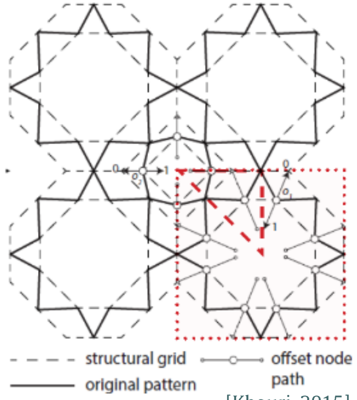


pattern

Base module

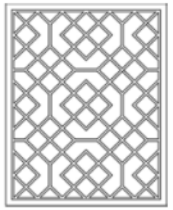
[Yaser Shahbazi, 2017]

### 2. Find variable junctions

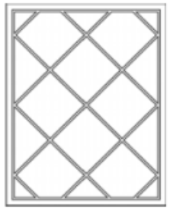



[Khouri, 2015]

### 3. Find the hierarchy of geometry



Lattice frame

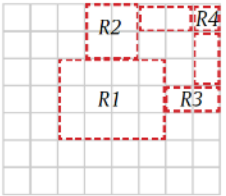


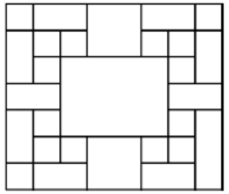
Global pattern

Local pattern

[Wu, 2012]

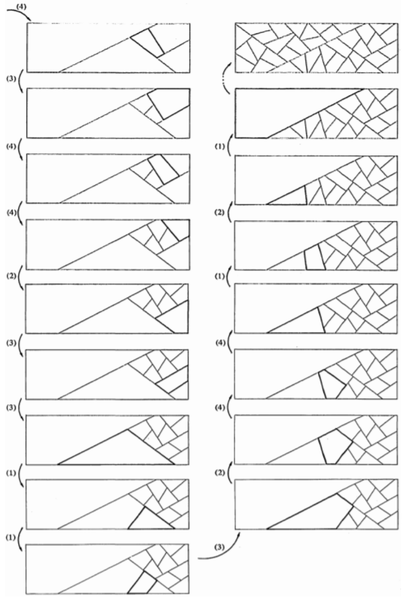
### 4. Find an equation for the proportional area



[Seungmook Kang, 2010]

### 5. Find Shape Grammar

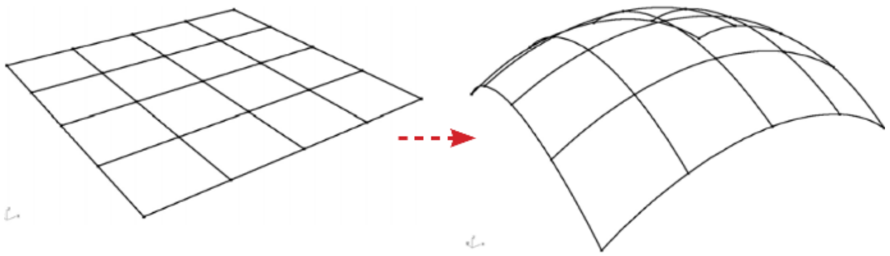


[Stiny, 1977]

## Grid-shell

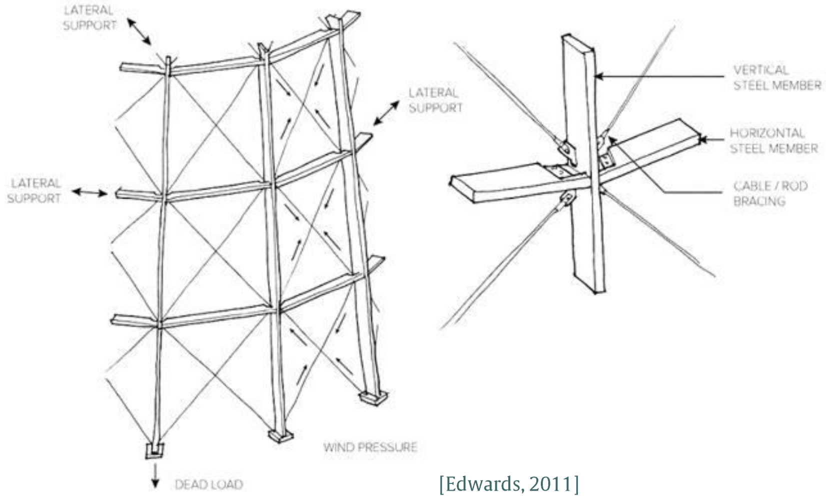
### Types of grid shell:

#### Strained grid-shell



- Bent after making a horizontal grid
- Buckling strength of material is important

#### Unstrained grid-shell

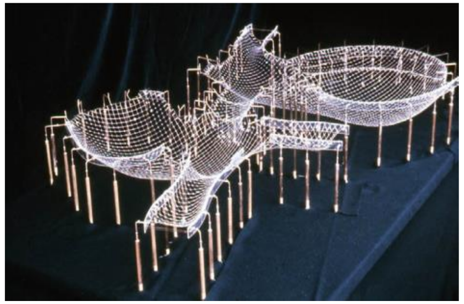



[Edwards, 2011]

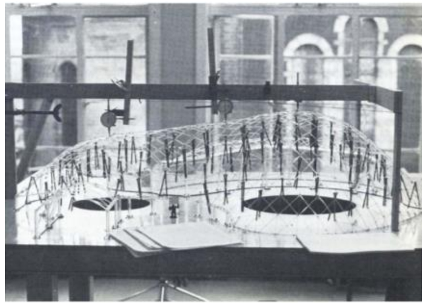
- Pre-bent  members are connected at the required angle
- Moment resistant connection is important

## Designing grid-shell:

### Dynamic Relaxation



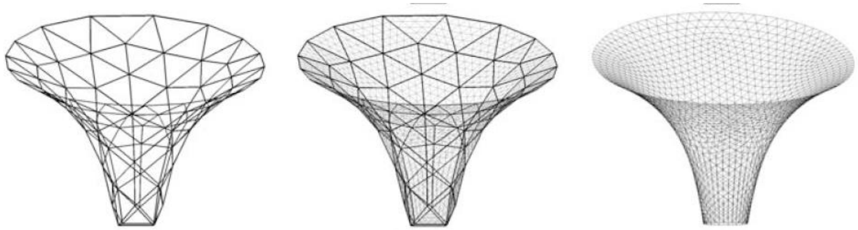
[Liddell, 2015]



[E. Happold, 1975]

- Gives compression only form
- Can be used for various tessellation
- Drawing the specific tessellation for desired shape is prolonged task

### Geometric Approach



[Dimcic, 2011]

- Used for pre-designed form
- Tessellation is drawn in steps asper the requirement of smoothness

## Research questions

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**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

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**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

**Sub-question 1:** *How to assess the structural performance of such line patterns?*

**Sub-question 2:** *How to parameterize such line patterns with static and variable junctions that can be used in a pattern grid for structural analysis?*

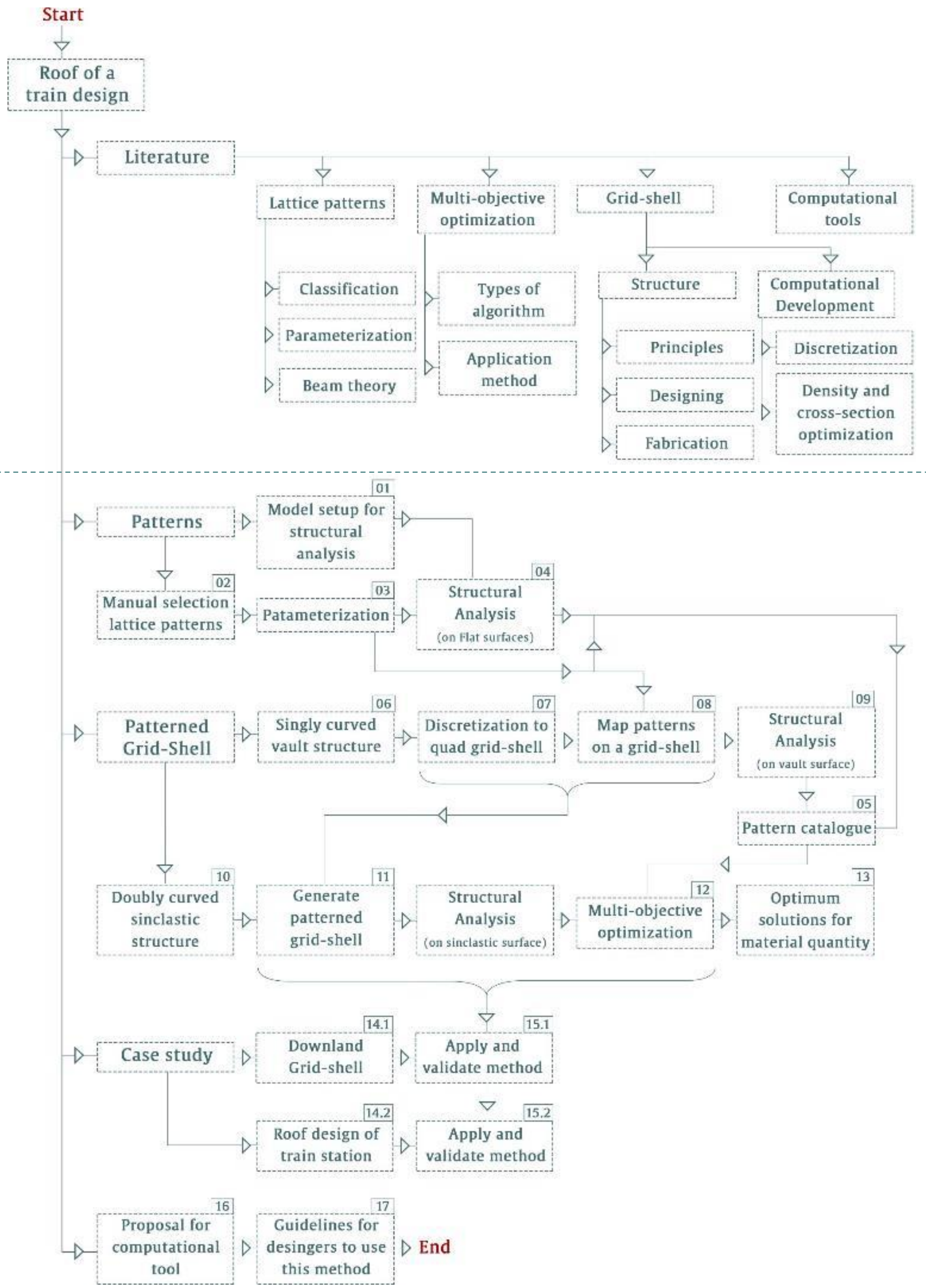
**Sub-question 3:** *In a parametric model, how to apply the patterns on a quadrilateral grid-shell and make a homogeneous grid-shell?*

**Sub-question 4:**

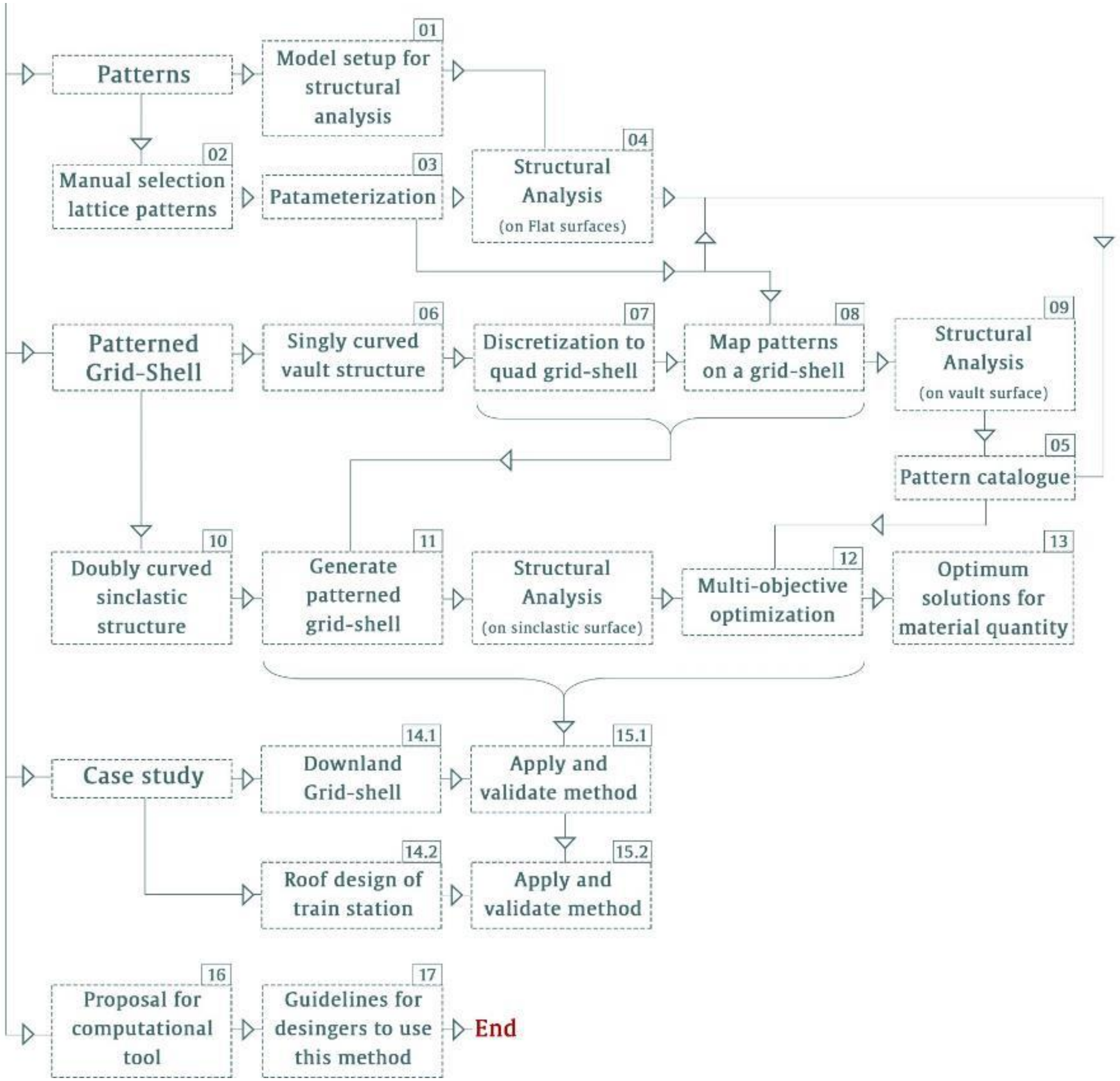
*Using multi-objective optimization, how to find the optimum set of cross-section of a member and density of the mapped pattern for which the grid shell performs similar regular quadrilateral grid shell?*

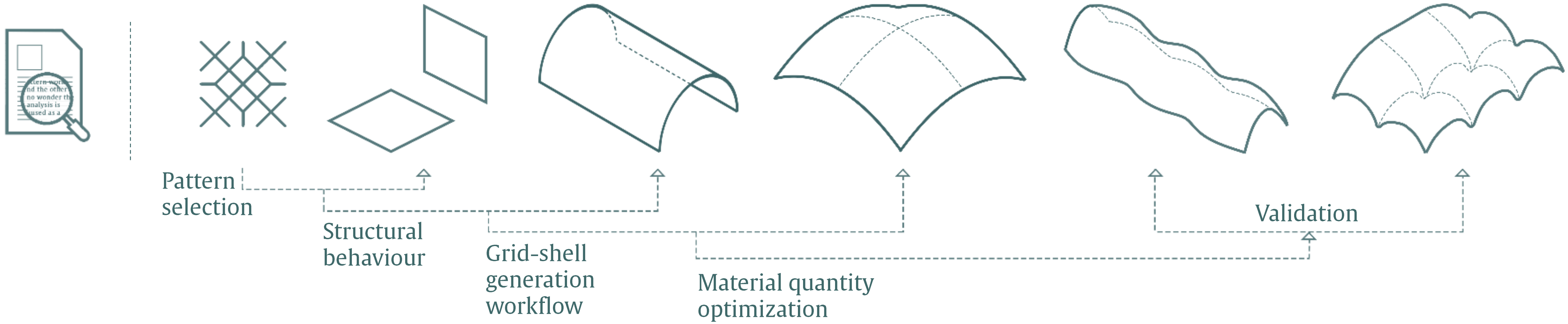
Literature research

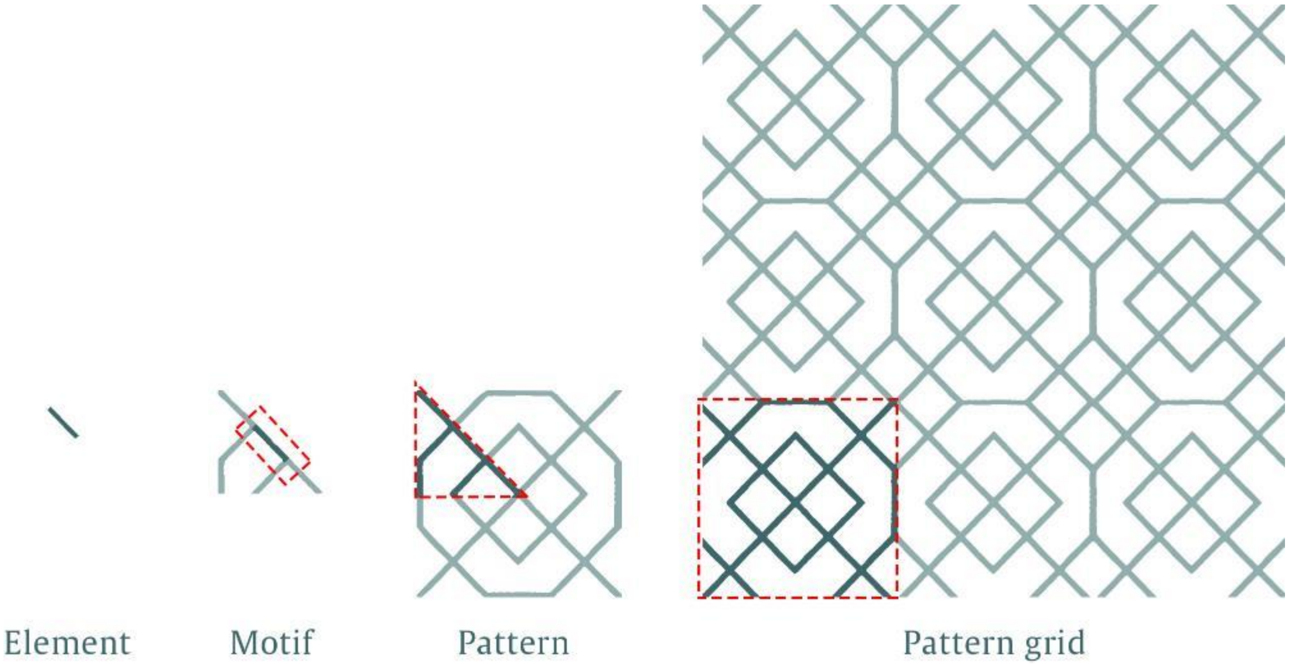
Project Development



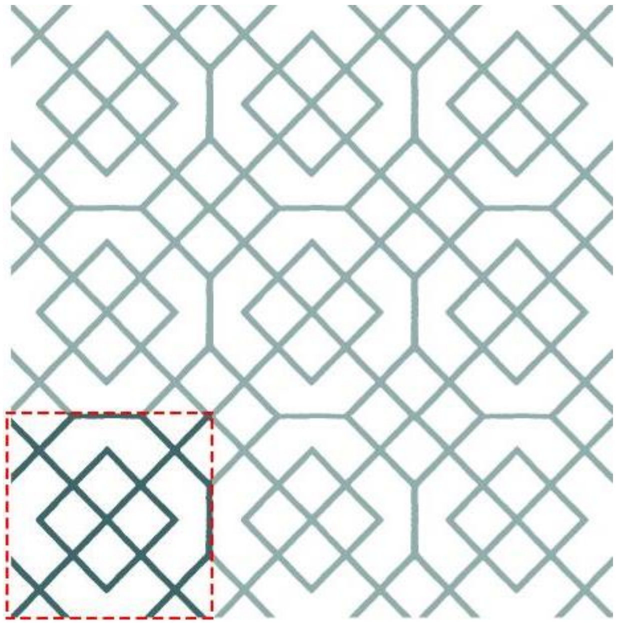
## Project Development




Pattern selection
Structural behaviour
Grid-shell generation workflow
Material quantity optimization
Validation


Element
Motif
Pattern
Pattern grid





**Grid density:**

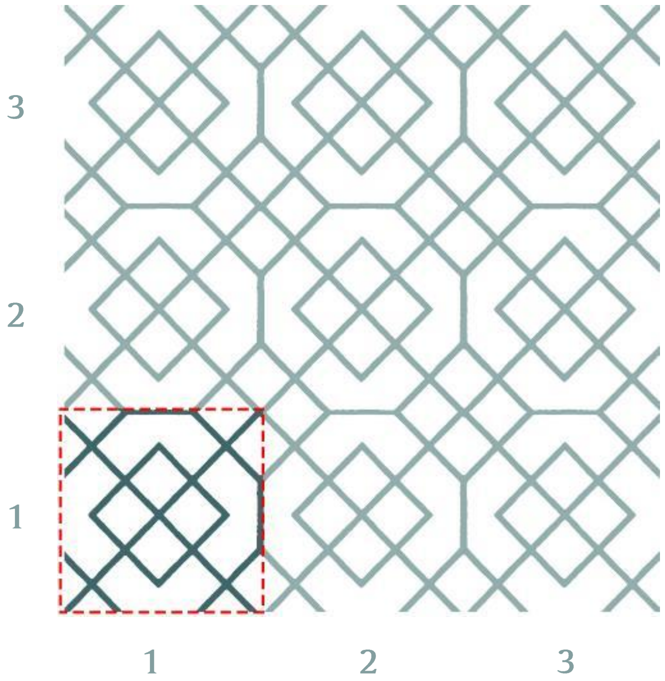
The total length of all the elements in Pattern grid. Higher the grid density better the structural stiffness.

**Grid Factor:**

A number by which the pattern is repeated in X and Y direction. (As the test module is 1m x1m square, the Grid factor is same in both directions).

**Mean Grid Density:**

A pre-decided number of grid density from which the closest possible grid density for each pattern is found.

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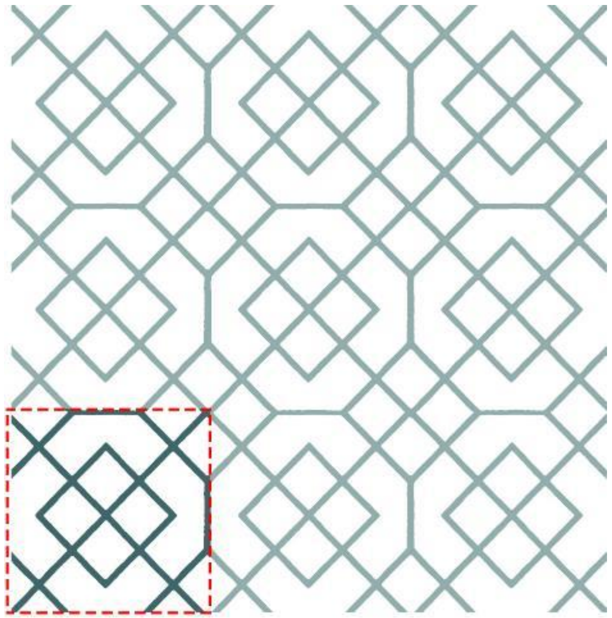

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**Mean Grid Density:**

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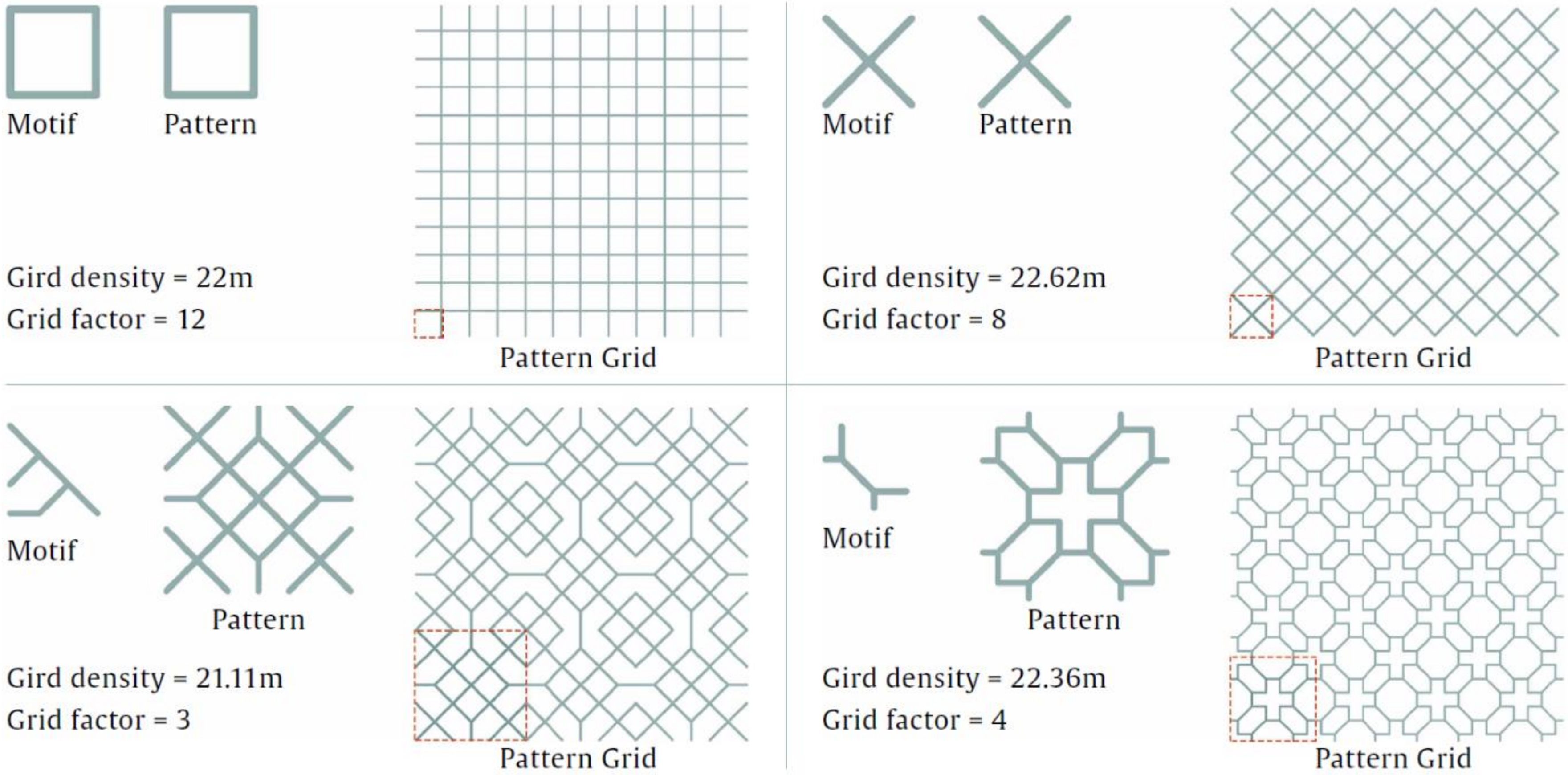
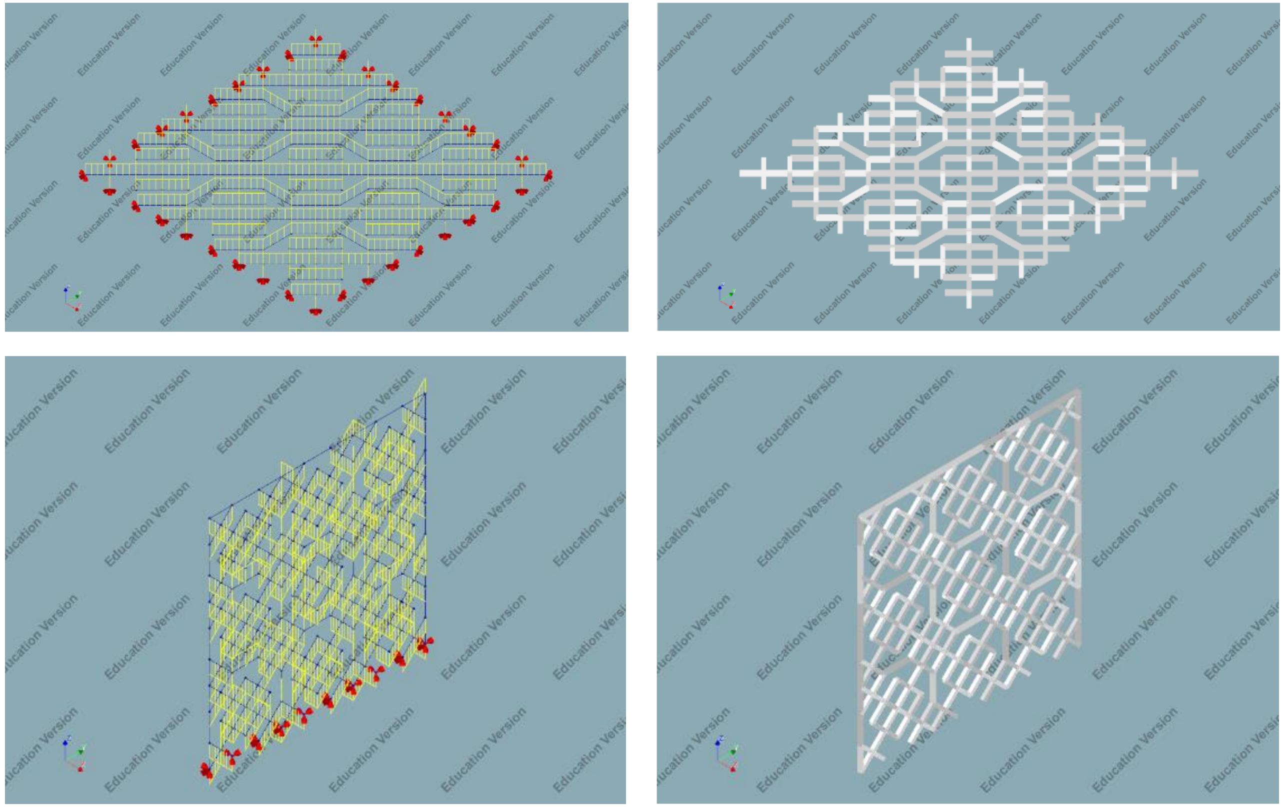
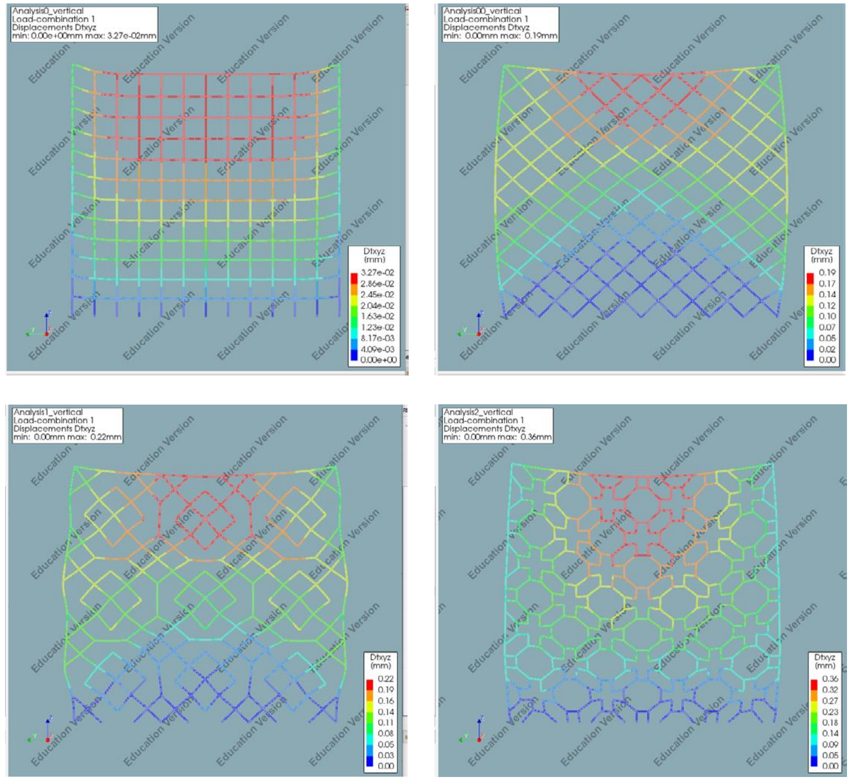
## Mean grid-density = 22m



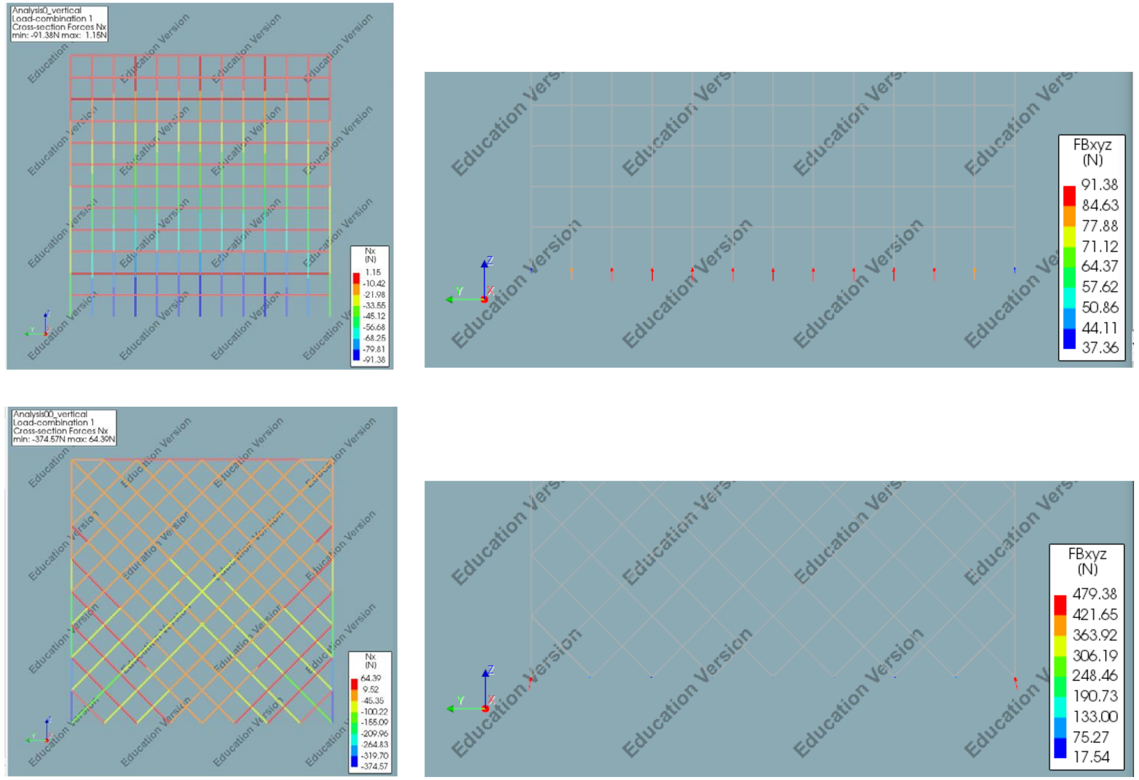
## Diana analysis



## Diana analysis

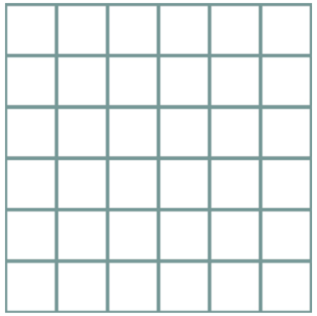


Deformation characteristics



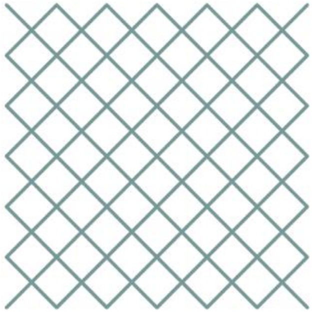

Normal force and reaction force

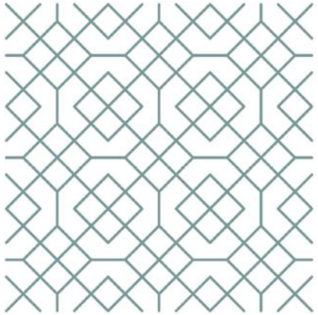
## Diana analysis



| Parallel Grid | Horizontal | Vertical |
|---|---|---|
| Deflection (mm) | 49.07 | 0.038 |
| Max reaction force (N) | 40.7 | 91.38 |
| Max compressive stress (N/mm2) | 31.13 | 0.59 |
| Max tensile stress (N/mm2) | 8.82 | 0.91 |
| Max shear stress (N/mm2) | 9.63 | 0.037 |
| Max banding moment (Nmm) | 5188.49 | 97.97 |
| Max normal force (N) | 40.7 | 91.38 |
| Max shear force (N) | 40.7 | 3.72 |

