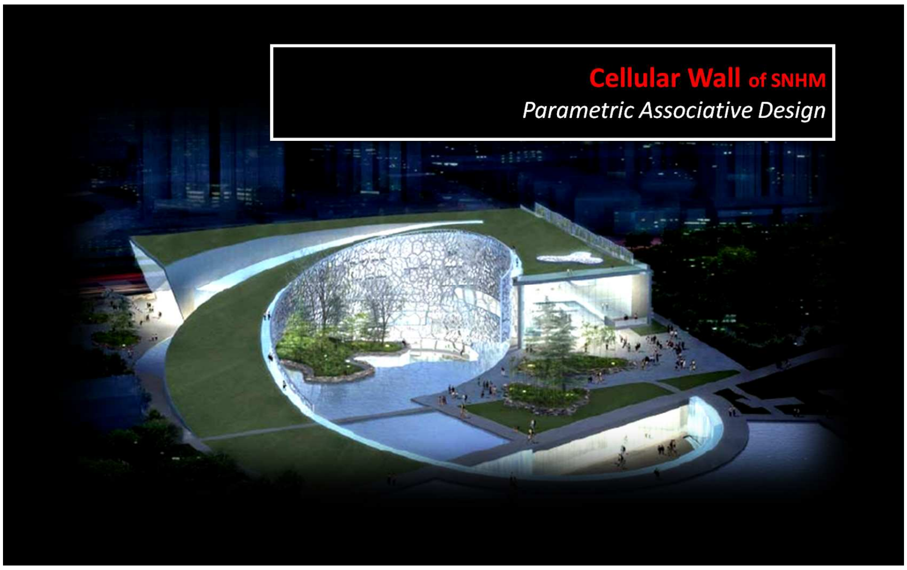
Cellular Wall Design With Parametric CAD Models



Final report Master's thesis project

L.(luyuan) Li

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TU Delft

Master's thesis

Cellular Wall Design
With Parametric CAD Models

Submitted in partial fulfillment of the
requirements for the degree of

MASTERS OF SCIENCE

in

CIVIL ENGINEERING

by

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Section of Structural Engineering

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Preface

This report documents the Master's Thesis project which I undertook to complete my study in Structural Engineering at the Faculty of Civil Engineering and Geosciences, Delft University of Technology. The project was in cooperation with DHV B.V. (the Netherlands). The purpose of this thesis is to explore an 'optimal' structure for the cellular wall of Shanghai Natural History Museum (SNHM), using parametric CAD models. All the source codes and implementation information can be obtained upon request via the author's e-mail: li_lyuan@hotmail.com.

"Where structure is a major consideration, the engineer should be a partner in evolving the design, so that the proper integration of structure and architecture can be achieved. It is of course his job to assist the architect to realize his architectural conception, and he must accept his role as an assistant. But he should be a useful assistant, and that means that he must understand and sympathies with the aims of the architect, so that he, in his own intuitive thinking, can arrive at proposals which will further the architect's wishes - just as a pianist in his own right should not deem it beneath his dignity to act as an accompanist, as long as he is nor asked to play with one finger. – Ove Arup"

This Master thesis project means more than just a graduation topic for me. It gave me a great chance to find a right attitude of structural engineer - Engineers do much more beside calculation, and it is very necessary to learn how to draw and design, to develop the spatial power of imagination and CAD skills, and to know the language and work methods of the future architectural partners. It recalled my enthusiasm for structures and design, which I wish I can keep in the future.

As new to the field of Computer Aided Design of innovative architecture, I got stuck for quite some time. At that moment, one member from Smart Geometry group shared with me quite a long, but interesting comment, which I would like to abstract and record here:

"This computation, geometry stuff is hard, and if you are new to it you won't get it over night. There are however strategies that will make it a lot more likely that you will be able to solve your own problem:

The first is to think about your problem, and when I say that I mean really think about it, think about it until your brain hurts, a lot. Then stop and go for a walk and stop thinking about your problem if you can.

Then once you are out back, draw the problem. When I say draw the problem, that's not a fancy picture of what it might look like (that might end up being helpful, but mostly it won't). You need to get a whiteboard, or just some white board pens (you can draw on bus shelters, windows, cars, anything!). There is a reason that physicists an mathematicians work on the walls, and it's not because they are all have psychological problems that make them into vandals, it's because it allows you to stand back, take in the information, and rub bits out to make it work. Your drawing won't be an image, it'll be a process, the action of drawing point1 and then point2 and deciding where point3 goes based on the first 2 points, and then realizing that point4 will never work with that rule set and starting again is the process that you'll need to follow. These drawings/ diagrams will probably look very little like the 'thing' that you are trying to make, but the experience will provide you with the knowledge to make your 'thing' work. Failing the actual success of the process to provide you with a solution, it provides you with something equally valuable, a clear and concise way of explaining your thought process to others. This does two things. It shows them your intent, far better than a text explanation, and it also shows your process, helping to avoid abortive work repeating your work, and also might show up the flaw in the system.

...

By all means ask questions, but back up the question by yourself, with some evidence of having dome some prior thought, and preferably some research. Bring some enthusiastic thinking, and some clear diagrams to explain thought processes!"

I couldn't totally agree with his opinion at that moment, but thanks for the comments, I did start to calm and really think about my own problem. Drawing indeed helped a lot during the process. As suggested, I learned to keep trying and do experiments until the solutions were found, reminding myself that innovative engineering should be both challenging and fun. It never fails to make me pull my hair, but when it's worked out, it's like having Christmas morning moments. As with the joy of juggling – you only find out what it really involves when you try to do it yourself.

One more thing I would like to record is a reminder that I was once wrong about, but learned from this thesis project: when introducing computational aided design in the structural design process, getting the advantage of efficiency and fast speed of calculation and design, we should never lose the basic principles of structural design. And as Alan Harris put it, 'The foundation of engineering is knowledge of material, not, as engineers are so often apt to preach, knowledge of mathematics' – structural design is art and knowledge about material.

Hereby, I would like to take this opportunity to thank a number of people:

My graduation committee, consisting of Prof. Vambersky, Sander Pasterkamp, Pierre Hoogenboom, Andrew Borgart, and Marco Schuurman (from DHV B.V), for their support. As my path meandered, the committee steered me in the right direction, for which I am grateful. They were patient and kind to discuss the problems with me every time when I got stuck, and teach me how to analysis and get to know my structures better. Without their inspiring comments and ideas this report would not be presented here.

My family, friends and colleagues, who have supported and encouraged me throughout my graduation study period, and/or contributed to this report.

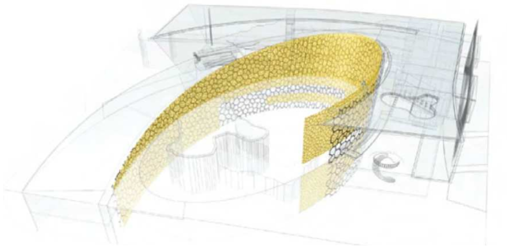
Delft, August 2009,

Luyuan Li

Contents

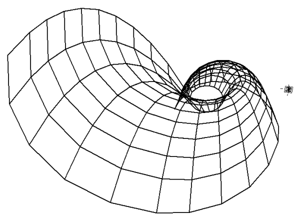
Summary

The primary structure of the cellular wall of Shanghai Natural History Museum (SNHM) can be defined as a grid structure on a single curved surface (developable), with a cell-like configuration. The shape of the wall (surface) is defined by two free-form curves, which explicate a ruled/lofted surface.



The cellular wall is one of the most captivating elements in the SNHM design. Besides its architectural appearance it also has an important function in the structural system to distribute both horizontal and vertical forces. It requires large efforts to create the optimal configuration that meets both its architectural and structural objectives. This includes the structural material of the cellular wall.

The objective of this Master’s thesis research is to explore an ‘optimal’ grid structure for the cellular wall. Since the geometry of the wall surface is determined in advance, the design exploration will focus on the grid/pattern generation, and the basic purpose of optimization is to explore a pattern in which elements are tuned up by different design constrains (requirements).



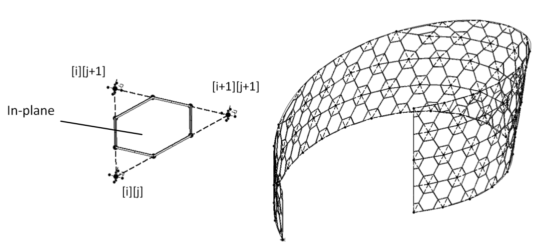
The chosen approach is to design the structural cellular wall by parametric CAD modeling via parametric design tools (GenerativeComponents, etc). These parametric associative tools generate the complex geometry by applying rules and capturing relationships among model elements and link the geometrical data to the analytical and drafting software. The typical modeling process and advantages of this approach will be exampled by a case study of Nautilus shell model (Chapter 4.2).

Chapter 2-4 will give some background information based on literature study, including the main topics of: SNHM project information and structural optimization proposals, Free-form/Special structural design technologies, and parametric associative design approach.

In Chapter 5, the design alternatives will be studied: a design exploration diagram will be draw to clarify the design constrains and their requirements, following the proposal of structural parameters. Various structural materials with construction methods will be compared, and some references study for the structural patterns and grid structures will be recorded. Study of grid structures with basic grid types (rectangular, triangular, hexagonal) will be performed to high-light the structural behaviors and design principles of cell-like grid.

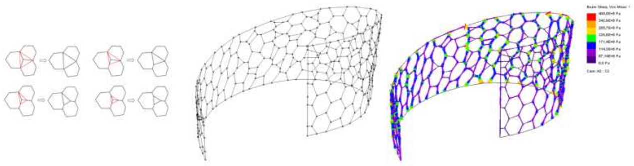
In Chapter 6 & 7, cell-like pattern exploration by parametric CAD modeling will be conducted, which includes building parametric CAD models and structural analysis. According to the grid generation technologies (pre-studied in Chapter3), the parametric models will be created in 3 categories:

1_ Structured grid models
Structured grids have advantages of easy to implement and good efficiency, but various grid sizes can’t be introduced or the grid cells will deform too much.

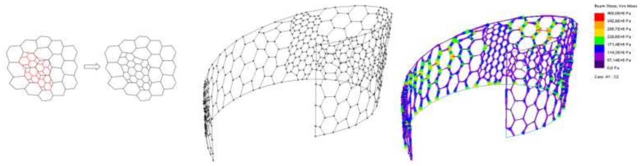


Regular grid will result in un-evenly distributed loads and stresses under the design load cases.
2_ Modified structured grid models

A_ Insert triangular elements, following the stiffness requirement: this method increases the total stiffness and creates moment-free nodes, but at the same time, it's easy to cause stress concentration.

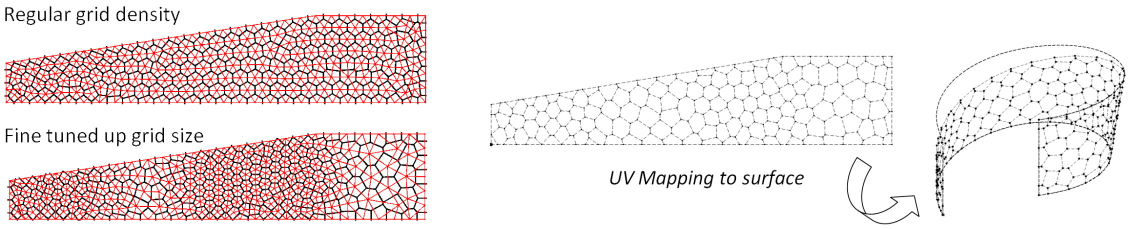


B_ Locally double-up hexagonal grid, following the strength requirement: The implementation of double-up grid is easier and results in a configuration of fractal geometry (local double rhythm).



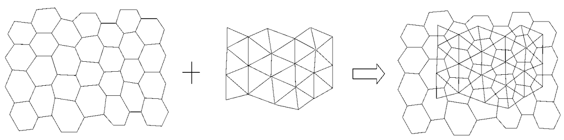
3_ Unstructured grid models

Unstructured grid models are generated via Voronoi Diagram. Some experiments have been done to find efficient methods to generate a point-set (grid points) and generate grid on the wall surface. The 'attract & repel' method and UV mapping tool were implemented in this design case.

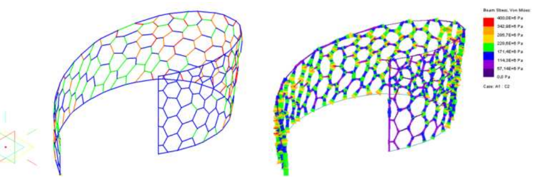


When the local densities of the grid structure are fine tuned up with the imposed load cases (structural requirements), the material will be used in an efficient way, which can be read from the analysis results – better forces distribution and low stress level. The local densities/grid sizes are changed smoothly, which brings nice design aesthetic.

[Suggestion]
In the modified structured grid models, by locally cutting-out triangles will cause stress concentration, which cannot efficiently increase the total stiffness. A suggested method is to corporate Voronoi diagram with the associated Delaunay triangulation, efficiently getting advantages of the stiff triangle components.



_ Member design
Another method is to apply different profiles (cross-sections) for individual beam elements according to the structural requirements. Although it will bring extra requirements for construction – carefully coded and stored, this approach provides quite an efficient structure.



Chapter 8 concludes the findings of this Master's thesis research as conclusions and recommendations for further research.

Chapter 1

Introduction

This chapter will give an introduction into the main topics of this Master's thesis project, concluding with the problem definition and the research goal.

> "Art is solving problems which cannot be formulated before they have been solved. The search goes on, until a solution is found, which is deemed to be satisfactory. There are always many possible solutions, the search is for the best – but there is no best – just more or less good.
> – Ove Arup"

1.1 Project and Topic

Project: Shanghai Natural History Museum (SNHM)
Architected by: Perkins +Will

Fig.1.1 Night view of Shanghai Natural History Museum (concept design)

Topic: Cellular Wall design with Parametric CAD Models

The cellular wall (the central wall of the main building) is one of the most captivating elements in the Shanghai Natural History Museum design. Besides its architectural appearance it also has an important function in the structural system to distribute both horizontal and vertical forces.

It requires large efforts to create the optimal configuration that meets both its architectural and structural objectives. This includes the structural material of the cellular wall. A good way to design the structural cellular wall is based on parametric CAD modeling via parametric design tools. The complex geometry is possible to be optimized by parametric associative software, which is capable of generating geometrical and structural models based on a set of variable parameters and link the geometrical data to the analytical and drafting software.

