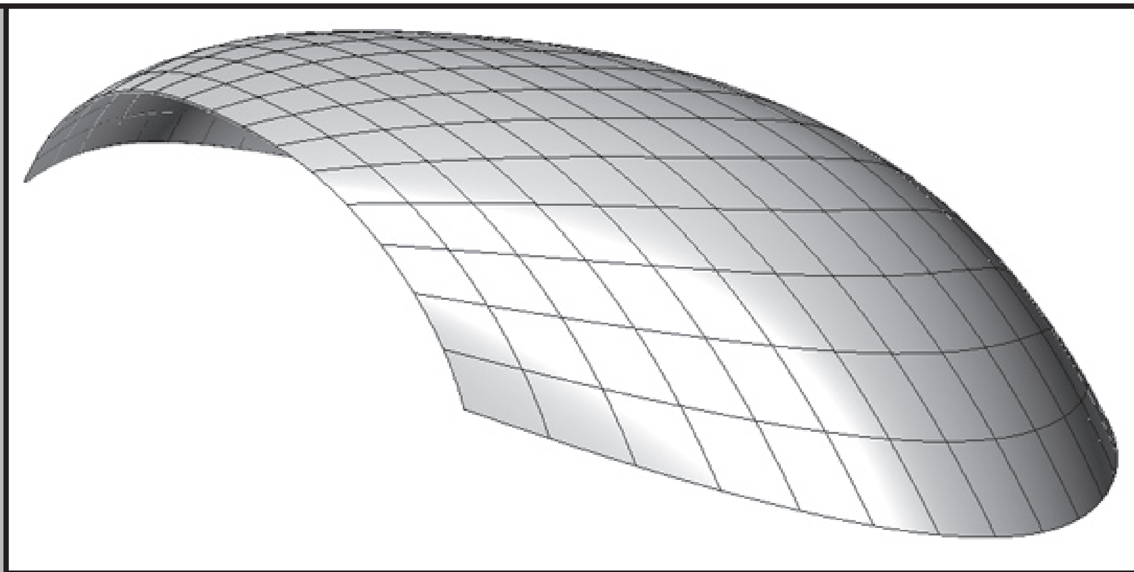
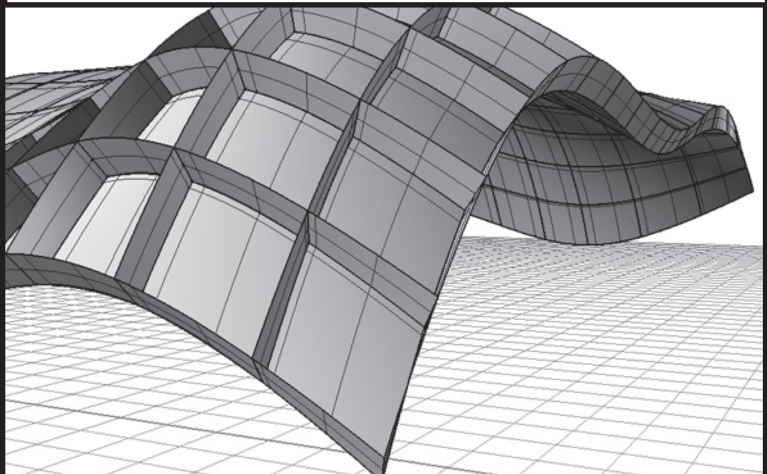
Prefabrication of concrete shells





Eline den Hartog
December 2008

structural design lab

TU Delft
Delft University of Technology

Prefabrication of concrete shells

Eline den Hartog
December 2008

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Building Engineering
Structural Design Lab

Master’s thesis committee:

Prof. ir. L.A.G. Wagemans
Ir. J.L. Coenders
Ir. A. Borgart
Dr. ing. S. Grunewald

Preface

This report is the product of my Master's thesis of the Master Building Engineering at the faculty of Civil Engineering of Delft University of Technology. This Master's thesis is performed at the Structural Design Lab. The Structural Design Lab is an educational and research body which deals with subjects of innovative structures, the relating (structural) design process and related technologies.

This Master's thesis is about the prefabrication of concrete shells. This report shows the results of the research to the different aspects of the design process of prefabricated concrete shells. On the basis of this research an overview of the design process of these types of shell is made. The process of segmentation and element generation of the shell and a case study in which the process is evaluated are presented.

I would like to thank my graduation committee, Prof. ir. L.A.G. Wagemans, Ir. J.L. Coenders, Ir. A. Borgart and Dr. ing. S. Grunewald for their guidance and ideas during the project. Furthermore, I would like to thank the other graduates in room 0.72 for their company during the coffee and lunch breaks. Last but not least I would like to thank my boyfriend and my family for supporting me during my study and my graduation in particular.

Eline den Hartog
Delft, December 2008

Summary

Introduction

The Fifties and Sixties of the previous century were the golden era of thin concrete shell roofs. Two characteristics that made these thin shells very popular are the strength, and the architectural exciting forms. After this golden era the construction of these thin concrete shells has stagnated. Reasons for this stagnation could be found in the difficulties that had to be encountered in the realization of these structures. One of the attempts to make the construction of shell more often build is with the prefabrication of the shell.

Problem definition

Not many free formed shell structures in prefabricated concrete have been build. One of the reasons for this is that the design and production process of free formed shells in prefabricated concrete is not efficient enough to make the construction of these shells feasible in most cases.

Research

During this Master's thesis it is tries to find the difficulties and possibilities of the different aspects of the design and production process of prefabricated concrete shells and to come with possible solutions to overcome these difficulties to make the construction of prefabricated concrete shells more feasible.

Design aspects

Structural analysis

The structural analysis of shell structures is made a lot easier with the introduction of finite element analysis software. However, for the use of these numerical programs some basic knowledge of the underlying theories and the mechanical behaviour of the structure are still essential.
With prefabricated concrete shells the strength, stiffness and location of the connections have to be taken into account during the structural analysis, because they influence the structural behaviour of the shell.

Grid generation

The grid generation method will be used to generate a grid over a free form surface that forms the basis of the division of the surface into elements. There are different types of grid generation techniques that can be divided in structured grids, unstructured grids and composite grids. From a theoretical point there is no optimal grid generation technique that results in the best grid for every surface. The most suitable grid generation technique for a surface depends on the geometry of the surface, the architectural design and the structural layout.

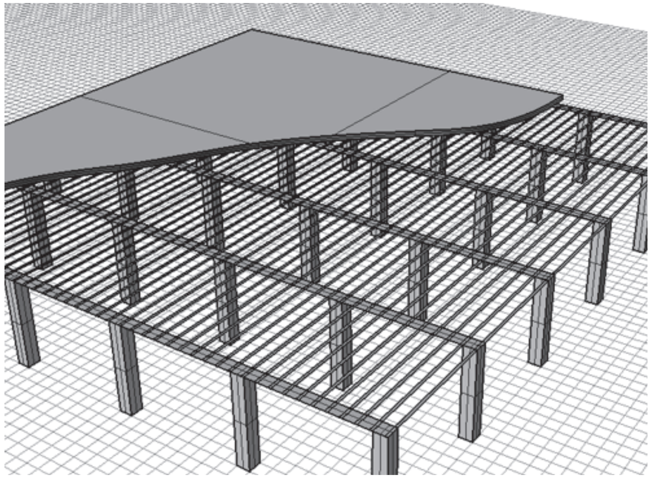
Concrete composites

The high performance fibre reinforced concrete composites form a good solution for the use in prefabricated concrete shell structures, they might make it possible that no ordinary reinforcement is used in the elements. There are many different types of high performance fibre reinforced concrete composites developed, that all have their own characteristics and are suitable for different applications. The most recently developed concrete composites, with different types of fibres added to it, have the best properties for the application in prefabricated shell structures.

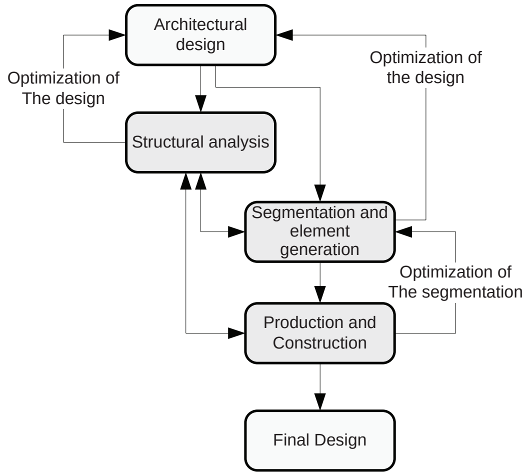
Formwork

The adjustable formwork is still in the experimental phase of its development and cannot be used jet for the production of elements for a real structure. The research does show that in the near future is should be possible to use the adjustable formwork.
The mould should be easy and fast adjustable in order to produce the different elements of the structure. The maximum size of the elements that have to produced with the flexible formwork is 3,0 x 3,0 m. The minimal radius of

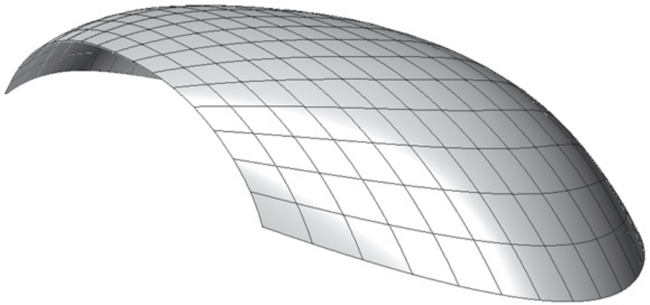
The aircraft museum in Duxford is one of the few prefabricated concrete shell structures.



Model of the adjustable formwork as it is in development at the moment.



A simplified scheme of the design process for the design of a prefabricated concrete shell structure.



The design of the case study with a grid that is generated by the design tool.

curvature that should be made with the adjustable mould is 1,0 m.
The most suitable technique for the creation of the edges is the placement of a (flexible) strip on the mould that has the shape of the edges. With this method all different types of edges are possible, there are no restriction on the possible angles, torsion or ridges in the edges.

Connection system

There are many different types of connection systems that can be used to permanently connect the elements to each other. The types of connection systems that are discussed in this theses are, the wet connection, a bolted connection, a post-tensioning connection, a welded connection, the glued connection and the fibre joint. The choice for a connection system will always be a consideration between the advantages and disadvantages of each systems and the properties of the design.

Production and construction

There will probably be only one mould available for the production of the elements. This means that the production of the elements can only be accelerated by making the production of each individual elements shorter.

Storage of the double curved elements is more difficult than storage of straight prefabricated concrete elements. For the storage special frames can be used that can also reduce the induced loads on the elements during lifting and transport.

During the construction of the shell the stability of the shell had to be ensured at all time. To do this temporary scaffolding and careful planning of the construction is necessary.

Design process

The goal of performing the process from the initial architectural design to the final design as an integral process is to achieve a maximal optimization of the design with the minimum amount of effort. The automation of some parts of the design process can ease the design of complicated structures, but thorough control of the found solutions will always be necessary. For optimization in the building industry there is most of the time not one solution that is the most optimal in all cases, this makes it more difficult to automate the optimization processes.

Design tool

The design tool generates a grid over the surface of the design and optimizes the grid with respect to the element size. After the generation of the grid the elements are generated and the size, shape and curvature of the elements are analysed.

The used grid generation method is the iscurve grid. The grid can be improved by rebuilding the surface, however this can give some deviation in the shape of the new surface compared to the original surface. The angles between the grid lines cannot be changed or improved, because the grid is based on the isocurves of the surface.

The optimization for the element size works very well, all generated elements are within the given requirements. The optimization of the grid with respect to the angles between the edges is not possible due to the type of grid generation method that has been chosen. To optimise the curvature of the elements the shape of the surface has to be optimized. The adaptation of the grid does not change the curvature of the surface.

Conclusions and recommendations

The integral design process of a prefabricated concrete shell is quite complicated due to the many different aspects that have to be taken into account at the same time and the many different possibilities to optimize the design. For most aspects there is not one solution that is the most optimal design choice for every design.

The developed design tool is capable of generating a grid over a lot of different surfaces. However not for every surface an optimal grid is generated. A large drawback of the used grid generation technique is that the angle between the grid lines cannot be optimized.

For the production and construction of the shell it is better when no reinforcement needs to be applied in the elements.

To make a next step in the development of prefabricated concrete shell it is advised to really build a prefabricated shell structure of which the elements are made with the adjustable formwork.

It is recommended to perform further research to the structural behaviour of prefabricated concrete shell structures. For the increase of the application of high performance fibre reinforced concrete composites it is advised that a design code is developed for these type of concrete composites.

Table of contents at a glance

1. Introduction	1
2. Mechanics	17
3. Grid generation	33
4. Concrete Composites	49
5. Adjustable formwork	67
6. Edges and connections	77
7. Production and construction	91
8. Design process	103
9. Geometry design tool	115
10. Case study	133
Conclusions & Recommendations	153
References	159
Appendices	165

Table of contents

1. Introduction **1**

1.1 Introduction 3
1.2 Recently build prefabricated concrete ‘shell’ structures 6
1.2.1 American Air museum, Duxford, 1997 6
1.2.2 The Shawnessy LRT station canopies Calgarry, Canada, 2003 8
1.2.3 Canopy at sanatorium Zonnestraal, Hilversum, 2005 10
1.2.4 Toll station for the Millau Bridge, France, 2005 11
1.2.5 Concluding remarks 12
1.3 Problem description and aim 14
1.3.1 Problem description 14
1.3.2 Aim 14
1.4 Approach 15

2. Mechanics **17**

2.1 Introduction 19
2.2 Surface Definition 20
2.2.1 Geometrical defined surfaces 20
2.2.2 Non-geometrical defined surfaces 22
2.3 Membrane and bending theory 24
2.3.1 Membrane theory 24
2.3.2 Bending theory 25
2.4 Finite Element Analysis 26
2.5 Shell buckling 27
2.6 Prefabricated concrete shell structures 28
2.7 Structural optimization 29
2.8 Conclusions 31

3. Grid generation **33**

3.1 Introduction 35
3.2 Terminology and requirements of the grid 36
3.2.1 Terminology 36
3.2.2 Grid requirements 36
3.3 Structured grids 38
3.3.1 Boundary-confirming grids 38
3.3.2 Translational grids 39
3.3.3 Isotope technique 39
3.4 Unstructured grids 40

	3.4.1 Octree approach	40
	3.4.2 Delaunay approach	41
	3.4.3 Advancing-front technique	43
3.5	Composite grids	45
	3.5.1 Block structured grids	45
	3.5.2 Overset grid	46
	3.5.3 Hybrid grids	46
3.6	Conclusions	47
4. Concrete Composites		**49**
4.1	Introduction	51
4.2	Steel reinforced concrete	52
4.3	Self compacting concrete	53
4.4	(Ultra) high performance concrete	54
4.5	Fibre reinforced concrete	55
	4.5.1 Types of fibres	57
	4.5.2 Fibre arrangements	58
	4.5.3 Production methods	58
	4.5.4 Properties of fibre reinforced concrete	59
4.6	Types of fibre reinforced concrete	61
	4.6.1 ECC	61
	4.6.2 Slurry Infiltrated Fibre CONcrete (SIFCON)	61
	4.6.3 Slurry Infiltrated Mat CONcrete (SIMCON)	62
	4.6.4 BSI/CERACEM	62
	4.6.5 Ductal	62
	4.6.6 CEMTEC	63
	4.6.7 Hybrid fibre concrete	63
	4.6.8 Evaluation	64
4.7	Conclusions	66
5. Adjustable formwork		**67**
5.1	Introduction	69
5.2	Strip mould	70
5.3	Pin bed mould	71
5.4	Recent developments	73
	5.4.1 Adjustable formwork I	73
	5.4.2 Adjustable mould II	74
5.5	Evaluation	75
5.6	Conclusions	76

6. Edges and connections **77**
6.1 Introduction 79
6.2 Edges 80
6.2.1 Angle of the element in cross-section 80
6.2.2 Angle of the element in plane 80
6.2.3 Form of the edges 80
6.2.4 Creation of the edges 82
6.3 Connections 84
6.3.1 Wet connection 84
6.3.2 Bolted connection 84
6.3.3 Post-tensioning connection 85
6.3.4 Welded connection 85
6.3.5 Glued connection 85
6.3.6 Fibre joints 86
6.3.7 Evaluation 87
6.4 Conclusions 89

7. Production and construction **91**
7.1 Introduction 93
7.2 Production 94
7.2.1 Virtual mould 94
7.2.2 Inserts for the edges 94
7.2.3 Preparation of the mould 95
7.2.4 Casting process 95
7.2.5 Demoulding 96
7.2.6 Storage of the elements 96
7.2.7 Evaluation 97
7.3 Transport 98
7.4 Construction 99
7.5 Tolerances 100
7.6 Conclusions 101

8. Design process **103**
8.1 Introduction 105
8.2 Design aspects 106
8.3 Relations between the aspects 107
8.4 The design process 110
8.4.1 Architectural design 110
8.4.2 Structural analysis 110
8.4.3 Segmentation and element generation process 111

	8.4.4 Production and construction process	112
	8.4.5 Optimization	113
8.5	Conclusions	114
9. Geometry design tool		**115**
9.1	Introduction	117
9.2	Grid generation	118
	9.2.1 Requirements	118
	9.2.2 Approach	119
	9.2.3 Grid generation techniques	119
	9.2.4 Evaluation	122
9.3	Generation of the elements	123
	9.3.1 Generation of the edges	123
	9.3.2 Division of the surface into elements	123
	9.3.3 Creation of the inner surface	123
	9.3.4 Creation of the elements	124
	9.3.5 Method of slicing the shell	124
	9.3.6 Evaluation	125
9.4	Element control	126
	9.4.1 Requirements	126
	9.4.2 Control of the element size	126
	9.4.3 Control of the angles between the edges	126
	9.4.4 Control of the element curvature	127
9.5	Design tool	128
	9.5.1 Description	128
	9.5.2 Testing and evaluation	130
9.6	Conclusions	132
10. Case study		**133**
10.1	Introduction	135
10.2	Architectural design	136
	10.2.1 Concept	136
	10.2.2 Model	136
10.3	Structural analysis	137
	10.3.1 Load definition	137
	10.3.2 Shell properties	139
	10.3.3 Analysis	140
	10.3.4 Conclusions	142
10.4	Detailing	143
	10.4.1 Shape of the elements	143

10.4.2 Connections 143
10.4.3 Foundation 146
10.5 Segmentation an geometry definition 147
10.5.1 Element size 147
10.5.2 Angles 147
10.5.3 Curvature 147
10.5.4 Geometry definition 148
10.5.5 Optimization 148
10.5.6 Evaluation 148
10.6 Production and construction 149
10.6.1 Production process 149
10.6.2 Storage 149
10.6.3 Transport 150
10.6.4 Construction process 150
10.7 Conclusion 151

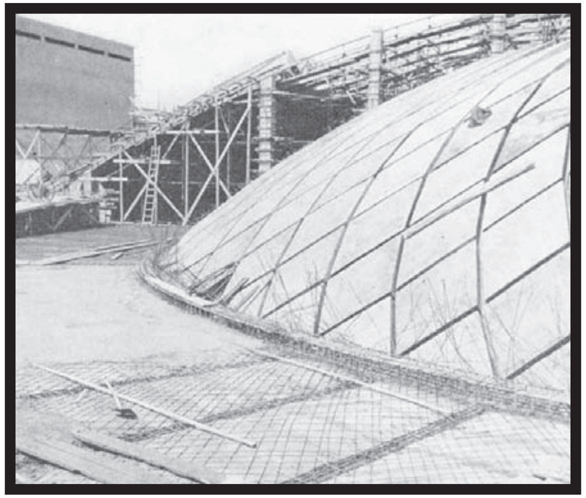
Conclusions & Recommendations 153

References 159

Appendices 165

Appendix 1 Personal data and graduation committee 167
Appendix 2 Gaussian curvature 169
Appendix 3 The test surfaces 171
Appendix 4 Rhino mesh tool 175
Appendix 5 Case study 177
Appendix 6 Functional and technical roof aspects 181

1. Introduction



In this chapter the background of the subject of this Master's thesis, prefabrication of concrete shells, will be described. An overview over some recently build prefabricated concrete shell structures has been given. And the problem description, the aim and the approach of this thesis will be outlined.

Turin exposition hall by P.L. Nervi. [12]

1.1 Introduction

The Fifties and Sixties of the previous century were the golden era of thin concrete shell roofs, many shell structures were build by famous designers like Candela, Torroja and Isler. Two characteristics that made these thin shells very popular are the strength, which allows them to cover very large areas, and the architectural exciting forms, which often made them seem to defy the laws of gravity. After this golden era the construction of these thin concrete shells has stagnated. Reasons for this stagnation could be found in the difficulties that have to be encountered in the realization of these structures. These difficulties are the technical difficulties of designing and constructing the shell and the high building costs of the shell.

Traditionally concrete shells were build using a plywood lining attached to a supporting formwork. Scaffolding was used to support the formwork. The plywood is used to obtain the required completely smooth surface. The use of plywood was relatively expensive, especially in Europe, even when the form could be re-used several times. Generally open forms were used, the use of these forms only limits the slope angle of the shell. Casting concrete in a thin layer on the curved shell surface is difficult. When the concrete mix is too dry the concrete cannot be compacted properly and has to be finished by hand and when the concrete mix is to fluid the concrete tends to sag and flow. Over the years several attempts have been made to reduce the construction costs and ease the construction of the thin shell.

One of these attempts is the use of an inflated membrane as a formwork. Shotcrete is sprayed on the inside of this form after the placement of the reinforcement. The main problems with this method is that the thickness and shape of the structure are difficult to control during the construction process and the tolerances of the construction are large.

Figure 1.1 Algeciras markethall by Torroja (1934). [64]

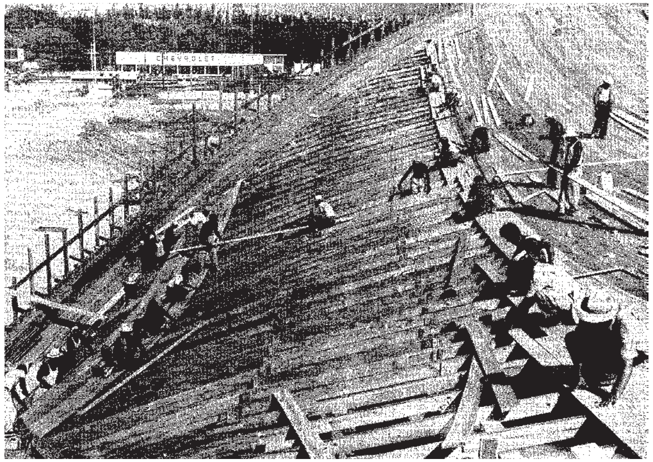


Figure 1.2 Construction of the formwork for a concrete shell structure.

Figure 1.3 Xochimiloco restaurant by Candela (1958). [64]

Figure 1.4 Deitingen service station by Isler (1968). [64]

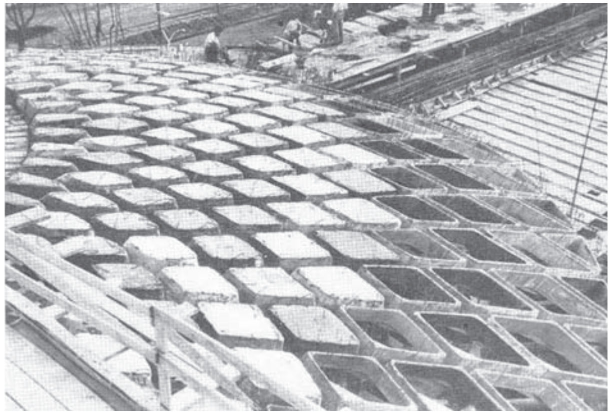


Figure 1.5 Prefabricated pans of the Turin Exposition hall in place, Nervi. [19]

Other attempts make use of a permanent formwork, like ferro-cement or steel plates. On these permanent forms reinforcement is placed and the additional concrete is cast. Nervi designed and constructed many structures with this technique. The main disadvantages of this system are the high costs and that re-use of the formwork is not possible.

Another way to create concrete shell structures is with the use of prefabricated concrete elements. In this case the shell is divided into elements, which are prefabricated. After production the elements are placed and connected on the building site. Benefits of this type of construction are the higher concrete quality that can be used, the higher building speed and the better logistic organization compared to in-situ cast concrete structures. A drawback of prefabricated concrete shell structures is that the formwork is still very expensive and re-use of the form is only occasionally possible. Other difficulties that rise with this type of shell structures are the construction of the shell and the connections between the elements.

Not many prefabricated concrete shells have been build in the past. But, there are some recent developments that might make prefabricated concrete shell structures more profitable. The prefabricated concrete shells and the development of these new techniques are the subject of this Master's thesis.

Mechanics

The structural analysis of thin shells is quite complex due to the three dimensional shape of the shell and the combination of in-plane and bending stresses in the shell. The introduction of finite element methods made the analysis of shells easier, but the exact influence of the joint on the force transfer is not known.

Segmentation

Another problem that rises is the division of the shell into elements. This division has its influence on the connections, the mould and the building method. The question is whether there is an ideal method that can handle all restrictions of these aspects and make an optimal division of the surface possible.

Concrete composites

The development of new fibre reinforced high strength concrete composites may give new opportunities for thin concrete shells. The fibres probably cannot replace all the ordinary reinforcement, but they can at least reduce the amount of reinforcement that is needed. This would make the reinforcement of the elements easier.

Formwork

If prefabricated panels are used to make a shell structure at this moment a standard fixed formwork is used. The main problem with this type of formwork is that so for each different element a new form has to be made and re-use of the form is almost impossible. A re-usable adjustable formwork may solve this problem. The adjustable mould can be based on the principle of individual in height adjustable pins covered by a rubber mat.

Connections

It is difficult to find an optimal connection system that can be used for every prefabricated shell structure. The requirements for the connections differ for each individual shell structure. For the placement of the elements some room for adjustment is needed, but a the same time a strong and stiff connection is required to ensure the stability of the shell.

Construction

The construction of the shell also causes some difficulties. Shell structures are strong and stable when they are finished, but during construction they are not capable of supporting themselves. The stability of the shell during construction has to be ensured with for example scaffolding. To minimize the amount of scaffolding and ease the assembly of the elements a good building plan is required.

The above described aspects and difficulties of the prefabrication of concrete shell structures are discussed in this thesis. Figure 1.6 shows a diagram with these aspects and the choices that already have been made to limit the research area of this thesis.
This thesis forms a continuation on the Master's thesis performed by M. van Roosbroeck. [19] The results of this thesis will be used as a starting point for this thesis.

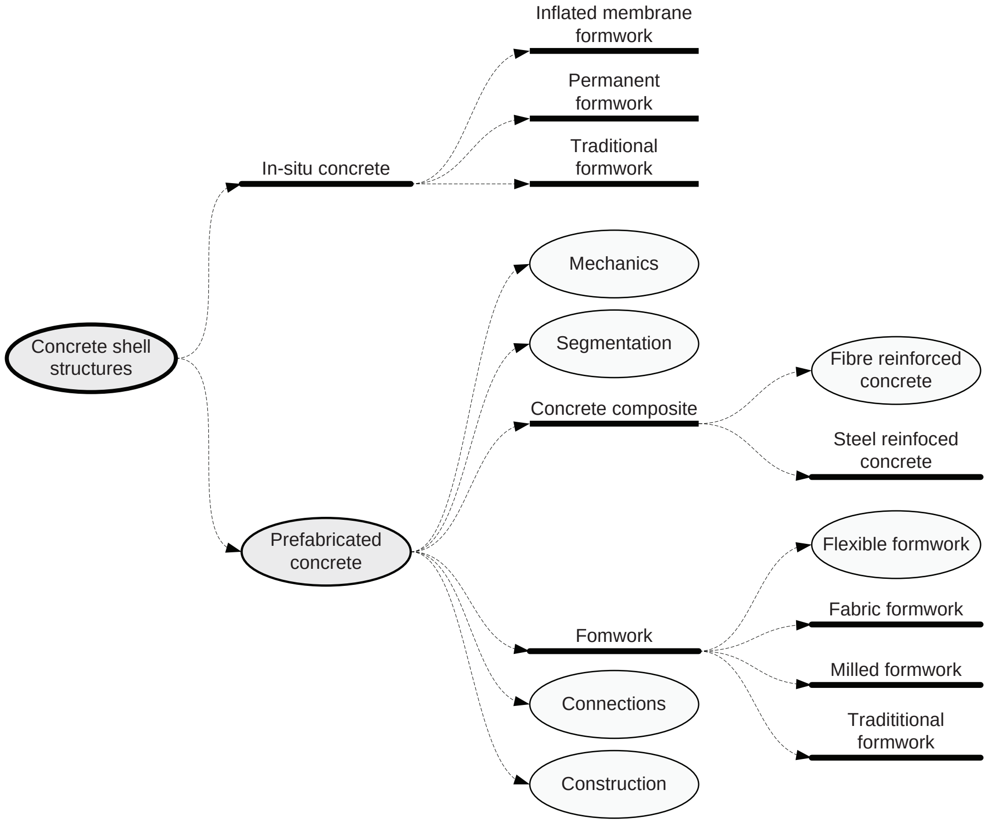


Figure 1.6 Schedule with the different aspects discussed in this Master's Thesis.

1.2 Recently build prefabricated concrete 'shell' structures

This paragraph gives an overview of prefabricated concrete 'shell' structures that are build in the last ten years. Every design will be described and whenever possible the mechanical behaviour, the segmentation, the concrete composition, the connections, the used formwork and the construction method will be discussed.

Figure 1.7 Aircraft museum in Duxford. [64]

1.2.1 American Air museum, Duxford, 1997

The aircraft museum was designed by Foster and Partners. The design consists of a single vaulted enclosure, with a glazed wall on the south overlooking the museum runway. The glazing is removable and its support construction can pivot to allow exhibits to be moved in and out of the museum. The glazed wall and the continuous glass strip around the base of the vault provide enough daylight in the museum, despite the fact that the structure is partly sunken into the ground. The roof was designed in such way that it can support the suspended aircraft.

Mechanical behaviour

The prefabricated concrete roof, works as a shells structure, and spans about 90 meter. The shell is supported by the upper precast concrete ring beam (see Figure 1.9), with a cross section of 1500 x 1000 mm. The upper ring beam is supported by columns made of welded rectangular hollow sections (RHS), who were placed on the lower ring beam. The cross section of the columns is 700 x 300 mm and they have a thickness of 30 mm. The lower ring

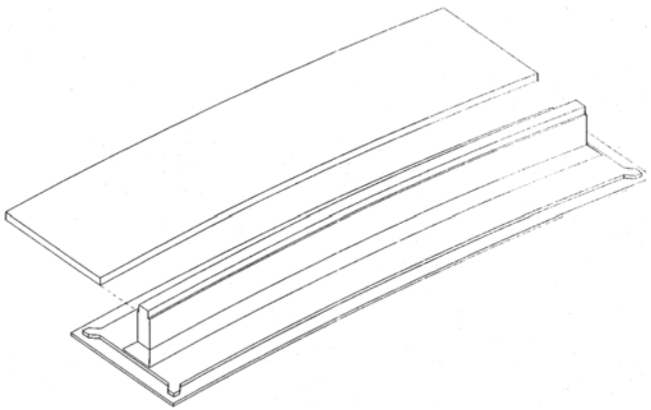


Figure 1.8 Curved T-shape precast concrete element with cover slap (not on scale) [28]

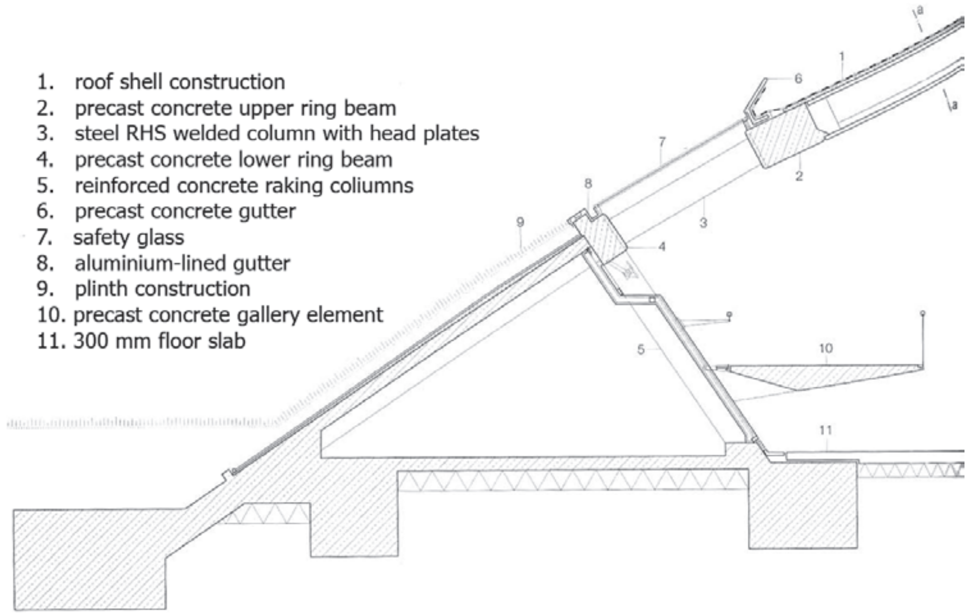


Figure 1.9 Detail of the roof shell [28]

beam has a cross section of 1000 x 600 mm. The lower ring beam is supported by a plinth construction and concrete raking columns of different sizes. The plinth construction consists of a green roof on a 250 mm in-situ concrete slab. It forms a tension ring which bears both horizontal and vertical forces from the roof shell.

Segmentation

The shape of the structure is a segment of a torus or donut shape (see Figure 1.11). It is a self-supporting concrete structure made out of prefabricated concrete elements. The shape is segmented by rotating a circle along the torus, creating curved elements. In this way a structured grid is created and most elements have the same shape and curvature. Only the elements on the edge of the structure have a different shape.

Concrete composition

The elements have been made out of precast reinforced concrete. They have been designed as a T-shape with a cover slap to create a smooth outer surface (see Figure 1.8). The flange of the elements is 100 mm thick and the cover slab is also 100 mm thick.

Connections

The connections have been designed as stiff in-situ connections. The seam between the elements is filled with stitching reinforcement and in-situ concrete, a so called wet connection. The stitching reinforcement consists of rods and stirrups.

Formwork

There was no detailed information found about the formwork that was used to cast the elements. But because almost all the elements are identical it is assumed that only one mould was needed. For the edge elements that differ slightly from the other elements the existing mould could have been adjusted.

Construction

The plinth slab and the floor have been made out of reinforced in-situ concrete. The other parts of the construction have been made out of precast concrete and have been connected together with wet connections. The precast elements have been placed on temporary scaffolding before the connection is made. After the connections had been made and the concrete has hardened the scaffolding could be removed.

