

Chapter 5

Design Alternatives of the Cellular Wall

This chapter will discuss the design alternatives of the cellular wall. A design exploration diagram has been drawn to clarify the design constraints and their requirements, following the proposal of structural parameters. Various structural materials with construction methods and different grid types have been compared. At last, some references study for the structural patterns and grid structures will be recorded.

“There is no method that enables us automatically to discover the most adequate structural type to fit a specific problem as it is faced by the designer. The achievement of the final solution is largely a matter of habit, intuition, imagination, common sense and personal attitude. Only the accumulation of experience can shorten the necessary labor or trial and error involved in the selection of one among the different possible alternatives.

- Eduardo Torroja”

5.1 Design Exploration Diagram

A Design Exploration Concept - ‘Constraints as design drivers’ was proposed by Axel Killian (MIT, 2006): “Design can be described as a process of emergence and discovery resulting from the definition of the constraints, their relationships, and the design problem. The constraints that form the boundaries of the problem can also serve as design drivers for possible design solutions. Understanding the constellation of constraints is crucial, and it goes hand in hand with the creation of design solutions. Every design move creates additional constraints and consequently triggers contextual responses.”

Constraints are generally viewed as limiting factors in design. But there is evidence in some research and architectural practice that constraints can trigger the development of innovative design solutions and are a powerful way to drive solution space. Constraints can help to focus design exploration through formulating the boundaries of available resources. There are various types of constraints that can be applied to a range of aspects of the design problem. While constraints may initially prove to be a limitation, over the course of the design process they can evolve to become a driver for innovative design solutions.

The first step to aid this transition is to externalize the constraints. It is a necessary step in constructing a design explorer. The analysis of the design problem through diagrams provides the dependency network between the constraints. In the next step of constructing the exploration framework, the constraints are translated into appropriate design representations. Finally, physical or digital implementation choices are made to complete the design explorer.

By integrating the design constraints, a basic design exploration diagram for the cellular wall of SNHM is shown in Fig.5.1. The objective of this cellular wall design exploration is pursuing an adaptive pattern/ configuration for the wall structure.

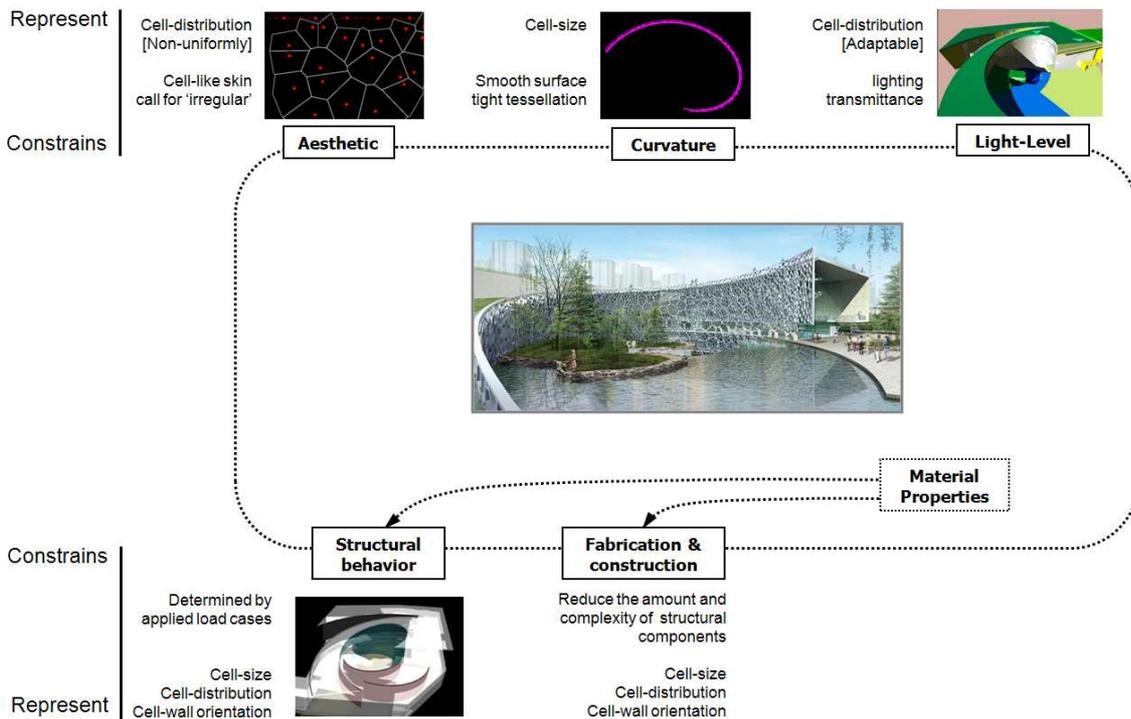


Fig.5.1 Design exploration diagram for the adaptive pattern

For the specific design case of this cellular wall, the geometry of the wall surface was determined in advanced. Thus, the design exploration should focus on an adaptive pattern (cell-like) – in which the parameters include: cell-size, cell distribution, cell-wall orientation etc. The goal of the design exploration process is to target an optimal combination of these parameters.

In the design exploration diagram, the main design constraints are: Aesthetic, Curvature (of the wall surface), Light-level, Structural behavior, and Fabrication&construction technologies. Each of them will have specific requirements for the design parameters. For example, the curvature of the wall surface restrains the cell-size - the sizes of the mesh elements should be small enough to smoothly represent the surface by tight tessellation. This is important for most double-curved free form architecture. However, in this case, the geometry of the surface is relatively simple, which reduces this requirement. In addition, some of these design constraints have conflicts with the others. For example, the Aesthetic constraint calls for an 'irregular' pattern to symbolize human cellular structure, while Fabrication&construction pursues a higher 'regular' level to reduce the technology complexity.

For structural optimization strategy, the main focus point is Structural behavior. This constraint is complicated, since various load cases (dynamic load/wind load/vertical load from the green roof, etc.) might be taken into account. As discussed in the former chapter, parametric design approach can be used for the rapid generation of computable design representations describing design alternatives. By analysis and evaluating of the design alternatives, an insight into the impact of the structural parameters on structural behaviors can be gained.

5.2 Material and construction technology

5.2.1 Structural Integrity



The cellular wall is comprised of three layers of material and structure:

- 1_ primary structure
Large scale pattern, as skeleton with important structural functions
- 2_ glass layer
A membrane of glass as façade cladding structure
- 3_ shading layer
Smaller scale pattern, with symbolic and shading functions

Normally, structural engineering is limited to linear elements and plates. The main structure of the cellular wall is also discrete and represented by linear elements – straight beams (as cell-wall) and plates – glass panels. These linear elements are load bearing structures. The shading layer is a non-structural element, which can be designed separately with more freedom.

Before we explore an optimal primary structure, a decision should be made for the integrity or separation:

- 1_ Integrate glass layer with the primary structure – In one hand, when the glass layer is integrated, there will be more constraints/requirements for the primary structure. In the very beginning of the design stage, this is a proper consideration. In another, integrating the glass layer with primary structure, there is no need for frames (for glass panels) or extra supporting systems - The primary lattice structure of the cellular wall can serve as supporting framework. This brings clean technology design aesthetic.
- 2_ Separate shading layer with the primary structure – since the shading layer is non-structural, it can be designed by light-weight material, which is easy to be installed or removed.

5.2.2 Primary structure

Primary structure of the cellular wall is a grid structure, for which, two optional materials can be chosen: precast concrete beam or hollow section steel tube. Since precast concrete is not popular in the Chinese building market, hollow section steel tube will be a good choice. It has popular application in structures, especially for free form architecture, since it is easy to fabricate and construct.

Tubular structures (by hollow section steel tubes) have been developed rapidly and used widely in China. According to official statistics, the consumption of steel tubes for structural use in building construction of China is increasing at a rate of 20% per year, covering a total weight of one million tons. By the end of 2007, steel tubes account for 30% of the total consumption of steel used in the newly built stadiums and gymnasiums matching with Beijing Olympic Games. Currently there are more than 120 fabricators of tubular structures in China, representing a new manufacturing industry.

Reported by Z.Y.Shen, W.Wang & Y.Y.Chen (Tongji University) in the 12th International Symposium on Tubular Structures (2008), current tubular structures in China were classified into three large:

1_Truss-type tubular structures

Greater load-bearing capacity and the increase in span can be achieved with the use of planar or special truss-type structures. Three main types of trusses which are mostly used in practice: Warren type truss with K-joints, Pratt type truss with N-joints (The large span shuttle-shaped trussed system applied to the restaurant and the press centre of Shanghai F1 international Circuit is an example), and Vierendeel type truss with T-joints (Vierendeel type truss is a type of truss without diagonals, in which shear forces are resisted by the vertical web members and chords, acting as a moment-resisting frame. The roof truss of Chongqing Jiangbei International Airport Terminal is one example of this type). Besides, CHS space trusses are commonly used as the main structural system in super high steel TV towers and high electricity transmission towers in China.

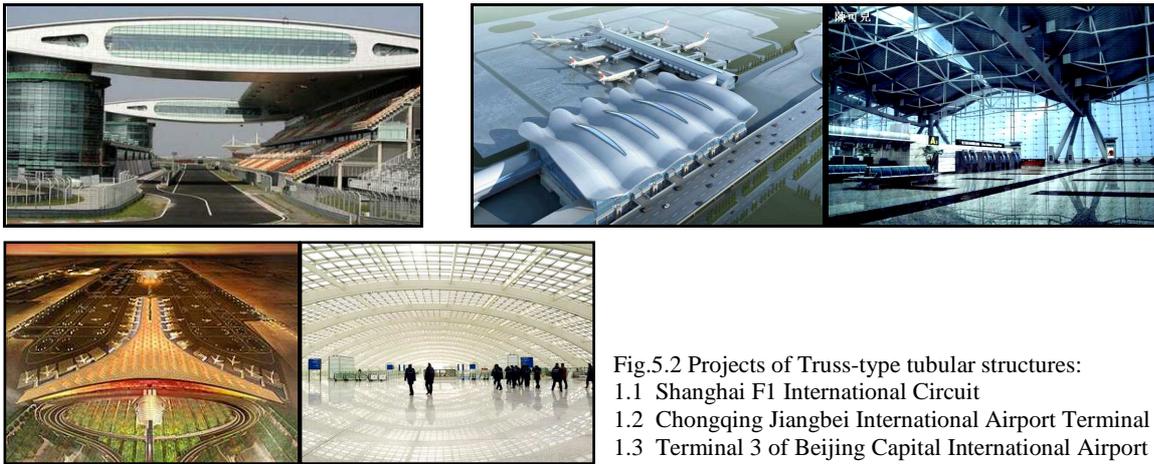


Fig.5.2 Projects of Truss-type tubular structures:
 1.1 Shanghai F1 International Circuit
 1.2 Chongqing Jiangbei International Airport Terminal
 1.3 Terminal 3 of Beijing Capital International Airport

2_Frame-type tubular structures

Frame-type tubular structures can be divided into two subclasses: high-rise moment resisting tubular frames (as Guangzhou New TV Tower and Twin Towers) and space frame tubular structures (as National Stadium and National Swimming Center). Space frame tubular structures usually have irregular configuration and demonstrate a frame behavior with significant special load transferring mechanism.

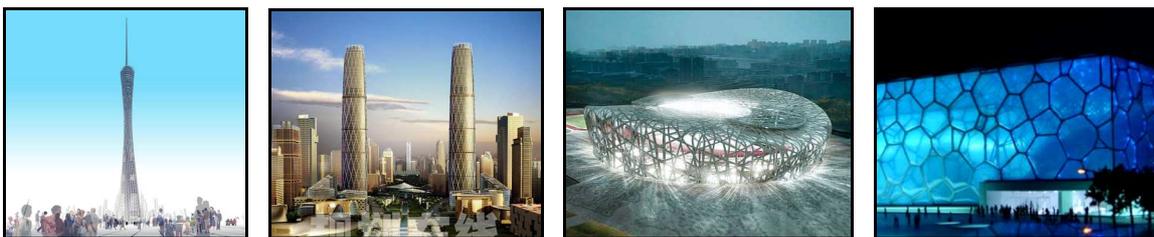


Fig.5.3 Projects of Frame-type tubular structures:
 2.1 Guangzhou New TV Tower
 2.2 West Tower of Guangzhou Twin Towers
 2.3 National Stadium (Bird's Nest)
 2.4 National Swimming Center (Water Cube)

3_Lattice shell tubular structures

Like space frame, lattice shell structures are three-dimensional skeletal structures. They are now the most widely used tubular structures for long-span buildings in China (for example, the National Grand Theater in Beijing and the Guangzhou Opera House). Guangzhou Opera (under construction) will be a landmark architecture of this city. It adopts 'double gravel' based irregular geometric configuration. The periphery of the building adopts three-dimensional grids folded plate and single layer reticulated shell structures. All

members of this structure are thin-wall box girder. Rigid joints made of case steel are used where planes intersect. The highest weight of the single joint is 37 tons and the longest one is 12m.



Fig.5.4 Projects of Lattice shell tubular structures:

3.1 National Grand Theater (Big Egg)

3.2 Guangzhou Opera House

For the lattice structure of the cellular wall, Rectangular Hollow Section (RHS) steel tube (welded together) has been chosen for its elements. Further structural design and evaluation will confirm this selection. [Based on the structural analysis results (Chapter 7), most beam elements in this lattice structure are under bi-axial bending and torsional moment cannot be ignored, thus, rectangular tubular steel is recommended in this case.]

5.2.3 Façade cladding structure

Glass differs from all other construction materials in that it is brittle: when glass components break they generally do so without warning. Thus, design for glass structures must focus on the specific properties of the material: its planarity in panel sizes, brittleness and compressive strength of a sheet of flat glass.

Proposal for the glass layer integration is to apply PSG (Point Supported Glass) system.

In PSG system, the glass panels are point supported by spider fittings. The holes in the glass are drilled in the glass panels to mechanically fix them to the supporting structure. This approach provides zero interruption of the all silicone glass joints, which can be of minimal width. The primary component is the stainless steel panel fixing bolt, which can either be rotational, reducing bending stress at the hole, or fixed for smaller glass panels. The bolts are attached to the primary structure by connecting arms in stainless mild steel or aluminum. [Source: PSG system by Novum Structures⁵, 2006]

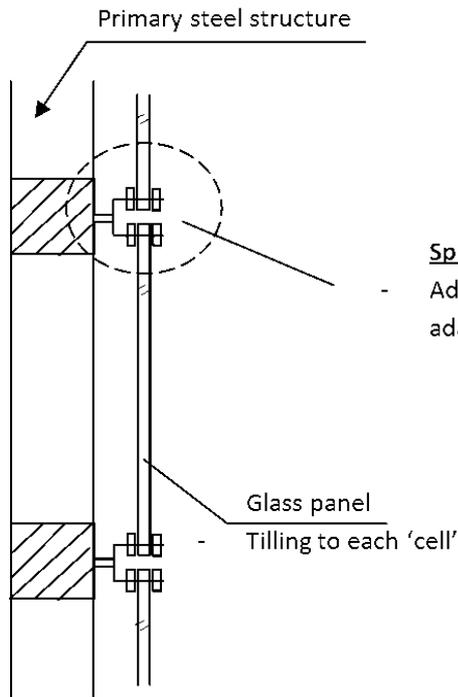


Advantages:

- 1_ No need for frames or extra supporting systems – the primary lattice structure of the cellular wall can be integrated in this system as supporting framework for supporting points, in order to create very clean technology design aesthetic;
- 2_ Suitable for sloped glazing – the angle can be adjusted, adapting to the specific geometry of the wall surface;
- 3_ Standard point supports can be applied – by changing and adjusting the location of the holes in each glass pane.

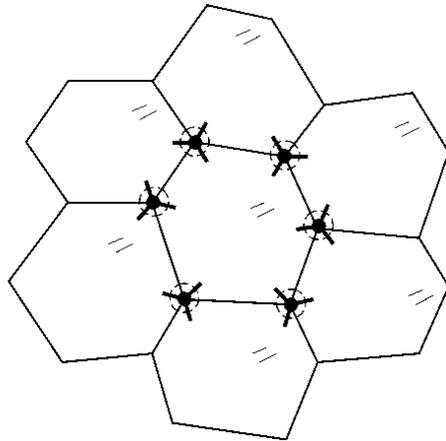
Since such an integrated system is applied, load cases by glass layer should be taken into account in the primary structure analysis. The loads resulted from glass façade include: the dead load of the glass panels and the wind load integrated on the glass surface, transmitted to the supporting point.