Parametric associative design approach is chosen and the innovative software GenerativeComponents is introduced in this project. GC is an associative and parametric modeling system used by architects and engineers to automate the design processes and accelerate design iterations. With such a software tool an adaptive parametric design model can be created and it enables the user to create and optimize a design graphically.

By combining the architectural design of the wall with structural principles in this model, the possibilities for the structure can be explored and optimized.

1.2 Problem State

The structural behaviors of the cellular wall are not easy to be observed or predicted, because of its complex geometry. Therefore, parametric associative design approach is very suitable for this design case. In this Master Thesis project, several concepts and fundamental information will be studied:

Architectural Geometry

An important part in the design of building with special design is the description and generation of the buildings as computer models, often because of their complex geometrical nature and behavior. The realization of freedom shapes in architecture poses great challenge to engineering and design. The complete design and construction process involves many aspects, including form finding, feasible segmentation into panels, functionality, materials, statics, and cost. Geometry alone is not able to provide solutions for the entire process, but a solid geometric understanding is an important step toward a successful realization of such a project. In particular, it is essential to know about the available degrees of freedom for shape optimization. Two main contents will be included in form description and generation: curves - surfaces definition and grid generation technologies.

Parametric Associative Design

Parametric design is used for the rapid generation of computable design representations describing design alternatives. Potential design alternatives are generated and evaluated in order to obtain the most promising solution. The parametric design approach can be seen as a design process which goal is to target the optimal combination of structural parameters. As a parametric associative tool, GenerativeComponents [Aish, 2005] offers many advantages for the design stage of modeling the structural geometry.

Tooling Design

A new approach toward use of computers in the structural design process – Structural Design Tools (SDT) approach – was proposed by Coenders and Wagemans, 2005. The basic concept is an abstract base model that initially be built for speed, communication, insight and control over large amounts of data and not for complexity, like the current analysis tools. Instead of using the computer for engineering purpose, the computer can be used for design purpose.

Design Exploration

A Design Exploration Concept - Constraints as design drivers - was proposed by Axel Killian, 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.

Adaptive Patterns

The basic purpose of optimization is to explore a grid structure in which all the elements are tuned up by different design constrains. 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 ‘Adaptive Patterns’ (cell-like), which was represented by parameters. The goal of the design exploration process is to target an optimal combination of these parameters.

1.3 Objectives

Design conditions

The cellular wall structure can be grouped by free form/special structures. These kinds of structures will require a unique design approach and optimization process. The specific design conditions for the cellular wall structure should be clarified first, which include: the geometric definition, the material process, the structural action forms, the load cases and design codes etc. This information will built up the foundation for further design.

Design alternatives

Potential design alternatives are generated and evaluated on order to obtain the most promising solution. The design alternatives for the cellular wall structure include the alternatives for: the structural materials and construction technologies, structural forms and configurations, detailing of connections and joints, etc. Different design alternatives should be analysis, compared and evaluated, by a series of evaluation criteria. In additions, some precedent works from referenced projects/researches will be studied to build up the background of design alternatives.

Adaptive patterns by parametric modeling

By implementation of parametric design strategy, cell-like grid structures with adaptive patterns will be explored for the cellular wall of SNHM. The main steps include:

1_Build up parametric CAD models: choose parameters --> find generation principles and algorithms --> build up models in programmable environment --> implementation and resulted models

2_To build up a design in a parametric associative way, different design step might require a design tool. Some computational tools should be built to aid the parametric analysis.

3_Analysis and evaluate the parametric models based on the architectural and structural objectives. Series of parameters should be experimented to explore the 'optimal' configuration.

Chapter 2

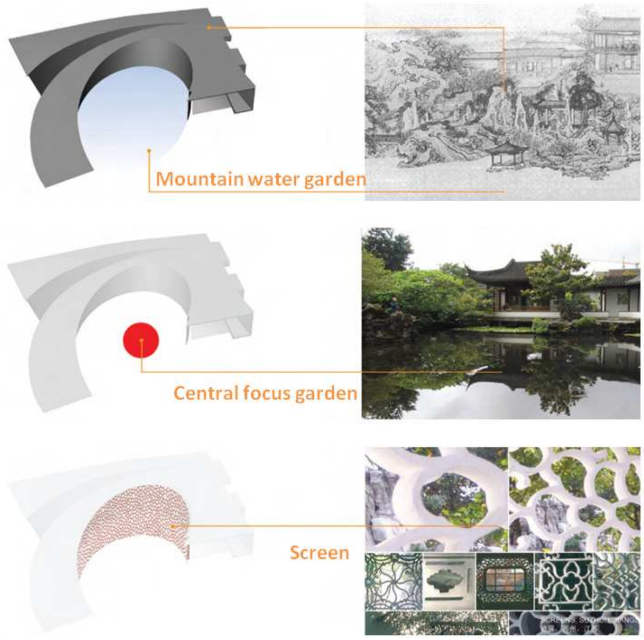
Project Information

This chapter will present some information of Shanghai Natural History Museum (SNHM) project, mainly based on the Green Building Study report form DHV B.V. These structural optimization suggestions will be taken into account as a starting point of the cellular wall design in this thesis study.

2.1 Architectural Concept Design

Design Concept - Traditional Influences

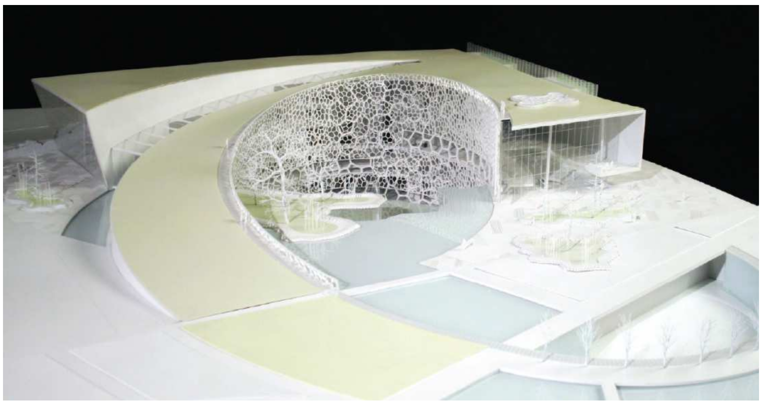
Through the museum's relationship to its site, the museum is intended to represent the harmonious togetherness of man and nature which forms the basis of Chinese culture. In traditional Chinese art and design, mountain and water are the basic elements of nature. In response to this, the museum was designed as an abstraction of the 'mountain water garden,' with the building acting as a mountain surrounding a body of water.



As in traditional design this building is seen as an approach to the spirit of nature not an imitation of it.

Screens composed of abstractions of natural patterns found in traditional garden pavilions are employed as structure and sun-protection for the glass wall enclosing the garden. This patterned surface also recalls human cellular organizational structures.

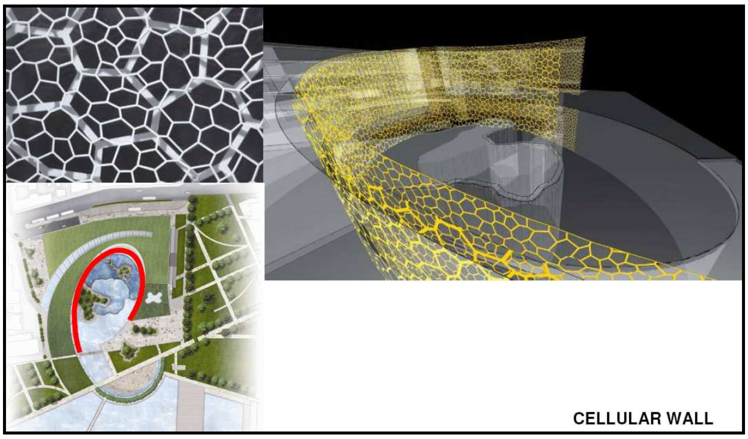
Thus, the experience of the museum will include the interplay of stone, earth, water, plants, walls, buildings and light as in traditional Chinese garden design.



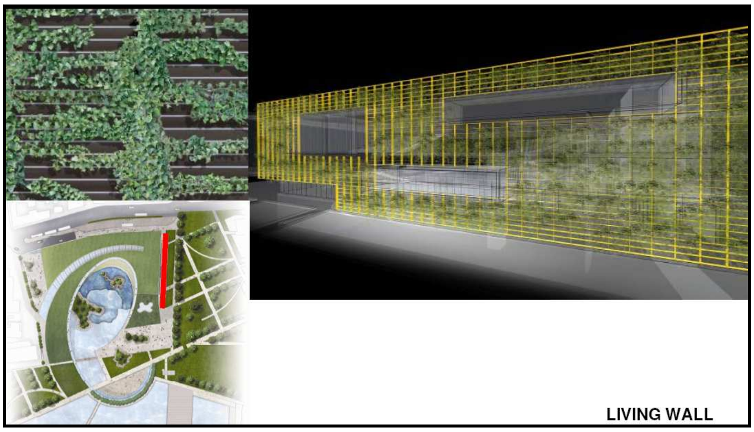
Wall systems

The museum is enclosed by three wall systems that express themes found within the exhibitory.

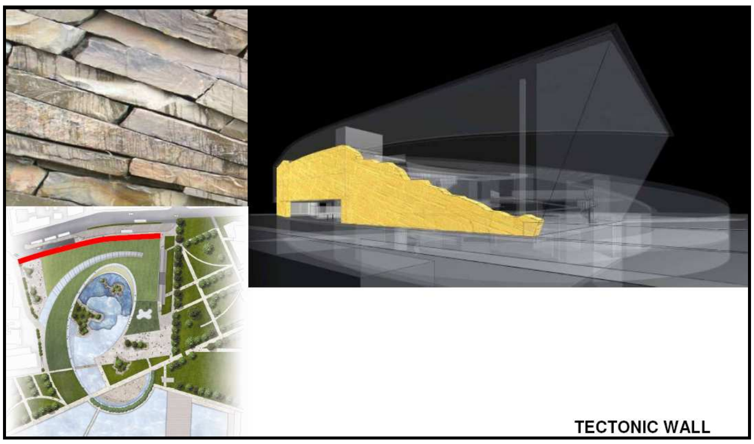
The south wall has patterns recalling ‘human cell structures’.
It is composed of three layers. A larger scale inner structure represents the skeletal structure of the body and supports the walls and roof of the museum. An outer layer composed of a smaller scale pattern represents the tissue and muscle of the body and provides sun shading for a membrane of glass which is the third layer.



The north wall is a living wall plane composed of a metal trellis covered with vines. This plane defines an arcaded walkway connecting the street with the park entry and provides shading for office windows. It also brings the horizontal plane of the park onto the vertical surface and represents the vegetation of the earth’s surface.



The west wall, which is the entry façade along the bus drop, is expressed as a tectonic plane of variegated and striated rock textures. This plane expresses the movement and stresses involved in the formation or the earth’s crust.



2.2 Structural optimization

A report "Study on Green Building Integration and Design Optimization" was provided by DHV in July 2008, giving structural optimization proposal for Shanghai Natural History Museum concept design, to achieve the maximum benefits of sustainability.

For the Shanghai Natural History Museum concept design, the following sustainable issues are discussed:
- Multidisciplinary design
- Adaptability: upgrading economic life span to match technical life span
- Effective use of material

2.2.1 Adaptability

Considering the life cycle of building, different life spans can be recognized for their components:

1_ Functional life span
2_ Economical life span
3_ Technical life span

For the museum it is very interesting to create an adaptable building that can react on future changes. These changes are based on unknown future needs, so it is hard to predict these. But the strong character of the building shows components that will certainly not change. The cellular wall, the ramp, the routing and the east and west façade are remarkable pieces that will keep the building attractive over time. To remain this strong architecture, these should not be designed for change. Between these long term architectural elements large spaces are developed for expositions, administrative functions, and parking among other things. These functions are specified by the client according to their current needs.

From a sustainable point of view it is to be advised to create a building in which different functional configurations can be made, without large efforts in terms of energy and material and without demolishing its strong architecture. **Considering the structural design it is advised to create a clear distinction between a primary structure and a secondary structure.**

The primary structure includes the concrete roof and ramp, the shear walls below the ramp, the cellular wall and the east and west façade. The basement walls are also an important part of the primary structure. These elements are designed for the entire life span of the building and support the strong architecture. Overall stability is ensured by these elements. The primary structure should be designed according to their technical life span. This means that extreme situations should be considered during the design (earthquakes, climate change, explosions, etc). Over-dimensioning of the primary structure is inevitable.

The secondary structure includes other elements from the load-bearing structure, like walls, columns and floor structures. These are designed according to the functional life span and must be able to change over time. This means the secondary structure should not be integrated into the primary structure.

2.2.2 Primary structure

In this study report, a primary structure has been proposed, which is designed for the entire life span of the building. Efficient use of material, focused on the primary structure, is mainly based on durable materials that require less maintenance.

1_Vertical load-bearing system

Concrete is a good structural material to show the massiveness of the building, because of the relative limited building height and the large, thick elements like the ramp and roof. To emphasize the internal routing below the ramp and to split up the primary and secondary spaces, various concrete walls are located below the ramp around the atrium, following the same route as the ramp. The structural cellular wall functions as a third wall support along this path. All walls continue down to the foundation.

In the open, orthogonal spaces around the ramp concrete columns are located for vertical support of roof and floors. Suggestion was given to separate the structure rigidly into a radial and orthogonal structure.

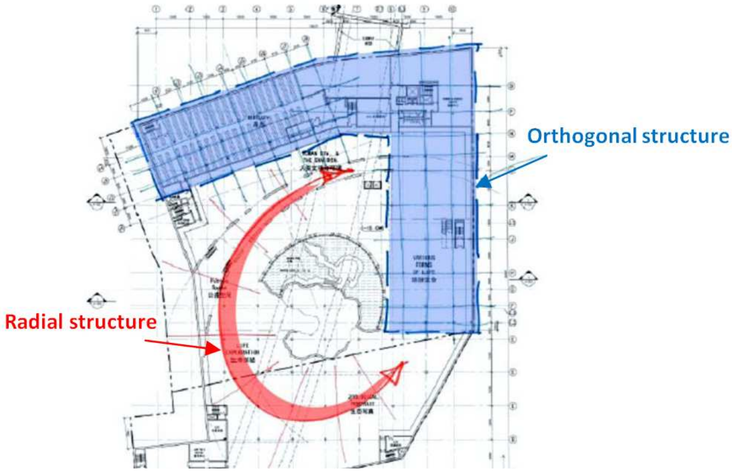


Fig 2.1 separation of a radial and orthogonal grid
Blue: a reinforced concrete structure, located with slabs and columns on an orthogonal grid
Red: the radial shape of the ramp and atrium

Here concrete walls and slabs emphasize the routing of the ramp. In the current design an orthogonal grid is used for the columns in the basement at the south side. An alternative on this subject is to use concrete walls instead, which continue the circular routing and span the distance above the subway tunnel that runs below the building. The tunnel and the building structure must be separated structurally to prevent vibrations from the metro entering the building structure.