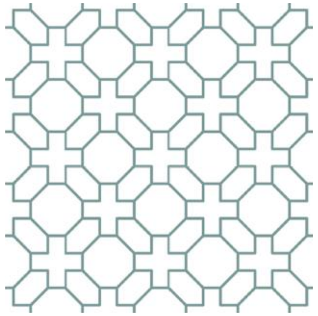
| Diagonal Grid | Horizontal | Vertical |
|---|---|---|
| Deflection (mm) | 34.46 | 0.19 |
| Max reaction force (N) | 74.63 | 479.38 |
| Max compressive stress (N/mm2) | 36.34 | 2.16 |
| Max tensile stress (N/mm2) | 40.49 | 4.32 |
| Max shear stress (N/mm2) | 2.85 | 0.0805 |
| Max banding moment (Nmm) | 6782.19 | 315.14 |
| Max normal force (N) | 78.84 | 374.57 |
| Max shear force (N) | 78.84 | 8.05 |





| B6b | Horizontal | Vertical |
|---|---|---|
| Deflection (mm) | 43.65 | 0.22 |
| Max reaction force (N) | 105.25 | 421.41 |
| Max compressive stress (N/mm2) | 50.1 | 3.96 |
| Max tensile stress (N/mm2) | 47.67 | 4.74 |
| Max shear stress (N/mm2) | 5.9 | 0.19 |
| Max banding moment (Nmm) | 8350.05 | 661.58 |
| Max normal force (N) | 108.79 | 275.57 |
| Max shear force (N) | \|-108.79\| | 18.66 |

| B15a | Horizontal | Vertical |
|---|---|---|
| Deflection (mm) | 57.9 | 0.36 |
| Max reaction force (N) | 72.79 | 287.64 |
| Max compressive stress (N/mm2) | 35.58 | 6.72 |
| Max tensile stress (N/mm2) | 16.12 | 7.03 |
| Max shear stress (N/mm2) | \|-16.18\| | 0.43 |
| Max banding moment (Nmm) | 5929.19 | 1146.04 |
| Max normal force (N) | 72.79 | 287.42 |
| Max shear force (N) | 72.79 | 43.5 |





Out of more than 300 different options 25 patterns are manually selected

**based on the preliminary conclusions of structural analysis.**

## Manual selection of patterns

Out of more than 300 different options **25** patterns are manually selected

**based on the preliminary conclusions of structural analysis.**

Conclusions ▷ 12 characteristics

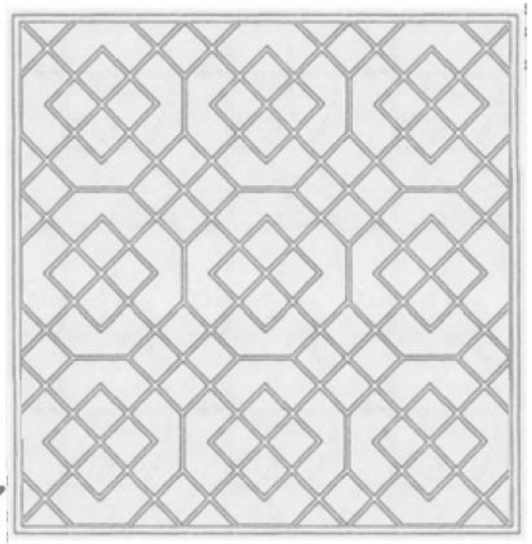
## Manual selection of patterns

Out of more than 300 different options **25** patterns are manually selected

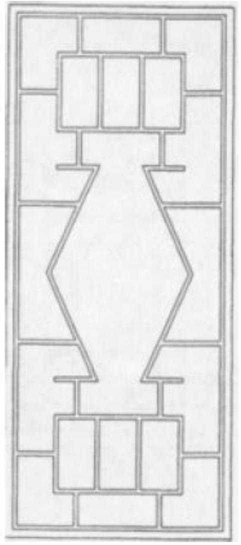
**based on the preliminary conclusions of structural analysis.**

Conclusions ▷ 12 characteristics

- Continuity in lattice grid



[Dye, 1974]



[Dye, 1974]

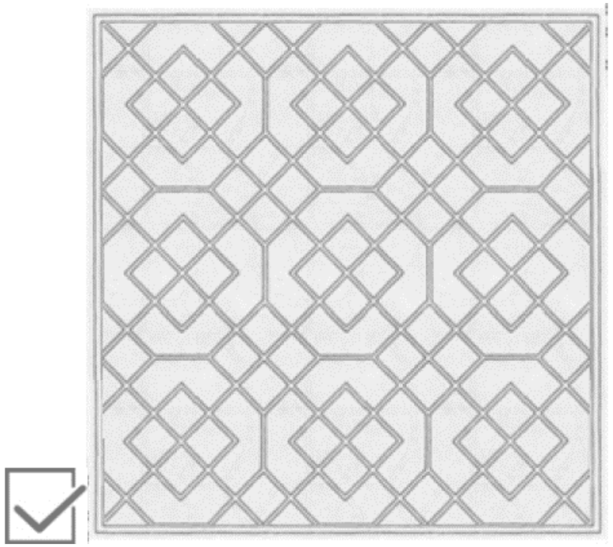
## Manual selection of patterns

Out of more than 300 different options **25** patterns are manually selected

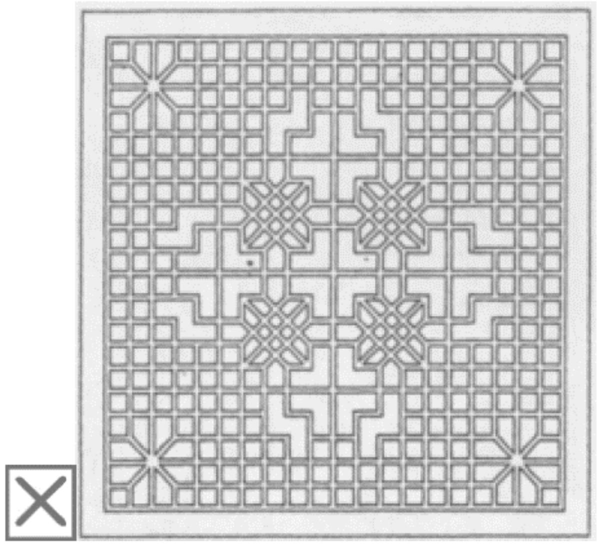
**based on the preliminary conclusions of structural analysis.**

Conclusions ▷ 12 characteristics

- Similar grid densities



[Dye, 1974]



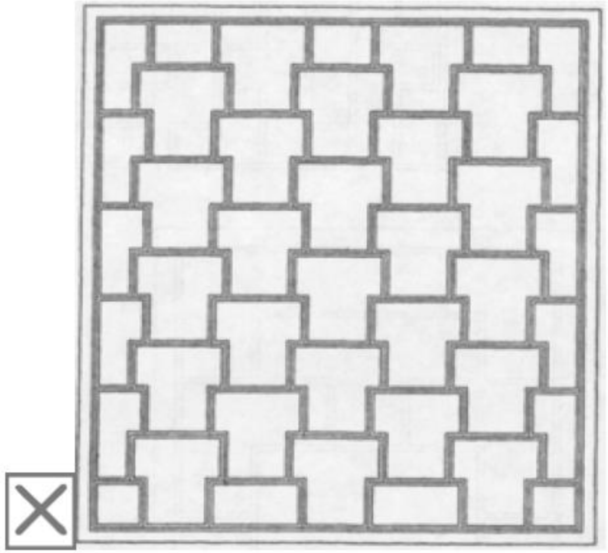
[Dye, 1974]

Out of more than 300 different options 25 patterns are manually selected

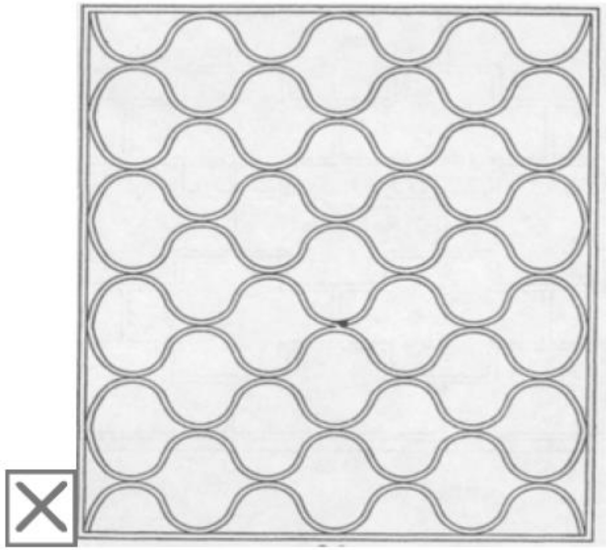
**based on the preliminary conclusions of structural analysis.**

Conclusions ▷ 12 characteristics

- Select unique native design



[Dye, 1974]



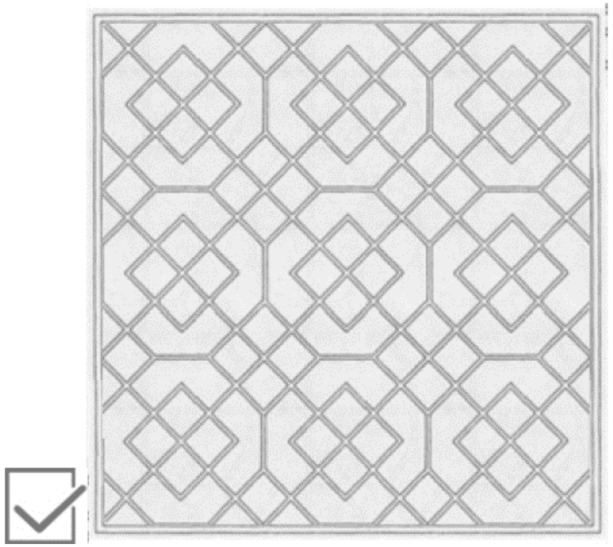
[Dye, 1974]

Out of more than 300 different options **25** patterns are manually selected

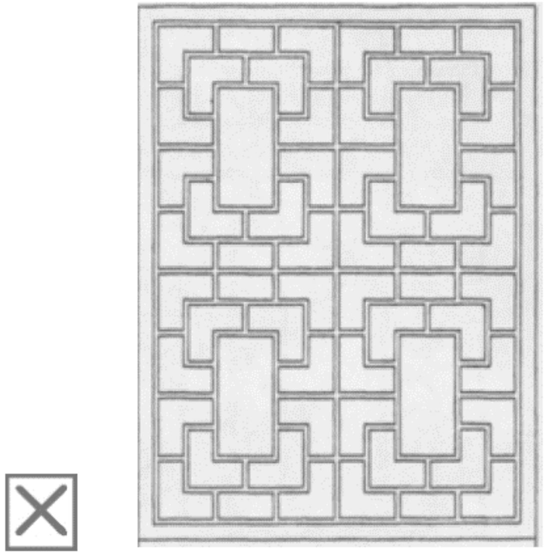
**based on the preliminary conclusions of structural analysis.**

Conclusions ▷ 12 characteristics

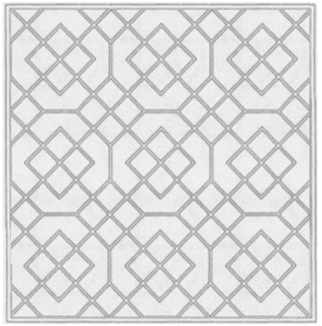
- Pattern which has same geometric configuration from all four sides



[Dye, 1974]

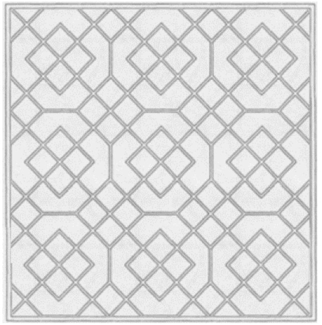


[Dye, 1974]

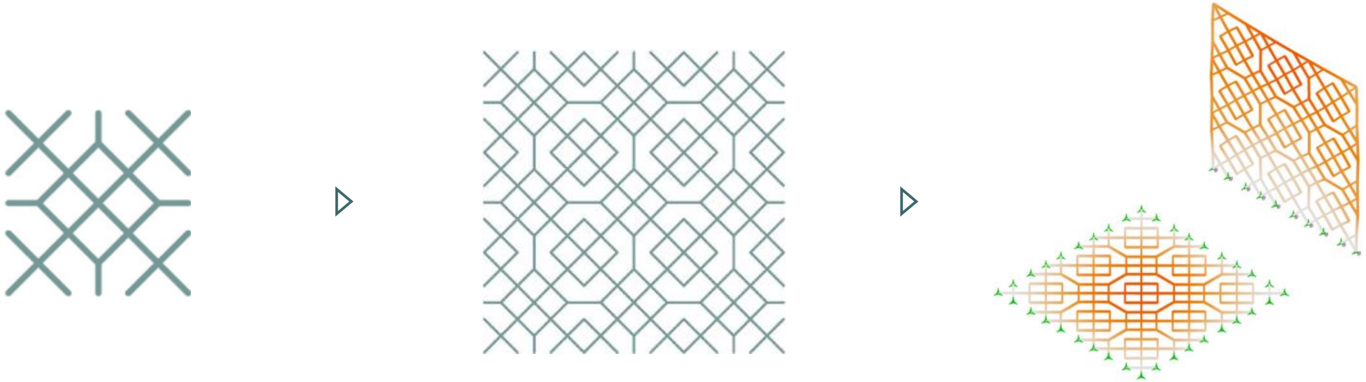


[Dye, 1974]

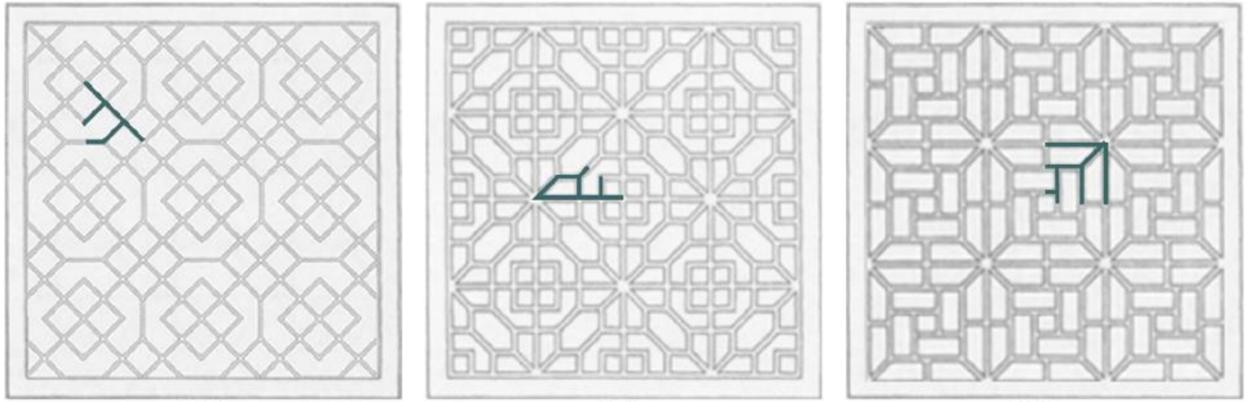
# Parametric workflow



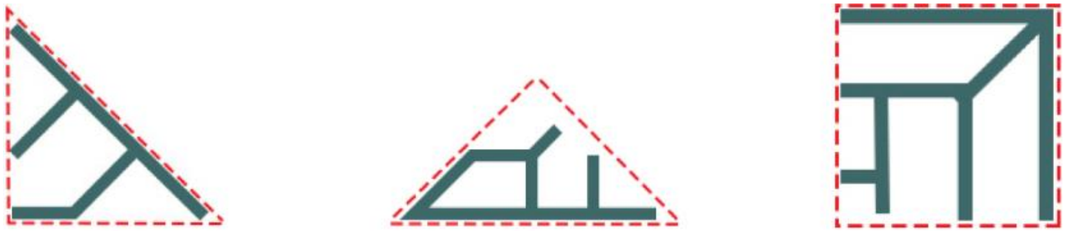
[Dye, 1974]



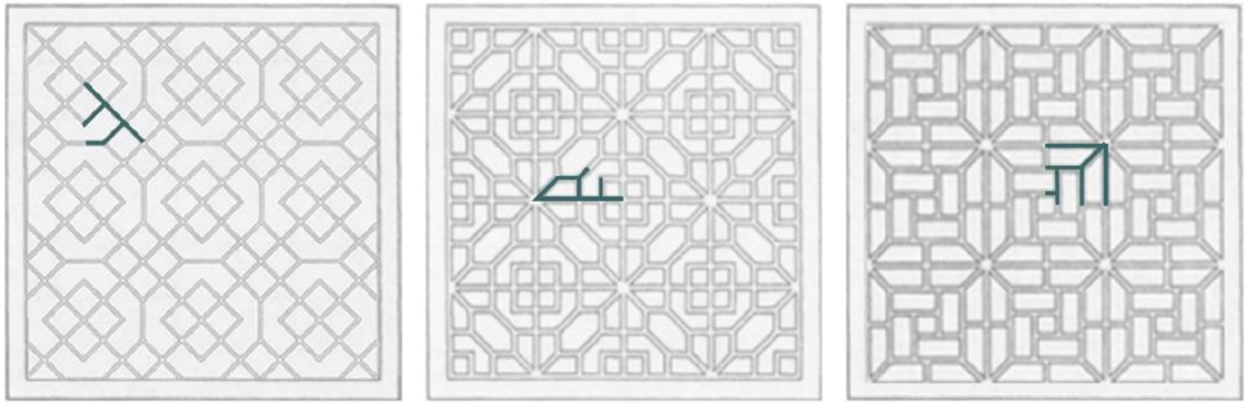
Parameterization → Pattern Grid Arrangement → Setup for Structural Simulation



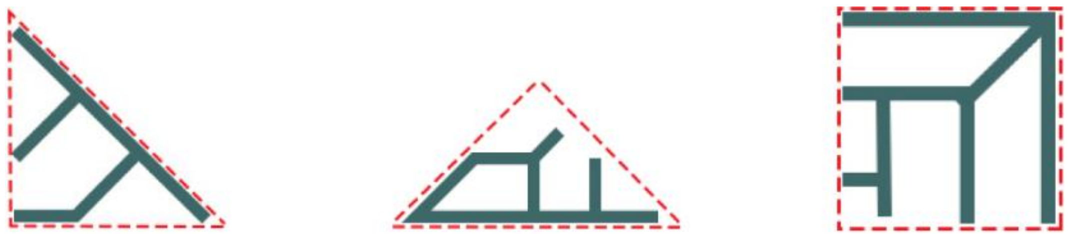
(1) (2) (3)



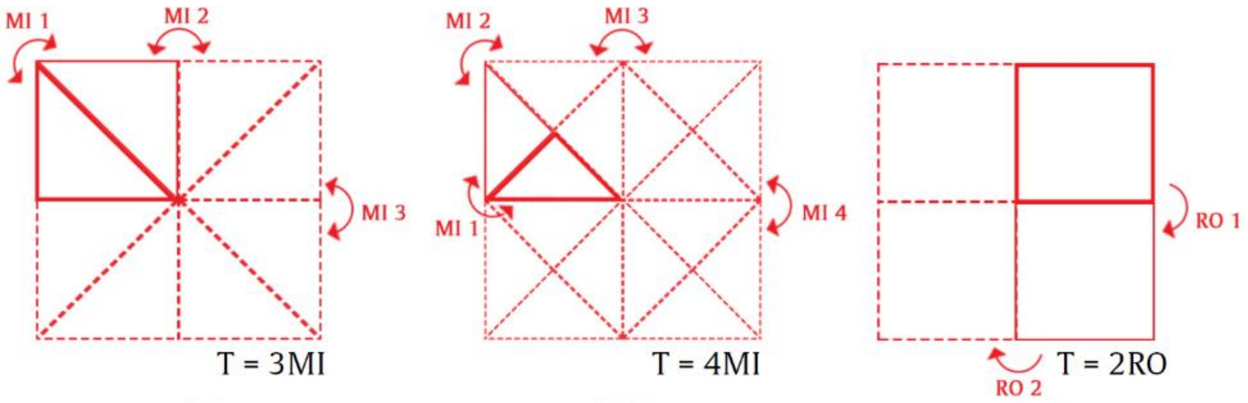
(1) (2) (3)



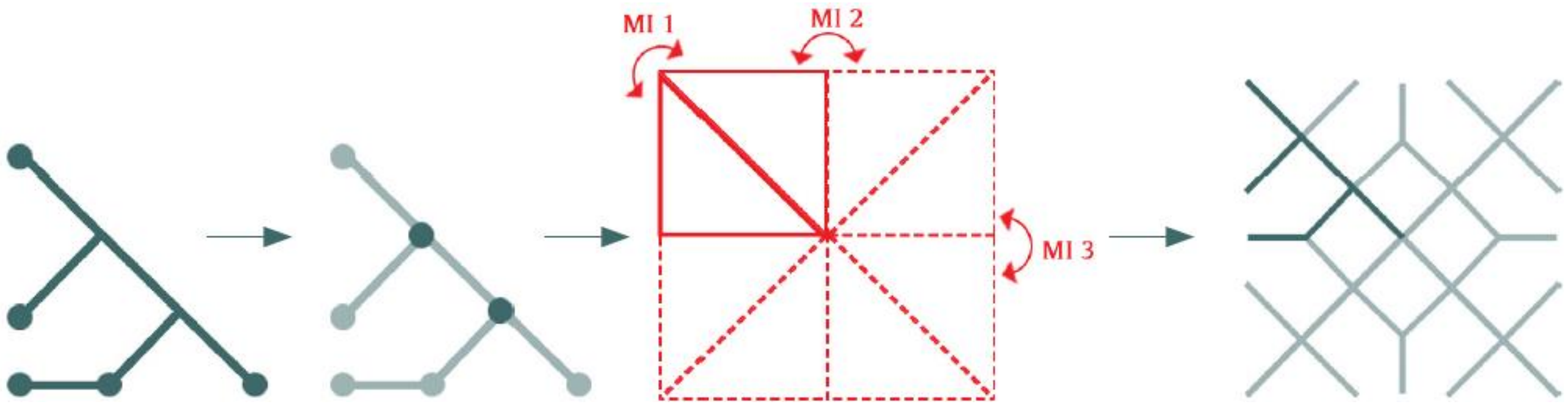
(1) (2) (3)

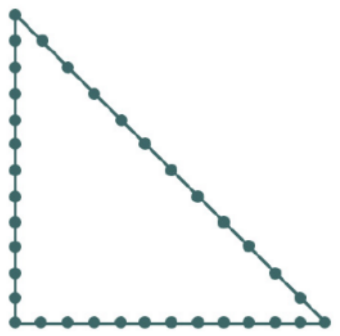


(1) (2) (3)

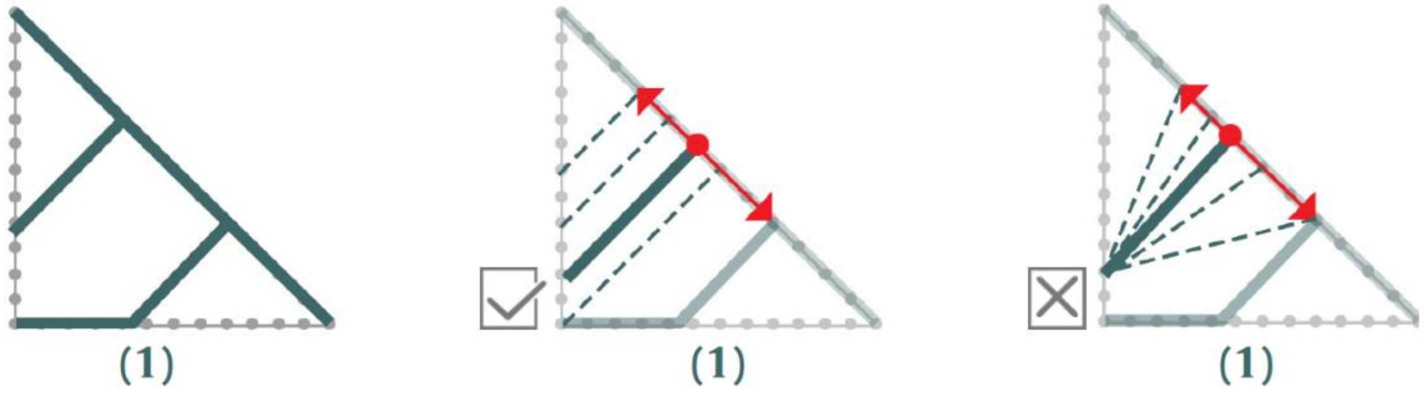


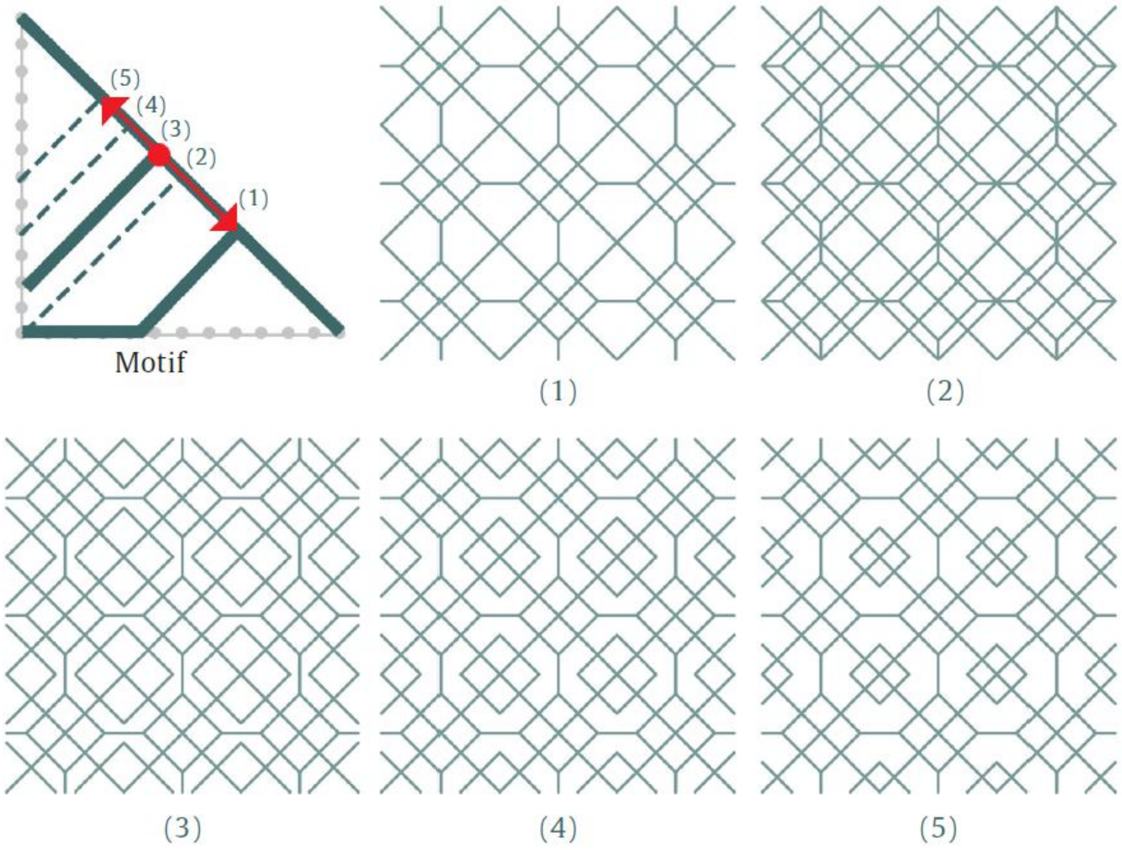

(1) (2) (3)


MI 1
MI 2
MI 3



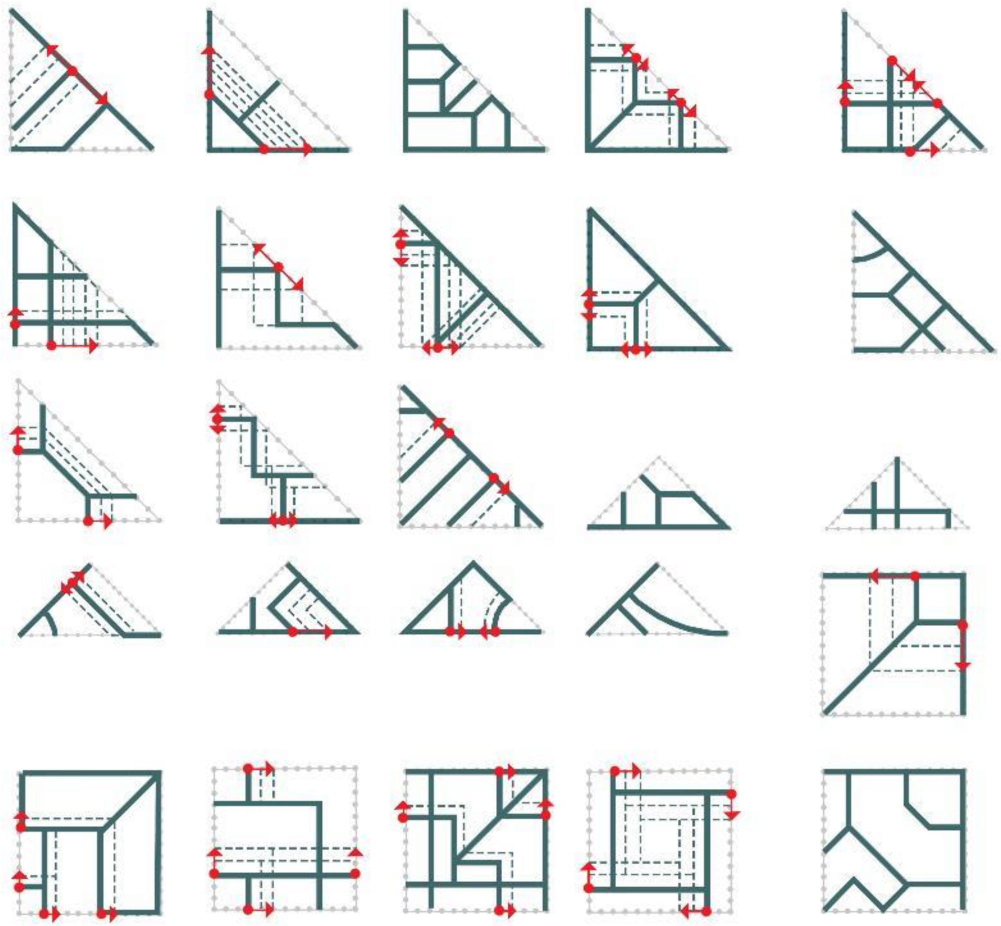



(1)
(1)
(1)

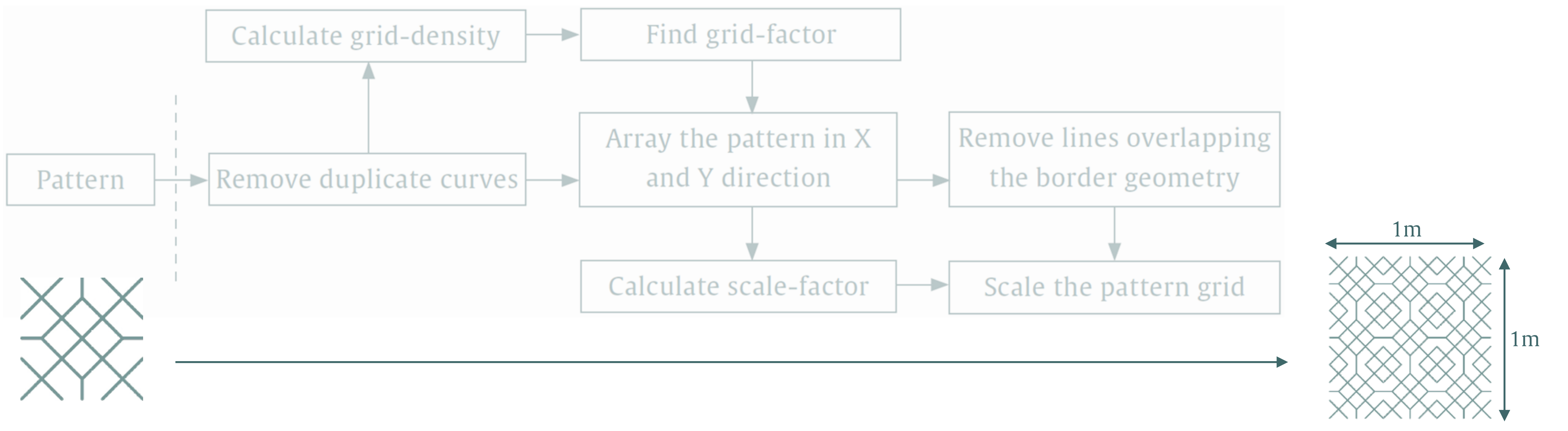

(5)
(4)
(3)
(2)
(1)
Motif
(1)
(2)
(3)
(4)
(5)