⁵ Novum Structures, a contractor for high-technology spatial architectural structures and enclosure ;
www.novumstructures.com

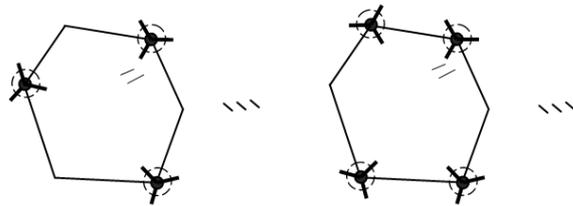


- Adjust the angle & height, adapting to the curvature

- Tiling to each 'cell'



- Apply standard support (Spider fitting)
- adjust the position of the 'holes' in each glass panel



(If the efficiency supporting can be guaranteed)

- Leave out some point supports to satisfy the 'in-plane' requirement

5.2.4 External shading layer

There are various functional requirements of glass structures: natural light supplying, energy generation, solar shading and anti-glare measures, etc. which can be integrated in the glass structures design. Some examples are showed in Fig.5.5. The third layer of the cellular wall is for shading – functional requirement.

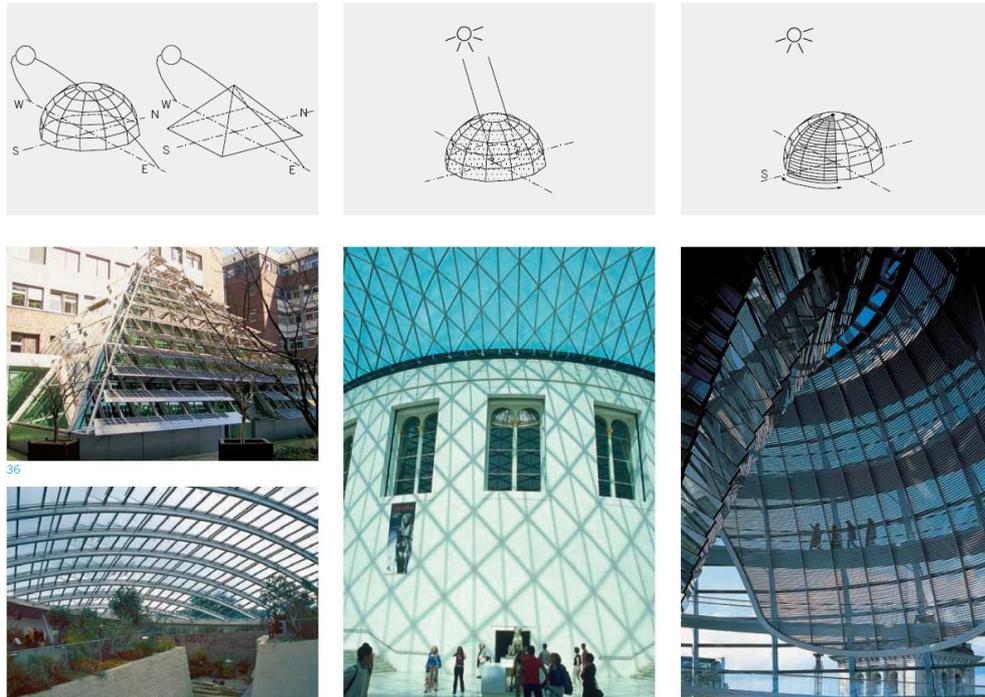


Fig.5.5 examples of glass structures for functional requirements [Source: Glass Structures]

(Left) Different levels of energy admitted through different sectors of double curved or folded roofs:

- 1_Glass pyramid partially covered by PV modules, Bewag Gelände Berlin, 1999, Arch.: A. Liepe and H. Siegelmann
- 2_Light and energy enters the dome from all sides, National Botanic Garden Wales, 1999, Arch.: Foster and Partners

(Middle) Integrated solar control in multi-curved glazing composed of flat panes does not require additional components for shading: Triangular panes with solar control coating, internal courtyard at the British Museum in London, 2000, Arch.: Foster and Partners

(Right) Adjustable solar shading on different sectors using additional internal or external measures: Rotating metal screen for internal solar control, Reichstag dome, Berlin, 1999, Arch.: Foster and Partners

Both the primary lattice structure and shading layer influence the light level of the building. Focus on the structural optimization of the primary structure, light analysis won't be included in this thesis study. Assumptions have been made that the shading layer is not integrated in structural system and it is a light weight structure which won't bring extra loads to the primary structure. Thus, there is no specific consideration for the shading layer in the following design study.

5.3 Basic Grid Types

5.3.1 Goal

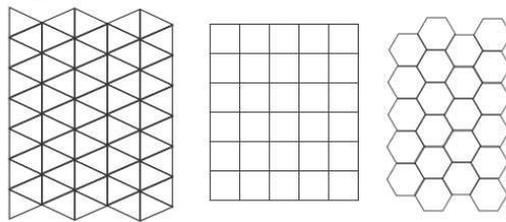
In the architectural concept design of Shanghai Natural History Museum, a cell-like grid structure was chosen for the central wall. Whether the selected structural form is suitable and efficient or not should be verified by structural design and analysis.

“For a continuous shell, the imposed load can be transmitted to the supports in a direct line to the supports, which keeps deflections small. But for a gridshell, the load cannot be transmitted directly but activates the laths, which deflect to a position in which there is equilibrium of forces (Happold & Liddell, 1975).”

For grid structures, the grid elements determine its structural properties (geometric stiffness) and the force trajectories, which significantly influence the structural behavior. In this section, several basic grid types (triangular/rectangular/hexagonal) will be analyzed and compared, in order to:

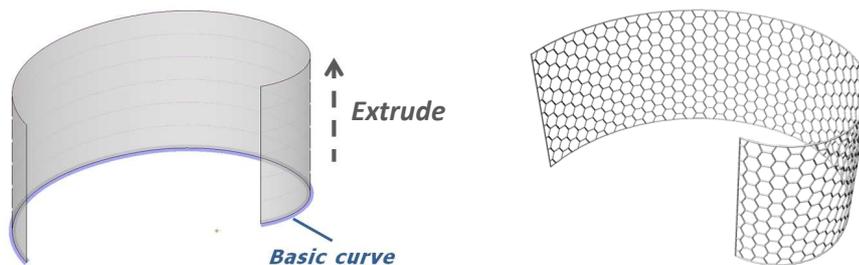
- 1_ provide recommendations of the most suitable/efficient structural form for this lattice wall structure;
- 2_ high-light the design principles of the cell-like grid structures, which will be further designed and optimized in the following chapters.

Regular Shapes that Fill or "Tile" the Plane

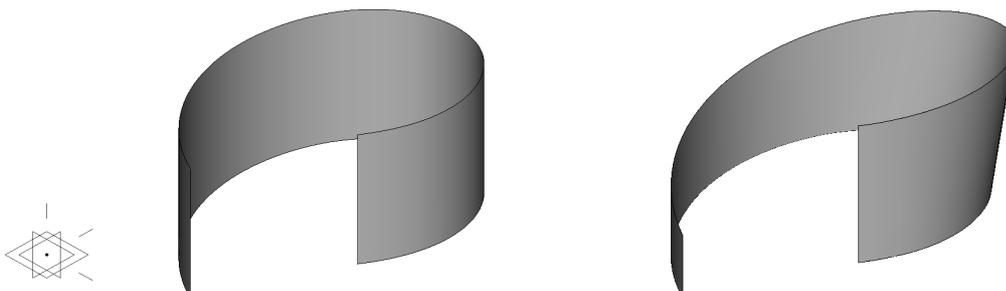


5.3.2 Parametric Model for Compared Grid Types

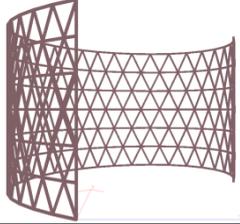
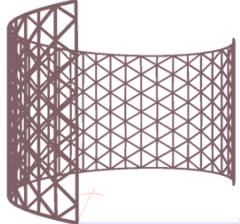
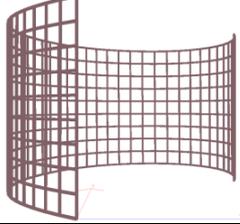
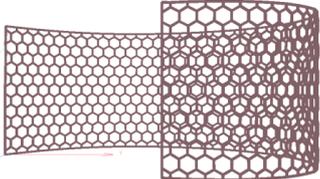
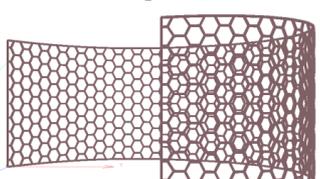
A parametric model is built to generate various types of grid on a single-curved Surface. For each grid type (triangular/rectangular/hexagonal), the parametric inputs are the basic curve (depicting walls extruded to a particular height) and the size of the grid elements.



Note: in this case, the surface of each compared grid model is simplified from the cellular wall (the same curvature, but neglecting the 'outward' incline level of the wall and the slope of the upper boundary):

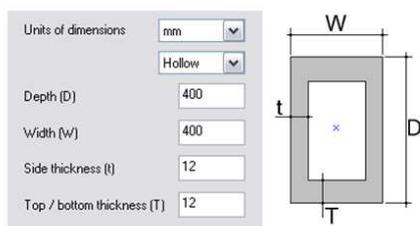


Information table [Compared grid types]

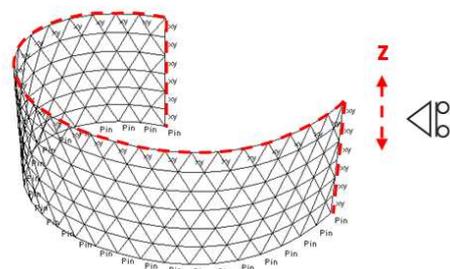
	Total Weight	Vertical load	Wind load	
Triangular_a 	4204.9 kN	 d=5.6m 1000kN 26001 kN	 A = 27.2m ² 48.9kN 4253,2kN	(per node) (total)
Triangular_b 	4636.7 kN	 d=5m 880kN 26400 kN	 A = 27.2m ² 48.9kN 4400,1kN	(per node) (total)
Rectangular 	3897.4 kN	 d=3.6m 660kN 25740 kN	 A = 11.8m ² 21.3kN 4053,4kN	(per node) (total)
Hexagonal_a 	4668.8 kN	 d=3.175m 567kN 25514kN	 A = 4.5m ² 8.15kN 4000,1kN	(per node) (total)
Hexagonal_b 	4338.1 kN	 d=3.175m 567kN 25999 kN	 A = 4.5m ² 8.15kN 3975,8kN	(per node) (total)

The same cross-section and boundary conditions are applied to different models, but the total self-weight and imposed loads have some differences (see information table above).

Cross-section

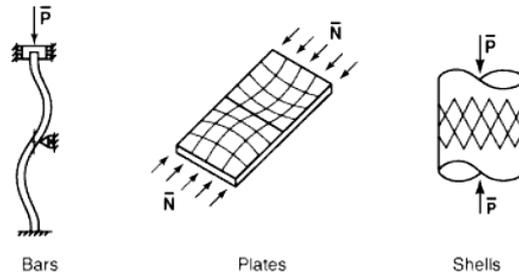


Boundary condition



5.3.3 Structural Analysis

1_Buckling Analysis

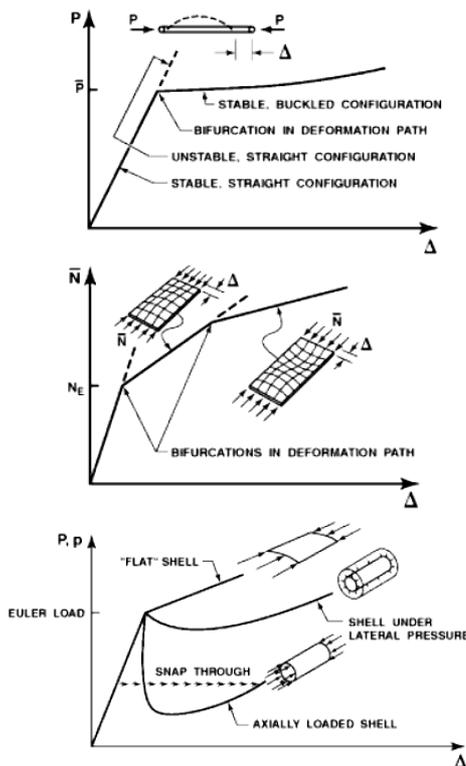


[Basic Buckling Problem]

Buckling is a failure mode characterized by a sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. This mode of failure is also described as failure due to elastic instability.

Structures might failure/collapse because of yielding or instability. Both of them might govern the load bearing capacity of a structure. For slender structures (slender column/thin plate/thin shell, etc.) buckling is very easy to occur. Thus, checking for the buckling instabilities behavior of this grid structure is very necessary.

Figures [Source: Robert M. Jones, 2006]:
(Above) fundamental buckling behaviors of three basic structural elements - bars, plates, and shells
(Right) load-deformation behavior for an axially loaded bar, an in-plane loaded plate and shells

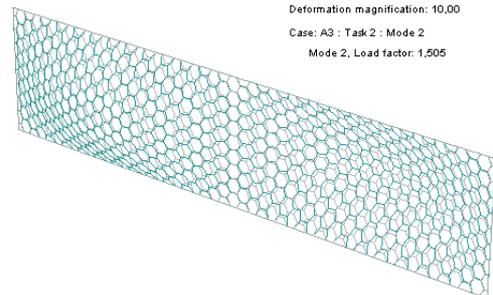
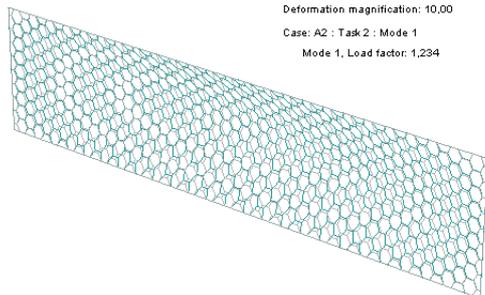
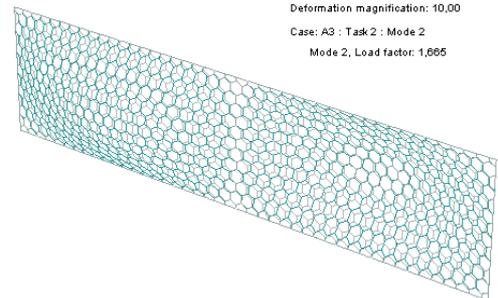
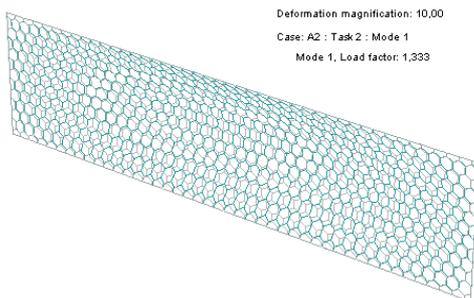
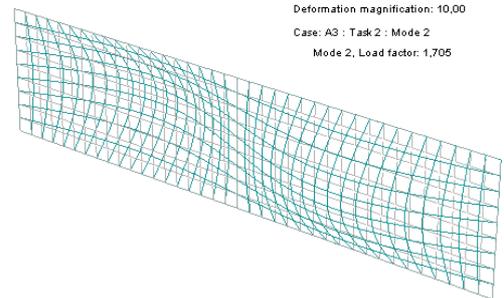
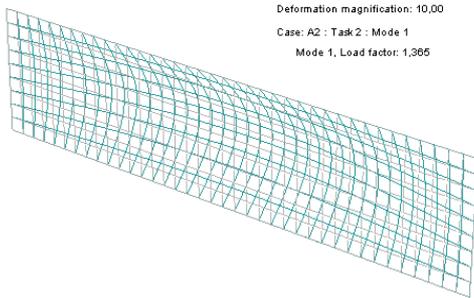
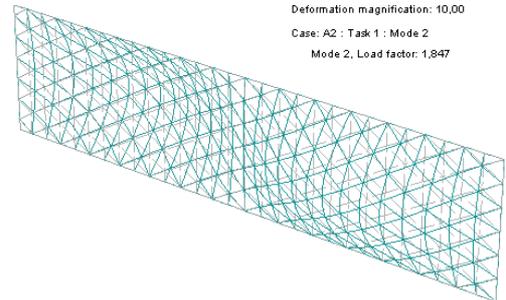
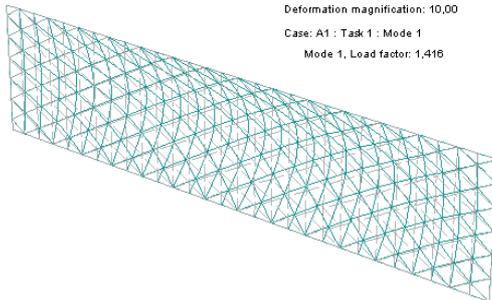
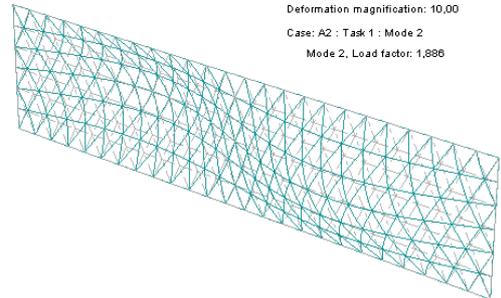
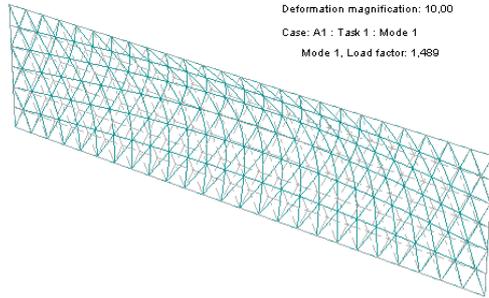