2_Stability system

In Shanghai structures must be capable to take up significant horizontal forces, mainly from wind and earthquakes. Due to the limited height and massiveness, earthquakes might be the critical horizontal load case. A good solution is to create a very stiff building that has the capacity to resist these seismic loads and that limits the displacements and accelerations. In the current design this has been applied by using big concrete columns that are moment fixed with the thick concrete floor and roof slaps. The large stiffness is guaranteed by the uniformly distributed columns over the plot.

An alternative for this solution is to gain stability from the thick roof and ramp slabs in combination with the shear walls, below the ramp, including the cellular wall, instead of the moment fixed columns. The walls are an important part of the architecture and already have bending stiffness, so there is no need for extra moment fixed connections. Due to the circular shape of the walls, stability is ensured in all directions.

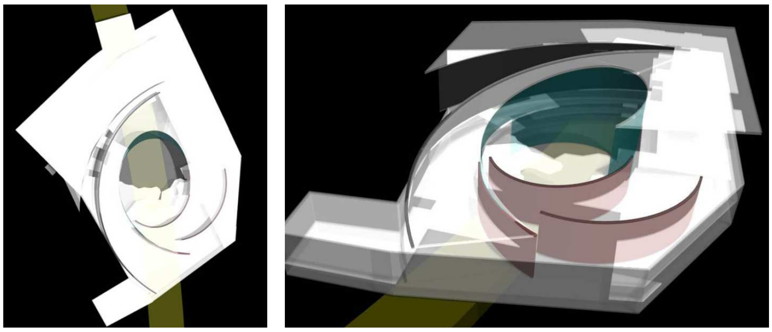


Fig 2.2 stability system of shear walls

The advantages of a certain system are as following:
- With little additions in size & reinforcement, overall stability can be guaranteed.
- No stability elements in façade
- No thick concrete cores around elevator shafts
- Freedom in adaptation of all main spaces
- More slender columns

During earthquakes the displacements and accelerations of the building, especially at the sides might be much more than with the moment fixed columns, because the stability elements are located in the centre. It is hard to predict the behavior of the structure during an earthquake, because of this non-uniform configuration. To gain a reliable prediction an intensive examination on seismic design is required. This examination deserves the preference, if a suitable and sustainable structure is required which functions effectively over the long term.

3_Roof and ramp structure

The ramp and the roof structure can have similar functions in the building.
- Horizontal distribution of loads to the various shear walls (diaphragm action)
- Providing thermal mass during extreme weather conditions
- Very large spans
- Irregular configuration due to the circular walls and altering spans

Using thick concrete slabs ensures both diaphragm action for stability and thermal mass. But a large thickness would also increase the self-weight of the roof. An efficient way to limit the self weight, without losing these advantages is to apply lightweight polystyrene blocks within the slab. By adding beam reinforcement in the slab, between the PS blocks, extra strength can be realized. This reinforcement and the block's shapes can be freely adjusted to the required direction, for both the radial and orthogonal grid.

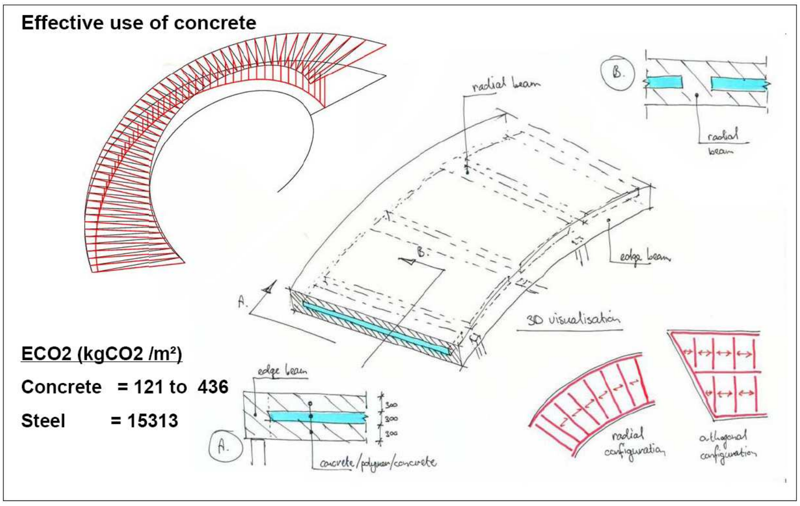


Fig 2.3 Ramp and roof structure

Another advantage of this system is the simple and cheap construction process. Many concrete structures are casted in situ in China. With this system the lower slab, including lower and beam reinforcement, are constructed first. Then the PS blocks are put in place, between the beam reinforcement. After finishing the upper slab reinforcement the upper slab can be poured. Advantages of concrete sandwich-structure:

- Increased thermal mass
- Increased spans
- Weight reduction
- Earthquake resilient

4_Cellular wall

The south wall has patterns recalling 'human cell structures'. It is composed of three layers. A larger scale inner structure represents the skeletal structure of the body and supports the walls and roof of the museum. An outer layer composed of a smaller scale pattern represents the tissue and muscle of the body and provides sun shading for a membrane of glass which is the third layer.

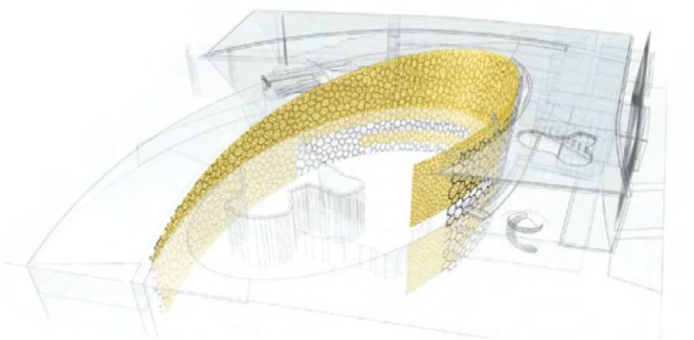


Fig 2.4 Sketch of the cellular wall

One of the service functions of this cellular wall is transparence for lighting. The museums lighting bears the following features compared with common buildings: On the one hand it should provide good visual environment for the visitors and on the other hand it should prevent the exhibits from being damaged by the lighting. This is the most distinguishing difference between the exhibition hall and common buildings in terms of lighting. Some specific considerations of architect & engineer:

1_ Adapt to changing environmental conditions
2_ Enable visual relation to the central water body
3_ Create a good educational value
4_ Regulate light intensity, glare protection and thermal comfort

Fig 2.5 sustainable design concepts

The primary structure of the cellular wall is steel lattice structure with cell-like patterns; it is an important component of the building systems of vertical load-bearing and stability. In the central, sufficient resistance to shear is provided by numbers of flat and curved vertical surfaces, tied together by the floors and green roof, as straightforward means of providing stability. The shear walls system are shown in Fig 2.9 - red lines are showing the main effective shear walls, including the cellular wall; and the blue dot lines are showing the walls/ façades that mainly built with glass, not strong structural components.

Fig 2.6 Shear walls shown by red lines

The cellular wall is one of the most captivating elements in the building design. It contributes a lot to the architectural appearance and functions. As a main component of the primary structure, the cellular wall has an important function in the structural system to distribute both horizontal and vertical forces. It requires large efforts to create the optimal configuration that meets both its architectural and structural objectives. This includes the structural material and construction technology of the cellular wall.

To optimize the structural pattern of the cellular wall, one proper design approach is parametric design with innovative software called Generative Components. This is an associative and parametric modeling system used by architects and engineers to automate the design processes and accelerate design iterations. With such a software tool an adaptive parametric design model can be created and it enables the user to create and optimize a design graphically. By combining the architectural design of the wall with structural principles in this model, the possibilities for the structure can be explored and optimized.

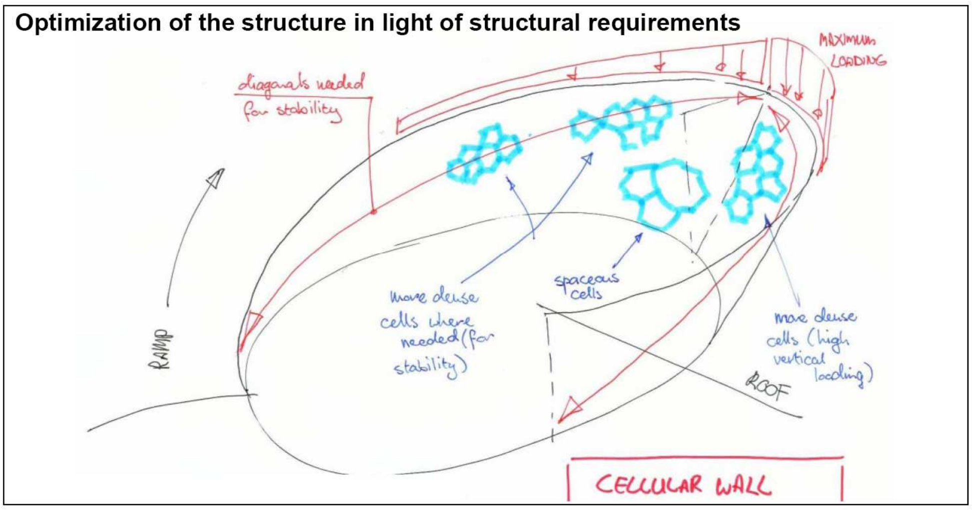


Fig 2.7 Structural principles of cellular wall configuration

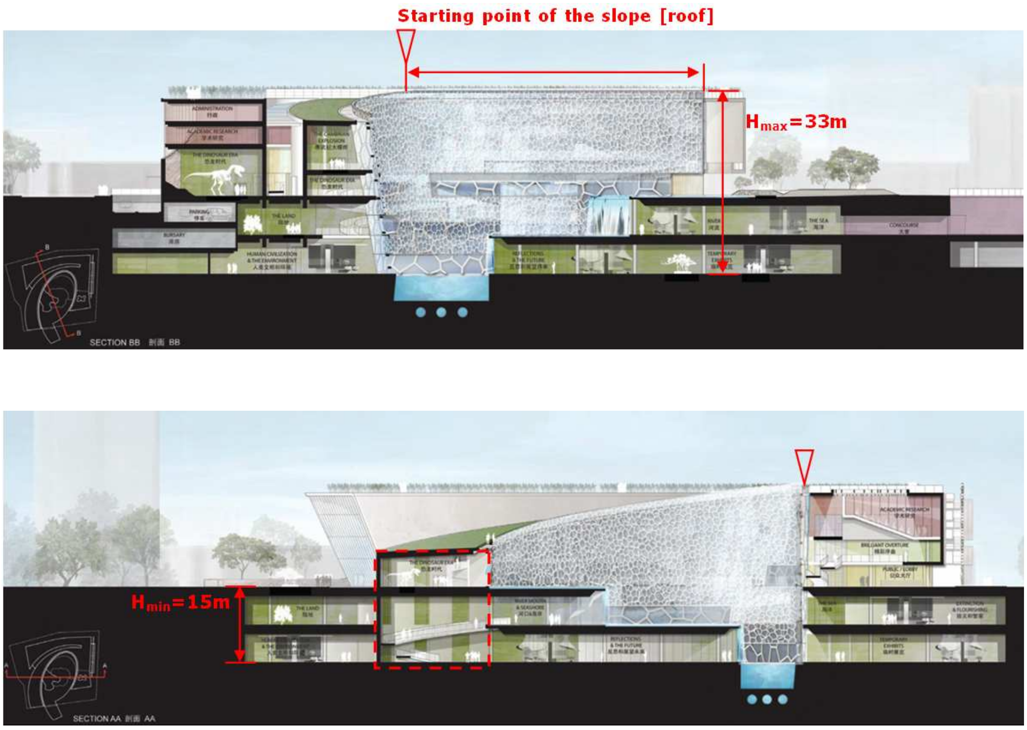


Fig 2.8 Geometry of the cellular wall in the building

Chapter 3

Free-Form/special Structures

Because of the non-standard building shape, the cellular wall structure can be grouped by Free-form/special structures. Some fundamental theory and technology of free form architecture and special structural design will be studied and presented in this chapter, to provide clues for further design study.

“I would distinguish the difference between the engineer and the architect by saying the architect’s response is primarily creative, whereas the engineer’s is essentially inventive.
– Peter Rice”

Creativity, the ability to create new ideas or things using your imagination.
Invention, something someone has made, designed or thought of for the first time.
(Macmillan Essential Dictionary)

3.1 Form description and generation

"An important part in the design of building with special design is the description and generation of the buildings as computer models, often because of their complex geometrical nature and behavior. Usually these buildings consist of complex relationships in the geometrical design of the building. An essential step to design, produce, assemble or construct these building is to provide a unique geometrical description for the geometry and topology. Since computation is essential for an efficient design process it is also essential to produce these computer models which relative ease. Since often the computer applications are complex, inaccessible and do not provide much inside in their behavior, this is not an easy task. One of the key differences between a regular design process of a rectangular building and a special structure is the step of the form description and generation which comes as an additional step within the design.

- *Structural Design, special structures"*

Architectural Geometry

The realization of freedom shapes in architecture poses great challenge to engineering and design. The complete design and construction process involves many aspects, including form finding, feasible segmentation into panels, functionality, materials, statics, and cost. Geometry alone is not able to provide solutions for the entire process, but a solid geometric understanding is an important step toward a successful realization of such a project. In particular, it is essential to know about the available degrees of freedom for shape optimization.

3.1.1 Curves and Surfaces

Curves and surfaces are basic elements in architecture.

1_ Traditional Surface Classes

Traditional Surface Classes are largely based on a simple 'kinematic' generation. They are swept by a profile curve undergoing a smooth motion.

For example:
Translating a curve c along a straight line results in an extrusion surface, whereas translating this curve along another curve d generates a translational surface.
A rotational surface is created by rotating c about axis A, whereas a ruled surface can be generated by moving a straight line.