Likewise out of **25** selected patterns, **81** options are generated

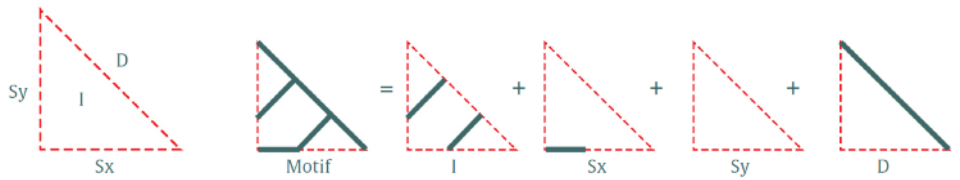




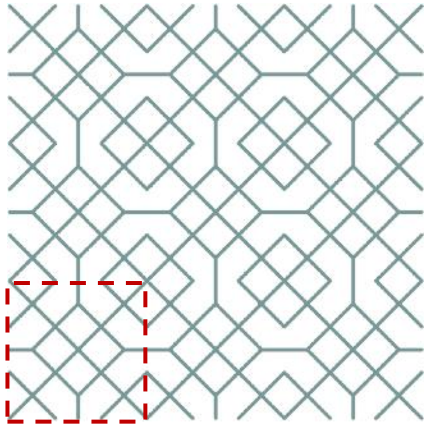



**Mean grid density = 22m**

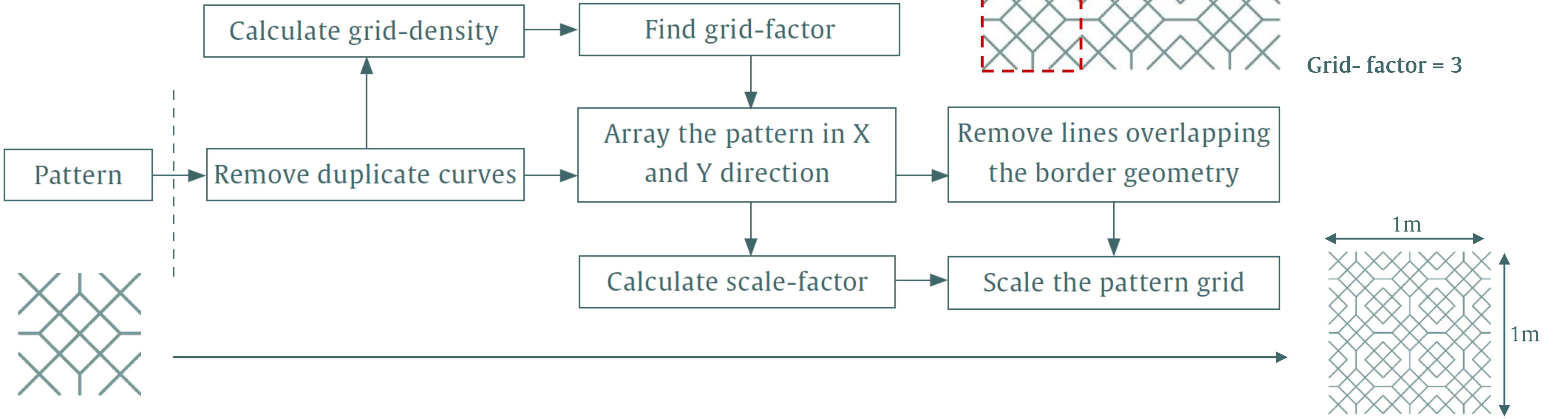
## Pattern grid-arrangement




$$\text{Grid density} = \frac{8n^2 I}{2} + \frac{8n^2(D + Sx)}{2} + \frac{8n^2 Sy - 4(2n)}{2}$$

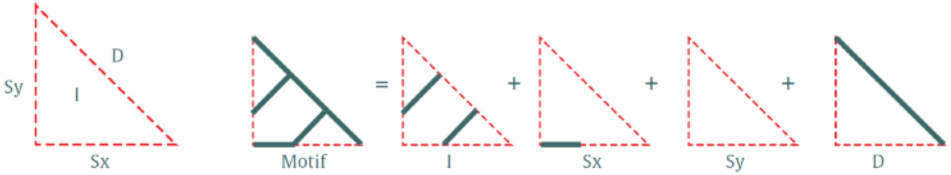


Grid- factor = 3

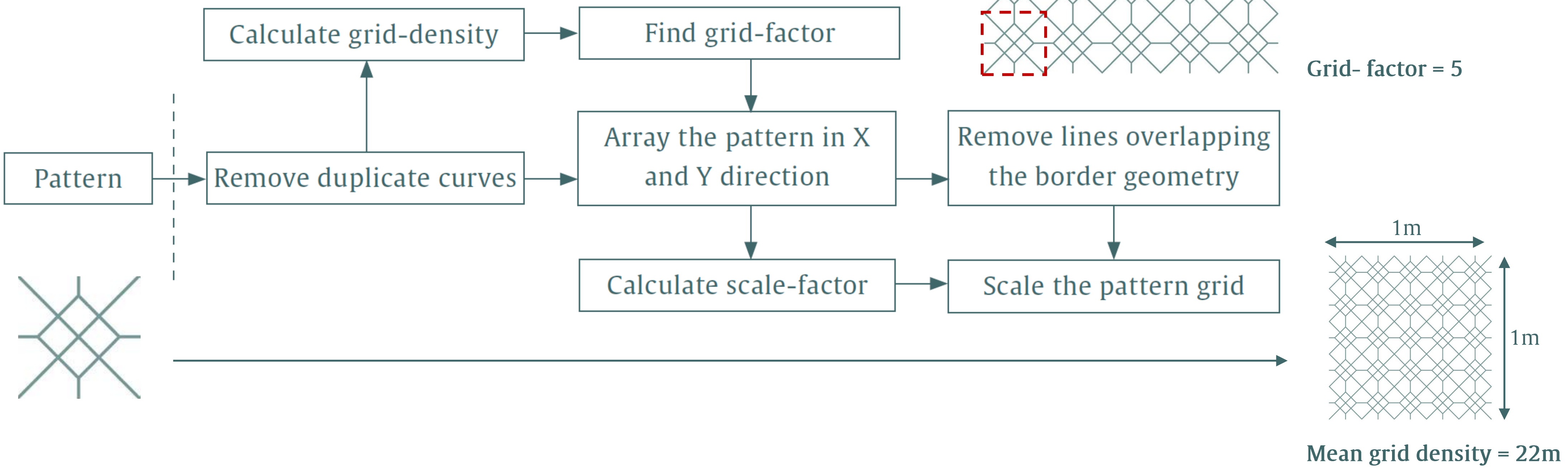


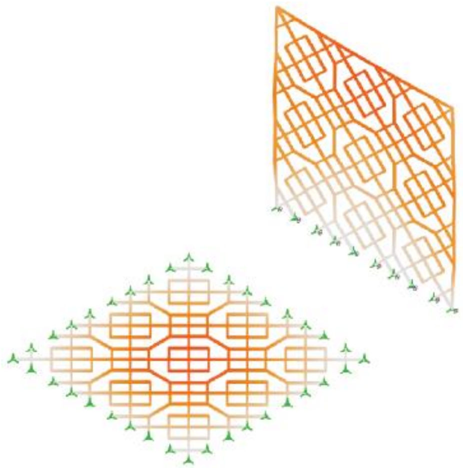

Mean grid density = 22m

## Pattern grid-arrangement

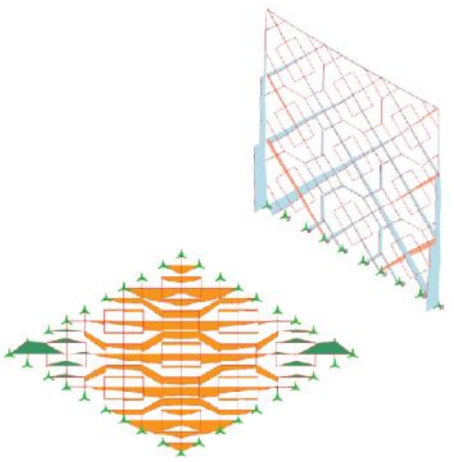



$$\text{Grid density} = \frac{8n^2 I}{2} + \frac{8n^2(D + Sx)}{2} + \frac{8n^2 Sy - 4(2n)}{2}$$





Deformation



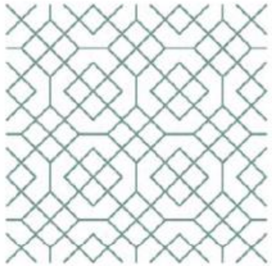
Bending moment My in horizontal orientation and normal force Nx in vertical orientation



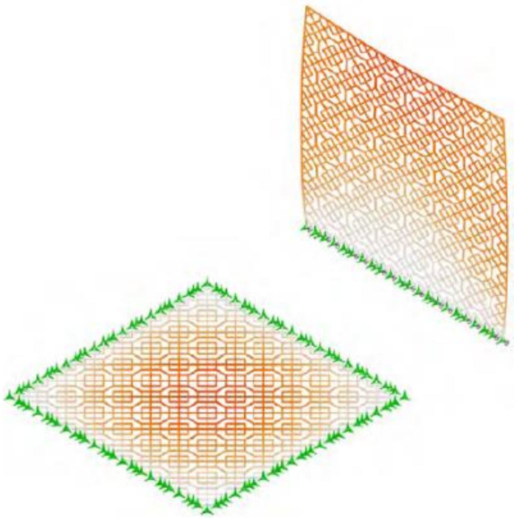
## Example 1 (B6b_4)

Motif

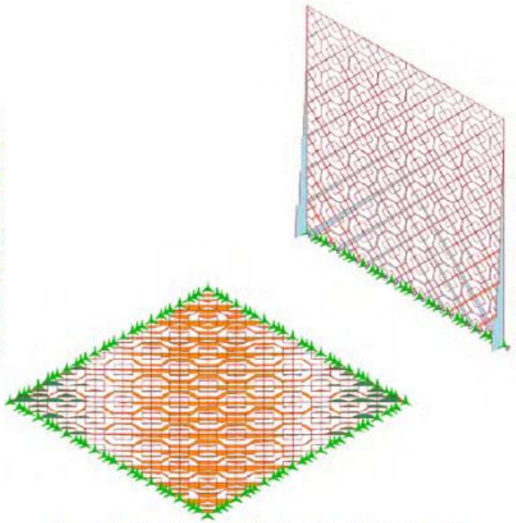
Pattern



Pattern Grid



Deformation in vertical and horizontal orientation

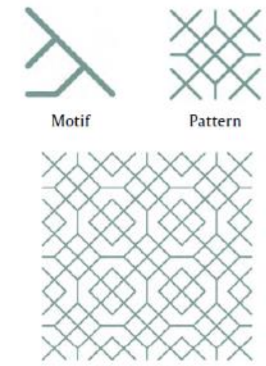


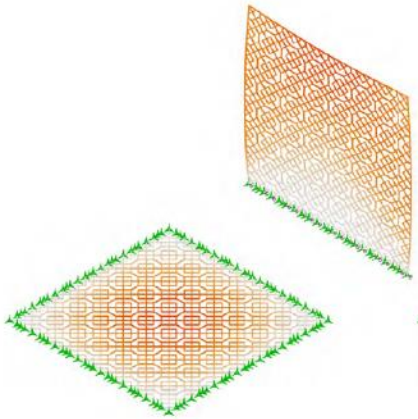
Normal force in vertical and bending moment in horizontal orientation

| | | |
|---|---|---|
| Transformation | 3MI | |
| Grid Density | 50.8643 | -2.0357 |
| Grid Factor | 7 | |

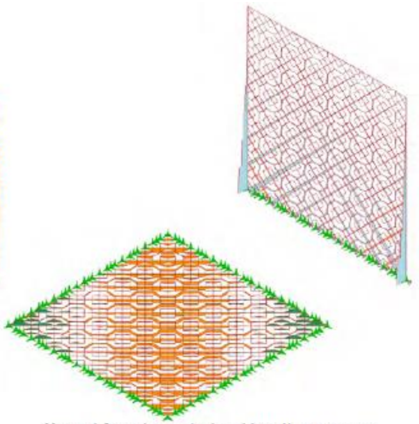
| | Horizontal | | Vertical | |
|---|---|---|---|---|
| | Value | % Difference | Value | % Difference |
| Deflection (mm) | 71.57 | -11.04 | 0.18 | 80.01 |
| Avg Max Axial Stress (MPa) | 20.74 | 13.08 | 0.73 | 70.71 |
| Avg Min Axial Stress (MPa) | -20.74 | 13.08 | -1.14 | 48.28 |
| Avg Normal Force (N) | - | - | -10.36 | 19.79 |
| Avg Bending Moment (Nmm) | 1,221.10 | 7.32 | 54.50 | 56.31 |
| Avg Shear Force (N) | 13.62 | 21.60 | 3.22 | 42.06 |
| Avg Utilizatio Ratio | 0.35 | 13.08 | 0.02 | 48.28 |

## Example 1 (B6b_4)



Deformation in vertical and horizontal orientation

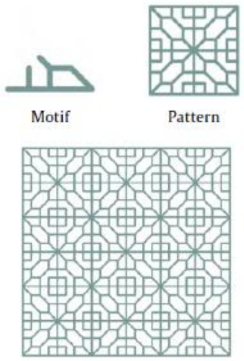


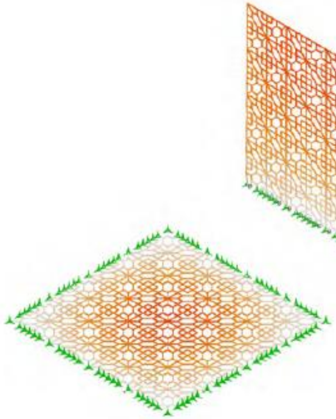
Normal force in vertical and bending moment in horizontal orientation

| | | |
|---|---|---|
| Transformation | 3MI | |
| Grid Density | 50.8643 | -2.0357 |
| Grid Factor | 7 | |

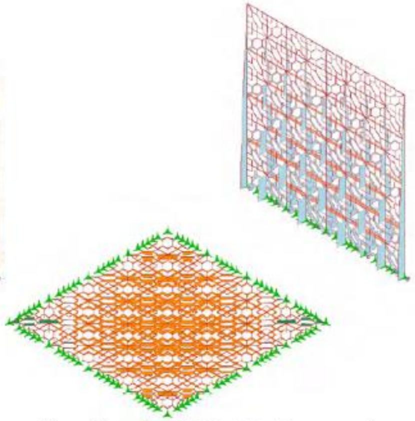
| | Horizontal | | Vertical | |
|---|---|---|---|---|
| | Value | % Difference | Value | % Difference |
| Deflection (mm) | 71.57 | -11.04 | 0.18 | 80.01 |
| Avg Max Axial Stress (MPa) | 20.74 | 13.08 | 0.73 | 70.71 |
| Avg Min Axial Stress (MPa) | -20.74 | 13.08 | -1.14 | 48.28 |
| Avg Normal Force (N) | - | - | -10.36 | 19.79 |
| Avg Bending Moment (Nmm) | 1,221.10 | 7.32 | 54.50 | 56.31 |
| Avg Shear Force (N) | 13.62 | 21.60 | 3.22 | 42.06 |
| Avg Utilizatio Ratio | 0.35 | 13.08 | 0.02 | 48.28 |

## Example 2 (B14a_1)



Deformation in vertical and horizontal orientation

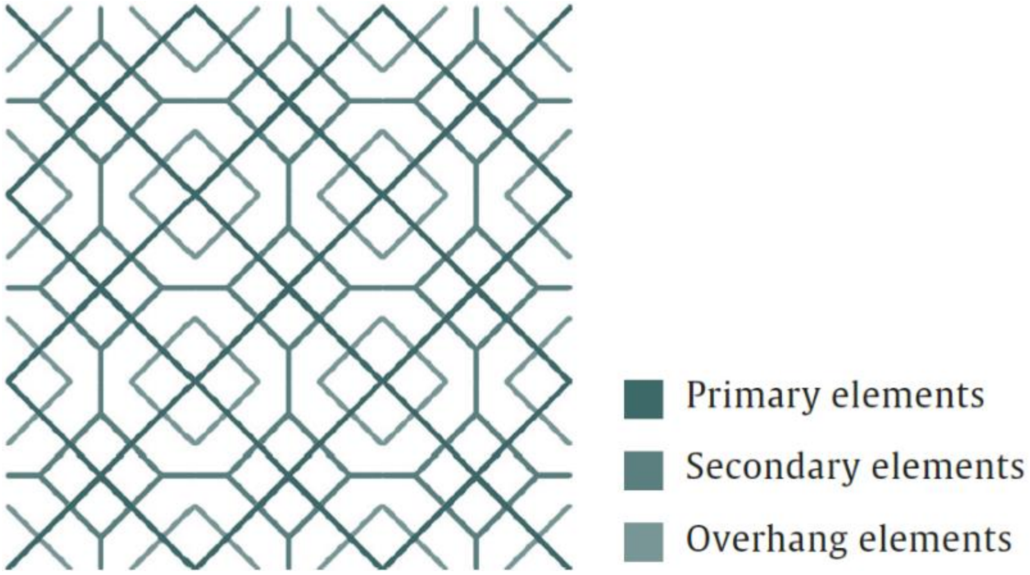


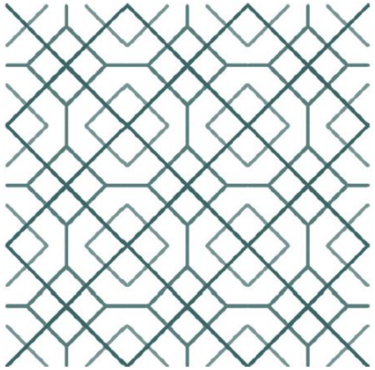
Normal force in vertical and bending moment in horizontal orientation

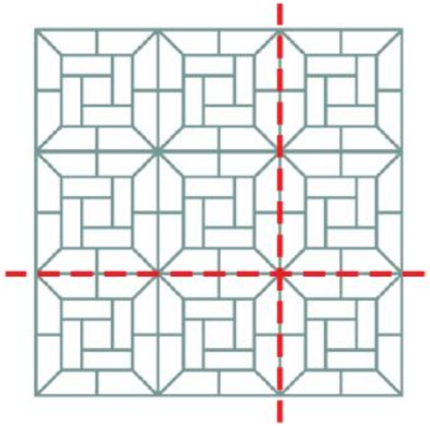
| | | |
|---|---|---|
| Transformation | 4MI | |
| Grid Density | 49.3137 | -3.5863 |
| Grid Factor | 4 | |

| | Horizontal | | Vertical | |
|---|---|---|---|---|
| | Value | % Difference | Value | % Difference |
| Deflection (mm) | 80.64 | 0.23 | 0.05 | -44.85 |
| Avg Max Axial Stress (MPa) | 17.93 | -2.28 | 0.15 | -65.91 |
| Avg Min Axial Stress (MPa) | -17.93 | -2.28 | -0.51 | -34.18 |
| Avg Normal Force (N) | - | - | -9.11 | 5.32 |
| Avg Bending Moment (Nmm) | 1,093.28 | -3.92 | 19.00 | -45.49 |
| Avg Shear Force (N) | 6.88 | -38.62 | 1.07 | -52.80 |
| Avg Utilizatio Ratio | 0.30 | -2.28 | 0.01 | -34.18 |

# Conclusion for patterns

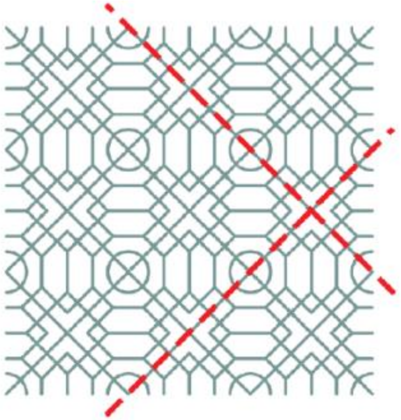






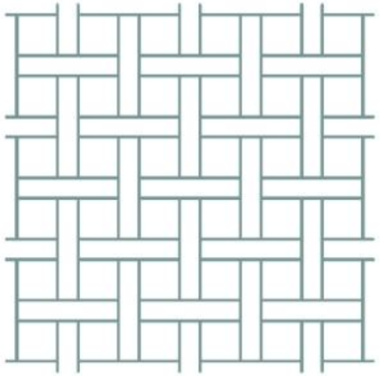
**Parallel direction**

- Performs good in vertical orientation



**Diagonal direction**

- Performs good in horizontal orientation



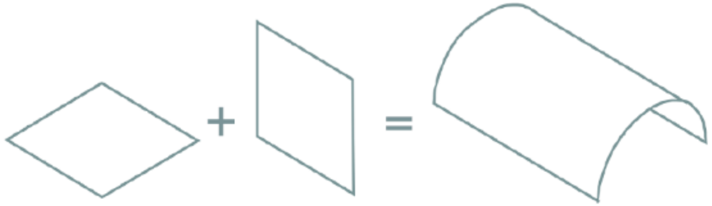
**No primary structure**

- High performance values

## Conclusion for patterns

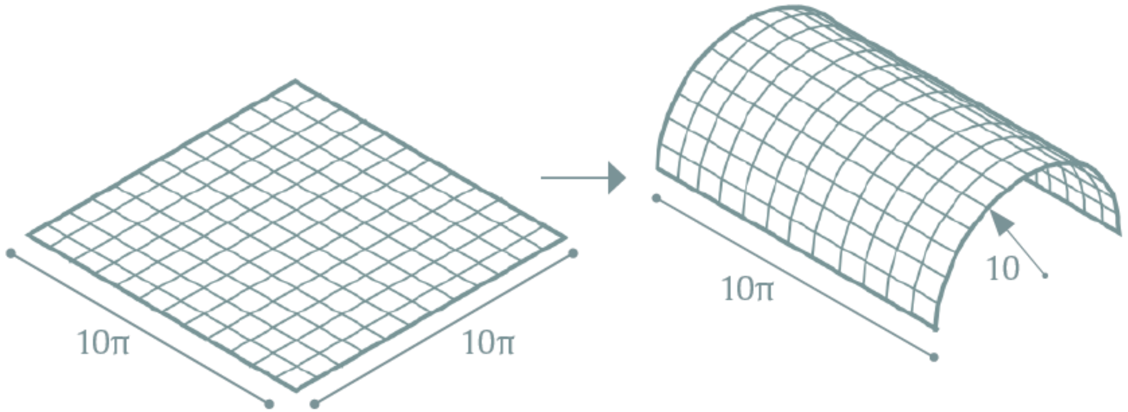
| | Name | Grid Density | Grid Factor | Trasfor mation | Horizontal orientation: Deflection (mm) | Avg Max Axial Stress (MPa) | Avg Min Axial Stress (MPa) | Avg Bending Moment (Nmm) | Avg Shear Force (N) | Utilizatio Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B6b_1 | 53.80712 | 10 | 3 MI | 59.84705 | 19.192404 | -19.192404 | 1122.018407 | 10.799397 | 0.319873 |
| 2 | B6b_2 | 49.25483 | 6 | 3 MI | 59.56602 | 20.366885 | -20.366885 | 1191.480643 | 8.902101 | 0.339448 |
| 3 | B6b_3 | 54.16414 | 7 | 3 MI | 72.815057 | 22.090213 | -22.090213 | 1301.320919 | 13.765882 | 0.36817 |
| 4 | B6b_4 | 50.86431 | 7 | 3 MI | 71.568955 | 20.743591 | -20.743591 | 1221.104882 | 13.623927 | 0.345727 |
| 5 | B6b_5 | 54.3594 | 8 | 3 MI | 69.295571 | 19.076642 | -19.076642 | 1118.668297 | 14.569109 | 0.317944 |
| 6 | B7b_1 | 54.04857 | 7 | 3 MI | 79.518382 | 17.901062 | -17.901062 | 1085.954282 | 7.099986 | 0.298351 |
| 7 | B7b_2 | 55.69849 | 7 | 3 MI | 80.96364 | 18.262552 | -18.262552 | 1110.290204 | 6.881624 | 0.304376 |
| 8 | B7b_3 | 48.87006 | 6 | 3 MI | 82.773986 | 19.131983 | -19.131983 | 1155.134684 | 6.788033 | 0.318866 |
| 9 | B7b_4 | 50.28427 | 6 | 3 MI | 82.774417 | 19.525843 | -19.525843 | 1175.687766 | 6.787438 | 0.325431 |
| 10 | B7b_5 | 51.69849 | 6 | 3 MI | 81.666724 | 19.845463 | -19.845463 | 1192.044803 | 6.793425 | 0.330758 |
| 11 | H11b_1 | 56.14214 | 4 | 3 MI | 87.692073 | 19.595721 | -19.595721 | 1240.576304 | 13.359395 | 0.326595 |
| 12 | H13a_1 | 53.11845 | 5 | 3 MI | 72.484833 | 17.65324 | -17.65324 | 1080.735711 | 6.858492 | 0.294221 |
| 13 | H13a_2 | 54.09476 | 5 | 3 MI | 72.871137 | 17.593831 | -17.593831 | 1083.827165 | 6.735434 | 0.293231 |
| 14 | H13a_3 | 55.07107 | 5 | 3 MI | 73.172886 | 17.490619 | -17.490619 | 1085.506328 | 6.737892 | 0.29151 |
| 15 | H14a_1 | 51.45178 | 5 | 3 MI | 80.495957 | 19.269503 | -19.269503 | 1213.446404 | 11.699645 | 0.321158 |
| 16 | H14a_2 | 49.43994 | 5 | 3 MI | 80.314169 | 18.990281 | -18.990281 | 1193.533058 | 11.499383 | 0.316505 |
| 17 | H14a_3 | 57.31371 | 6 | 3 MI | 79.803952 | 17.926512 | -17.926512 | 1112.169136 | 11.320923 | 0.298775 |
| 18 | H14a_4 | 50.96362 | 5 | 3 MI | 77.582036 | 18.898502 | -18.898502 | 1182.381831 | 10.771103 | 0.314975 |
| 19 | H14a_5 | 48.95178 | 5 | 3 MI | 77.966052 | 18.508392 | -18.508392 | 1153.597238 | 10.112517 | 0.308473 |
| 20 | H14a_6 | 56.72792 | 6 | 3 MI | 76.941411 | 17.439111 | -17.439111 | 1078.352352 | 10.642463 | 0.290652 |
| 21 | H14a_7 | 50.47547 | 5 | 3 MI | 74.650104 | 18.425522 | -18.425522 | 1146.822477 | 10.263399 | 0.307092 |
| 22 | L3a_1 | 55.55922 | 5 | 3 MI | 78.980666 | 17.353059 | -17.353059 | 1077.350223 | 8.105001 | 0.289218 |
| 23 | L3a_2 | 55.07107 | 5 | 3 MI | 78.238295 | 17.606068 | -17.606068 | 1087.541243 | 7.827201 | 0.293434 |
| 24 | L3a_3 | 54.58291 | 5 | 3 MI | 77.386109 | 17.78055 | -17.78055 | 1093.581856 | 7.974659 | 0.296342 |
| 25 | L3a_4 | 54.09476 | 5 | 3 MI | 76.409584 | 19.722625 | -19.722625 | 1209.009974 | 7.349358 | 0.32871 |
| 26 | L3a_5 | 53.6066 | 5 | 3 MI | 76.835297 | 20.833583 | -20.833583 | 1262.062496 | 7.963339 | 0.347226 |
| 27 | L3a_6 | 55.07107 | 5 | 3 MI | 78.52902 | 17.193145 | -17.193145 | 1068.17377 | 8.472605 | 0.286552 |
| 28 | L3a_7 | 54.58291 | 5 | 3 MI | 77.800563 | 17.429401 | -17.429401 | 1076.302583 | 8.035431 | 0.29049 |
| 29 | L3a_8 | 54.09476 | 5 | 3 MI | 76.959991 | 17.571946 | -17.571946 | 1080.577789 | 8.095061 | 0.292866 |
| 30 | L3a_9 | 53.6066 | 5 | 3 MI | 75.987458 | 19.445294 | -19.445294 | 1193.108539 | 7.383694 | 0.324088 |
| 31 | L3a_10 | 53.11845 | 5 | 3 MI | 76.35164 | 20.636677 | -20.636677 | 1248.792016 | 8.280867 | 0.343945 |
| 32 | Q5a_1 | 55.10457 | 8 | 3 MI | 94.700598 | 17.722297 | -17.722297 | 1107.459872 | 8.149014 | 0.295372 |
| 33 | Q5a_2 | 50.29983 | 7 | 3 MI | 100.28436 | 18.602559 | -18.602559 | 1171.553048 | 8.331365 | 0.310043 |
| 34 | Q5a_3 | 52.63317 | 7 | 3 MI | 104.487353 | 19.106695 | -19.106695 | 1206.253213 | 8.809917 | 0.318445 |

| | Name | Grid Density | Grid Factor | Vertical orientation: Deflection (mm) | Avg Max Axial Stress (MPa) | AvgMin Axial Stress (MPa) | Avg Normal Force (N) | Avg Bending Moment (Nmm) | Avg Shear Force (N) | Utilizatio Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B6b_1 | 53.80712 | 10 | 0.119507 | 0.646674 | -1.084178 | -10.997511 | 50.361426 | 3.896257 | 0.01807 |
| 2 | B6b_2 | 49.25483 | 6 | 0.194597 | 0.724157 | -1.162824 | -10.974681 | 54.91169 | 2.85573 | 0.01938 |
| 3 | B6b_3 | 54.16414 | 7 | 0.18533 | 0.806158 | -1.247631 | -11.054369 | 59.754702 | 3.535866 | 0.020794 |
| 4 | B6b_4 | 50.86431 | 7 | 0.178345 | 0.729878 | -1.143098 | -10.36313 | 54.496527 | 3.215579 | 0.019052 |
| 5 | B6b_5 | 54.3594 | 8 | 0.159593 | 0.643885 | -1.042932 | -10.023587 | 49.074951 | 3.283307 | 0.017382 |
| 6 | B7b_1 | 54.04857 | 7 | 0.044501 | 0.03641 | -0.365624 | -8.317073 | 11.699934 | 0.918942 | 0.006094 |
| 7 | B7b_2 | 55.69849 | 7 | 0.045378 | 0.016511 | -0.354109 | -8.517386 | 10.789159 | 0.773711 | 0.005902 |
| 8 | B7b_3 | 48.87006 | 6 | 0.046319 | 0.017266 | -0.358627 | -8.639429 | 10.946828 | 0.695278 | 0.005977 |
| 9 | B7b_4 | 50.28427 | 6 | 0.046399 | 0.019799 | -0.372294 | -8.923388 | 11.413783 | 0.725996 | 0.006205 |
| 10 | B7b_5 | 51.69849 | 6 | 0.046226 | 0.02602 | -0.391641 | -9.262569 | 12.168291 | 0.813179 | 0.006527 |
| 11 | H11b_1 | 56.14214 | 4 | 0.060816 | 0.258854 | -0.607128 | -8.778141 | 25.189863 | 1.711344 | 0.010119 |
| 12 | H13a_1 | 53.11845 | 5 | 0.040285 | 0.152485 | -0.499276 | -8.752348 | 18.978374 | 1.294714 | 0.008321 |
| 13 | H13a_2 | 54.09476 | 5 | 0.044562 | 0.138789 | -0.49177 | -8.894264 | 18.362856 | 1.079467 | 0.008196 |
| 14 | H13a_3 | 55.07107 | 5 | 0.046209 | 0.144098 | -0.507182 | -9.14923 | 18.96542 | 1.150414 | 0.008453 |
| 15 | H14a_1 | 51.45178 | 5 | 0.067428 | 0.424524 | -0.763872 | -8.607468 | 34.561748 | 2.437371 | 0.012731 |
| 16 | H14a_2 | 49.43994 | 5 | 0.063129 | 0.458915 | -0.785868 | -8.287613 | 36.205253 | 2.417668 | 0.013098 |
| 17 | H14a_3 | 57.31371 | 6 | 0.048291 | 0.333902 | -0.660054 | -8.232996 | 28.912641 | 2.547718 | 0.011001 |
| 18 | H14a_4 | 50.96362 | 5 | 0.067408 | 0.463717 | -0.798243 | -8.47943 | 36.707161 | 2.258415 | 0.013304 |
| 19 | H14a_5 | 48.95178 | 5 | 0.058762 | 0.447488 | -0.772418 | -8.210882 | 35.483686 | 2.366692 | 0.012874 |
| 20 | H14a_6 | 56.72792 | 6 | 0.041225 | 0.238126 | -0.562731 | -8.19097 | 23.297326 | 2.464623 | 0.009379 |
| 21 | H14a_7 | 50.47547 | 5 | 0.060949 | 0.441916 | -0.776106 | -8.45209 | 35.432528 | 2.275597 | 0.012935 |
| 22 | L3a_1 | 55.55922 | 5 | 0.056545 | 0.288321 | -0.642617 | -8.932763 | 27.082128 | 1.734243 | 0.01071 |
| 23 | L3a_2 | 55.07107 | 5 | 0.052929 | 0.284256 | -0.639508 | -8.970244 | 26.871893 | 1.758937 | 0.010658 |
| 24 | L3a_3 | 54.58291 | 5 | 0.044967 | 0.22253 | -0.579592 | -9.016377 | 23.341276 | 1.917389 | 0.00966 |
| 25 | L3a_4 | 54.09476 | 5 | 0.036361 | 0.028699 | -0.414591 | -9.726484 | 12.917086 | 0.820309 | 0.00691 |
| 26 | L3a_5 | 53.6066 | 5 | 0.041963 | 0.212884 | -0.614182 | -10.150877 | 24.075123 | 1.802434 | 0.010236 |
| 27 | L3a_6 | 55.07107 | 5 | 0.059824 | 0.289547 | -0.640783 | -8.854263 | 27.066173 | 1.735865 | 0.01068 |
| 28 | L3a_7 | 54.58291 | 5 | 0.055536 | 0.283223 | -0.63595 | -8.897114 | 26.74239 | 1.763104 | 0.010599 |
| 29 | L3a_8 | 54.09476 | 5 | 0.04655 | 0.217237 | -0.571897 | -8.9427 | 22.964429 | 1.928118 | 0.009532 |
| 30 | L3a_9 | 53.6066 | 5 | 0.036994 | 0.011801 | -0.394378 | -9.632958 | 11.838819 | 0.75802 | 0.006573 |
| 31 | L3a_10 | 53.11845 | 5 | 0.041044 | 0.190702 | -0.588558 | -10.068822 | 22.683464 | 1.836354 | 0.009809 |
| 32 | Q5a_1 | 55.10457 | 8 | 0.072032 | 0.359251 | -0.663927 | -7.69311 | 29.76016 | 2.20921 | 0.011065 |
| 33 | Q5a_2 | 50.29983 | 7 | 0.083844 | 0.382877 | -0.677023 | -7.443853 | 30.8367 | 1.912319 | 0.011284 |
| 34 | Q5a_3 | 52.63317 | 7 | 0.091665 | 0.363819 | -0.661458 | -7.504506 | 29.819956 | 1.844863 | 0.011024 |



**Aim:**

- Design a parametric workflow to generate patterned grid-shell
- Compare the structural performance all the patterns with each other
- Compare the structural performance all the patterns with flat structure


10π
10π
10π
10

**Material:**

- Pine wood

**Cross-section :**

- 15cm x 24.75cm (H/B ratio is 1.65)

**Joints:**

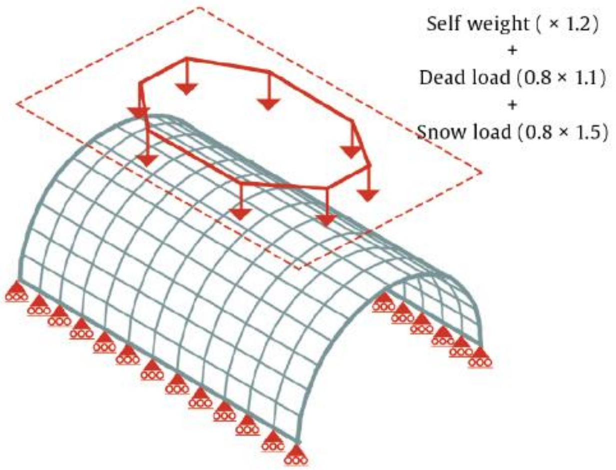
- Fixed joint (metal connection)