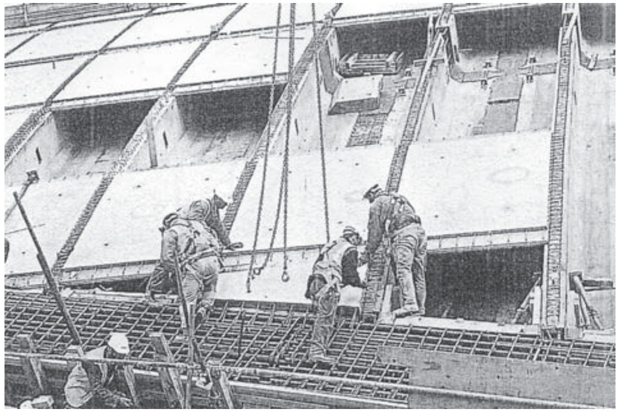


Figure 1.10 The shell during construction. [28]

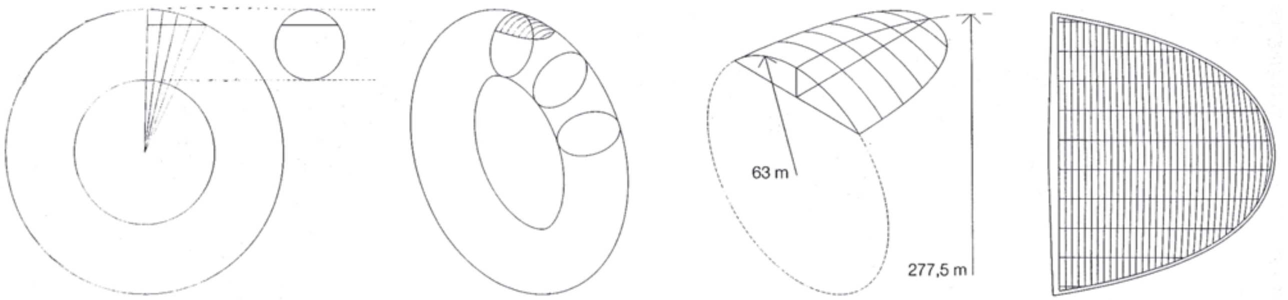


Figure 1.11 Geometry of the roof shell. [28]

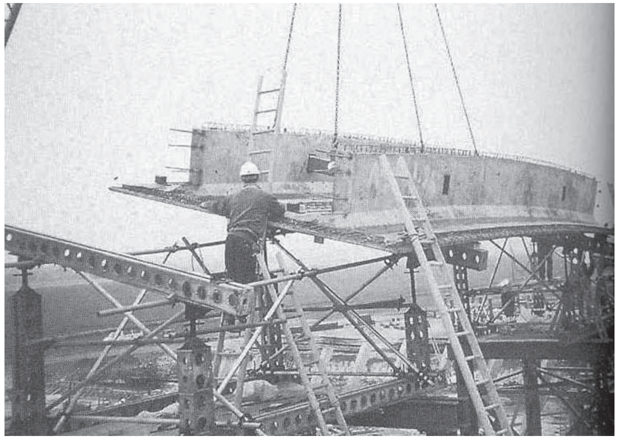


Figure 1.12 Placement of the elements on the temporary scaffolding [28]

Figure 1.13 The connection between the column and the shell trough three struts. [58]

1.2.2 The Shawnessy LRT station canopies Calgarry, Canada, 2003

The shed of the Shawnessy light rail transit station in Calgarry consists of twenty-four ultra thin shell canopies supported by single slender columns. The canopies span in both directions 5,1 and 6 meter respectively and have a minimum thickness of only 20 mm. The canopies should protect the commuters from the elements.

Mechanical behaviour

The canopies consist of a part of a cylinder rising out at an angle to a slightly curved shell base (see Figure 1.15). This cylindrical shell and the slightly curved shell base can be very thin due to the small bending moments in these parts of the canopy. The connection between the cylindrical part and the flatter part of the canopy has been made as a reinforced rib, so it is able to take the higher tension forces in this part of the canopy. The open end of the cylindrical shell is tied by a reinforced tie beam and the other edges of the canopy are also made as reinforced beams.

The canopies are supported by three struts that are connected to a single column that supports the canopy (see Figure 1.13). Two of the struts are connected to the corners at the open side of the cylindrical shell. The last strut is connected to the middle of the canopy at other side.

Segmentation

A complete canopy consists of two half shells joined together with a bolted seam at the apex of the curve and a beam tension tie across the opening at the base. (See Figure 1.14) Once assembled, this unit is stable. Prior to as-

Figure 1.14 The different parts of a canopy before connection. [26]

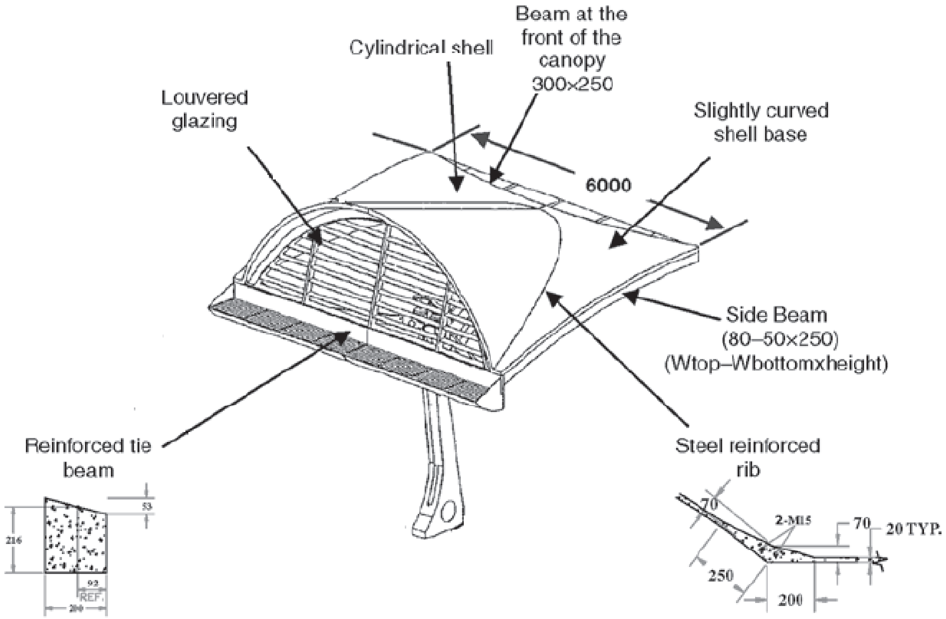


Figure 1.15 Schematic picture of one canopy. [26]

sembly the individual elements are very sensitive to forces induced by handling and storage.
The same shell elements are used for all 24 canopies of the shed, so re-use of the formwork was possible in casting the shell and the columns.

Concrete composition

The station has been constructed with new concrete technology. The thin shells of the canopies have been made out of a fibre reinforced ultra-high performance concrete (UHPC) called Ductal® which was not reinforced with standard steel bars. The shell parts are only reinforced with poly-vinyl alcohol fibres. Steel reinforcing bars are only used for the reinforced rib between the cylindrical shell and the slightly curved shell base, the tie beam, and the beams at the sides of the canopy. The concrete has been developed and manufactured by Lafarge North America and offers a unique combination of high strength and ductility in a highly mouldable product with excellent surface characteristics. The compressive strength of the used material is 150 N/mm^2 and the flexural strength is 18 N/mm^2.

This was the first time this new material was used for a shell structure, so a full scale prototype testing was performed at the University of Calgary's Centre for Innovative Technology. The full scale prototype was tested under the design dead and live load for snow and wind uplift. Also a determination of the prototype response to dynamic loading was made. Finite Element Method (FEM) was used to determine the critical load cases and the boundary conditions required on the edge of the prototype to simulate the neighbouring panels in the full structural unit.

Connections

The two halves of a single canopy have been bolted together with grout injected into the connections. The struts were attached to the shells and columns with welded connections.

Formwork

The precast canopy components were individually cast and consist of half shells, columns, tie beams, struts and troughs. The canopy forms were constructed out of plate steel. A 3D computer model was used to create the mould. The surface of the mould was covered with an epoxy based liner to provide an uniform finish of the concrete. Form deflections and stresses were analysed by FEM to ensure the form would meet the required tolerances and deflection criteria. Repetition of the form of the elements permitted re-use of the formwork.
The columns and half shell part were injection cast in closed steel forms. The injection casting was used to influence the fibre orientation in the elements. The orientation of the long slender fibres algin in the casting direction. To avoid shrinkage cracks, the moulds were rotated at specified times during initial curing and the half shells were demoulded twelve hours after casting. The troughs were cast through displacement moulding and the struts and tie beams were produced using conventional casting techniques.

Figure 1.16 Placing of the canopies on the columns. [38]

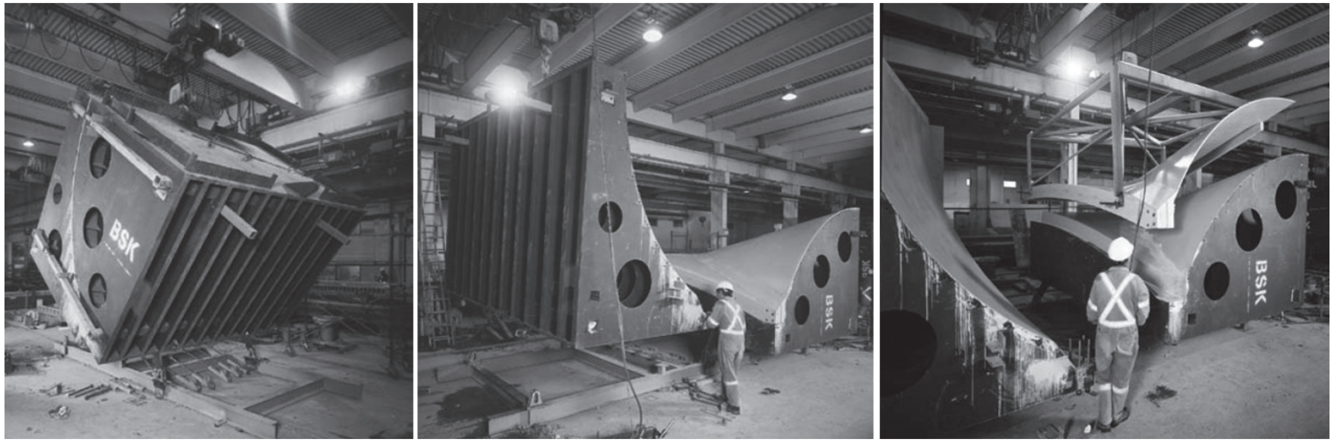


Figure 1.17 Casting process of the half shell elements. [38]

Figure 1.18 The canopy at sanatorium Zonnestraal. [64]

Construction

With the experience from the laboratory, the right- and left- half shells, along with the tie beams, were pre-assembled in the factory and then transported to the site. At the site, the columns were installed first and temporary scaffolding was placed. The canopies were placed onto the temporary scaffolding, and the struts were attached to the shells and columns with welded connections.

The canopies are bolted together to create a roof that is about 76 m x 5 m wide. Because the canopies are supported at three points, with a long moment arm to the column, each individual canopy has little resistance to torsion. Therefore the design required a sequence of three canopies to be connected together to adequately resist torsion. Supporting the canopies on temporary scaffolding allowed the canopies to be connected before any load was introduced into the system. At every third canopy an expansion joint was used to allow expansion and contraction of the canopy roof system.

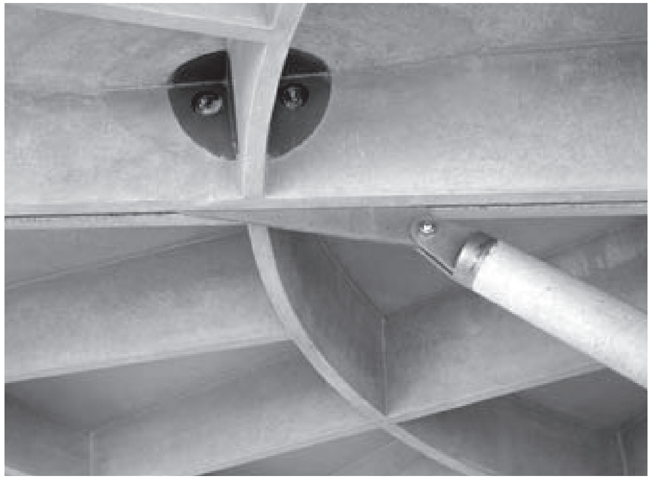


Figure 1.19 Detail of the connection between the branches and the roof. [50]

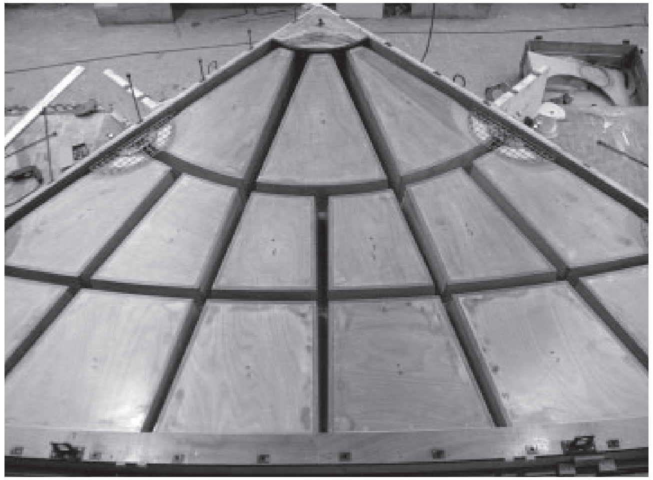


Figure 1.20 Formwork for the elements of the canopy. [64]

1.2.3 Canopy at sanatorium Zonnestraal, Hilversum, 2005

To show the developments in concrete technology and construction techniques in the last 75 years the Dutch concrete association (Betonvereniging) developed a canopy for the sanatorium Zonnestraal in Hilversum. The engineering firm ABT and Henket & Partners architects designed the 8 x 8 meter canopy as a thin plate in steel fibre reinforced ultra high performance concrete (UHPC) supported by a single column, made out of stainless steel.

Mechanical behaviour

The canopy is designed as a single column with the roof plate on top of it. The canopy roof is not a real 'shell' because the forces in the canopy are taken mainly trough bending. The roof plate is only 25 mm thick, but stiffened with ribs in radial and transversal direction. These ribs have a thickness of 40 mm. The roof is connected to the column by four 'branches' to reduce the cantilever length of the canopy. These branches are also made out of fibre reinforced UHPC and have a double curved organic shape.

Segmentation

The roof is segmented in four equal parts. This is done to make the handling of the elements during production, transport and construction easier. The branches are also cast individually. The equal part of the roof elements and the branches, made re-use of the forms possible.

Concrete composition

The roof is constructed with a UHPC mixture called BSI/CERACEM consisting of cement, steel fibres of 20 mm long and 0,3 mm in diameter, silica fume and calcined bauxite. This UHPC is denser than ordinary concrete which leads to a higher durability of the concrete. This concrete is also much stronger than ordinary concrete, what makes more slender constructions with larger spans possible.

A large disadvantage of the material is its prize. It is much more expensive than ordinary concrete. But because more slender structures are possible this partly compensates the more expensive material.

Connections

The four parts have been bolted together on site. For the connection between the canopy and the branches also bolts have been used. To lead local peak forces into the roof plate stainless steel components have been designed to reinforce these connections.

The branches have been connected to the column with a bolted connection on the upper side of the column. At the bottom the branches rest on stainless steel consoles.

Formwork

The ribs and the roof surface are cast as one piece. For the four identical parts a plywood formwork is used. The form is placed in such a way that the upper side of the roof is horizontal. To be able to cast the circular edge of the canopy a double curved edge formwork was used. For the demoulding of the elements a combination of lifting and air pressure is used.

For the construction of the curved branches a double curved mould had to be made. A three-axial milling-machine was used to create the form of the branches in a massive ply-wood plate. The steel tube of the column forms the third part of the formwork. Before casting of the concrete the surface of the mould was flattened with filler and varnish.

Construction

On site all the elements have been placed on their final position, with the help of a temporary scaffolding, and are then bolted together.

1.2.4 Toll station for the Millau Bridge, France, 2005

The toll station is situated about four kilometres north of the Millau viaduct in France. The architect Michel Herbert imagined the roof as a ‘wing in torsion’. The toll stations entire length of 98 m is rotated by 23 degrees to form a helically warped structure. The twisted and curved concrete roof has a size of 98 x 28 meter and is supported by a slender steel structure. Each of the, on four axes placed, supporting structure consists of two sets of six inclined columns.

Mechanical behaviour

This is not a real ‘shell’ structure, but it acts more as a plate on supports. The load transfer in the roof will be mainly trough bending, because the curvature of the roof is to small to provide ‘shell action’. This can also be seen in the design of the elements. The elements are designed as hollow core sections and are therefore especially suitable for the transfer of bending moment.

Segmentation

The roof is cut in the transversal direction into 54 elements, with a length of 28 meter. The elements created in this way are all differently shaped concrete elements. The elements are about 85 cm thick at the centre, 10 cm thick at the ends and designed as a hollow core element.

Concrete composition

The use of the concrete mixture BSI/CERECAM made the impressive shape possible. BSI/CERECAM is a steel fibre reinforced concrete. The 20 mm long fibres fill 1.5 to 3% of the volume of the concrete and increase not only the tensile, but also the shear capacity of the concrete. This has a positive effect on the designer’s freedom and a reduction of the amount of steel reinforcing bars. [19]

Figure 1.21 Millau bridge toll station [64]

Figure 1.22 Details of the columns. [64]

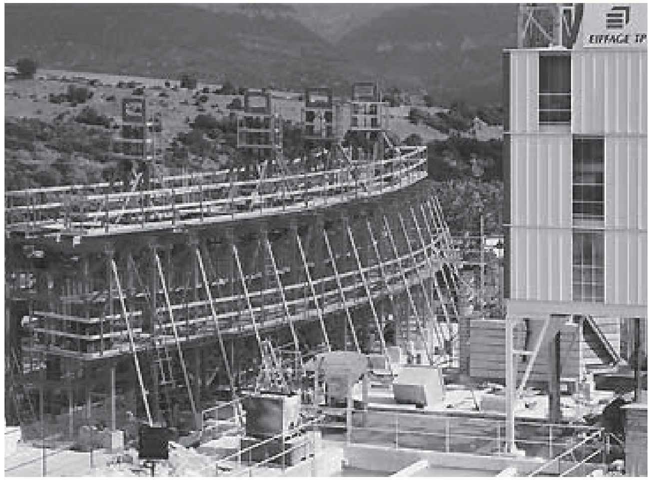


Figure 1.23 On-site casting factory and concrete mixing plant. [61]

Figure 1.24 Temporary scaffolding for the installation of the precast elements. [64]

Connections

The elements have been bolted together when installed on their final position. After all the elements were placed, the roof has been post-tensioned to increase the capacity of the roof.

Formwork

The elements, which weigh up to 65 ton, have been produced in an on-site factory using a special steel formwork and a stationary concrete mixing plant. The steel structure of the formwork made it possible to construct elements without any tie points. The complicated segment design is characterized not only by the three dimensional accuracy but also by the excellent concrete finish.

In order to achieve an exact fit and obtain an accurate transition of forces between the individual segments, each segment has been directly cast on to the element in front. The segment production corresponds with the later installation and assembly procedure. After hardening each segment has been lowered in the casting installation to a new place to make it possible to cast the next element on top of the previously cast element. (See Figure 1.25) After this the element has been moved out and placed on the storage yard where it stays till the final installation. With this system it has been possible to complete one segment every three days.

Construction

After prefabrication, the elements have been installed on a temporary scaffolding structure and were bolted together. After the placement of the elements, they have been post-tensioned to each other by means of twelve tension strands. This results in a permanent connection between the elements.

1.2.5 Concluding remarks

There are only a couple applications of prefabricated concrete shells in the last 10 years. Most prefabricated concrete structures with double curved elements that have been built in the last ten years are discussed in this paragraph. Here some concluding remarks of this study are given.

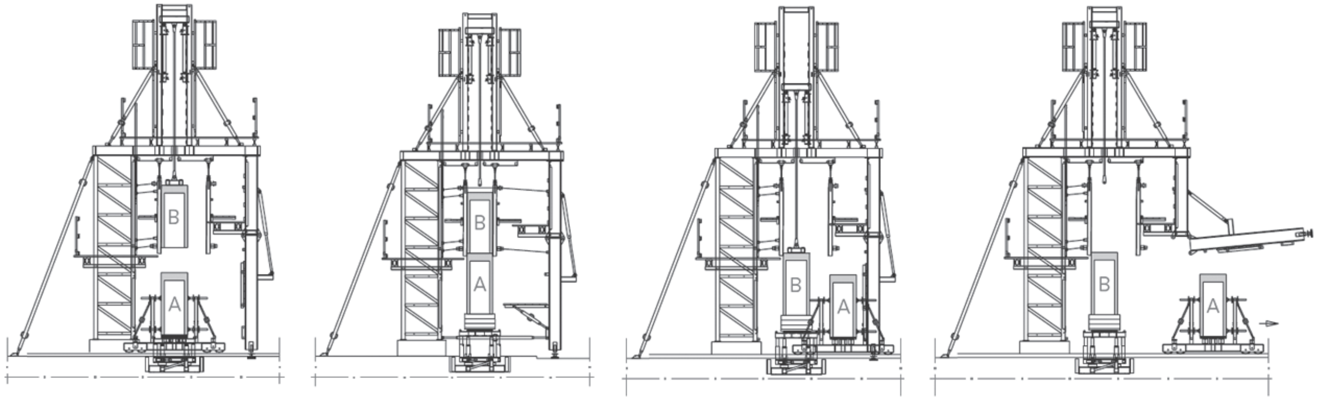


Figure 1.25 Schematic representation of the construction process of the element for the tollgate canopy. [61]

Mechanical behaviour

Not all structures with double curved concrete elements function as a real shell structure where membrane forces are developed in the shell. Most of the structures transfer the forces mainly trough bending. The type of mechanical behaviour results in differently shaped elements for both types of force transfer. When shell action is developed in the shell the elements are very thin and slender. In the structures were the forces are transferred mainly trough bending the elements are thicker, have ribs or are designed as hollow core sections. In this thesis the focus will be on the design of real shell structures.

Segmentation

In most designs it has been tried to segment the structure in such a way that one or more equally shaped elements originate from the segmentation. In this way only one or a couple moulds are needed and re-use of the form is possible. Only with the Millau toll station this is not done, here every element is different. So the research to a flexible mould can be useful, because it provides more freedom of design for prefabricated concrete structures when not all elements need to be the same.

Concrete composition

For the last three designs of prefabricated concrete shells new concrete compositions are used. For these shells the ultra high performance fibre reinforced concrete mixtures Ductal and BSI/CERACEM are used. The high strength of this type of concrete makes it possible to design more slender structures and in combination with the fibre reinforcement no or very little ordinary reinforcement is needed.
A disadvantage of these materials are the costs, they are a lot more expensive than ordinary concrete. This is partly compensated by the more slender designs that are possible, but they are still very expensive. Another disadvantage is that almost nothing about these new materials is recorded in regulations and still a lot of experiments are needed to get to know all possibilities and drawbacks of the material. But overall fibre reinforced concrete composites might make the production of prefabricated concrete shells easier.

Connections

There are three different types of connections that have been used for the analysed shells: a wet connection, a bolted connection and welded connections. In structure were no high performance concrete was used the connections were made as wet connections. In the structures with high performance concrete bolted connections, sometimes in combination with post-tensioning strands or grouting, and welded connections are used.

Formwork

When the mould has to be used several times it has to be durable and should not deform to much. For this reason most forms are made out of multiplex or steel. When a multiplex form with a complex shape has to be made a multi-axial milling machine is used. The mould can also be made by hand, but this is more laborious. As the material for the mould also polystyrene can be used but this is less durable than steel or multiplex. The production of these complex mould is difficult and expensive. The use of an adjustable formwork might reduce the costs for the mould and make the production of the elements easier.

Construction

Most prefabricated concrete shells are constructed with the use of a temporary scaffolding system. Sometimes elements are already partly assembled in the factory, like with the Shawnessy station. When a large amount of large elements has to be made a factory on site, like with the Millau toll gates, can be economical. In this way a lot is saved on the transport costs and time.

1.3 Problem description and aim

1.3.1 Problem description

Not many free formed shell structures in prefabricated concrete have been build. One of the reasons for this is that the design and production process of free formed shells in prefabricated concrete is not efficient enough to make the construction of these shells feasible in most cases.

One of the problems with the design process is that there is no segmentation method available that can be applied easily to all types of free form surfaces. Another problem is that the mechanical behaviour of shells in prefabricated concrete should become known and controllable.

The problems in the production process can be divided in difficulties with the formwork, the concrete reinforcement, and the connection system. The use of formwork is very inefficient when for every different element a new form is needed. Reinforcing a double curved element is very labour intensive and expensive. There is no system available with which the elements can be connected fast and easily and that can be used for the different connections in the structure.

1.3.2 Aim

The aim of this Master's thesis is to find the difficulties and possibilities of the different aspects of the design and production process of prefabricated concrete shells and to come with possible solutions to overcome these difficulties to make the construction of prefabricated concrete shells more feasible.

To reach this goal the focus of this Master's thesis will be on the following aspects:

- An investigation of the mechanical behaviour of prefabricated concrete shells, to find the possibilities and difficulties that have to be encountered during the design.
- An investigation to find a segmentation method that is capable of making an efficient subdivision of the design of the shell surface and the development of a computational segmentation tool to use this method.
- An investigation of the possibilities and difficulties of fibre reinforced composites for the use in prefabricated shell structures.
- An investigation to the possible designs for the connection between the elements in prefabricated concrete shells.
- An investigation to the development of a flexible formwork for the construction of double curved concrete elements.

1.4 Approach

This paragraph describes the method through which the aim of this Master's thesis will be reached.

Part I Design Aspects

First the different aspects of the design and production process are investigated.

Chapter 2 'Mechanics' gives a short introduction in shell mechanics and discusses different aspects of the structural analysis of (prefabricated) shell structures.

In Chapter 3 'Grid generation' the existing grid generation methods that can be used to generate a grid over the designed surface are investigated. This grid should be used for the segmentation of the shell surface.

In Chapter 4 'Concrete composites' an overview of the of properties of different types of concrete, with a special focus on (ultra) high performance and fibre reinforced concrete, is given. In this chapter also some recently developed fibre reinforced concrete mixtures are described. On the basis of the overview of the different types of the fibre reinforced concretes the most suitable concrete composition and reinforcing method, for the fabrication of concrete shells made out of double curved elements, has been defined.

Chapter 5 'Adjustable formwork' describes the different studies to the flexible pin-bed mould, which is still in an experimental phase of its development. The characteristics of the adjustable formwork as it will be used in the proceeding of the thesis are defined.

In Chapter 6 'Edges and connections' the formation of the edges and connections of the elements has been studied. Different methods to create the edges of the elements are described and evaluated. In this chapter the different methods that can be used as connection system are described and evaluated.

Chapter 7 'Production and construction' considers the production of the elements, the construction of the shell, and some other aspects of the design and construction of the prefabricated concrete shells.

Part II Design process

After analysis of the different aspects of the design and construction of prefabricated concrete shells in Chapter 8 'Design process' the design process of prefabricated concrete shells has been analysed. This chapter shows in different diagrams how the shell should be designed and optimized.

In Chapter 9 'Geometry design tool' the development of the design tool is described. The design tool generates the grid over the surface, defines the shape of the elements and controls the size, shape and curvature of the elements.

Part III Case study

In Chapter 10 'Case study' a case study is performed in which the different aspects of the thesis come together.

Part IV Conclusions and Recommendations

In the 'Conclusions and recommendations' the conclusions of this thesis and some recommendations for further research are given.

2. Mechanics

Before a structure can be build different calculations on the structures strength, stiffness and stability have to be made. This chapter discusses different aspects of the mechanical calculations of shell structures, like the membrane theory, the bending theory and finite element methods.

The Olanesti well station (1960). [64]

2.1 Introduction

Loads applied to shell surfaces are carried to the foundation by the development of compression, tensile and shear stresses acting in the in-plane direction of the surface. The thickness of the surface does not allow the development of appreciable bending resistance. Thin shell structures are uniquely suited to carry distributed loads by in-plane forces or membrane forces.

At free-formed and geometrical defined surfaces the membrane theory often does not hold and some of the bending field components are produced to compensate the shortcomings of the membrane field in the disturbed zone. This is also the case at the supports of shell and when point loads are applied on the shell surface. These disturbances have to be described by a more complete analysis which will lead to a bending theory of thin elastic shells.

In paragraph 2.2 different methods for surface definition, based on geometrical or non-geometrical definition, are presented. After this an introduction about shell mechanics will be given. In paragraph 2.3 the membrane and bending theory are discussed. Paragraph 2.4 discusses the finite element analysis. A short introduction of shell buckling is given in paragraph 2.5 and some specific characteristics of prefabricated shells are given in paragraph 2.6. At the end of this chapter structural optimization is discussed in paragraph 2.7 and some concluding remarks are given in paragraph 2.8.

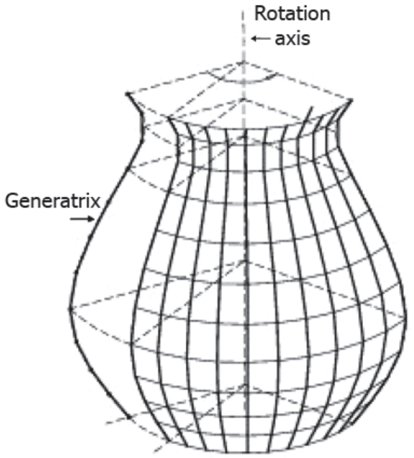


Figure 2.1 Example of a surface of revolution. [59]

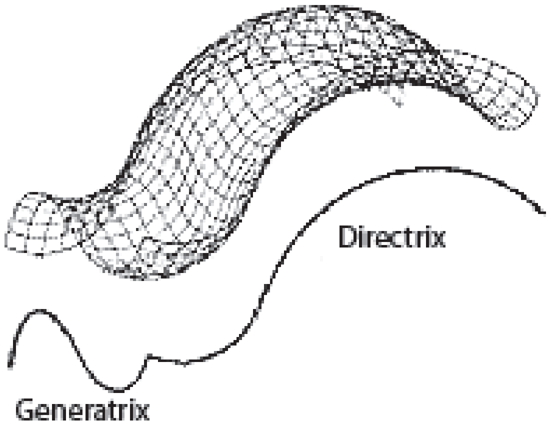


Figure 2.2 Example of a surface of translation. [19]

2.2 Surface Definition

A shell can be defined as a thin rigid three-dimensional structural form enclosure in a volume bounded by a curved surface. A shell surface may assume virtually any shape. The geometry of a shell can also be described by the curved shape of the middle surface and the thickness of the shell. [3]

2.2.1 Geometrical defined surfaces

Geometrical defined surfaces are surfaces that can be defined by means of parameters and mathematical functions. This makes it possible to describe irregular double curved surfaces. The more complex the shape, the more effort is required to describe the geometry in an accurate way. As the geometry is defined by mathematical formulas, the best and easiest way of representing the design is by making use of a computer. One method of geometrically specifying surfaces is to consider them as paths or traces of straight lines and curves. Examples of this are surfaces of revolution, translational surfaces or ruled surfaces. The main advantage of these surfaces is that they are rendered by line segments so there is already a grid generated that can be used to segment the surface into elements. Another way to geometrically specify surfaces relies on the special mathematics and procedures summarized under the name NURBS. These surfaces are not that easy to segment compared to the translational, rotational and ruled surfaces. There are also more advanced techniques like T-splines that are based on NURBS, but these are not discussed here.

Revolution

Surfaces of revolution are generated by the revolution of a plane curve, the meridional curve or generatrix, around an axis, the axis of revolution. Some examples of surfaces of revolution are conical shells, circular domes, spheres and torus shapes.

Translation

Surfaces of translation are generated by sliding a plane curve along another curve, while keeping the orientation of the sliding curve constant. The latter curve, on which the original curve slides, is called the director of the surface. The other curve, that slices over the directrix, can be called the generator or generatrix of the surface.

Ruling

Ruled surfaces are generated by sliding each end of a straight line on their own generating curve, while remaining the straight line parallel to a prescribed direction or plane. The generated straight lines are not necessarily at right angles to the planes containing the generating director curves.

NURBS-techniques

NURBS, Non-Uniform Rational B-splines, are mathematical representations on n-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc or curve to the most complex 3-D organic free-form surface or solid. [19] Because of this flexibility and accuracy NURBS are ideal to describe free-form structures and they can be used in any process from illustration and animation to manufacturing. NURBS-surfaces are specified by a complex combination of mathematical objects, formulas and procedures, which interact to specify a new form in an iterative way. Designers that use these description techniques make use of special modelling programs, like Rhinoceros, to work with NURBS-techniques.

A NURBS curve is defined by its degree, a set of weighted control points and a knot vector. NURBS can be used to describe any curve. To describe any possible surface, instead of one parameter, two parameters are to be used in combination with a NURBS representation. By varying both parameters over their full ranges, a surface will be generated. By holding one parameter constant and varying the other across the full range will generate a curve that is called an isoline. Frequently surfaces are visualised by using a set of evenly spaced isolines in each direction.

Curves can be of any degree (n), but the degree usually is 1, 2, 3 or 5. NURBS lines are of degree 1, NURBS circles and parts of circles are of degree 2 and most free-form curves are of degree 3 or 5.

The control points determine the shape of the curve. Each point of a curve is computed by taking a weighted sum of a number of control points. The weight of each point varies according to the governing parameter. The weight of any control point is only non-zero in one interval of the parameter space. Within that interval the weight changes according to a polynomial function (the basis function) of a certain degree.

The knot vector is a sequence of parameter values that determines where and how the control points affect the NURBS curve. The number of knots is always equal to the number of control points plus the curves degree plus one. The knot vector divides the parametric space in intervals, referred to a knot spans. The individual knot values are not meaningful by themselves; only the ratios of the difference between the knot values matter.

The basis function describes how each geometric constraint contributes to the final value of the curve. The values of the basis functions at any point along the curve indicate the amount of influence each control point has on the shape of the curve on that point. The resulting general equation of a curve can be described as the summing of the product of each geometric constraint and its basis function.

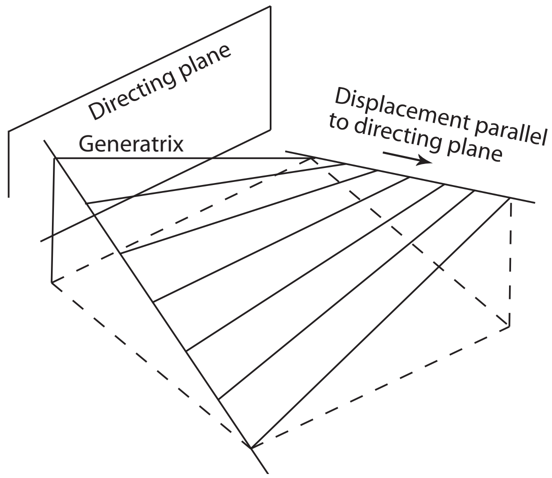


Figure 2.3 Example of a ruled surface.

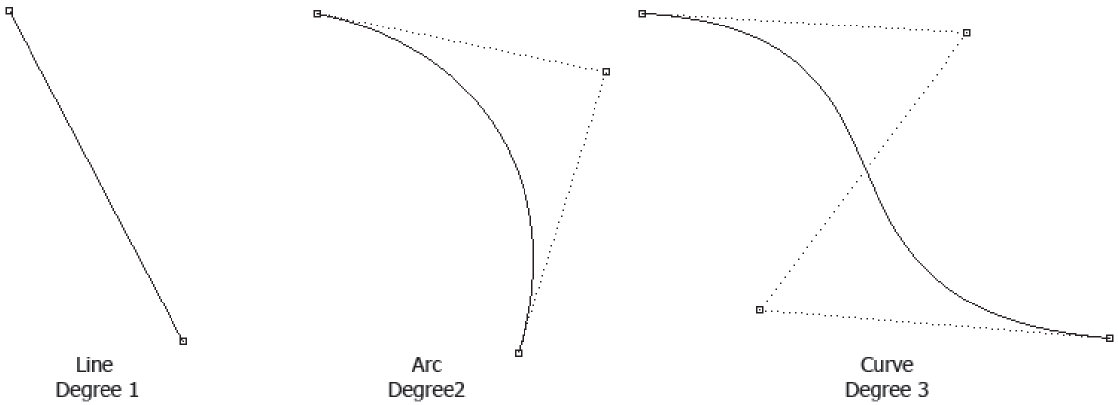


Figure 2.4 NURBS curves of different degrees.