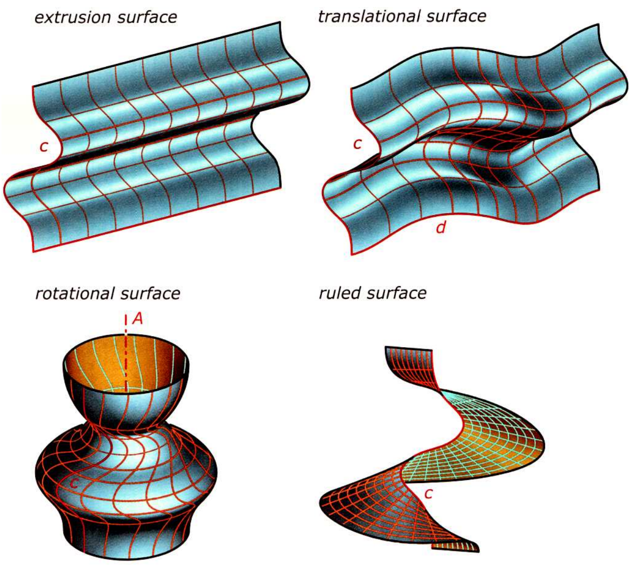


Fig.3.1 Four types of traditional surfaces
[Source: Architectural Geometry]

2_ Free Form curves and surface

Free Form curves - Basic knowledge of the generation and properties of freeform curves allows the designer to choose the best scheme for the task at hand and to employ it efficiently. Once the curves are mastered, freeform surface modeling can be preceded.

Three types of free form curves used in design: Bézier curves are among the most widely used freeform curves. They possess an intuitive geometric construction via the *de Casteljau algorithm*, which is based on repeated *linear interpolation*. Bézier curves are completely defined by control polygons. B-Spline curves offer local shape control. They can be generated by iteratively refining a given polygon – a process called *curve subdivision*. Non-uniform rational B-Spline (NURBS) curves have further fine-tuning possibilities via weights associated with the control points. They are used to draw the most complex planar and spatial form curves.

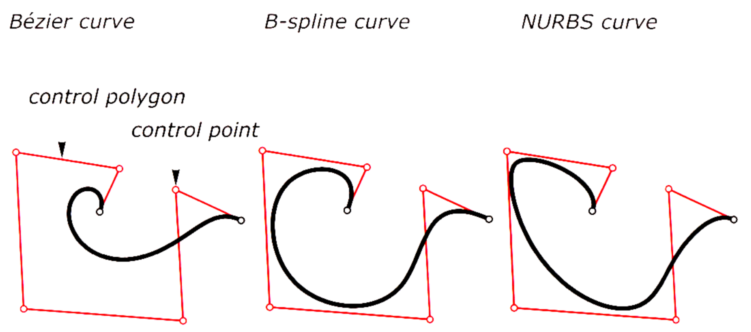


Fig.3.2 three types of free form curves used in design [Source: Architectural Geometry]

Table: Design handles for freeform curves

	Control points	degree	Weights
Bézier	×		
B-Spline	×	×	
NURBS	×	×	×

Symbol × means that this design handle can be set by the user. For Bézier curves, the user can only modify the control points because the degree follows from the number of control points and the weights are equals to 1. For a B-Spline curve, the user can set the control points and the degree but the weights are all equals to 1. Only for a true NURBS curve can the user employ all three design handles. NURBS curves inherit the useful properties of B-Spline curves.

Free Form surface

Bézier surfaces are just families of Bézier curves. They have the same drawbacks as their curve counterparts: As soon as one degree is too high, they poorly represent the shape of the control mesh. Moreover, changing one control point has a global effect – which makes editing difficult.

To avoid this problem, one can use B-Splines for the surface definition. Such a B-Spline surface is also defined by a quadrilateral control mesh. However, in addition the degrees for the u- and v-curves can be chosen. The implications of the degree on the smoothness of the surface are the same as for curves.

Another straightforward extension is the use of NURBS surface, which have a weight attached to each control point. The effects of changing a weight are the same as for NURBS curves.

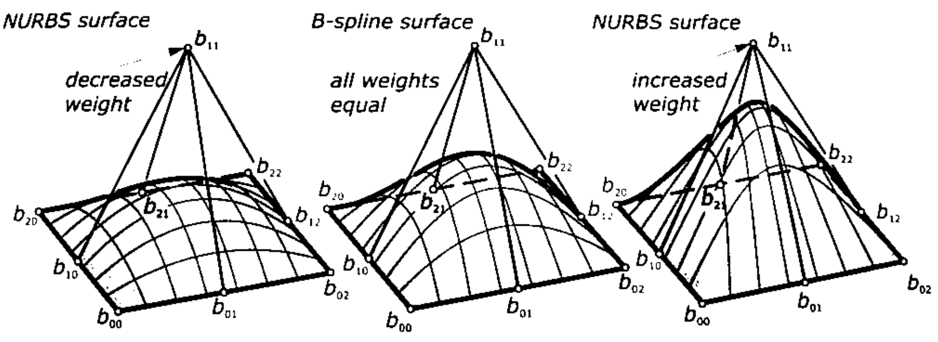


Fig. 3.3 weights as shape parameters of NURBS surfaces :
increasing a weight pulls the surface towards the corresponding control point,
decreasing a weight shows a push-away effect [Source: Architectural Geometry]

3.1.2 Grid generation technology

With the definition and generation information of curves and surface, the geometry problem comes to a polygon phase – discrete surface. This section will focus on describing methods to describe a geometrical complex continuous surface in a discrete way that is sufficiently accurate to represent a design free formed surface. This discretisation of the continuous surface is done by generating a grid on the surface. Grid generation is an important step in the structural design process, since the architectural shape is translated into structural elements.

According to Liseikin [1999], some important terms for grid generation can be listed out:

1_ There are two general notions of a grid in an n-dimensional bounded domain or on a surface: the grid is considered as a set of algorithmically specified points of the domain or the surface. These points are called **grid nodes**. The grid is considered as an algorithmically described collection of standard n-dimensional volumes covering the area of the domain or surface. The standard volumes are referred to as **grid cells**.

2_ The boundary points of one dimensional cells are called the **cell vertices**. These vertices are the grid nodes. The grid nodes are consistent with the grid cells in that they coincide with the cell vertices.

3_ A one dimensional cell is a closed line or segment, whose boundary is composed of two points. A two dimensional cell is two dimensional simply connected domain, whose boundary is divided into a finite number of one dimensional cells, referred to as the **cell edges**. Normally, the cells of two dimensional domains or surfaces are constructed in the form of triangles or quadrilaterals. The specific choice of the cell shape depends on the geometry.

4_ Grids can be divided in two fundamental different classes: structured and unstructured. These classes differ in the way in which the mesh points are locally organized:

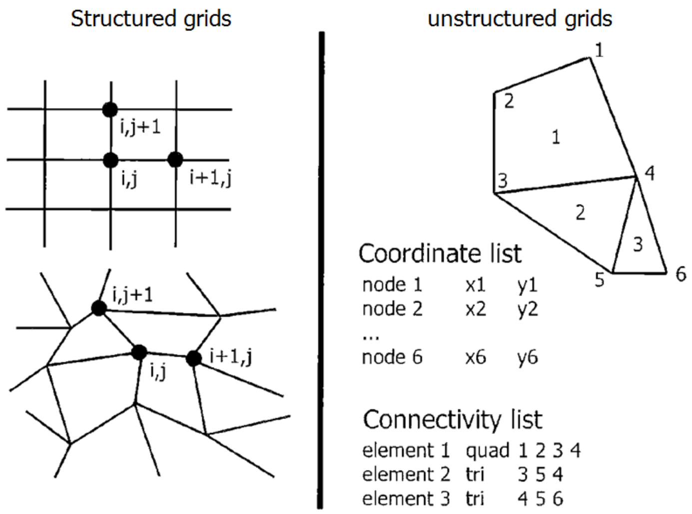


Fig. 3.4 The logic of structured and unstructured grids [Gable, 1996]

- **Structured grids**
  Structured grids has local organization of the grid points and a form of the grid that is not dependant on their position, they are defined by **general rule**. The nodes and connections in a structured grid have a fixed relationship to one another. The connectivity of the grid is implicitly taken into account.
- **Unstructured grids**
  Unstructured grids have a connection with neighboring grid nodes that varies from point to point. Thus, they require for explicit **statements of the connectivity** between nodes.

5_ The two fundamental different classes of mesh rise to three additional subdivisions of grid types: **Block Structured Grids**, **Overset Grids** and **Hybrid Grids**. These kinds of grids possess to some extend the features of both structured and unstructured grids.

Grid requirement

The traditional use of the grid generation is aiming to discrete a domain or surface in such a manner that computation of physical quantities is as efficient as desired.

1_ Grid size
The number of grid points is an indication of the grid size, the maximum value of the lengths of the cell edges is an indication of the cell size. Generation techniques for grids need to posses the ability to increase the number of grid nodes.

2_ Grid organization
Grids need to have some organization of their nodes and cells. This organization should identify neighboring points and cells.

3_ Grid deformation
Cell deformation characteristics are formulated as some measures in the difference between the deformed cell and the standard or least deformed cell. Standard elements are elements with edges of equal length. Typically, cell deformation is characterized by the aspect ratio; the angles between the cell edges and the volume of the cell. The major requirement for grid cells is that they must not be folded or degenerate any points or lines.

4_ Consistency with Geometry
The accuracy of the interpolation of a discrete function is considerably influenced by the degree of compatibility of the mesh with the geometry of the physical domain (complex surface).

5_ Grid Validity
The grid must be valid, for example, there should be no (unwanted) holes or self-intersections. This is a quite obvious requirement, but various (mainly unstructured) grid generation techniques require checking for these conditions.

Basic grid generation methods

Structured grid

Structured grids are in structural engineering the most utilized grid. The main reasons are the simplicity to generate the grid because these follow often from the design of the shape and the predictable and regular shape of the elements. The second reason is the easiness to adapt the mesh size, element size and element organization.

Two techniques are often used in the practice, the **Block-Structured Grids** and **Structured Grid by Analytical Approach**. **Boundary-Conforming Structured Grids** is a third method, often used in other engineering disciplines. This method is suitable to generate grids over simple surfaces.

- **Boundary-Conforming Structured Grids**

An efficient structured grid is one whose generation relies on a mapping concept. The idea is to choose a computational domain Ξ^n with a simpler geometry than that of the physical shell shape X^n and then to find a transformation $x(\xi)$) between these domains which eliminates the need for a non-uniform mesh when approximating the physical quantities (Haas, 1962).

A boundary-fitted coordinate grid in the region X^n is commonly generated first on the boundary of X^n and then successively extended from the boundary to the interior of X^n. This process is analogous to the interpolation of a function from a boundary or to the solution of a differential boundary value problem. On this base there have been developed three basic groups of methods of grid generation with the mapping approach;
_ *Algebraic methods*, which use various forms of interpolation or special functions
_ *Differential methods*, based mainly on the solution of elliptic, parabolic and hyperbolic equations in a selected transformed region

_ *Variational methods*, based on optimization of grid quality properties

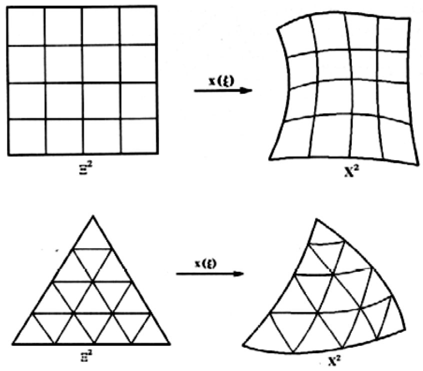


Fig.3.5 Boundary-conforming quadrangular & triangular grid [Liseikin, 1999]

In practice, the structured grid generated by mapping approach is today not in this form in use. This is because of the difficulty to find one transformation factor x(ξ), to generate a grid over a complex 3D shape of the designed structure.

Unstructured grid

Structured grids lack the flexibility and robustness for handing domains with complicated boundaries, or the grid cells may become to skewed and twisted. Unstructured grids can be the solution for the problem of producing grids in regions with complex geometry. Because of the irregularity of the distribution of the nodes, cells are obliged to have any particular shape. In addition, there are no restrictions to the connectivity of the neighboring grid cells, cells can overlap or enclose each other. Unstructured grids provide the most flexible tool for the discrete description of a complex geometry.

Unstructured grids allow an instinctive approach to local adaptation, by either insertion or removal of nodes. Grid refinement of an unstructured system can be accomplished locally by dividing the cells in the proper zones into smaller cells. Unstructured grids also allow deleting cells in regions where the geometry is not that complex. In practice, the overall time required to generate unstructured grids for complex geometries is much shorter than for structured grids.

Although the generation time of an unstructured grid is shorter than that of a structured one, using unstructured grids brings about a more complicated numerical algorithm because of the data management system. This data management system requires a special algorithm to number and order the nodes, edges, faces, and cells of the grid. In addition, extra computational memory is needed for storing this information on the connection between the cells of the mesh.

Advantages of unstructured grids are:

- Generality, there is no need to think about block decomposition
- Straightforward grid refinement.

Disadvantages are:

- Inefficiency on many conventional hardware configurations
- Not straight forward to get an efficient parallelization
- Descretisation formulas are often complicated

- **Octree Approach**

In the Octree approach the region of the shell is first covered by a regular Cartesian grid of cubic cells in 3D, or squares in 2D. Then the cubes containing segments of the domain surface are recursively subdivided in eight cubes until the desired resolution is reached. The cells intersecting the body surfaces are formed into irregular polygonal boundary cells (see Fig.3.6).

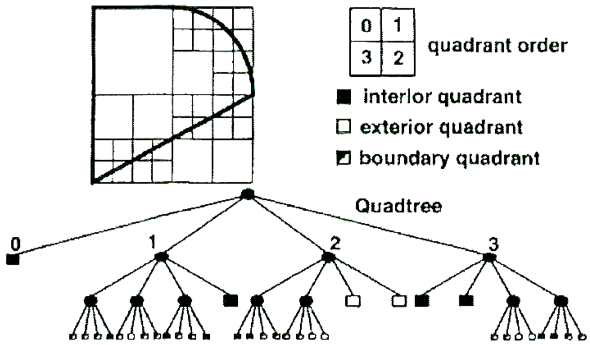


Fig.3.6 Example of the Octree approach [Thompson, 1999]

The grid generated by this Octree approach is not considered as the final one, but serves to simplify the geometry of the final grid, which is commonly composed of tetrahedral cells built from the polygonal cells and the remaining cubes (Liseikin 1999). The main drawback of the Octree approach is the inability to match the grid with a prescribed boundary surface. The grid on the surface is not constructed as desired on forehand, but is derived from the irregular volume cells that intersect the surface. A second disadvantage of the Octree approach is the rapid variation in cell size near the boundaries.