**Planarity:**

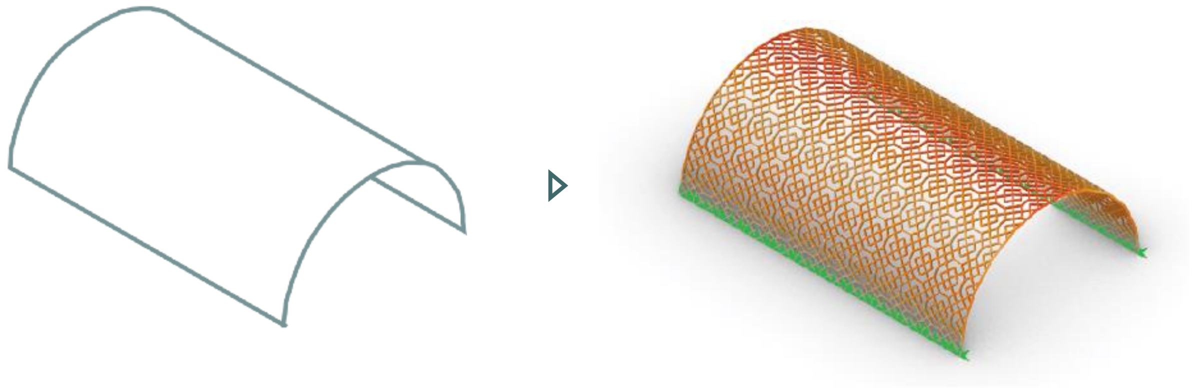
- Linear elements without bend

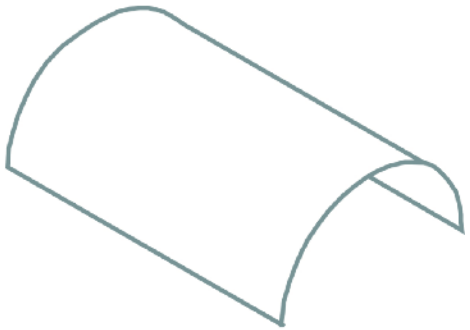
**Grid Density :**

- Grid density is used which is closest to 3200m

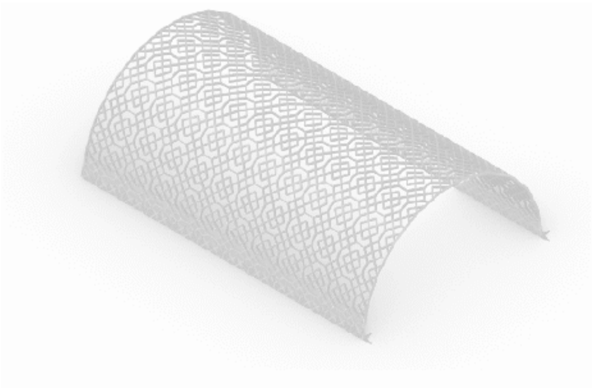


## Parametric workflow

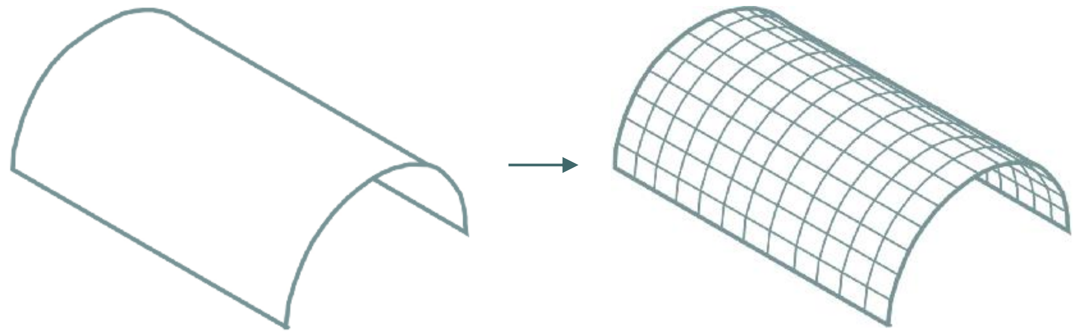




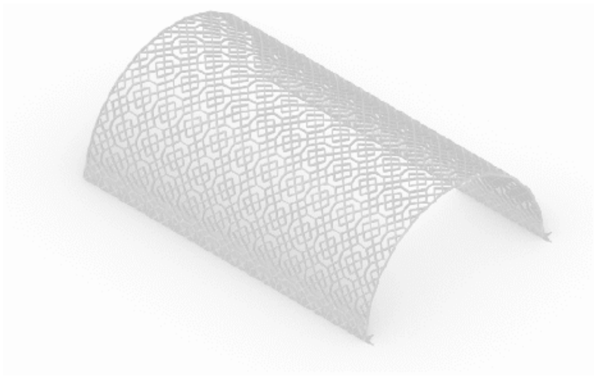
- Untrimmed surface of form



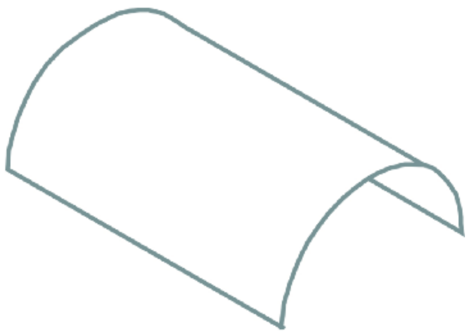


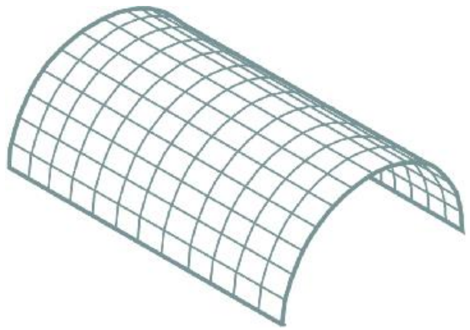


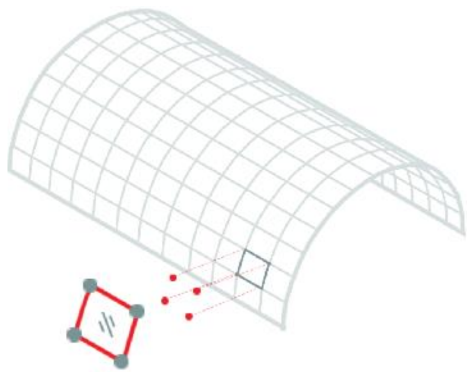
- Untrimmed surface of form
- Mesh division as per grid factor



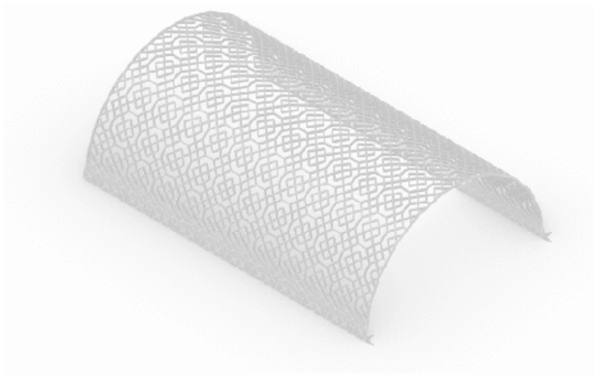
## Parametric workflow



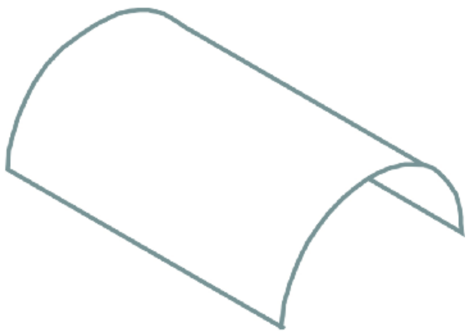




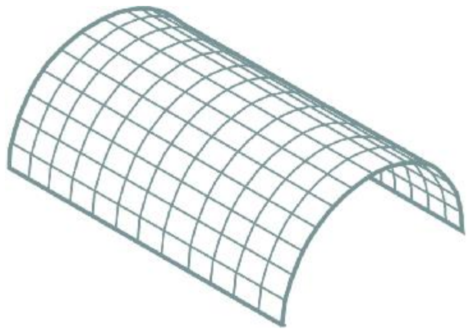
- Untrimmed surface of form
- Mesh division as per grid factor
- Regenerate individual surfaces



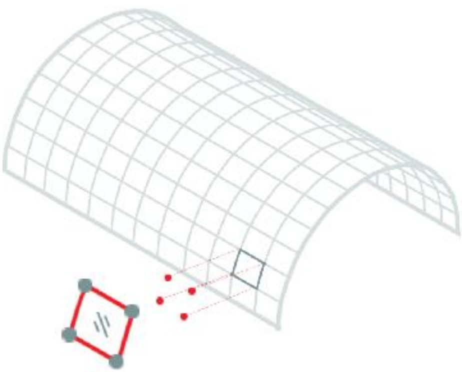
## Parametric workflow



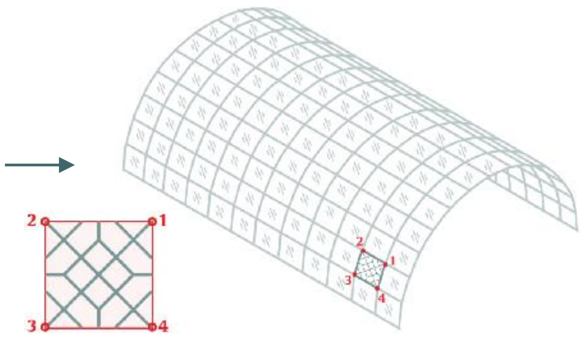
- Untrimmed surface of form



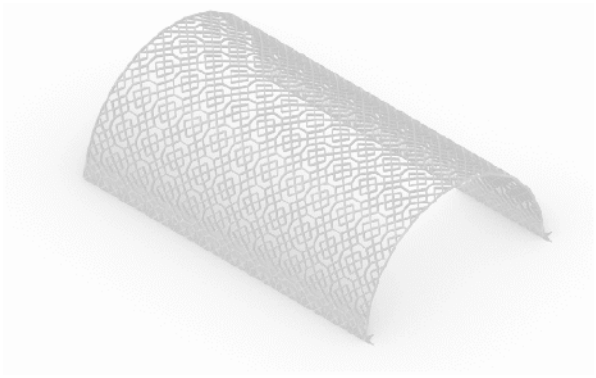
- Mesh division as per grid factor



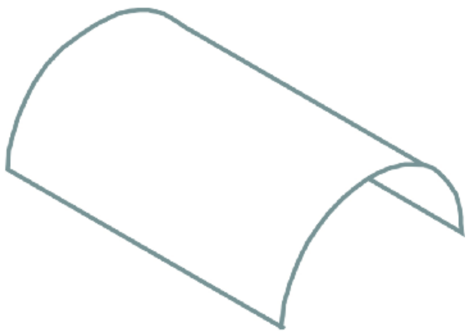
- Regenerate individual surfaces

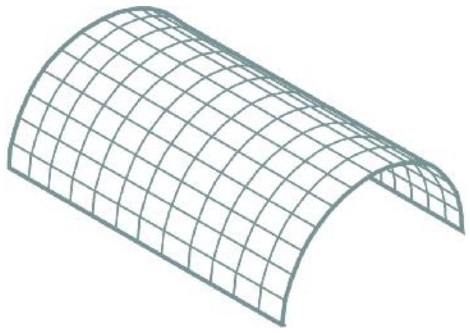


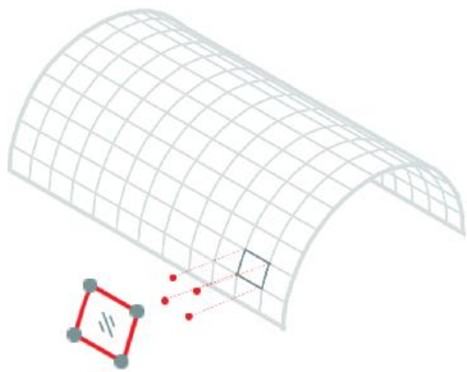

- Morph patterns with reference

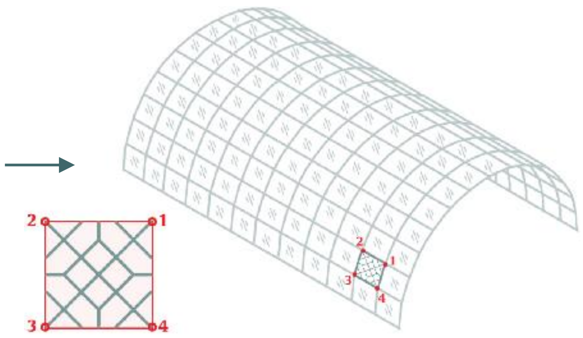


## Parametric workflow

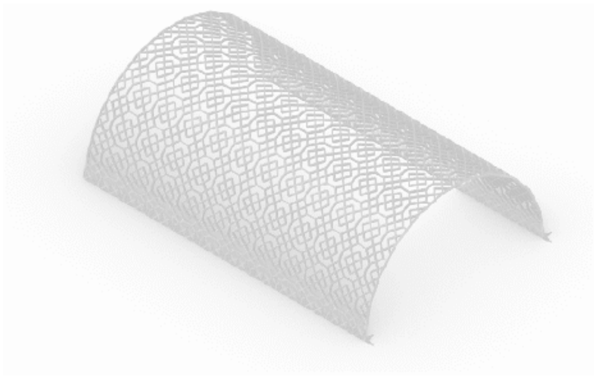


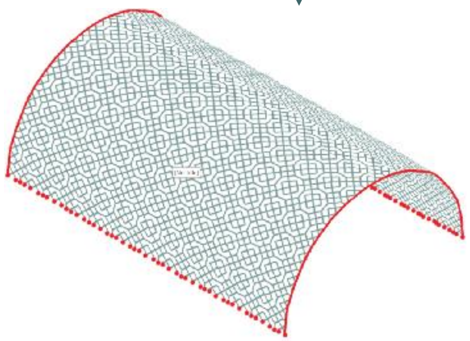






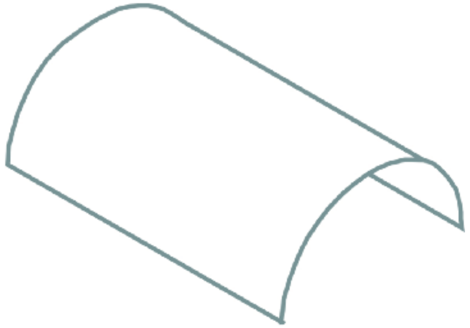

- Untrimmed surface of form
- Mesh division as per grid factor
- Regenerate individual surfaces
- Morph patterns with reference



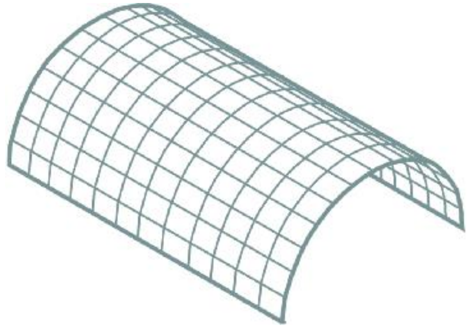


- Arrange ends and support points

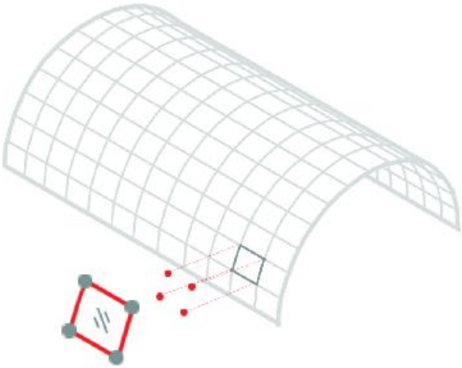
## Parametric workflow



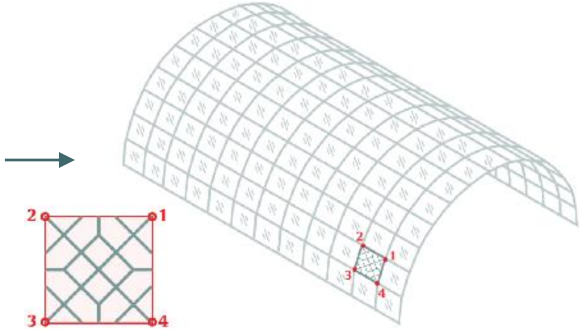
- Untrimmed surface of form



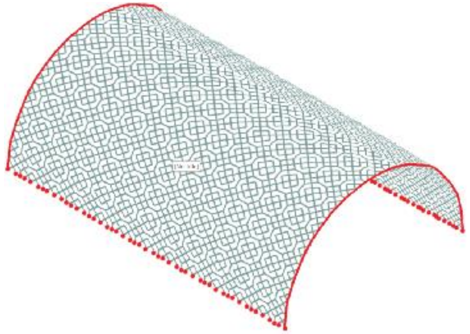
- Mesh division as per grid factor



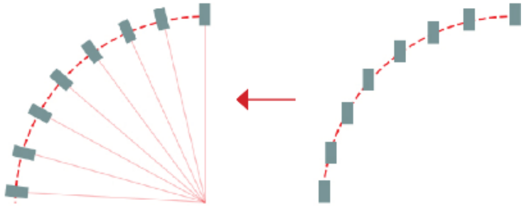
- Regenerate individual surfaces



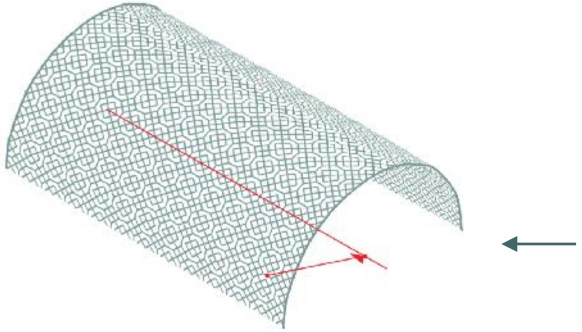

- Morph patterns with reference



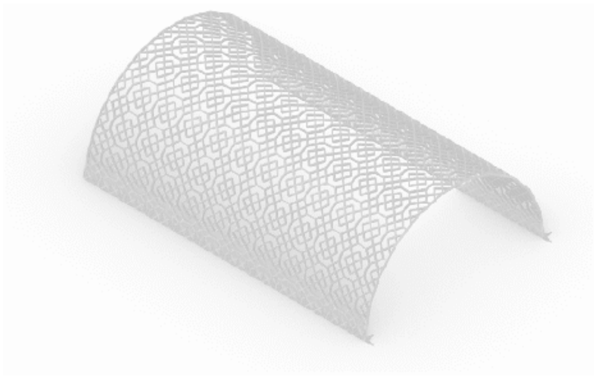
- Arrange ends and support points



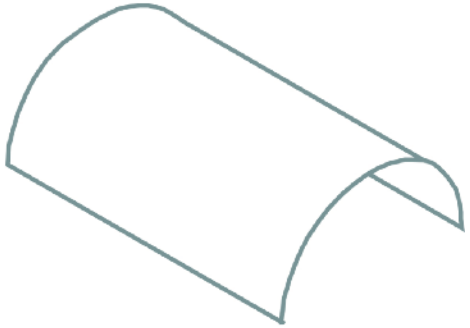
- Rotating local Z axis



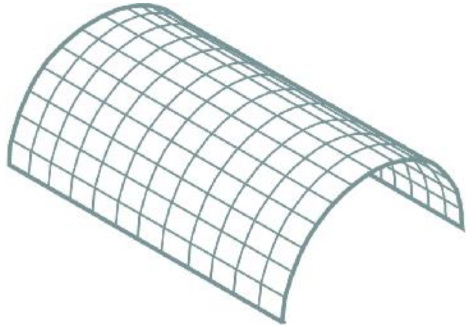
- Direction vector for cross-section



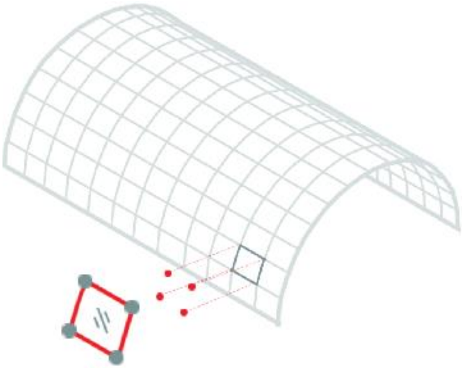
## Parametric workflow



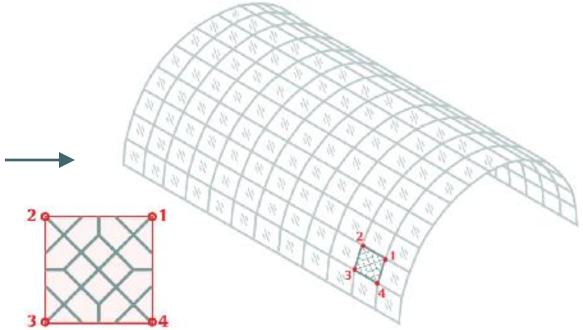
- Untrimmed surface of form



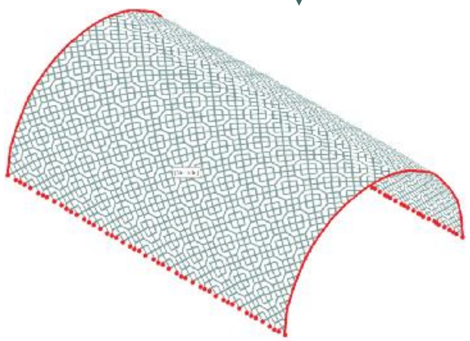
- Mesh division as per grid factor



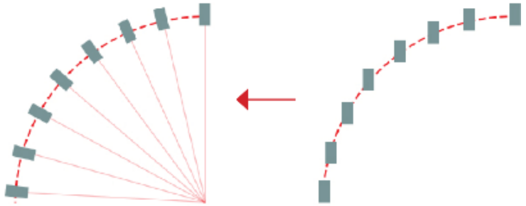
- Regenerate individual surfaces



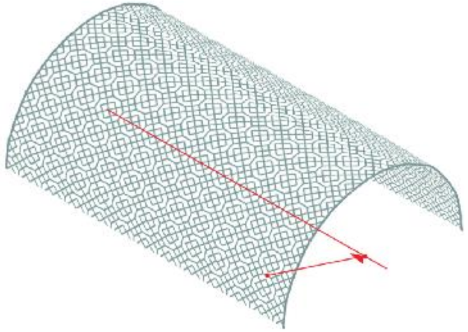
- Morph patterns with reference



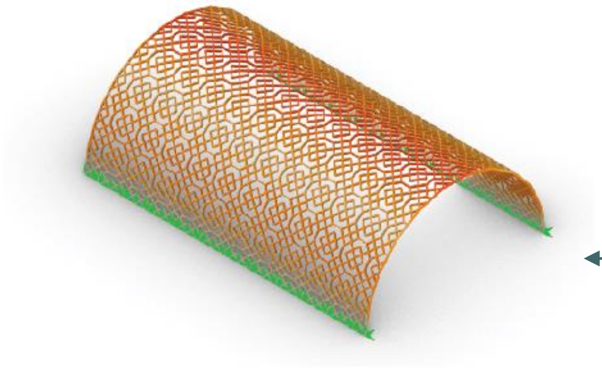
- Arrange ends and support points



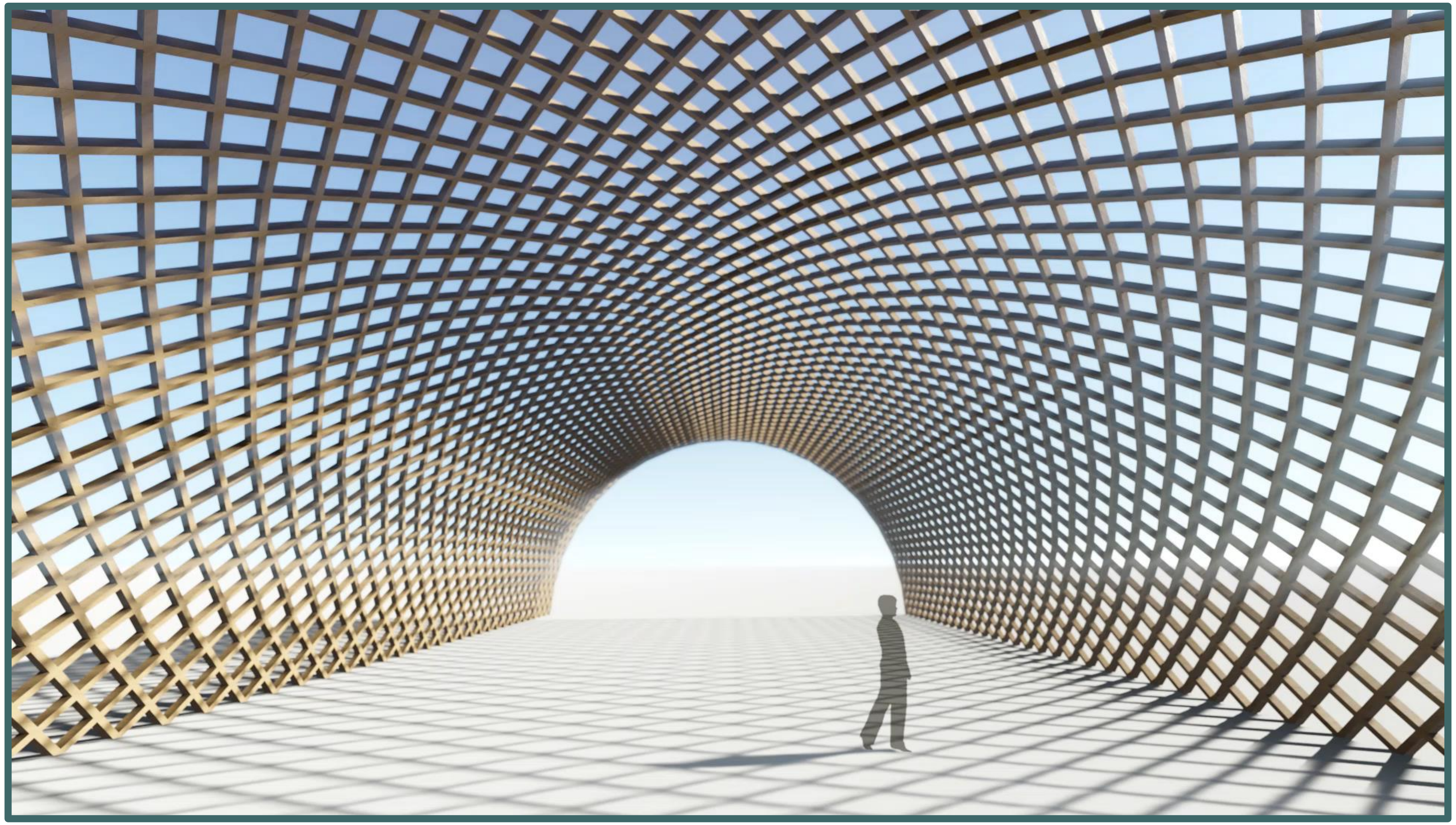
- Rotating local Z axis



- Direction vector for cross-section



- Setup for structural analysis



## Example 1 (B6b_4)

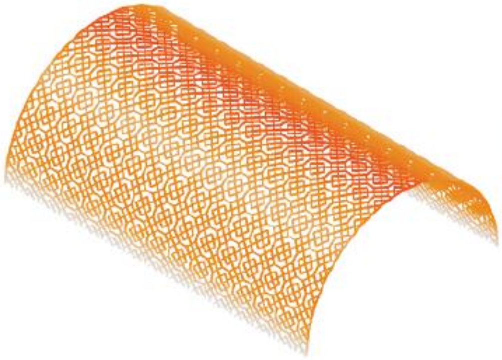
Experiential quality

Grid density : 3255.96

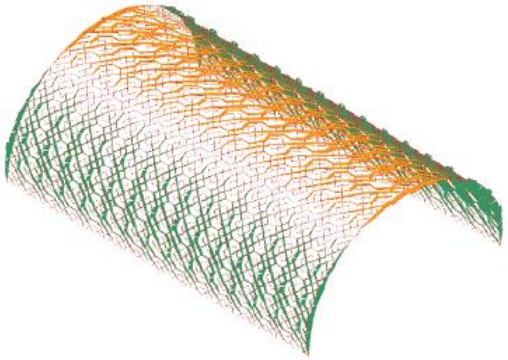
Grid Factor : 19

| | Value | % Difference |
|---|---|---|
| Deflection (mm) | 173.02 | 29.86 |
| Avg Max Axial Stress (MPa) | 4.70 | 22.50 |
| Avg Min Axial Stress (MPa) | -4.70 | 22.50 |
| Avg Normal Force (N) | -12,537.36 | 27.25 |
| Avg Bending Moment (Nmm) | 81,36,800.00 | 14.28 |
| Avg Shear Force (N) | 5,152.50 | -11.25 |
| Avg Utilizatio Ratio | 0.08 | 22.50 |
| Buckling Factor | 3.56 | -13.56 |

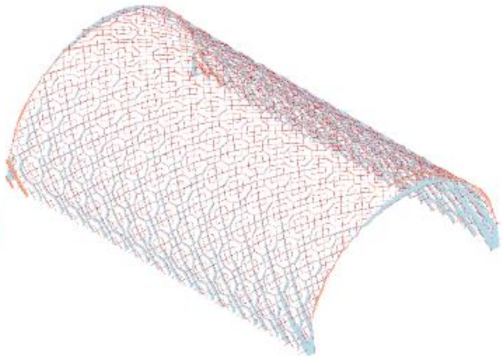
Structural performance



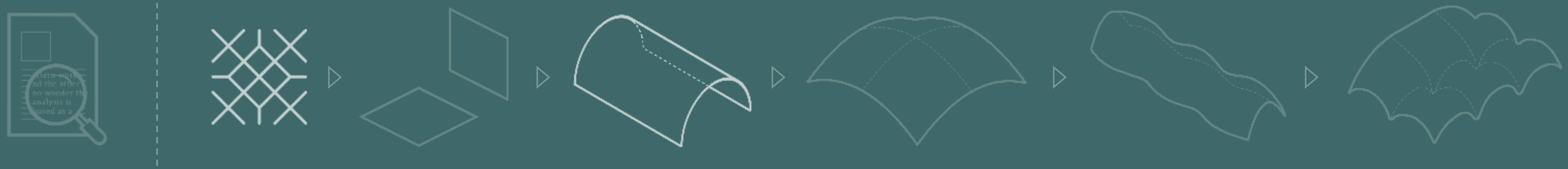
Deformation in Vault



Bending moment in Vault



Normal force in Vault





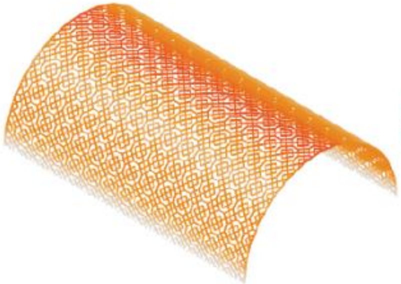
## Example 1 (B6b_4)

Experiential quality

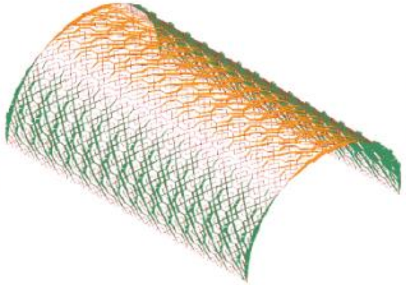
Grid density : 3255.96
Grid Factor : 19

| | Value | % Difference |
|---|---|---|
| Deflection (mm) | 173.02 | 29.86 |
| Avg Max Axial Stress (MPa) | 4.70 | 22.50 |
| Avg Min Axial Stress (MPa) | -4.70 | 22.50 |
| Avg Normal Force (N) | -12,537.36 | 27.25 |
| Avg Bending Moment (Nmm) | 81,36,800.00 | 14.28 |
| Avg Shear Force (N) | 5,152.50 | -11.25 |
| Avg Utilizatio Ratio | 0.08 | 22.50 |
| Buckling Factor | 3.56 | -13.56 |

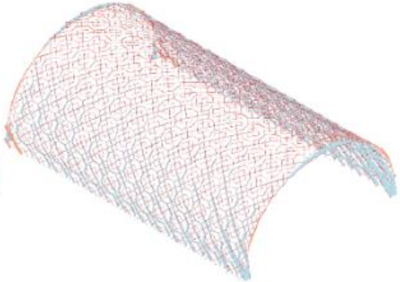
Structural performance



Deformation in Vault



Bending moment in Vault



Normal force in Vault

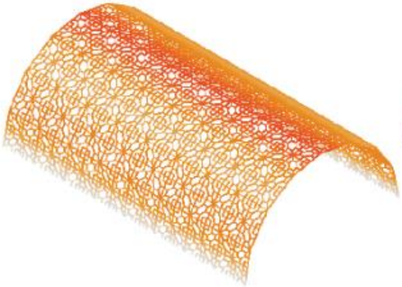
## Example 2 (B14a_1)

Experiential quality

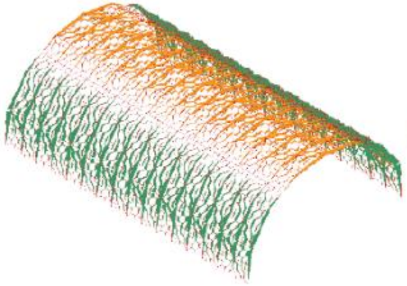
Grid density : 3213.69
Grid Factor : 8

| | Value | % Difference |
|---|---|---|
| Deflection (mm) | 113.40 | -14.88 |
| Avg Max Axial Stress (MPa) | 3.48 | -9.38 |
| Avg Min Axial Stress (MPa) | -3.48 | -9.38 |
| Avg Normal Force (N) | -9,882.90 | 0.31 |
| Avg Bending Moment (Nmm) | 66,60,200.00 | -6.46 |
| Avg Shear Force (N) | 4,420.17 | -23.87 |
| Avg Utilizatio Ratio | 0.06 | -9.38 |
| Buckling Factor | 4.25 | 3.23 |