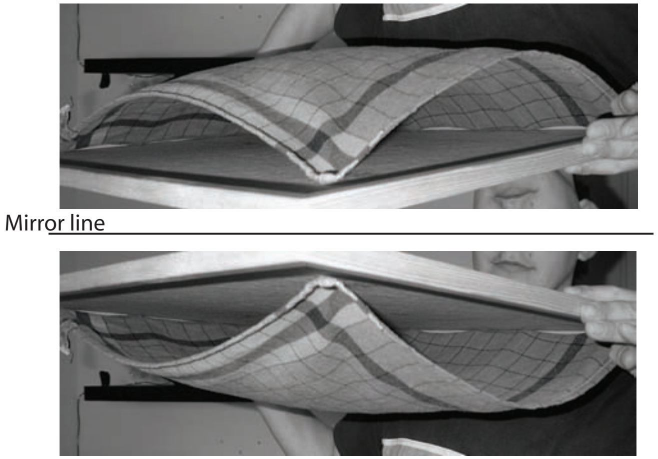


Figure 2.5 Example of a wet cloth model.

2.2.2 Non-geometrical defined surfaces

The non-geometric surface generation is another way to define surfaces. The most methods for non-geometric surface generation are form finding methods, which can be subdivided into experimental and analytical or numerical methods. Hanging nets and soap bubbles are well known examples of experimental form finding methods. Analytical form-finding methods, such as the 'force-density' method and the 'dynamic relaxation' method are mainly the numerical counterparts of the physical, experimental methods. The objective of these form finding methods is to find an equilibrium state of a structure. When the right boundary conditions and form giving agents are applied irregular double curved surfaces are generated.

Physical form finding

Physical form finding methods are surface generation methods that make use of an actual model. Form finding processes require form giving agents, which have in this case a natural, physical character. Examples of form giving agents are earth gravity, air pressure or prestress. Physical modelling processes are used to find an equilibrium for different types of situations.

Nature is seen as a source of inspiration for both architects and civil engineers. When looking to optimization the evolution has produced many optimized structures in nature. In the world of nature structures are often optimized for withstanding forces of gravity. Structures in nature that have inspired engineers and architects in the past are for example cellular structures like honeycombs, dragonfly wings, spider webs, bones and skeleton structures, sea shells, leaf structures and tree structures.

Hanging models are physical models that are shaped to their equilibrium state by gravity forces. Common used physical hanging models are wet cloth models, hanging chain models and hanging net models. Due to the used materials in hanging models, when hanging, they only contain tension forces. When inverting the model the

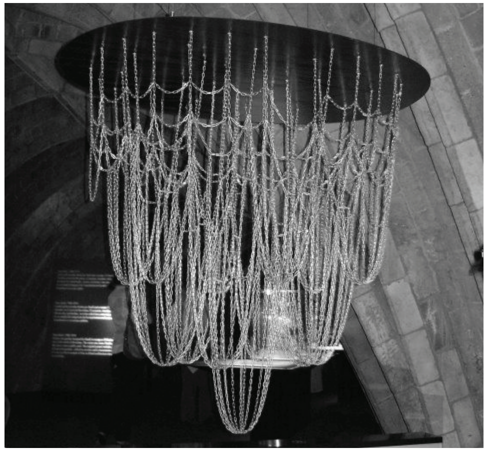


Figure 2.6 Hanging model of the Sagrada Familia. [48]

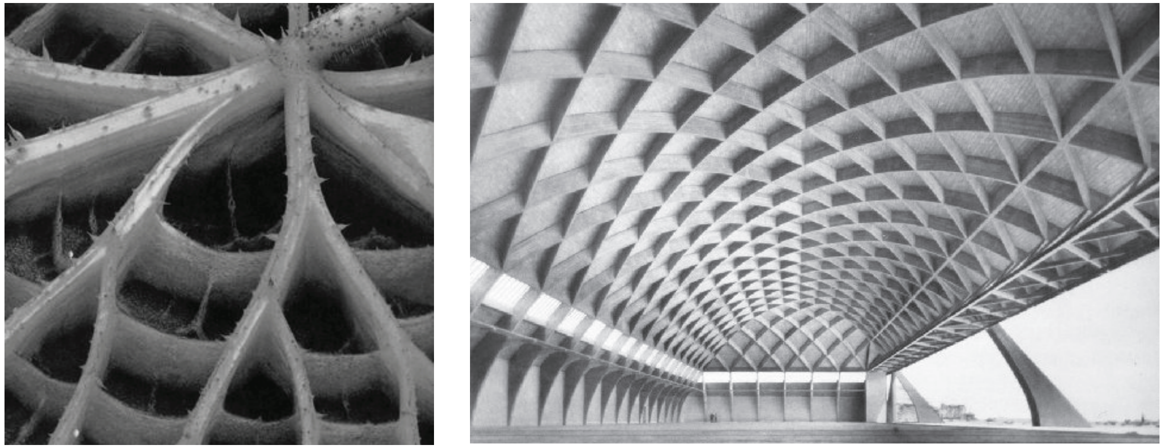


Figure 2.7 The ribs Nervi used for his hangars are an example of a human 'translation' of the natural principle of ribbed structures, like in the Victoria amazonica. [24, 64]

compression line or surface of the structure is found. Concentrated loads on the model can be applied by hanging heavy elements in the model. Gaudi, for example, hung little bags filled with sand in his models to simulate concentrated loads.

Soap films find the equilibrium shape of a minimal surface between preset (closed) boundaries. [24] With soap film modelling two main types of surfaces can be derived. The first one is to find the minimal surface for membrane structures and shells. Here the soap film shapes itself to a minimal surfaces between the set boundaries. The second one finding surfaces for pneumatic structures. Here an over-pressure is applied in the soap bubble and an internal (pneumatic) load is created to drive the forming process.

Structures that adapt to their environment according to a set of rules and strategies are called adaptive structures. They can be seen as physical form finding, since the structure finds it own form by adapting to the environment, not in a scaled down model, but in full scale reality. The rules and strategies of the system are the driving force of the form finding process and the structure reaching its own structural optimum. [24]

Analytical form finding

Analytical form finding methods enable designers to produce minimal surfaces, without making actual physical models. These methods are aimed at finding analytical minimal surfaces and are to be considered as the numerical counterparts of the physical methods. Analytical form finding cannot be seen as a replacement for the physical form finding methods, they form an addition to them.

To find the minimal surface of a membrane, the dynamic relaxation method solves the geometric non-linear problem by equating it to a dynamic problem. Dynamic characteristics of the membrane need to be specified. For the form finding process, the pre-stresses in the membrane are fixed. The basis of the method is to trace step by step for small time increments the motion of each node of a structure until, due to artificial damping, the structure comes to a static equilibrium. The form finding process may start from an arbitrary geometry specification. The motion is caused by imposing a stress or force in some or all of the components of the structure. For load analysis, which must start from a correct initial or prestress equilibrium state the motion is caused by suddenly applying the loading.

The force density method uses a linear system of equations to model equilibrium states of non-linear systems such as pre-stressed cable nets under prescribed force density ratios. The method is based on force density ratios (cable force divided by cable length) that need to be defined for each element of the net. Different ratios give different equilibrium shapes for the net, the higher the force density, the shorter the element for a given force. When the force densities for a node are equal and evenly distributed around the node, the minimal surface is found.

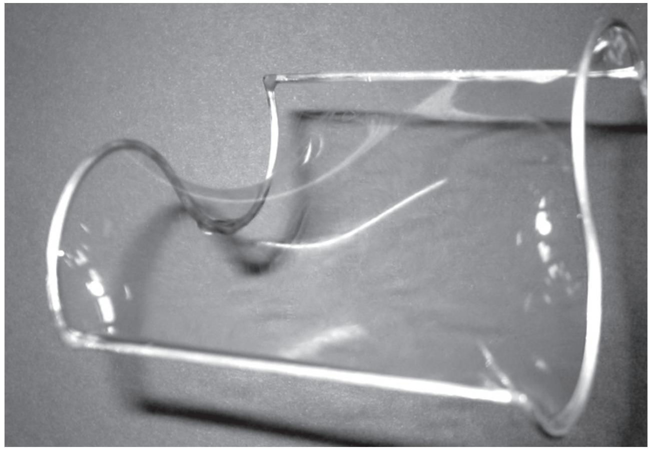


Figure 2.8 Soap film model. [24]

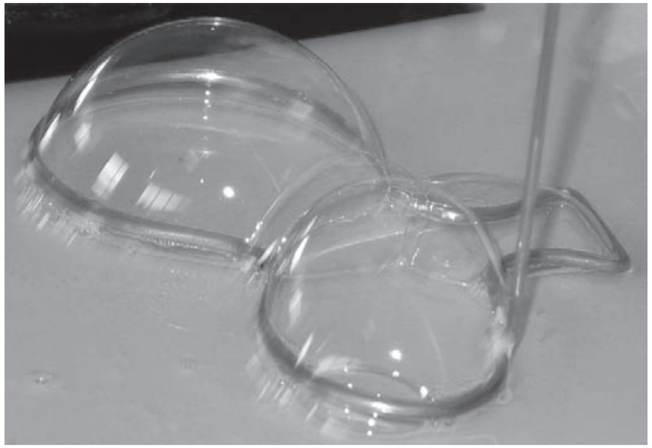


Figure 2.9 Pneumatic soap film model. [24]

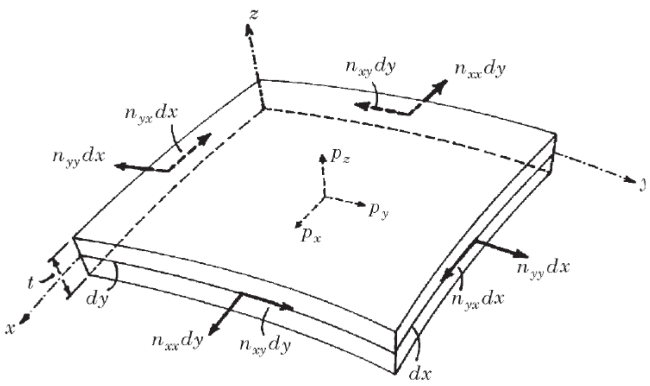


Figure 2.10 Stress resultants and load components on a shell element. [3]

2.3 Membrane and bending theory

2.3.1 Membrane theory

Because of the small thickness-to-radius ratio of a thin shell, the flexural rigidity is much smaller than the extensional rigidity. A thin shell subjected to external loads therefore mainly produces membrane stress resultants. The theory that describes this structural behaviour is called the membrane theory.

The basic assumption of the membrane theory is that a thin shell produces a pure membrane stress field and no bending stress actions are developed. The membrane theory is only applicable if certain boundary and loading conditions are met. These conditions are:

- No sudden changes of the curvature are allowed.
- No sudden changes of the thickness are allowed.
- No concentrated loads allowed.
- The reactions at the edges must be directed tangentially to the middle surface and support arrangements must be made to allow this.

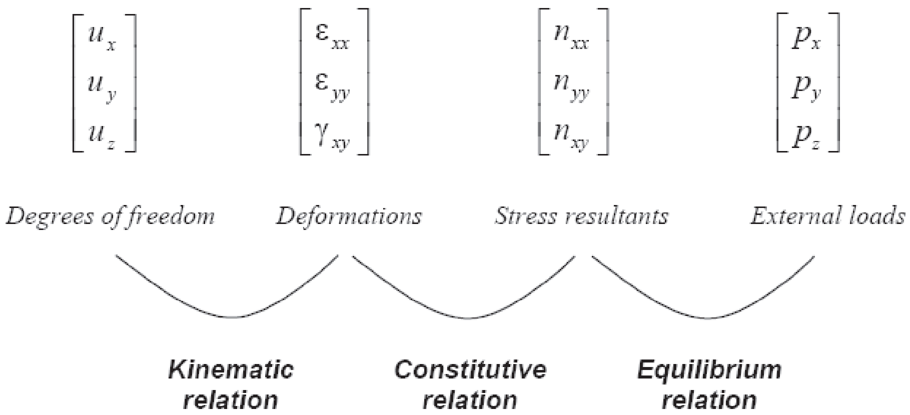


Figure 2.11 Relation between the different vectors. [3]

In case of a pure membrane stress field only normal and longitudinal shearing stresses are produced, which are uniformly distributed through the thickness. The bending stress resultants are small compared to the in-plane stress resultants for a thin shell. The stress resultants acting on a shell element, without the bending stress resultants, are shown in Figure 2.10. The coordinate system can be placed on the middle surface according to the principal curvatures of the shell. But it is better to rotate the coordinate system in such a way that it can be placed in an arbitrary direction, for example along an edge of the shell.

For an element three force equilibrium conditions between the stress resultants and the load components can be set up. The positive action of the load components, acting on the middle surface of the shell element, is taken according to the positive directions of the three axes of the coordinate system.

The load component vector p is defined by:

$$p = [p_x \;\; p_y \;\; p_z]^T$$

Consistent with the three load terms in the load component vector p, the displacement vector u is defined by three displacements:

$$u = [u_x \;\; u_y \;\; u_z]^T$$

The displacements u_x and u_y are the displacements tangential to the middle surface and the displacement u_z is the displacement normal to the middle surface.

The membrane theory is based on the assumption that a thin shell produces a pure membrane stress field and that bending stress actions are not developed. The stresses are thus uniformly distributed. Because of the equality of the shearing stresses, the stress vector σ is defined by:

$$\sigma = [\sigma_{xx} \;\; \sigma_{yy} \;\; \sigma_{xy}]^T$$

The stresses on the middle surface are thus described by the normal stresses, σ_{xx} and σ_{yy}, and by the shearing stress

σ_{xy}. The three stress resultants are obtained by integrating these stresses over the thickness t of the shell. Since the stresses are uniformly distributed this integration is equal to the multiplication of the stress vector with the thickness:

$$s = \sigma t = [n_{xx} \;\; n_{yy} \;\; n_{xy}]^T$$

When it is assumed that the shell material behaves linear elastic, conform Hooke's law, the strains are, corresponding to the stresses, uniformly distributed over the thickness of the shell. The deformation of the middle surface is therefore completely described by the strain vector e defined by:

$$e = [\varepsilon_{xx} \;\; \varepsilon_{yy} \;\; \gamma_{xy}]^T$$

The deformation of the middle surface is thus described by the normal strains, ε_{xx} and ε_{yy}, and by the shearing strain γ_{xy}.

The relations between the different vectors are presented in Figure 2.11.

2.3.2 Bending theory

In the regions where the membrane theory does not hold, some (or all) of the bending field components are produced to compensate the shortcomings of the membrane field in the disturbed zone. These disturbances have to be described by a more complete analysis, which leads to the bending theory of thin elastic shells. [3]

When the bending field components are developed, they often only have a local range of influence and they attenuate rapidly. In many cases the bending behaviour is restricted to places where the membrane theory does not hold. Therefore the undisturbed and major part of the shell behaves like a true membrane. This unique property of shells is a result of the curvature of the spatial structure.

The bending theory can be seen as an extension of the membrane theory. The load component vector p and the displacement vector u are still the same. But the other two vectors differ from the vectors used in the membrane theory. Due to the presence of the bending field components the bending stress resultant and the twisting stress resultant m_{xx}, m_{yy}, and m_{xy} have to be added to the stress resultant vector s. The strain vector e also changes, here the bending deformations κ_{xx}, κ_{yy} and ρ_{xy} are added. This results in changes in the relations between the vectors.

More information about the membrane theory can be found in 'Theory of shells' of J. Blauwendraad and J.H. Hoefakker [3].

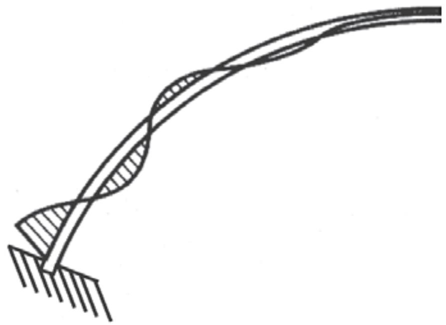


Figure 2.12 Fixed edge conditions induce bending in the shell surface. The bending moments damp out rapidly. [22]

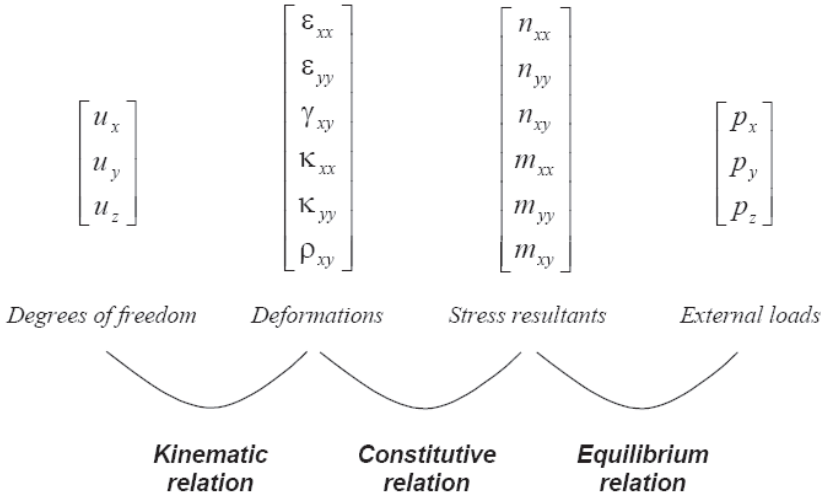


Figure 2.13 Relation between the different vectors. [3]

2.4 Finite Element Analysis

Finite element analysis (FEA) is a computer simulation technique to analyse thin free-formed geometrical defined and form-finding shells and other structures. A common use of FEA is the determination of stresses and displacements in mechanical objects and systems. It uses a numerical technique called the finite element method (FEM). Development of the finite element method in structural mechanics is usually based on an energy principle such as the virtual work principle or the minimum total potential energy principle. The virtual work principle approach is more general as it is applicable to both linear and non-linear material behaviours.

In general, there are three phases in any computer-aided engineering task, like finite element analysis:

- Pre-processing, defining the finite element model and environmental factors to be applied onto it.
- Analysis, find the solution of finite element model.
- Post-processing, analysis of the results using visualization tools.

The first step in using FEA, pre-processing, is constructing a finite element model of the structure that has to be analysed. The input of a topological description of the structure's geometric features is required in most FEA packages. This can be in either 1D, 2D or 3D form, although 3D models are predominantly used. The primary objective of the model is to realistically replicate the important parameters and features of the real model. Once the finite element geometric model has been created, a meshing procedure is used to define and break up the model into small segments. In general, a finite element model is defined by a mesh network, which is made up of the geometric arrangement of elements and nodes. Nodes represent points at which features such a displacements are calculated. Elements are bounded by sets of nodes, and define localized mass and stiffness properties of the model.

The next stage of the FEA process is the analysis. The FEM conducts of a series of computational procedures involving applied forces, and the properties of the elements which produce a model solution. Such a structural analysis allows the determination of effects such as deformations, strains and stresses which are caused by applied structural loads such as force, pressure and gravity.

These results can then be studied using visualization tools within the FEA environment to view and to fully identify implications of the analysis. Numerical and graphical tools allow the precise location of data such as stresses and deflections to be identified.

In a structural simulation, FEA helps tremendously in producing stiffness and strength visualisation and also in minimizing weight and cost. FEA allows detailed visualisation of where structures bend or twist, and indicates the distribution of stresses and displacements. The desired level of accuracy required and associated computational time requirements can be managed simultaneously. There are different commercial software packages, like ANSYS and DIANA, that provide facilities for generating the mesh, graphical display of input and output, which facilitate the verification of both input data and interpretation of the results.

2.5 Shell buckling

Buckling is one of the major failure modes of shell structures. Shell structures are often highly sensitive to initial imperfections and therefore have buckling loads much lower than those computed for perfect structures. These imperfections include dents, residual stresses, temperature stresses, inhomogeneities, creep, shrinkage, eccentricity of loading and first order deformations. The shell structures that are very sensitive for imperfection are for example cylinders and radially compressed domes, hyppars on the other hand are not sensitive to imperfections. [24]

The value of the compressive load at which buckling occurs is called the critical load. For the stability of a shell, it is necessary to determine the critical buckling load. The critical load can be computed using formulas or a finite element program. This the load is reduced by a factor that takes into account the imperfection sensitivity. The result needs to be smaller than the design load that acts on the shell. This factor is experimentally determined and is often called the ‘knock down factor’. Finite elements programs can compute critical load factors and the associated normal modes. The real critical load is represented by the smallest load factor because a shell will buckle at the first opportunity it gets. For shell that are sensitive to imperfections the maximum load factor might be as small as 1/6 of the critical load.

If a shell is very sensitive to imperfections a different kind of finite element analysis is needed. In this geometrical nonlinear analysis. The load is applied in small increments for which the displacements are computed. Figure 2.5 shows the results of different finite element computations of a simply supported shallow dome.

In most cases the maximum load predicted with measured imperfections are within 10% of the experimental maximum load. The maximum load is mainly affected by three types of imperfections; geometry, support stiffness and inelastic effects. Experience show that of all geometrical imperfections that are possible with the given amplitude the one affine to the buckling shape gives the smallest maximum load. [24]

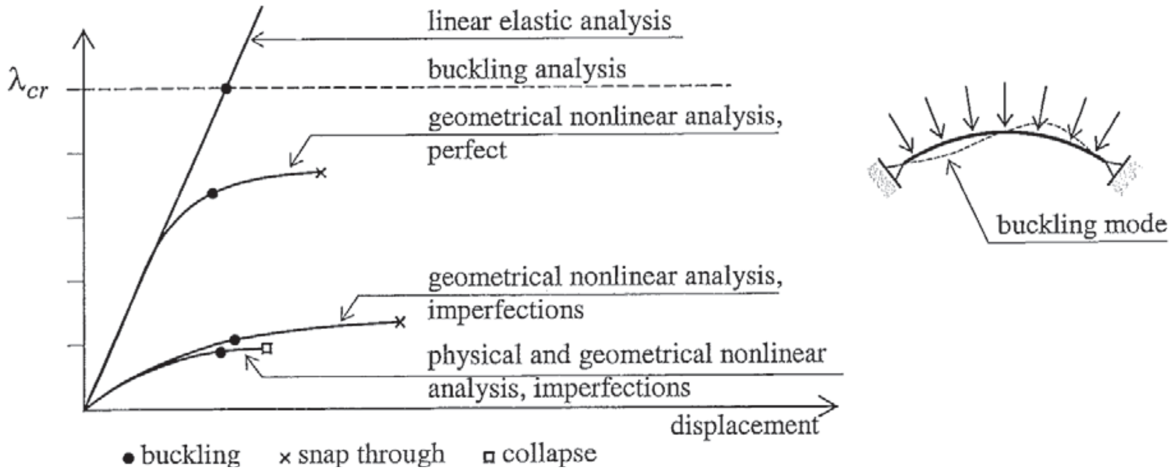


Figure 2.14 Shell finite elements analysis of a shallow dome. [24]

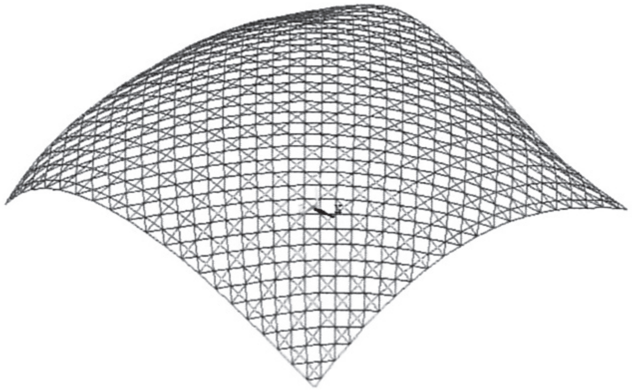


Figure 2.15 Buckling behaviour of a shell with bending stiff connections. [30]

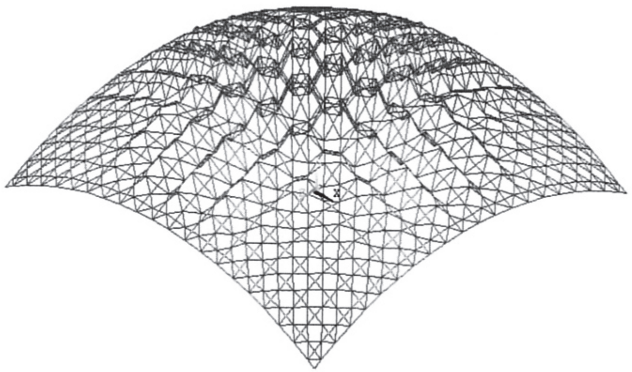


Figure 2.16 Buckling behaviour of a shell with hinged connections. [30]

2.6 Prefabricated concrete shell structures

The mechanics of prefabricated concrete shell structures differ from these of in-situ concrete shell structures. The difference is that the prefabricated shells consist of different prefabricated elements that are connected to each other on site and the in-situ shell is a monolithic structure. The strength and stiffness of the connections have to be taken into account during the structural analysis of the shell, because they influence the possible failure modes, the strength and the stability of the shell structure.

In theory there are three different instability failure modes for prefabricated concrete shell structures [30]:

- The shell fails, but the elements still act together as one structure.
- A chain reaction of buckling between the elements develops that makes the complete shell instable.
- Element failure due to buckling inside one element.

With a hinged connection there will always be a chain reaction of buckling and with a bending stiff connection there will always be the first type of buckling, where the shell fails but the elements still act together. The stiffness of the connection where the transition between these two types of buckling takes place differs for each design. To ensure that a shell structures fails on the first type of buckling, when it fails on instability, the stiffness of the connection has to be larger than the stiffness at the transition point.

It is most likely that a prefabricated concrete shell structure fails at the joints between the different elements or in the shell close to the joints. So in order to perform a sound structural analysis the place and type of connections has to be known.

2.7 Structural optimization

Structural optimization can be seen as the search for a better solution for a structural problem by generating additional sensitivities with respect to non-considered parameters. The optimized structure is better and more efficient than the initial structure. However this seems to be a very simple principle, the question how to define the optimization problem and to which extend it is executed is not.

In the optimization process first a shape is chosen for which the structural behaviour according to the given load cases and support conditions is evaluated. After the stresses, displacements, buckling loads and other safety requirements are checked a new and better design can be proposed by means of a sensitivity analysis. The process is repeated until the desired optimum is obtained.

Shape-sensitive structures like shells require high quality design to obtain an optimal membrane design. Since in many situations this optimal shape is not obvious, the need for optimization techniques is clear. To fulfil the basic membrane oriented design rules, a modification of the original design could substantially improve the structural behaviour reaching the ideal of a pure membrane stress in compression for all loading conditions. Optimization for shells results in a highly nonlinear optimization problem. This means that, in order to generate a reliable design by structural optimization, the nonlinear structural responses, like buckling or plasticity, must be considered.

A distinction can be made between size optimization, material optimization, topology optimization and shape optimization, even though these optimization techniques may have a lot of overlapping.

Size optimization refers to the optimization of the size of structural elements in a structure. The initial geometry is not changed. Size optimization leads to an optimal structure with respect to the weight and overall stiffness or strength satisfying the equilibrium condition and the boundary constraints. It results in structures with modified cross-sections of structural elements.

Material optimization is everyday practice for engineers. Material optimization is related to the optimal use of material in the structure. The goal is to achieve an optimum in material use and stress distribution.

The topology of a structure can be defined as the spatial arrangement of structural members and joints. Consequently, topology optimization means varying the connectivity between structural members of discrete structures or between domains of continuum structures.

Shape optimization refers to a technique in which the shape and thickness of a structure are optimized. The shape optimization method leads, by the aim of minimum of the total strain energy during form modification, to a membrane oriented design. By shape optimization the original design can be adapted in order to lower tension and bending stresses and progress to a more advantageous membrane state. This type of optimization is the most suitable for the optimization of shells.

Computational Optimization Algorithms

As the optimization of structures becomes dependent of an increasing amount of criteria, finding the best solution becomes very complicated. The development of computational optimization algorithms has advanced spectacular over the last decades. Various optimization algorithms with all kinds of application fields have been developed. Computational optimization algorithms often use a combination between different types of optimization, for example an integrated shape and topology optimization.

One of the most popular specific algorithms for structural optimization is Evolutionary Structural Optimization (ESO). ESO is a topology optimization method and thus involves consecutive removal of low stresses material until the maximum stress in the remaining material part is reached. The software makes use of finite element techniques to determine stresses.

Genetic algorithms are the most used general algorithms. The Darwinian based method generates every iteration new solutions by selection and crossover of previous obtained solutions in order to end up with a higher fitness generation. Random mutation of the new generation increases the change of reaching a global optimum. The process is repeated several times, keeping the size of the population constant.

Optimization software must still be further developed as the bulk of investigations are concentrated on cross-sectional optimization, 2D shape optimization. The nonlinear behaviour is usually not taken into account as it greatly increases the complexity of the problem. This makes it difficult to optimize a shell structure, but the progression may foresee in sufficient optimizing shell software in the future. [17]

2.8 Conclusions

- Surfaces of revolution, translational surfaces and ruled surfaces can not be used to define any free form surface, but the advantage of these surfaces is that they are defined by line segments so there is already a grid generated that can be used to divide the surface into elements.

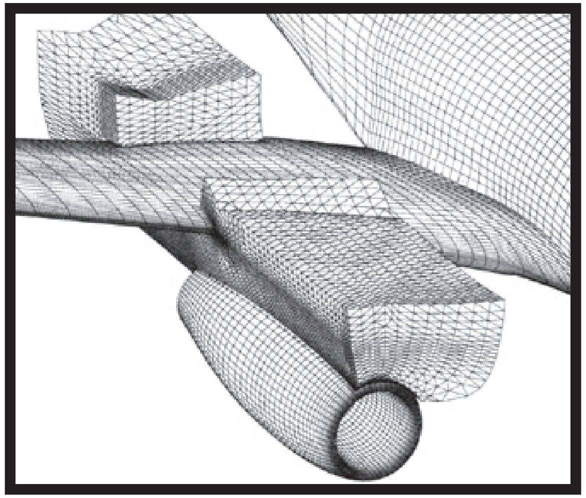
- NURBS can be used to define any free form surface, but the segmentation of these surfaces can be more difficult compared to the segmentation of the other geometrical defined surfaces.

- Finite element analysis, with the use of specialized software, makes the structural analysis of shell structure a lot easier. However, for the use of these numerical programs some basic knowledge of the underlying theories and the mechanical behaviour of the structure are still essential.

- The strength, stiffness and location of the connections influence the structural behaviour of the shell and have to be taken into account during the structural analysis of the shell.

- For shell structures the structural behaviour has to be optimized to the ideal of a pure membrane stress in compression for all loading conditions. This process of optimization is very complex, because in most cases the most optimal shape is not obvious and there is a large amount of criteria that has to be taken into account.

3. Grid generation



In order to be able to build a structure of prefabricated concrete elements the surface has to be segmented. There are different techniques that can be used for grid generation, which all have their strengths and weaknesses. In this chapter several of these techniques are considered and evaluated.

A part of a hybrid grid generated over the surface of an aircraft. [23]

3.1 Introduction

Liseikin [12] defines a grid as a pre-processing tool or a foundation on which physical, continuous quantities are described by discrete functions and on which the differential equations are approximated by algebraic relations for discrete values that are then numerically analysed by the application of computational codes. Grid generation techniques are commonly used for numerically solving physical problems. These problems are described by partial differential equations and solved by finite element or finite difference methods. In these and other cases a grid is only a utility to reach a higher goal.

In this Master's thesis the grid generation is used to segment the surface of a free formed or a shell structure in elements that can be cast in concrete. The aim of the grid generation is to describe a geometrical complex continuous surface in a discrete way that is sufficiently accurate to represent a designed free formed surfaces.

This chapter will provide a basic introduction into the fundamental concepts and approaches of grid generation techniques. First the terminology of grids and some grid requirements will be described in paragraph 3.2. The following paragraphs will describe three fundamentally different categories of grids and their generation techniques; structured grids, unstructured grids and composite grids. In the last paragraph some concluding remarks are given.

3.2 Terminology and requirements of the grid

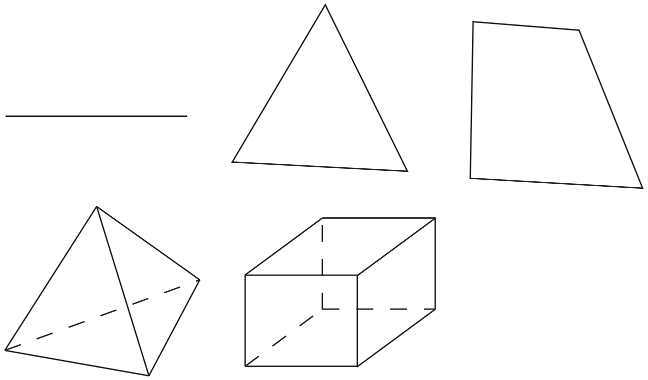


Figure 3.1 Typical grid cells.

3.2.1 Terminology

There are two general notions of a grid in an n-dimensional bounded domain or on a surface. One of these considers the grid as a set of algorithmically specified points of the domain or the surface. The points are called the grid nodes. The second considers the grid as an algorithmically described collection of standard n-dimensional volumes covering the necessary area of the domain or surface. The standard volumes generated by grid generation techniques, are referred to as grid cells. The boundary points of the one dimensional cells are called the cell vertices. These vertices are the grid nodes. Thus the grid nodes are consistent with the grid cells in that they coincide with the cell vertices. For cells in an n-dimensional domain or surface, there are commonly used n-dimensional volumes of simple standard shapes. (See Figure 3.1)

There are two fundamental classes of grid popular in the numerical solution of boundary value problems in multi-dimensional regions: structured and unstructured. These classes differ in the way in which the mesh points are locally organized. When the local organization of the grid points and the form of the cells do not depend on their position but are defined by a general rule the mesh is considered as structured. When the connection of the neighbouring grid nodes varies from point to point the mesh is called unstructured. The connectivity of structured grids is implicitly taken into account while the connectivity of unstructured grids has to be described explicitly by an appropriate data structure procedure.

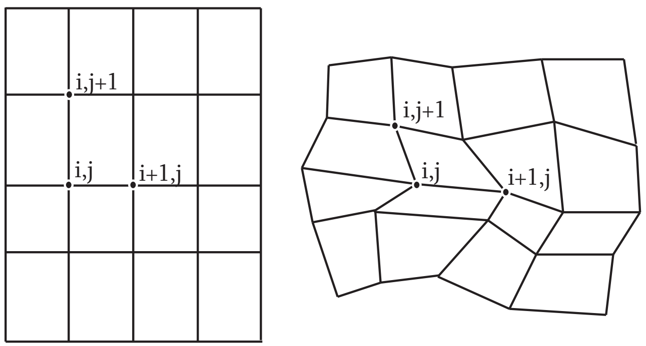


Figure 3.2 The position of the grid points and the form of the cells in a structured grid are defined by a general rule.

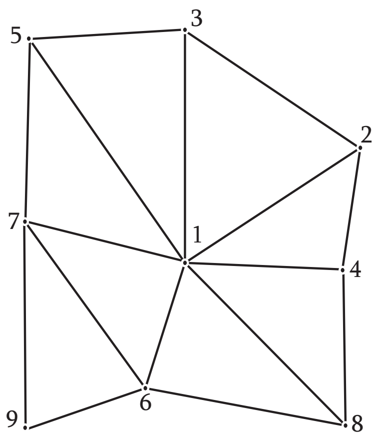


Figure 3.3 With unstructured grids the connection of neighbouring nodes varies from point to point.

The two fundamental different classes of grid give rise to three additional subdivisions of grid types: block structured grids, overset grids and hybrid grids. These kind of grids possess to some extend the features of both structured and unstructured grids.

3.2.2 Grid requirements

With grid generation for traditional use the grid should discretize a domain or surface in such manner that the computation of physical quantities is carried out as efficient as desired. The accuracy, a component of the efficiency of the computation, is influenced by a number of grid factors. These factors are grid size, grid topology, cell shape and size and the consistency of the grid with the geometry and the solution.

Grid size and cell size

The grid size is indicated by the number of grid points, while the cell size implies the maximum value of the length of the cell edges. Grid generation techniques need to possess the ability to increase the number of grid nodes. At the same time the edge lengths of the resulting cells should be reduced in such a manner that they approach zero as the number of nodes tends to infinity.

Element shape

The elements of which the surface can be composed of can have any shape. In representing 3D objects triangular and quadrangular meshes are the most common used.

Grid organization

The grids should have some organization of their nodes and cells. This organization should identify neighbouring points and cells.