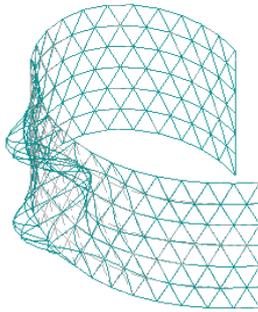
The use of finite element buckling analysis in the stability design of structures allows complex geometries and load and boundary conditions to be considered. Two approaches are possible: a linear bifurcation buckling analysis can be carried out to determine the bifurcation load of the perfect structure. Reduction factors can then be applied to account for the geometric imperfections and plasticity. Alternatively a fully non-linear analysis can be performed with deflections, geometric imperfections and plasticity properly modeled. In this thesis study, the first approach was taken in the general grid types study (Chapter 5.3.3) and cell-like grid parametric design (Chapter 7). For the structural design in this thesis study, an acceptable buckling load factor of 6 was chosen to evaluate the grid structures.

[Applied Finite Element Analysis Technique - Linear Eigenvalue Analysis in GSA]

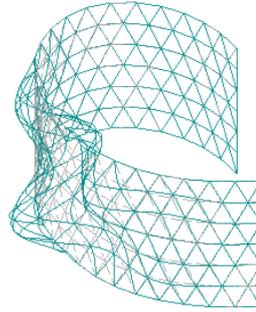
Eigenvalue analysis has been used to determine the critical buckling load of the perfect form of each structure. This is performed numerically using a linear perturbation procedure. First the stiffness matrix at the state corresponding to the base state loading on the structure is stored (in this case the base state is the unloaded condition and the matrix used is the original stiffness matrix), and then a small perturbation or imposed load is applied. The program then derives the initial stress matrix due to the imposed load and an eigenvalue calculation is performed to determine a multiplier to the imposed load at which the structure becomes unstable. Thus the buckling load can be calculated.

Buckling analysis Results [grids on flat plates]

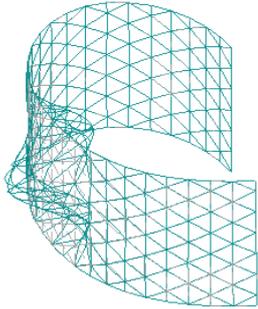


Buckling analysis Results [grids on curved panels]

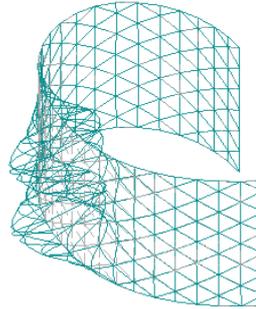
Deformation magnification: 10,00
Case: A3 : Task2 : Mode 1
Mode 1, Load factor: 27,66



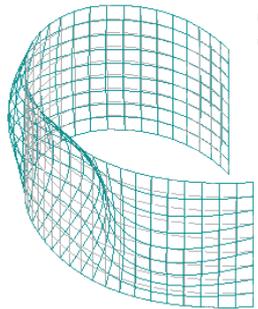
Deformation magnification: 10,00
Case: A4 : Task2 : Mode 2
Mode 2, Load factor: 28,27



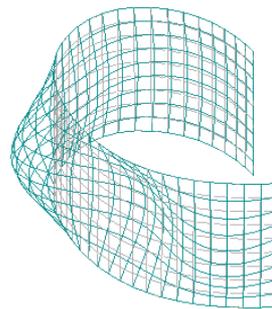
Deformation magnification: 10,00
Case: A3 : Task2 : Mode 1
Mode 1, Load factor: 29,07



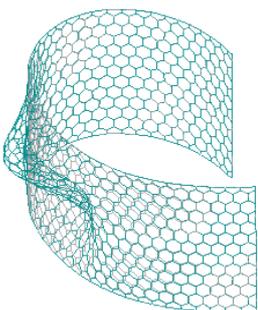
Deformation magnification: 10,00
Case: A4 : Task2 : Mode 2
Mode 2, Load factor: 30,91



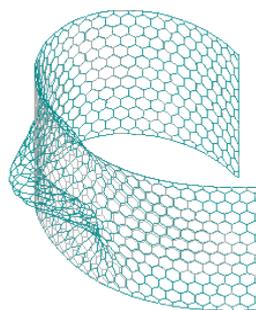
Deformation magnification: 10,00
Case: A3 : Task2 : Mode 1
Mode 1, Load factor: 9,140



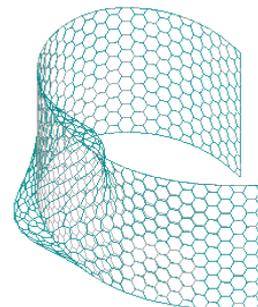
Deformation magnification: 10,00
Case: A4 : Task2 : Mode 2
Mode 2, Load factor: 9,281



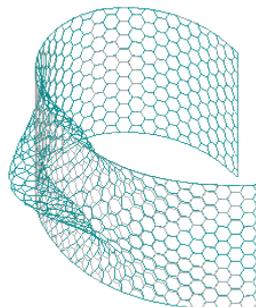
Deformation magnification: 10,00
Case: A3 : Task2 : Mode 1
Mode 1, Load factor: 15,29



Deformation magnification: 10,00
Case: A4 : Task2 : Mode 2
Mode 2, Load factor: 15,81



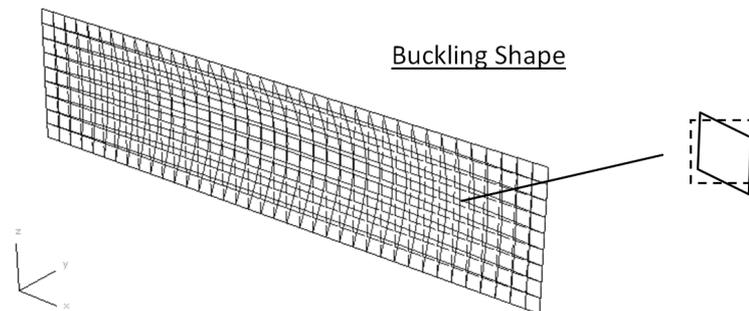
Deformation magnification: 10,00
Case: A3 : Task2 : Mode 1
Mode 1, Load factor: 12,73



Deformation magnification: 10,00
Case: A4 : Task2 : Mode 2
Mode 2, Load factor: 14,24

Grids on flat plates

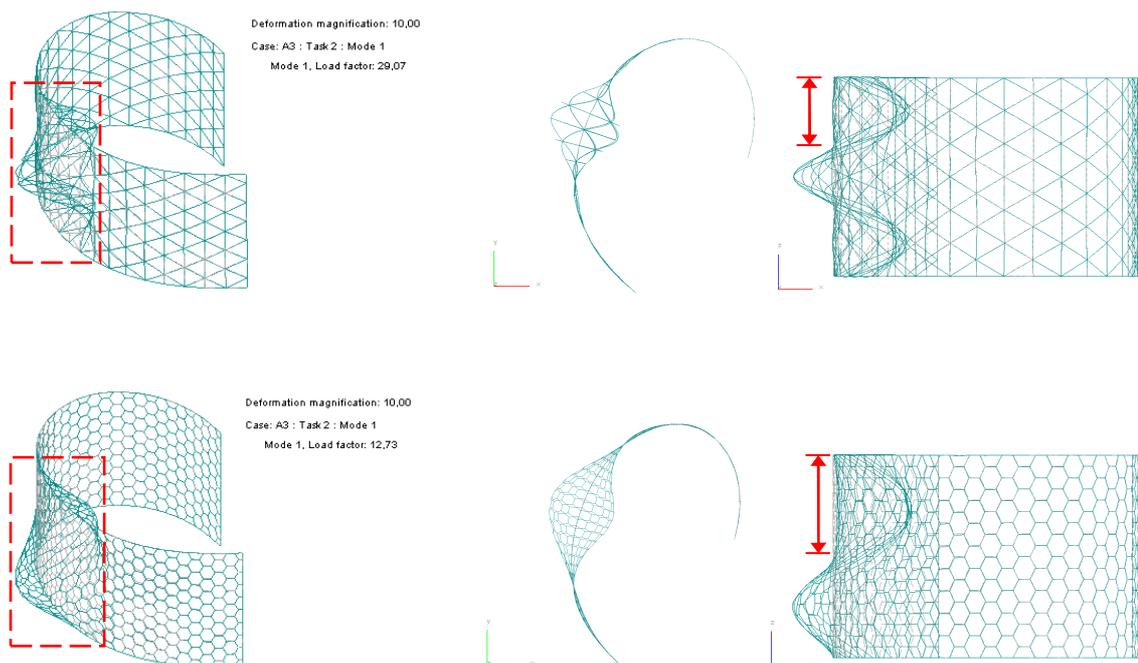
For the 2D grid structures (in these cases, all the elements have the same section properties), the grid types determine the force trajectory, therefore the compressed elements/regions within the grid structure and the level of the compression are decided. These significantly determines the buckling behaviors. Furthermore, the flat plates are fully supported at boundaries. In-plane stiffness of the grid structure helps to prevent large distortion of the grid elements (example see the figure below), which also has influence to the overall buckling behavior. Triangular grid has in-plane stiffness, which come out the highest buckling load factor.

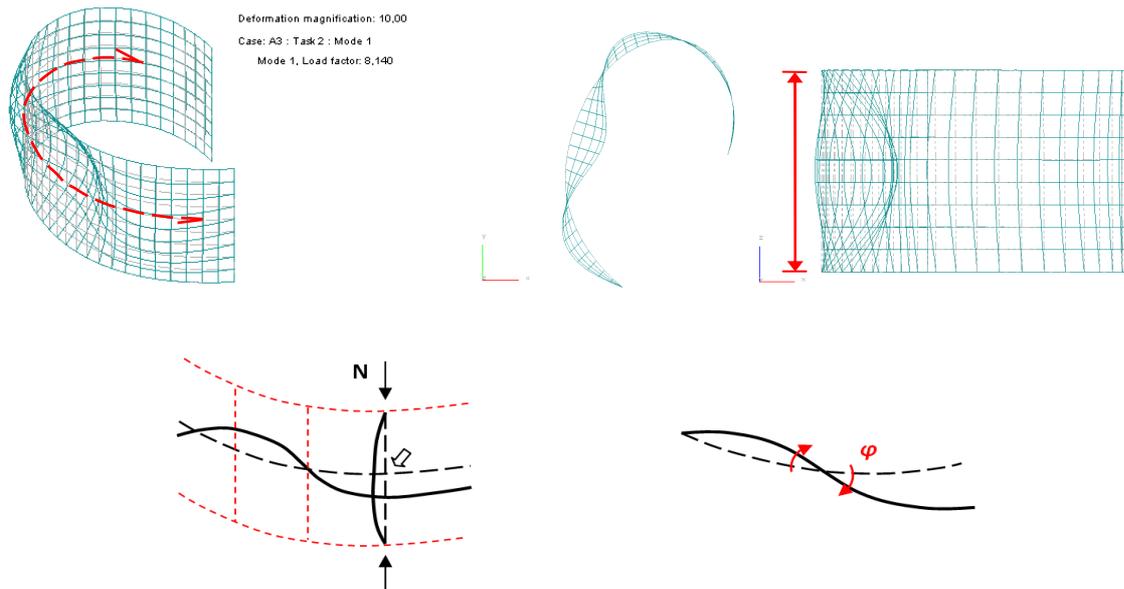


Grids on curved panels

By comparing with the 2D grids on flat plates, one can find that the buckling load factors of the grid structures are significantly increased by the curvature of the facade – more than 10 times, mostly (see the buckling analysis results in former pages).

For different grid types on curved panels, the differences are also obvious: The triangular grid and the hexagonal grid have higher buckling loads than the rectangular grid. And triangular grid is much higher. The reason for this is that the rectangular grid gives little lateral support to the main buckling area, while the triangular and hexagonal grids give more support to the main buckling area. This is confirmed by the buckling shapes that the buckling areas are restrained within local regions in triangular and hexagonal grids, while the buckling almost extends to the entire circumference in rectangular grid (This can also be described by different buckling lengths).





For rectangular grid: In one hand, grid elements only have curvature in one single direction (horizontally) and the paths of force transporting (to the supports) are very long. Thus, little lateral support can be provided. In another, due to the continuity of the horizontal components, in which a cable rotation φ occurs easily, it is difficult to restrain the deformation within a small area. Both of them weaken the out-of-plane stiffness of the rectangular grid structure (see buckling analysis results of the rectangular grid on curved panel – small buckling load factor, and wide buckling area).

1_Geometric Stiffness of grid elements

In classical plate theory, the stiffness properties of plates are defined by:

$$\text{In-plane stiffness: } K = \frac{Et}{(1-\nu^2)} \qquad \text{Out-of-plane stiffness: } D = \frac{Et^3}{12(1-\nu^2)}$$

In which, E is the Young's modulus, ν is the Poisson's ratio of the plate material, and t is the thickness of the plate.

To summarize the properties of different grid types, the geometric stiffness of grid/lattice structures can also be split into two distinct components: K (in-plate stiffness) and D (out-of-plate stiffness) - equivalent as the stiffness properties of solid plates. The properties for each grid type are listed in the table below:

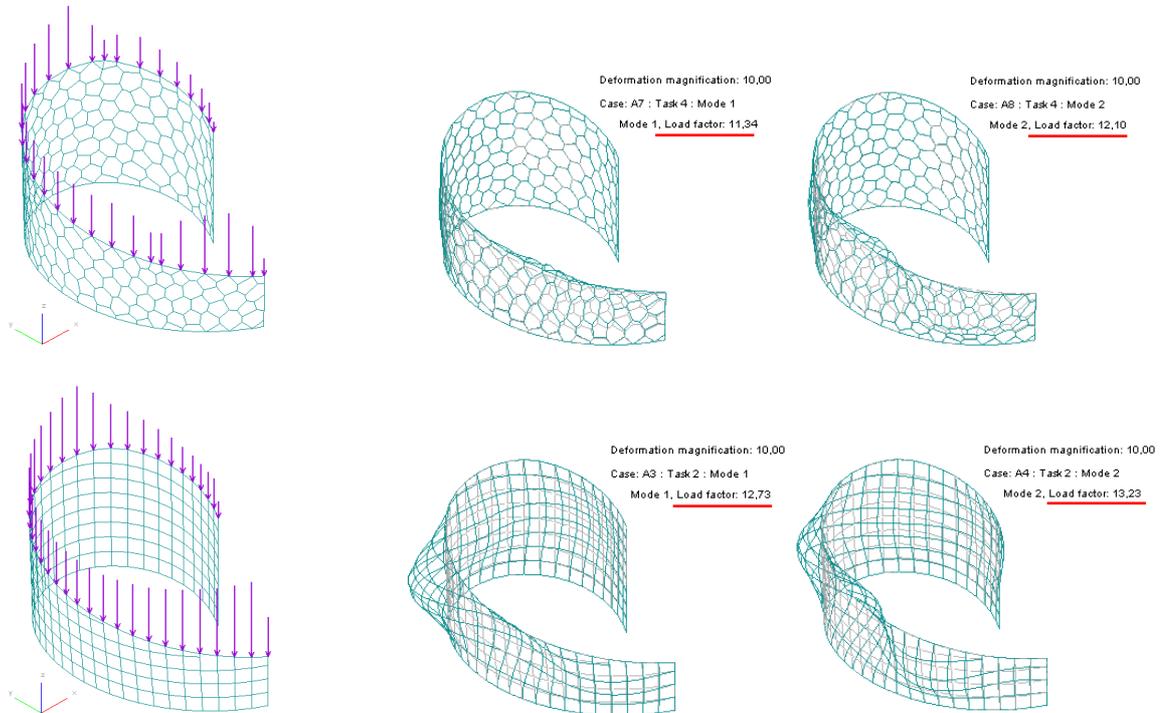
+ High level - Low level

Grid types	K (in-plate)	D (out-of-plate)
Solid plates	++	++
	++	++
	-	-
	-	+

In sum, triangular grid has large in-plane and out-of-plane stiffness, thus it shows the highest buckling capacity in the case of curved panels (much higher than the other two grid types). Hexagonal grid has a relatively large out-of-plane stiffness but little in-plane stiffness, it also shows large buckling load factor. Rectangular grid has low level in both in-plane and out-of-plane stiffness properties, it shows the worst buckling behavior – the smallest buckling load factor and a very large buckling area. These stiffness properties can be further confirmed by the following linear-static-analysis. [Note: the comparison and summary is only for the specific **grid orientation** shown in the models.]