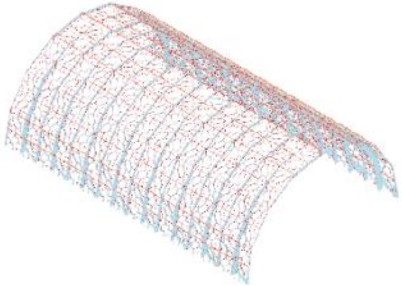
Structural performance



Deformation in Vault

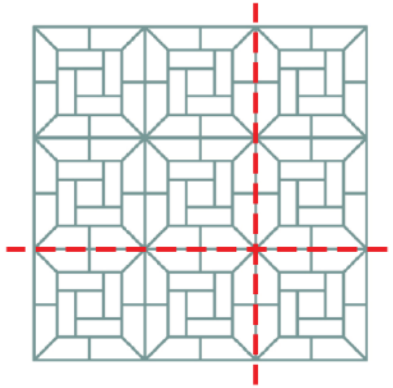


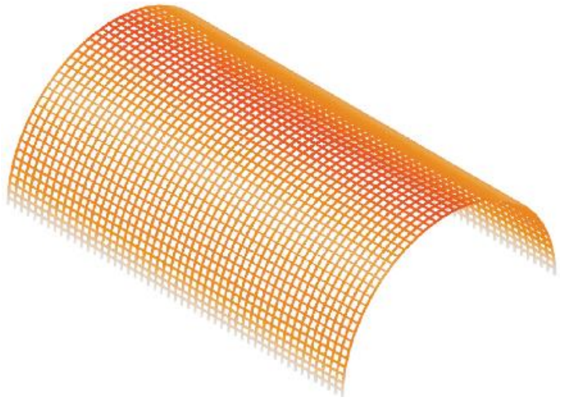
Bending moment in Vault

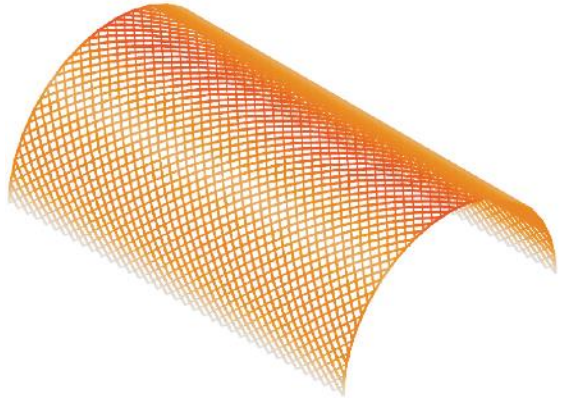


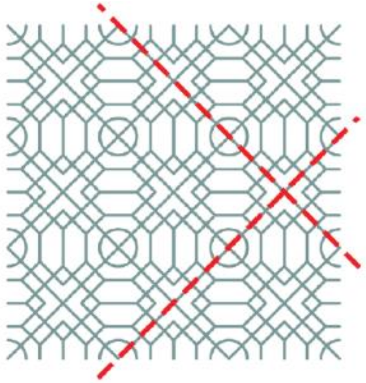
Normal force in Vault









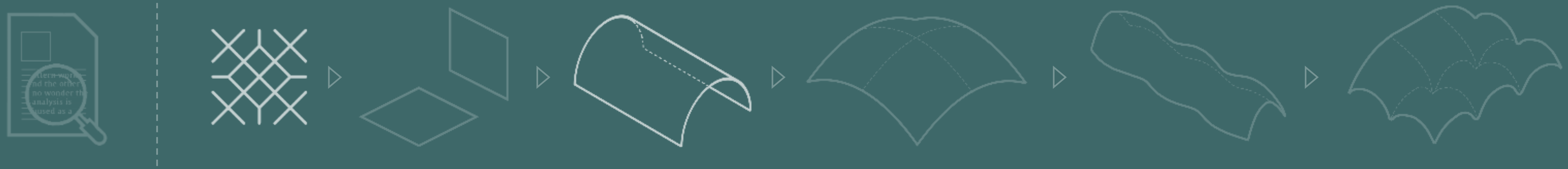


| | Parallel grid | | Diagonal grid | |
|---|---|---|---|---|
| | Value | % Difference | Value | % Difference |
| Deflection (mm) | 99.11 | -25.61 | 150.98 | 13.32 |
| Avg Max Axial Stress (MPa) | 2.94 | -23.31 | 5.13 | 33.66 |
| Avg Min Axial Stress (MPa) | -2.94 | -23.31 | -5.13 | 33.66 |
| Avg Normal Force (N) | -9,120.55 | -7.43 | -12,566.06 | 27.54 |
| Avg Bending Moment (Nmm) | 59,63,500.00 | -16.24 | 85,53,700.00 | 20.14 |
| Avg Shear Force (N) | 1,908.36 | -67.13 | 5,434.90 | -6.39 |
| Avg Utilizatio Ratio | 0.05 | -23.31 | 0.09 | 33.66 |
| Buckling Factor | 5.29 | 28.65 | 4.15 | 0.73 |

## Conclusion

| | Name | Grid Density | Grid Factor | Vault grid-shell Deflection (mm) | Avg Max Axial Stress (MPa) | Avg Min Axial Stress (MPa) | Avg Normal Force (N) | Avg Bending Moment (Nmm) | Avg Shear Force (N) | Utilizatio Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B6b_1 | 53.80712 | 10 | 142.674739 | 4.526132 | -4.526132 | -12003.35927 | 7.96E+06 | 5295.29218 | 0.075436 |
| 2 | B6b_2 | 49.25483 | 6 | 143.818666 | 4.998356 | -4.998356 | -12936.70664 | 8.50E+06 | 5764.24522 | 0.083306 |
| 3 | B6b_3 | 54.16414 | 7 | 181.170517 | 5.081687 | -5.081687 | -13521.19348 | 8.72E+06 | 5479.03834 | 0.084695 |
| 4 | B6b_4 | 50.86431 | 7 | 173.019128 | 4.700963 | -4.700963 | -12537.36331 | 8.14E+06 | 5152.50442 | 0.078349 |
| 5 | B6b_5 | 54.3594 | 8 | 167.197557 | 4.3592 | -4.3592 | -11675.58168 | 7.60E+06 | 4889.2192 | 0.072653 |
| 6 | B7b_1 | 54.04857 | 7 | 127.747519 | 3.201299 | -3.201299 | -8541.624977 | 6.31E+06 | 2885.27058 | 0.053355 |
| 7 | B7b_2 | 55.69849 | 7 | 132.819886 | 3.363313 | -3.363313 | -8983.894735 | 6.68E+06 | 2832.16039 | 0.056055 |
| 8 | B7b_3 | 48.87006 | 6 | 131.205011 | 3.364779 | -3.364779 | -9011.632136 | 6.70E+06 | 2722.7343 | 0.05608 |
| 9 | B7b_4 | 50.28427 | 6 | 128.8562 | 3.386394 | -3.386394 | -9099.710881 | 6.71E+06 | 2676.23182 | 0.05644 |
| 10 | B7b_5 | 51.69849 | 6 | 131.56074 | 3.606567 | -3.606567 | -9824.516329 | 7.16E+06 | 2808.78534 | 0.060109 |
| 11 | H11b_1 | 56.14214 | 4 | 110.828579 | 3.511762 | -3.511762 | -9758.138038 | 6.63E+06 | 5616.45503 | 0.058529 |
| 12 | H13a_1 | 53.11845 | 5 | 98.575846 | 3.30986 | -3.30986 | -9677.236131 | 6.41E+06 | 5052.70742 | 0.055164 |
| 13 | H13a_2 | 54.09476 | 5 | 96.499585 | 3.427171 | -3.427171 | -9648.531026 | 6.53E+06 | 4035.05818 | 0.05712 |
| 14 | H13a_3 | 55.07107 | 5 | 94.465886 | 3.433348 | -3.433348 | -9536.164471 | 6.51E+06 | 3647.75506 | 0.057222 |
| 15 | H14a_1 | 51.45178 | 5 | 107.228648 | 3.683131 | -3.683131 | -9364.753331 | 6.89E+06 | 6155.69451 | 0.061386 |
| 16 | H14a_2 | 49.43994 | 5 | 107.450646 | 3.569813 | -3.569813 | -9034.457573 | 6.71E+06 | 6464.49082 | 0.059497 |
| 17 | H14a_3 | 57.31371 | 6 | 107.499951 | 3.388919 | -3.388919 | -8715.588231 | 6.43E+06 | 6962.85358 | 0.056482 |
| 18 | H14a_4 | 50.96362 | 5 | 107.083752 | 3.675677 | -3.675677 | -9337.30702 | 6.81E+06 | 6285.09028 | 0.061261 |
| 19 | H14a_5 | 48.95178 | 5 | 107.136068 | 3.475002 | -3.475002 | -8956.70773 | 6.54E+06 | 6754.79941 | 0.057917 |
| 20 | H14a_6 | 56.72792 | 6 | 106.773644 | 3.200233 | -3.200233 | -8617.106877 | 6.12E+06 | 6971.87067 | 0.053337 |
| 21 | H14a_7 | 50.47547 | 5 | 106.665669 | 3.533503 | -3.533503 | -9246.603068 | 6.63E+06 | 6613.36324 | 0.058892 |
| 22 | L3a_1 | 55.55922 | 5 | 100.983818 | 3.457286 | -3.457286 | -9391.946523 | 6.48E+06 | 4929.07514 | 0.057621 |
| 23 | L3a_2 | 55.07107 | 5 | 100.262975 | 3.364561 | -3.364561 | -9515.340874 | 6.37E+06 | 5357.22647 | 0.056076 |
| 24 | L3a_3 | 54.58291 | 5 | 99.181397 | 3.224124 | -3.224124 | -9489.845507 | 6.14E+06 | 5669.43182 | 0.053735 |
| 25 | L3a_4 | 54.09476 | 5 | 96.958732 | 3.330966 | -3.330966 | -10178.32067 | 6.51E+06 | 3132.47606 | 0.055516 |
| 26 | L3a_5 | 53.6066 | 5 | 101.030634 | 3.723025 | -3.723025 | -10917.47268 | 7.08E+06 | 4928.91213 | 0.06205 |
| 27 | L3a_6 | 55.07107 | 5 | 103.000299 | 3.50522 | -3.50522 | -9593.164974 | 6.56E+06 | 5057.6157 | 0.05842 |
| 28 | L3a_7 | 54.58291 | 5 | 102.25371 | 3.397674 | -3.397674 | -9716.045165 | 6.43E+06 | 5475.27063 | 0.056628 |
| 29 | L3a_8 | 54.09476 | 5 | 101.119968 | 3.244212 | -3.244212 | -9653.615312 | 6.18E+06 | 5804.77914 | 0.05407 |
| 30 | L3a_9 | 53.6066 | 5 | 98.790645 | 3.344235 | -3.344235 | -10290.24223 | 6.55E+06 | 3289.25887 | 0.055737 |
| 31 | L3a_10 | 53.11845 | 5 | 102.792309 | 3.677666 | -3.677666 | -10962.75957 | 7.06E+06 | 5482.21989 | 0.061294 |
| 32 | Q5a_1 | 55.10457 | 8 | 146.90749 | 3.505169 | -3.505169 | -8657.220986 | 6.70E+06 | 7445.40733 | 0.058419 |
| 33 | Q5a_2 | 50.29983 | 7 | 151.583651 | 3.575811 | -3.575811 | -8502.324746 | 6.82E+06 | 6961.31077 | 0.059597 |
| 34 | Q5a_3 | 52.63317 | 7 | 164.586507 | 3.813874 | -3.813874 | -8715.839244 | 7.37E+06 | 6673.98026 | 0.063565 |

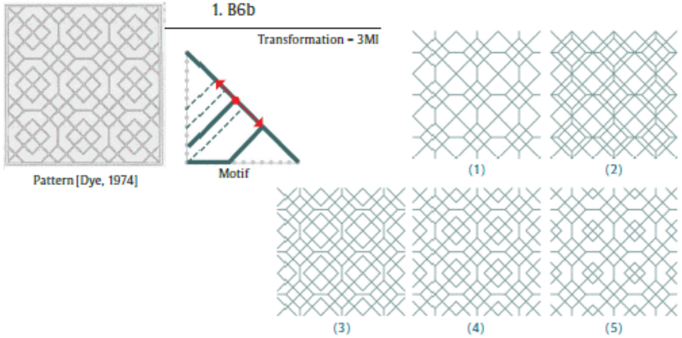
| | Name | Grid Density | Grid Factor | Vertical orientation Deflection (mm) | Avg Max Axial Stress (MPa) | AvgMin Axial Stress (MPa) | Avg Normal Force (N) | Avg Bending Moment (Nmm) | Avg Shear Force (N) | Utilization Ratio |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B6b_1 | 53.80712 | 10 | 0.119507 | 0.646674 | -1.084178 | -10.997511 | 50.361426 | 3.896257 | 0.01807 |
| 2 | B6b_2 | 49.25483 | 6 | 0.194597 | 0.724157 | -1.162824 | -10.974681 | 54.91169 | 2.85573 | 0.01938 |
| 3 | B6b_3 | 54.16414 | 7 | 0.18533 | 0.806158 | -1.247631 | -11.054369 | 59.754702 | 3.535866 | 0.020794 |
| 4 | B6b_4 | 50.86431 | 7 | 0.178345 | 0.729878 | -1.143098 | -10.36313 | 54.496527 | 3.215579 | 0.019052 |
| 5 | B6b_5 | 54.3594 | 8 | 0.159593 | 0.643885 | -1.042932 | -10.023587 | 49.074951 | 3.283307 | 0.017382 |
| 6 | B7b_1 | 54.04857 | 7 | 0.044501 | 0.03641 | -0.365624 | -8.317073 | 11.699934 | 0.918942 | 0.006094 |
| 7 | B7b_2 | 55.69849 | 7 | 0.045378 | 0.016511 | -0.354109 | -8.517386 | 10.789159 | 0.773711 | 0.005902 |
| 8 | B7b_3 | 48.87006 | 6 | 0.046319 | 0.017266 | -0.358627 | -8.639429 | 10.946828 | 0.695278 | 0.005977 |
| 9 | B7b_4 | 50.28427 | 6 | 0.046399 | 0.019799 | -0.372294 | -8.923388 | 11.413783 | 0.725996 | 0.006205 |
| 10 | B7b_5 | 51.69849 | 6 | 0.046226 | 0.02602 | -0.391641 | -9.262569 | 12.168291 | 0.813179 | 0.006527 |
| 11 | H11b_1 | 56.14214 | 4 | 0.060816 | 0.258854 | -0.607128 | -8.778141 | 25.189863 | 1.711344 | 0.010119 |
| 12 | H13a_1 | 53.11845 | 5 | 0.040285 | 0.152485 | -0.499276 | -8.752348 | 18.978374 | 1.294714 | 0.008321 |
| 13 | H13a_2 | 54.09476 | 5 | 0.044562 | 0.138789 | -0.49177 | -8.894264 | 18.362856 | 1.079467 | 0.008196 |
| 14 | H13a_3 | 55.07107 | 5 | 0.046209 | 0.144098 | -0.507182 | -9.14923 | 18.96542 | 1.150414 | 0.008453 |
| 15 | H14a_1 | 51.45178 | 5 | 0.067428 | 0.424524 | -0.763872 | -8.607468 | 34.561748 | 2.437371 | 0.012731 |
| 16 | H14a_2 | 49.43994 | 5 | 0.063129 | 0.458915 | -0.785868 | -8.287613 | 36.205253 | 2.417668 | 0.013098 |
| 17 | H14a_3 | 57.31371 | 6 | 0.048291 | 0.333902 | -0.660054 | -8.232996 | 28.912641 | 2.547718 | 0.011001 |
| 18 | H14a_4 | 50.96362 | 5 | 0.067408 | 0.463717 | -0.798243 | -8.47943 | 36.707161 | 2.258415 | 0.013304 |
| 19 | H14a_5 | 48.95178 | 5 | 0.058762 | 0.447488 | -0.772418 | -8.210882 | 35.483686 | 2.366692 | 0.012874 |
| 20 | H14a_6 | 56.72792 | 6 | 0.041225 | 0.238126 | -0.562731 | -8.19097 | 23.297326 | 2.464623 | 0.009379 |
| 21 | H14a_7 | 50.47547 | 5 | 0.060949 | 0.441916 | -0.776106 | -8.45209 | 35.432528 | 2.275597 | 0.012935 |
| 22 | L3a_1 | 55.55922 | 5 | 0.056545 | 0.288321 | -0.642617 | -8.932763 | 27.082128 | 1.734243 | 0.01071 |
| 23 | L3a_2 | 55.07107 | 5 | 0.052929 | 0.284256 | -0.639508 | -8.970244 | 26.871893 | 1.758937 | 0.010658 |
| 24 | L3a_3 | 54.58291 | 5 | 0.044967 | 0.22253 | -0.579592 | -9.016377 | 23.341276 | 1.917389 | 0.00966 |
| 25 | L3a_4 | 54.09476 | 5 | 0.036361 | 0.028699 | -0.414591 | -9.726484 | 12.917086 | 0.820309 | 0.00691 |
| 26 | L3a_5 | 53.6066 | 5 | 0.041963 | 0.212884 | -0.614182 | -10.150877 | 24.075123 | 1.802434 | 0.010236 |
| 27 | L3a_6 | 55.07107 | 5 | 0.059824 | 0.289547 | -0.640783 | -8.854263 | 27.066173 | 1.735865 | 0.01068 |
| 28 | L3a_7 | 54.58291 | 5 | 0.055536 | 0.283223 | -0.63595 | -8.897114 | 26.74239 | 1.763104 | 0.010599 |
| 29 | L3a_8 | 54.09476 | 5 | 0.04655 | 0.217237 | -0.571897 | -8.9427 | 22.964429 | 1.928118 | 0.009532 |
| 30 | L3a_9 | 53.6066 | 5 | 0.036994 | 0.011801 | -0.394378 | -9.632958 | 11.838819 | 0.75802 | 0.006573 |
| 31 | L3a_10 | 53.11845 | 5 | 0.041044 | 0.190702 | -0.588558 | -10.068822 | 22.683464 | 1.836354 | 0.009809 |
| 32 | Q5a_1 | 55.10457 | 8 | 0.072032 | 0.359251 | -0.663927 | -7.69311 | 29.76016 | 2.20921 | 0.011065 |
| 33 | Q5a_2 | 50.29983 | 7 | 0.083844 | 0.382877 | -0.677023 | -7.443853 | 30.8367 | 1.912319 | 0.011284 |
| 34 | Q5a_3 | 52.63317 | 7 | 0.091665 | 0.363819 | -0.661458 | -7.504506 | 29.819956 | 1.844863 | 0.011024 |



# Pattern Catalogue

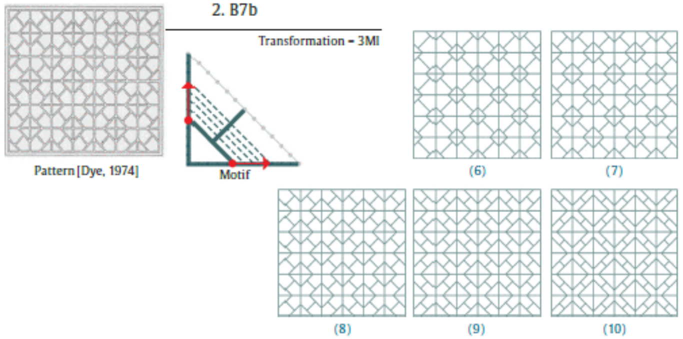
## 1. B6b

Transformation - 3MI



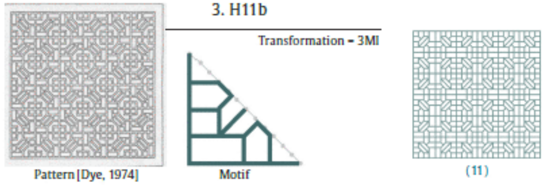

## 2. B7b

Transformation - 3MI

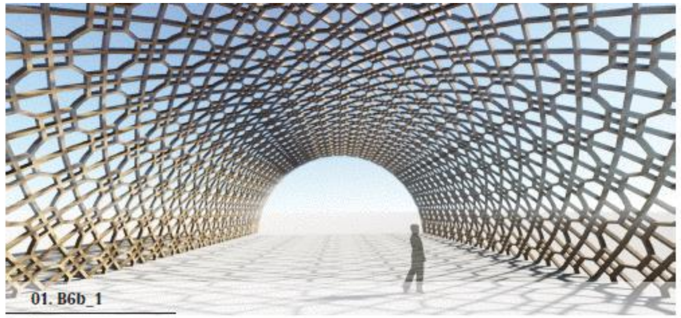



## 3. H11b

Transformation - 3MI

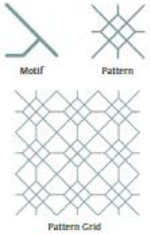


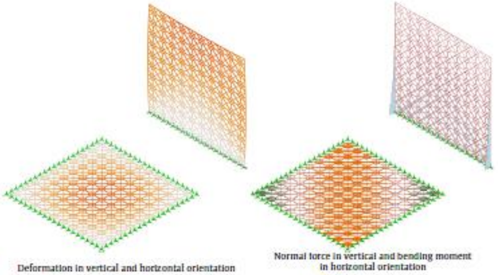

162

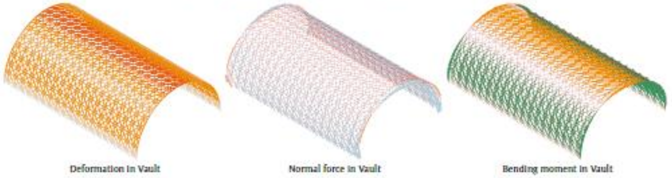


## 01. B6b_1

| | | |
|---|---|---|
| Transformation | 3 MI | |
| Grid Density | 53.8071 | 0.90712 |
| Grid Factor | 10 | |




| | Horizontal | | Vertical | | Vault | |
|---|---|---|---|---|---|---|
| | Value | % Difference | Value | % Difference | Value | % Difference |
| Deflection (mm) | 59.85 | -25.61 | 0.12 | 20.62 | 142.67 | 7.09 |
| Avg Max Axial Stress (MPa) | 19.19 | 4.62 | 0.65 | 51.25 | 4.53 | 17.94 |
| Avg Min Axial Stress (MPa) | -19.19 | 4.62 | -1.08 | 40.64 | -4.53 | 17.94 |
| Avg Normal Force (N) | - | - | -11.00 | 27.12 | -12,003.36 | 21.83 |
| Avg Bending Moment (Nmm) | 1,122.02 | -1.39 | 50.36 | 44.45 | 79,64,600.00 | 11.86 |
| Avg Shear Force (N) | 10.80 | -3.61 | 3.90 | 72.13 | 5,295.29 | -8.79 |
| Avg Utilizatio Ratio | 0.32 | 4.62 | 0.02 | 40.64 | 0.08 | 17.94 |
| Buckling Factor | - | - | - | - | 4.39 | 6.70 |

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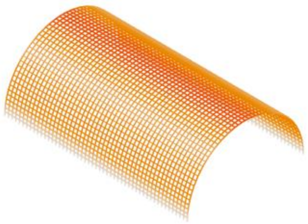
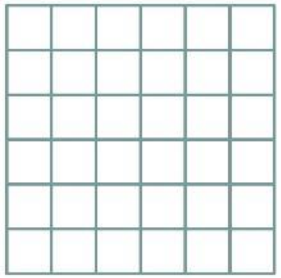
**Aim:**

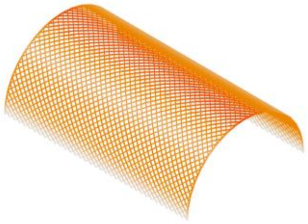
- Arrange multi-objective optimization setup to find optimum material quantity.
- Validate the usability of results in pattern catalogue.

## Use of Pattern Catalogue

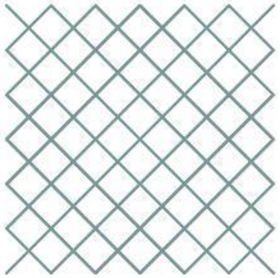


82





83



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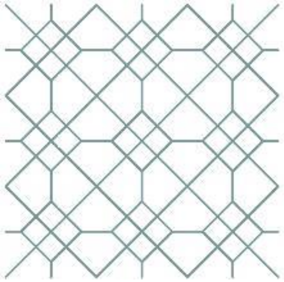
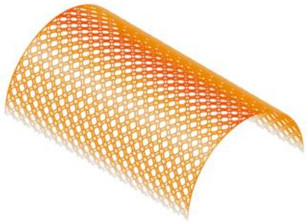
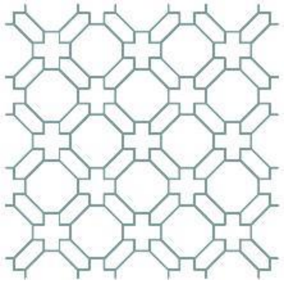
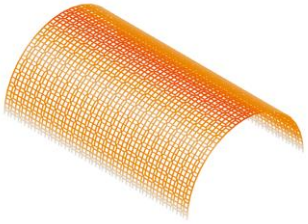


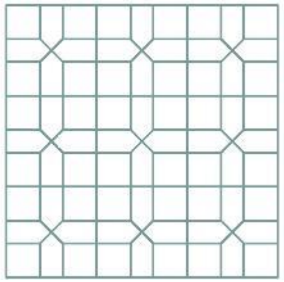


45



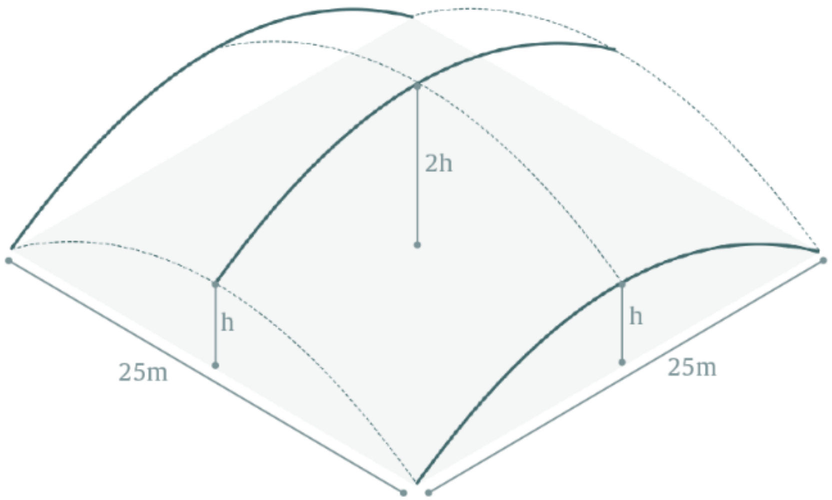


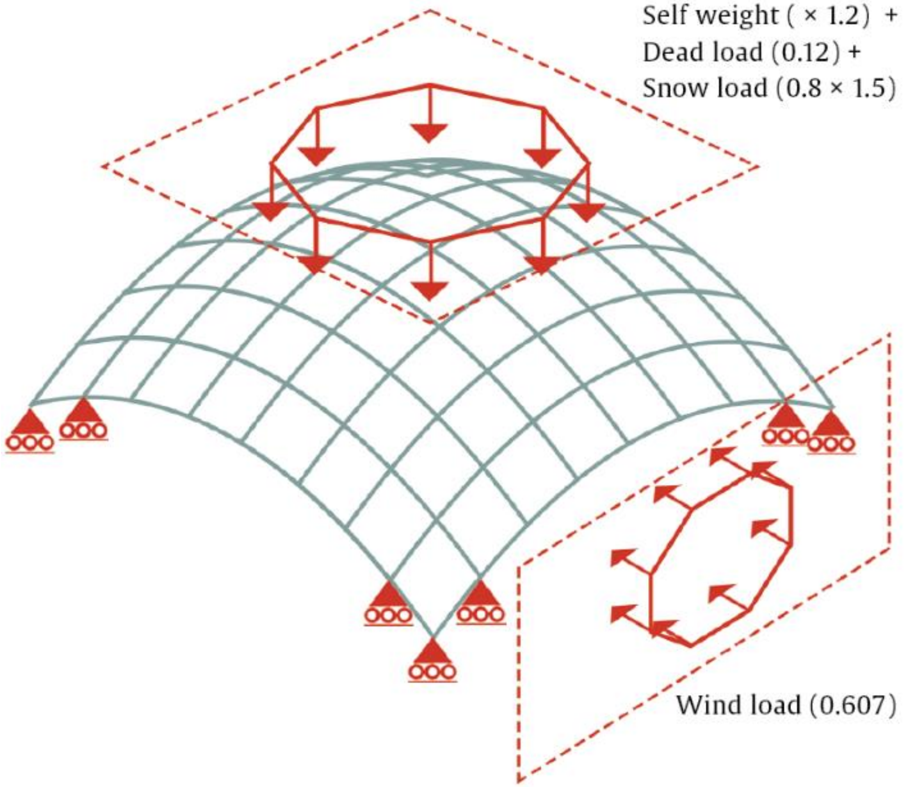
65

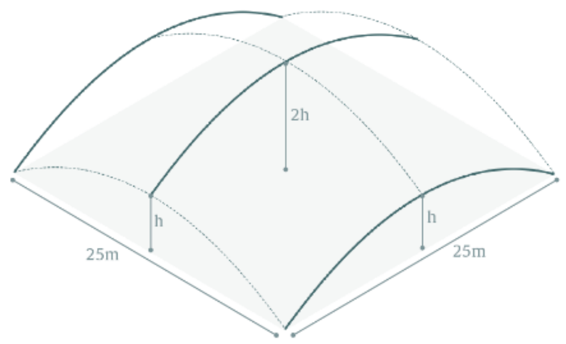


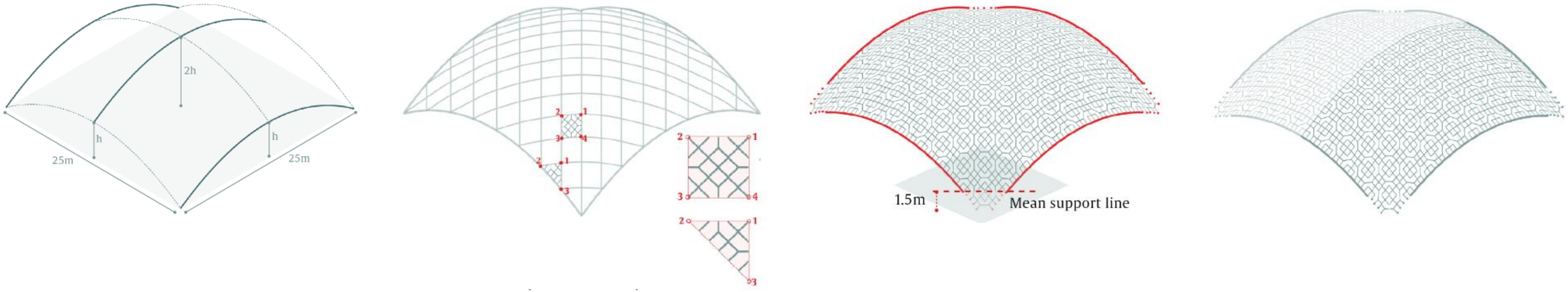
| | Value | % Difference | Value | % Difference | Value | % Difference | Value | % Difference | Value | % Difference |
|---|---|---|---|---|---|---|---|---|---|---|
| Deflection (mm) | 99.11 | -25.61 | 150.98 | 13.32 | 142.67 | 7.09 | 198.68 | 49.12 | 109.15 | -18.08 |
| | 1 | | 4 | | 3 | | 5 | | 2 | |

## Model properties

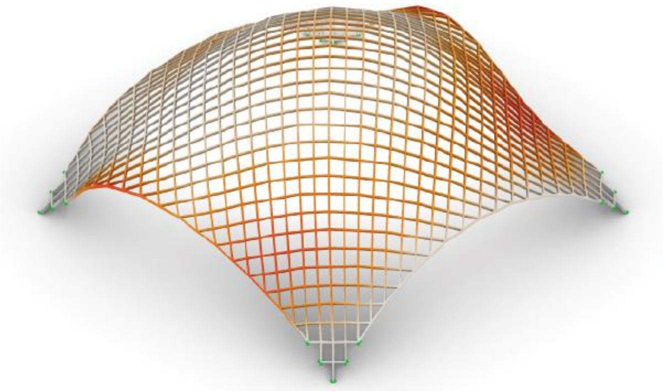



Self weight ( × 1.2) +
Dead load (0.12) +
Snow load (0.8 × 1.5)
Wind load (0.607)


2h
h
h
25m
25m


2h
h
h
25m
25m
1
2
3
4
1.5m
Mean support line





Scaled visualization of deflection

Grid factor = 10
Cross-section width = 100.7mm
Height of opening = 6m

| | Results | Allowable results |
|---|---|---|
| Deflection (mm) | 141.3 | Span/250 = 141.42<br>Height of C/S = 166.15 |
| Max normal stress (MPa) | \|-30.36\| | 60 |
| Buckling factor | 3.13 | 2 |
| Max. utilization ratio | \|-0.506\| | 1 |
| Grid density (m) | 1684.2 | - |
| Volume (m3) | 28.18 | - |

## Allowable limits

**Allowable Deflection:**

- Height of cross section

  or

- Shell span/250 (whichever is less)

**Allowable maximum normal stress:**

- Less than the yield strength of a material (<60 MPa)

**Allowable buckling factor:**

- >2

**Minimum grid factor:**

- 7 (to make it less course mesh)

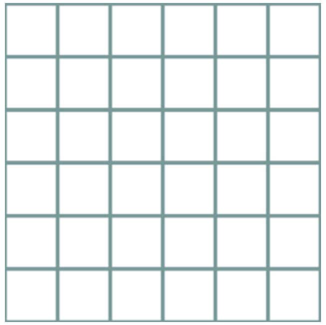
## Multi objective optimization setup

| Objectives | Parameters |
|---|---|
| (V) Minimize Volume | (b) Cross-section width |
| (△) Minimize Deflection (till the allowable limit) | (g) Grid factor (for grid-dentity) |
| (U) Maximize avg. Utilization ratio | (h) Heigth of opening |



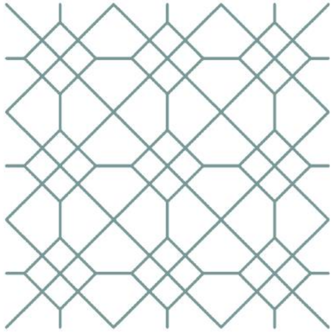
Rank as per the deflection of vault in catalogue

1



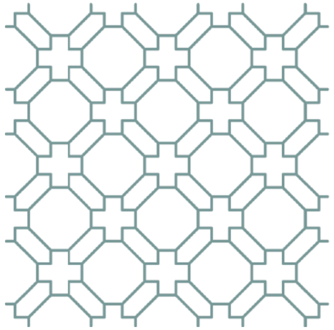
82

3



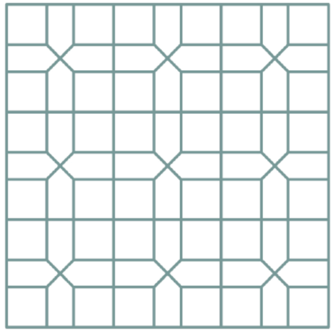
01

4



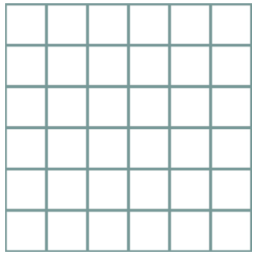
45

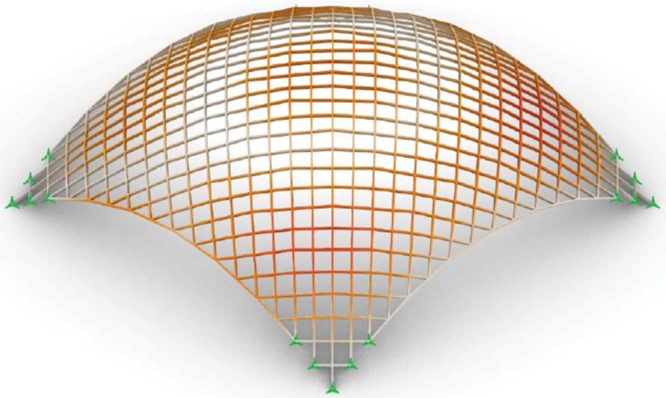
2



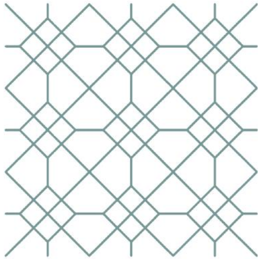
65

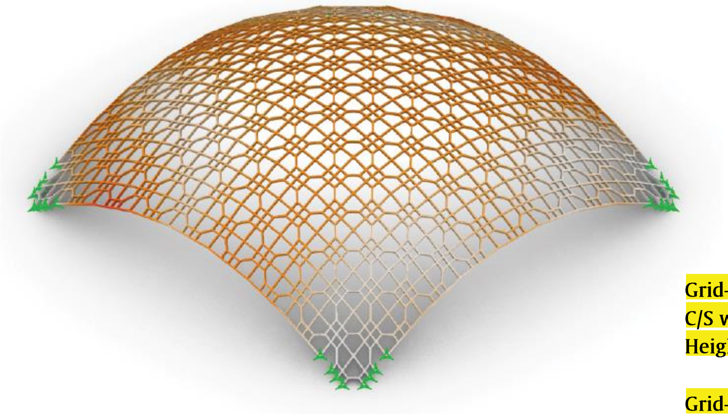
## Material quantity optimization





| | Pattern 82 (Parallel grid) | | | |
|---|---|---|---|---|
| | Input | Fitness value | Performance value | |
| | | {48;19;0} | | |
| | 8 | 813.88855 | 28.528732 | |
| | 11.36 | 2.690664 | 133.291409 | |
| | 5.25 | 6.253283 | 0.159916 | |
| | | {48;40;0} | | |
| | 8 | 501.030608 | 22.383713 | |
| | 10.2 | 0.522938 | 135.459135 | |
| | 4.66 | 4.943838 | 0.202272 | |
| | | {48;41;0} | | |
| | 8 | 477.184321 | 21.844549 | |
| | 10.1 | 5.607733 | 141.589806 | |
| | 4.51 | 4.806999 | 0.20803 | |
| | | {49;11;0} | | |
| | 8 | 479.076971 | 21.887827 | |
| | 10.11 | 4.947112 | 140.929185 | |
| | 4.51 | 4.822345 | 0.207368 | |
| | | {49;22;0} | | |
| Grid-factor | 8 | 479.076971 | 21.887827 | Volume |
| C/S width | 10.11 | 4.947112 | 140.929185 | Deflection |
| Height | 4.51 | 4.822345 | 0.207368 | Utilization ratio |
| | | {49;28;0} | | |
| | 8 | 479.076971 | 21.887827 | |
| | 10.11 | 4.947112 | 140.929185 | |
| | 4.51 | 4.822345 | 0.207368 | |
| | | {49;47;0} | | |
| | 8 | 511.424068 | 22.614687 | |
| | 10.28 | 5.15865 | 130.823423 | |
| | 4.5 | 5.106027 | 0.195847 | |