- **Delaunay triangulation & Voronoi Diagram**

Many free-form or form-finding designs involve complex regions that are not easily amenable to pure structured grids. Structured grids may lack the required exibility and robustness for handling complex surfaces, or the grid cells may become too skewed or twisted. Therefore, the unstructured grid concept is considered as one of the appropriate solutions to the problem of producing grids in regions with complex shapes.

Delaunay Triangulation In general, the Delaunay approach connects neighboring points, of some previously specified set of nodes in the region of the shell surface, to form tetrahedral cells in such a way that the circumsphere trough the four vertices of a tetrahedral cell does not contain any other point. The following subsections discuss the three major techniques for generating triangles based on the Delaunay criterion; Voronoi Diagram, Edge Flipping Algorithm and Incremental Bowyer-Watson Algorithm.

Voronoi Diagram The Delaunay triangulation has a dual set of polygons referred to as the Voronoi Diagram or the Dirichlet Tessellation. The Voronoi Diagram can be constructed for a random set of points on the surface of a structure. Given a set of points in the plane, the idea is to assign to each point a region of influence in such a way that the regions decompose the surface of the structure. To describe a specific way to do that, let S element of R2 be a set of n points and define the Voronoi region of p element of S as the set of points x element of R2 that are at least as close to p as to any other point in S (Edelsbrunner 2001):

$$V_p = \{x \in R^2 || |x - p|| \leq ||x - q|||, \forall q \in S$$

The Delaunay triangulation is obtained by drawing each Delaunay edge from one endpoint straight to the midpoint of the shared Voronoi edge and then straight to the other endpoint. For each triangle formed in this way there is an associated vertex of the Voronoi diagram which is at the circum-centre of the three points which form the triangle. Thus each Delaunay triangle contains a unique vertex of the Voronoi diagram and no other vertex within the Voronoi structure lies within the circle centered at this vertex. Fig.3.7 depicts the Voronoi polygons and the associated Delaunay triangulation.

It is apparent from the definition of a Voronoi polygon that the degeneracy problems can arise in the triangulation procedure when three points of a potential triangle lie on a straight line or four or more points are cyclic. These cases are readily eliminated by rejecting or slightly moving the point which causes the degeneracy from the original position.

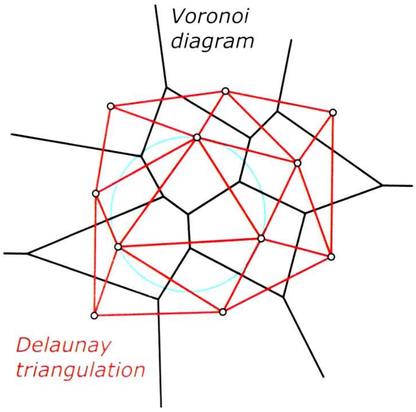


Fig.3.7 Voronoi diagram and the associated Delaunay triangulation [Source: Architectural Geometry]

Centralized Voronoi Diagram:

There is a remarkable procedure that may fix some input points and changes the remaining ones so that they are closer to the barycenter of their corresponding Voronoi regions. The resulting Centralized Voronoi Diagram (Fig.3.8) also produces very nicely shaped triangles in the associated Delaunay triangulation. Thus, to regularize a set of points, one may use an iterative procedure. In any step, it computes the Voronoi Diagram and moves each point toward the barycenter of its Voronoi cell. Steps of this algorithm:

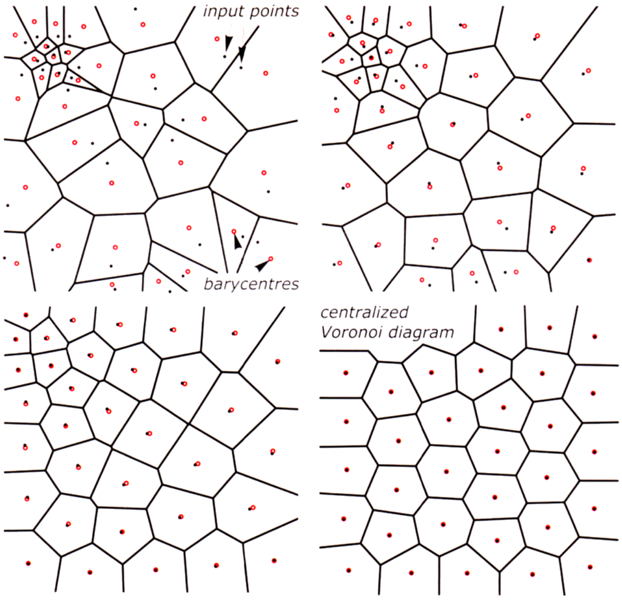


Fig.3.8 Steps of Centralized Voronoi Diagram [Source: Architectural Geometry]

- **other methods**

There are some other methods to generate unstructured girds, for example, **Bowyer-Watson Algorithm**, **Edge-Swapping Algorithm**, And **Advancing Front Approach** – no further introduction or discussion in this report.

Adaptive Meshing

For all the grid generation methods, a pre-defined grid density is required. This grid density is chosen to give an acceptable accuracy in the approximation of the surface by the grid. It is possible to specify certain properties of the final grid before the start of the grid generation, for example a higher grid density near sharp discontinuities in the boundary of the surface or a coarsened grid over large, smooth areas of the surface. Using an iteration process for the grid generation that adapts to the characteristics of the surface can lead to a better discretisation of the free formed surface. There are two parts to this adaptive grid generation technique.

1. Measurement of the local error between the generated grid and the free formed surface. The required density can then be calculated by dividing the measured error by the required error and multiplying it to the local order of the grid generation method. The required distribution of the grid density should be equally distributed with the error in the approximation by the grid.
2. Re-generating the grid with the specified grid density distribution. The adaptive meshing must be capable of t refinement and coarsening. There are three methods for grid refinement:

Mesh point movement - The original mesh connectivity is maintained, but the mesh nodes are moved. This method can only cope with relatively small adjustments without introducing very distorted cells, but it allows refinement/coarsening and is fast. This method is very suitable for structured grids, which require a fixed connectivity, where the ability to refine and coarsen is important.

Local refinement - Grid cells are locally sub-divided. Surrounding cells will also have to have some degree of subdivision to maintain a valid grid (for example no nodes on triangle edges). This method is fast and allows coarsening by reversing the subdivision, merging cells. The mesh connectivity is changed, so this method is only suited for unstructured meshed.

Total remeshing - The grid is completely regenerated with the new density parameters. This is the most general method, but it is not fast and there is no simple way to reverse the refinement. With Delaunay triangulation processes, extra points can be added to the existing triangulation to refine the mesh.

Grid generation for the cellular wall

From a theoretical point of view, there is no best suited grid generation approach to be chosen. The best grid generation technique for a particular design depends on the geometry of the surface, the architectural design, and the structural layout.

In the cellular wall design case, the step of discrete surface as structural components is very important. The primary structure is a grid structure. The quality of the grids determines significantly influences the multi-functions, including the structural and architectural functions. [Examples of these functions can be read in the Design Exploration Diagram in Chapter 5.1]

3.2 (Structural) Design Conditions

3.2.1 Theoretical framework and design variables

Proposed by P.Th. Vermeij [TUDelft, 2006] in his paper, a theoretical framework for free form structural design can be set up for structural design conditions.

In the domain of structural design, ‘material’, ‘force’ and ‘geometry’ are the main constituents, each contributing with their own field of science. Ruled by laws of physics, together these constitutes determine how a structure receives a load (with a certain magnitude, direction and behavior in time), by which structural mechanism (with what resulting stress distribution and deformation) the internal configuration of material transports this load, until it is discharged. The complexity of the form also diffuses the insight in the structural action, where rules of thumb do not exist (Wagner, 1999). Architectural and economical considerations are taken into account as boundary conditions.

Theoretical framework includes design variables and their use in structural design research.
1_ Geometrical definition (geometry)
2_ Structural action (force)
3_ Material processing (material)

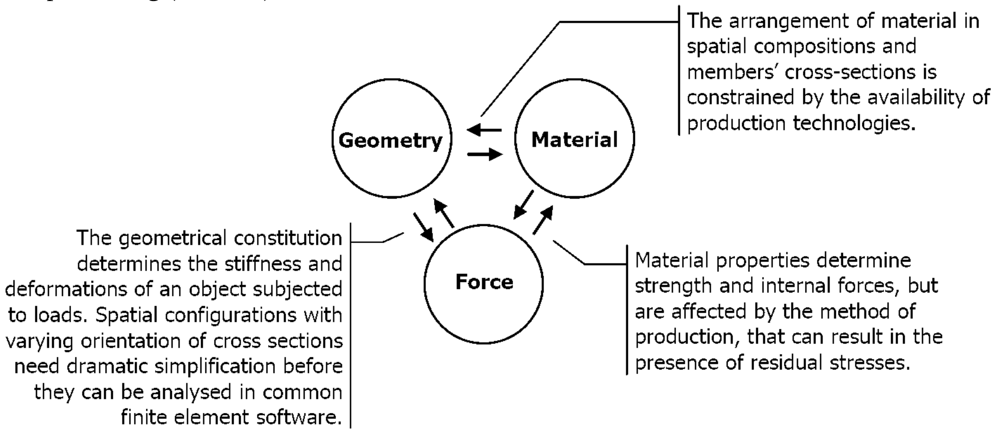


Fig.3.9 Theoretical framework [P.Th.Vermeij, 2006]

The three design variables adopted in this theoretical framework are highly interrelated, as is exemplified through general notions in Fig.3.9. Some relationships are critical: some geometrical constructs can only be materialized through specific manufacturing processes.

To handle the design variables, framework can be presented with sub-categories:
1_ the geometrical definition is subdivided into 0-, 1-, 2- and 3-dimensional objects, commonly known as points, curves, surfaces and volumes. They are needed to define an element in geometrical sense. In addition to the n-dimensional classification, transformation techniques of extruding, scaling and rotating are included. Thus the geometrical classification contains information on how the shape was created, which is useful to couple the geometrical definition to manufacturing techniques.
2_ the structural action is subdivided into vector-, section-, surface- and form action, of which also combinations do exist in either superposition or interaction (Engel 1999). Each class of structural action corresponds to a typical type of stress, that later will link to appropriate materials and geometrical arrangements.
3_ material processing is subdivided in additive, subtractive and formative techniques, as well in fabrication of two-dimensional elements.

With this technical framework, the actual (structural) design conditions can be discussed. In the following part, the design conditions for the three main constituents of the cellular wall structure will be described and explicated. They can function as a starting point from which the structural design and optimization strategies will be developed.

3.2.2 Definition to the cellular wall

1_ Geometry definition

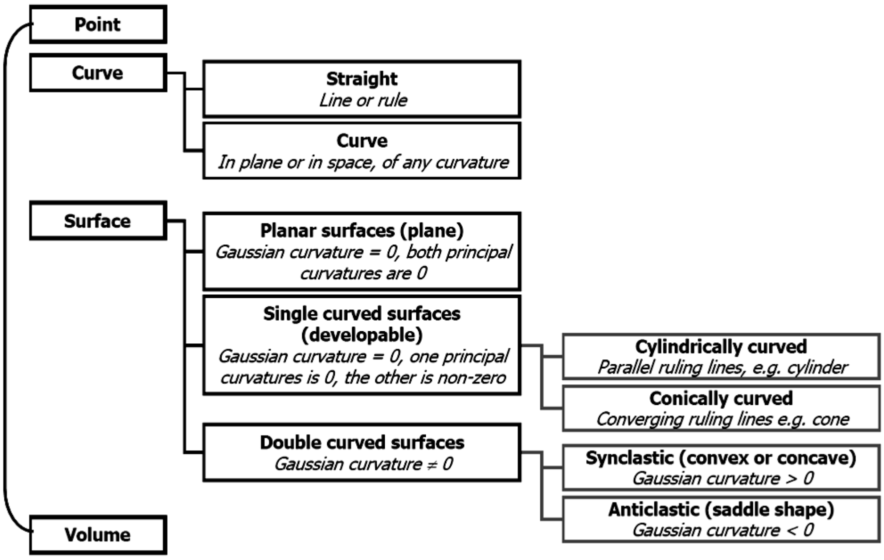
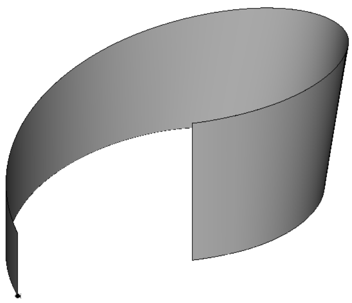


Fig.3.10. Descriptive classification of geometry [P.Th.Vermeij, 2006]



The surface of the cellular wall (of SNHM) can be defined as **Single curved surface (developable)**, which is curved in only one direction (one of the principal curvatures is zero) and can therefore be unrolled to a plane.

The merely geometrical feature of being developable is important when it comes to materialization, for which in principle all sheet materials are candidate. Developable surfaces can be cylindrically or conically curved.

To be more specific, the surface is defined by two free-form curves (explicating a Ruled/Lofted surface). Examples of Ruled surface and Lofted surface are showed in Fig.3.11, so does the wall surface generation.

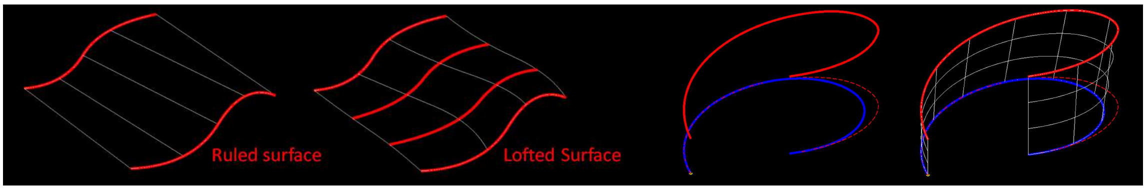


Fig.3.11. Ruled / Lofted surfaces definition and generation

Structural topology

The geometry of the surface has been defined. It is relatively simple, comparing to most of the free form structures. However, the geometry problem should include the surface discretion – polygon grid generation. As discussed before, grid generation is a very critical step in this cellular wall design case.

The structural topology defines the way structural members are connected together. It defines how the structural members are related to each other. When this structural topology is lined to/associated with the building shape, the geometry of the structure can be the result.