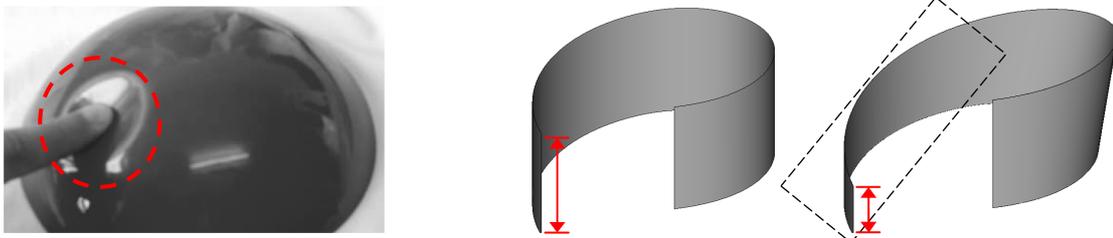
2_Geometry/shape of the facade

When the real geometry of the facade (including the 'outward' incline level and the slope of the upper boundary) is applied to the grid structure, an unexpected phenomenon can be found: the hexagonal grid doesn't show this advantage in buckling behavior any more, comparing with the rectangular grid (see figures below – the buckling load factor of hexagonal grid is smaller than the rectangular grid, and the buckling shape is a bit close to the rectangular grid).



Note: Both grid models are applied the same cross section (with similar total weights) & the same boundary conditions; Load case: the same amount of vertical load on top

The reason for this is that when the height of the extruded surface is reduced (locally shaped as a strip cut out from shell), there is not enough material surrounding to create stiffness to restrain the buckling within a local area. In that case, geometry/shape of the facade over governs the buckling behavior rather than K and D (geometric stiffness of the grid elements). Some geometric ratios (for example, h/a – height to the curvature of the cylindrical shell) will also determine the buckling capacity of this grid structure.



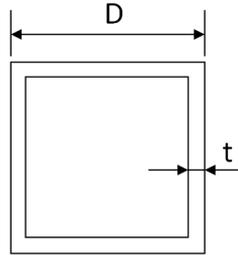
Figures:

(Left) the deformation of a simply supported spherical cap - the shell middle surface is stretching due to the loading; and the loading is carried mostly by normal forces from the surrounding materials

(Right) the main difference between two facade surfaces – in the actual surface the height is reduced on one side, thus the amount of material (vertical) is limited

Member/local buckling problem [Width-thickness ratio D/t]

The choice has been made to apply rectangular hollow section steel beams in the grid structure. Section profiles were defined as STD RHS (Standard Rectangular Hollow Sections) with isotropic properties. A section profile is showed in the figure below. In which, D is the depth/width and t is wall thickness [the same for side/top/bottom]



To reduce the weight on steel, smaller wall thickness plates should be adopted in the design of box section. If the width-thickness ratio of steel plates for welded thin-wall box members is quite large, local buckling on the compressed plates occur easily.

The conception of effective width can be used in calculating the bearing capacity of thin-wall member with box section for its post-buckling strength (Chen Shaofan.2001, Chen Ji.2003). However, there is limited stipulation of effective width in the design codes of steel structure in China (GB50017) and foreign countries, especially for the members under bi-axial bending. A research of this problem was done by China Architecture Design and Research Group [Beijing, China], and a new method to estimate effective width for welded thin-wall box section is presented, based on a case study of the National Stadium [Bird's Nest, Beijing, 2008] - box members $\square 1200 \times 1200 \times 10(20) \times 10(20)$ (mm).

In this thesis study, no further consideration or in-depth study for this local buckling problem will be taken, but only give foundation for the cross-section estimation.

In Eurocode-3, 'slender section' is defined as: Cross-section in which it is necessary to make explicit allowance for the effects of local buckling which prevent the development of the elastic capacity in compression and/or bending. Local buckling is very obvious and affects the elastic bearing capacity of section under compression and bending. And the width-thickness ratio of steel plates for the welded thin-wall box member is:

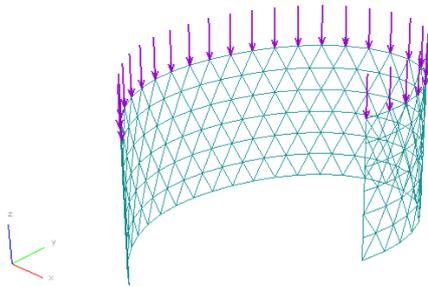
$$b_0/t_w > 40\sqrt{235/f_y}$$

For Steel S355, Width-thickness ratio of slender section is $D/t > 40\sqrt{235/355} \approx 32.5$

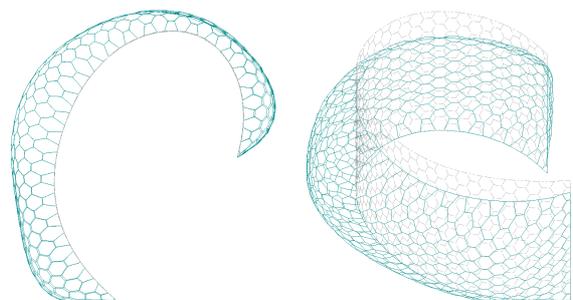
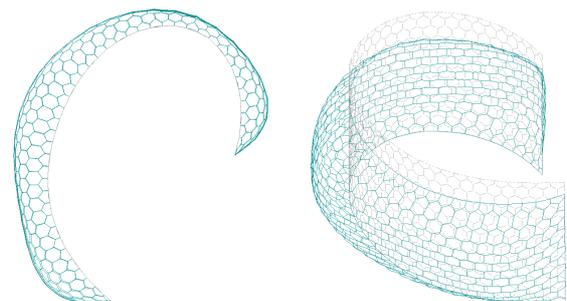
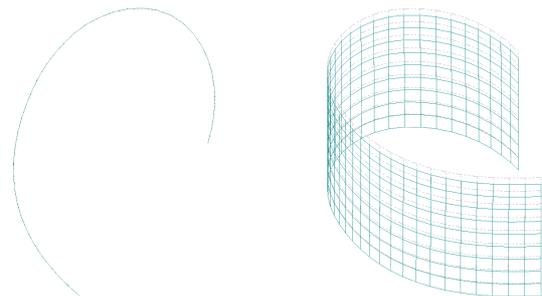
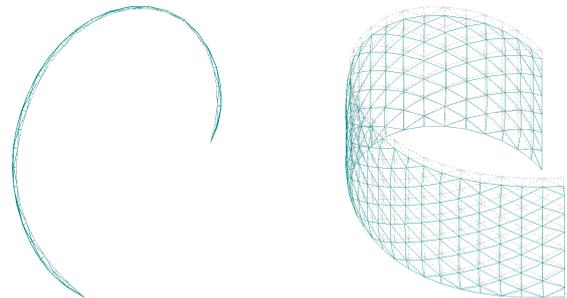
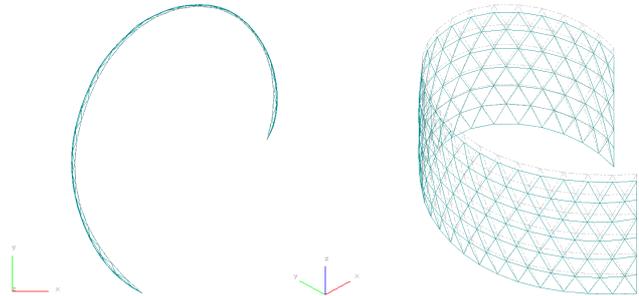
In the following parametric design of the cellular wall structure, this value [$D/t < 32.5$] will be used as a reference for member profiles design.

2_Linear Static Analysis

Load case 1 – Vertical load on top



Deformation

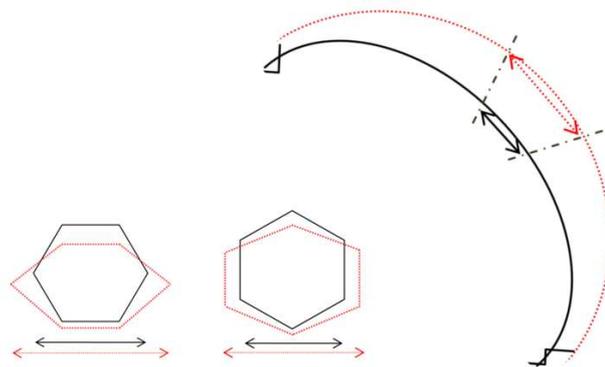


[All graphs: Deformation magnification = 320]

Deformation [Linear Static Analysis - Vertical load]

Under pure vertical loads [in-plane], the grid structures still have out-of-plane deformation, due to the curvature of the surface. As declared in the summary of buckling analysis:

- 1 Triangular grid has large in-plane and out-of-plane stiffness, thus the deformations – both in-plane and out-of-plane – are quite small.
- 2 Hexagonal grid also has relatively large out-of-plane stiffness, but little in-plane rigidity. In this load case, its deformation is significantly large among different grid types. Such a large deformation is mainly caused by the little stiffness/rigidity of the hexagonal elements: hexagon elements are easily deformed in-plane, and after the in-plane deformation, the circumference of the overall grid structure becomes longer, which also result in large out-of-plane deformation.



From the deformed shape, the hexagonal lattice networks act as deployable structure, which makes the joints (beam-beam connection) critical in this structure system. In the following analysis results, it can be found that very large bending moments appear at the joints (can be notable in combined stresses). Foldable structures are mainly made of kinematic joints, which is flexible to free the rotation of the bars. In this hexagonal grid structure (heavily-loaded), solutions should be found to create stiffer/ rigid joints to reduce the rotation of beam elements, in order to prevent too large deformation.

- 3_ Rectangular grid has little in-plane and out-of-plane stiffness. However, the orientation/direction of the imposed load and the force trajectory determine the deformation mostly. Under the specific load case – vertically loaded only, the rectangular grid structure acts like a group of column. Horizontal components almost did not make contribution in this grid structure (see the forces graph in the following pages).

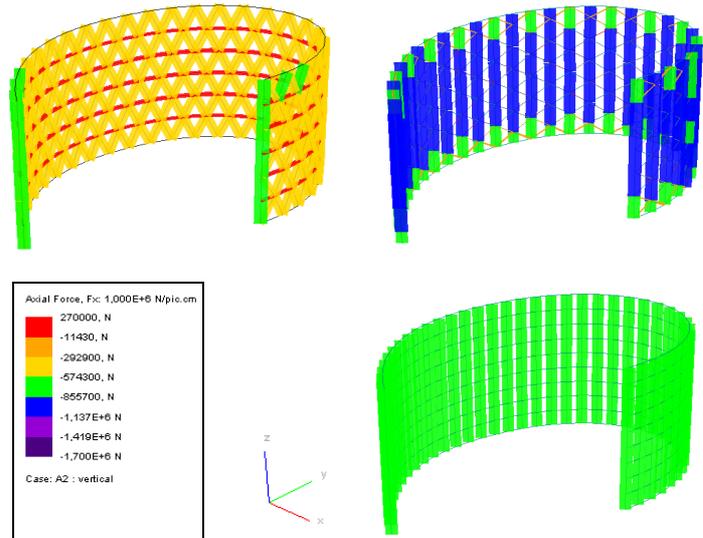
In the load case of vertical load only, rectangular grid (close to column model) is the most economic structure, comparing with other two grid types. However, the fact that rectangular grid has little in-plane and out-of-plane stiffness decreases its capacity for other load cases. These remarks can be confirmed by the wind load analysis – horizontally loaded – in which the rectangular grid has significantly large out-of-plane deformation (see Load case 2 – Wind Load; Deformation). Thus, to evaluate a grid type is economic/efficient or not, mainly determined by the design load cases.

Axial Forces – Fx

[LC: vertical load]

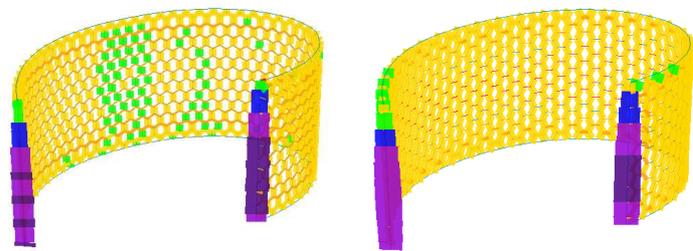
1_Tensile elements

There are very notable tensile rings in the first triangular grid; Tensile elements can also be found in the hexagonal grid, but without continuity, and they are not very efficient to transfer the load to the supports; Difference shows in the recctangular grid, under the pure vertical load, only vertical components under compression, the horizontal components do not contribute in this grid-network. Instead of horizontal elements, the non-vertical elements in the second triangular grid are activate in their grid-network.