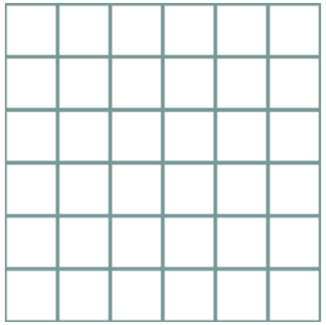


| | Pattern 1 (B6b_1) | | | |
|---|---|---|---|---|
| | Input | Fitness value | Performance value | |
| | | {48;36;0} | | |
| | 7 | 648.753757 | 25.470645 | |
| | 10.25 | 3.269245 | 139.251318 | |
| | 4.55 | 6.322551 | 0.158164 | |
| | | {49;5;0} | | |
| | 7 | 657.683156 | 25.645334 | |
| | 10.27 | 4.437253 | 140.419326 | |
| | 4.64 | 6.368088 | 0.157033 | |
| | | {49;12;0} | | |
| | 7 | 669.632999 | 25.877268 | |
| | 10.33 | 0.797328 | 136.779401 | |
| | 4.56 | 6.401967 | 0.156202 | |
| | | {49;35;0} | | |
| | 7 | 648.753757 | 25.470645 | |
| | 10.25 | 3.269245 | 139.251318 | |
| | 4.55 | 6.322551 | 0.158164 | |
| | | {49;38;0} | | |
| | 7 | 648.753757 | 25.470645 | |
| | 10.25 | 3.269245 | 139.251318 | |
| | 4.55 | 6.322551 | 0.158164 | |
| | | {49;39;0} | | |
| Grid-factor | 9 | 573.218311 | 23.941978 | Volume |
| C/S width | 8.79 | 5.639845 | 141.621918 | Deflection |
| Height | 4.55 | 6.811432 | 0.146812 | Utilization ratio |
| | | Modified | | |
| Grid-factor | 9 | 23.996484 | 23.941978 | Volume |
| C/S width | 8.8 | -4.701645 | 140.683718 | Deflection |
| Height | 4.55 | 0.146292 | 0.146812 | Utilization ratio |

## Material quantity optimization

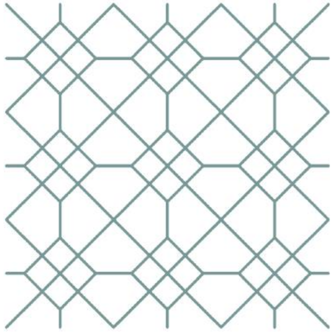
Rank as per the deflection of vault in catalogue

1



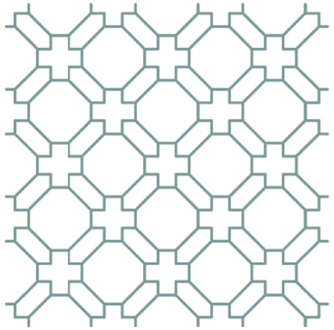
82

3



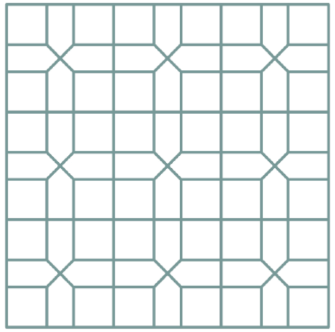
01

4



45

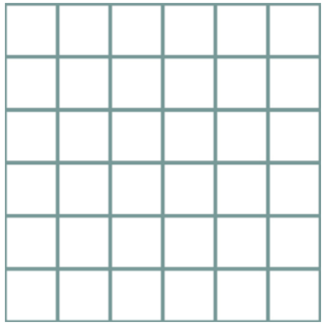
2



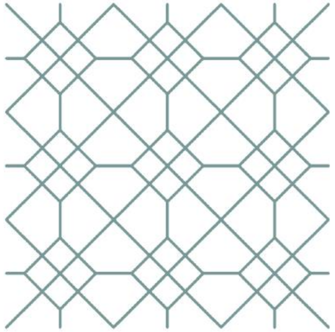
65



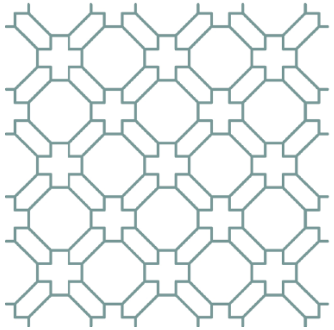
| | 82 | 01 | 45 | 65 |
|---|---|---|---|---|
| Rank as per the deflection of vault in catalogue | 1 | 3 | 4 | 2 |
| **Volume** | 21.88 | 23.94 | 26.79 | 23.36 |
| **Deflection** | 140.92 | 140.68 | 139.95 | 139.52 |
| **Utilization ratio** | 0.20 | 0.14 | 0.18 | 0.17 |
| Rank as per the volume | 1 | 3 | 4 | 2 |
| | | 9.6 % ^ | 22.66 % ^ | 6.9 % ^ |



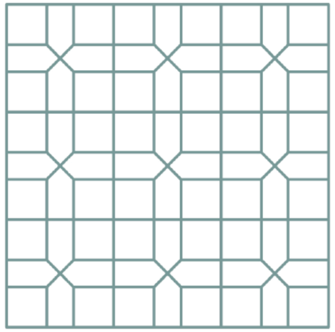
82



01



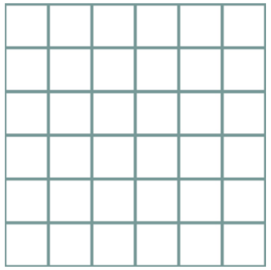
45

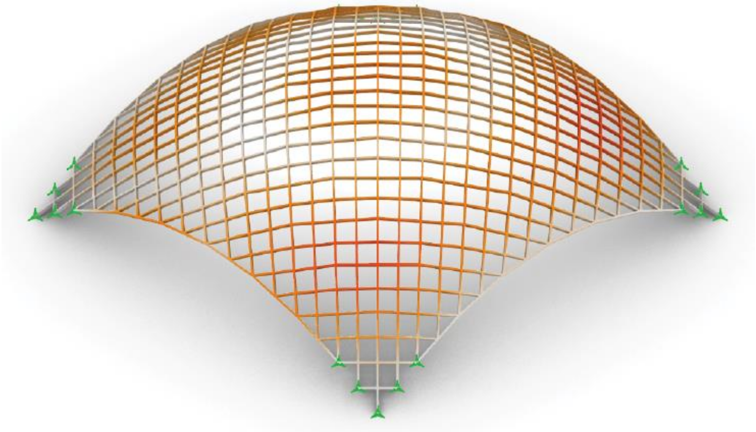


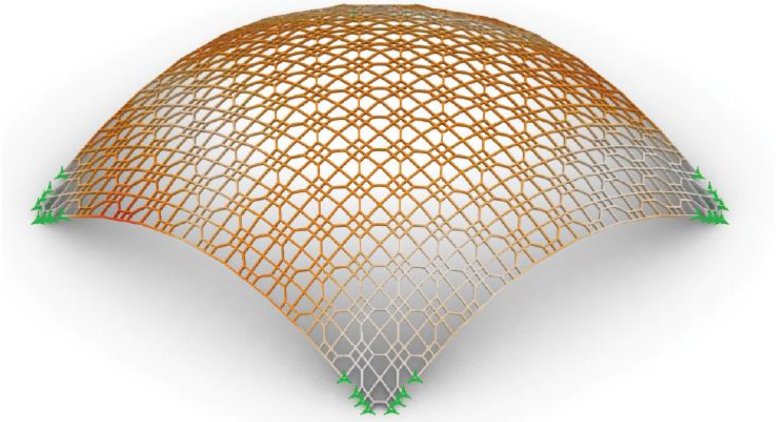
65

## Material quantity optimization

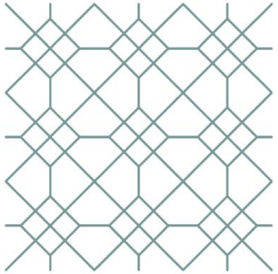
82





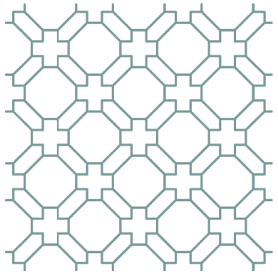


1

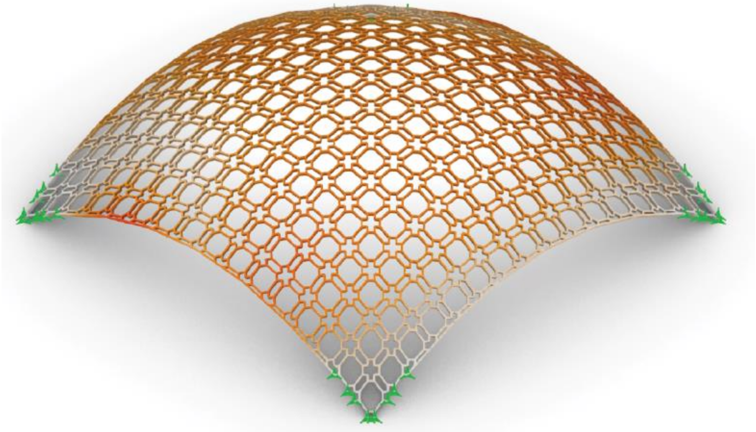


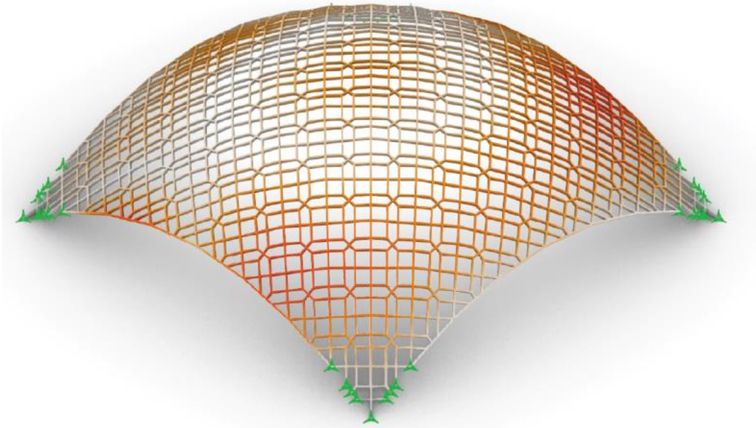
9.6 % ^

45

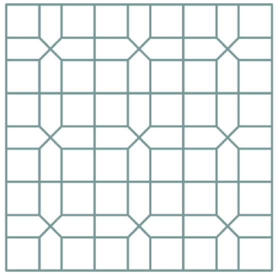


22.66 % ^





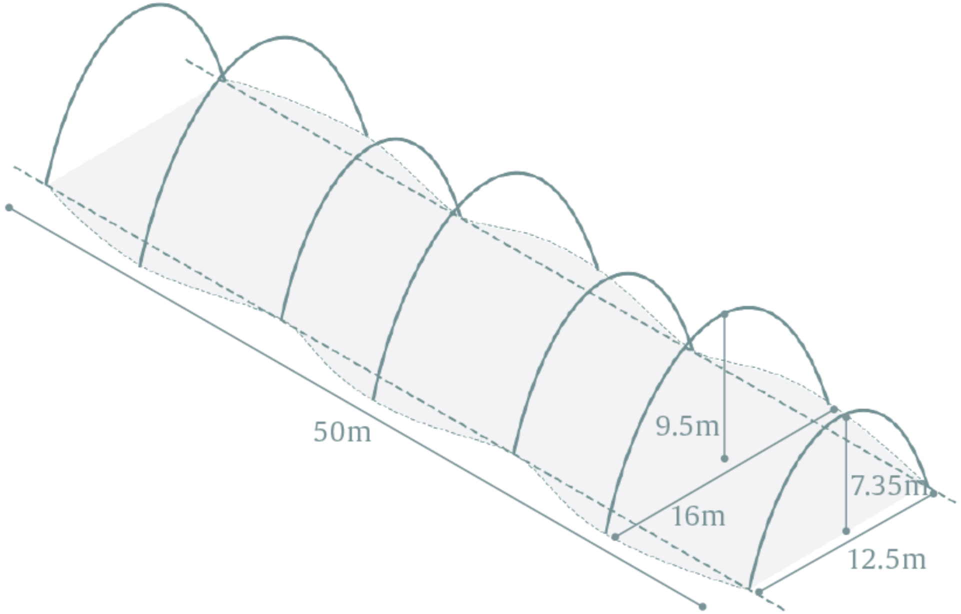
65



6.9 % ^

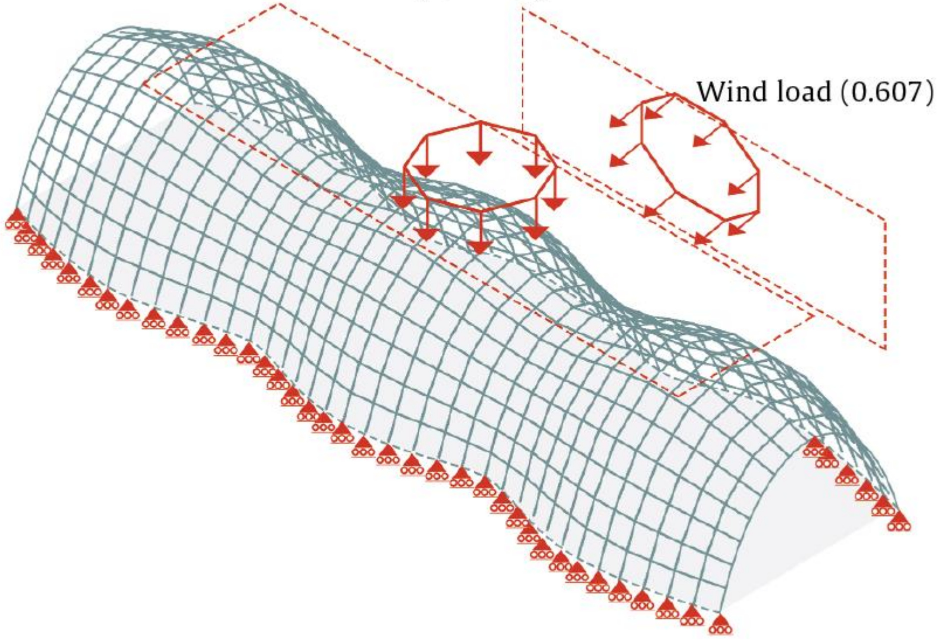
## Case study 1 (Existing building)

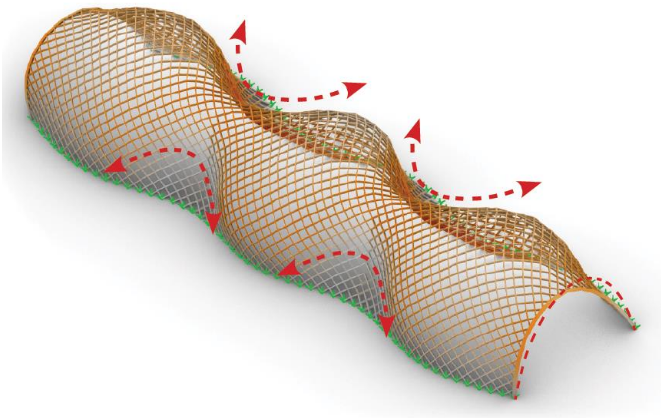

[Weald and Downland Gridshell, 2020]



## Case study 1 (Existing building)


[Weald and Downland Gridshell, 2020]





Scaled visualization of deflection

Grid factor = 10
Cross-section width = 90.6mm

| Pattern 83 | Results | Allowable results |
|---|---|---|
| Deflection (mm) | 63.79 | Span/250 = 64<br>Height of C/S = 148.66 |
| Max normal stress (MPa) | \|-19.12\| | 60 |
| Buckling factor | 13.19 | 2 |
| Max. utilization ratio | \|-0.318\| | 1 |
| Grid density (m) | 2925.13 | - |
| Volume (m3) | 41.14 | - |

## Allowable limits

**Allowable Deflection:**

- Height of cross section

  or

- Shell span/250 (whichever is less)

**Allowable maximum normal stress:**

- Less than the yield strength of a material (<60 MPa)

**Allowable buckling factor:**

- >2

**Minimum grid factor:**

- 7 (to make it less course mesh)

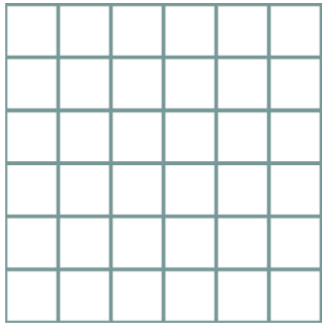


## Multi objective optimization setup

| Objectives | Parameters |
|---|---|
| (V) Minimize Volume | (b) Cross-section width |
| (△) Minimize Deflection (till the allowable limit) | (g) Grid factor (for grid-dentity) |
| (U) Maximize avg. Utilization ratio | |

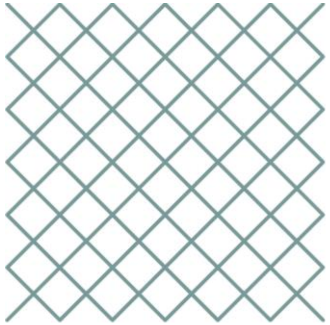
Rank as per the deflection of vault in catalogue

1



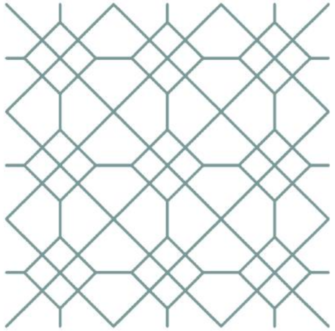
82

4



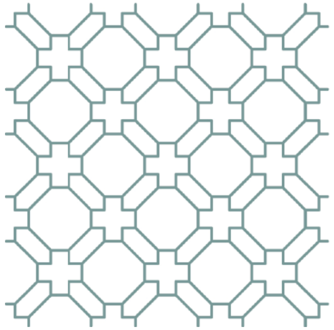
83

3



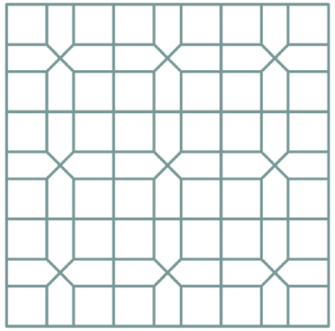
01

5



45

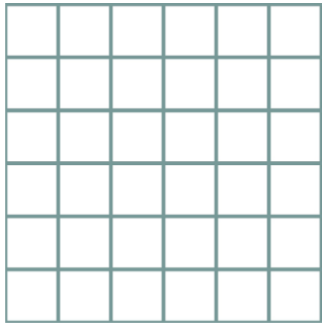
2



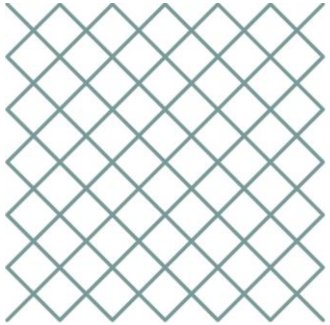
65



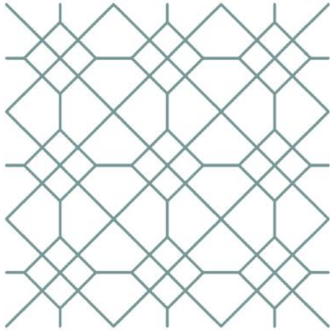
Rank as per the deflection of vault in catalogue: 1, 4, 3, 5, 2



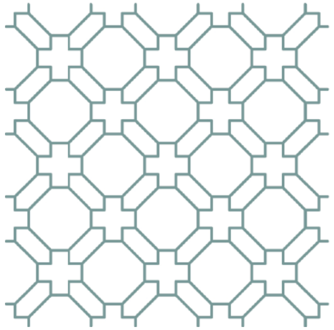
82



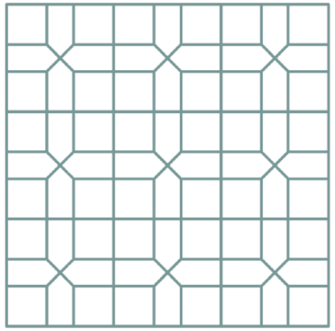
83



01



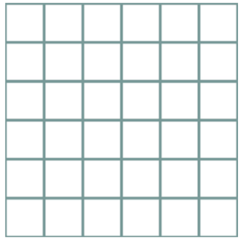
45



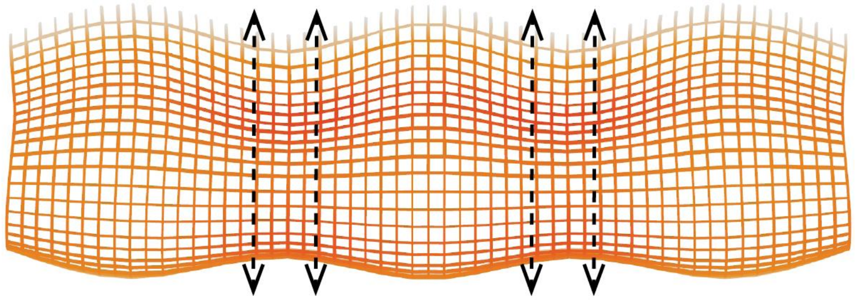
65

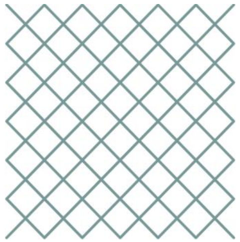
| | 82 | 83 | 01 | 45 | 65 |
|---|---|---|---|---|---|
| Rank as per the deflection of vault in catalogue | 1 | 4 | 3 | 5 | 2 |
| **Volume** | 67.15 | 38.94 | 30.03 | 45.37 | 61.37 |
| **Deflection** | 63.80 | 63.90 | 63.72 | 63.10 | 63.95 |
| **Utilization ratio** | 0.08 | 0.09 | 0.10 | 0.09 | 0.08 |
| Rank as per the volume | 5 | 2 | 1 | 3 | 4 |



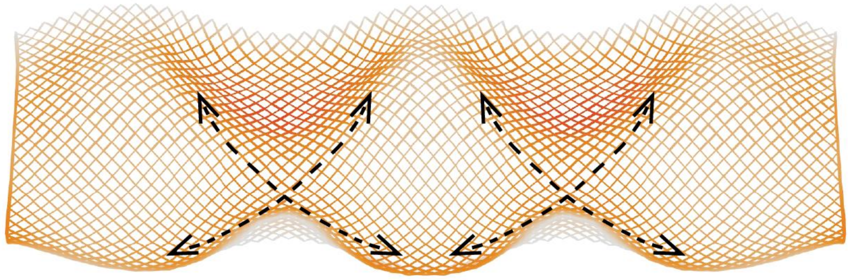


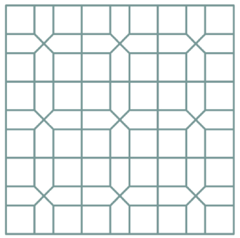
Parallel grid



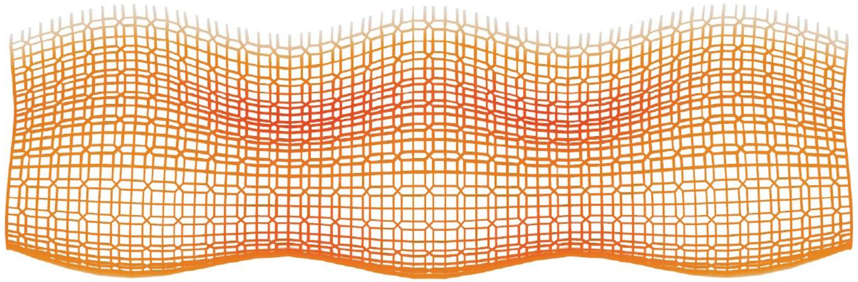


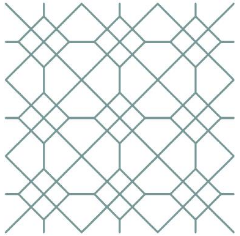
Diagonal grid



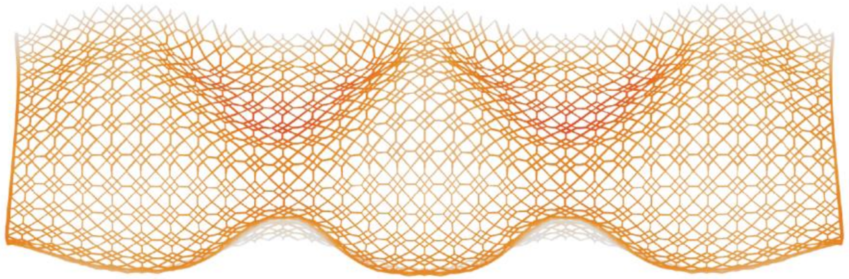


65

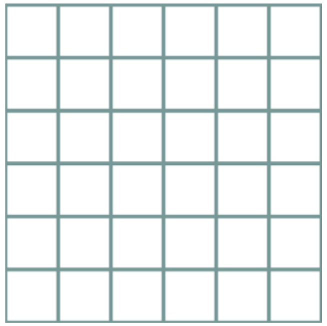


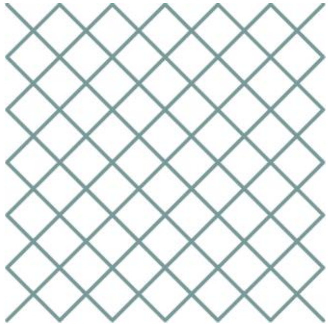


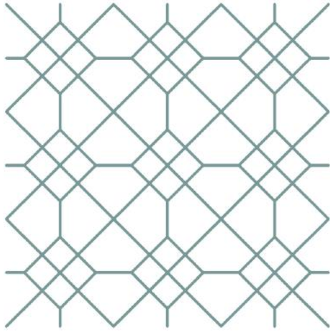
01

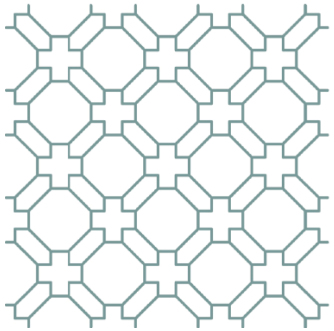


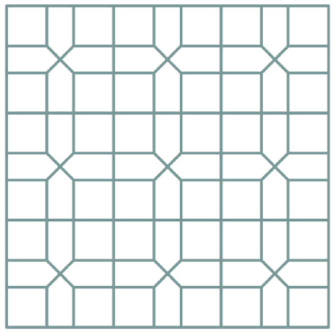




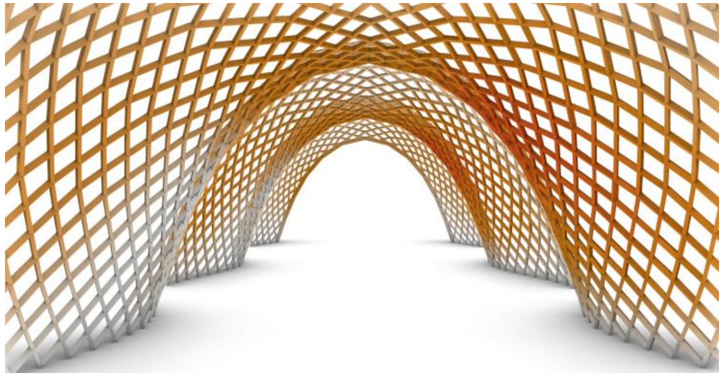


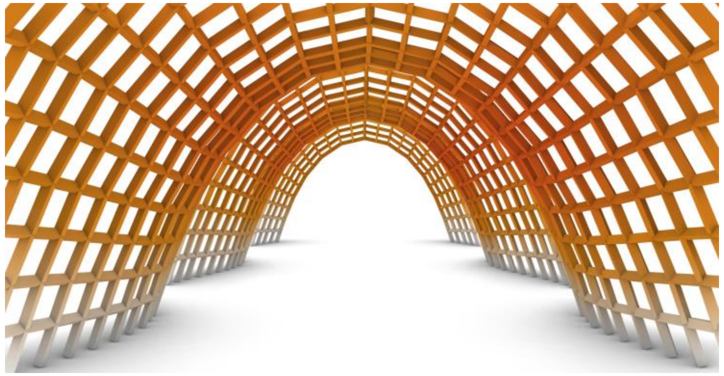


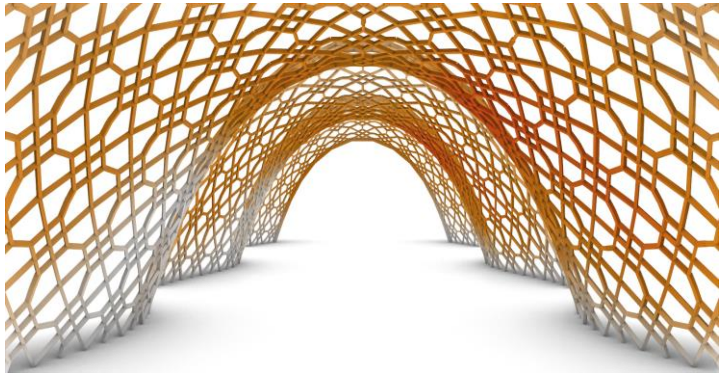


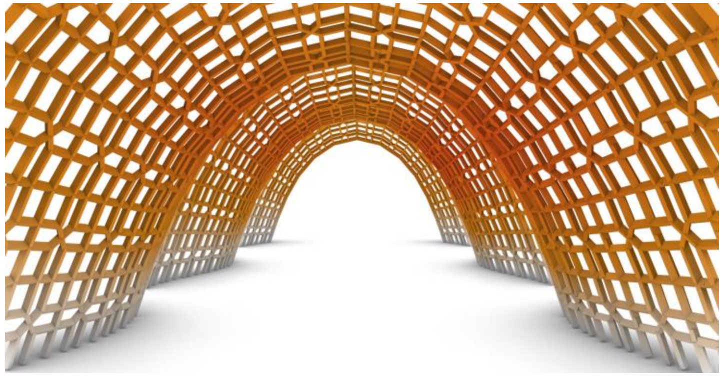


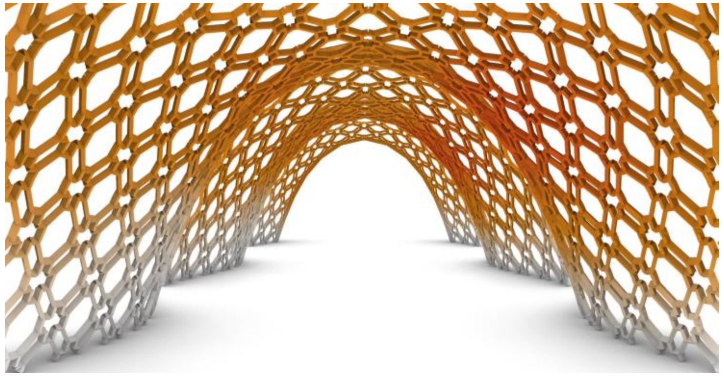
| | 82 | 83 | 01 | 45 | 65 |
|---|---|---|---|---|---|
| Rank as per the deflection of vault in catalogue | 1 | 4 | 3 | 5 | 2 |
| **Volume** | 67.15 | 38.94 | 30.03 | 45.37 | 61.37 |
| **Deflection** | 63.80 | 63.90 | 63.72 | 63.10 | 63.95 |
| **Utilization ratio** | 0.08 | 0.09 | 0.10 | 0.09 | 0.08 |
| Rank as per the volume | 5 | 2 | 1 | 3 | 4 |