2_ Structural actions

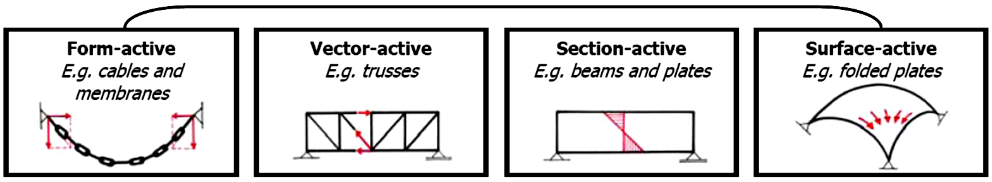


Fig.3.12. Four mechanisms of structural action and examples of components featuring them

Structure systems	Types
Form-active	Cable structures Tent structures Pneumatic structures Arch structures
Vector-active	Flat trusses Curved trusses Transmitted flat trusses Space trusses
Section-active	Beam structures Rigid frame structures Beam grid structures Slab structures
Surface-active	Plate structures Folded plate structures Shell structures

Definition by Engel (1999):
Form-active structure systems are systems of flexible, non-rigid matter, in which the redirection of forces is effected by a self-found FORM design and characteristic FORM stabilization.
Vector-active structure systems are systems of short, solid, straight lineal members (bars), in which the redirection of forces is effected by VECTOR partition, i.e. by multi-directional splitting of single forces (compressive or tensile bars).
Section-active structure systems are systems of rigid, solid, linear elements, including their compacted form as slab, in which the redirection of forces is effected by mobilization of SECTIONAL (inner) forces.
Surface-active structure systems are systems of flexible, but otherwise rigid planes (resistant to tension, compression, shear), in which the redirection of forces is effected by SURFACE resistance and particular SURFACE form.

Note: Structures acting in surface-action consist of a surface, as form-active structures could be composed of too. The difference between both structural systems is defined through the nature of the material the surface is made of: form-active structures do not resist to compression, tension and shear, whereas material in surface-active structures do.

The Cellular wall can be defined as a heavily-loaded grid network on single curved surface. Since the grid structure is designed as surfaces of rigid material, structural action may be mainly associated to the surface-active mechanism.

3_ Materials

Geometrical class of element		Manufacturing process: **Additive** *Moulding constraints may apply!*	**Subtractive**	**Formative** *Moulding constraints may apply!*	**2D-fabrication**
Curvilinear elements of constant cross section	**Straight** (0D-E)	Pouring Expanding Casting Layering	Milling		Cutting
	Planar curve (1D)			Single axis bending	
	Space curve (1D)			Double axis bending	
Surface elements of constant thickness	**Planar** (0D-E-E)				Cutting
	Single curved (1D-E)			Single axis bending	
	Double curved	"	"	Stretching (requires significant force)	
Other volumetric elements		"	"		

Key:
Element cannot be produced through this method
Possible but little appropriate since less elaborate processes are available
Most appropriate

Materials problem can be described a material processing. And three different processes for the production of elements are commonly distinguished: additive, subtractive and formative (as shown in the table above). The specific material processing of the cellular wall will be further discussed in Chapter 5 – Design alternatives.

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[2] Book ‘Grid Generation Methods’, V. D. Liseikin, editor, 1999

[3] Book ‘Handbook for Grid Generation’, Joe F.Thompson, editor, 1999

[4] J.L. Coenders, 2007. Reader CT5251: Structural Design – Special Structures. Delft University of Technology, faculty of Civil Engineering and Geosciences

[5] Martijn Veltkamp, 2006, ‘Free form structural design - Schemes, Systems & Prototypes of Structures for Irregular Shaped Buildings’, PH.D thesis, TUDelft

[6] P.Th. Vermeij, 2006, ‘Parametric Associative Desgin for Free Form Architecture’, Msc thesis, TUDelft

[7] Carl Gable, Harold Trease and Terry Cherry, 1996, ‘Automated Grid Generation from Models of Complex Geologic Structure and Stratigraphy’

Chapter 4

Parametric Associative Design

The design strategy chosen for the cellular wall structure is parametric associative design. This chapter will discuss this approach. The general concept will be described, accompanied by some project examples and a vision on how this approach can benefit structural design. A parametric tool – GenerativeComponents will be introduced, exampled by a basic case-study of special formed structure (Nautilus Shell).

> “Computer programs can do all sorts of things. But remember that the computer has no intelligence – only the ability to do lots of repetitive tasks very quickly.
>
> – Williams, 2005”

4.1 Parametric Associative Design Approach

4.1.1 Parametric Associative Design

Parametric design is, in a sense, a rather restricted term; it implies the use of parameters to define a form when what is actually in play is the use of relations.

From an elementary point of view, there is not a clear boundary between what can be called parametric design and what is called computer aided drafting or modeling. In these cases, forms are created by combining basic entities that are inserted in the model after a basic template, which includes their "proper parameters", is filled. A line, for example, is an entity that becomes part of a model once two parameters, its length and its direction, are specified. However this does not work for complex elements where we want relations to be maintained while modifying their parts independently.

Building elements can be grouped in families that tend spontaneously to be parameterized. To describe a family, to elaborate a primary design of a family, we only need two things: a topological description specifying the parts that constitute it and the relations they maintain with each other and a dimensional scheme specifying priorities and dimensional constraints. In this way we can define an abstract collection of elements and insert them in our models. What if we want to modify the inserted elements? This is where parametric design, in a promising way, properly started, in CAD-CAM[1].

The parametric 3D computer modeling process works like a conventional numerical spreadsheet. By storing the relationships between the various design features and treating these relationships like mathematical equations, it allows any element of the model to be changed and automatically regenerates the model in much the same way that a spreadsheet automatically recalculates any numerical changes.
As such, the parametric model becomes a "living" model which is constantly responsive to change, offering a degree of design flexibility not previously available. The same technology also allows curved surfaces to be "rationalized" into flat panels, demystifying the structure and building components of highly complex geometric forms so they can be built economically and efficiently.

An important application of parametric design approach is in the structural engineering for Complex Geometry / Free-Form Architecture. This approach can be fully defined by “Parametric Associative Design”: The first adjective, parametric, refers to the fact that the computer is used to generate designs by making use of parameters. Parametric design is used for the rapid generation of computable design representations describing design alternatives. Potential design alternatives are generated and evaluated in order to obtain the most promising solution. The parametric design approach can be seen as a design process which goal is to target the optimal combination of structural parameters. The second adjective, associative, refers to an approach which enables the designer to link the different parameters of the structural design to each other. The result is such a design approach is a collection of linked parameters that describe the structural design. It new becomes possible to change the values of parameters at the end of the design process, even parameters that were set in the first stages of the design process.

4.1.2 Design Tool concept

A new approach toward use of computers in the structural design process – Structural Design Tools (SDT) approach – was proposed by Coenders and Wagemans, 2005. The basic concept is an abstract base model that initially be built for speed, communication, insight and control over large amounts of data and not for complexity, like the current analysis tools. Instead of using the computer for engineering purpose, the computer can be used for design purpose.

One SDT example is given based on OpenStrategy Form Finding framework[2] – a framework towards a theoretical and implementation model for form finding and structural optimization techniques. This model could contain form finding, structural optimization, and generative and iterative calculation techniques by a high-level object-model for the optimization subject. By SDT approach, a similar model structure will be built as a carrying medium for the models (Fig.4.1). Instead of only storing parameters in the structure an

[1] CAD – Computer Aided Design; CAM – Computer Aided Manufacturing

[2] OpenStrategy Form Finding framework has proposed by J.L.Coenders and L.A.G.Wagemans in earlier work

optimization-like structure will be used, which can also store associative and relational boundaries and constraints, so that the SDT will be able to test their own validity, consistency and applicability. The SDT approach is able to follow the current developments in analysis tools by interfacing to them, but tools must be built specific for design purpose.

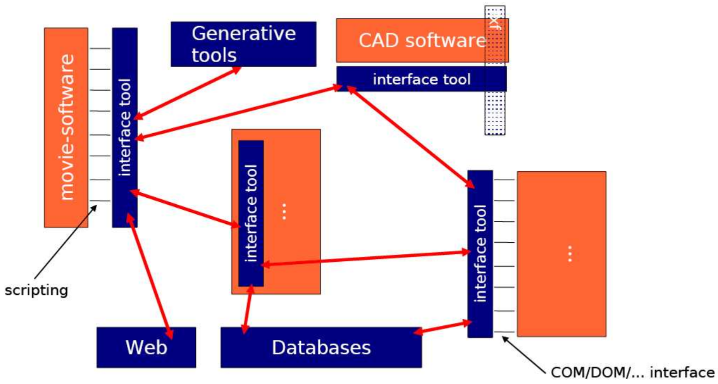


Fig.4.1 a diagram of SDT example [Coenders & Wagemans, 2005]

An important aspect of the Structural Design Tools concept is the parametric associative character of the design tools. Parametric design is used for the rapid generation of computable design representations describing design alternatives. Potential design alternatives are generated and evaluated in order to obtain insight into the impact of the structural parameters on the final integral design. With adding associatively to the structural design process, design steps are linked and the possibility of adjusting the parameters in the end of the design process is reached. With designing structures for Complex Geometry/ Free Form Architecture, this ability is very valuable. Since there is little design experience with these kinds of structures, it is hard to predict what the impact of a design decision on the final design is. The ability of defining the values of the structural parameters at the end of the design process leads to a more efficient structural design process.

Building up a design in parametric associative way, each design step requires a design tool to be developed. Making the process parametric associative, the alternatives for the separate structural elements of building can be quickly evaluated, and also the interaction between the different design steps. In this way, it is possible to alter the parameters at the end of the total design process, whereby an optimization toward an integral building design is possible. In Chapter 7 several computational tools have been built for aiding the parametric design.

4.1.3 Multi-Parametric structural design

A research paper of "multi-parametric structural design" was presented by design engineers Bollinger + Grohmann, 2008, with their own projects.

In the 20th century, the classification of structures according to defined building typologies was the central to engineering design. Driven by the innovation architecture – especially free form structures, things start to be changed: some structural engineers move away from the notation of a building being a variant of an established type, by considering each structure as an individual case in point with inherently complex behavior. Bollinger + Grohmann conceive of structure as an integral part of architecture. The overall performance of an architectural project results from negotiating and balancing a complex network of multifaceted, interrelated requirements.

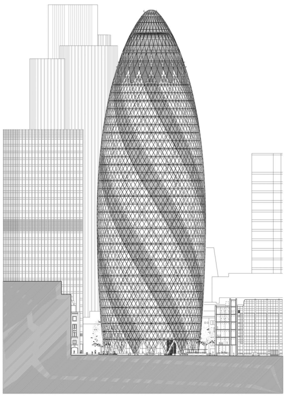
A project's diverse design criteria can be understood as a network of interdependent nodes. Once this network settles into a state of equilibrium of various influences a high level of integral performance of the building and its structure has been attained. This capacity cannot be achieved through single parameter optimization of the overall system, as the linearity of such processes cannot account for the complexity of architectural projects.

4.1.4 Project Examples of parametric design

In the recent past, several new projects have been released by means of parametric design process:

Project: Swiss Re, London, 2004
Architect: Foster and Partners
Structural engineer: Arup

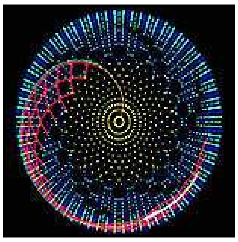
Foster approach on Swiss Re was to seek robust software that every participant in the design process had access to Excel. The geometry of the project was communicated as an Excel spreadsheet and a method statement on how to generate the geometry. The specialist subcontractors' resultant geometry was then inspected by Foster's design team and any divergence discussed and eliminated. Swiss Re also demonstrates the interaction of physical models, made by the architects, and their digital models, a flip-top from the physical to digital and back again, until all the consequences of the geometry are fully understood. [ACADIA/AIA, 2006]

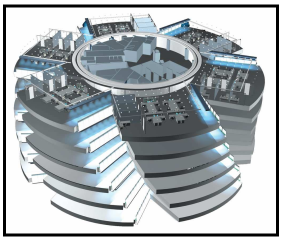


[Source: ArchitectureWeek.com]

Structure system: The 180-meter tall tower is supported by an efficient structure consisting of a central core and a perimeter "diagrid" a grid of diagonally interlocking steel elements. Some traditional central-cored buildings of this height would use the core as a means of providing the necessary lateral structural stability. Because of the inherent stiffness of the external diagrid, the central core is required to act only as a load-bearing element and is free from diagonal bracing, producing more flexible floor plates.

A fundamental characteristic of the Swiss Re building is the use of a consistent unifying system combined with a constantly varying geometry vertically through the building. This type of geometry is particularly suited to a parametric design approach: many of the detailed design conditions can be investigated by setting up fixed mathematical relationships between a relatively limited numbers of geometric parameters designing the building shape. This approach was used to drive optimization of structural components and details, and to generate 3D model geometry for analysis, coordination and structural design.





(Left) Top-view: parametric nodes of the tower's computer model. [Source: ArchitectureWeek.com]
(Mid) Twisting floor plans of Swiss Re [Source: www.ansys.com]
(Right) 'Diagrid' structure of Swiss Re [Source: www.pixelmap.com]

Project: Guangzhou TV and Sightseeing Tower ('Super-model')
Guangzhou, China, 2009
Architect: Information Based Architecture (IBA), Amsterdam
Structural engineer: Arup

The Guangzhou TV and Sightseeing Tower comprises an external steel frame and inner central concrete core. This core is for the lifts, escape stairwell and vertical building services risers. The structure is an impressive feat of technical expertise and elegance, but with a 610m high the tower has posed some tough engineering design challenges. Its slim waistline and complex geometry required the team to walk a tightrope between architectural form, safety and cost. [ARUP, 2008]

[Source: www.skyscrapercity.com]

Structure system: The hyperboloid structure is in the form of a twisted and tapering tube. It comprises an external steel frame and inner central concrete core. The outer steel-framed structure consists of 24 steel columns with concrete in-fill, a series of 46 oval-shaped rings of different sizes and single-direction diagonals throughout the structure. Columns, rings and diagonals form together a web that varies over the section of the tower. The columns are all perfectly straight although they lean over to one direction, giving the tower a dynamic twist. The rings are placed on the far inside of the columns so that they spatially miss each other and are connected off-centre. This makes the inside view to be dominated by the rings, while the view from the outside is dominated by the sloping columns.

The form is generated by two ellipses, one at the foundation level and the other at an imaginary horizontal plane just above 450m high. The tightening caused by the rotation between the two ellipses is the reason for the tight 'waist', and is in the form of a twisted rope. One of the main issues that had to be kept in mind regarding the cost was the client's desire to have the tightest 'waist' possible. According to the architect Mark Hemel, "This was a complex issue since the waist size relates to multiple issues. For instance; the number of lifts needed to transport the public up and down the building determines the minimum space needed for the core. The position of the core in turn is affected by the desire to have a rotating restaurant at the top of the building. On top of this, any change in the waist size results in a change in density of the structure altering the wind resistance. All these issues affect the amount of structural steel needed to create a stiff structure. This makes this building an example of a complex structure for which intensive studies were done in order to come to an optimized result."