Cell and grid deformation

The cell deformation characteristics can be formulated as some measures of the departure of the cell from a standard, least deformed one. Standard elements are those with edges of equal length. The least distorted quadrilaterals are squares. Cell deformation is characterized through the aspect ratio, the angles between the cell edges and the volume or area of the cell.

Consistency with geometry

The accuracy of the numerical solution of a partial differential equation and of the interpolation of a discrete function is considerably influenced by the degree of compatibility of the mesh with the physical domain. The grid nodes must adequately approximate the original geometry, the distance between any point of the domain and the nearest grid node must not be too large. This distance must approach to zero when the grid size tends to infinity. Another requirement for consistency with the grid is concerned with the approximation of the boundary of the physical domain by the grid. There have to be a sufficient number of nodes, which can be considered as the boundary ones, so that the set of edges formed by these nodes models the boundary efficiently.

3.3 Structured grids

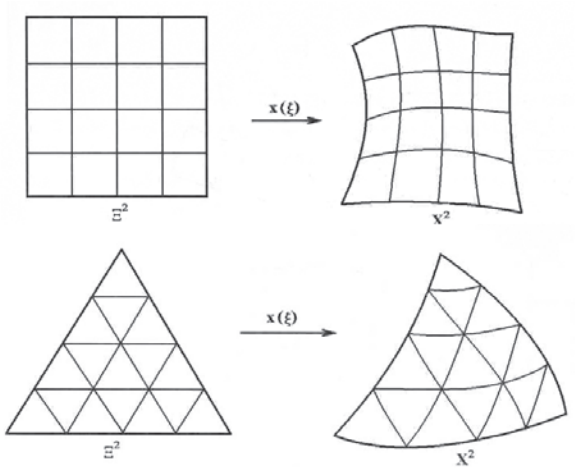


Figure 3.4 Transformation of a complex geometry X^n to a simpler geometry Ξ^n by using a parametrisation $x(\xi)$. [12]

A grid can be classified as structured, when the local organization of the grid points and the form of the cells do not depend on their position, but are defined by a general rule.

3.3.1 Boundary-confirming grids

Concept

The most popular and efficient structured grids are those whose generation relies on a mapping concept. According to this concept the nodes and cells of the grid in an n-dimensional region X^n are defined by mapping the nodes and cells of a reference grid in some standard n-dimensional domain Ξ^n with a certain transformation from Ξ^n to X^n. The domain Ξ^n is referred to as the logical or computational domain. The domain X^n is referred to as the physical domain. The idea is to choose a computational domain Ξ^n with a simpler geometry than that of the physical domain 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 complex geometry. If the computational domain and the transformation are well chosen the transformed domain should be accurately represented by a small number of equally spaced mesh points. In practice there will be a trade off between the difficulty of finding the transformation and the number of uniformly spaced points required to find the solution with the desired accuracy.

The requirements imposed on the grid and the cell size are realized by the construction of a uniform grid in Ξ^n and a smooth function $x(\xi)$. The consistency with the geometry is satisfied with a transformation $x(\xi)$ that maps the boundary of Ξ^n onto the boundary of X^n.

Method

The generation of boundary-confirming grids can be performed by a number of approaches and techniques. 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. On this basis there have been three basic groups of methods of grid generation developed:

- 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.

In the algebraic approach the interior points of the grid are commonly computed through formulas of transfinite interpolation. The simple algebraic methods enable the grid to be generated rapidly and the spacing and slope of the coordinate lines to be controlled by the coefficients in the transfinite interpolation formulas. In parts of the surface where the shape is more complicated, the algebraic approach does not give very good results. So the algebraic approaches are commonly used to generate grids in regions with smooth boundaries that are not highly deformed or as an initial approximation in order to start the iterative process of improving a grid.

For regions with arbitrary boundaries, differential methods based on the solution of elliptic and parabolic equations are commonly used. The interior coordinate lines derived through these methods are always smooth, being a solution of these equations, and thus discontinuities on the boundary surface do not extend to the region.

Variational methods are widely used to generate grids which are required to satisfy more than one condition, such as nondegeneracy, smoothness, uniformity, near-orthogonality or adaptivity, which cannot be realized simultaneously with algebraic or differential techniques. Variational methods take into account the conditions imposed on the grid by constructing special functionals defined on a set of smooth or discrete transformations. A comprise grid is obtained with the optimum transformation for a combination of these functionals.

Boundary confirming grids are easy to implement and have a good accuracy. But it can be difficult to find a transformation factor for complex three dimensional shapes. There can also be problems with preserving the structured nature of the grid when doing local grid refinement.

3.3.2 Translational grids

The translational surface is generated by translating any spatial curve, the generatrix, over another random spatial curve, the directrix. Surfaces generated with this technique are covered with a planar quadrangular mesh. Subdividing the directrix and generatrix equally results in a grid with constant length and planar mesh.

For elements, generated with this method, this means that the elements all have the same size but the elements are not equally shaped. Varying the element size can be done by varying the generatrix's distances sliding over the directrix. This method is only suitable to generate a grid configuration for geometrical defined surfaces, that are generated by translation, rotation or ruling.

3.3.3 Isotope technique

With this method the shape or the surface is 'sliced' in plural directions by parallel curves, with a certain mutual distance. When the surface is sliced in two or three perpendicular directions quadrangular elements are formed by these curves. These elements are the final elements of the generated grid. The shape and size of the elements can be varied by changing the mutual distance between and the direction of the curves. The BMW pavilion 'Bubble' build for the IAA '99 in Frankfurt is an example of a structure were the isotope technique is used to generate a grid in three directions

This method is a suitable for the segmentation all types of free form surfaces. The result is a structured an regularly organised grid. There only is no optimization of the grid possible and the elements do not always have a good, optimal shape. When the free formed surface does deviate a lot this method generates a grid with a large variation in elements size. In the case that the surface is curved over more than 180 degrees the grid generation method will give two intersection points with the surface.

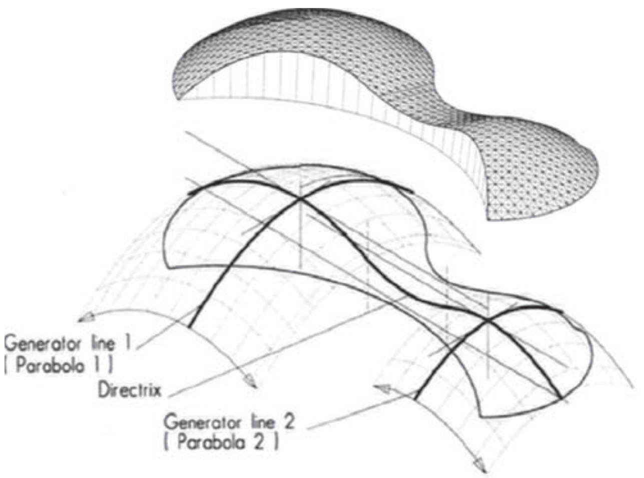


Figure 3.5 Translational surface, generated by one directrix an two generatrixes, of the Berlin Zoo Hippo house. [39]

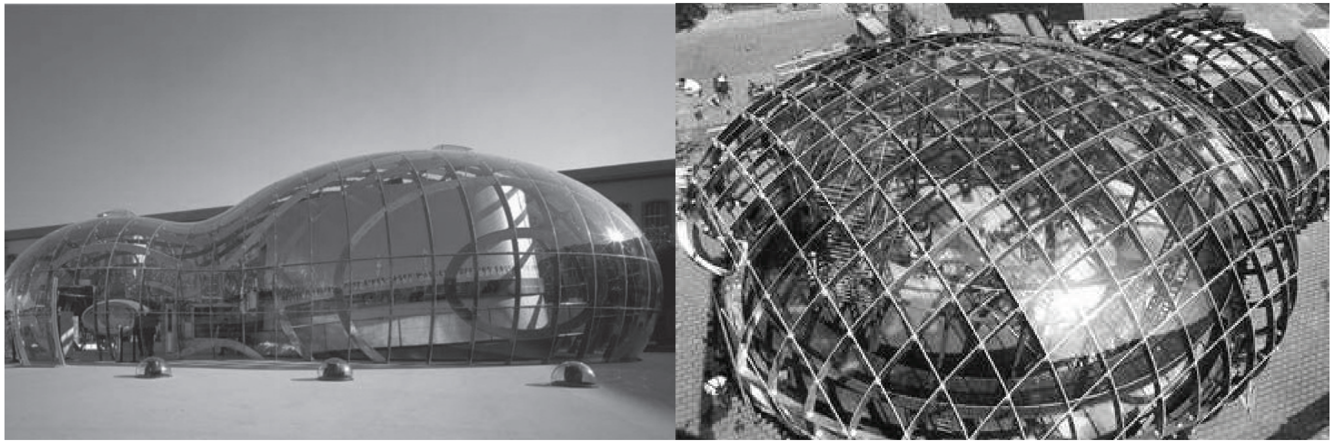


Figure 3.6 Isotope technique used for the BMW pavilion 'Bubble'. [54]

3.4 Unstructured grids

Many free formed surfaces have a complex geometry that is not easily represented by structured grids. Structured grids lack the required flexibility and robustness for handling complex surfaces, and the grid cells may become too skewed and twisted.

Unstructured grids can be a solution for the problem of producing grids in regions with complex geometry. An unstructured grid can have irregularly distributed nodes and their cells are not obliged to have one standard shape. Beside this the connectivity of neighbouring grid cells is not subject to any restrictions, the cells can overlap or enclose each other. Unstructured grids provide the most flexible tool for the description of a shape's geometry by a mesh.

Unstructured grids allow an instinctive approach to local adaptation, by either insertion or removal of nodes. Cell refinement in an unstructured grid can be accomplished locally by dividing the cells into smaller ones. Unstructured grids also allow deleting grid cells in regions where the geometry is not that complex.
Unstructured grids can be obtained with cells of arbitrary shape, but are generally composed of triangles (2D) or tetrahedrons (3D). There are fundamentally three approaches for the generation of unstructured grids; octree approach, Delaunay procedures and advancing-front techniques.

3.4.1 Octree approach

In the octree (3D) or quadtree (2D) approach the domain of the object is first covered by a regular Cartesian grid of cubic shells (3D) or squares (2D). Considering the two

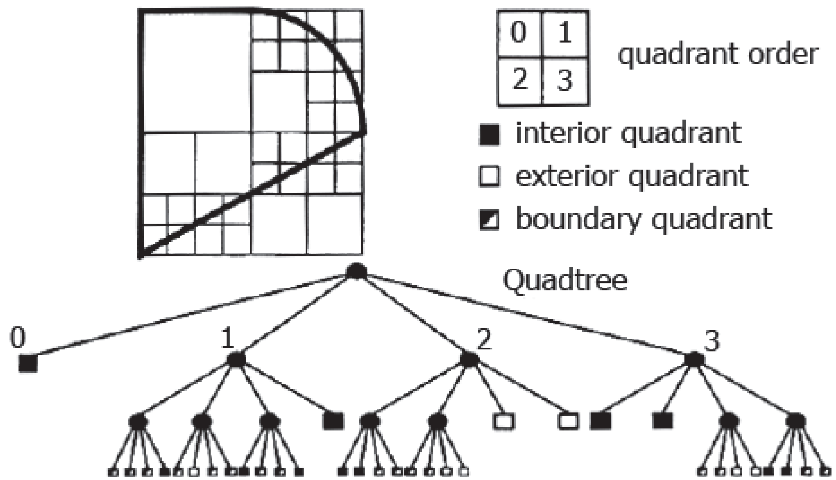


Figure 3.7 Example of the octree approach. [23]

dimensional case the square is subdivided into four equal quadrants. Each quadrant is examined to determine if it is subdivided based on the given subdivision criteria. A common used subdivision criteria is to refine the cell if it contains any of the boundary of the object. This subdivision is repeated until the subdivision criteria are satisfied throughout the domain. This subdivision process defines a tree structure where the nodes in the tree correspond to rectangles at a particular point in the process.

There are a variety of options available to create elements once the tree has been defined. The tree cells that are interior to the domain of the object are meshed with procedures that take specific advantage of the simplicity of the cell's topology and shape, and use the knowledge of the tree structure to determine the influence of neighbouring cells on the mesh within the cell of interest.

Meshing of the cells that contain portions of the boundary of the object is a more complex process. There are different methods for meshing the boundary cells of the grid:

- Apply an element removal procedure starting from a basic cell level boundary representation.
- Development of a Delaunay triangulation based on the mesh vertices of the cell level boundary representation, which is followed by an algorithm that ensures that the resulting surface triangulation is topologically compatible and geometrically similar.
- Creation of tetrahedral elements from a given surface triangulation using an element removal procedure.
- Creation of hexahedral elements to fill the region between the interior cells and the model boundary.

The first two procedures operate strictly accounting for the intersections of the model and cell boundary entities, they are vulnerable to small, poorly shaped elements caused by boundary cells that just touch the model boundary. The last two procedures create elements in the region between the model boundary and interior cells without strict adherence to the boundary formed by the interior octants. Therefore they are not susceptible to the creation of poorly shaped elements caused by the boundary cells that just touch the model boundary.

The octree approach is a good method to develop an unstructured mesh over a free formed surface. The main drawback of the octree approach is the inability to match a prescribed boundary surface grid, so the grid on the surface is not constructed beforehand as desired but is derived from the irregular volume cells that intersect the surface. Another drawback is its rapid variation in cell size near the boundary. Since each surface cell is generated by the intersection of a hexahedron with the boundary there arise problems in controlling the variation of the surface cell size and cell shape.

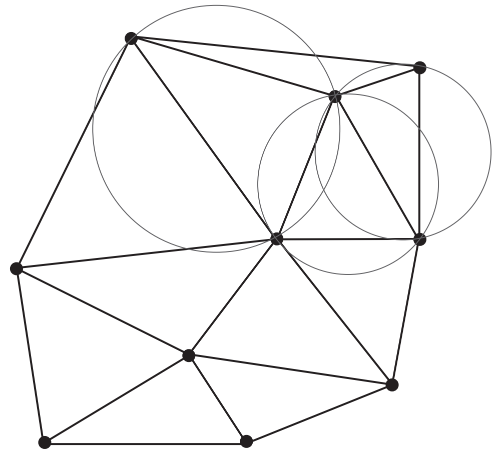


Figure 3.8 Delaunay triangulation with empty circumcircles.

3.4.2 Delaunay approach

The Delaunay approach connects neighbouring points, of some specified set of nodes in the region of the shell surface, to form tetrahedral cells in such a way that the circumsphere through the four vertices of a tetrahedral cell does not contain any other point. This definition is valid for a three dimensional application. For a two dimensional approach, the Delaunay triangulation, the definition reduced to no points within the circumcircle through the three vertices of the triangular cell.

There are several ways of generating an unstructured grid based on the Delaunay criterion. The three most common used are discussed below.

Voronoi Diagram

For a random set of points the Voronoi diagram marks off the region of space that lies closer to each point than the other points. In Figure 3.9 the lines show the Voronoi diagram, forming a tessellation of the space surrounding the points. Each Voronoi tile (hatched area around P) consists

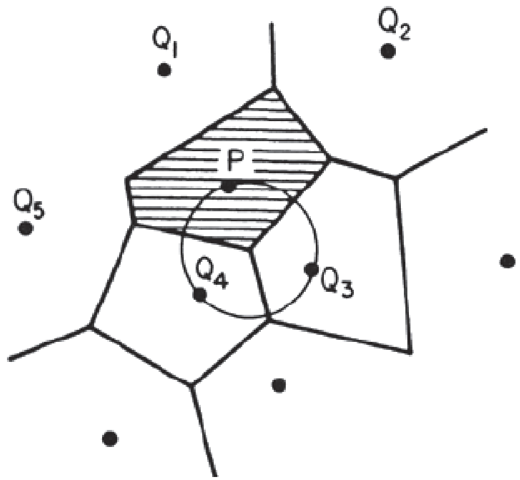


Figure 3.9 Voronoi diagram. [23]

of the region of the plane that is closer to that point than to any other point. The edges of the tiles are formed by the perpendicular bisectors of the lines connecting neighbouring points. Each vertex of the Voronoi diagram is the circumcentre of the triangle formed by three points. This unique triangulation is the Delaunay triangulation and is such that the circumcircle through each triangle contains no points other than its forming points.

Problems with this approach can rise in the triangulation procedure when three points of a potential triangle lie on a straight line or when four or more points are cyclic. These cases van be eliminated by rejecting or slightly moving a point that causes the problem.

Bowyer-Watson Algorithm

The Bowyer-Watson algorithm is an incremental technique that triangulates a set of points in accordance with the requirement of the Delaunay triangulation. The algorithm starts from some initial triangulation. This initial triangulation commonly consists for a two-dimensional domain of a square divided into two triangles which contain the given points.

To obtain a Delaunay triangulation, the following algorithm is followed:

- A new grid node is added to the triangulation, chosen from a given set of points or is found in accordance with some user-specified rule to supply new vertices.
- All the existing cells whose circumcircle contain the new grid point are identified.
- The found cells are removed, which creates a convex cavity, the so called Delaunay or inserting cavity.
- A new triangulation is formed by joining the new point to all the boundary vertices of the inserting cavity.

This algorithm is repeated until the necessary requirements for grid quality have been satisfied.

Edge-swapping algorithm

The edge swapping algorithm makes use of the equiangular property of a Delaunay triangulation, which states that the minimum angle of each triangle in the mesh is maximized. [12] Assuming there is some triangulation of a given set of points, the swapping algorithm transforms

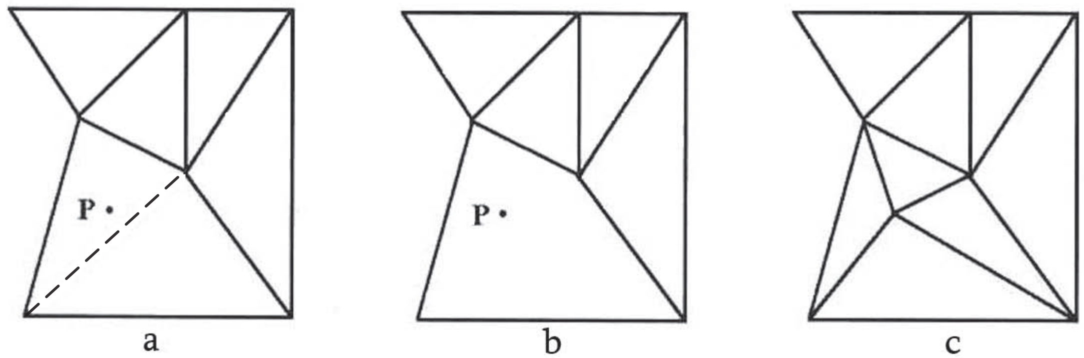


Figure 3.10 Different stages of the Boyer-Watson algorithm. In the first stage (a) a new grid node is added and the cells whose circumcircle contain this point are identified. In the next stage (b) the found cells are removed and in the last stage (c) a new triangulation is formed. [12]

it into a Delaunay triangulation by repeatedly swapping the positions of the edges in the mesh in accordance with the equiangular property. For this purpose, each pair of triangles which constitutes a convex quadrilateral is considered. This quadrilateral produces two of the required triangles when one takes the diagonal which maximizes the minimum of the six interior angles of the quadrilateral, as shown in Figure 3.11. Each time an edge swap is performed, the triangulation becomes more equiangular. The end of the process results in the most equiangular triangulation.
The minimum angle of each triangle in the mesh is maximized. This has the advantage that the resulting mesh is optimal for the given point distribution, in that there are usually not many extremely skewed cells.

Insertion of new points

All Delaunay triangulation methods assume that the points to be triangulated are already known. These methods thus only address half of the grid generation problem. There are two approaches for sequential point insertion which provide a refinement of planar Delaunay triangulations. For both methods some measures of the grid quality, such as the minimum angle, the ratio of maximum to minimum edge length, and the ratio of circumradius to inradius, are used to generate new points. The approaches are:

- Point placement at the circumcentre of the maximum triangle; A simple but effective approach that consists in placing a new point at the circumcentre of the cell with the largest circumradius and iterating this process until the maximum is less than some prescribed threshold.
- Voronoi-segment point insertion; This approach consists in inserting a point along a segment of the Voronoi tessellation. This technique provides an opportunity to generate one or possibly several new triangles having the prescribed size of the final grid.

Evaluation

The Delaunay triangulation is very popular in practical applications because Delaunay triangles are nearly equilateral. Beside this the maximum angles are minimized and the minimum angle is maximized. These properties give some grounds to expect that the grid cell of a Delaunay triangulation are not too deformed.

A major drawback of the Delaunay triangulation are the problems that arise with describing fixed boundaries or edges. To overcome this disadvantage some grid generation approaches of constrained triangulation are developed. In the first approach the Delaunay property is overridden at points close to the boundaries and consequently the previously generated boundary grid remains intact. In the second, the points are added in the form of a skeleton to ensure that breakthroughs of the boundary do not occur. The last method is to recover the boundary edges which are missing during the process of Delaunay triangulation, after the triangulation is completed.

3.4.3 Advancing-front technique

With the advancing front technique the grid is generated by building cells progressively one at a time and marching from the boundary into the volume by successively connecting new points to points on the front until all previously unmeshed space is filled with grid cells. [12] Such a procedure allows an unstructured grid to be generated automatically from a surface representation of the complex geometry. The advancing-front technique needs some initial triangulation of the boundaries of the geometry, this triangulation forms the initial front. The marching process includes the construction of a new cell, which is built by connecting either some points on the front or connecting a newly inserted point with the vertices of a suitable face on the front.

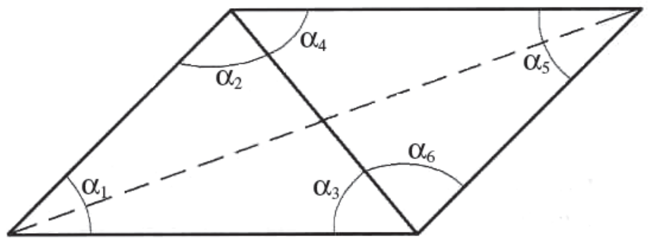


Figure 3.11 Triangulation which maximizes the minimum angle of the interior angles of the quadrilateral. [12]

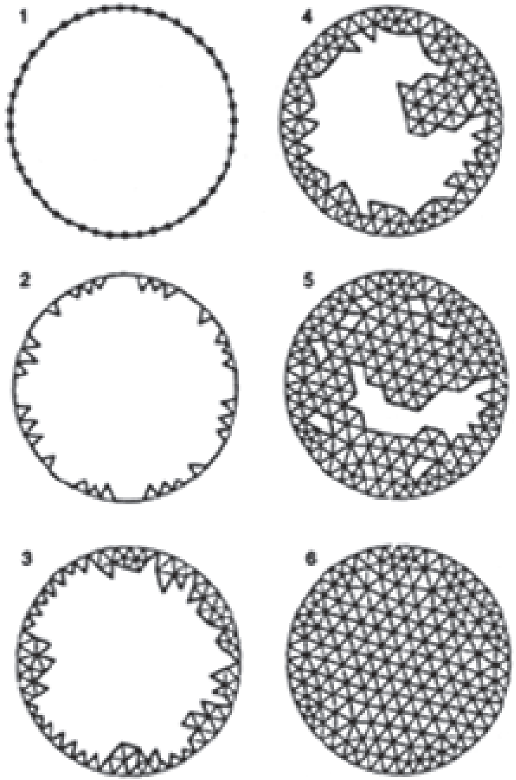


Figure 3.12 Different stages of the advancing front technique. [23]

To generate cells with acceptable angles and lengths of the edges, the advancing front method requires a preliminary specification of local grid spacing and directionality at every point of the computational grid. The spacing is described by defining two orthogonal directions (for 2D) together with a length scale for each direction. The procedure proceeds by listing all faces which constitute the front and then selecting an appropriate edge on the front. The choice of the edge is very important, since the quality of the grid may be affected by this choice. The face where the grid spacing is the smallest is selected. A collection of vertices on the front which are appropriate for connection to the vertices of the selected face to form a tetrahedron is searched. A new point is created which is consistent with the ideal position determined from the background information about grid spacing and directionality. Each sequential tetrahedron formed by the face and the ordered points is then checked to find out whether it intersects any face in the front. The first point which satisfies the test and gives a tetrahedron of good quality is chosen as the fourth vertex for the new tetrahedron. The current triangle is then removed from the list of front faces, since it is now obscured by the new tetrahedron. This process continues until there are no more faces in the list of front faces and until the domain is fully meshed.

The advancing front technique offers the advantage of high-quality point placement and integrity of the boundary. The efficiency of the front advancing process largely depends on the arrangement of the grid points in the front, especially at sharp corners. If large variations in grid spacing are present, grid generation by the advancing front method can become problematic. The advancing front technique is quite complex and therefore time consuming, due to the need for searching nearby nodes and edges and the complex intersection checking.

3.5 Composite grids

With the composite grid generation strategy the geometric complex region division is divided into a few contiguous sub-domains, which can be considered as the cells of a coarse unstructured grid. After this subdivision, separate structured grids are generated in each sub domain. Combining these local grids, a mesh will be acquired that is referred to as a composite grid. The grids are locally structured at the level of the individual blocks, but globally unstructured when considered as a collection of blocks. This strategy allows that the most appropriate grid configuration can be applied in each region.

The generation of the composite grid is a combination of the earlier described structured and unstructured grid generation techniques. For composite grids the main challenge is to connect the different structured grids in such a way that the geometric complex surface is efficiently described. The three methods that are most common are block structured grids, overset grids and hybrid grids.

3.5.1 Block structured grids

A common idea in a block structured grid technique is the use of different structured grids or coordinate systems in different regions, allowing the most appropriate grid configuration to be used in each region. Grids of this kind can be considered as locally structured at the level of an individual block, but globally unstructured when viewed as a collection of blocks. Block structured grids are considerably more flexible in handling complex geometries than structured grids. However the generation of the block structured grids may cost considerably more time and user interaction than the single block structured grid. The main reason for using multiblock grids rather than single block grids are:

- The geometry of the free formed surface is complicated. It has for example multiple connected boundaries, cuts and cavities.
- The free formed surface can be divided into sub domains in which the properties of the surface are similar. Different layouts of a structured grid are required to adequately describe the complex surface.
- The free formed surface behaves in a non uniform way, zones of smooth and rapid variation of different scales may exist.

The requirement of mutual positioning or communication of adjacent grid blocks can also have a considerable influence on the construction of locally structured grids and on the accuracy of the approximation of the free formed surface by the grid. There are several ways of connecting the different blocks. The coordinate lines defining the grid nodes of two adjacent blocks do not need to have points in common. The blocks can also be joined smoothly or non-smoothly. If the coordinate lines do not have to join this considerably simplifies the algorithm for constructing the grid in a block. If a smooth transition is desired this causes serious difficulties for structured mesh generation.

The choice of the topology in a block depends on the geometry of the computational region and the choice of the transformation of the region into the block and has a considerable influence on the quality of the grid. There are two ways of specifying the computational region for the block:

- As a complicated polyhedron which maintains the schematic form of the block sub-domain.
- As a solid cube or a cube with cuts.

With the first approach the problem of constructing the coordinate transformation $x(\xi)$ is simplified and this method is often used to generate a single block grid in a complicated domain. The second approach is based on a simple geometry of the computational domain but requires a complicated transformation $x(\xi)$. The choice of the grid

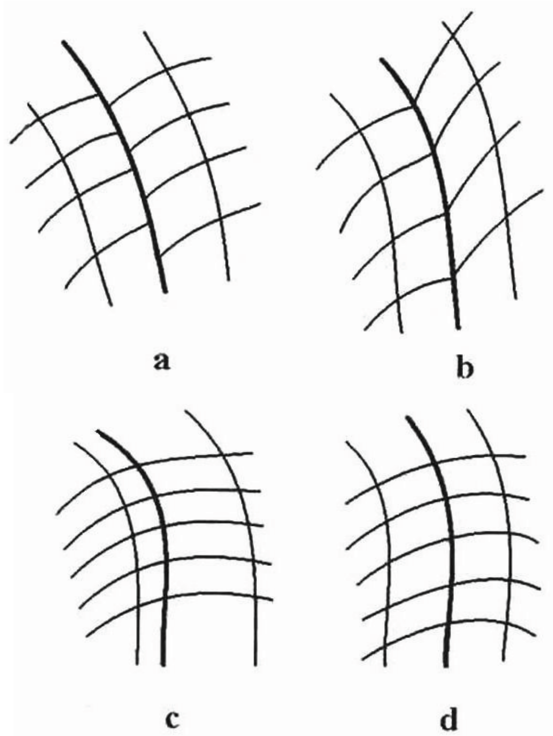


Figure 3.13 The different types of connection between contiguous blocks in a block structured grid; a) discontinuous, b) & c) non-smooth, and d) smooth. [12]

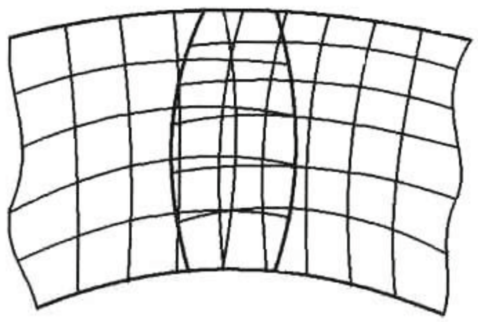


Figure 3.14 Example of an overset grid. [12]

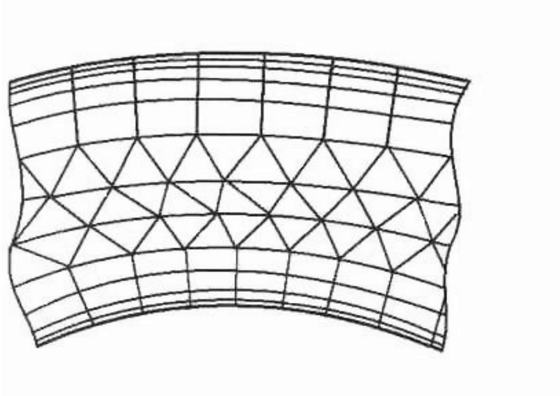


Figure 3.15 A fragment of a hybrid grid. [12]

topology in a block depends on the structure of the solution, the geometry of the domain and on the topology of the grid in adjacent blocks, in case of continuous or smooth grid lines. For complex geometries it is difficult to choose the grid topology of the blocks, because each block in the surface has its own natural type of grid topology, but these topologies are often not compatible to each other.

3.5.2 Overset grid

The partition of block structured grids into different domain has the restriction that the different blocks have to be adjacent to each other. Overset grids are released from this restriction and the different blocks are allowed to overlap each other. The global grid is obtained as an assembly of structured grids which are generated separately in each block. These structured grids are overset on each other with data communicated by interpolation on overlapping areas of the block.

The fact that the blocks are allowed to overlap significantly simplifies the problem of the selection of the blocks covering the surface geometry. But for generating a grid over a free form surface the overset grid approach seems to be unfit, due to the overlapping areas of the grids.

3.5.3 Hybrid grids

Hybrid numerical grids are meshes which are obtained by combining both structured and unstructured grids. These grids avoid the problems with overset grids by replacing the overlaid regions with an unstructured grid connecting the structured grids. Hybrid grids are formed by joining structured and unstructured grids on different parts of the region or surface. A structured grid is generated about each chosen boundary segment These structured grids are required not to overlap. The remainder of the domain is filled with the cells of an unstructured grid.

This combination of grid types not only allows the benefits of both structured and unstructured grids to be attained simultaneously, but also allows high grid quality to be achieved throughout the domain due to the appropriate use of each element type.

3.6 Conclusions

- The grid generation method will be used to generate a grid over a free form surface that forms the basis of the division of the surface into elements.

- A structured grid can be used to describe any complex double curved surface, but the complexity of a surface determines the degree of suitability for applying a fully structured grid generation technique.

- The translational grid produces double curved elements that all have approximately the same size. The shape of the elements is generally not to deformed. The main drawback is that it can only be used for geometrically defined surfaces generated by translation, rotation or ruling.

- The isotope technique can also be used to describe any complex double curved surface and generates double curved elements. But the shape of the generated elements is not always optimal.

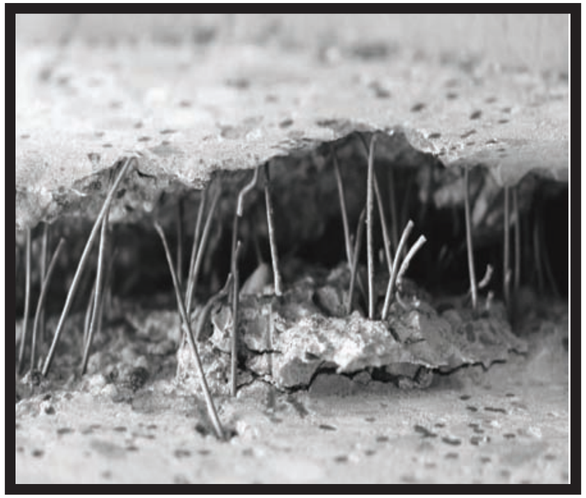
- Unstructured grids provide the most flexible tool for the discrete description of a complex geometry. This flexibility at the same time leads to the main drawbacks of unstructured grids, the grids are complex, there is no predictable organisation and the elements are not of the same size.

- Composite grids are a combination between structured and unstructured grids. This strategy allows that the most appropriate grid configuration can be applied in each region an the positive features of both structured and unstructured methods are combined.

- From a theoretical point of view it can be concluded that there is no optimal grid generation technique that results in the best grid for every surface

- The best suited grid generation technique depends on the geometry of the surface, the architectural design and the structural layout.

4. Concrete Composites



This chapter gives an overview over the recently developed concrete composites with high strength and fibre reinforcement. It also describes the possibilities and difficulties of these new composites.

4.1 Introduction

Concrete is a building material that is characterised by a good workability, freedom of design, a high compressive strength and low cost. The main disadvantages of the material are the low flexural and tensile strength, which is roughly only one tenth of the compressive strength. Tensile and bending forces in the concrete can be absorbed by an adequate reinforcement. In general steel bars are used as reinforcement. To protect the reinforcement against corrosion a minimum thickness of the concrete cover is required. This thickness varies between 20 to 50 mm and depends on the exposure class. This results in a minimum thickness of reinforced concrete elements of approximately 60-120 mm.

In slabs the reinforcement is applied in mats made out of steel reinforcing bars. When the elements are double curved this gives an extra difficulty placing the reinforcement, because the reinforcing mats have to be bend by hand in order to follow the curvature of the mould, so it is time- and labour intensive to reinforce these elements.

For prefabricated concrete shells slender and thin elements with double curvature are preferred. This kind of elements are hard to make with regular steel reinforced concrete. A solution for this might be found in fibre reinforced high performance concrete. For example textile reinforcement consisting of polymers, carbon or alkali-resistant glass fibres can be used to replace the steel reinforcement. Due to the improved corrosion behaviour these elements can be very thin and still have a high load carrying capacity.

Recently many different types of (ultra) high performance fibre reinforced concrete have been developed. In this chapter a general description of steel reinforced concrete, self compacting concrete, high performance concrete and fibre reinforced concrete has been given. In paragraph 4.6 it has been tried to describe the most important types, preferences and possible applications of fibre reinforced concrete. In paragraph 4.7 a general overview has been created whether different types fibre reinforced concrete are applicable for prefabricated shells. On the basis of this overview the best concrete composition and reinforcing method for the fabrication of concrete shells made out of double curved elements has been defined.

Figure 4.1 Curved reinforcement for a prefabricated concrete element. [20]

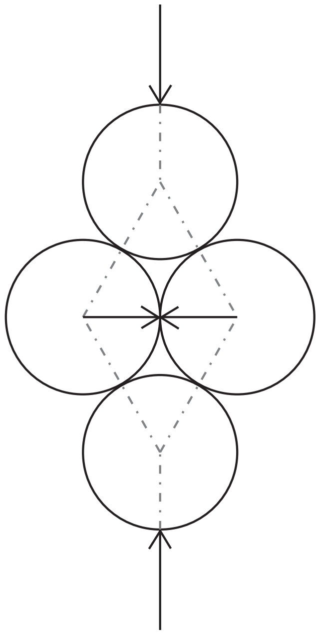


Figure 4.2 Simplified scheme of the force flow in concrete. A large compression force results in a much smaller tension force on the contact surfaces between the grains.