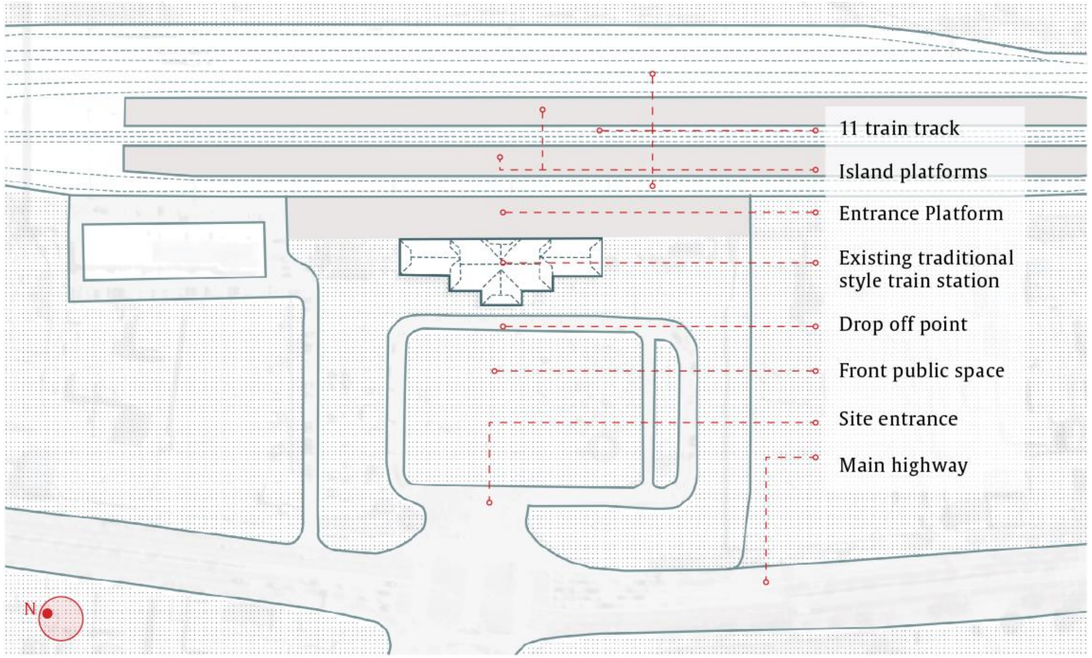


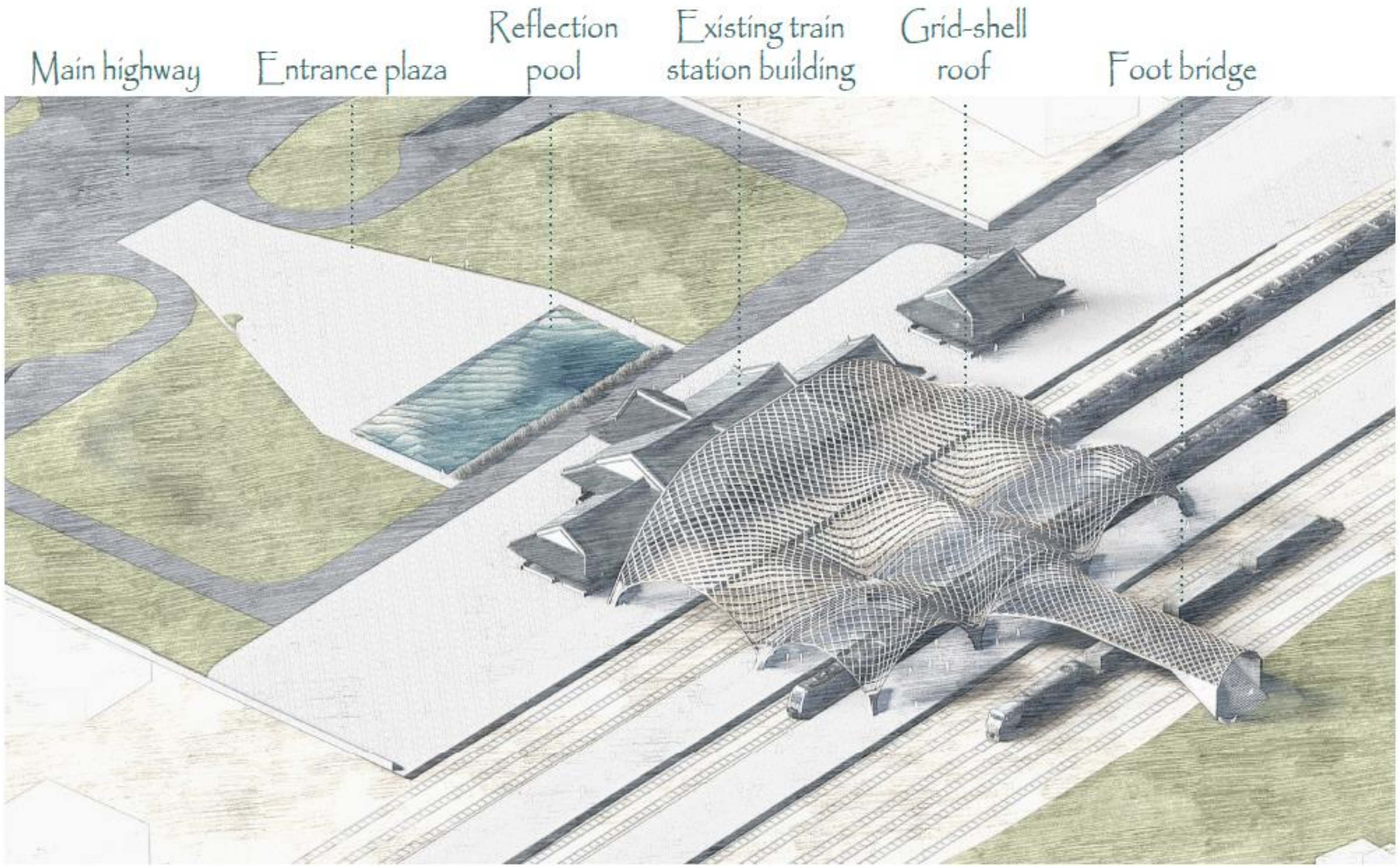


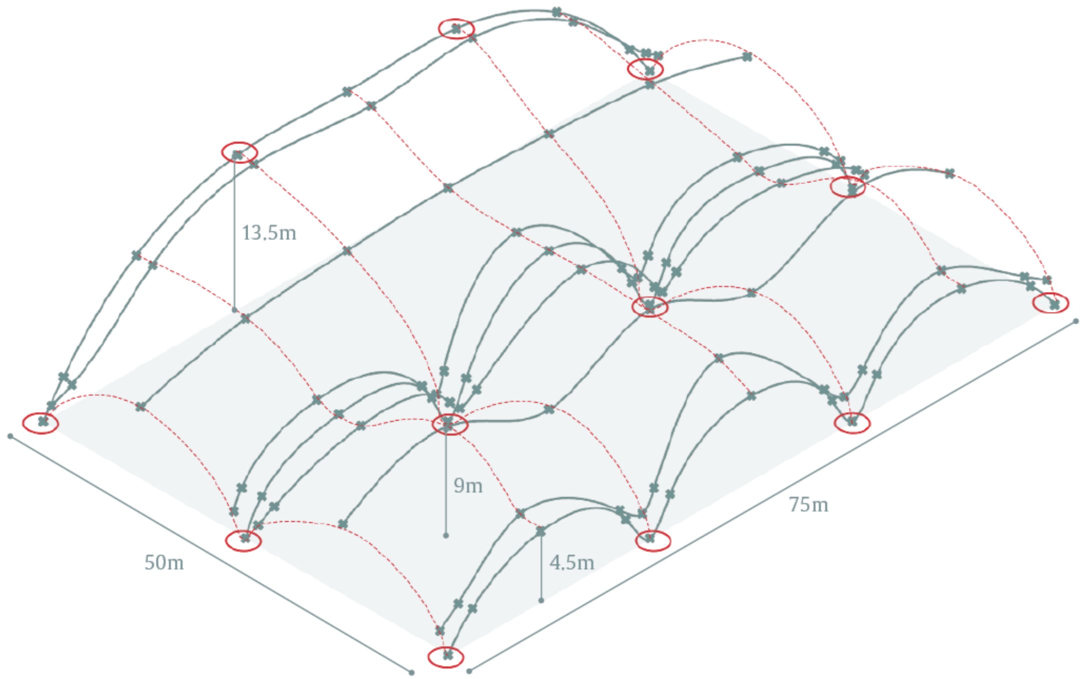


# Roof design

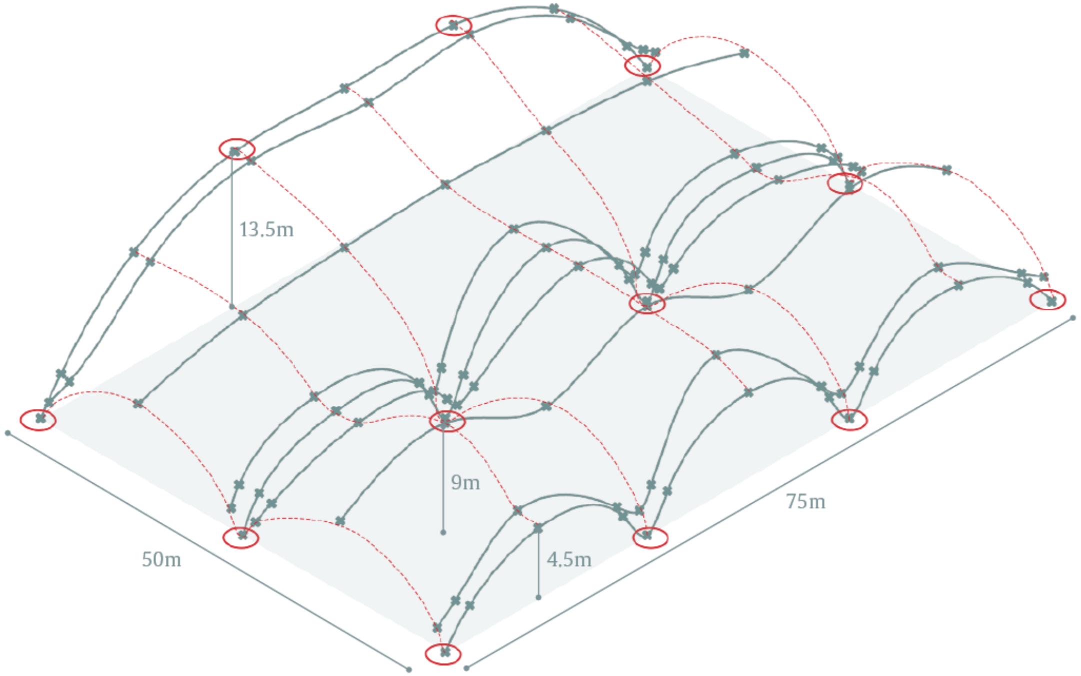
[Project Scope, 2019]



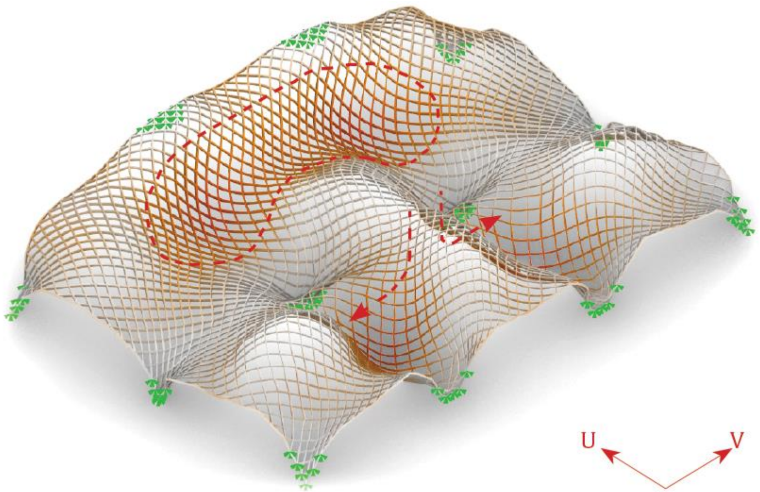

Main highway
Entrance plaza
Reflection pool
Existing train station building
Grid-shell roof
Foot bridge


13.5m
9m
4.5m
50m
75m




13.5m
9m
4.5m
50m
75m






Scaled visualization of deflection

Grid density = 7796m
Cross-section width front = 16.84mm
Cross-section width rear = 13.15mm

| Pattern 82 | Results | Allowable results |
|---|---|---|
| Deflection (mm) | 141.3087 | Span/250 = 141.42 |
| | | Height of front C/S = 277.86 |
| | | Height of back C/S = 216.97 |
| Max normal stress (MPa) | \|-59.94\| | 60 |
| Buckling factor | 6.845276 | 2 |
| Max. utilization ratio | \|-0.99\| | 1 |
| Grid density (m) | 7796.548 | - |
| Volume (m3) | 291.573 | - |

## Allowable limits

### Allowable Deflection:

- Height of cross section

  or

- Shell span/250 (whichever is less)

### Allowable maximum normal stress:

- Less than the yield strength of a material (<60 MPa)

### Allowable buckling factor:

- >2

### Minimum grid factor:

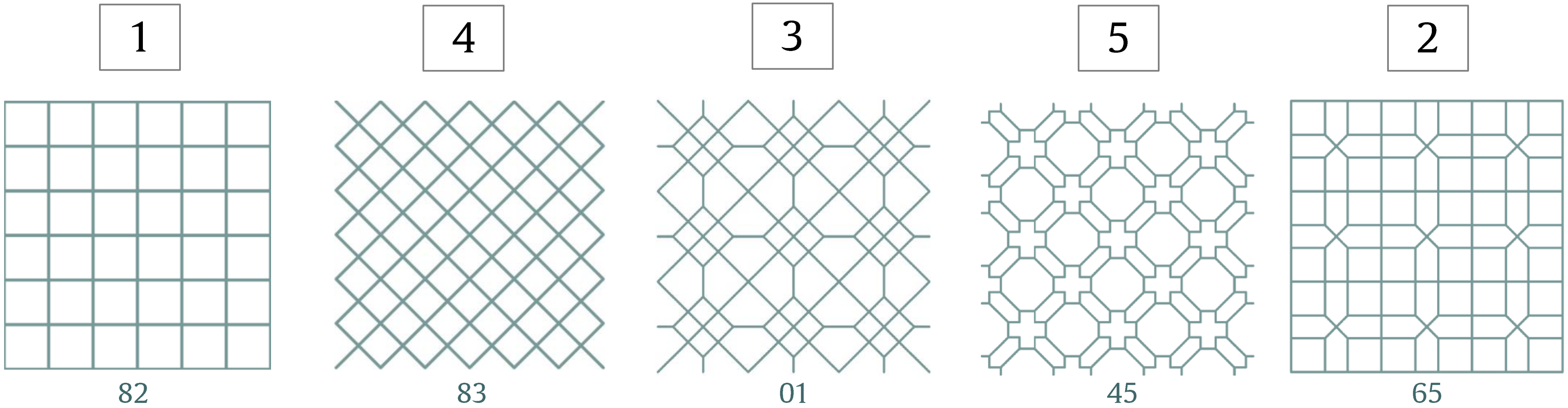
- 7 (to make it less course mesh)

## Manual optimization plan

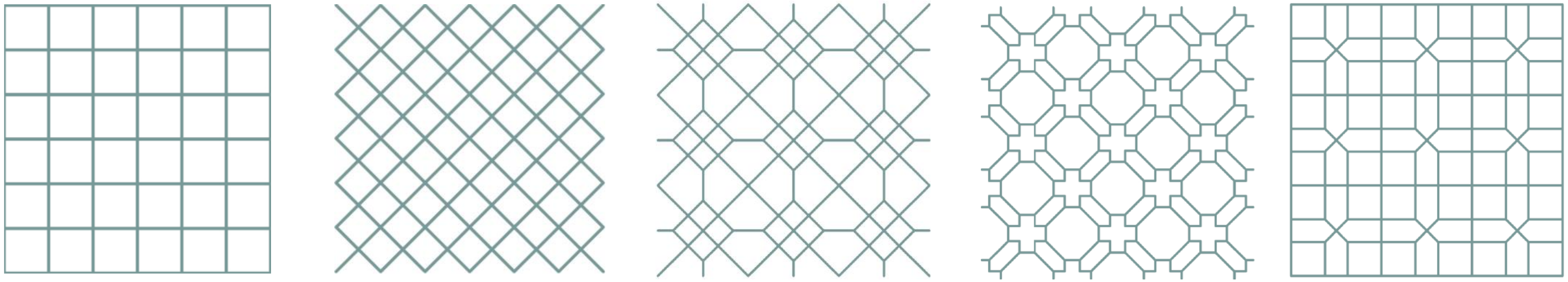
| Target | Parameters |
| --- | --- |
| Minimize Volume | Cross-section width for front side |
| Minimize Deflection (till the allowable limit) | Cross-section width for rear side |
| Minimize Normal stress (till the allowable limit) | |



Rank as per the deflection of vault in catalogue

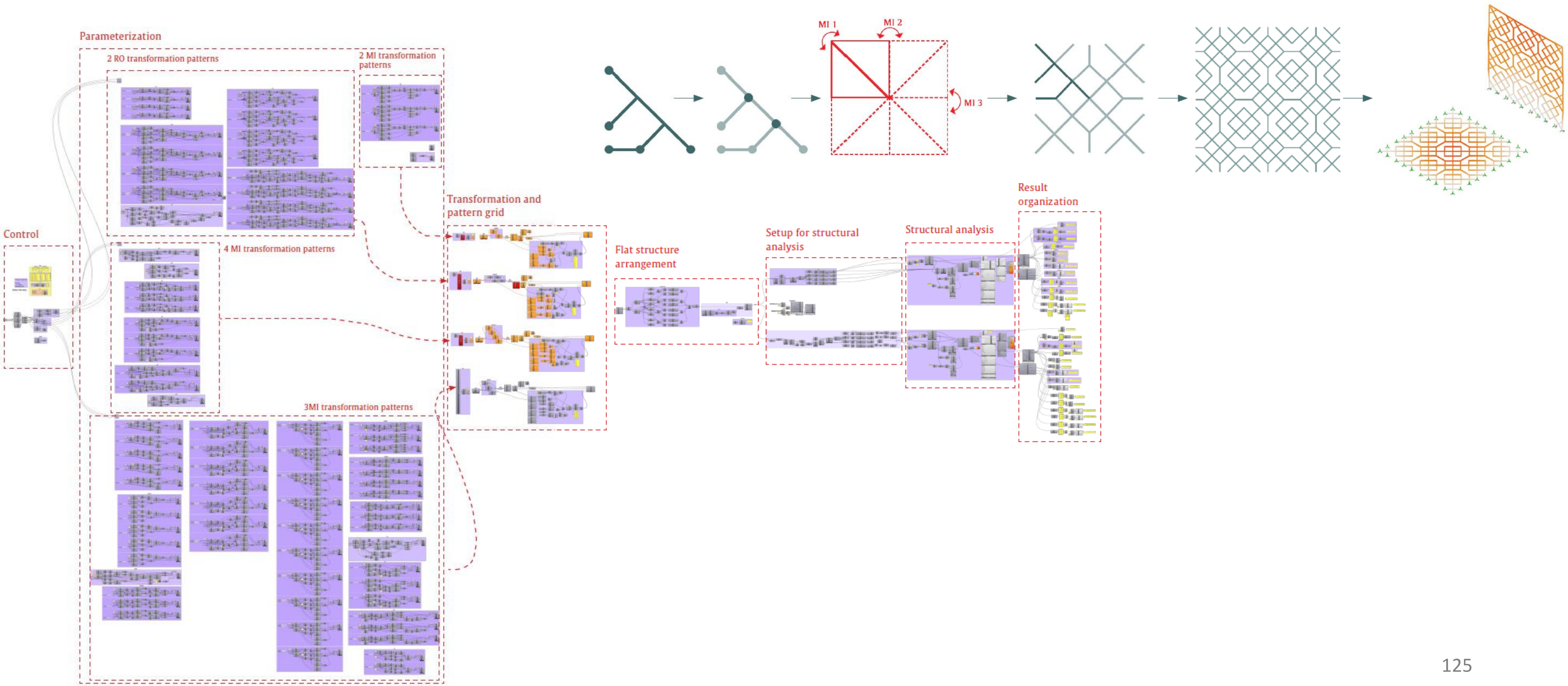




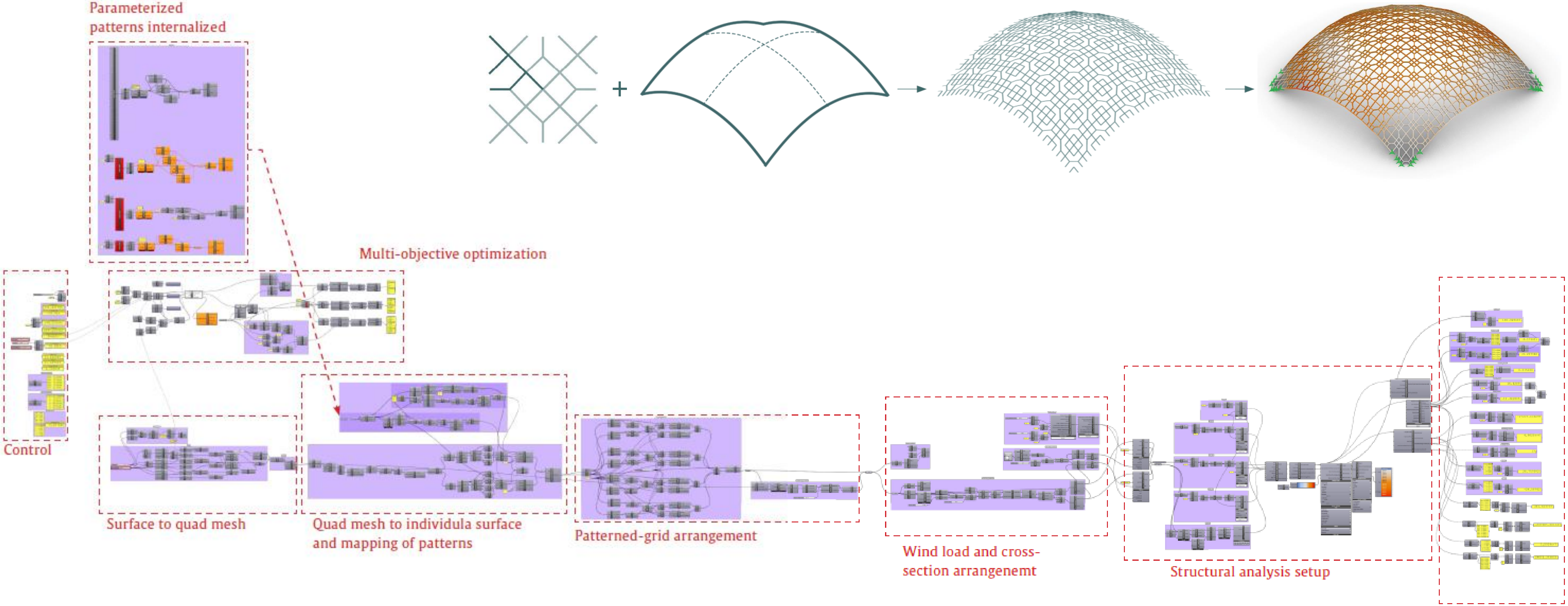


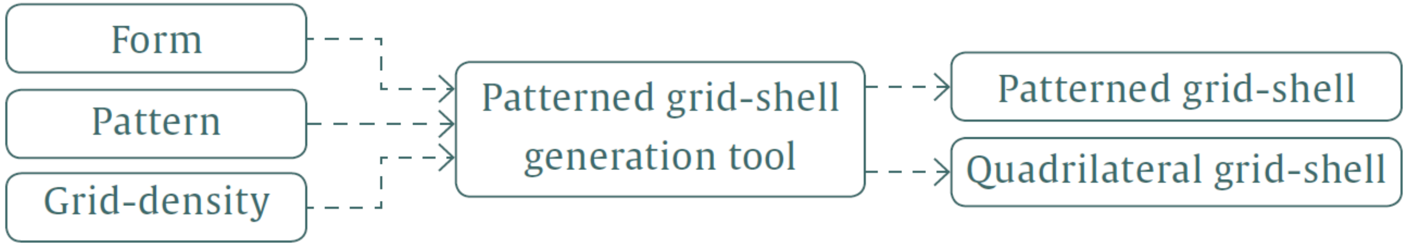
| | 82 | 83 | 01 | 45 | 65 |
|---|---|---|---|---|---|
| Rank as per the deflection of vault in catalogue | 1 | 4 | 3 | 5 | 2 |
| **Volume** | 291.57 | 509.19 | 409.90 | 528.30 | 324.07 |
| **Deflection** | 141.31 | 141.30 | 141.34 | 141.29 | 141.29 |
| **Max. Normal stress** | \|-59.94\| | \|-59.88\| | \|-59.97\| | \|-59.82\| | \|-59.90\| |
| Rank as per the volume | 1 | 4 | 3 | 5 | 2 |

# Application in practice



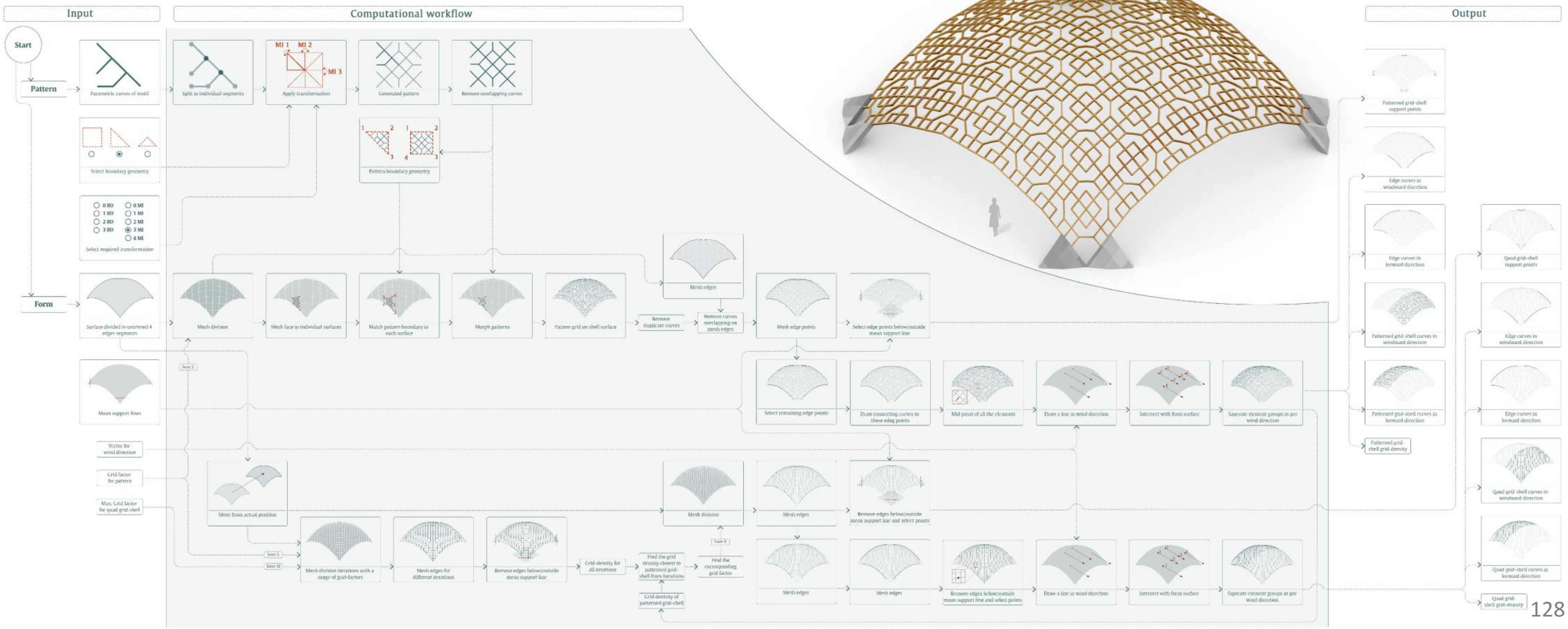
## Application in practice



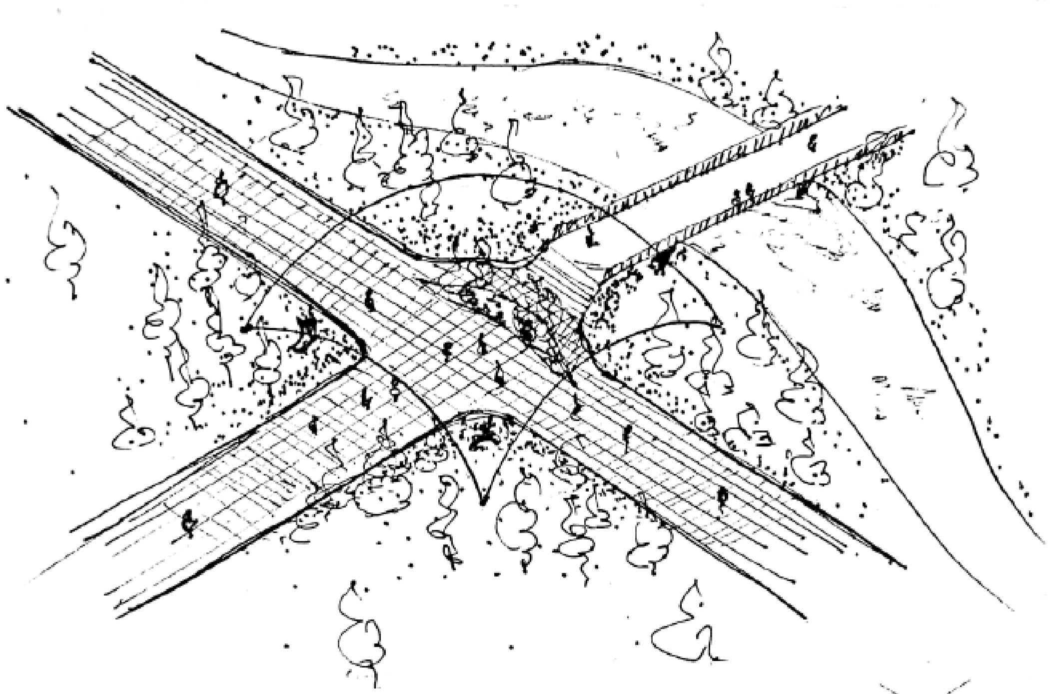

Form
Pattern
Grid-density
Patterned grid-shell generation tool
Patterned grid-shell
Quadrilateral grid-shell