The complex geometry was possible due to parametric associative software, which is capable of generating geometrical and structural models based on a set of variable parameters and link the geometrical data to the analytical and drafting software.

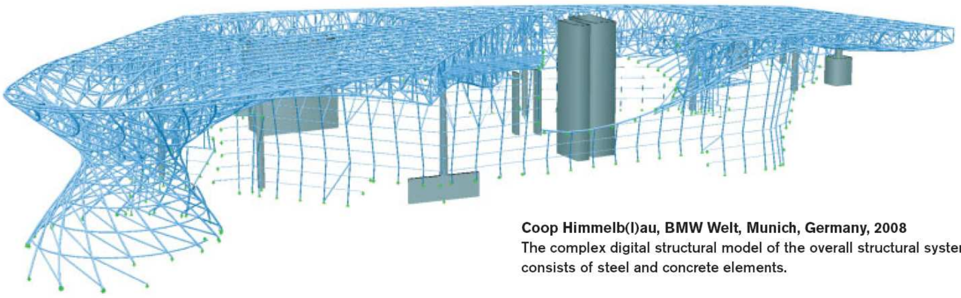
Project: BMW Welt, Munich, 2008
Architect: Coop Himmelb(l)au
Structural engineer: Bollinger + Grohmann

"The structures we develop do not need to adhere to idealized typologies, which are usually in conflict with the architect's concepts anyway. Rather result from a multiparty design process.
- Bollinger + Grohmann"

[Source: http://www.e-architect.co.uk]

During the competition, Bollinger + Grohmann developed a double-layered girder grid which demarcates the upper and lower boundaries of the roof-space phase in alignment with the architectural concept of a floating cloud. Driven by the simulation of anticipated loading scenarios, the initially planar girder grid was deformed so that the upper layer assumed a cushion-like bulge. The lower layer also reacts to a number of spatial and structural criteria; for example, the roof integrates the customer lounge, a large incision that opens the views towards the famous BMW headquarters tower and channels the forces to the defined bearing points. The combined capacity of both girder grid layers to act as one spatial structure with locally differentiated behavior is achieved through the insertion of diagonal struts within the interstitial space. In response to local stress concentrations, the structural depth of the system varies between a maximum of 12 meters and just 2 meters in areas of less force. In the northern part of the building the roof merges with a double cone, typical of Coop Himmelb(l)au's work, to form a hybrid shape. Similarly, the related bending behavior of the roof structure gradually transforms into the shell-like behavior of the double cone.

From a structural engineering perspective one particular challenge proved to be the geometric complexity of building elements and their interaction, as each local change had consequences on the global scale of the system. This high level of interdependency needed to be integrated in the analytical models of the structure, which required, for example, the set up of an extensive model of the complete roof structure including all load-bearing elements. Any significant change to the stiffness of one of the cores, for instance, had considerable repercussions for the overall behavior of the structure necessitating the re-evaluation and recalculation of the overall system. Consequently, this elaborate, iterative design process depended entirely on intense collaboration with the architects and related, clearly defined protocols of data exchange.



Coop Himmelb(l)au, BMW Welt, Munich, Germany, 2008
The complex digital structural model of the overall structural system which consists of steel and concrete elements.

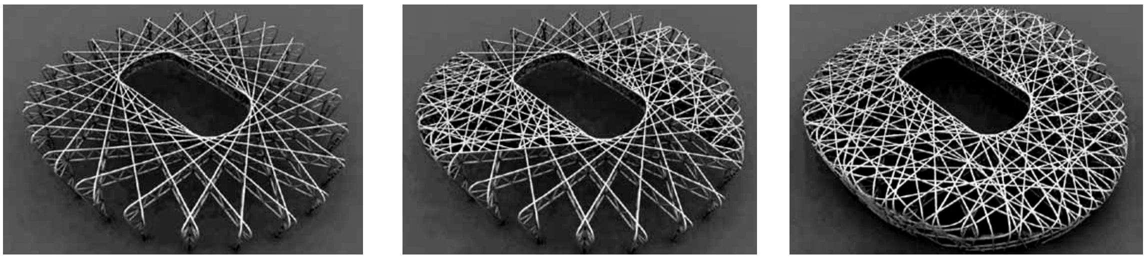
Project: National Stadium ('Bird's nest'), Beijing, 2008
Architect: Herzog & de Meuron
Structural engineer: Arup

Arup defined the geometry of the bowl using a powerful new computer software programme, specifically written for this purpose. The software is programmed parametric so that many layouts can be generated just by altering some of the generation rules. [ARUP, 2006]

[Source: http://en.beijing2008.cn]

The project was designed, in a sense, from the inside out. The seating bowl geometry was set first, with a focus on optimizing the sight lines and drawing the seats as close as possible to the field of play. The overall form of the outer structure was then configured to create a smooth, curved wall and roof around the seating. The base of this outer shell lies along an ellipse. Interior walls are vertical, forming an elliptical cylinder, while the saddle form of the roof is cut from a toroid. The outer walls trace a warped surface between the edge of the roof and the elliptical base.

These overall surfaces are constructed from a seemingly random pattern of structure. But the primary structure is actually derived from a simple geometric principle and structural system. Twenty-four columns rise from the ellipse at the base to support trussed portal frames spanning the stadium. These trusses are arranged to run tangentially along an oval roof opening, creating a complex geometry that, when coupled with secondary tube members, generates the nest-like appearance.



[Source: http://www.structuremag.org/article.aspx?articleID=754]
(Left) Trussed Portal Frames Span the Stadium
(Mid) Secondary Tubes Coupled with the Frames Create the Random Pattern
(Right) Secondary Tubes Coupled with the Frames Create the Random Pattern

The portal frame system supports gravity loads effectively, pulling structural demand from the roof towards the walls. It also provides positive seismic resistance. The truss members are actually box sections up to 3.9 feet (1.2 meters) on a side, and fabricated from plates.

Although the interior seating bowl is roughly elliptical in plan, an efficient, repetitive, modular structural design was developed that yielded economies in fabrication in particular. The column grids to the east and west of the field were set out in a series of concentric circles with large radii of curvature, while those to the north and south were arranged similarly with smaller radii. The result was a repetitive system with two grid patterns supporting the four main quadrants. Transition zones were limited to corner areas. The structural system was made up of precast concrete step-and-seating units spanning to sloped beams.

4.2 GenerativeComponents

4.2.1 About GenerativeComponents

GenerativeComponents is a parametric CAD software developed by Bentley Systems. Such a program defines geometry by applying rules and capturing relationships among model elements. In doing so, the process of drawing shifts from reliance on the mouse to reliance on scripting. It's known as Smart Geometry - a technology for describing the underlying rule-set of a geometric form – potential exists for it to become the basis of a new field of AEC[3] consultancy centered around geometric exploration.

The advantage of using such a system is that the geometry becomes rationally defined. This allows designers to explore variation in these geometric relationships and parameter values, with the resulting geometric model automatically rebuilt at various levels of detail and completeness, as determined by the designer. Instead of being drawn into struggle of creating geometry the designer is free to focus on the underlying conceptual principles, leaving the arduous task of modeling to the software.

"GenerativeComponents is an associative and parametric modeling system used by architects and engineers to automate the design processes and accelerate design iterations. It gives designers and engineers new ways to efficiently explore alternative building forms without manually building the detail design model for each scenario. It also increases their efficiency in managing conventional design and documentation. GenerativeComponents captures and graphically presents both design components and abstract relationships between them. This capability lets GenerativeComponents go beyond making geometry explicit; it makes design intent explicit as well. Although designers are working graphically, based on intuition and experience in architectural design, their work is captured in logical form." [Bentley, 2006]

When using the program, the designer is presented information in three different ways, as shown in Fig.4.2. The first is the model view which contains the 3D representation of model elements. The second is the symbolic view which indicates visually the relationships among the model elements. Finally, the script file is the editable lines of code which capture the history of how the model was drawn.

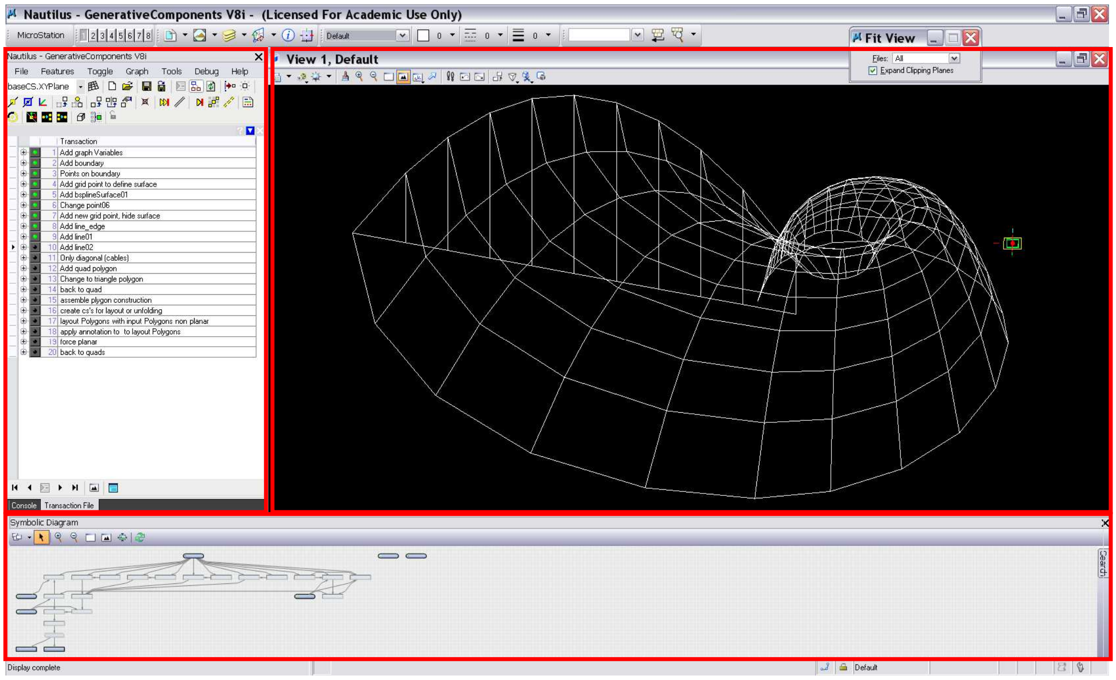


Fig.4.2. Interface of GenerativeComponents (Version 08.11.05.36)

[3] AEC – Architecture, Engineering, Construction

Feature structure

The core GenerativeComponents design framework (Fig.4.3) presents fundamental geometry types and operations and related measurement operations. A designer can use these to generate special components, and compositions of such components forming a complete design configuration. In parallel, an engineer can use the fundamental measurement operations provided by the GenerativeComponents framework to read the design geometry. The GenerativeComponents framework can also be used to build evaluative tools which can address key issues of building performance. Finally, the design geometry can be reinterpreted from the perspective of digital fabrication.

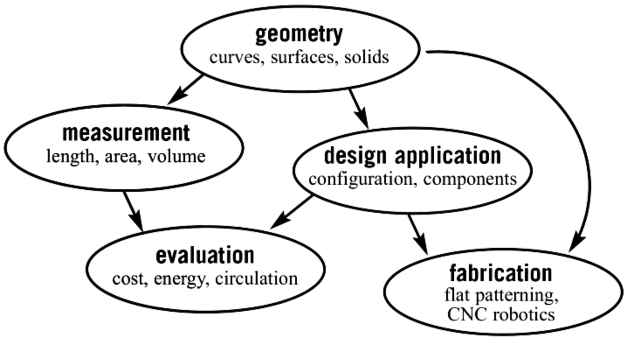


Fig.4.3 GenerativeComponents design framework

GenerativeComponents consists of a rich set of predefined geometric types and relationships, which can be combined and used by the designer to capture new, more complex geometric relationships and operations. Rather designer can extend the tool set with his own user-defined, rule-based, project-specific features; Feature modeling is parametric embodiment of “don’t repeat yourself” methodology of computation. The idea is to create a few components and massively apply them over scaffold geometry.

The function of “create user’s own feature” have been applied in the parametric model of cell-like grid structures: the hexagonal in-pack feature (Chapter 6.2.2) – which was automatically applied to each triangular grid on the entire surface – changing the pattern from triangular to hexagonal, in order to reduce the complexity of topology; and the fractal hexagon feature – double-up the selected hexagonal grid by filling in smaller hexagons. (Chapter 6.3.1)

Instead of using the GCScript, features can also be written in Visual Basic / C# and integrated into GenerativeComponents as a dynamic link library (.dll) file. This gives a large space for investigate multi-functional modeling process in the programmable environment by GenerativeComponents. One example is the ‘rcqhull’ plug-in (Chapter 6.4.2) – which was used to generate Delaunay triangulation and Voronoi Diagram, by building up an interface between mesh tool ‘Qhull’ and GenerativeComponents.

4.2.2 A general case study

This case study[4] was done to illustrate a **typical modeling process** with GenerativeComponents.
The primary structure is a lattice shell built by steelwork, with a conceptual shape of 'Nautilus'. For case study, limited variables in the parametric design were taken into account, and the consideration was mainly based on the structural functions.