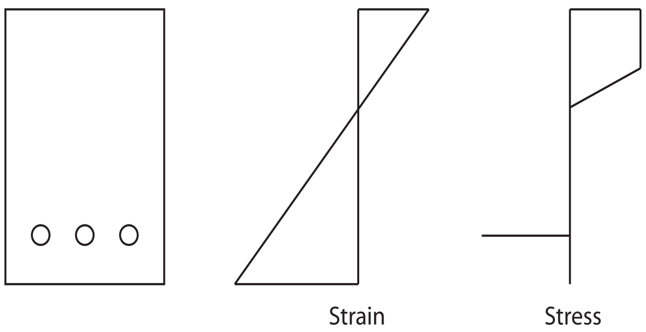


Figure 4.3 The strain and stress distribution of a reinforced concrete beam in bending show that the tension in the lower part of the beam is taken by the reinforcement and compression in the top is taken by concrete.

4.2 Steel reinforced concrete

Concrete is a hard material that is capable of taking large compression forces and consists of a mixture of cement, sand, gravel and water in the right proportions. This mixture hardens by the chemical reaction between cement and water.

The ratio in which the water and cement are mixed into the concrete influences the strength of the concrete, the higher the water-binder ratio the lower the concrete strength. The amount of water also influences the workability of the concrete mixture, more water is needed for a better workability. With a large water binder ratio not all water is used to react with the cement grains, so some water is still left in the pores of the concrete and can cause micro cracks due to shrinkage of the concrete. An optimum between strength and workability has to be found. Normally a water cement ratio of 0,4 or a little higher is used. Then most of the water can react with the cement and the mixture has still a good workability. Often a superplasticizer is added to the mixture to improve the workability of the concrete, and be able to reduce the water binder ratio.

After casting the concrete needs to be compacted with vibrating energy to let the air bubbles out of the mixture, and minimize the air that stays in the concrete.

The arrangement of the grains in the concrete makes that only a small matrix force is needed to take a large vertical force. The grains are, in normal strength concrete, the strongest part of the concrete. Failure of the concrete under compression will start at the contact surface between the additive grains and the cement stone at the moment the tension force cannot be taken any more and micro cracks develop. The micro cracks grow to macro-cracks and end up in failure of the element. This kind of failure can occur very suddenly without any warning in the form of large cracks or large deformations of the concrete.

To make the failure of the concrete less brittle reinforcement can be added, so according to the regulations always a minimum amount of reinforcing bars have to be added to prevent brittle failure.

The tension strength of normal strength concrete is very low, only 1/10 to 1/15 of the compression strength. So in most calculations the tension strength of the concrete will be neglected. In order to be able to take tension forces steel reinforcing bars are added to the concrete members. The tension force in the concrete members is almost completely taken by the steel reinforcement.

Reinforced elements are designed in such a way that the reinforcement is applied on places where tension is expected. In this way the bending moments in the element can be taken in an efficient way. When a force is applied the concrete takes the compression force and the reinforcement takes the tension force, after the development of some micro cracks. This is can be seen in Figure 4.3, where the stress and strain distribution in a reinforced concrete beam in bending is shown. The tension in the lower part of the beam is completely taken by the steel reinforcement and the compression in the top of the beam is taken by the concrete.

Due to shear forces in concrete elements diagonal cracks can occur, which can cause brittle failure if no measures are taken to prevent this. When the shear force is too large to be taken by the concrete reinforcement has to be applied. It seem logical to apply diagonal reinforcement, because in this way the cracks are crossed perpendicularly. This is however not workable in practise, so vertical stirrups are applied to reinforce the concrete for shear forces.

4.3 Self compacting concrete

Compacting concrete is a very unpleasant activity and it saves a lot time when it can be eliminated from the casting process. To improve working qualities on the site and save time self compacting concrete was developed. Self compacting concrete (SCC) is very fluid and does not require any compacting after casting. It has such a viscosity that air bubbles can migrate to the outer surface of the fresh concrete, without adding any compacting energy to the concrete. [10] Since its introduction the use of SCC is widely spread. It is nowadays used for almost all prefabricated concrete elements. Another field of application is the use on site for constructions where compacting of the concrete causes problems due to the shape of the elements, the density of the reinforcement or the accessibility of the mould.

The idea of SCC is to add a little more cement paste than necessary for good functioning of the hardened concrete. This extra cement paste forms a thin layer around the aggregate grains that makes them 'float' in the mixture. (See Figure 4.4) The thin lubrication layer around the grains decreases the shear stresses and makes the material very fluid. Because these layers are very thin they do not influence the characteristics of the hardened concrete.

Internal friction can be decreased even more by adding fine fillers and superplasticizer to the mixture. Fine fillers have a grain diameter that lies between the diameter of fine sand and the diameter of cement grains. This makes the concrete structure very dense and because of this dense packing the concrete strength will automatically be relatively high.

Self compacting concrete is also beneficial for fibre reinforced concrete elements. The fluidity of self compacting concrete can be used in the prefab-concrete industry very well to influence the orientation of the fibres in the concrete. With a controlled flow of the mixture during casting the fibres can orientate themselves in the right direction, which can also be the direction where tension forces are present in the construction. In this way the tension properties of the fibres can be optimized.

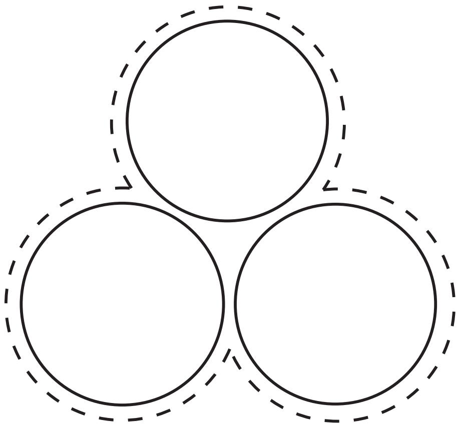


Figure 4.4 'Floating grains' in self compacting concrete. [41]

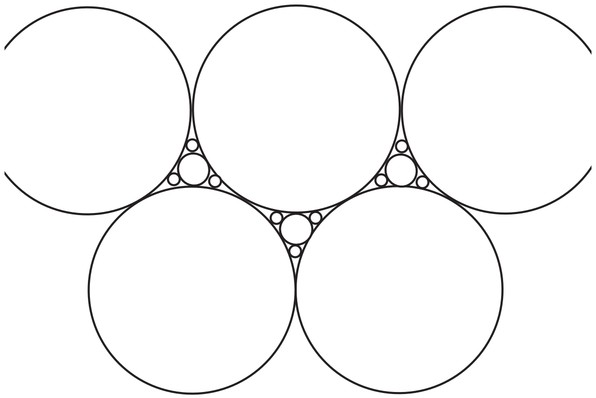


Figure 4.5 Optimal packing arrangement where each grain fills the voids between the larger grains.

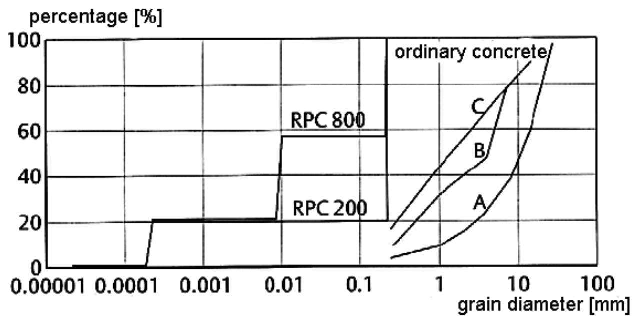


Figure 4.6 The discontinuous distribution of grain sizes of high performance concrete compared to the continuous distribution of grain sizes of ordinary concrete. [4]

4.4 (Ultra) high performance concrete

High performance concrete (HPC) is concrete with a compressive strength of at least 65 N/mm^2. When the characteristic compressive strength is more than 115 N/mm^2 the concrete is called ultra high performance concrete (UHPC). Characteristic for UHPC is the fast and high strength development and the dense structure which gives a very durable concrete. The basic principles of mixture design of (ultra) high performance concrete are described below.

Improve the homogeneity

The homogeneity of the material is improved by reducing the size of the coarse aggregates. In this way the variation in the stress in the hardened concrete is reduced. The coarse aggregates are replaced with very fine sand or stronger materials like bauxite, with a maximum size up to 8 mm.

Optimize the packing arrangement

To optimize the packing density of the mixture fine fillers, such as silica fume and fly ash, are added to fill the voids between the cement particles. This maximizes the packing density of all grains so that each class fills the voids of the larger class. (See Figure 4.5) To get an optimal mixture the distribution of the grain sizes is discontinuous and not continuous like with normal strength concrete. (See Figure 4.6) The sizes of the aggregates vary between a limited 'diameter domain', which differ in such way that the voids between the larger grain are filled by a smaller material and an optimal mixture is formed.

Reduce the water-binder ratio

In normal strength concrete a water/binder ration of about 0,4 is used. For high strength concrete the water/binder-ratio is reduced and lies between 0,12 and 0,20. In this way all the water in high strength concrete is used for the hydration of the cement. The remaining cement particles, that are not hydrated, act as fillers. To keep the mixture workable superplasticizer is added.

Addition of fibres

A negative aspect of the dense and high strength matrix is that it results in a very brittle material, with a higher brittleness than normal strength concrete. To overcome this defect and increase the deformation ability short thin fibres can be added to the concrete mixture. All ultra high performance concrete mixtures that are developed contain fibres.

Improvement of the micro structure

The microstructure can be improved by heating the structure at an optimum temperature, usually at 90 ^{0}C for two days during hardening. This enhances the pozzolanic reaction of micro silica and results in a reduction of the porosity. The porosity can be reduced even more, to almost zero, when the heat treatment is combined with the application of compression. [13]

4.5 Fibre reinforced concrete

Fibre reinforced concrete (FRC) is concrete to which fibres are added to improve the concrete characteristics. Most fibre reinforced concretes are also high or ultra high performance systems.

Fibres are most commonly discontinuous and random distributed through the cement matrix. They are not as efficient in withstanding tensile stresses as conventional reinforcement. But because they are more closely spaced than conventional reinforcement they are better in crack control and improve the ductility of the concrete. It is important to recognize that in general, fibre reinforcement is not a substitute for conventional reinforcement

Before matrix cracking the reinforcing fibres do not play a major role in the strength resisting system of the fibre composites. In fibre reinforced composites the fibres have the most important role in the post cracking zone. In this phase the fibres bridge across the cracked matrix. They can serve two functions in a well-designed composite:

1. They may increase the strength of the composite over that of the matrix by providing a mean of transferring stresses and loads across cracks. This implies an ascending stress-strain curve after first cracking and this behaviour is referred to as strain hardening.
2. They increase the toughness of the composite by providing energy absorption mechanisms, related to the debonding and pull-out processes of the fibres bridging the cracks. This occurs even when the stress-strain curve is descending after first crack (strain softening).

As cracking occurs the load is transferred to the fibres in the concrete. To prevent failure the load-bearing capacity of the fibres should be greater than the load on the composite at first crack and the bond between the fibres and the concrete should be high enough to prevent pull-out failure of the fibres. Multiple cracking is the phase when more cracks occur at a constant stress level that is equal to first crack stress. The stress-strain curve of this phase is horizontal or slightly ascending. After multiple cracking the concrete matrix is divided by parallel cracks and an additional tensile load will cause stretching or pull-out of fibres.

For continuous and aligned fibres the overall mechanical behaviour of FRC composite can be described in three stages of the tensile stress versus strain curve (Figure 4.8) by the ACK-model:

1. The elastic range;
2. Multiple cracking;
3. Post-multiple cracking.

The ACK-model is the first analytical model for the development and growth of multiple cracks in continuous fibre concrete. The actual concrete composite consists of short fibres with a nonlinear orientation trough the matrix, instead of long aligned fibres in the AKC-model, this influences the characteristics of the concrete. The efficiency of the fibre reinforcement depends on the fibre length, the fibre orientation and the fibre-matrix shear bond strength. The fibre efficiency is expressed in terms of an efficiency factor.

Different types of fibres have a different influence on the concrete properties. Long fibres have a better bonding than short fibres and can therefore have an effect on wider cracks. Long fibres can increase the ductility and bearing capacity of the concrete by bridging larger macro cracks. Short thin fibres on the other hand are better for increasing the tensile strength by bridging micro cracks in the concrete.

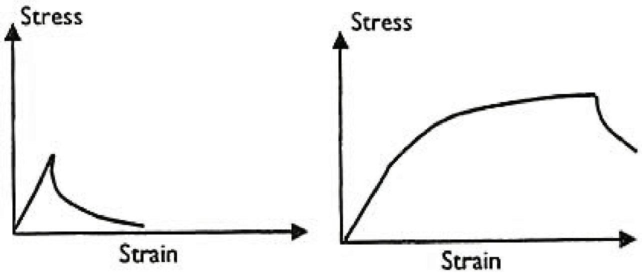


Figure 4.7 Schematic description of strain softening (left) and strain hardening (right) in tension. [1]

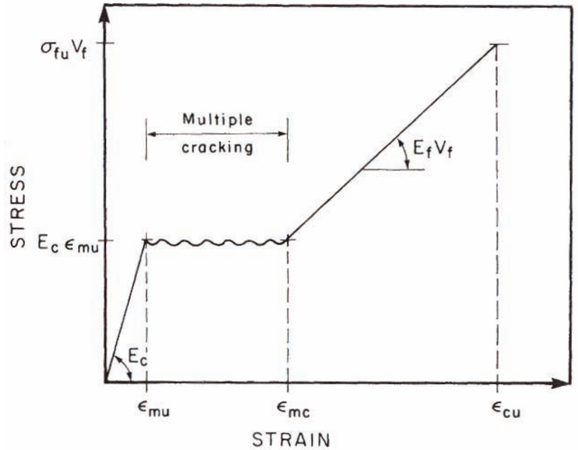


Figure 4.8 Schematic description of the stress-strain curve, based on the ACK-model. [1]

The workability of the concrete is strongly influenced by the length of the fibres. It is not possible to put a large amount of long fibres in the concrete, while this is possible for short fibres. The fibre content of short fibres can be increased up to 5 to 10 %, for long fibres the maximum fibre content is about 2,5%.

Long term performance

The special structure of fibre reinforced concrete and the characteristics of the fibres in the concrete may lead to long-term effects which are different from those of conventional concrete.

Changes in properties can be accounted for by several processes:

- Fibre degradation due to chemical attack;
- Fibre-matrix interfacial physical interaction;
- Fibre-matrix interfacial chemical interactions;
- Volume instability and cracking. [1]

Fibre degradation can result from direct attack of the fibres by the cement matrix due to a reaction with the highly alkaline pore water or from attack by an external agent which penetrates through the cement matrix into the fibre. Alkaline degradation occurs in glass fibres and natural fibres, while degradation due to penetration of external agents is more characteristic for steel fibres. The mechanisms are different, but the outcome is the same, namely reduction in strength and toughness over time.

The microstructure is sensitive to changes at the fibre-matrix interface over time. Due to continued hydration and densening of the interfacial transition zone. The influence of the micro structural changes could be particularly large in the case of thin filaments whose surface area is rather large. The bond in such systems is close to the critical bond, where transition from fibre pull-out failure to fibre fracture may occur. A result of this effect is an increase in strength and reduction in toughness over time.

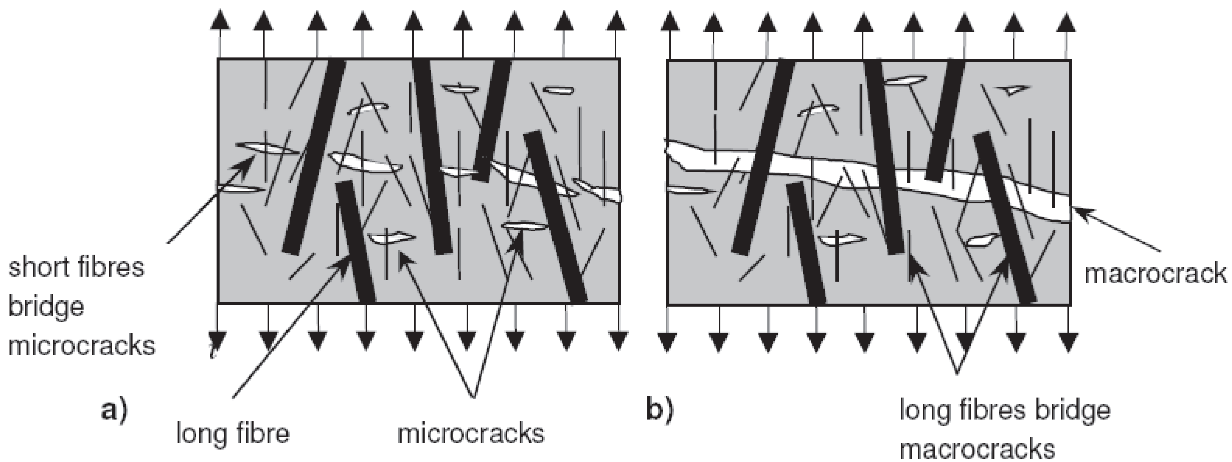


Figure 4.9 The influence of short fibres on bridging micro cracks a) and long fibres on bridging macro cracks b). [13]

Many of the long-term performance problems of fibre reinforced cement composites are not the result of changes in the composite properties, but are rather induced by volume changes in the material, due to temperature and humidity changes. [1] The change in dimensions might cause a range of problems which go beyond reduction in the properties of the material itself. In application of thin sheets of fibre reinforced cements these changes may lead to bowing and to micro and macro cracking of the panels.

4.5.1 Types of fibres

Different type of fibres can be used to reinforce the concrete. The most common applied fibres are steel fibres, glass fibres and synthetic fibres.

Steel fibres

By adding steel fibres the strength characteristics of the concrete are positively influenced. Especially the tensile strength and the ductility of the concrete are improved. The ductility of the concrete is the ability of the concrete to withstand additional loads after the formation of the first cracks. Steel fibres also have a positive influence on the fire safety of the concrete. The amount of steel fibres in the concrete varies. In ultra high performance concrete, with a compressive strength of more than 200 N/mm^2, very fine fibres are used and the amount of fibres can vary between 250 to 800 kg of fibres per m^3.
The fibre orientation cannot be controlled very accurate and the fibres are randomly distributed through the concrete. At the edges the fibres can be orientated to one side. Most fibres are orientated in the casting direction. A consequence of this random fibre orientation is that the fibre reinforcement is less effective than traditional reinforcement.

Steel fibres are available in different thicknesses, lengths and shapes. They can be made of thin or wire steel. The mechanical bonding with the concrete can be improved by creating fibres with a more complicated geometry like bends and waves.

Steel fibres corrode at the concrete surface. In practice it turned out that this has no negative consequences on the durability of the construction. The inner side of the concrete is not damaged but with visual concrete this has to be taken into account. An alternative is the use of stainless steel or thermal galvanised fibres.

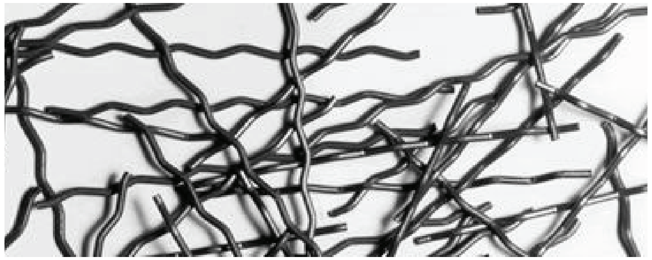


Figure 4.10 Steel fibres.

Synthetic fibres

The most used synthetic fibres are made of polypropylene. Because of the size and weight of the fibre millions of fibres are present in a cubic metre of concrete, with a normal dose of about 0,9 kg per m^3. Good fibres have some sort of coating to improve the mixing ability, to prevent air encapsulation and to improve the bonding properties of the fibres. Synthetic fibres are not visible on the concrete surface.

There are two sorts of polypropylene fibres; fibrillated fibres and monofilament fibres. Fibrillated fibres are thicker than monofilament fibres and are applied in the form of mats. Monofilament fibres are thinner, can have a curvature and are applied as single fibres.

Synthetic fibres have no influence on the strength characteristics of the concrete and cannot be used as replacement of conventional reinforcement. But they do strengthen the structure of the concrete which has the following benefits:

- Prevention of plastic shrinkage cracks;
- Improvement of the permeability of the concrete;
- Higher impact resistance of the concrete;
- Higher durability for freezing and thaw salt;
- Higher fire safety.

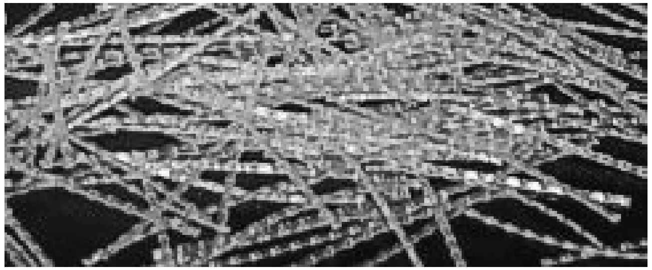


Figure 4.11 Synthetic fibres.

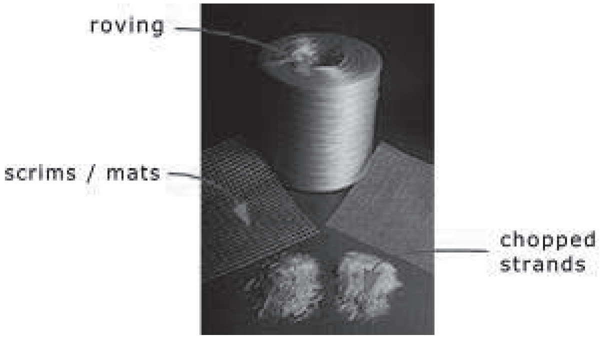


Figure 4.12 Different types of glass fibres. [56]

Glassfibre

Glassfibre reinforced concrete (GRC) composites have been developed mainly for the production of thin sheet components. The fibres add flexural, tensile and impact strength and the resulting material allows the production of strong, lightweight, products used in architectural, civil engineering and many other applications.
For the production of GRC Alkali Resistant (AR) glassfibre is used, which is essential due to the high alkalinity level in cement, which make the the long term performance of E-glassfibres is very poor. When AR-glassfibres are used the long-term performance is still a major criterion with the use of GRC.

Glass fibres are produced in a process in which molten glass is drawn in the form of filaments, through the bottom of a heated platinum tank or bushing. Usually, 204 filaments are drawn simultaneously and they solidify while cooling outside the heated tank. They are then collected on a drum into a strand consisting of the 204 filaments. Prior to winding the filaments are coated with a sizing which protects the filaments against weather and abrasion effects as well as binding them together in the strand. The fibres are used as chopped strands, roving or mats.

There are a couple different production methods for GRC, but the most common ones are hand-spray and premix. For the hand-spray method a special spray gun is used to simultaneously deposit chopped glassfibres and cementitious slurry onto a mould. After compacting, this is done by hand using a spring roller, a second layer is sprayed and compacted. Using the spray technique allows high percentages (4%-6%) of glass fibres to be used. This gives the better mechanical properties than the other technique. With the cast premix method the glass fibre is mixed into the cementitious slurry and the resulting material is poured into the mould and compacted. The mould for the premix proces can be more complex than those for the spray method. The mechanical properties are lower, due to the lower fibre content of 1,5%-3,5%, the higher water/cement ratios, the shorter fibre lengths and the 3-dimensional fibre orientation.

4.5.2 Fibre arrangements

The type of fibre arrangement can roughly be divided in two different systems; monofilament fibres or fibre mats.

Monofilament fibres

The most frequent used type of fibre arrangement is with monofilament or single fibres. The fibres are distributed trough the composite mixture. The arrangement of the fibres is pretty random and hard to control, but can be influenced by the casting direction of the concrete. The fibres also tend to align along the walls of the formwork. There is a large variety of different types and sizes of fibres that can be used. Long fibres have a larger negative influence on the workability of the mixture than short fibres.

Fibre mats

The application of fibre mats is particularly attractive for fabrication of thin elements, where cement paste or mortar is impregnated into a fabric. With fibre mats or fabrics longer fibre lengths are possible. The fibre mats can be both woven and non woven. Woven fibre mats can be made of glass or synthetic filaments, for now woven mats steel fibres can be used.

4.5.3 Production methods

The fibres can be added in different ways to the concrete mixture. Fibres reduce the workability of the concrete so a maximum volume percentage of fibres can be added to the concrete. This percentage depends among other things on the production method.

The first method is the premix process, where all ingredients are combined in a mixer and the fibres are simply treated as an extra ingredient of the cement mix. With this method a fibre content up to about 2% can be added, be-

cause the fibres reduce the workability of the mixture.
A technique, that is primarily used for glass fibre reinforced concrete is the spray-up process. Chopped glass an cement slurry are sprayed simultaneously on to the forming surface. This technique is used to produce thin sheets and a fibre content up to about 6% can be added to the concrete.

A modification of the normal shotcreting techniques can be used for steel and polypropylene fibres. This technique is good for lining of tunnels and for the stabilization of rock slopes. With shotcreting a relative high volume of fibres can be added to the mixture.

To produce dense materials with a high fibre content layers of fibres in the form of mats or fabrics can be placed in the mould. These mats are impregnated with a cement slurry and then vibrated or compressed.

Continuous production of a composite mix with special machinery can produce a continuous composite which has a thin shaped geometry. Based on the use of continuous reinforcement (fabrics, mats) in processes as pultrusion or a mix with discrete short fibres which is extruded to the desired shape.

4.5.4 Properties of fibre reinforced concrete

The properties of fibre reinforced high performance concrete differ a lot among the different types. Due to this it is hard to derive common design properties that are valid for all types. At the moment almost nothing in written about high performance and fibre reinforced concrete in regulations. In the Netherlands NEN 6720 is valid for concrete with a maximum strength of 65MPa and CUR97 is valid for concrete strengths up to B105, without steel fibres. For fibre reinforced concrete with higher strengths there are still no regulations, but the French recommendations ('Bétons fibrés à ultra-hautes performances, Recommandations provisoires', januari 2002) can be used for calculations.

Unlike conventional concrete the tensile and compressive behaviour of fibre reinforced concrete differs when it is loaded in different directions since the concrete behaviour is highly dependent on fibre directions.

Behaviour under compression

Due to the fibre bridging effect the compressive strength of the concrete is increased with about 15% when 2,5 vol.% of fibres is added. Beside this effect the fibres improve the ductility of the concrete and prevent brittle failure.

For structural calculation of HPFRC under compression a Poison's ratio of 0,2 can be used and the Youngs modulus is around 50 GPa [25]. The compressive strength can still be tested with conventional cylindrical specimen. The conventional calculation assumptions can still be used for the design calculations of HPFRC, only the turning points have to be adjusted.

Development of the compression strength in time

The result of some measurements done in different investigations [4] show that the development of the concrete strength in time is influenced by the water-binder ratio. In a concrete with a lower water-binder ratio the strength develops faster. In general it can be said that when the 28-day strength is higher the strength also develops faster. Only to high performance concrete large amounts of superplasticizer are added, which also influences the strength development. This means that the development of the strength is slowed down on the first day. The superplasticizer makes the concrete workable but also influences the strength development at the start of the hardening process.

Behaviour under tension

Normal concrete has a very low tensile strength that in some cases even can be neglected. The tensile strength of HPFRC is much higher, compared to normal concrete. The fibres have a positive contribution to the tensile strength of the concrete. The tensile strength of fibre reinforced concrete can give a significant contribution to the strength of an element under tension.

Creep

Creep is the in time increasing changes in the shape of concrete with equal loading. Creep depends strongly on the water-binder ratio, a lower water-binder ration gives less creep. In general concretes with a higher strengths (and a lower water-binder ratio) are less sensitive for creep compared to lower strength concretes. [4]

Shrinkage

There are different types of shrinkage, all with a different cause. Shrinkage can result in shortening of construction elements or micro cracks. It is found that autogenous shrinkage has the largest share in the total shrinkage. The reason for this large share can be found in the low water-binder ratio. This causes self dehydration of the concrete. Beside this the dense structure of the concrete hinders the fluid transport in the concrete. [4]
French researchers advice to take into account a shrinkage shortening of about 0,57 ‰ for BSI and 0,55 ‰ for Ductal. [4]

4.6 Types of fibre reinforced concrete

There are different types of fibre reinforced concrete developed. All of them have different contents and fibres, and because of that different characteristics. Some of them are discussed here. Considered are the composition, the characteristic and weather it is already used or possible future applications.

4.6.1 ECC

'Engineered Cementitious Composites' (ECC) are strain hardening composites with a normal strength matrix (compressive strength of about 70 N/mm^2) and a moderate fibre content of about 2% by volume. They contain synthetic fibres with a high elastic modulus that are not more than 20 mm long and have a diameter of less than 0,05 mm. A typical ECC has a tensile strain capacity of 3%-5%, with multiple cracks spaced less than 3 mm, although its tensile strength is still in a relatively normal range: between 4 N/mm^2 and 7 N/mm^2, while the PVA-fibre (Polyvinyl alcoholic fibre) content is still controlled around 2%-3% by volume [25]. The relatively short fibres with a very high length-diameter ratio allow the fibres to act both on the scale of the material and the scale of the structure. This result in a strain hardening, multi-cracking and ductile material. [34]

The very high length-diameter ratio of the fibres produces ECC that is usually highly viscous when fresh, particularly when they contain 2% or more fibres by volume. They are therefore not necessarily very easy to place using conventional techniques. The extrusion placing technique would seem preferable and ideally suited to the material, because the fibres are very flexible.

Potential application of the material are products and structural members that require noncorroding fibres and multi-cracking behaviour.

4.6.2 Slurry Infiltrated Fibre CONcrete (SIFCON)

SIFCON is produced by filling the formwork with bulk fibre and then injecting a fluid mortar slurry that coats the fibres. The fibres are usually placed manually in the formwork and then densified by vibration. With this production technique fibre volumes as high a 20% can be achieved, while workability problems in placing are avoided. With such high fibre contents it is possible to increase the flexural strength and toughness by more than an order of magnitude, compared with the unreinforced matrix or to a matrix reinforced with a low fibre volume.

The mix composition of the slurry is very important. To achieve a correct filling the slurry must be extremely liquid, with water-cement ratios very much higher than for other types of FRC. The slurry consists of cement, fine sand particles and in many cases fly ash and silica fume. To improve the flow properties usually superplasticizers are needed.

In the preparation of these composites special attention is required to avoid non-uniform fibre distribution. The orientation of the fibres can have a considerable influence on the properties. Due to the technique to incorporate the fibres the material is highly anisotropic. Because of this anisotropic structure the mechanical behaviour is also highly anisotropic.

The type and size of the steel fibres may also affect the properties of the composite. Fibres with a high aspect ratio (fibre length-diameters ratio = l/d l = fibre length d = fibre diameter) are used to improve the tensile strength of the material.

As a result of the specific mechanical and laying properties the industrial applications of SIFCON are limited. The most promising application is for paving material and

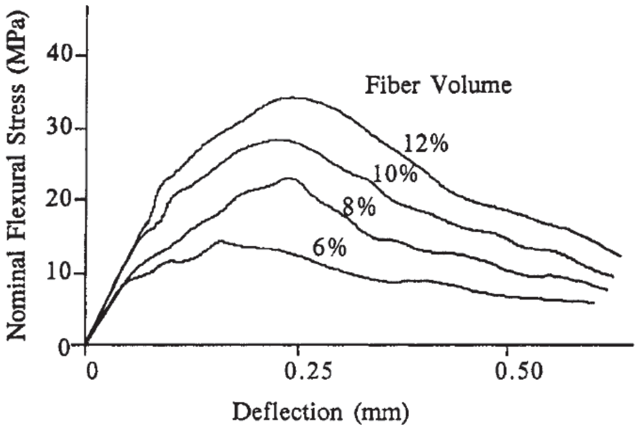


Figure 4.13 Typical flexural stress-deflection behaviour of SIFCOM. [27]

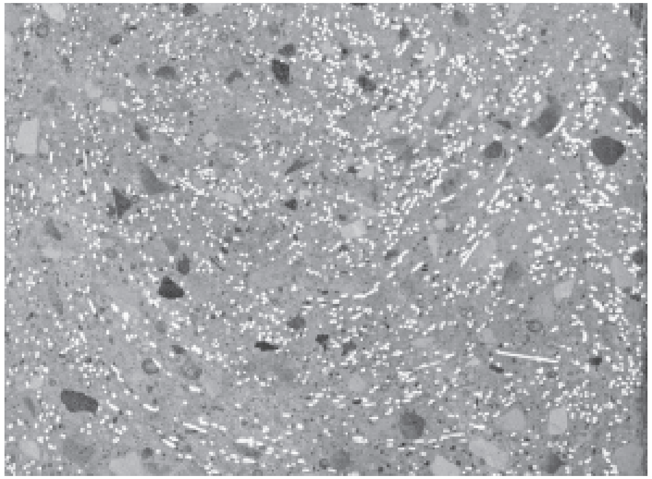


Figure 4.14 BSI/CERACEM in the hardened state, beam cross section of 125 x 125 mm. [11]

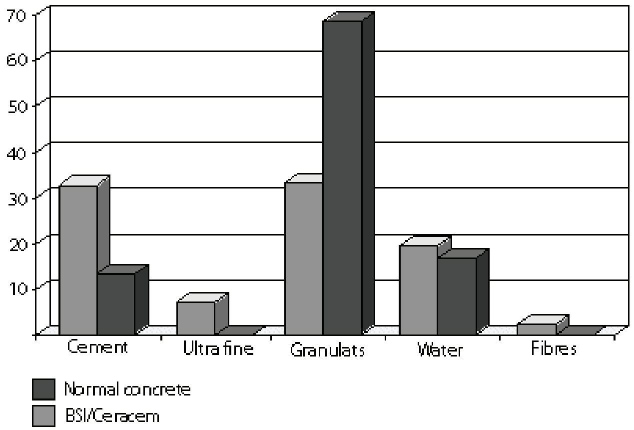


Figure 4.15 Composition of BSI/Ceracem compared to the composition of ordinary concrete. [51]

pavements. Using SIFCON it is possible to obtain industrial slab repairs as SIFCON is a multi cracking material. There have been some industrial applications of this type, but in view of the very high cost of the technique these are exceptional cases.

4.6.3 Slurry Infiltrated Mat CONcrete (SIMCON)

SIMCON is an advanced version of SIFCON, where prefabricated fibre mats are infiltrated with a highly fluid cement slurry. The steel fibres are placed in a mat. A roll of densely packed steel fibres is manufactured at a specified thickness with designed fibre volume and fibre dimensions.

With this technique higher aspect ratios are possible and the orientation of the fibres can be controlled better. Fibres with a length of 241 mm and a diameter of 0,33 mm can be used and a fibre alignment of 60-70 % can be created in the production of the mat. Due to this the fibre content can be reduced to volume fractions in the range of 3-5 % and still obtain good mechanical properties compared to SIFCON. With a fibre content in the range of 3-5 % a tensile strength of 10-16 N/mm2 possible.

The cement slurry has a water-cement ratio of 0,35. Sand and micro silica are added as a filler material and superplasticizer is added to increase the workability. Vibration, after pouring, is needed to get a thorough penetration of slurry into the steel fibre mats.

The flexural behaviour of SIMCON is characterized by multiple cracking and high ductility pattern. With increasing the actual fibre volume of SIMCON the ultimate flexural strength and toughness of the concrete are increased. As the fibre volume fraction becomes too high the improving of the flexural strength is diminished due to crowding of fibres within the composite. Crowding of fibres may also affect the slurry penetration which could have an impact on the flexural strength of the material.