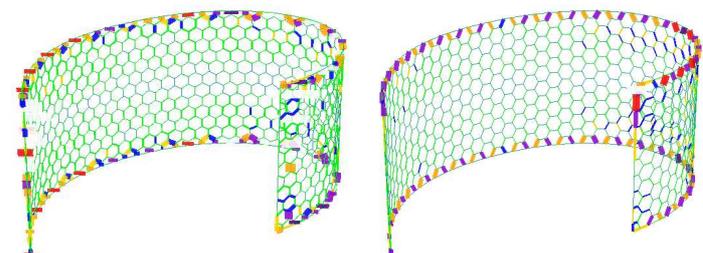
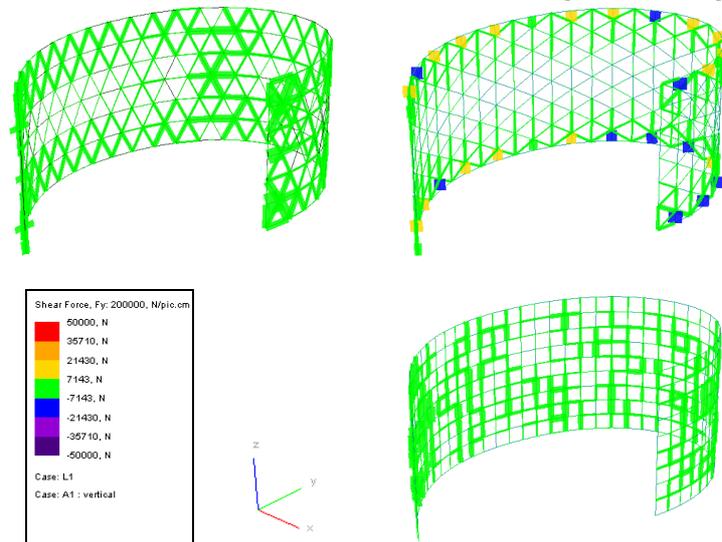
2_Large vertical load at edges

For the hexagonal grid, elements are non-stiff, not efficient for in-plane load bearing. Thus, the rigid edge beams (verical) take up very large vertical load. Related: see Reaction Forces



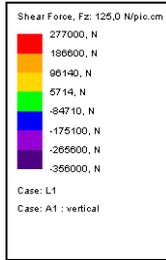
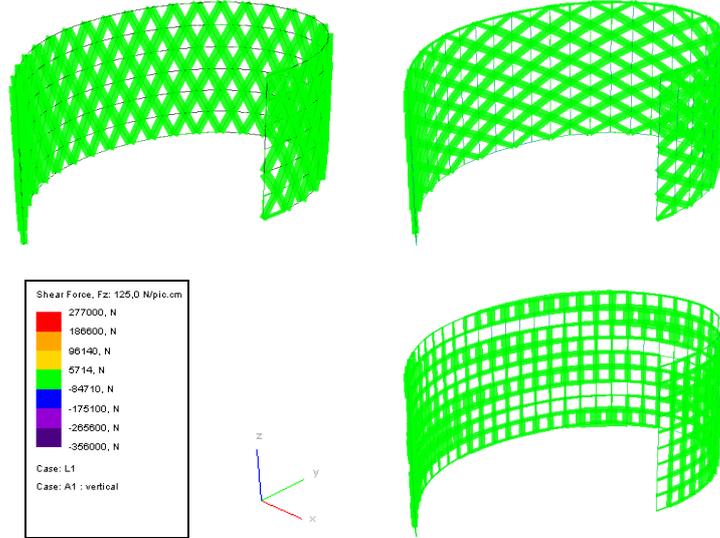
Shear Forces - Fy

[LC: vertical load]



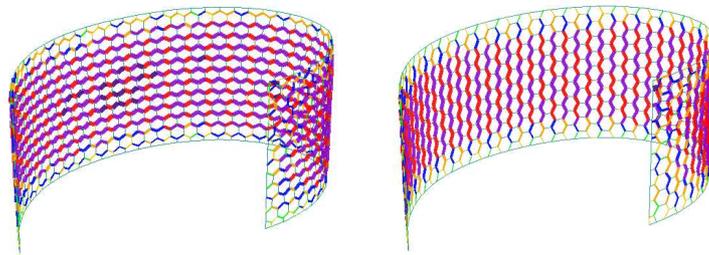
Shear Forces - Fz

[LC: vertical load]



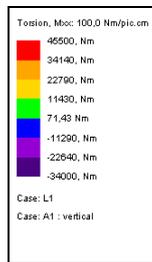
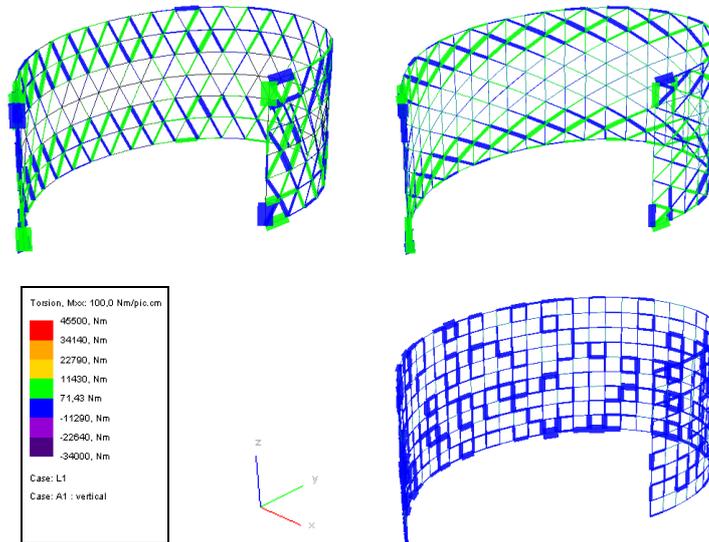
When vertically loaded, the average axial forces in different grid types are similar, but the shear forces and bending moments are much larger in the hexagonal grid.

Large shear forces and bending moments in the incline beam elements:

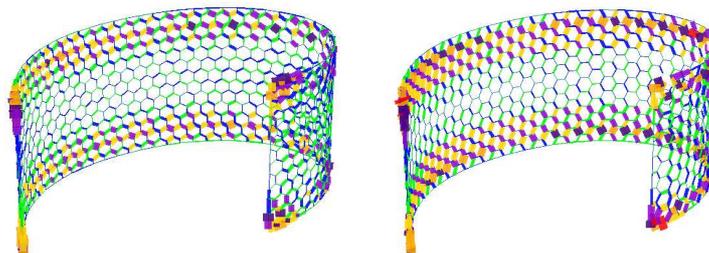


Torsional Moment - Mxx

[LC: vertical load]

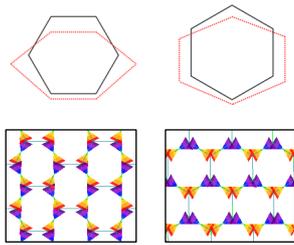


Torsion is not a neglectable problem in hexagonal grid;
Thus, box members (Rectangular hollow section) are suitable for this grid structure.

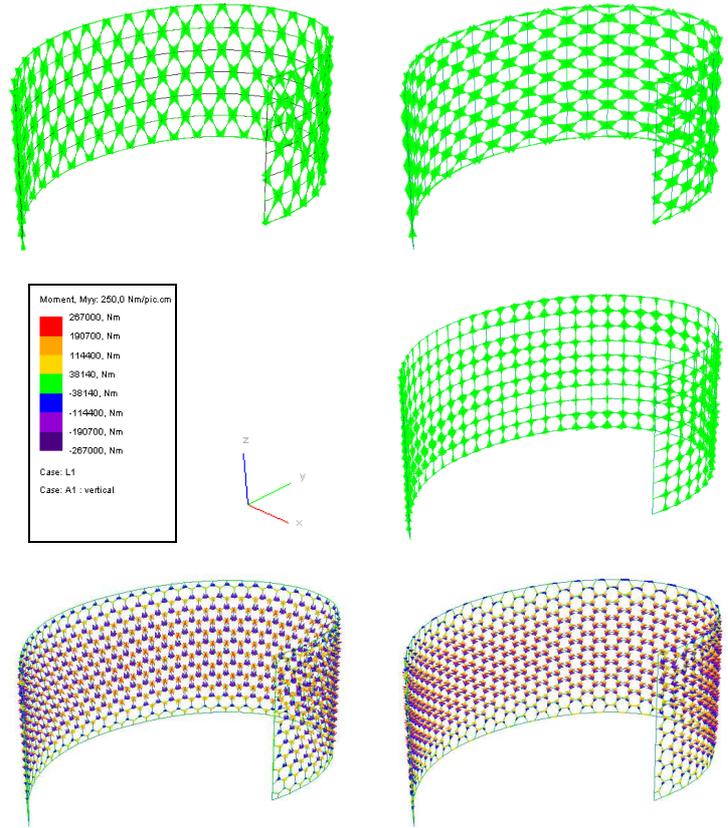


In-plane Moments - Myy

[LC: vertical load]

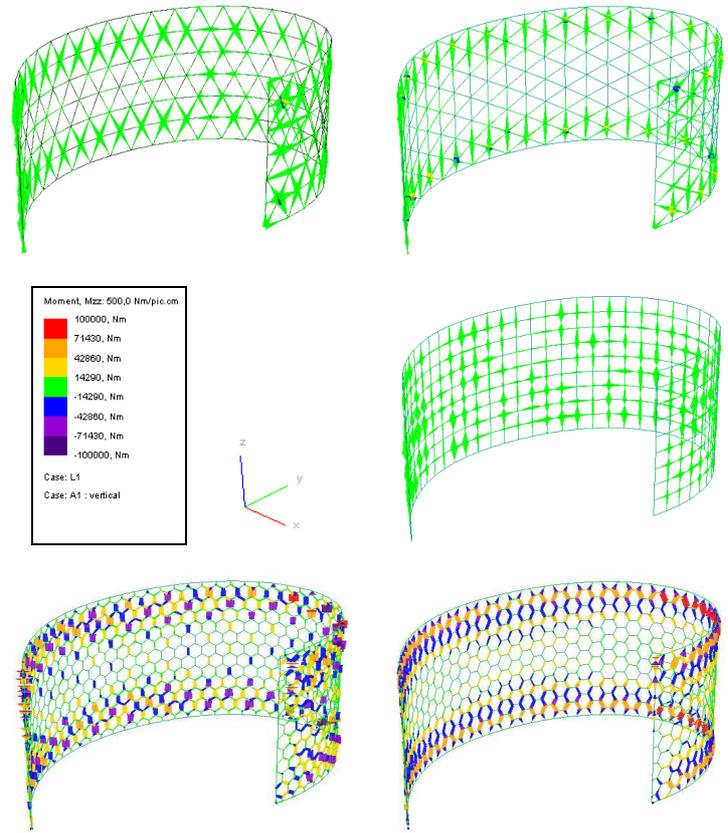


Close-up of the in-plane bending moment (Myy) in hexagonal grid – very large bending moments at joins/connections



Out-of-plane Moments - Mzz

[LC: vertical load]



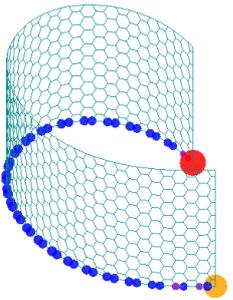
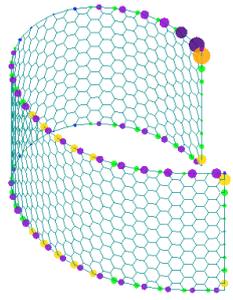
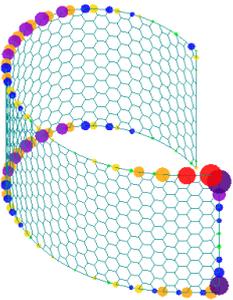
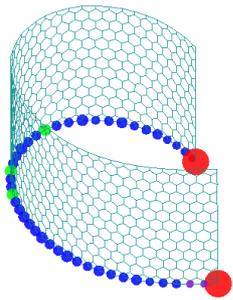
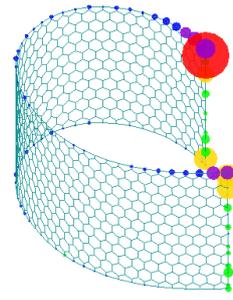
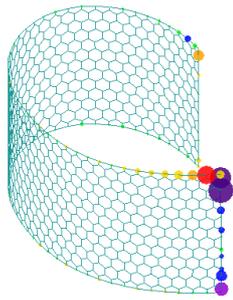
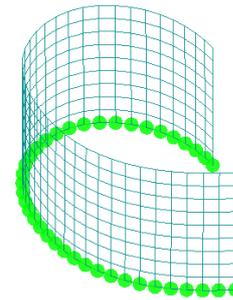
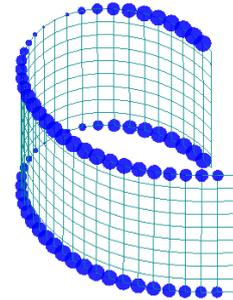
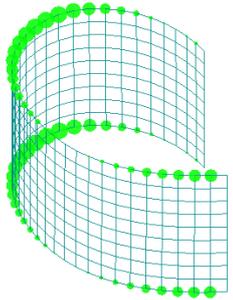
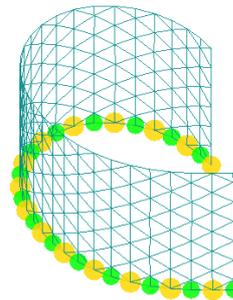
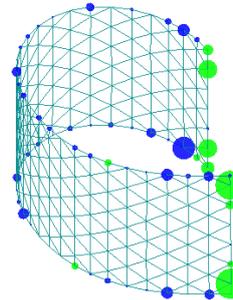
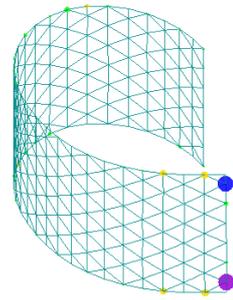
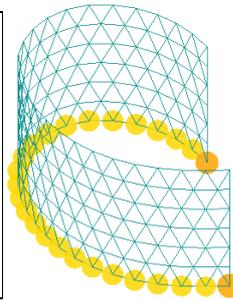
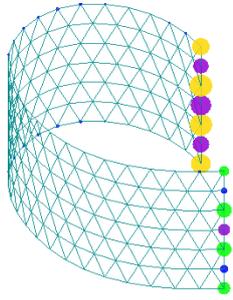
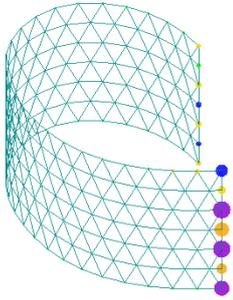
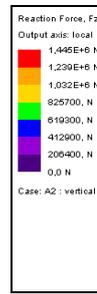
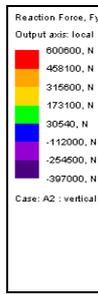
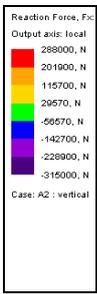
Reaction Forces

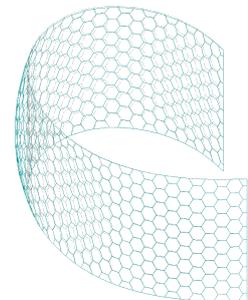
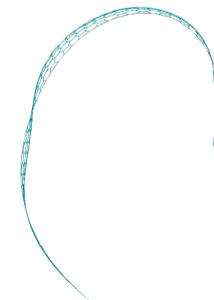
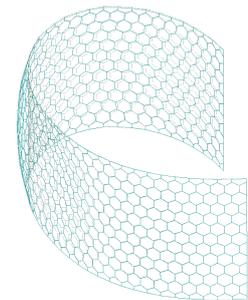
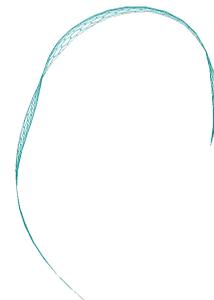
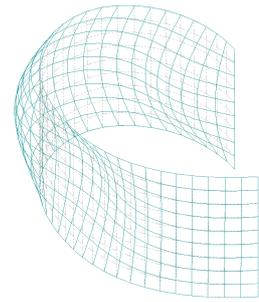
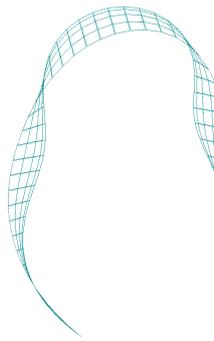
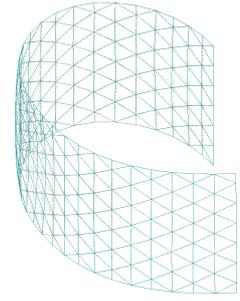
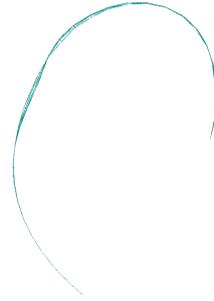
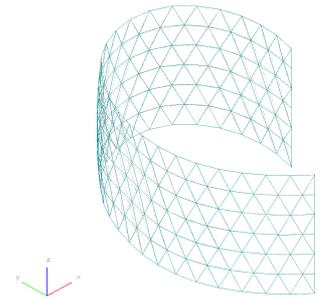
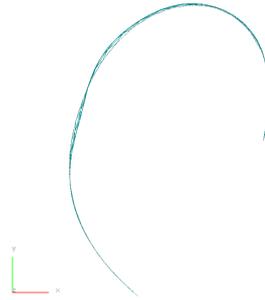
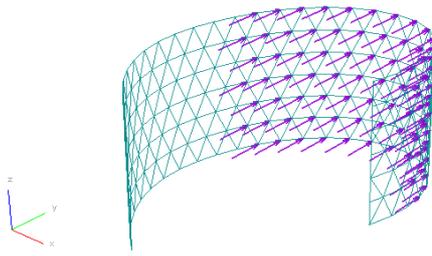
[LC: vertical load]