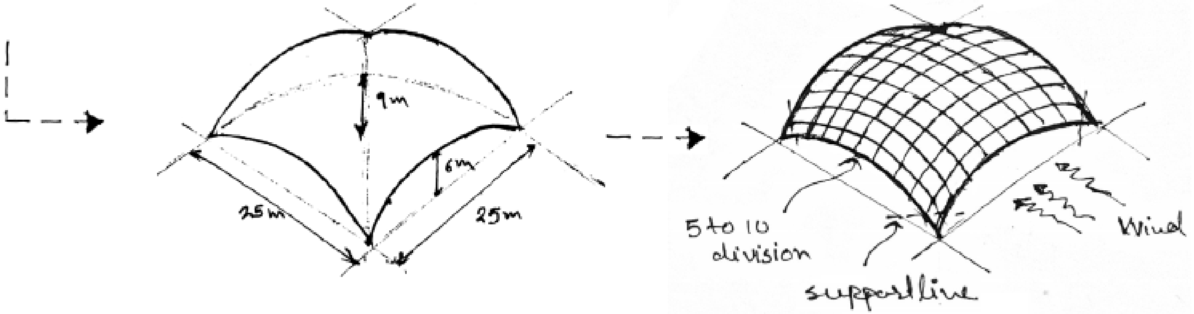
# Computational tool

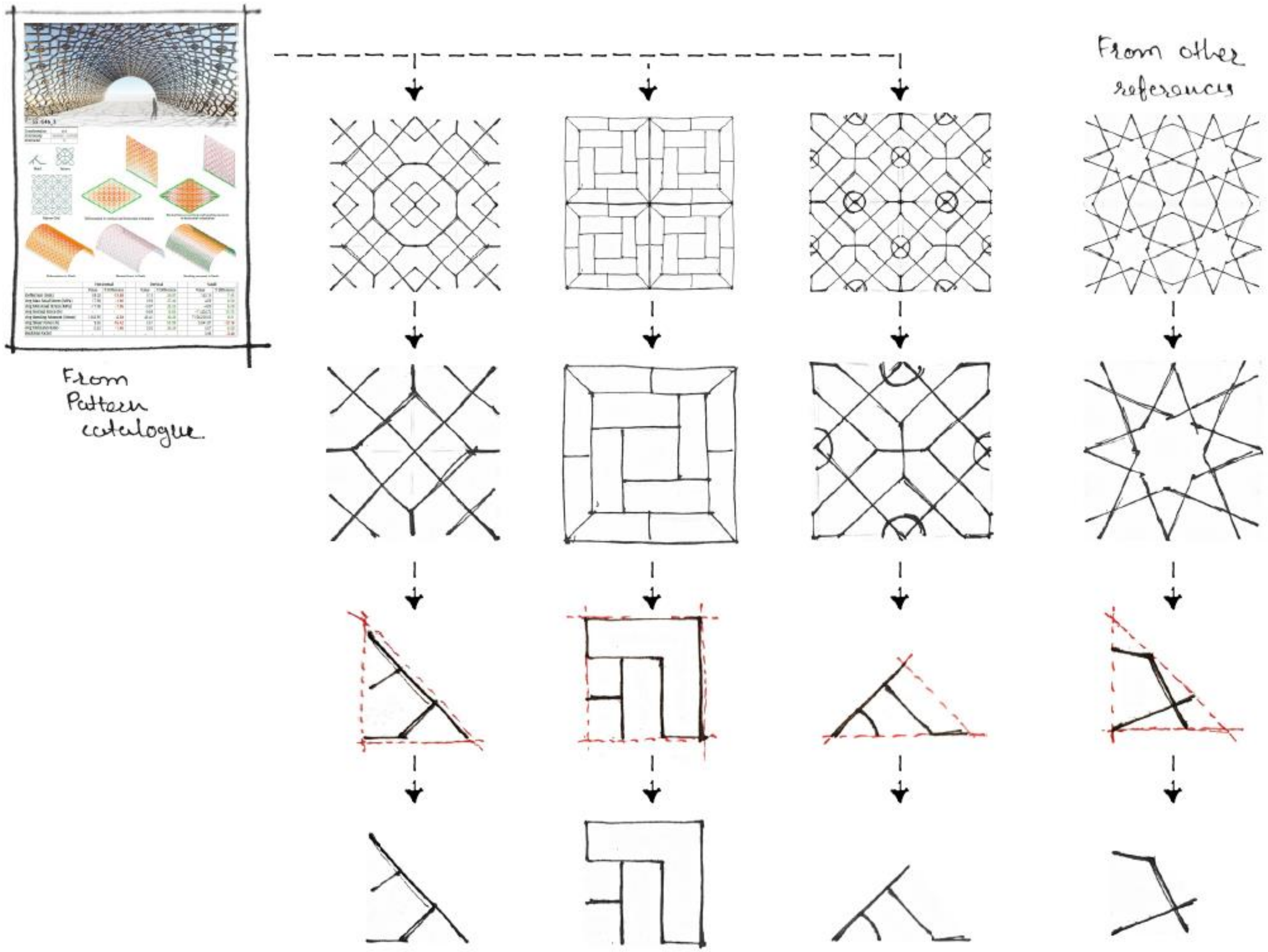

## Patterned grid-shell generation workflow



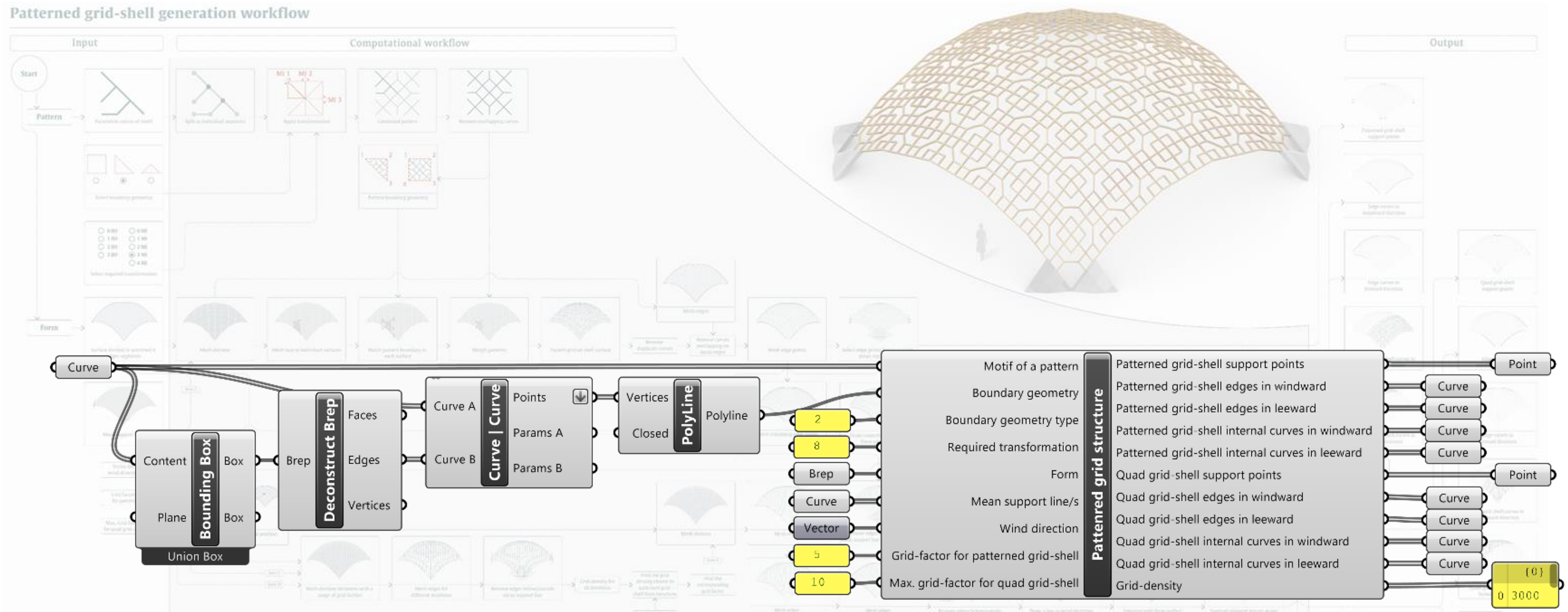
## Computational tool





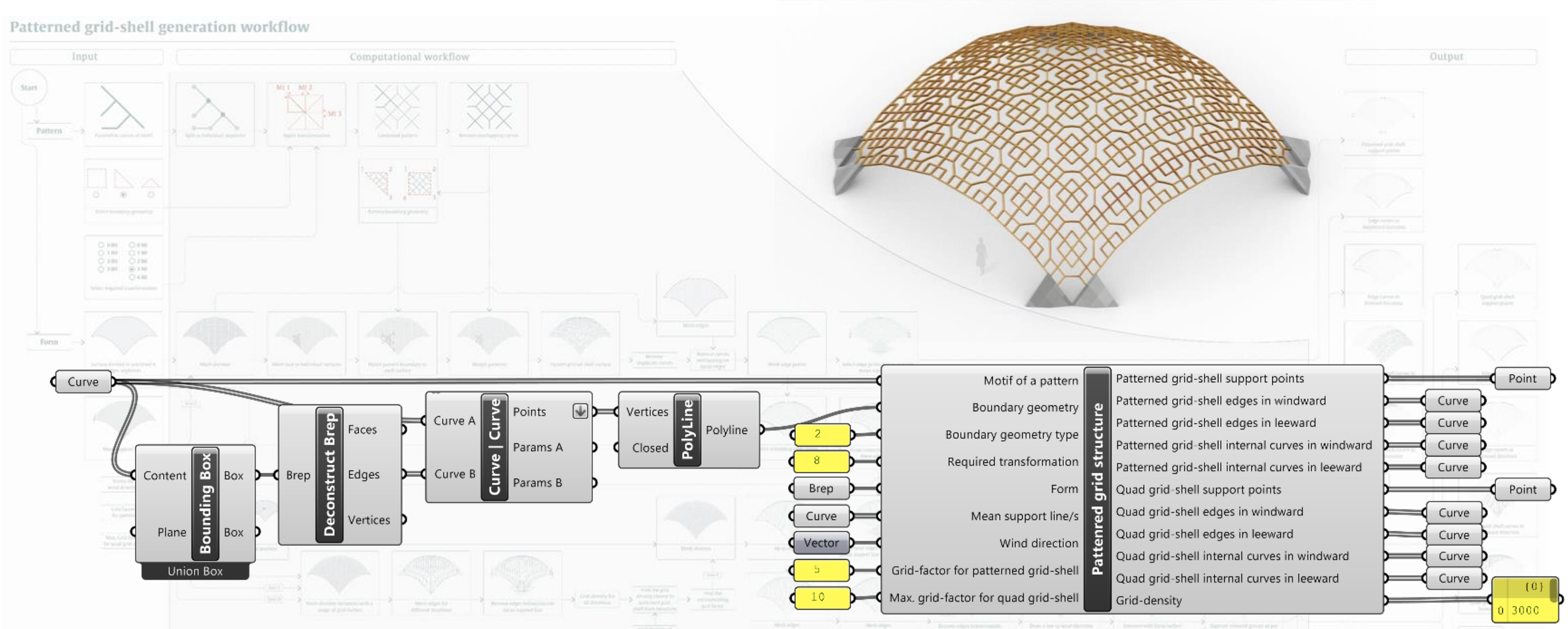

From other references
From Pattern catalogue

## Computational tool


Example image of tool

## Computational tool


Example image of tool

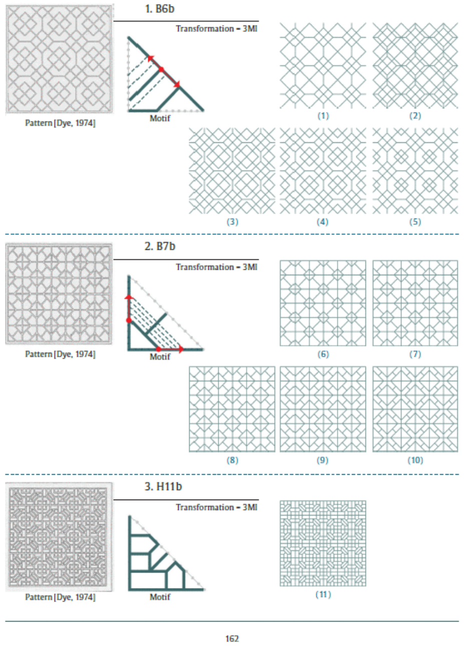
## Utility

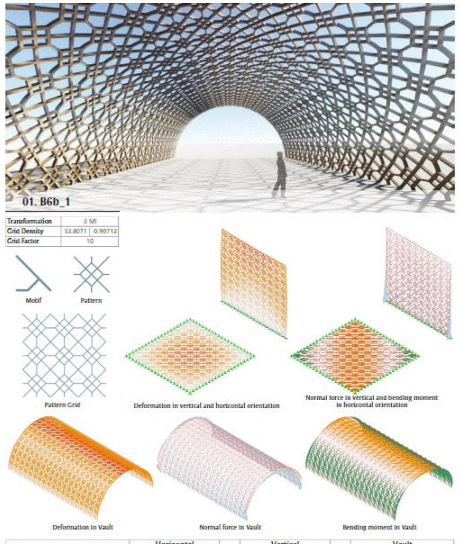
## Guidelines to make choices

- Computational designing
- Structural analysis

## Pattern catalogue

- Parameterization
- Structural performance




| | Horizontal | | Vertical | | Vault | |
|---|---|---|---|---|---|---|
| | Value | % Difference | Value | % Difference | Value | % Difference |
| Deflection (mm) | 59.85 | -25.61 | 0.12 | 20.62 | 142.67 | 7.09 |
| Avg Max Axial Stress (MPa) | 19.19 | 4.62 | 0.65 | 51.25 | 4.53 | 17.94 |
| Avg Min Axial Stress (MPa) | -19.19 | 4.62 | -1.08 | 40.64 | -4.53 | 17.94 |
| Avg Normal Force (N) | - | - | -11.00 | 27.12 | -12,003.36 | 21.83 |
| Avg Bending Moment (Nmm) | 1,122.02 | -1.39 | 50.36 | 44.45 | 79,64,600.00 | 11.86 |
| Avg Shear Force (N) | 10.80 | -3.61 | 3.90 | 72.13 | 5,295.29 | -8.79 |
| Avg Utilizatio Ratio | 0.32 | 4.62 | 0.02 | 40.64 | 0.08 | 17.94 |
| Buckling Factor | - | - | - | - | 4.39 | 6.70 |

172

## Research question

**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

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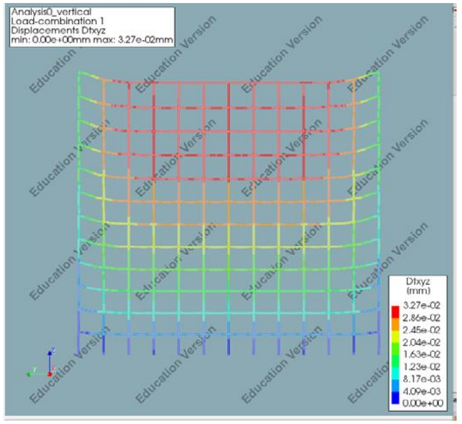
1. Structure of patterns
2. Parameterization of a patterns
3. Generating patterned grid-shell
4. Material quantity optimization

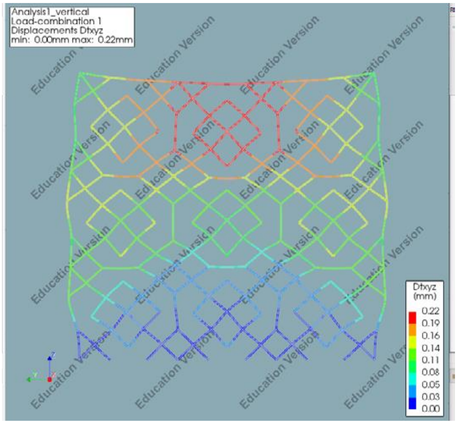
## Research question

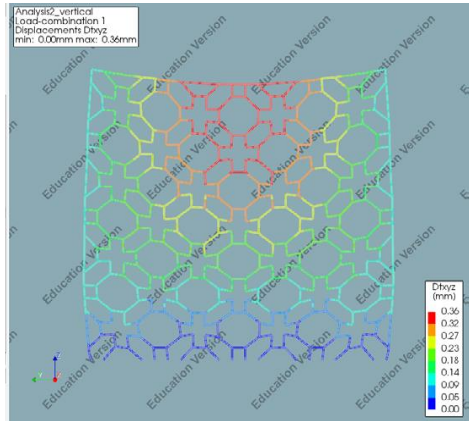
**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

1

Structure of patterns



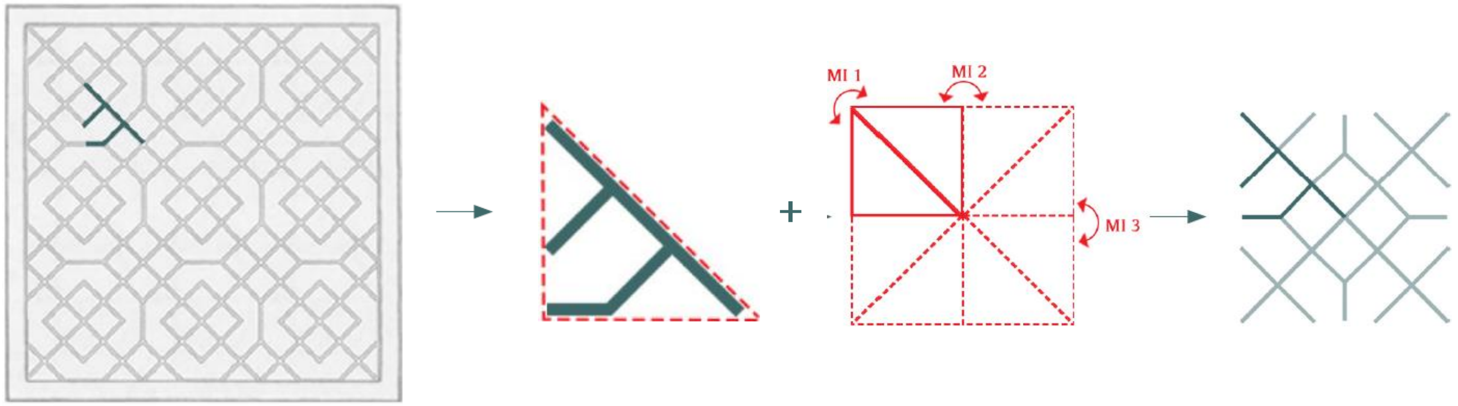



## Research question

**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

2

Parameterization of a patterns

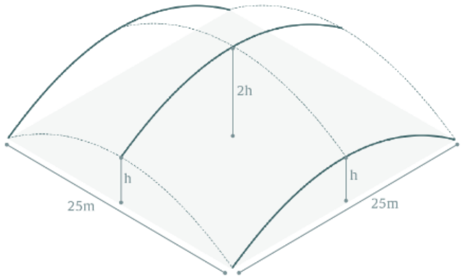


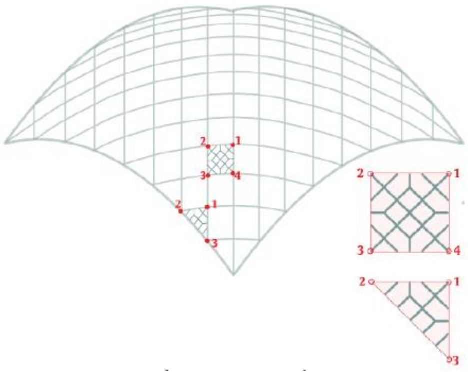
## Research question

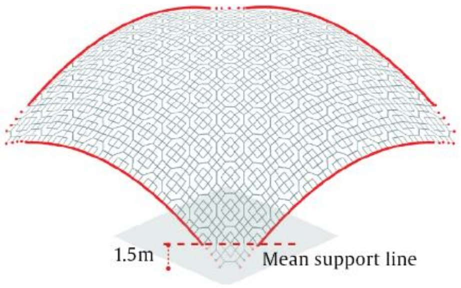
**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

3

Generating patterned grid-shell



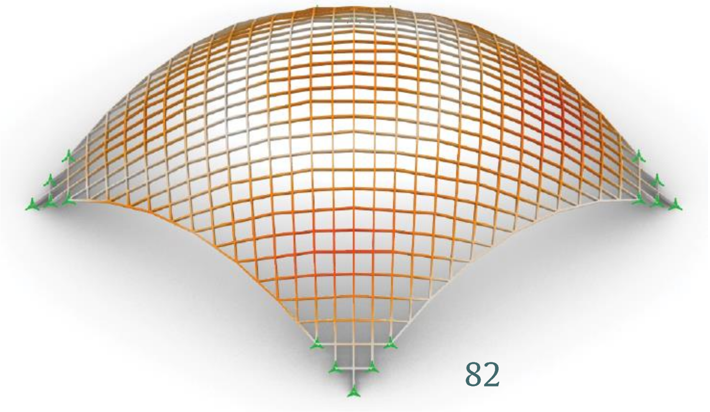


## Research question

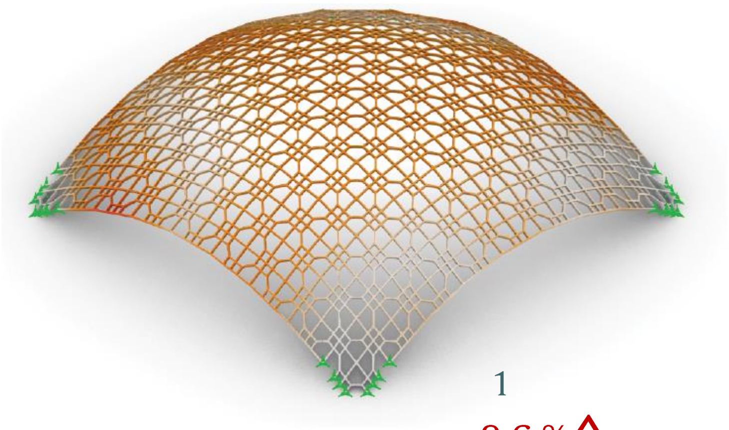
**Main Question:** *With the help of parametric workflow, how to design an urban grid shell structure, where the line patterns (in this case, north Asian lattice pattern) are selected based on the structural performance and used in load distribution as a grid geometry?*

4

Material quantity optimization



82



1

9.6 % ^

## End note

*This method is an attempt to utilize the ancient traditional art of lattice patterns in contemporary architectural style with the help of building technology. By which, it aim to establish socio-cultural sustainability in built environment. However, it certainly consumes comparative high amount of material than the conventional methods. Thus, it has a tread-off between material usage and socio-cultural sustainability, which a designer can balance.*

## End note

*This thesis is dedicated to all the designers as an encouragement to adapt the ethos of a city/town from a different layer of urban settlements in their designs. It will create much more vibrant and unique cities and technology has an enormous potential to make it sustainable for us!*

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Thank you.

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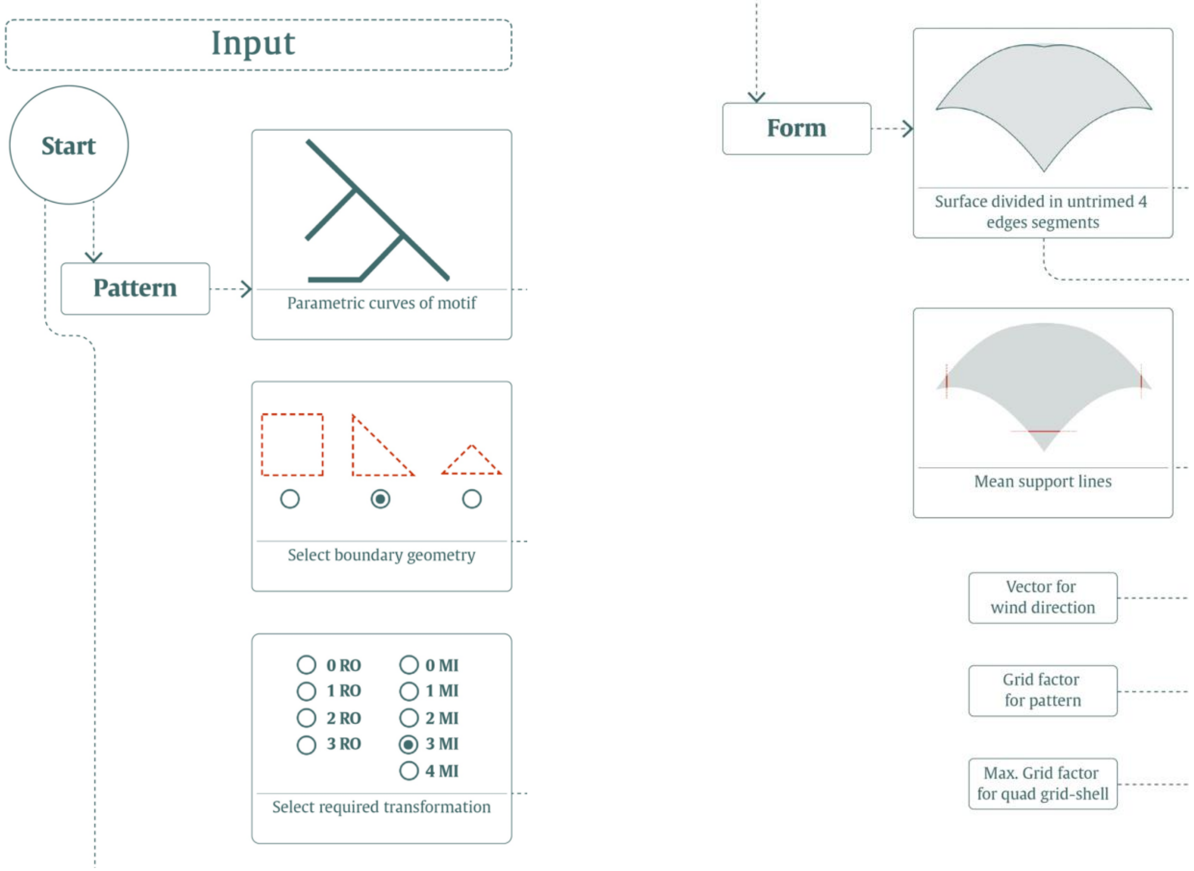
**SECOND MENTOR :** Ir. Peter Eigenraam

**DELEGATE EXAMINERS :** Dr. H.T. Remoy

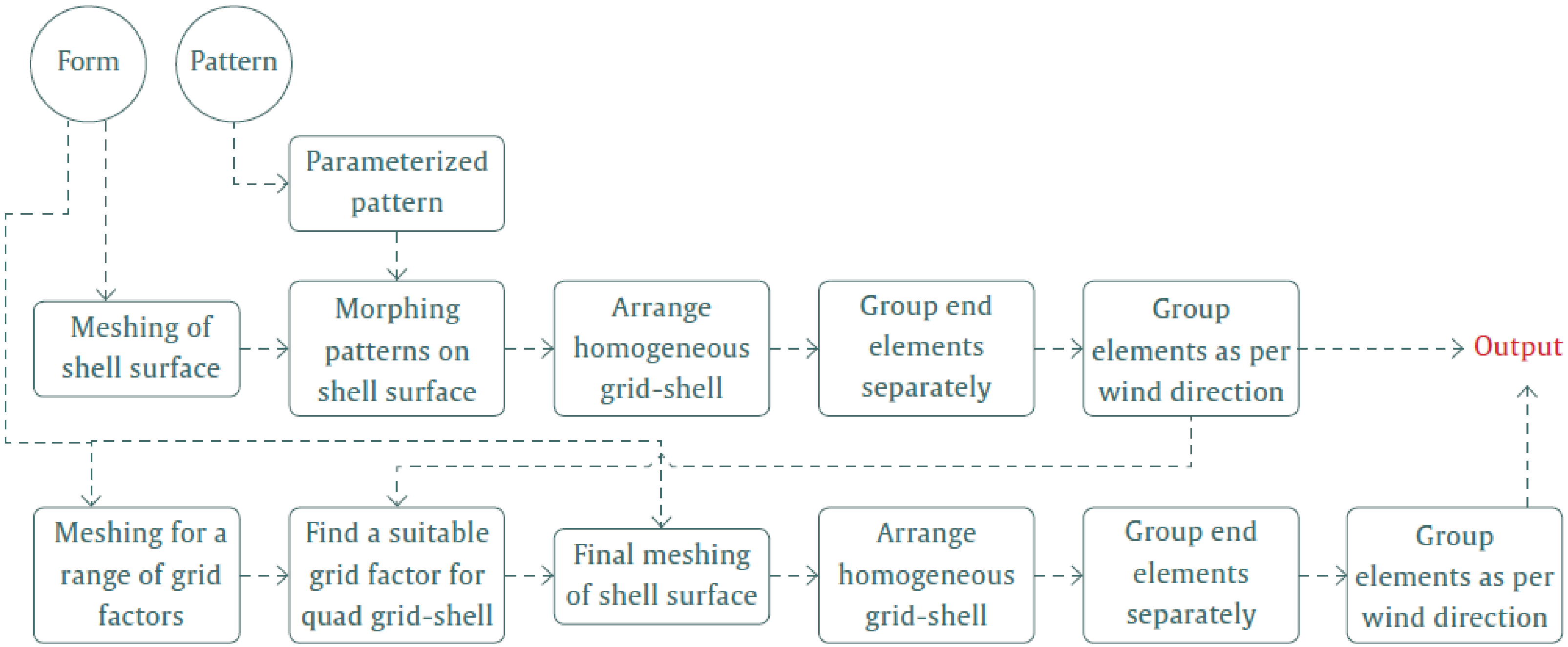
TU Delft
Delft University of Technology

30/06/2020

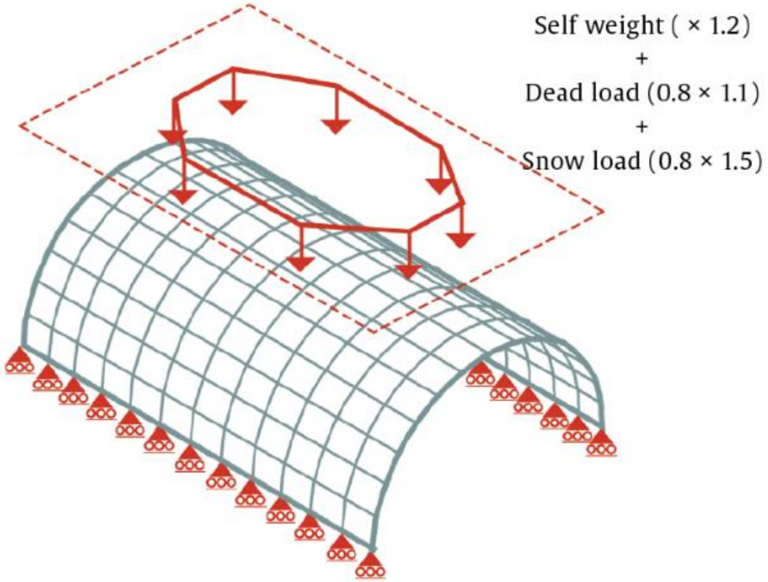
## Computational tool

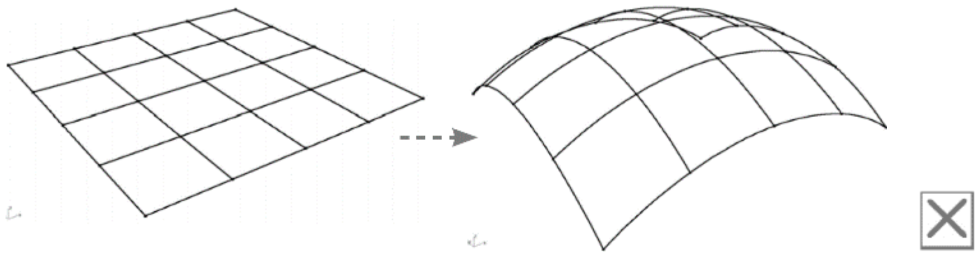



## Computational tool

- The simultaneous exploration of patterns, materials, cross-sections and planarity of beam.
- Variation in grid-density and cross-section as per load distribution.
- Development of joints with topology optimization technique.
- More elaborate use of multi objective optimization by optimizing the overall moment of joints.
- The workflow can be coupled with dynamic relaxation methods in plug-ins like Kangaroo.
- The workflow can be further developed to generate patterned grid-shell with 3D patterns (different version of spaceframe)



[Seele, 2014]

[Tim M. Worsfold, 2018]

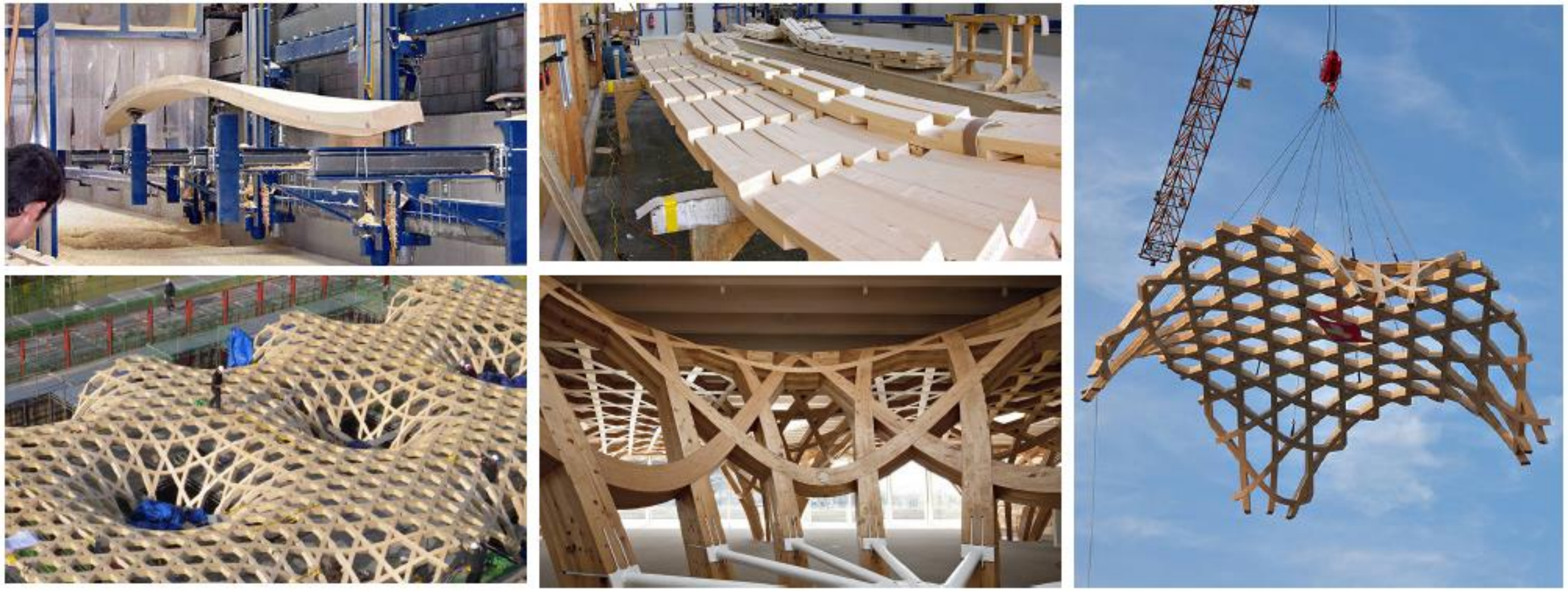
[Seele, 2014]

[Seele, 2014]

[Tim M. Worsfold, 2018]

[Seele, 2014]

Roof of a Lobby [Rondina, 2014]



Bending of wooden elements (top left), Bent beams with grooves (top middle), Assembled roof (bottom left),
Metal joint at supports (bottom middle), Assembly of a per-fabricated roof segment (right) [Rondina, 2014]

## Patterned grid-shell generation

- Only compatible for rectangular grid at the present and related pattern.
- Grid divisions is similar throughout the surface. Variations of grid-density is not possible.
- Need more elaborate logic to end different patterned grid-shells at the supports.
- Workflow is limited to linear elements. Curved elements are not generated.

## Structural performance results

- Comparison is derived only based on different geometries, different materials, cross-section shape and sizes are not explored.
- For joints, fixed configuration is used and possible stiffnesses are not considered.
- The reference results in pattern catalogue are validated to be useful with single curvature surface (like vault, sinclastic or anticlastic surfaces). For surfaces with more than one curvatures the results may differ from the expectations.

## What should have had done differently

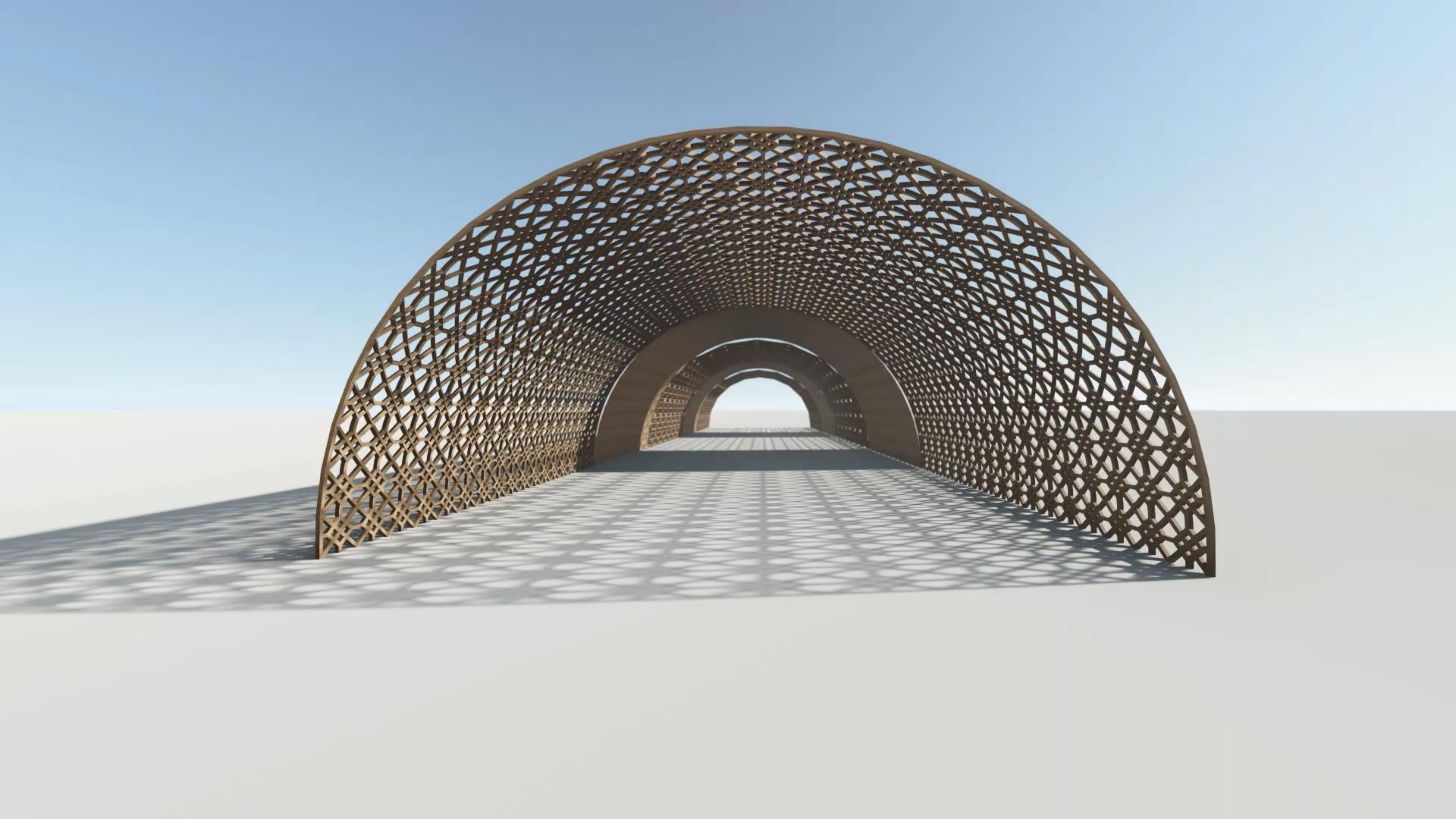
Should have given more time between flat structure and vault structures to study possible fabrication techniques

**For**

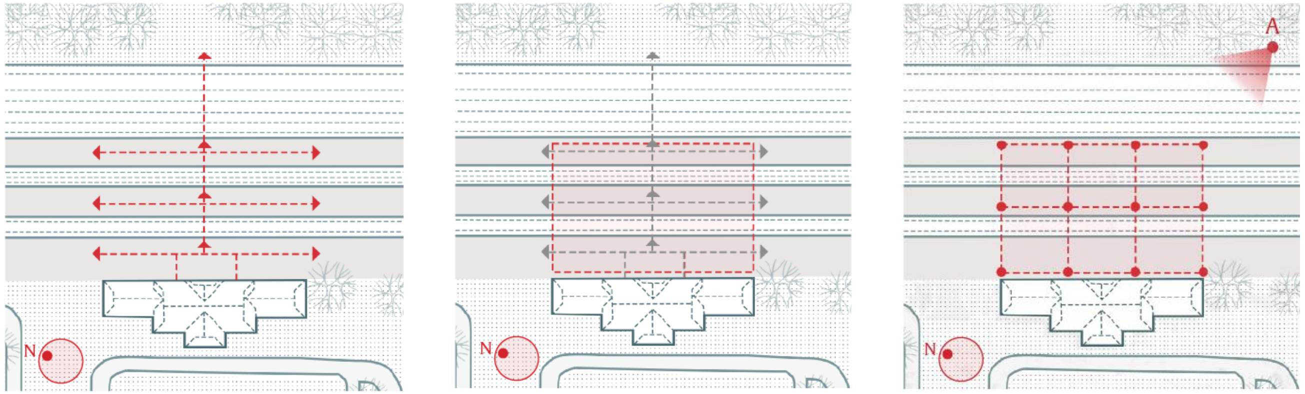
Different edge element cross-section

Preliminary idea of joints

Better smoothness of generated grid-shell






N
N
A
N