A variety of application for SIMCON have been considered, but of greatest interest are the us for rehabilitation of structures, seismic resistant components, blast-resistant structures and thin precast products. A modified SIMCON system called DUCON was evaluated for floor applications. In this system the reinforcement consists of mat layers, rather than discrete fibres, allowing better control of the reinforcement as well as production of cages with cavities.

4.6.4 BSI/CERACEM

BSI/CERACEM is a commercially available mixture composed out of a patented premix developed by Sika and Eiffage. The premix is made out of Portland cement, micro silica and aggregates with a maximum diameter of 7 mm. The mixture is reinforced with straight steel fibres or synthetic fibres up to 3,5 Vol.% . The steel fibres have a round cross-section of 0,3 mm in diameter, and have a total length of 20 mm. They are normal strength steel fibres, this implies that they have a tensile strength of at least 1250 N/mm^2.

It is a self-compacting, ultra high strength mixture with an average compressive strength of 175 N/mm^2 and a bending strength of 45 N/mm^2 [51]. Lappa [11] also defined the material as strain hardening and deflection hardening.

One of the most well know applications of this concrete mixture is the toll building of the Millau viaduct in France (See Chapter 1). Other applications are the canopy roof at the Sanatorium ‘Zonnestraal’ in Hilversum (See Chapter 1), and beams for a nuclear power plant and road bridges.

4.6.5 Ductal

Ductal is developed by Lafarge, Bouygues and Rhodia. Ductal consists of a Portland cement and silica fume matrix, reinforced with either organic polymer or steel fibres, with additional fillers including wollastonite, sand and plasticizers. Its name implies that is shows a high deformation ability. Ductal is also commercially available in a pre-mixed package including the pre-mixed powders, the fibres and the admixtures and can be mixed in a normal industrial mixer.

The concrete is self-compacting in most cases, and vibration is only necessary occasionally. Ductal is adaptable to any placing technique like cast-in place, injection casting, pumping or extrusion. The product may be thermally treated after casting, the elements then are subjected to temperatures of 60 to 90 ºC for 48 to 72 hours. This heat treatment improves the mechanical characteristics of the concrete and enables speed of completion. The fineness of Ductal's raw materials and the fluidity of the mix provides a material with the ability to replicate the micro-texture of the form surface or special mould textures.

The characteristic value of the compressive strength is between 150 and 180 N/mm², when the concrete has a thermal treatment during hardening. The compressive strength of concrete without thermal treatment is only 100 to 140 N/mm². The tensile strength of Ductal varies between 5 and 8 N/mm² depending on whether the material is thermally treated. The same is valid for the flexural strength that varies respectively between 15-20 N/mm² and 30-40 N/mm². [52]
Ductal has been used for the Shawnessy light rail station (See Chapter 1). Another applications is the highway bridge in Wapello Country, IOWA, North America.

4.6.6 CEMTEC

CEMTEC$_{multiscale}$ has been developed at the Laboratoire Central des Ponts et Chausées (LCPC) and contains steel fibres with three different lengths and a total quantity of fibres of 11% by volume [37]. The idea of mixing short fibres with longer ones is that the fibres can act both at the scale of the material, by increasing the tensile strength and at the scale of the structure, by increasing the bearing capacity and the ductility. [37] The short fibres act on the micro cracks, for this a large number of small-diameter fibres is needed. To be able to act on macro cracks the fibres should be long enough to be adequately anchored in the matrix. The long fibres can increase the bearing capacity and the ductility of the material while the short fibres improve the tensile strength.

The mixture is composed out of cement, silica fume and sand. Short fibres are needed for the workability, which is strongly linked to the length diameter ratio. For the workability long fibres must be used in much lower percentages than short fibres. To improve the workability also superplasticizer is added.

From an experimental study at the LCPC it is found that the average compressive strength is 220 N/mm² and the average bending tensile strength is very high, reaching 61.5 N/mm².

The material is used for the rehabilitation of a bridge in Switzerland. According to Rossi [37] it should be possible to construct structures or manufacture structural members without reinforcement in addition to the fibres. He also thinks that CEMTEC$_{multiscale}$ is one of the most promising cement composite material able to accept this challenge.

4.6.7 Hybrid fibre concrete

Hybrid fibre concrete is developed by Markovic [13] during his PhD-thesis at the University of Technology in Delft, it is a fibre concrete that combines short and long fibres in the same mixture. The goal of combining short and long fibres is to improve both the tensile strength and the ductility of the concrete. He used short straight fibres, (fibre length = 6-13 mm) and long hooked fibres (fibre length = 30-60 mm) made of high-strength steel, with a strength f_y = 2500 N/mm².

The water-binder ratio of the concrete is 0,2. The compressive strength of the hybrid fibre concrete ranges from

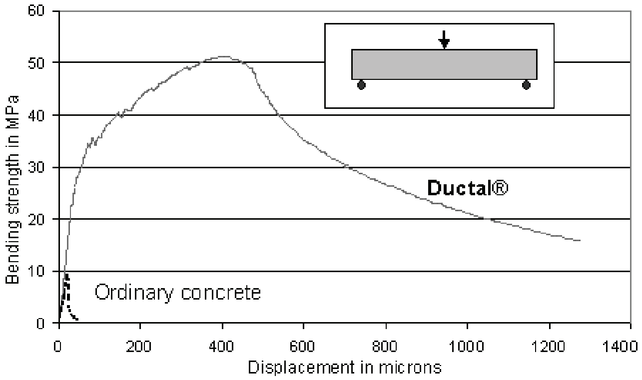


Figure 4.16 The bending strength deflection graph of Ductal compared to normal strength concrete. [52]

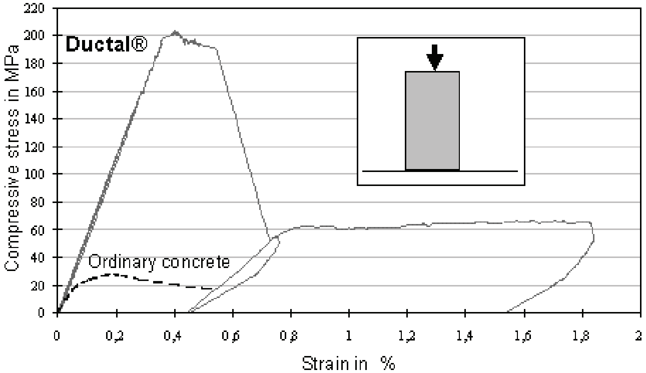


Figure 4.17 The compressive strength strain graph of Ductal compared to normal strength concrete. [52]

100 to 130 N/mm^2. With the three-point bending test a flexural strength up to 40 N/mm^2 was achieved for hybrid-fibre concrete with in total 2,0 vol.-% of short and long fibres. The maximum tensile strengths that were achieved were 10-12 N/mm^2, with the same percentage of fibres.

This concrete is not used in practice jet. But Markovic [13] did a case study in which long-span prestressed beams designed in hybrid-fibre concrete were compared to the solution in conventional concrete C55/65. It was found that the beams in hybrid-fibre concrete are 2,5 to 4 times lighter than the conventional ones and that no conventional reinforcement was needed in the hybrid-fibre concrete beams. In this way the higher material cost can be fully compensated. Beside this it is expected that the durability of the structures made with hybrid-fibre concrete is better compared to the durability of ordinary concrete structures. This can further decrease the maintenance cost for hybrid fibre concrete structures.

4.6.8 Evaluation

The aim of this chapter is to define which type of concrete composite has the best properties for the fabrication of double curved concrete elements for prefabricated structures. The requirements for optimal concrete composite are:

- The production of slender and thin elements which are smooth (double) curved has to be possible.
- No or as less as possible steel reinforcing bars should be used to reinforce the elements.
- It must be possible to cast the concrete with an adjustable formwork.
- The concrete composite should have a fast strength development so the elements can be demoulded as fast as possible after casting the concrete.
- The concrete composite should preferably be self compacting, because compacting thin elements on the adjustable formwork is difficult.

These requirements make that not all discussed concrete composites are as suitable. The discussed concrete composites will be evaluated by checking them with the requirements.

An overview of some characteristics of the different types of fibre reinforced concrete that are described in the previous paragraph can be found in Table 4.1. In this table normal strength concrete (C35/45) and high strength concrete without steel fibres (C90/105) are added.

ECC are composites of normal strength reinforced with synthetic fibres. The characteristics of this type of concrete do not differ a lot from normal concrete of the same strength. Only the tensile strength is a little higher.

SIMCOM and SIFCON are both concretes composed of a fibre mat that is injected or infiltrated with a fluid cement slurry. These mixtures have a very high fibre content and due to this the concrete mixture has to be very fluid to give a good penetration of the concrete and compacting of the concrete is needed. The mixtures are made of normal strength concrete. The characteristics make that this type is especially good for the repair of structures.

Ductal and BSI/CERACEM are both commercially available as premixed packages. These concrete mixtures are self compacting high strength mixtures reinforced with steel or organic polymer fibres. The fibre reinforcement combined with the high strength of the mixture makes that slender elements can be designed from which steel reinforcing bars are eliminated as much as possible. The mixtures Ductal and BSI/CERACEM are both already used for different prefabricated shell structures with double curved elements.

CEMTEC$_{multiscale}$ and hybrid fibre concrete are self compacting (ultra) high strength mixtures reinforced with different types of fibres in one mixture. This makes that the fibres can increase the bearing capacity, the ductility and the tensile strength of the concrete. Because of the high tensile strength the ordinary steel reinforcement can be reduced to the minimum or eliminated completely from the designed elements. These mixtures are not commercially available yet, but have promising characteristics for the use in prefabricated shell structures with double curved elements.

CEMTEC$_{multiscale}$ and hybrid fibre probably have the best characteristics for the use in double curved prefabricated concrete elements. But these mixtures are not commercially available jet an there is therefore almost no experience with the use of these mixtures in practice. Another aspect that influences the choice for a concrete mixture is the price. In general high performance concrete composites are very expensive. The concrete price increases exponentially when the compression strength is increased. Although this high price is partially compensated by the more slender and thin construction that can be made, normal or lower strength composites might also be a good, less expensive alternative. What the most optimal concrete composite is differs for each individual design, there is not a concrete composite that is the best in all cases.

		35/45 [16]	C90/105 [16]	ECC [34]	SIFCON [1],[27]	SIMCON [1], [27]	Ductal [4],[52] (no thermal treatment)	Ductal [4],[52] (thermal treatment)	BSI/CERACEM [4],[41],[51]	Hybrid fibre concrete [1], [13]	CEMTEC$_{multiscale}$ [1],[37]
Compressive strength	N/mm^2	45	105	70	-	69	100-140	150-180	175	100-130	220
Tensile strength	N/mm^2	2,2	3,5	3,7	28	14-16	5	8	-	10-12	20
Bending tensile strength	N/mm^2	-	-	-	-	29	15-20	22	17	40	60
Modulus of Elasticity	N/mm^2	30000	36667	-	-	-	45000	50000	64000	-	55000
Relative density	kg/m^3	2405	-	-	-	-	2350	2500	2800	-	2915
Water-binder ratio		0,4	-	0,45	0,26	0,35	0,2	0,2	0,14	0,2	0,2
Types of fibre				Synthetic fibres	Bulk fibre	Fibre mat	Steel fibres + wollastonite	Steel fibres + wollastonite	Straight steel fibres	2 different types of steel fibres	3 different type of steel fibres
Length	mm			20	-	240	13-15	13-15	20	6-13 and 30-60	-
Diameter	mm			0,05	-	0,33	0,2	0,2	0,16-0,3	0,16-0,2 and 0,5-0,71	-
Average fibre volume				2%	5-20%	3-5 %	2%	2%	3,50%	3%	11%(1)

Table 4.1 Characteristics of the described concrete mixtures with fibre reinforcement.
(1) The 11% fibre volume is including wollastonite.

4.7 Conclusions

- The high performance fibre reinforced concrete composites form a good solution for the use in prefabricated concrete shell structures.

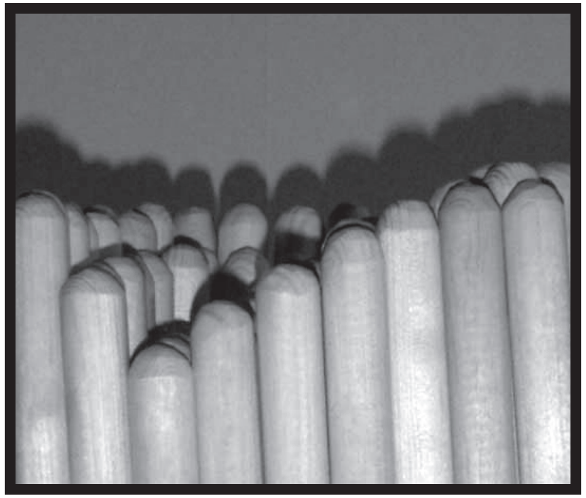
- In general it can be said that the higher the concrete strength the more expensive the concrete is. These high cost for the concrete mixture can be (partly) compensated by the more slender structures and less maintenance of the structure.

- To make the high performance fibre reinforced concrete composites applied for structures more often more research has to be done to define regulations for the design with these concrete composites.

- There are many different types of high performance fibre reinforced concrete composites that all have their own characteristics and are suitable for different applications.

- The most recently developed concrete composites, with different types of fibres added to it, have the best properties for the application in prefabricated shell structures.

5. Adjustable formwork



This chapter gives an overview over the development of the adjustable formwork for the production of double curved prefabricated concrete elements.

Detail of the flexible mould of M. van Roosbroek [19]

5.1 Introduction

In the sixties of the previous century Renzo Piano invented an innovative solution for the construction of a free form shell structure. A scale model of the shell should be placed in a machine that determined the height of each point. These measured heights are electronically transferred to a system of vertical pistons. The system enlarges a part of the shell a specified number of times and gives each piston the right height. The mould, formed by placing a flexible mat on the pistons, could be used for the construction of polyester elements. This system was never really used, because at that time the force analysis of this type of shells was not possible.

Most developments of an adjustable formwork for the construction of double curved elements are based on the principle of Renzo Piano. The forms are all composed of vertically adjustable pistons. The main difference between the different moulds is the distance between the pistons and the type of cover that is placed on the pistons.

Beside the use of an adjustable formwork there are some other methods that can be used to produce double curved elements. One of these methods is a milled formwork. This type of formwork is only economical when the form can be re-used several times, what is not possible in most cases. This method and other possible methods are not considered in this thesis, because the adjustable formwork is expected to be the best way to improve the production process of prefabricated concrete shells.

This chapter discusses different adjustable moulds that are developed in the past and that are in development at the moment.

In paragraph 5.2 the system developed by H. Jansen [10] for the fabrication of double curved glass fibre reinforced plastic facade elements is discussed. In this mould the pins are placed not to close to each other and wooden strips covered with a rubber mat are used to form the smooth curvature of the mould.

M. van Roosbroeck [18] developed a mould for the production of double curved concrete elements. In this formwork the pistons are placed close to each other and are covered with a flexible layer in order to create a smooth surface. This formwork is discussed in paragraph 5.3.

The two moulds that are described in paragraph 5.2 and 5.3 are not build at full scale. Only some test were done with small scale models of which the shape has to be adapted manually. In paragraph 5.4 the moulds of D. Rietbergen are discussed. The first mould developed by him is still small but can be set up automatically with a computer program. The second mould is still under construction and is an improved larger version of his first mould.

In the last paragraph of this chapter some concluding remarks are given on the development of the adjustable formwork.

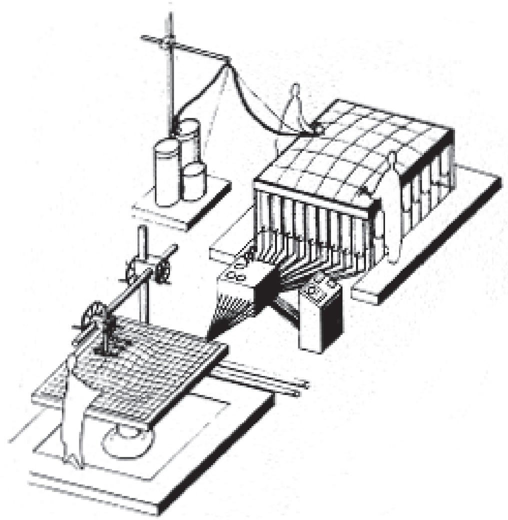


Figure 5.1 Renzo Piano's idea for and adjustable formwork for the fabrication of double curved elements. [5]

5.2 Strip mould

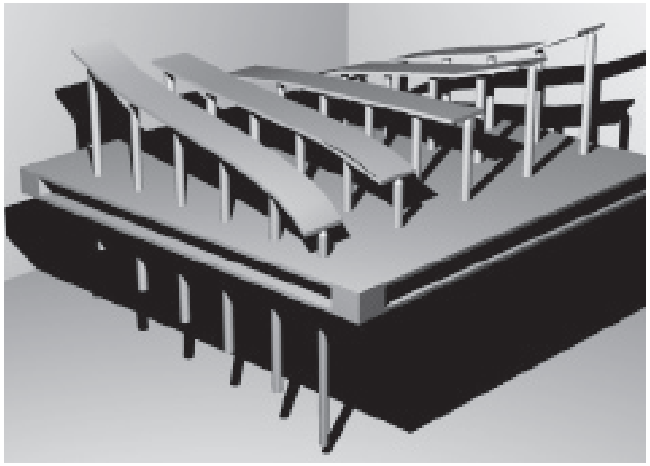


Figure 5.2 Strip mould as designed by H. Jansen with 1 layer of strips. [10]

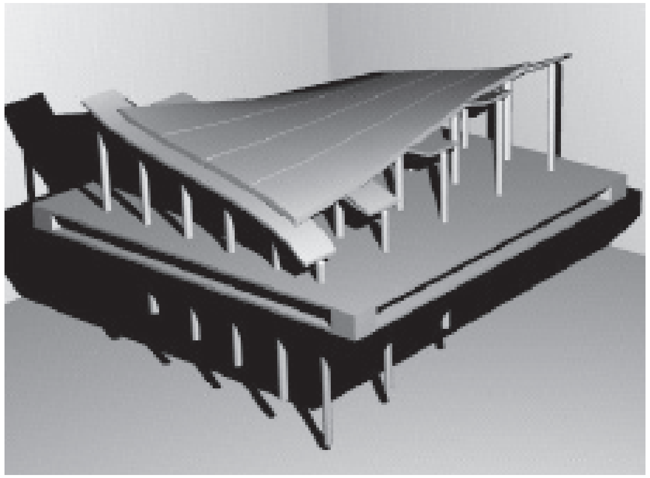


Figure 5.3 Strip mould as designed by H. Jansen. [10]

The strip mould consists of a pin bed mould covered with two layers of thin wooden strips, with a certain width. The angle between the arrangement of the two layers is 90 degrees. On top of these strips a rubber mat is placed to give the elements a smoother surface. The double curved surface is created by the interaction between the strips. H. Jansen designed a strip mould for the construction of double curved glass fibre reinforced plastic facade elements. [10] With some modifications the principle of this mould can also be used for casting concrete elements.

The pins do not need to be placed as close together as with the pin bed mould, described in the next paragraph, because the wooden strips have a higher stiffness than the rubber mat. This gives a large reduction in the number of pins that are needed for the mould. A drawback of this is that when the distance between the pins in increased the possible radii of curvature that can be made decreases, this might make the mould less flexible.
The strips have to be stiff enough to keep the deflection, under the weight of the wet concrete, between two pins as small as possible, to get elements with a smooth surface. But on the other hand a too large stiffness of the strips can cause a limited minimal curvature of the strips.

For the strip mould it is necessary to be able to adjust the tangent at the beginning and end of the strips. In this way it is possible to create a smooth transition between the different elements. This can be done with an extra line of pins or by a forced rotation of the last pins of each row. [10]

Evaluation

With this mould a continuous double curved surface can be created with a relative small amount of pins. Only the optimum has to be found between the minimization of the number of pins and the maximum curvature the mould can make. When there are too little pins not all elements can be made and the maximal curvature gives restrictions to the design and segmentation of the shells.

To create a smooth transition between the elements there has to be an extra line of pins to adjust the tangent at the edge of the elements. This makes the mould more expensive and more difficult to handle.

The strips have to be connected to the pins in such way that the connection is flexible enough to make movement of the pins possible, but not too flexible that the strips will not be pushed into a curved shape when the pins are moved.

By adjusting the pin bed a three dimensional surface is created in which the pin bed can be seen as a collection of control points. In computer program a NURBS surface could be used to represent the shape of the element. The number of control points in the computer program can not be larger than the number of pins in the mould. When that is the case it is not possible to approach the shape of the curved surface with the mould.

5.3 Pin bed mould

The pin bed mould is a mould consisting of vertical pistons which are all separately adjustable in height. The pins are covered with a flexible layer to create a smooth surface on which the concrete can be cast. This layer must have the ability to deform to the different shapes of the mould and at the same time be strong enough to stay in shape by the forces acting on the layer during the hardening of the cast concrete. The pins are small and are positioned close together to improve the quality of the produced surface.

Van Roosbroeck [19] described the flexible mould of M. Quack, this mould can produce double curved concrete elements with a maximum size of 4,5 x 3,38 m and a maximum curvature of 1.5 m. This is an open mould that can be used for the construction of double curved facade elements of glass-fibre reinforced sprayed mortar. Van Roosbroeck [18] suggested using a closed mould, with two pin bed moulds placed above each other. With this mould elements with an upper and lower curved side and a varying thickness can be created. Beside this self compacting concrete, which is more fluid than sprayed mortar can be used and is it possible to get smoother surface at both sides of the elements.

Pins

The pins have to be adjustable in height to achieve this different drive systems can be used. The type of drive systems for the pins depends on the force the pins should be able to generate to deform the flexible layer. This force depends on the type of material, the thickness of the layer and the elongation length. Other aspects that influence the choice for the drive system are the available sizes and the price of the systems.

Van Roosbroeck [19] suggested using the 'ACTIONJAC^{tm} Metric MSJ Worm Gear Screw Jacks' from Nook Industries [60]. This system can generate a high peak force ranging from 5 to 200 kN. The used jack screw driven pins have a lifting screw diameter of 15,7 mm and a maximum peak force of 5 kN. A disadvantage of this system is that the motor is placed in a cube under the lifting screw. The pins can therefore only be placed close together when the motors are not placed in one ground plane. It was assumed that a distance of 30 mm between the centres of two pins can be achieved.

Flexible layer

The material that is attached to the pins has to be strong enough to withstand the load of the concrete without any visible deformations. At the same time it must have a large enough elastic deformation capacity to make the curvature of the elements possible.

According to M. van Roosbroeck [19] a composed layer of a thermoplastic foil and a rubber layer is the best combination of materials to form the mould with. The thin layer of rubber can be stretched with a small force and follows the curvature of the pins better than a thick rubber layer. The thermoplastic softens when heated and hardens when cooled. This process is reversible and may be repeated many times. This make that the material can be deformed when heated and is strong enough to transfer the forces of the concrete to the pins without to large deformations when cooled again.

Evaluation

If the flexible mould is made in the way as described above the mould can be used to cast many different elements. Because the pins are placed close to each other, it is possible to create elements with almost any curvature. Due to the combination of thermoplastic and rubber layers the surface of the cast elements is smooth.
The combination of the upper and lower mould makes it possible to cast elements of self compacting concrete.

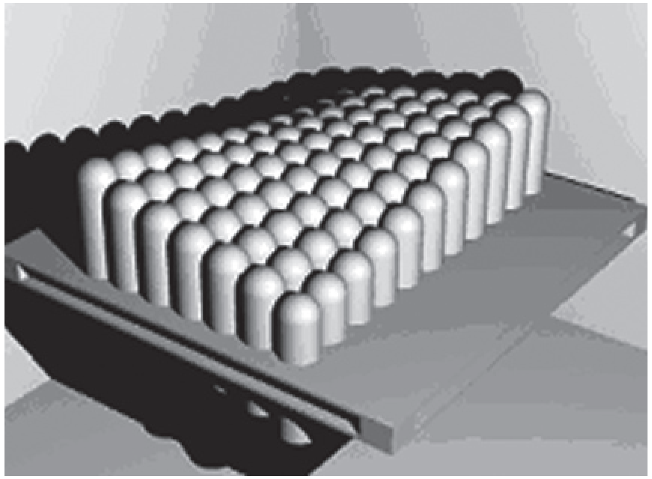


Figure 5.4 Computer model of the pin bed mould. [19]

Properties of the pin-bed mould	
Maximum length of the elements	3,00 m
Maximum width of the elements	3,00 m
Maximum height of the elements	1,44 m
Distance between to pins	30 mm
Pin diameter	15 mm
Thickness of the concrete elements	100 mm
Thickness of the rubber layer	0,5 mm
Thickness of the polypropylene layer	3,0 mm

Table 5.1 Properties of the pin-bed mould as defined by M. van Roosbroeck. [19]


Figure 5.5 Model of the pin bed mould made by M. van Roosbroeck. [19]


Figure 5.6 Concrete element made with the mould of M. van Roosbroeck. [19]

The cast elements in the closed mould are smooth and curved at both sides of the element.

But there are also some difficulties with the mould as described above. The first problem is the deformation of the thermoplastic layer. Thermoplastic materials are weak and easy to deform in a certain temperature range, for polypropylene this is about 165 °C. The thermoplastic layer has to be carefully heated to this temperature using an oven or an infrared radiator. After heating the material can be deformed using a mould in combination with air pressure or a contra-mould. After deformation the layer has to be cooled carefully. This is a time consuming process to perform for each element and not possible in the suggested configuration of the mould.

To make this mould a very large amount of pins is needed, for example a single mould of 2,00 x 2,00 m consists about 4400 pins with the suggested pin configuration. For a closed mould the double of this amount of pins is needed. This makes the mould very expensive to purchase. Beside the prize this makes the mould also very vulnerable to pin defects. When a pin is defect it is hard to reach the pin to replace or repair it.

The driving shaft of the suggested pins is placed in a box at the bottom of the pins the size of this box is about 168 x 105 mm. This mean that distance of 30 mm between the cores of the pins is hard to achieve, even when the shafts are not mounted in one plane.

5.4 Recent developments

In 2008 D. Rietbergen [41] is performing his PhD-thesis, at the Faculty of Architecture of Delft University of Technology, that also involves the development of an adjustable mould for the production of double curved concrete facade elements. For this research a small adjustable mould was build with a size of 950 mm by 950 mm, consisting of 36 pins. On the basis of the experiments performed with this mould in the end of 2008 a new larger and improved adjustable mould is being build in cooperation with Hurks beton, a Dutch company specialized in prefabricated concrete. These two recently developed moulds are the largest recent developments on the adjustable formwork and are discussed in this paragraph.

The PhD thesis of D. Rietbergen is concentrated on facade elements. This means the elements do not have a load bearing function. The elements will be mounted on the load bearing structure and only need to be able to carry their own weight and transfer the forces that act on the element to the load bearing structure. This makes it possible that no reinforcement is placed in the elements, the concrete elements are only reinforced with the fibres.
The fact that the elements are mounted to the load bearing structure and not connected to each other, makes the type of connection system that will be used different and it also influences the construction of the edges.

5.4.1 Adjustable formwork I

The size of this mould is 950 mm x 950 mm and it consists of 36 manually assembled pins. The pins can be adjusted in height by means of a computer program. This program can give each pin an assignment in the shape of a height and a speed. This assignment is stored on a chip in the pin. When each pin had its assignment the height of all pins can be adjusted at once.

The pins are mounted in six rows of six pistons. The distance between the pistons is 190 mm. There are different configurations of the pins possible. With this mould an ordinary matrix configuration is used. The pins are placed on a rail so other configurations could have been tested. This has not be done jet, because it is not assumed that a better result will be achieved with another type of configuration of the pins.

On the pins a 12 mm thick rubber layer is placed that forms the casting surface of the mould. The cover is reinforced with two perpendicular layers of springs that are placed above each other in the rubber. These springs ensure that the deflection of the rubber under the weight of the wet concrete between two pins is small enough to give the elements a smooth surface. At the same time the springs should keep the rubber cover flexible enough to let the cover take the required shape.

The cover is not fixed to the mould, this means that the rubber cannot be pulled into the required shape and the deformation of the cover has to take place through gravity. Fixing the rubber to the pins might make more shapes of the mould possible, but it also requires a better deformation capacity of the rubber cover. When the rubber is attached to each pin the deformations become very local and this might not improve the result of the cast elements.
Another problem that occurs when the rubber is not fixed to the mould is that it can move over the pins. This makes that, when the cover moves a bit before casting the cast element may not have exactly the required shape.
From the above it can be concluded that the cover has to be attached loosely to the pins, to prevent local peak stresses in the rubber and moving of the cover.

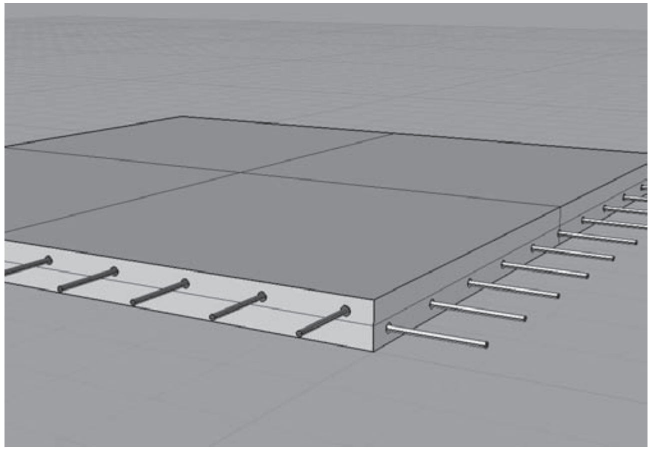


Figure 5.7 Example of the reinforcing springs placed in the rubber cover that is placed over the pins.

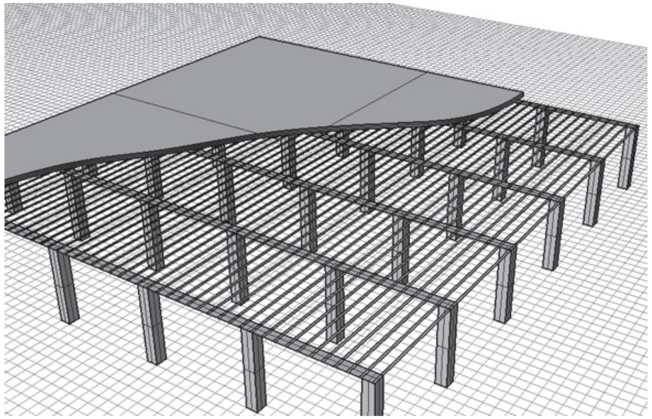


Figure 5.8 A small model that show the idea of the second adjustable mould. In one direction strips are placed on top of the pins. In the other direction a dense net of strips is placed that might be integrated with the rubber cover.

The minimal radii of curvature that are possible with this mould are found by experiment. The smallest radius of curvature that can be produced with the mould depends on the shape of the surface. With a saddle shape surface it was possible to cast an element with a minimal radius of 600 mm. With a dome shaped surface the minimal radius that was produced was 800 mm. When the mould is improved, for example by fixing the cover to the pins, even smaller radii of curvature might be possible.

For the fabrication of the test elements ECC was used. The concrete was poured out over the mould, that was already brought in the double curved shape, and levelled afterwards.

5.4.2 Adjustable mould II

In the end of 2008 a new mould is in production. This mould is being made with the help of Hurks Beton, a Dutch company specialized in precast concrete.

This mould will be larger than the first mould, at least 1,2 x 1,2 m. The distance between the pins in this mould is 40 cm. In one directions the pins are covered with a flexible strip connecting the strips in one row. In the other direction a large amount of strips is placed that are connected to each other forming a dense net of flexible strips. On top of these strips a rubber cover will be placed that should ensure a smooth surface of the concrete elements. This rubber layer might be integrated with the upper layer of strips.

Because this mould is still in production during the writing of this report no information is available about the quality and properties of the elements cast with this mould. But it is expected that at the curvatures achieved with the previous mould can also be made with this mould.

The idea is to use the mould to produce facade elements, this means that insulating the elements is necessary. To implement the insulation easily in the elements, sandwich elements, where the insulation material is placed between two layers of concrete, will be produced.
To test the mould at first 40 mm thick fibre reinforced concrete elements will be cast. When the result with the single elements are satisfying the step to sandwich elements might be made.

5.5 Evaluation

The pins

From the previous paragraphs it can be seen that the distance between the pins is one of the main variables of which a most optimal value has to be found. This distance directly influences the amount of pins that is needed for the mould and the curvatures that are possible with the mould. Indirectly it also influences the price and vulnerability of the mould. When the distance between the pins is decreased the number of pins and minimum curvatures of the elements that can be made with the mould increase. At the same time the more pins there are in the mould the more expensive and the more sensitive for failure of the pins the mould becomes.

Surface of the mould

Different materials can be used to cover the pins and form the surface of the formwork. These coverings should make sure that the surface of the elements is smooth. For the material and thickness of the cover an optimum has to be found between stiffness and flexibility. The deflection of the cover between two pins under the weight of the wet concrete has to be as small as possible, to create a smooth element. But on the other hand the cover has to be flexible to make deformation of the surface possible.

There are different types of covers discussed in the previous paragraphs. The covers can be divided in two main principles. In the first a strengthened rubber layer is placed directly on top of the pins, like with the pin bed mould. In the second principle method the rubber is not strengthened and placed on top of two layers of strips that are placed on the pins, like with the strip mould. In general both method are good, but depending on the design of the mould one of the method might be preferred above the other. The first method is better when the pins are relatively close together, when the pins are more apart the second method gives better results.

Open or closed mould

During the design of the mould the choice has to be made whether a closed double mould or a open single mould will be used.

A closed double mould consists of two flexible moulds that are places above each other. This configuration makes the mould suitable for casting elements of very fluid concrete composites or casting elements with a varying thickness. A drawback of a closed mould is that compared to the single mould the double mould is twice as high and the double amount of pins are needed. This makes the mould a lot more expensive and more difficult to handle. Beside this care has to be taken that no air that stays entrapped in mould during the casting of the curved elements.

With a single mould it is more difficult to get a perfect finishing on both sides of the element. It is not possible to use very fluid concrete composites, but the open mould is very suitable for spray casting techniques that allow a high fibre content.

From the point of view of the costs and the size of the mould it is better to use a single mould. A closed mould will be too expensive.

5.6 Conclusions

- It can be seen that the adjustable formwork is still in the experimental phase of its development. At the moment it cannot be used jet for the production of elements for a real structure. But the research does show that in the near future is should be possible to use the adjustable formwork.

- To make the adjustable formwork feasible it should be not to expensive to produce and should be re-usable many times for both single or double curved elements.

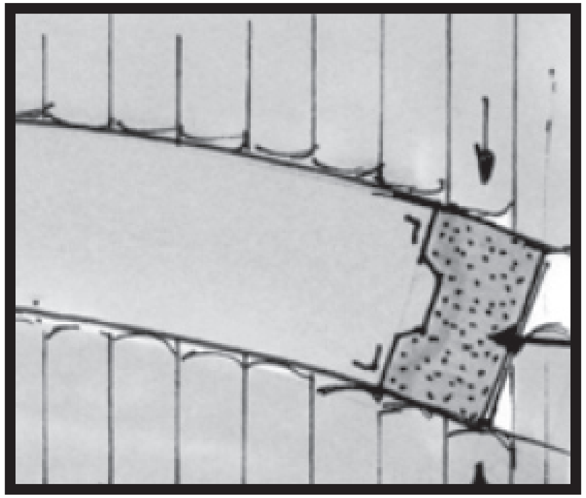
- The mould should be easy and fast adjustable in order to produce the different elements of the structure.

- The maximum size of the elements that have to produced with the flexible formwork is 3,0 x 3,0 m, but it should also be possible to produce smaller elements with the form.

- The minimal radius of curvature that should be made with the adjustable mould is 1,0 m.

- The formwork should be suitable for casting of high performance fibre reinforced concretes, possibly with some steel reinforcement bars inserted into the elements.

6. Edges and connections



In prefabricated concrete shell structures the connections between the elements are of great importance, they provide the integrity of the building. In this chapter possible connection systems and different methods to create the edges of the prefabricated concrete elements are described and evaluated.