Rx

Ry

Rz

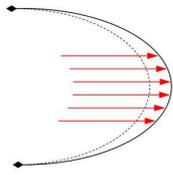


Load case 2 – Wind Load**Deformation**

All graphs: Deformation magnification = 160

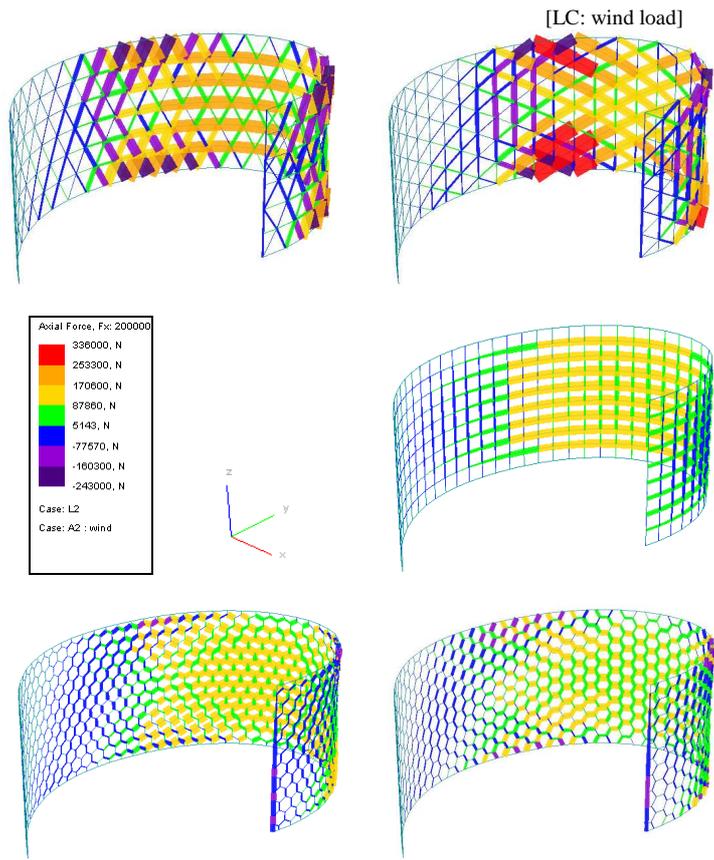
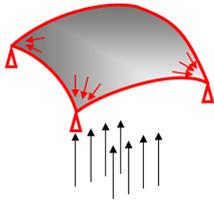
Axial Forces – Fx

Cable action by form (curvature)

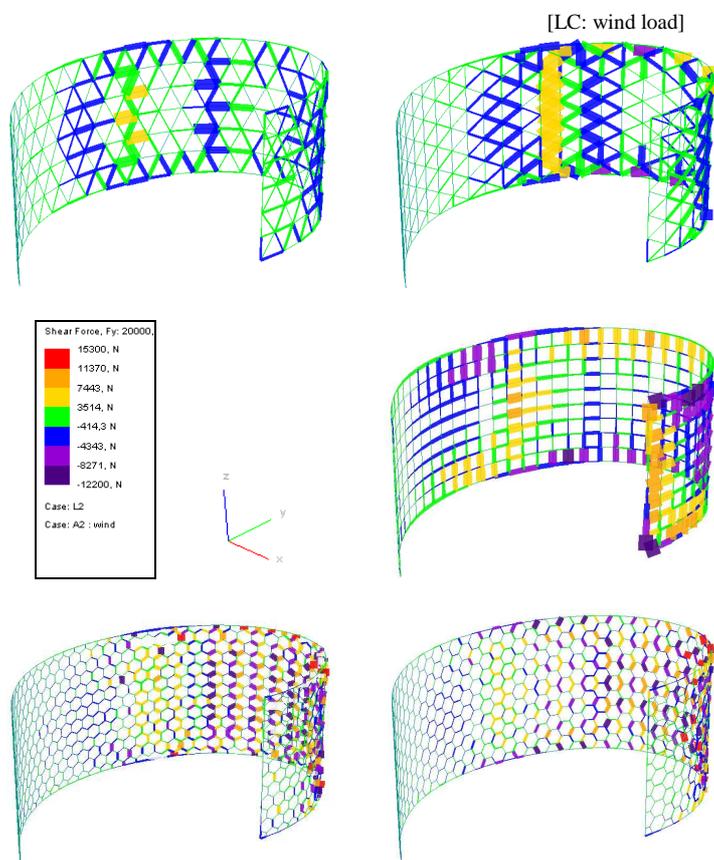


From the resulted deformation under wind load, the worst case appears in the rectangular grids network: as explained before, because of the very little in-plane and out-of-plane stiffness;

In addition, there are 'diagonal' components in triangular and hexagonal grids, which can transport the load to supports (corners of the loaded area) quickly; while in rectangular grid, horizontal components have longer activated distances.

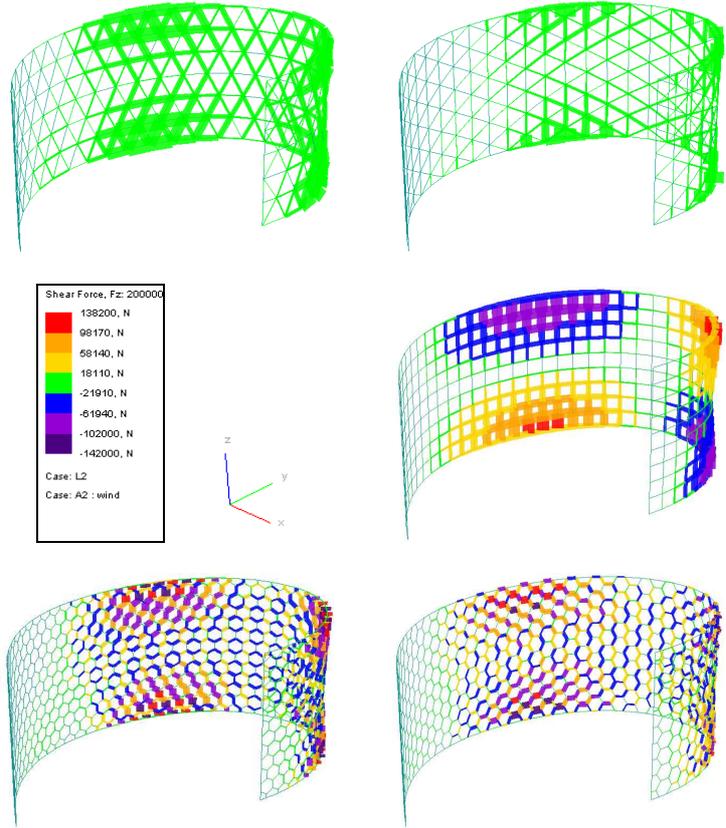


Shear Forces - Fy



Shear Forces - Fz

[LC: wind load]

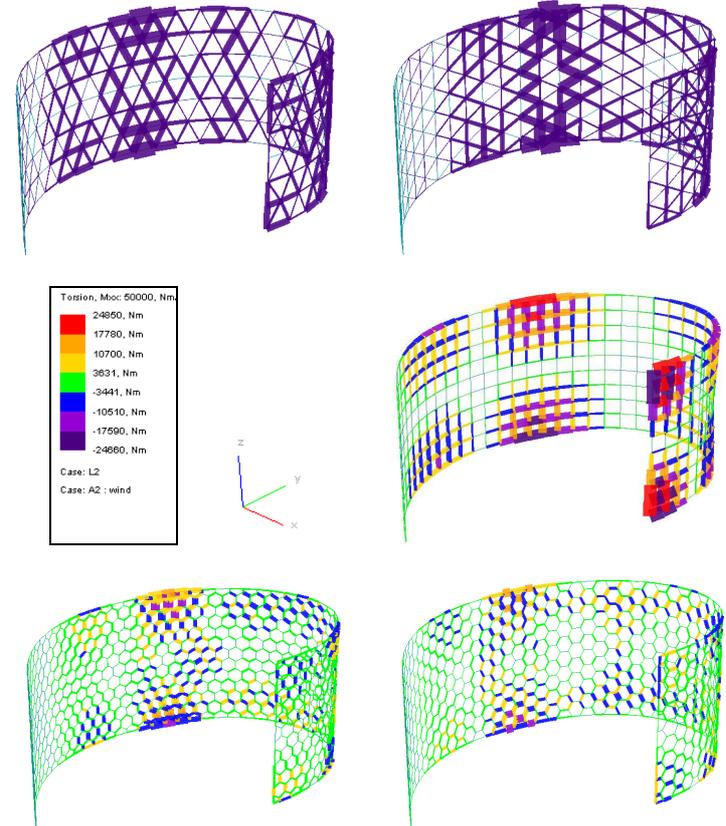


Large in-plane shear forces occur at the corners of the loaded-area. Triangular grid has large in-plane stiffness; advantage can be viewed easily from this graph;

[Note] In general, Forces are more dispersed in the hexagonal grid structure.

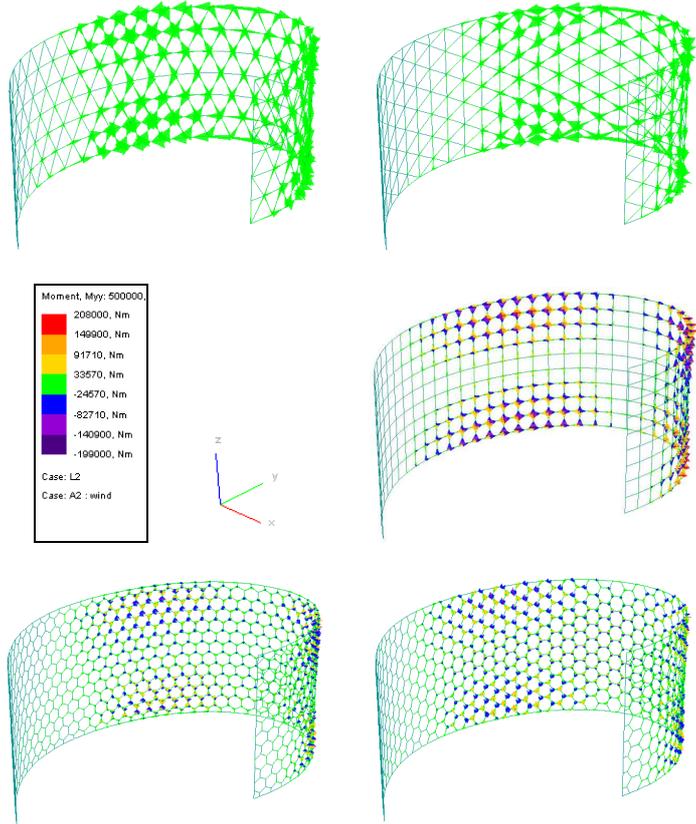
Torsional Moment - Mxx

[LC: wind load]



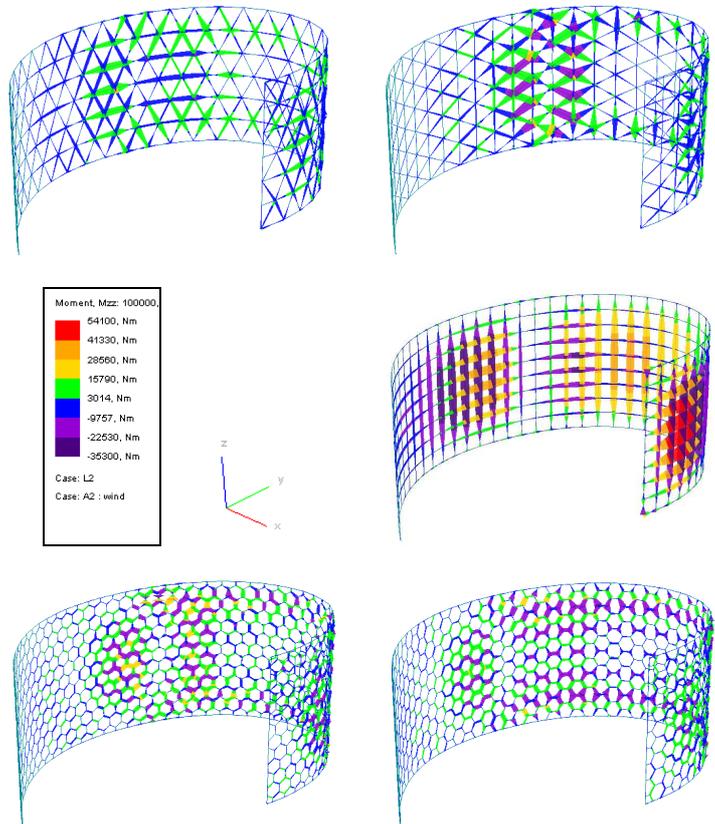
In-plane Moments - Myy

[LC: wind load]



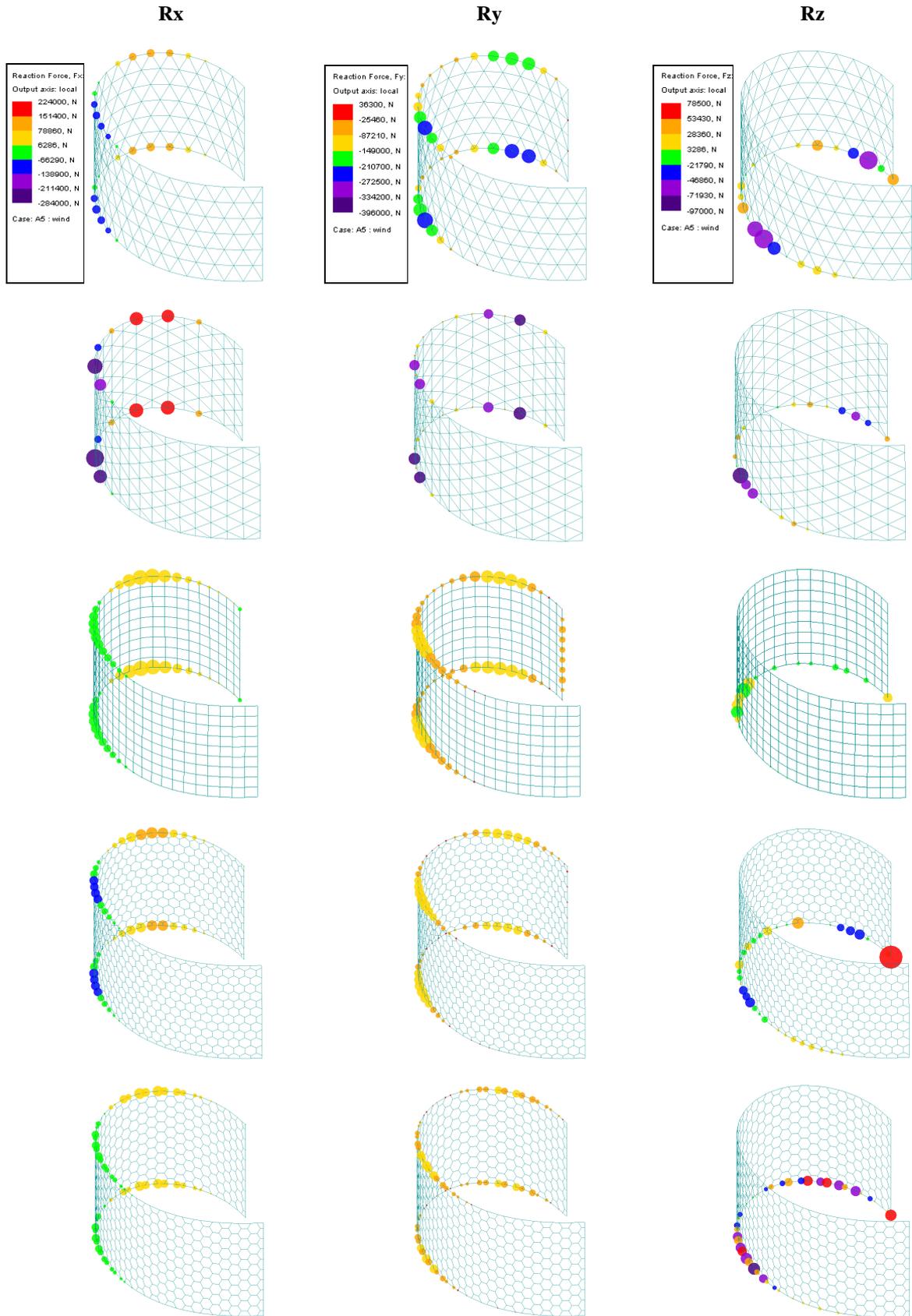
Our-of--plane Moments - Mzz

[LC: wind load]



Reaction Forces

[LC: wind load]



5.4 Multi-Criteria Evaluation

Criteria for evaluation of a structure can be structural, like stresses in the structural elements, the deflection of the structure under live load etc. or non-structural. Design codes provide guidelines for structural design, for examples a maximum value for the ratio between the deflection and the span of the structure. Following these guidelines, a structure should always comply with the set criteria. However, these structural criteria are not distinctive aspects on which to compare different design alternatives (in parametric design strategy, different parameter configurations). Non-structural criteria provide better means for the comparison of the design alternatives.