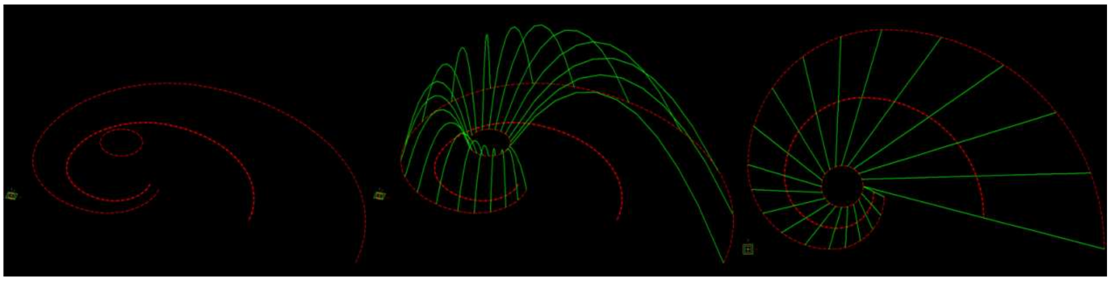


Fig.4.4 The geometry (Surface) was basically defined as:
Path by spiral curve in golden ratio [**Red**] and Parabola thrust lines along the path [**Green**]

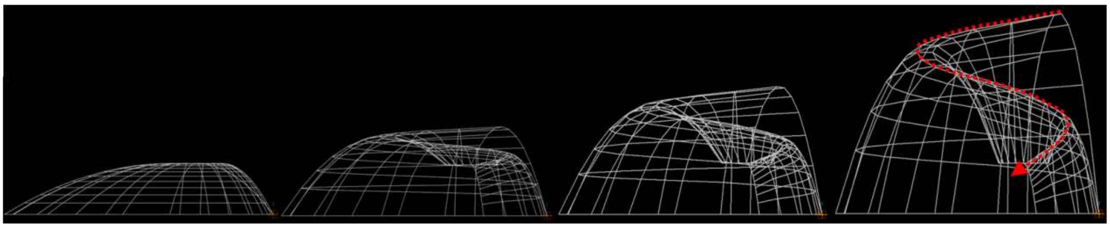


Fig.4.5 Surfaces showed by the construction lines:
Main variable of the structural form was the slope of the vertex

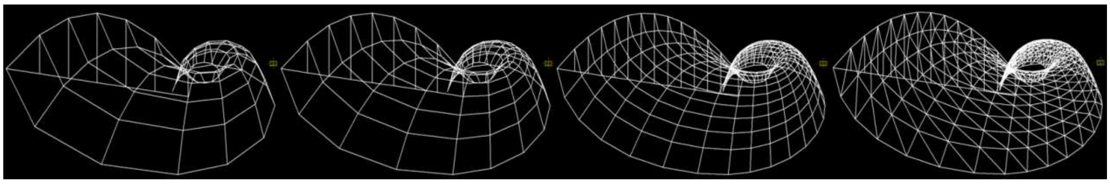


Fig.4.6 Decompose the surface into structural components [Steel Lattice Shell]

Fig.4.4-4.6 shows a 3D model of a surface constructed using cross-sectional control points/curves, which in turn have been created on planes defined on primary Spiral curves (Boundary and middle curves Red in Fig.4.4). Overlaid on the surface are a 2D array of points Uniformly/parametrically spaced in the space of the surface, and then overlaid on the points are a series of quadrilaterals. This configuration might represent the design of an 'idealized' roof surfaces which must be panelized into fabricatable sub-components.

In this model the following variations are possible: (A) the boundary curves – including the outer spiral and inner circle - can be change (Fig.4.4) (B) the slope of the Parabolic vertex can be modified to improve the shape (Fig.4.5) (C) the number and spacing of the grid points on the surface can be defined in the surface 2D parameter space (Fig.4.6) (D) various alternative 'lacing' option are available to use the points on the surface to populate either planar or non-planar quadrilaterals panels or triangular panels (Fig.4.6) This is a system of geometric relationships. It is unlikely that the designer can define and manage these relationships without some computational support to externalize and record his design intent in an editable and re-executable form.

[4] The conceptual structural form with a Nautilus shape was abstracted from the author's previous design assignment "new pavilion for the Mekelpark, TU Delft", 2008

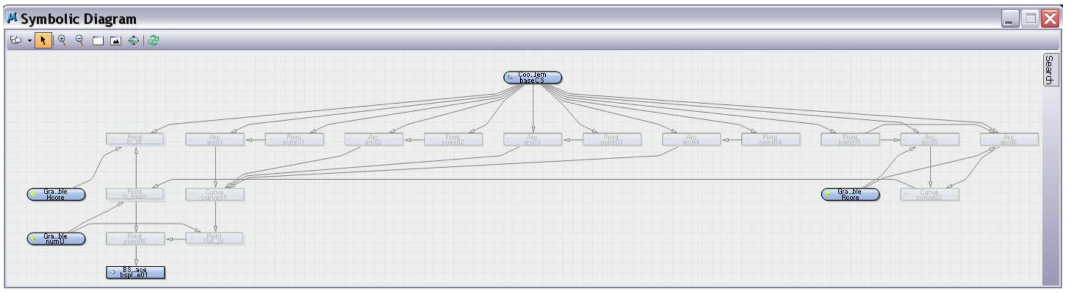


Fig.4.7 Symbolic diagram of the 3Dmodel

Fig.4.7 show the Symbolic model, which externalizes and presents these relationships in an explicit graphical firm. This is a system of ‘multiple representation’, in which for each component of the model there is a direct correspondence between the graphic and symbolic representations. The designer can observe and modify these relationships by locating a component of the model either in its 3D graphical form (in the 3D model) or in its symbolic representation (in the Symbolic model). A component can be an explicit geometric element with a graphical representation, such as a point, plane, curve, and surface, solid. Alternatively, a component can be more abstract, such as a variable, expression, conditional statement, or even a user defined script. It may not have a graphical representation, but nevertheless it still contribute to the logical system of relationships which will result in some geometric expression.

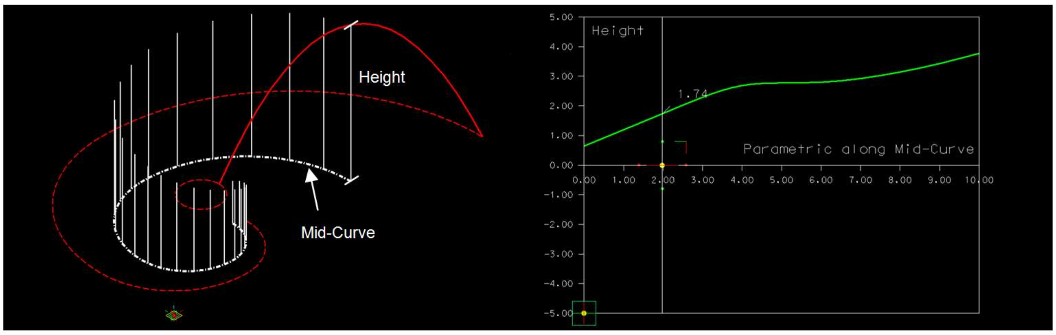


Fig.4.8 Parabola thrust line defined by Mid-Curve and predetermined Height (Left); Law-Curve (Right)

The 3D model showed in Fig.4.4-4.6 with explicit control points, used to define and manipulate the dependent curves and planes, using familiar techniques of ‘direct manipulation’. Sometimes designers maintain relationships which are essentially geometric in nature, but the controlling geometry is not necessarily of the same dimensionality as other aspects of the design model, and may not be defined in the same ‘model space’ as the resulting design. In this example, the main surface model is defined in 3D geometry. However, the profile (or ridge lines) of this surface can also be defined in 2D, independent of the main 3D model. This would be as if the Mid-Curve (Fig.4.8 Left) was unfolded to be a line; the height of each parabola thrust line was defined by its parametric value (position) along the Mid-Curve. This can be achieved by using a ‘Law Curve’ model (Fig.4.8 Right). A Law Curve is essentially a geometrically defined ‘function’, which returns values for Y (the dependent variable) given a range of values for X (the independent variable) and a curve that defines the relationship between X and Y. In this case, the values of X represent the distance along the Mid-Curve and the values of Y represent the vertex of the parabolic thrust line.

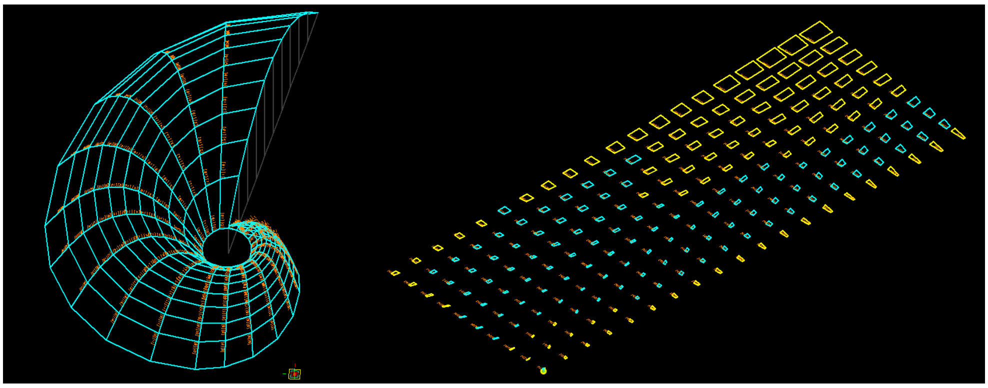


Fig.4.9 Assembly the components (quad-polygon); Color of the polygons shows the put-of-plane level

Design is not only about specifying and evaluating the resulting configuration, but also anticipating how that configuration can be materialized. The non-planar quadrilateral panels are a case in point. **Fig.4.9 Fabrication Plan** showed how the array of panels can be unfolded into a series of planar strips, with each strip having an external cutting profile. The conceptual design for the structure was a steel Lattice structure with glass façade, and a quad-pattern was used in this case, thus a checking if the out-of-plane level of the each quad element is acceptable for the brittle material (glass) is necessary. In Fig.4.9 the color of the polygons shows their out-of-plane level. Besides, in a fabrication plan, the choice of lines color for the cutting and scribing lines can be defined to match the power setting of a standard laser cutter.

Summary of the Case Study

1_Advantages of the strategy

The significance of this example is that it shows how the designers can achieve two important advances: (1) Design their own design tools (and created his own GUI - Graphical User Interface) and (2) Formalize and externalize their design process, in a form which is understandable, editable and re-executable. So having defined this process, the designers can explore variations within the solution space, not in some rigid parametric way, but by using an intuitive process of 'direct manipulation' and 'hand-eye coordination'. The whole process was intuitively controlled in dynamics and at the same time the designers can be closer to the materialization of the design than at any stage since the craft era. To arrive at this combination of intuition and control, the designers have to be skilled in the logic of design, in order to define and refine the complex system of geometric, algebraic and logical relationships which is the essential foundation of this process.

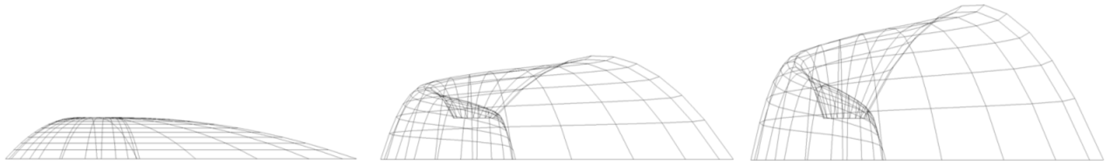
2_Design exploration & structural optimization

In this case study, the GenerativeComponents model is created using two main scripts: the first containing variables written to help define the base geometry and to provide the ability to test alternate geometric configurations during the structural optimization studies – shape optimization; the second written to generate the typical/standard lacing configuration for geometry – to discrete the geometry into structural elements. This provides the flexibility to change the internal lacing options.

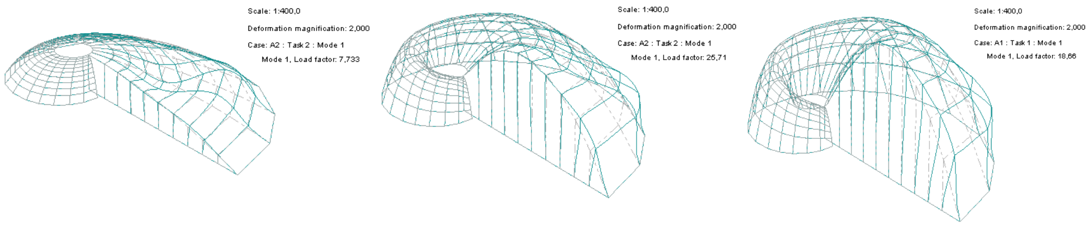
Data exported from the GenerativeComponents model was used for optimization studies of the steelwork members, which investigate a large number of separate geometric configurations. The alternatives studies included changes in the height to span ratio of the arch profile at each cutting slide, changes to the lacing type & size, and a combination of both – which resulted in an initial study of several separate geometric configurations – three of them are listed below:

Abstract from the structural analysis results

Load case: self-weight only
All models were assigned the same cross-section/element profile

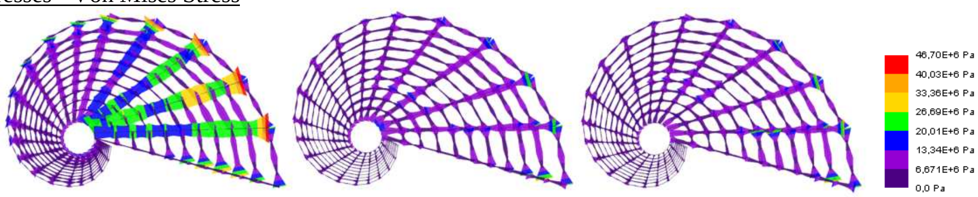


<u>Modal Analysis – Buckling load & buckling shape</u>

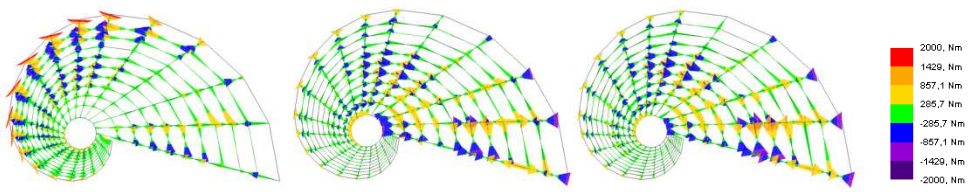


<u>Static Linear Analysis</u>

<u>Beam Derived stresses - Von Mises Stress</u>



<u>Out-of-plane bending moment (Mzz)</u>



Height [m]	4 ~ 4	4 ~ 10	4 ~ 15	
Total weight [kN]	413.82	462.39	516.41	in models

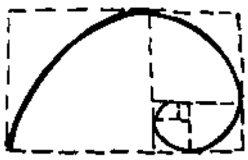
With the parametric model, the ratio of height-span can be explored to build up a good structural form;

For structural engineers, using GenerativeComponents can give them the abilities to create and rationalize the geometry and eliminate errors that might result from manual modeling methods; to quickly regenerate a number of different geometric configurations used for the optimization studies – which can yield a cost-effective and efficient structural design.

GC ORDER

Parameter

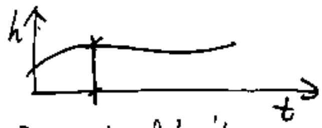
a — Dimension of the basic spiral curve



(Golden Ratio 1.618...) proportion to 'a'

↓

h — Height(s) of the parabola thrust lines



(Determined by 'Law-curve')

↓

n_u — Number(s) of grid points in two principle directions [u – along spiral curve
n_v — v – along thrust line(s)]

↓

Grid types (Basic: □, △, ⬡ ...)

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