Creation of the edge by inserting a strip in the flexible mould. [19]

6.1 Introduction

The connections in a free form structure of prefabricated concrete are important, because they need to transfer the forces in the shell from one element to another and they provide the structural integrity of the complete structure. The connections that are generally used in the prefab industry cannot be applied on prefabricated shell structures directly. So for this type of structures a new connection system has to be designed. This connection system must enable a good force transfer between the elements and the form of the connections must not hinder the construction of the shell.

The thickness of the shell gives some difficulties creating the elements. This thickness makes that in an element three different parts of the surface can be identified. These are the inner surface, the outer surface and the middle surface, see Figure 6.1. The middle surface is generally used for the structural analysis of the shell. The outer surface is used to generate the mesh for the segmentation of the surface. The inner surface combined with the outer surface are used to create the elements and form the visualisation of the actual shell. The way the inner and outer surface are connected defines the form of the edge of an element. The edges of the elements can be created in different ways. A study has been be carried out to find the best way to create the edges of the elements.

In paragraph 6.2 the creation of the edges is discussed and in paragraph 6.3 the different options for the connection system are discussed. Paragraph 6.4 gives some concluding remarks of this chapter.

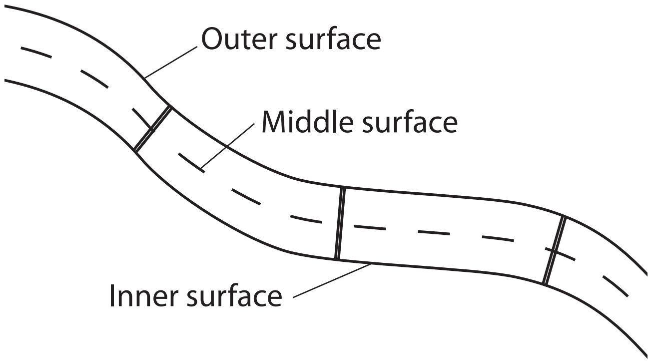


Figure 6.1 A segment of a shell with the three surfaces (inner, outer and middle) that can be distinguished.

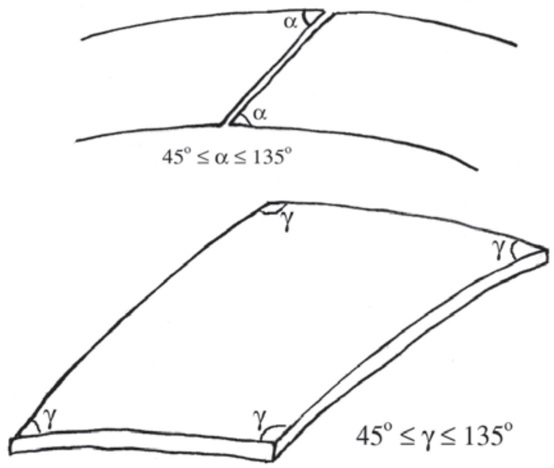


Figure 6.2 Minimum and maximum angle in the cross-section (above) and in the plane of the element (below).

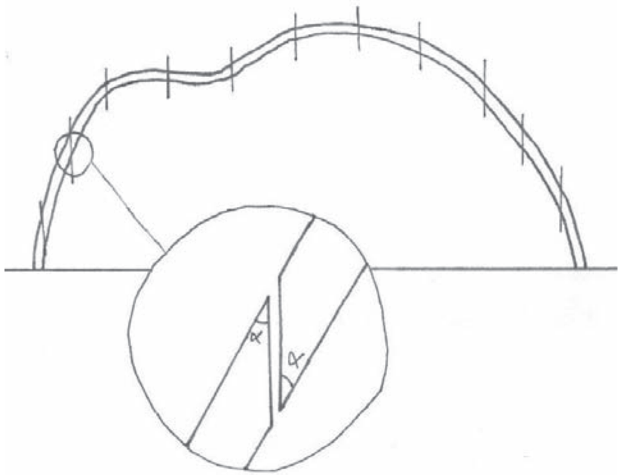


Figure 6.3 Cross-section of an example of a shells that is sliced vertical in different elements.

6.2 Edges

The shape of the edges is important for a good fit between the different elements. The fact that the elements have a certain thickness can give some difficulties with the form and creation of the edges. In this paragraph the form and creation of the edges are discussed.

6.2.1 Angle of the element in cross-section

The angle between the edges of the elements in cross-section can in theory vary between 0 and 180 degrees, but concerning the vulnerability of the elements to damage during transport and handling the sharpness of the edges is limited. The minimum angles in the cross-section is set on 45 degrees, this is thought to be an creatable angle. Angles smaller than 45 degrees are possible, but require that the vulnerable points of the elements are cast in situ after the placement of the element in the construction. Concerning the connection systems and the vulnerability during assembly it is better to approach angles of 90 degrees.

6.2.2 Angle of the element in plane

The angles between the edges of the elements in the plane of the elements can in theory also vary from 0 to 180 degrees. Here the minimum angle is set on 45 degrees, and so the maximum angle is limited to 135 degrees. This is done, because sharper angles are very vulnerable for damage during transport and handling. It is better to try to let all angles be about 90 degrees, because than the corners of the elements are the least vulnerable.

6.2.3 Form of the edges

There are different ways to cut the outer surface in order to form the edges of the elements. The methods that can be distinguished are vertical, horizontal, perpendicular and radial to the surface. Beside these standard methods combinations with or variations on those methods can be used to slice the shell in different elements. The chosen method influences the shape of the edges of the elements, the production method of the elements and construction method of the structure.

Vertical

When the outer surface of the shell is cut vertically in different elements all grid lines on the surface of the shell are crossed in a vertical direction to create the elements. (Figure 6.3) This results in corners of around 90 degrees in parts of the shell where the shell alignment is nearly horizontal. But when the shell surface is almost vertical this results in very small angles between the edges in the cross-section of the elements.

Horizontal

When the outer surface of the shell is cut horizontally in different elements all grid lines on the surface of the shell are crossed in a horizontal direction to create the elements. (Figure 6.4) When the shell alignment is almost

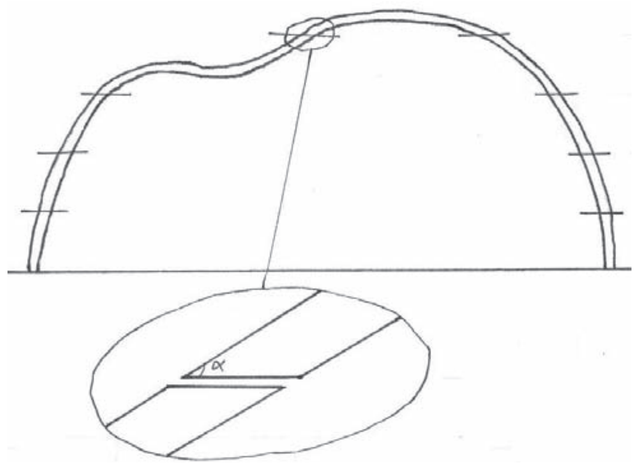


Figure 6.4 Cross-section of an example of a shells that is sliced horizontal in different elements.

vertical this type of slicing the angles between the edges of the elements in the cross-section are almost 90 degrees. But when the shell surface is nearly horizontal this type of cutting results in small angles in the cross section of the elements.

Combination of vertical and horizontal

The two methods of slicing the shell that are discussed above can be combined to improve the form of the edges. (See Figure 6.5) When a combination of horizontal and vertical slicing is used the creation of sharp angles between the edges in the cross section of the elements can be prevented. At every edge of the elements the best way, which results in the largest angle between the edges in the cross section of the element, to cut the outer surface is chosen. If for example vertical slicing results in an angle between the edges in the cross section of the element that is smaller than 45 degrees horizontal slicing must result in an angle larger than 45 degrees. In this way the angle of the element in the cross-section will never be smaller than 45 degrees.

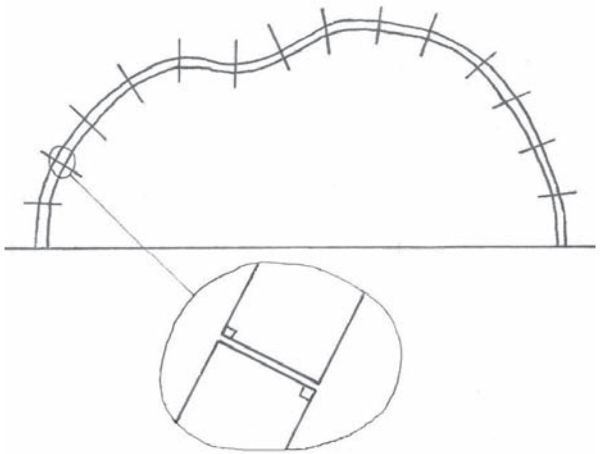


Figure 6.6 Cross-section of an example of a shell that is sliced perpendicular to the surface.

Perpendicular

The outer surface of the shell can also be cut perpendicular to the surface. This means that the shell is sliced by a surface that is always perpendicular to the shell surface. (Figure 6.6) When this method is used the angle between the edges of the element in cross-section is always 90 degrees. A disadvantages of slicing the shell in this way is that the edges of the elements can be in torsion, this means that the edges can be curved in stead of flat. (Figure 6.7) This can give extra difficulties with demoulding the elements and the construction of the shell.

Semi-perpendicular

As a variation on the perpendicular slicing the outer surface of the shell can be cut with a flat plane perpendicular to one point on the shell. The main difference with the perpendicular method is that the edge is always flat and without any torsion. The angle in the cross-section of the element will not all the time be exactly 90 degrees due to the curvature of the shell, but no too sharp angles will oc-

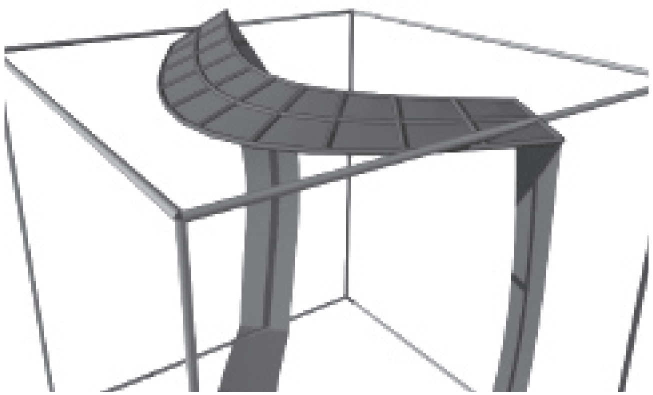


Figure 6.7 A disadvantage of slicing a shell in perpendicular is that the edges are under torsion. [5]

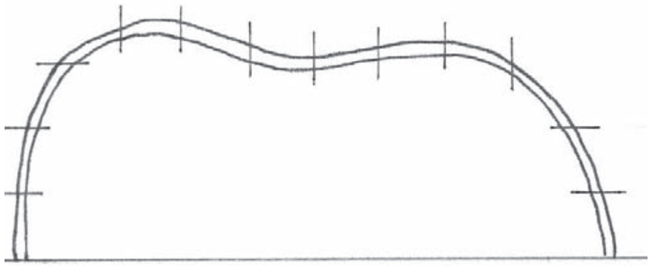


Figure 6.5 Cross-section of an example of a shells that is sliced by the combination horizontal and vertical slicing.

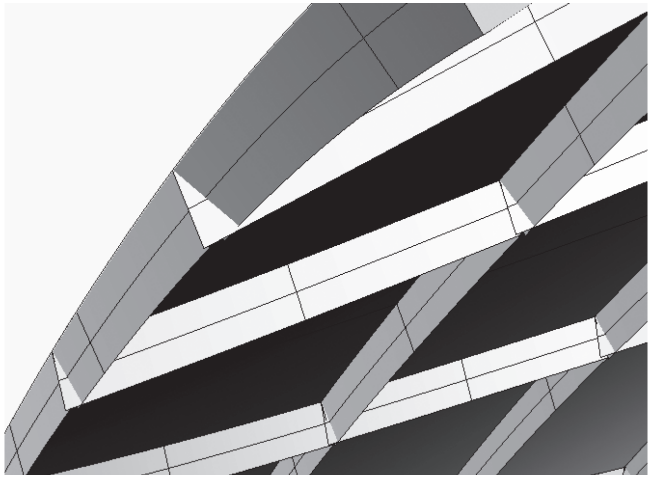


Figure 6.8 Incorrect alignment of the edges with semi-perpendicular edge generation.

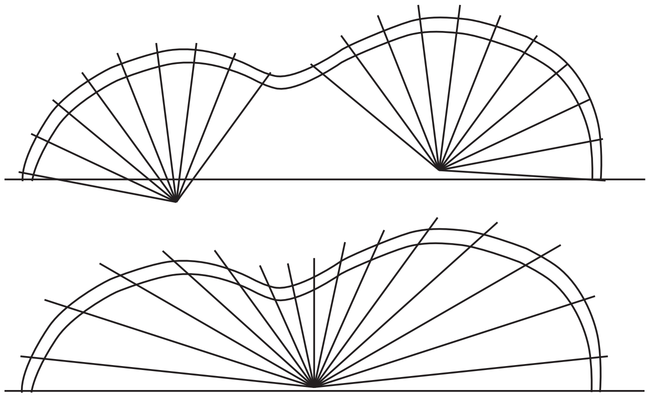


Figure 6.9 Two cross-sections of a shell that is cut radial in different elements.

cur. The main drawback of this method is that problems occur with the alignment of the corners of the different elements at the inner surface of the shell.

Radial

With this method the outer surface of the shell is cut radial from one or more centre points in different elements. This method can give good results when the shell surface has some sort of dome shape. The main drawback of this method is that the angle between the edges in the cross section of the elements cannot be controlled very well and sharp and vulnerable corners may exist.

Evaluation

Before evaluating the discussed methods for slicing the shell the requirements that are set for the edges are stated below:

- From the point of view of production of the elements and construction of the structure flat edges without torsion are preferred.
- The angle between the edges in the cross-section of the element may vary from 45° to 135°, but angles around the 90° are preferred.

These requirements make that not all methods can be used.

The vertical and horizontal slicing the surface in different elements result, at some places in the shell surface, in sharp angles between the edges in the cross-section of the elements that are smaller than 45 degrees. This makes these methods unsuitable. The combination method of horizontal and vertical slicing seems very suitable. It results in flat edges and the angle in the cross-section of the element is never smaller than 45 degrees but varies between 45 and 135 degrees.

The perpendicular method results in angles between the edges in the cross-section of the element of 90 degrees. The only disadvantage of this method is that the edges of the element can be in torsion. The semi-perpendicular method eliminates this disadvantage, but problems occur with the alignment of the edges at the inner side of the surface.

The radial method is especially suitable for dome shaped surfaces. But this method is unsuitable for most other surfaces because it can result in sharp angles between the edges in the cross-section of the elements.

From the evaluation above it can be concluded that the combination method and the perpendicular method are the most suitable methods for the creation of the edges. One of these techniques will be worked out further and used in the segmentation process to create the edges of the elements.

6.2.4 Creation of the edges

There are different methods with which the edges can be created. The construction method for the edges influences the type of edges that can be created and the type of connection system that can be used.

Sawing

A method for the formation of the edges of the elements is to saw the edges of the elements in the desired angle after the concrete is hardened. With this method in principle all possible angles are possible, but only when the edge is not curved. Edges that are rotated or in torsion are difficult to saw accurately, so this is considered to be not possible. Other drawbacks of this method are the relatively large loss of concrete material and that it is not possible to create ridges in the edges. [19]

Contra-moulding

With this method a previously cast element is used to produce the following element. This principle was used for the construction of the elements of the Millau viaduct toll gates, see also Chapter 1 'Introduction'. An advantage of this method is that there is a perfect fit between the elements, because they are cast next to each other. But this method does need a lot of extra handling with the elements, because they have to be placed in the right position for the contra-moulding. When the elements are rectangular and have other elements on four sides, this technique requires a good organisation to keep the process going and cast all elements correctly. With this technique not all edges of an element can be created with contra-moulding. There are always some edges that have to be created with another technique, like sawing or inserting a strip.

Inserting a strip

A method for the formation of the edges of the elements is to insert an extra strip in the mould that forms the edges of the element. This strip can be made of different (flexible) materials. The edges can have any shape, ridges and torsion in the edge are no problem and all possible angles in the cross-section of the element are possible. The main disadvantage of this method is that some extra actions are needed to produce the strips and place them on the mould. [19]

Evaluation

Which of the above described methods is the most suitable method for the creation of the edges depends on the design and segmentation of the shell and type of connection system that will be used

With sawing only straight edges without any ridges can be created and it is only possible to produce straight edges. This make this technique less suitable for most connection systems and perpendicular slicing of the edges.

Contra moulding creates elements that perfectly fit onto each other, but a lot extra handling with the elements are needed to create the edges. Beside this there is always another technique needed to make the edges that can not be created with contra moulding.

Insertion of a strip in the mould makes all different types of edges possible, there are no restriction on the possible angles, torsion or ridges in the edges.

The insertion of a strip in the mould is the most suitable technique in most cases and will be used for the production of the edges in the proceeding of this Master's thesis. In some special projects it might be possible that one of the other technique is better. Before a technique is chosen the other possibilities should always be considered.

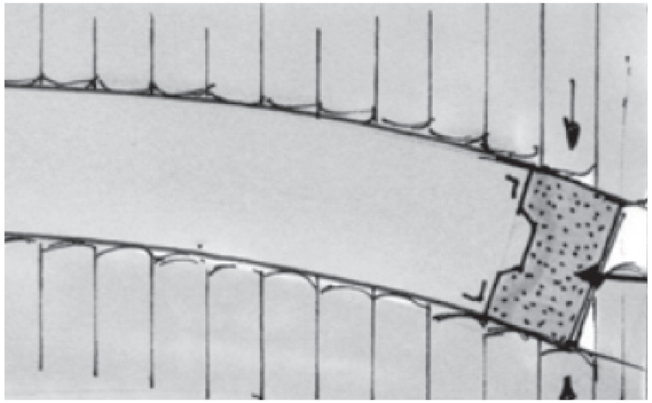


Figure 6.10 The formation of an edge with the insertion of a strip in the pin-bed mould. [19]

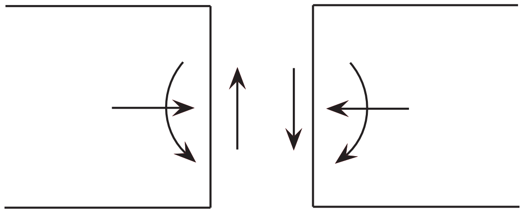


Figure 6.11 The forces that act on the connection between the different elements.

6.3 Connections

The design of connections for precast concrete elements concerns both the structural requirements and the method of construction. The main purpose of the structural connection is the transfer of forces between the different precast elements and to obtain structural interactions when the system is loaded. The ability of the connection to transfer the action forces is vital to the stability and load carrying capacity of the entire structure. The forces that have to be transferred are compression, tension and shear forces, bending and torsion.

Beside the structural requirements there are also some other aspect that have to be taken into account during the design of the connection. Many precast concrete connection details are not vulnerable to fire and require no special treatment. Other connections, like bolted or welded connections, where weakening by fire would jeopardize the structure's stability should be protected to give the same resistance as the structural frame.
The need for movement in a structural system, due to for instance the concrete creep and shrinkage, temperature variations and support settlements should be considered. If the need for movement is not considered there will be a risk of damage to the connection zone.
At the location of the connection often additional reinforcing bars, plates and other inserts are required and little room is left for the concrete. The space needed for reinforcement and the needed concrete cover have to be taken into account during the design of the connection.
The connections should preferably behave in a ductile manner; this means that large plastic deformations take place before failure. Simplicity of the connection makes the chance of mistakes during construction smaller and will probably make the connection less expensive.

In the proceeding of this paragraph different types of connection methods will be described and evaluated.

6.3.1 Wet connection

A wet connection is a connection where the two elements are placed next to each other at a certain distance. The seam between the elements can be reinforced with steel bars and is filled with mortar to connect the elements permanently. The reinforcement is applied to strengthen the connection.

A benefit of a wet connection is that the elements do not have to fit perfectly. Some deficiencies in the size and the shape of the edge can be taken by the wet connection.
This connection system gives a good strong connection that is can transfer, besides tension and compression forces, also bending moments and torsion. The load introduction of the forces into the elements is equally spread over the edge of the elements.
The final connection has a good durability and can resist extreme forces due to for example fire. The connection however is not especially suited for the use with UHPFRC elements.
Disadvantages of a wet connection are the fact that it is labour and time intensive to place the extra reinforcement and the mortar in the seam between the elements. The placement of the mortar is also dependent on the weather, when it freezes or rains the mortar cannot be placed. After the mortar is placed it takes some time for the mortar is hardened and the strength of the connection has developed.

6.3.2 Bolted connection

With a bolted connection the elements are connected to each other by means of bolts. In the elements provisions have to be made to attach the bolts. This can be with special holes in the elements or with some steel provisions for the bolts that are inserted in the mould before casting.

A bolted connection provides a high strength connection system that is easy and fast to assemble. The stiffness an capability of taking bending of a bolted connection depends on the design of the connection. The forces in the connection are introduced into the concrete locally, and if the connection is not designed properly too high peak forces may exist.
If the connection is designed properly there are good adjustment possibilities. Problems with this type of connection are found in the price of the system, it is expensive to make this connection durable. The steel of the bolt is sensitive for corrosion and also a good fire protecting coating has to be applied.
The design of a bolted connection is very important it determines the strength, the load introduction, the ease of assembly and the durability of the connection. It can be difficult to design a good connection that can be used all over the shell surface, especially when the curvature and shape of the elements change over the surface.

6.3.3 Post-tensioning connection

In a post-tensioning connection the elements are provided with ducts trough which continuous tendons are placed. After the placement of all elements the continuous tendons are tensioned and fixed at the edges of the shell surface. To make sure the alignment of the elements is perfect, before the cables are tensioned, a temporary connection with epoxy resins can be made.

The post-tensioning connection with continuous cables does not only provide a strong connection between the element it also increases the tensile strength of the complete shell. The loads of the post-tensioning stress is introduced in the outer elements. This can give very high peaks stresses in the concrete around the anchor points of the tension cables.
A drawback of this type of connection is that the elements need to have a minimal thickness, because the duct for the cable has to be placed in the elements.

To install this type of connection the elements have to be fixed temporarily before the tension can be applied on the elements. This complicates the assembly of the elements. When the tension is applied on the elements a very durable connection is made that is very suitable for the use with UHPFRC elements, due to the high compression strength of this type of concrete composites.

6.3.4 Welded connection

When a steel provision is inserted in the mould before casting the elements can be welded together to form a permanent connection.

A welded connection can be a very strong connection. When the inserts that are welded together are designed properly the load introductions can also be good and no peak stresses develop in the concrete. The fact that the insert are welded together makes that the adjustment possibilities are small and the tolerances of the elements also have to be very small.
It is very hard to make a good weld on the building site. So the assembly of the elements with a welded connection is difficult and not weather independent. The steel inserts that are welded together have to be protected against corrosion to make the connection durable. This type of connection is suitable for the use with UHPFRC.

6.3.5 Glued connection

A recently developed connection system is the glued connection. In gluing technology the assembly parts are joined by the use of plastic or liquid adhesives that harden by chemical or physical processes. The strength of the adhesive joint is caused by two major forces, the adhesive and cohesive forces. In civil engineering epoxy resins are normally used to temporarily fix prefabricated concrete elements that are finally fastened with mechanical measures. In this use the adhesive act more as a sealing and do not have to be capable bearing the constructional loading for the whole life service. Since UHPC is a very homo-

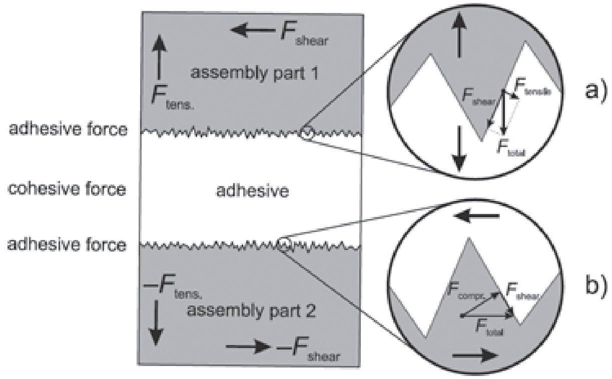


Figure 6.12 Epoxy joint of a rough surface in detail; a) tensile load b) shear stress. [6]

Figure 6.13 The Gartnerplatz bridge in Kassel. [6]

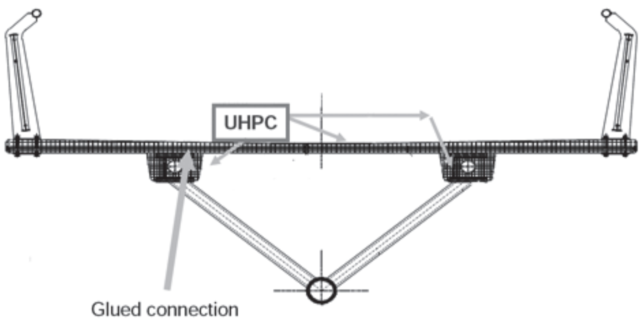


Figure 6.14 Cross-section ogf the Gartnerplatz bridge in Kassel. [6]

geneous material with respect to its mechanical properties, the properties on the surface regions are the same as the properties of the bulk material, and has a high tensile strength it is suitable for gluing of the elements.

To obtain optimal results in the application of gluing technology the surface properties of the parts are most important. This means that the concrete surface has to be roughened and loose particles and other impurities have to be removed before the application of the epoxy resins to ensure a firm mechanical bonding of the adhesives to the UHPC surface. After the subsequent element is placed vibration can be used to make sure the target thickness of the joint is reached. The benefits of this type of connection is that it is easy applicable and that the shear and tension stresses can be transmitted very homogeneously. The tensile and bearing strength of the epoxy resin are practically identical with the tensile strength of the UHPC itself.

This type of connection is used for the first time in the Gartnerplatz Bridge in Kassel that spans the river Fulda over a length of about 140 meter. In this bridge the precast UHPC deck plates are glued to the upper chords of the truss structure without any additional mechanical bonding devices. Before the application a series of tests was performed to test the strength and durability in all weather and climatic conditions of glued UHPC connections, made with an epoxy resin of Sika. The tensile strength of the tested prisms was between 6 and 7 N/mm^2 and the flexural tensile strength between 10 and 13 N/mm^2. [6] The specimen failed within the concrete structure adjacent to the epoxy layer.

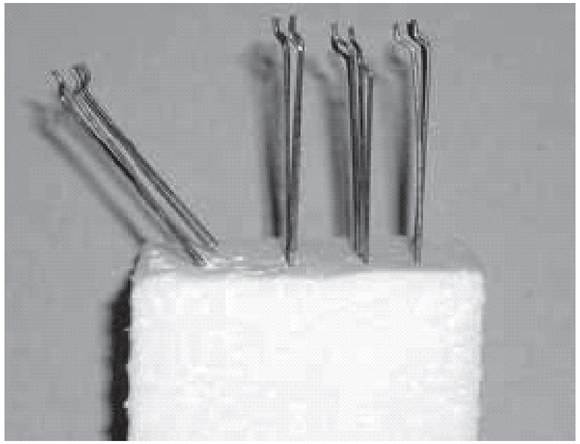


Figure 6.15 Supporting ribbon with fibres. [21]

Also some long-term stability tests were performed by fixing specimens in a frame under different thermal and climatic conditions for 56 days. The shear stress in the epoxy layer during these tests was 2 N/mm^2. The strength of the specimen after 56 days was between 12 and 16 N/mm^2. [6]
The tests showed that the failure occurred in most cases in the concrete matrix.
The testing program showed that there are still some questions left and to make gluing a more often used method in the building industry and civil engineering some more testing has to be done.

6.3.6 Fibre joints

The fibre joint is actually an alternative of the wet connection, where fibres are used in steads of reinforcing bars. The fibres used in UHPFRC are not suitable for use in the connection, due to their small dimension. Therefore fibres with a diameter of 0,7 mm, a length of approximately 60 mm and a hooked end are used. These fibres are inserted into a supporting ribbon that can also serve as a formwork for the edges of the elements (See Figure 6.15). This type of joint can transfer all forces on the connection, also forces oblique to the joint.

This type of joint is suggested by A. Lichtenfeld in [20]. In his paper he refers to some tests that have been performed to determine the load bearing capacity of the joint. For the tests on the construction joint specimens with a concrete height of 40 mm and a fibre content of 0,26% and 1,3% were used. The fibre overlap is 28 mm. The test results show that the applicable bond stress increases with a lower fibre content, this results from the reduced concrete damage due to a decrease in stress. The larger applicable bond stress coincides with a rather large deformation. Based on these first tests a required fibre content of 0,87% is derived, with an applicable bond stress of 8 N/mm^2 and an overlap of 30 mm for UHPC with an axial tensile strength $f_{ct,ax}$ of 12 N/mm^2. On basis of these primary tests further testing has to be performed to further investigate the strength properties and durability of the connection.

6.3.7 Evaluation

Before the different types of connection systems are evaluated the requirements for the connections are stated below:

- The load bearing capacity of the connection may not determine strength of the complete shell structure.
- At the place where the loads are introduced into the element no very high peak forces may exist.
- The connection has to function in every occurring situation.
- The connection system needs to have a possibility of adjustment to the tolerances of the construction and the elements.
- The connection system must be able to be applied on elements made of UHPFRC.
- The connections system should provide a fast, easy and weather independent assembly of the elements.
- The connection system should have a good durability.

The properties of the different connection systems, with respect to the different requirements stated above, are summarized in Table 6.1. This table show that all different connection systems have their advantages and disadvantages. There is not one connection system that can be considered a the most optimal connection system. The choice for a connection system will always be a considering between the advantages and disadvantages of each systems and also depends of the properties of the design.

On the basis of the properties of the connections the wet connection, glued connection and bolted connection will be used to develop a connection for the case study in the proceeding of this thesis.

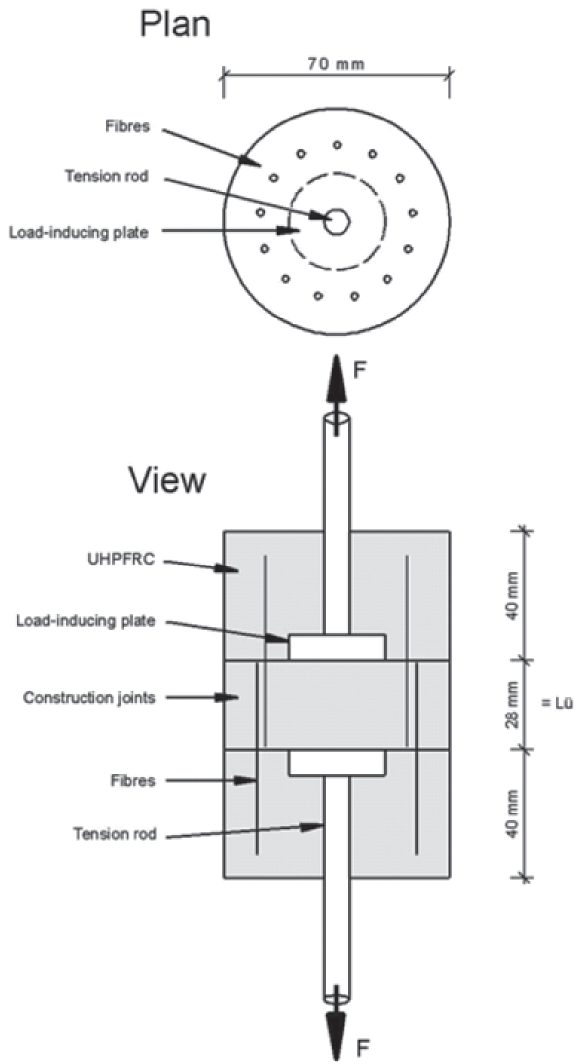


Figure 6.16 Test setup for the test with the fibre reinforced construction joint. [21]

	Wet connection	Bolted connection	Post-tensioning connection	Welded connection	Glued connection	Fibre joint
Connection strength	Strong	Strong, but stiffness and moment capacity difficult to ensure.	Strong and increased tensile capacity of the shell due to compression of the elements.	Strong	Strong, but long term performance not completely known.	Strength and durability properties not completely known.
Load introduction	The loads are introduced equally spread over the edge of the elements.	High peaks stresses can occur, but should be avoided with proper a design.	High peak forces in outer elements where tension tendons are anchored can occur.	No peak stresses in the concrete should occur.	The loads are introduced equally spread over the edge of the elements.	The loads are introduced equally spread over the edge of the elements.
Adjustment possibility	Enough room for adjustment due to space between the elements.	Depending on the design, a good design has enough room for adjustment.	Not very large	Small	Not very large, but depends on the thickness of the layer of glue.	Sufficient
Suitable for use with UHPFRC	Not especially suitable, due to large difference in strength of mortar and concrete.	Suitable	Very suitable, due to high compression strength of the concrete.	Suitable	Very suitable, due to homogeneity of the concrete.	Very suitable
Ease of assembly	It is labour intensive to place reinforcement and mortar, but the placement of the elements is easy.	When connection is designed properly the assembly is easy.	Complicated due to temporary fixing that is needed and the application of post-tensioning.	Difficult, due to welding on site.	Edges have to be roughened and cleaned carefully before the application of the epoxy layer.	Mortar should be placed in a relative narrow joint and the fibre may not bend during assembly.
Assembly speed	Slow, mortar need time to harden and gain strength and the placement of the mortar is weather dependent.	Fast and weather independent assembly possible with a good design.	Slow, all elements have to be placed and fixed temporarily before tension can be applied.	When the weld is made the connection is strong, but careful preparation before welding is essential.	Slow, the edge have to be treated before the epoxy can be applied and the epoxy need some time to harden and gain strength.	Slow, mortar needs some time to harden and gain strength.
Durability	Good	Good, when protected properly against corrosion and fire.	Good	Good, when protected properly against corrosion and fire	Still some research to long term performance needed.	Not known, research needed.

Table 6.1 Overview of the properties of the different connection systems.

6.4 Conclusions

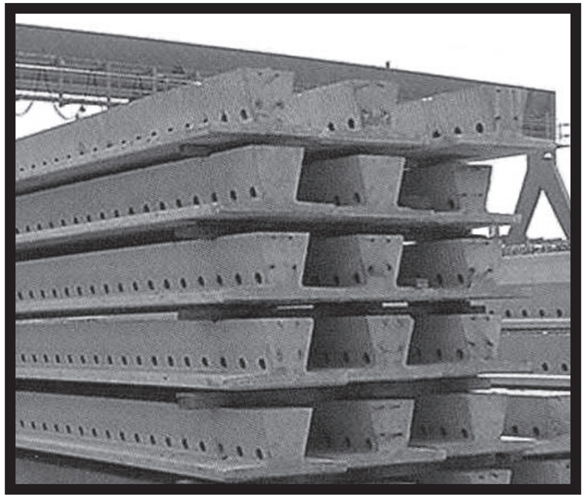
Edges

- The two best methods to create the edges of the elements, for most surfaces, are the combination method and the perpendicular method.
- The combination method combines both horizontal and vertical slicing and results in flat edges of which the angle in the cross-section of the element is never smaller than 45 degrees but varies between 45 and 135 degrees.
- The perpendicular method results in angles in the cross-section of the element of 90 degrees. The only disadvantage of this method is that the edges of the element can be in torsion.
- The most suitable technique for the creation of the edges is the placement of a (flexible) strip on the mould that has the shape of the edges. With this method all different types of edges are possible, there are no restriction on the possible angles, torsion or ridges in the edges.

Connections

- There are many different types of connection systems that can be used to permanently connect the elements to each other. The types of connection systems that are discussed in this theses are, the wet connection, a bolted connection, a post-tensioning connection, a welded connection, the glued connection and the fibre joint.
- For some connection systems it is necessary that reinforcing bars or other inserts are placed in the elements. For other systems it is not possible to place reinforcing bars in the concrete.
- The choice for a connection system will always be a consideration between the advantages and disadvantages of each systems and depends of the properties of the design.
- On the basis of the properties of the connections the wet connection, glued connection and bolted connection will be used to develop a connection for the case study in the proceeding of this thesis.