“When optimizing building structures, it is essential to consider all relevant aspects of the design, which leads to a multidisciplinary design optimization problem. - Geyer and K.Rueckert, 2005”

In most structural design cases, design considerations are limited to physical criteria, for example, stiffness and the amount of material that is not sufficient for building design. However, other important objectives should be taken into account are low costs, sustainability, functionality, aesthetics and feasibility in terms of constructing. As Geyer and K.Rueckert [2005] stated, the objectives for structural optimization in building design can be divided into three groups (Fig5.6):

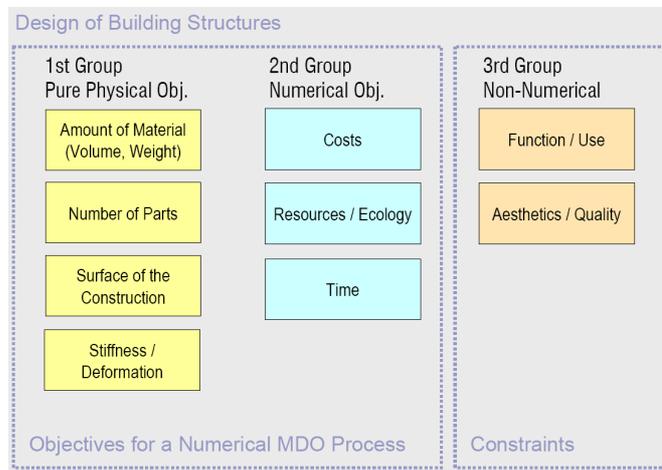


Fig5.6 Objectives in building design [Geyer and K.Rueckert, 2005]

The 1st group comprises the parameters which depend only on physical phenomena. The amounts and quantity in this group are direct results of the calculation of the design model. Therefore, the objectives in this group only depend on the physical as well as the geometrical phenomena, and the chosen configuration described by design variables.

The 2nd group is also numerical but not only related to physical aspects but also to an assessment based on non-physical judgment. To this group belong objectives like costs, ecological aspects and the time for construction. These aspects require the assessment of an expert considering the effort for the construction, the situation of the market with its prices for material, constructing, and transportation as well as ecological guidelines. This expert's knowledge leads to characteristic factors and threshold values which are able to transform quantities of the first group into values of the second group.

Fig5.7 shows an outline of the different objectives of the first and the second group which occur during the live-cycle of a building. The linking shown in the figure is exemplary only. The real model requires more links which are neglected in the figure for the reason of clarity.

The 3rd group represents the non-numerical aspects. In contrast to other engineering disciplines, in building design non-numerical aspects like aesthetics are of a major importance. These nonnumeric aspects lead to an important limitation of conventional optimization in the design process that arises from translating various criteria into numerical values. Not all aspects can be expressed by numbers or in differentiable functions as it is the case for aesthetic criteria for instance. Only the user can assess these aspects in an adequate way. For the step of automatic and user independent optimization, the non-numerical aspects have to be implemented as constraints containing functional and aesthetic considerations.

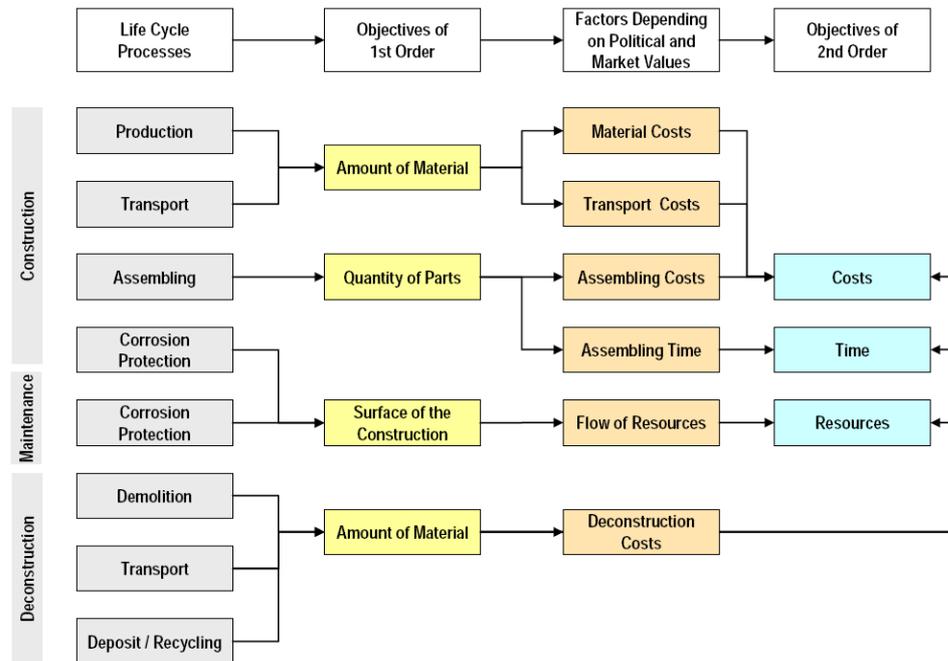


Fig5.7 Dependencies of the objectives on the physical model [Geyer and K.Rueckert, 2005]

Multi-Criteria Evaluation in the concept stage

Multi-Criteria Evaluation is a tool to get insight in the main differences between design alternatives. In the concept stage, it helps the designers to make well founded decisions of suitable structure(s) from all the alternatives. The multi-criteria evaluation includes a wide range of consideration, and evaluation should be provided by different parties – architects, contractors, visitors (of the museum) etc.

This thesis study more focus on explore a optimized structure which fits the architectural concept design, thus, decision was made only to provide a very rough comparison/evaluation of the alternatives. The following part is such an evaluation for different grid types compared in the former section.

Aesthetical value

Design alternatives should be compared with the vision of architectural concept design from the architects. The alternatives with close shapes of the architectural design have a higher score. This results in the fact that architectural value is based on the opinion of the architect. The hexagonal grid fits the architectural concept design – a natural pattern that recalls human cellular organizational structures.

In addition, a captivating function of lattice/grid structure is the light transparence. In one hand, more natural light can be used, increasing the sustainable level. In another, nice view to the enclosed central garden can be created, so does beautiful shading. Thus, the light level analysis of the grid structure can be an important aspect.

[Costs]

The cost of a structure is no doubt an important factor. However, to estimate the cost is very difficult. Estimation can be roughly made, for example, the costs of the connections are based on the amount and difficulties of the connections. And by reducing the amount of different connections (pursue a high degree of regularity), costs can be reduced.

In the very beginning of structural design stage, ‘Cost’ can be simplified and represented by two aspects:

- Efficiency of the material use (the cost of material) and
- Technical value of the structure (the cost of fabrication and construction)

Efficiency

The basic idea of 'Efficiency' in structural design is to use the least material to build up a load-bearing structure for applied loads. For any specific load case, there will be one (or more) structural forms suitable for bearing this load (comparing with other structural forms, they can use less material to achieve the same goal), which come out economic structures.

In previous grid type study, for vertical load, the rectangular grid is most efficient, while under wind load, triangular and hexagonal grids have much higher efficiency. In addition, for each grid type, the distribution and properties of the grid elements can also be optimized, to increase the efficiency. For example, an even force-distribution/low level stress within the grid structure represents fully utility of the grid elements.

The concept of Lightweight Structure can be introduced here: lightweight structures are characterized by having a rather small mass relative to the applied load, which is determined through an optimization process. The design principles of lightweight structures can be used as references for the structural design that by means of efficiency optimization.

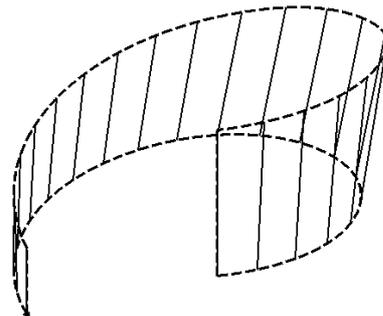
“Six basic rules of lightweight structures:

- 1_ Avoid bending stresses;*
 - 2_ Carry tensile forces with low weight, even across long distance;*
 - 3_ Carry compression forces over short distances to avoid stability problems and unnecessary added mass in the struts;*
 - 4_ When compression forces must be carried across long distances, incorporate them into self-stabilizing system (pre-stress, e.g.);*
 - 5_ Give planar components in compression an appropriate shape to secure them against stability failure;*
 - 6_ Short-circuit the forces within the load-bearing system can result in lightweight structures, and thereby allow simple foundations.*
- by Werner Sobek”*

Technical value

Technical value is based on the technical difficulties and technical properties of each design. Besides the design technologies, it mainly includes the technologies of fabrication, assembly and construction of a structure. Because of the non-standard shape, the cellular wall requests for relatively high (construction) technology. The topology of the grid structures influences the technical difficulties very much.

For a ruled surface which is formed by a series of straight lines (see figure on right), rectangular grid is no doubt the simplest for construction, following by triangular grid. Hexagonal grid has more complex topology, thus the (construction) technical difficulty is increased. Especially, when randomness is introduced in the grid structure (as the architectural concept – an irregular pattern is required to better represent the idea of human cellular structure). Solution(s) should be found for correctly coordinating the elements for construction. Besides, some strategies like to apply different (cross-section) profiles to beam elements will also increase this complex.



Evaluation Table

(Table: rough evaluation for three basic grid types)

Grid type \ Criteria	Aesthetical value	Efficiency	Technical value
Triangular	- -	+	+
Rectangular	-	+	++
Hexagonal	++	-	-

Criteria for cell-like grid structure

In the following design exploration (Chapter 6&7), assumption was made that the architectural concept determines the basic structure form – a cell-like grid structure. Thus, in the following study, specific design will be implemented for an optimized cell-like structure.

The optimization strategy focus on the **efficiency of the structure**, thus, the following objectives were defined in order to evaluation the configuration of the design parameters. This information will be provided for each configuration:

1_Virtualized information

Graphs of stresses/forces distribution and deformation level

2_Quantity information

Amount of steel (= total self-weight)

Amount of glass (= glass thickness \times facade surface area \times density)

Amount of joins

Amount of beam elements

The design objectives defined in such a way that a trade-off in the configuration of the design parameters is inevitable. For example, when setting the design parameter for the grid density, an economic trade-off between the material cost for the glazing (glass) and the cost for a joint / connection should be made. Small sizes of cell elements by high grid density will reduce the thickness of glass panels; therefore, the amount of glass is reduced. But the number of nodes in the grid structure will be increased at the same time.

In addition, depending on various circumstances, the designer will have to define a list of weight factors that sets the relative importance of the different design objectives in relation to each other. If further use for this evaluation approach will be applied, more consideration and some weight factors should be introduced, which are not included in this thesis study.

5.5 Reference projects/researches

Case 1: HTA (Honeycomb Tube Architecture)

Published by ATA Association members in 2006, an innovative architectural system - honeycomb tube architecture formed by a hexangular tube construction was discussed. The authors believe that HTA has long-lasting potential as sustainable architectural system that can accommodate the vertiginously changing functions and usages of urban residential architecture designed for lifelong occupancy as well as those of multifunctional, mixed-use architecture. Precast prestressed concrete and steel are the two structural materials that have been considered for the production of honeycomb tubes.

Volume I introduced honeycomb-tube architecture designed from precast prestressed concrete.

“Precast prestressed concrete (PC) technology is a construction method that combines both precast and prestressed concrete technologies. With this method, complete quality control guarantees high durability, connections are simple, and there is an exceptionally high degree of freedom. Joint methods are the same for any derivation of hexagrams or hexagons. To ensure further earthquake resistance, we established the basic principle to utilize base isolation technology together with honeycomb technology.”

- Kunio Watanabe”

From the prototype of honeycomb tube elements (Fig.5.8), some solutions for weak in-plane stiffness of hexagonal grid can be found:

- _ Increased section profiles at the joints
- _ Divisions at the middle of beams, where the invert point of bending moments locate
- _ Floors act as tensile rings, to prevent large deformation of hexagonal elements

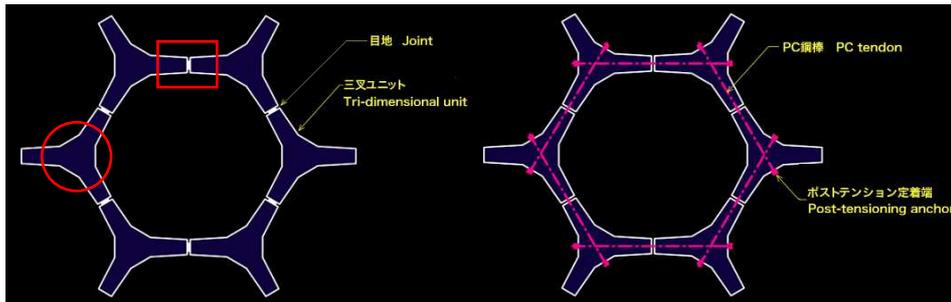


Fig.5.8 member division in PC honeycomb (left) and the layout of post-tensioning tendons (right)



Fig.5.9 full scale model and test (The resulted capacity is 6 times of self-weight)

Volume II introduces honeycomb architecture with a steel construction.

Change in construction material results a need for a new method of construction. The “fractal geometry” concept is introduced for steel honeycomb structure. Honeycomb element can keep the prototype when changing its size; therefore an adaptive honeycomb structure can be created by the same configuration (basic prototype) – different sizes. Composition of structural elements and the connection details of this system are show in Fig.5.10.

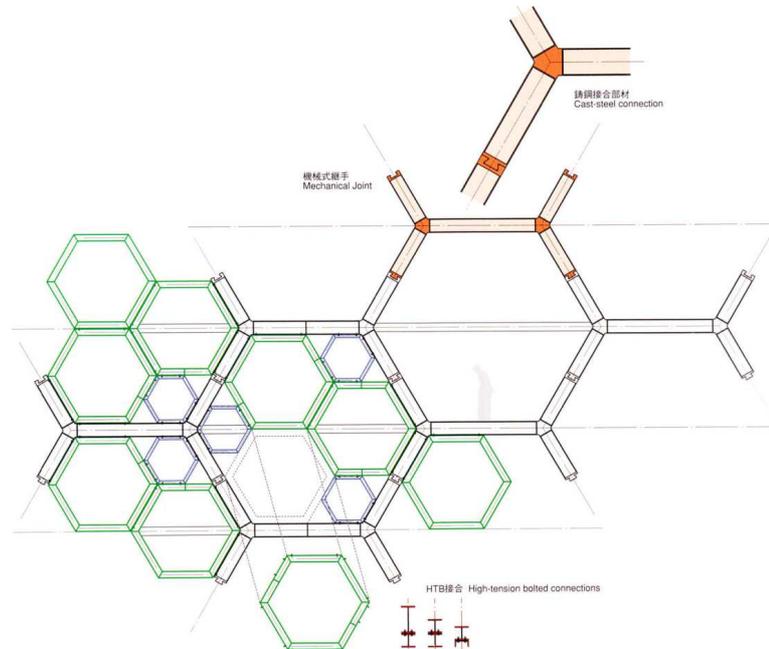


Fig.5.10 The productivity of fractal honeycombs (Structural composition by Steel tubes)
(Details: Cast-steel connection / Mechanical joint / high-tension bolted connection)

Four types of fractal pieces are tested and analysis by ATA Association. Test experimentation results show that the fracture/cracks start from the smallest honeycomb, following the failure in the outer honeycomb. [Note: in these experiments, the section profiles are reduced when the size of hexagons are decreased.]

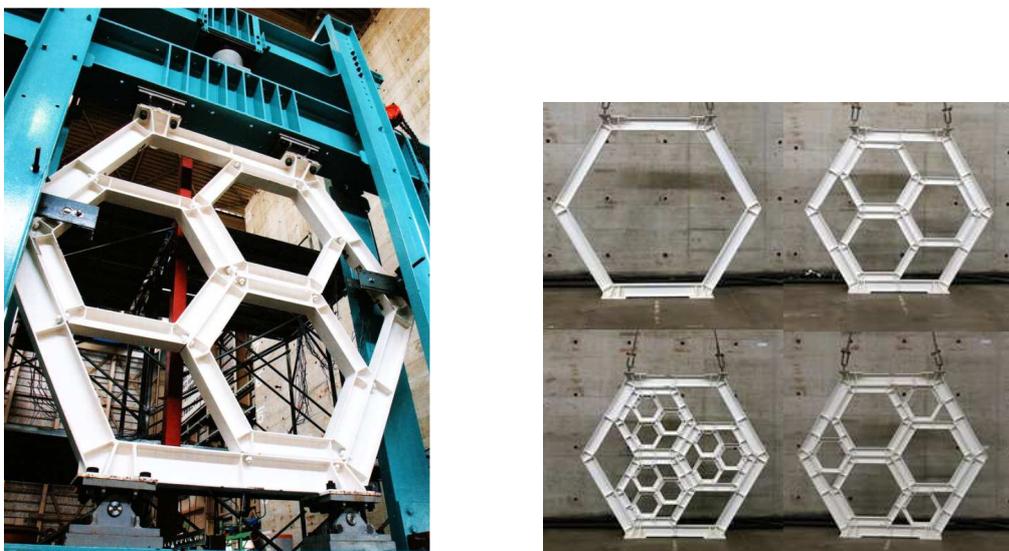


Fig.5.11 Experiments for four types of pieces

Case 2: Structural patterns

Project: CCTV Headquarters, Beijing, 2008
Designed by Rem Koolhaas, Engineered by Arup

The winning design for the 473,000m², 234m tall CCTV building thus combines administration and offices, news and broadcasting, program production, and services – the entire process of Chinese television – in a single loop of interconnected activities around the four elements of the building: the nine-storey “Base”, the two leaning Towers that slope at 6° in two directions, and the 9-13 storey “Overhang”, suspended 36 storeys in the air. The public facilities are in a second building, the Television Cultural Centre (TVCC), and both are linked to a third service building that houses major plant as well as security.

Generally, such a high-rise could be supported from its core, but Arup soon realized CCTV would have to engage the towers’ entire cross-section. Both towers, which naturally want to fall over in the direction of the overhang, are further challenged by a net slope of 10 degrees. The whole form became a tube where every external face is a structural diagonal grid in a regular two-storey pattern to coincide with the towers’ double-height studios.

“Wasting resources in China is a capital offence, so we were very keen to make this perform optimally.”
- Arup Engineer Chris Carroll”

The idea of classical core was completely lost in this case. This new kind of configuration put the onus on the skin throughout; making it impossible to second-guess what was going on. The bracing that goes around the structure in changing pattern: where stress was needed, where there was more intensity, the pattern was doubled-up so there was a double rhythm. Furthermore, unreadable on the façade, the floor plates make the triangulation.

Structural pattern is expressed on the façade. If only the pattern is taken and columns and the floors are removed, a very unusual pattern emerged (Fig.5.11). By forcing this onto the façade, the effect was to give an open-ended and changing look.

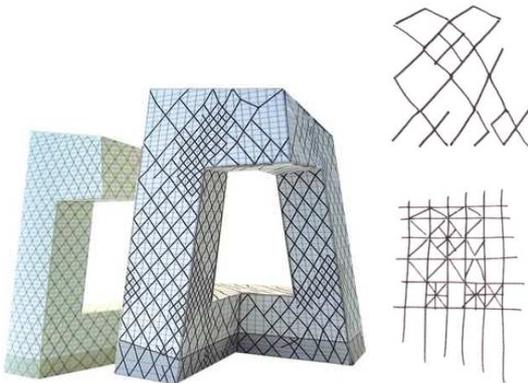


Fig.5.11 Structural patterns for CCTV Headquarters

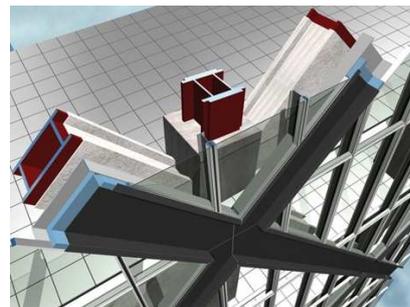


Fig.5.12 Sectional view through façade structure

Project: Banque Lambert Headquarters, Brussels, Belgium, 1963
Architected by SOM / Gordon Bunshaft

The envelope of the Banque Lambert headquarters uses the structural grid of the building to produce a directional latticed affect, through special concrete structural units that are displaced to the exterior. The glass enclosure is set back from the free-standing exterior structure – the inverse of the typical curtain wall – to prioritize the lattice on the exterior. The precast concrete units are tapering in one direction and the pin-point between them emphasizes the horizontal over the vertical, giving directionality to the lattice.

This building shows integration of the structure and the skin – “relations between parts” (Fig.5.13): the concrete lattice facade is engaged with the floor slab, the glazing (glass) panels and the service systems. The degree to which these relationships are set characterized the emerging design strategies for designers to cope with the constructional challenges.

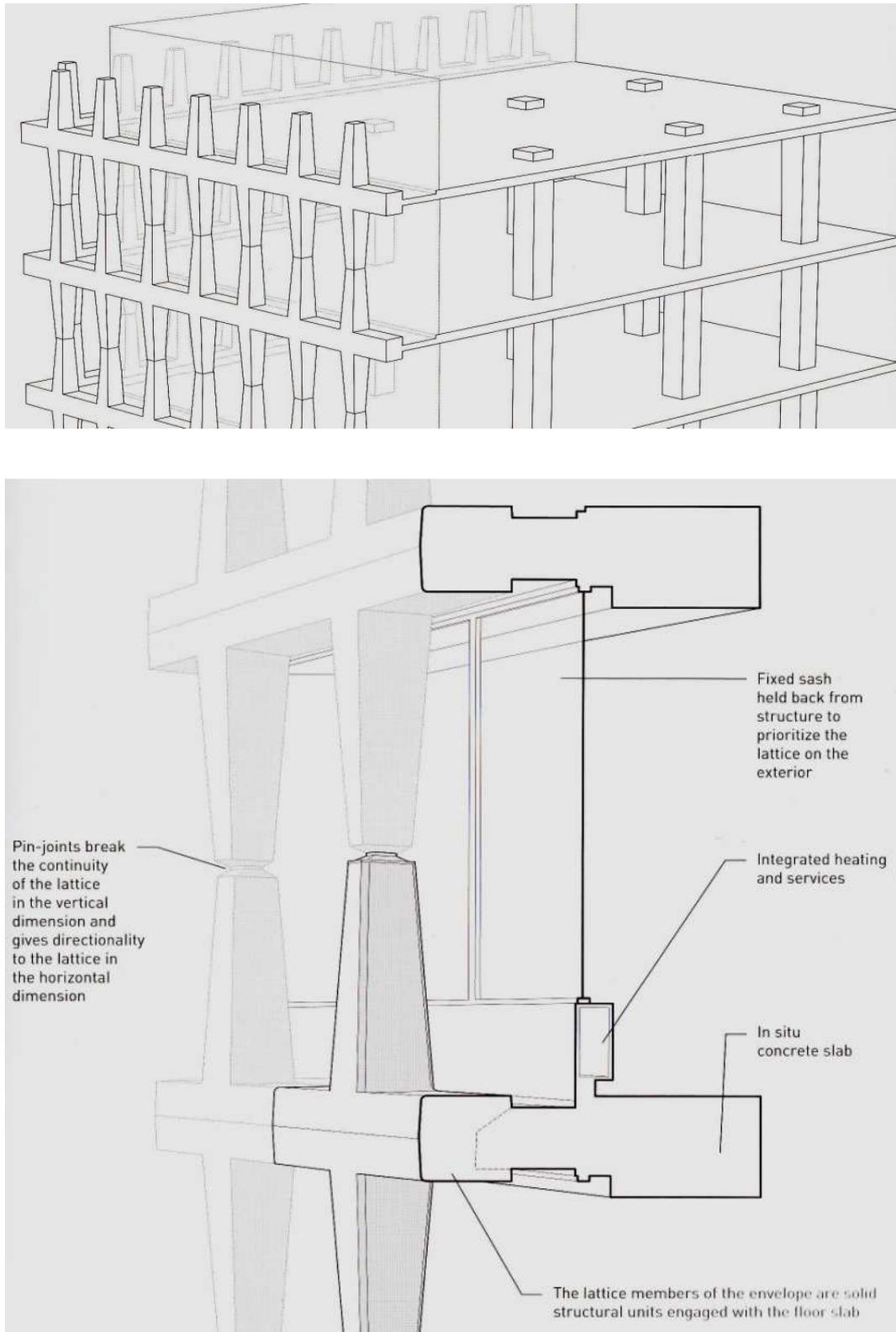


Fig.5.13 Integration of the structure parts

Case 3: Geometry tricks for irregular patterns

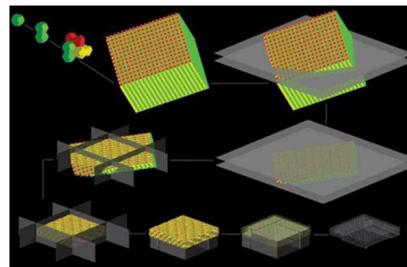
Project: National Swimming Center (Water Cube), Beijing, 2008
 Architect: PTW Architects + CCDI + ARUP

Geometrical Puzzle

“How can space be partitioned into cells of equal volume with the least area of surface between them? – Kelvin’s Conjecture, 1887”

Theoretical physicists had been trying to solve Kelvin’s Conjecture for over one hundred years. Kelvin himself proposed that the solution was a 14-sided polyhedron with six square sides and eight hexagonal sides. In 1998, two physicists, Denis Weaire and Robert Phelan, using computer generated simulations of foam, found a more efficient solution: three quarters of the cells have 14 sides, while the rest are dodecahedra with 12 sides. [It’s known as the Weaire-Phelan Structure.]

The structure, when sliced at arbitrary angles, appears ‘totally random and organic’. That is plausible as the solution to a ‘box of bubbles’. Although the organic design of the building’s structure appears random, the unique geometry is actually highly repetitive and buildable. The resulting structure is very ductile and ideally suited to the seismic conditions found in Beijing.



Sculpting a 3D model

Challenge still exists for computational modelling related to construction. Arup and its design partners used Bentley MicroStation and Microsoft Visual Basic for Applications (VBA) scripts to produce a 3D model and drawings in the shortest possible time to compete in the Beijing Olympics venue design competition.

A 3D array of the cell was generated in Bentley Structural and MicroStation TriForma, and then it was rotated about two axes and sculpted into building. The cut surface planes of the remaining elements form the flanges of the composite structure, while the internal elements form the webs. A 3D centreline wire-frame was created and exported to structural analysis program for engineering. The analysed model was output to a text file containing geometric and structural member design data. Next, a MicroStation VBA routine was written to use the text file to create a complete 3D model of the steel structure. By enabling MicroStation Development Language (MDL) functions, the model could be created as surfaces, solids, or structural elements as appropriate.

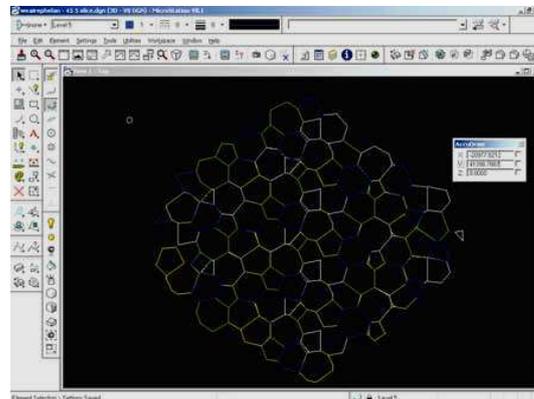
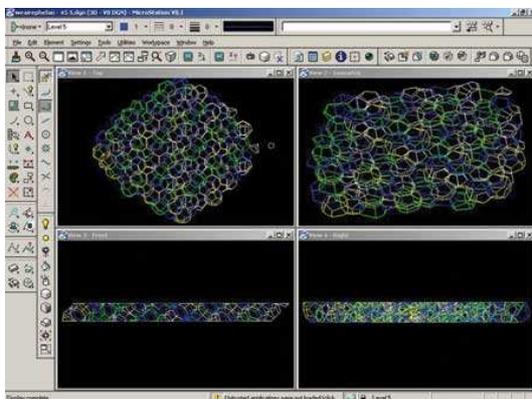
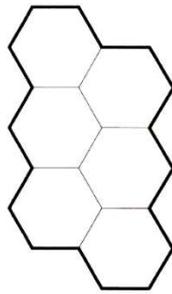


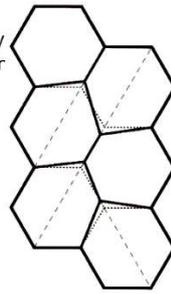
Fig.5.14 A Skewed Plane Cutting the Regular Foam Produces a Random Geometry

Project: Aichi Spanish Pavilion, Aichi, Japan, 2005
 Architect: Foreign Office Architects

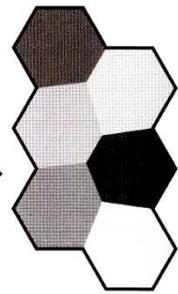
The Aichi Pavilion creates a differentiated affect through patterning, based on a tile unit produced from a module of six regular hexagons.



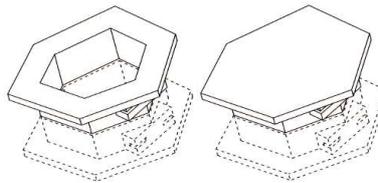
1 Distorting the hexagonal geometry within the perimeter produces a regular module of six unique tiles.



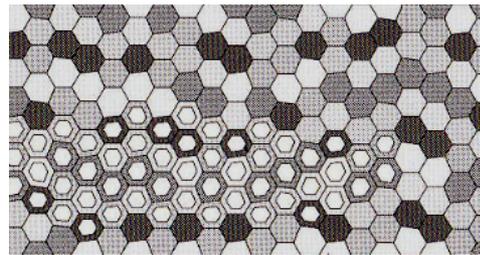
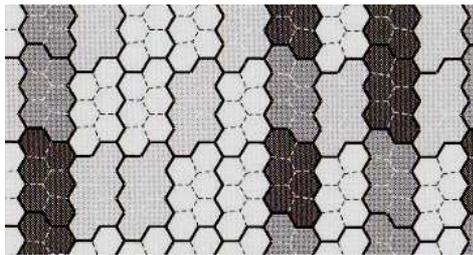
2 Each of the six tiles is coded with its own color, further differentiating the tiles.



3 Each of the six shapes is cast as a glazed ceramic tile, produced in both solid and perforated versions. Each tile has front and back halves, connected by brackets that are clamped into a supporting stanchion.

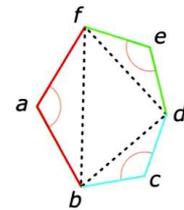
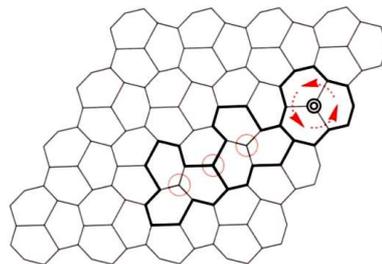


The basic unit of six tiles is mirrored and rotated to produce four orientations of the modules, which are then aggregated to form the pattern of the façade. Color adjacencies between the modules further obscure the original module of six tiles, increasing the differentiated affect.



Other geometric solution for irregular patterns [Source: Architectural Geometry Book]:

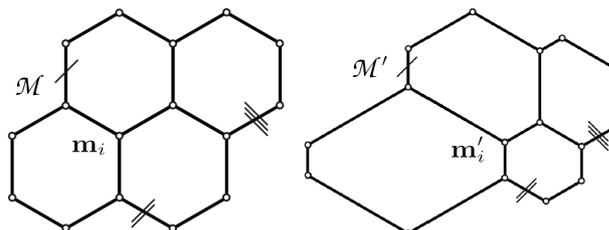
1_ Reduce different cell elements - irregular hexagonal tiling by standard elements:



$$fa=ab, bc=cd, de=ef$$

$$\sphericalangle a = \sphericalangle c = \sphericalangle e = 120^\circ$$

2_ Reduce different nodes - when the corresponding edges are parallel, standard nodes (with the same angle divisions) can be applied for the irregular mesh: [\mathcal{M} and \mathcal{M}' are so-called 'parallel mesh']



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