7. Production and construction



In this chapter the production of the prefabricated elements and the construction of the shell are considered.

Stored precast concrete elements. [2]

7.1 Introduction

With the design of a prefabricated concrete shell different aspects have to be taken into account. This chapter discusses the aspects of the design process that concern the production and construction of the shell structure.

The production of the elements takes place when the design of the structure is completed. During the design the production of the elements is already considered, to take the restrictions from this process into account in the design.

After the production of the elements they have to be transported to the site. This transport can be done with different means of transportation, boat, train or truck. But it is most likely that the elements will be transported by road. To this transport different restrictions on the size and weight of the elements are given.

The construction method will also give its restraints for example on the segmentation method and the connections between the elements. Of course the precise construction method is different for every design, but some general comments about the needed tolerances, scaffolding and lifting points can be given.

The production of the elements is discussed in paragraph 7.3. After this the transport of the elements is discussed in paragraph 7.3. The construction and the tolerances are discussed in respectively paragraph 7.4 and 7.5.

7.2 Production

It is assumed that for the production of the elements a flexible pin bed mould will be used. This is an expensive mould and there will probably be only one mould available for the production of the elements.

Because there is only one mould available the production process can only be shortened by speeding up the production of each individual element. This can be done by, fast demoulding after casting, fast adjustment of the mould for the next element and fast preparation of the mould for casting. With the preparation of the mould is meant the placement of the reinforcement and other inserts in the mould.

7.2.1 Virtual mould

To set-up the mould the height of the pins in the mould has to be adjusted so that the shape of the element is formed. To determine the height of each pin an element is placed on a virtual mould. The virtual mould is a digital model of the adjustable formwork that is used to determine the settings of the real adjustable formwork.

The orientation in which the element is placed in the construction is in most cases not the most optimal orientation for the production of the element in the adjustable mould. The best orientation of the element for production is when the pins are least ejected. This means that the orientation of the element must be as horizontal as possible and the element has to be rotated before it can be placed on the mould. To reach the desired orientation the element has to be rotated around two perpendicular axes. The line of rotation is a line that goes through the lowest points of the element in both directions. First the rotation in one direction is performed and then the second rotation line is placed and the rotation around the other axis is performed.

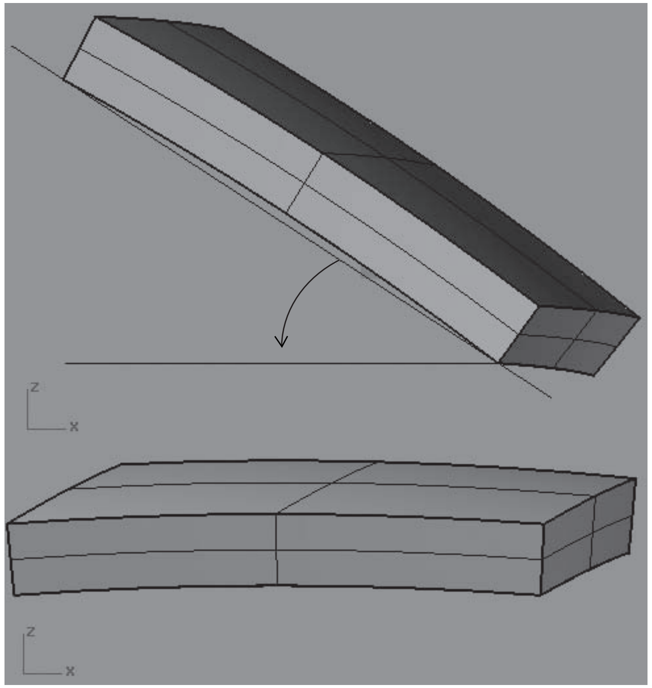


Figure 7.1 The rotation of an element around one axis to the right orientation for the placement on the adjustable formwork. After this rotation the elements has to be rotated around the other axis.

When the element is placed in the virtual mould, the locations of the pins and the ejection length of each pin has to be defined. To determine the ejection length of the pins a grid, that represent the pins in the real formwork, is projected on the surface of the element. After this the length of the line between the point on the surface and the corresponding point on the bottom of the box can be determined. This length is the ejection length of the pin.
Both van Roosbroeck [19] and Rietbergen [41] made a program with which the height of the pins in the mould can be determined on the basis of a digital model of the elements.

Besides the height of the pins, also the place of the edges has to be determined with the help of the virtual mould. The outlines of the element can for example be printed on a large sheet of paper that can be placed on the adjustable formwork to mark the places where the inserts for the edges can be placed.

The complete process of setting up the mould can be summarized as follows:

1. Extract an individual element.
2. Place the element on the virtual mould.
3. Rotate the element to the right orientation.
4. Project the grid of the mould on the element surface.
5. Determine the ejection length of each pin.
6. Determine the place of the edges of the element.
7. Placement of the inserts and adjustment of the real mould.

7.2.2 Inserts for the edges

To cast the elements inserts, that form the edges of the elements, have to be made. The inserts can be placed on the mould before the mould is brought into the curved shape or after the mould is deformed.

When the inserts are placed into the mould when the mould is already in the curved shape. The inserts should have the exact shape of the edges. This means that not only the applied ridges have to be formed, also the torsion of the edge has the be transferred to the edge.
These inserts have to be made of a material that is easy to shape, like wood or expanded polystyrene foam (EPS). To form the inserts a multi-axial milling machine can be used. The computer model of the edges can be used to cut the insert in the right shape with a milling machine.

The inserts can also be placed on the mould before the mould is brought in the deformed shape. This means that the inserts should have enough deformation capacity to let it take the correct shape after deformation. The insert will rotate in line with the rotation of the mould. Only the rotation of one edge will probably not be the same all over the length of the edge so the insert must allow a varying rotation of the insert over the length of the insert. In other words it must be able to create an edge in torsion only by the rotation of the mould surface. This means that a flat edge that is mounted perpendicular on the mould surface is automatically is deformed to the right shape by the deformation of the mould. This can make the production of the inserts for the edges easier, because no complicated inserts with edges in torsion have to be made with the use of milling machines. This types of inserts might also make re-used if the inserts possible.
There might be some difficulties with the alignment of the two strips at the corners of the elements. To find out whether this gives real problems some tests have to be performed.
The only task is to find the right type of insert that is strong but also has the flexibility of to deform into the right shape by rotation of the mould. The first idea is to make the inserts of thin flexible strips that are mounted on the mould with a couple vertical strips that are placed perpendicular to the edge strip. These strips do also support the edge strip during the hardening of the concrete. (See Figure 7.2)

The second method can simplify the production of the inserts for the edges. This method is especially suitable when the edges are perpendicular to the surface. When the edge are flat or have an other orientation to the surface this method is less suitable.
The first method is good for elements with flat edges and when the angle between the edge and the surface varies and is less suitable for edges in torsion.

7.2.3 Preparation of the mould

Before the concrete can be cast the inserts which form the edges have to be placed on the mould. The provisions that might be needed for the transport of the elements and the connections between the elements also have to be placed on the mould. When necessary, the steel reinforcement has to be placed on the mould before casting. If the element needs steel reinforcement the mould has to be brought into the curved shape before casting, because the reinforcing bars cannot be deformed by the mould after casting. It should be possible to place the reinforcement and inserts in the mould correctly orientated and within the necessary tolerances with a minimum amount of effort. The more things, inserts, reinforcement etcetera, that have to be placed in the mould the longer it takes to prepare the mould for casting. It is desirable to repeat details as much possible, to make the preparation on the mould less complicated. When all inserts and the reinforcement have been placed on the mould the concrete can be poured into the mould to cast the element.

7.2.4 Casting process

Casting concrete in a thin layer on the curved shell surface is difficult. When the concrete mix is too fluid the concrete tends to sag and flow. The elements will be too thick in the lower parts and too thin in the upper parts of the mould. To prevent this the fibre reinforced concrete can be poured into the mould when the surface of the mould is still flat. The mould is brought to the deformed curved shape when the concrete is starting to get a little bit hard-

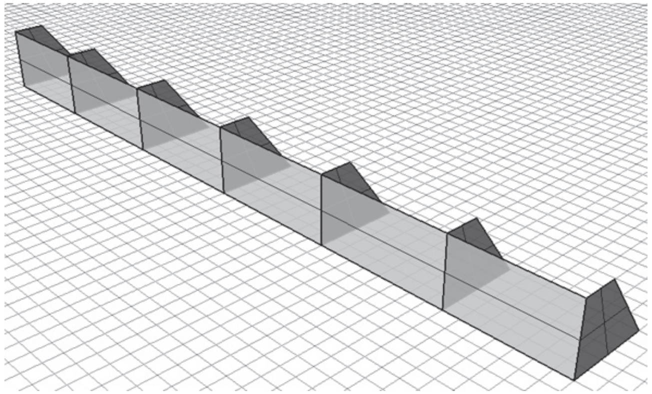


Figure 7.2 Design of the inserts that form the edges of the elements.

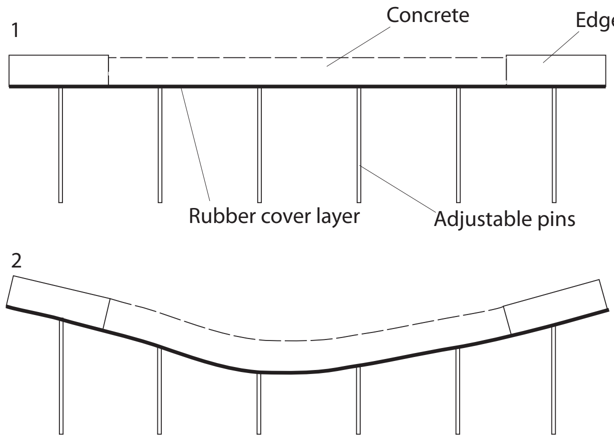


Figure 7.3 Casting principle of the adjustable mould.
(1) The concrete is poured into the mould when it is still flat.
(2) The deformation of the mould takes place when the concrete is partly hardened.

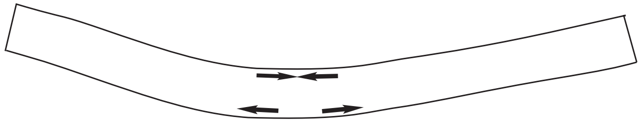


Figure 7.4 Due to the deformation of the partly hardened concrete some tension or compression stresses may develop in the curved parts of the elements.

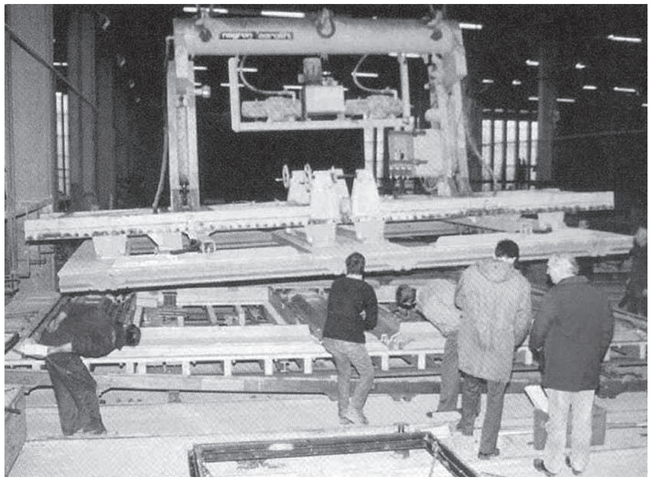


Figure 7.5 A flat element lifted by a vacuum lifting machine. [2]

er. This method of casting prevents that elements with an undesired varying thickness are cast. A possible drawback of this method for casting the elements is that in the more curved areas some tension or compression stresses might be present due to deforming the partly hardened concrete. This might influence the stresses in the completed structure.

Whether the mould will be deformed before or after pouring the concrete into the mould depends on the type of concrete that will be used for the elements. When a sprayed mortar is used it can be sprayed on the deformed mould without a large risk of sag or flow of the concrete. But when a more fluid concrete composite is used it might be better to bring the mould to the curved shape after casting.

7.2.5 Demoulding

Before the elements are placed in their final position they have to be lifted several times. During these lifts special care has to be taken not to damage the elements. The first time the elements have to be lifted is with the demoulding of the elements. At this moment the concrete does not have its full strength yet, and the elements are very sensitive for cracking and damage.

The lifting of the elements out of the mould of flat elements can be done with a vacuum lifting machine. This is very suitable for vulnerable elements that are easily damaged. Another advantage is that, for this type of lifting, no lifting provisions are needed. The standard vacuum lifting machines are not suitable for lifting double curved elements. It might be possible to adapt these machines and make vacuum lifting for double curved elements possible, but this is probably very expensive.

For demoulding also a turning table can be used. On this table the mould is placed and it can turn the mould and the element in a vertical position for demoulding and transportation, by crane, to the storage pit. For transport by crane provisions for the attachment of crane hook have to be added to the mould before casting. It might be possible to place the adjustable mould on a turning table, but this makes the mould more complicated and difficult to handle. Besides this the vertical transport of the elements makes that large transport loads are induced on the elements.

Another idea that for demoulding the elements is to use a couple ties that are placed under the element before casting to lift the element. The ties have to be placed under the rubber cover, that is placed on top of the pins, to keep the surface of the element smooth. For demoulding the ties are attached to a crane and the element can be carefully lifted from the mould. The rubber cover is lifted with the element and can protect the element during storage. For this method no lifting provisions have to be inserted into the elements.

7.2.6 Storage of the elements

After production the elements have to be stored several times on different locations. The elements are demoulded shortly after production, before they reach their final strength. At this time the type and place of the support of the elements during storage is very important. Wrong storage can cause cracks or unnecessary deformation.

The curvature of the elements makes it more difficult to store the elements. They cannot be stored in the same way as straight beams or flat floor elements, on top of each other separated with support blocks. It is suggested to use a special frame with six in height adjustable pins for the storage of the elements. On top of the pins a square support block can be placed, to spread the weight of the element more equally. This support should be able to rotate freely around the top of the pin to get the optimal orientation for supporting the element. The pins can be simple screw pins, that can be adjusted in height manually. The frames can be made in such way that several elements can be stored on top of each other to save storage space.

The amount of frames that will be needed to store all elements of a shell depends on the amount of elements in the shell. For a large shell many frames might be necessary, what makes the construction of the shell more expensive. But the size of the elements depends mainly on the size of the formwork. This means that the formwork also determines the size of the frames and re-use of the frames for different shells is possible.

For transport the element have to be loaded on and of the truck. This can be done lifting each individual element with a crane. When the elements are stored on the frame, this frame can be used to place the element onto the truck. In this way the elements are exposed less to large transportation loads and are protected against damage during transport.

7.2.7 Evaluation

To speed up the production process the production of each individual element has to be as fast as possible. The production time of the elements is influenced by the set up time of the mould and the hardening time of the concrete. To make the preparation of the mould faster and easier it is preferred that no reinforcement is needed in the elements.

A lot time can be saved when the same elements is used a couple times. In this case the shape of the mould does not need to be adjusted between the casting of two elements.

The storage of the elements on special frame is expensive, but eases the storage and transport of the elements and protects elements against damage.

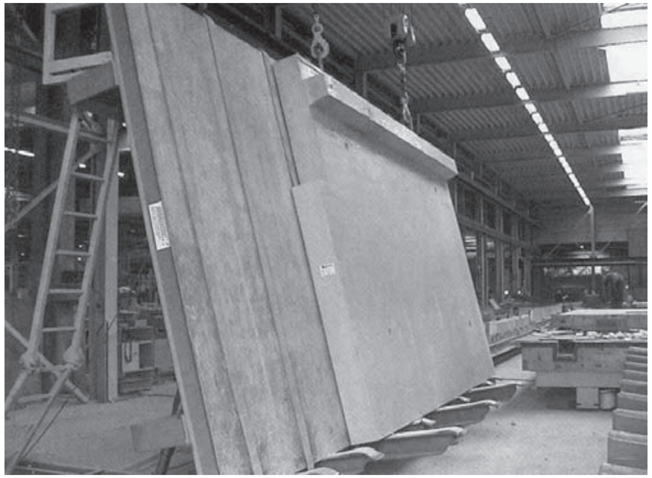


Figure 7.6 Precast concrete element on a turning table. [2]

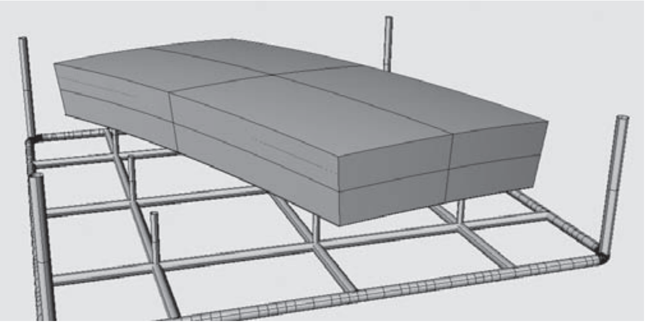


Figure 7.7 Model of the frame to store the double curved elements.

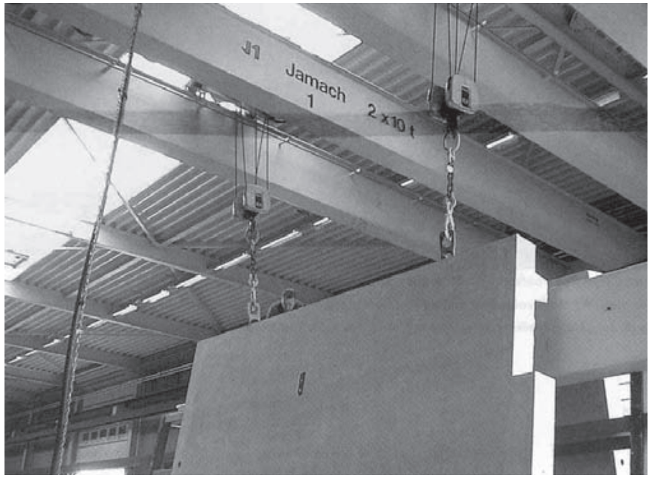


Figure 7.8 Element transported with a crane in the factory. [2]

7.3 Transport


Figure 7.9 Concrete elements on a low loader. [2]

When the elements are not produced on site, they have to be transported from the factory to the building site. Depending on the facilities near the factory and near the site the elements can be transported by road, by rail or by water. Rail or water transport will not be used very often, because in most cases not both the factory and the building site are close to a rail way or a large enough water way. These ways of transportation will only be used is very special cases. For the most materials transport by road is the most efficient way of transportation.

In the Netherlands there are restrictions on the sizes of the vehicle and the transported load. When these dimensions are exceeded a special transport licence is needed. These limitations are:

- The maximum length of a single load is 12 meter.
- The maximum width of the load is 3,0 meter.
- The maximum height of the vehicle with the load is 4,0 meter.

When a low loader is used for the transport of the element, of which the platform has a height of about 1 meter, the maximum height of the load is approximately 3 meter.

For the weight of the vehicle, including the load, there are also limitations. The maximum load of a truck combination is 50 ton. A truck weighs about 20 ton, so the maximum the load on the truck is about 30 ton, The maximum load on one axle of the truck can be set on about 10 ton. More information about the regulations can be found on www.rdw.nl/tet.

7.4 Construction

When the elements are produced at the same time the work on the building site can start. Before the elements can be placed the work on the foundation or construction on which the shell is going to be placed has to be finished. Beside this probably also some scaffolding or other type of temporary supports for the elements have to be placed. When the site is prepared for the placement of the elements they will be transported to the building site and the construction of the shell can start.

The construction sequence of the shell is already determined during the design process. The loads that are induced on the elements during construction are often larger than the service loads on shell. Designing the connections and the elements these extra loads have to be taken into account and special measures have to be taken to prevent damage due to these loads. This can be done by strengthening the connection or the elements and by placing temporary supports.
The stability of the shell and the individual elements should be guaranteed at any moment during construction. To do this scaffolding will be necessary.

With the design of the connections the placing movements should be taken into account to prevent connection details that makes placement of elements impossible. The torsion in the edges makes the placement of the elements more difficult and makes that a larger adjustment area is needed to place the elements.

To place the elements they are lifted by a crane and are carefully lowered into their final position. Before the elements are disconnected from the crane support they have to be fastened and their stability has to be guaranteed. Depending on the type of connection system that is used the elements are fastened permanently directly after placing or first with a temporary connection. In this case the final connection will be made after more elements are placed or it takes more time for the connection to gain enough strength to secure the element. This is for example the case with a wet connection, while a bolted connection can be made while the element is still supported by the crane.

When all elements are placed and the connection are made the temporary supports can be removed and the construction can be finished.

Figure 7.10 Temporary scaffolding used during the construction of the canopy at sanatorium ‘Zonnestraal’.

7.5 Tolerances

The size and shape of the mould and the elements cast with it is never absolutely perfect, therefore there are always some deviations in the shape of the elements. The tolerances can be defined as the maximum allowable deviation in the size and shape of the elements and the construction. Deviations have basically two reasons. The first are inaccuracies caused by humans and the second physical reasons. The total deviation of a prefabricated structure is the result of the following part deviations.

Product deviation

Product deviations are for example deviations in the size of the elements and temperature expansion. The size and shape of the mould is never absolutely perfect, therefore there are always some deviations in the size of the elements.
Due to the change in temperature the size of the concrete elements varies. To prevent cracking of the concrete the concrete must have space to expand and expansion joints have to be placed in the structure.

Erection deviation

For the assembly or connection of the elements some extra tolerances may be needed. There must be some space for handling and placement of the elements.

Deviation of the work done at the site

The work done at the site is commonly not performed as exact according to the plan as in the prefabrication concrete technology.

All these possible deviations have to be taken into account during the design of the structure. If this is not done correctly there is the risk on damage or delay during construction.

The reasons for the total deviation are the same for any structure where units are produced off site, regardless of the material. However, when something is not quite right concrete is a little more difficult to alter or adjust compared to for instance steel or wood. Therefore one has to pay more attention to tolerances in prefabricated concrete structures and to develop connection details that have the necessary room for adjustment. A connection should always be as adjustable as possible. Preferably the connection detail should be adjustable in three directions. This may be difficult to combine with a requirement for simplicity.

7.6 Conclusions

- For the production of the elements they have to be placed on the mould in the orientation of the element in which the pins of the mould are least ejected. To reach this orientation the elements have to be rotated.

- There are different types of inserts that can be used to form the edges of the elements. The shape of the inserts depends on the form of the edges and whether they are placed on the mould before or after the mould is brought into the deformed shape.

- To make the production of the elements easier and faster no steel reinforcing bars should be applied in the elements.

- Storage of the double curved elements is more difficult than storage of straight prefabricated concrete elements. For the storage special frames can be used that can also reduce the induced loads on the elements during lifting and transport.

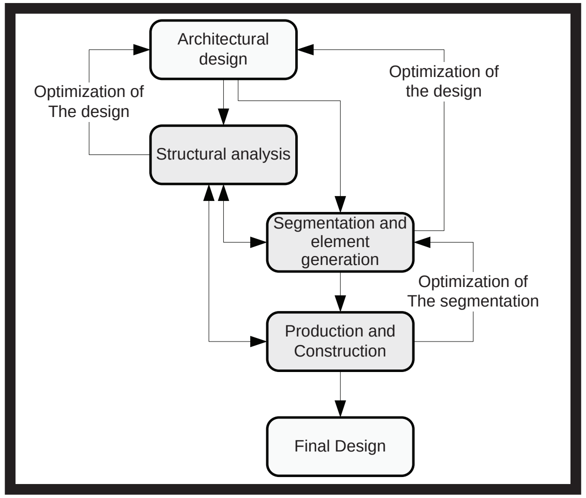
- The element can best be transported by road. This makes that the maximum elements size and weight are limited. The maximum length of a load is 12 meter and the maximum width is 3 meter. The maximum weight of the transport loads is about 30 ton.

- During the construction of the shell the stability of the shell had to be ensured at all time. To do this temporary scaffolding and careful planning of the construction is necessary.

- The elements are placed in the construction with the help of cranes. To make lifting of the elements with a crane possible, lifting provisions, like hooks, have to be attached to the elements. The lifting of the elements on these hooks might induce forces into the elements that are much larger than the standard design load. These loads have to be taken into account during the design of the shell.

- There are different types of deviations present in a structure that can be divided in product deviations and erection deviations. The maximum allowable deviations are defined by the tolerances of the structure.

8. Design process



In this chapter the different aspects of the building process will be outlined and the relations between these aspects will be discussed.

8.1 Introduction

After analysis of the different aspects of the design, production and construction of prefabricated concrete shells in this chapter the relations between these aspects and the design process of these shells will be analysed.

In the complete building process of prefabricated concrete shells three different phases can be distinguished, the design, the production and the construction. In the design phase the complete design for the shell is made. In the second phase, the production, the elements are produced. In the last phase, the construction, the shell is build. In this chapter only the design process is discussed, because this is the most complicated phase of the building process.

The design of prefabricated shell structures is very complex. The process has the be performed as an integral process, where the design, the structural analysis and the segmentation are treated at the same time. To make the analysis of the design process a little less complicated only the shell structure is considered, even though it might be a part of a larger structure. All other parts of the structure, like for example the foundation, the cladding or the interior design, are left out of consideration.

In paragraph 8.2 the different aspects of the design process are introduced. After this the relations between these aspect are given in paragraph 8.3, and in paragraph 8.4 the complete design process is analysed.

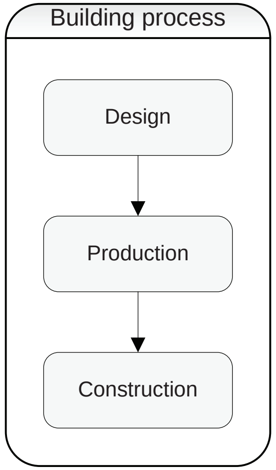


Figure 8.1 The complete building process can be divided in three parts, the design, the production and the construction of the shell.

8.2 Design aspects

The aspects that have to be taken into account during the design of a prefabricated concrete shell will be called the design aspects. The different design aspect that are distinguished here are:

- Architectural design
- Segmentation and element generation process
- Structural analysis
- Production and construction
- Formwork
- Concrete composition
- Connection system
- Element size, shape and curvature

The architectural design is the design for the building made by the architect. This design is in most cases the starting point of the design process.

The segmentation and element generation process is the process in which the shell is divided into the different elements. This process generates a grid over the shell surface, defines the edges of the elements and can isolate the individual elements of the shell.

During the structural analysis the strength, stiffness and stability of the designed shell are determined and controlled according to the valid building codes. The stresses and deflections of the shell have to be within the requirements for all load cases.

In the aspect production and construction the production and construction process of the shell are determined. Here for example the production sequence of the elements, the building sequence and the placement of the scaffolding are determined.

The formwork gives the choice for the mould with which the elements will be made and the restrictions this mould gives for the shape and production of the elements.

The concrete composition gives the choice for the material of which the elements will be made and the properties of this material.

The connection system determines how the edges are made and the properties of the connection system that will be used to connect the elements to each other.

The element size, shape and curvature give the restrictions or choices for the size, shape and curvature of the elements. The choice for the element requirements is made mainly on the basis of other choices that have been made for example for the transportation method and the type of formwork that will be used.

Beside the aspects that are discussed in this paragraph a lot more aspects, that influence the design process can be determined. With the aspects discussed here it is tried to find the most important aspects concerning the structure of the shell. All other aspects are left without consideration. With these aspects it should be possible to give a pretty complete overview of the design process of the shell structure that at the same time will not be too complex.

8.3 Relations between the aspects

The different aspects of the design process influence each other in different ways. For the aspects defined in the previous paragraph the relations between them are given in Figure 8.2. These relations are defined with the help of the relationship scheme defined by Van Roosbroek [19]. The relations that are determined here are not exactly the same relations as Van Roosbroeck defined. The relations given in the scheme are explained below.

1. Relation architectural design & segmentation and element generation process

The architectural design will be used to segment the shell surface and generate the elements. When the segmentation has been analysed the architectural design might be changed to make a more optimal segmentation of the shell possible.

2. Relation architectural design & structural analysis

The architectural design will be used to perform the structural analysis of the shell design. On the basis of the results of this analysis the shape of the surface may be changed, to get a more optimal force transfer in the shell.

3. Relation structural analysis & segmentation and element generation process

With the structural analysis of the shell surface the place of the edges of the elements has to be taken into account. The strength of the connections is probably not the same as the element strength so the place of the edges might influence the structural behaviour of the shell.

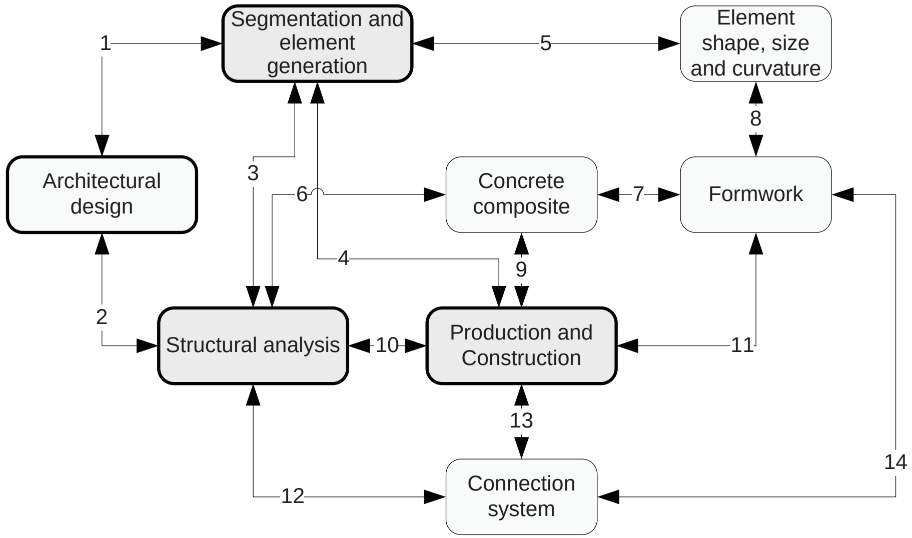


Figure 8.2 The relationship scheme of the relations between the different aspects of the design process.

4. Relation segmentation and element generation process & production and construction

The segmentation and the shape of the elements influence the production of the elements and the construction of the structure. When the generated elements cannot be produced or give problems with the construction of the shell the segmentation or the shape of the elements has to be improved.

5. Relation segmentation and element generation process & element size, shape and curvature

During the segmentation of the surface the requirements for the size, shape and curvature of the elements have to be taken into account. When the generated elements do not fulfil the requirements for the elements size, shape and curvature the segmentation has to be improved until all element fulfil the requirements.

6. Relation structural analysis & concrete composite

The strength properties of the concrete composition influence the structural analysis of the shell. The thickness of the shell and the needed reinforcement in the elements are determined by the interaction between the concrete composition and the shell analysis. With the strength properties of the concrete and the determined forces in the shell the thickness of the shell and the possible needed reinforcement in the elements can be calculated.

7. Relation concrete composite & formwork

The type of concrete composition influences the production of the elements. Different concrete compositions may require different casting methods. The type of formwork that will be used therefore influences the choice of the type of concrete composite.

8. Relation formwork & element size, shape and curvature

The elements will be produced in the flexible pin-bed mould. The size of the mould gives restrictions to the maximum size of the elements. The formwork does also give restrictions for the maximum curvature of the elements.

9. Relation concrete composite & production and construction

The type of concrete composite that will be used for the elements influences the production of the elements. Each concrete composite has its own casting method and hardening time. These properties influence the time needed for casting and hardening of the concrete. The construction of the shell is also influenced by the concrete composite. The strength of the elements influence the type of scaffolding and lifting method that will be used for placing the elements.

10. Relation structural analysis & production and construction

The forces that are imposed on the elements and the structure during the construction of the shell are often larger than the service loads on the structure. So the construction of the shell has to be carefully planned taking into account the construction forces. These forces also have to be taken into account during the structural analysis of the shell.

11. Relation production and construction & formwork

The type of formwork that will be used influences the production of the elements. On the basis of the type of formwork the time that will be needed to set up the mould in the right shape between the casting of two elements can be determined.

12. Relation structural analysis & connection system

The type of connection system that will be used influences the force transfer in the shell. The strength and stiffness of the connection has to be determined while taking the forces in the shell into consideration.

13. Relation production and construction & connection system

On the basis of the chosen connection system the assembly process of the elements can be determined. The connection system determines how the elements should be placed and how the connection should be made. Depending on the type of connection the speed of construction and the place and amount of scaffolding can be determined.

The production method is also influenced by the connection system. The needed tolerances can be determined on the basis of the connection system. The production method and production speed are influenced by the amount of inserts for the connection that have to be placed into the mould and the effort it takes to place these inserts correctly.

14. Relation connection system & formwork

The type of formwork and the method with which the edges are created influences the design and choice of the connection system. The shape of the edges that can be made and the type of inserts that can be used influence the design of the connections.

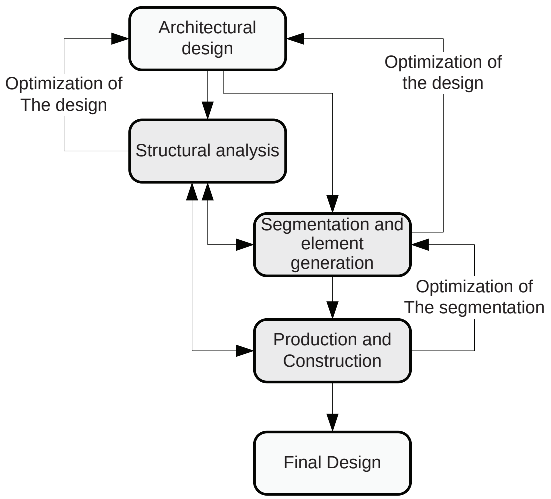


Figure 8.3 The simplified design process of a prefabricated concrete shell structure.

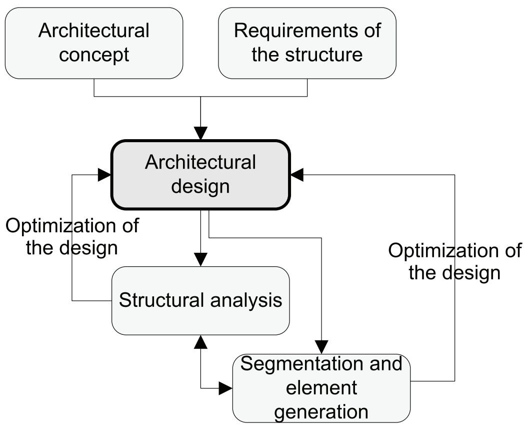


Figure 8.4 Relations of the architectural design with other aspects of the design-process

8.4 The design process

In figure 8.3 the integral design process for the design of prefabricated concrete shells is shown in a very simplified scheme. With the term integral it is meant that the design aspects of the design process are considered at the same time and not separately after each other. This process is determined based on the scheme with the relations between the different aspects shown in the previous paragraph. In this simplified scheme of the design process, the design choices, like the concrete composite, formwork and connection system, are not shown. The results of the different design aspects are used to improve the other aspects of the process in different optimization routines. The result of this process is a design for the shell structure in which all aspects are taken into account and are improved as much as possible.

The architectural design can be seen as the starting point in this design process. On the basis of this design the first calculations and the first segmentation are made. The results of these first calculations and segmentation can be used to modify and improve the shape of the shell. Between the segmentation and element generation process and the structural analysis of the shell a continuous interaction takes place improving both processes. On the basis of the generated elements the production and construction process will be designed. This process will be used to optimise the generated elements and improve the structural analysis of the shell. This process of design, calculation and optimization will be repeated until the required optimization level is reached.

8.4.1 Architectural design

The architectural design is made on the basis of the requirements for the building and a design idea or concept of the architect. On the basis of the architectural design a concept for the segmentation will be made. This can be either on the basis of the architectural concept or on the possible segmentation methods that can be used for this type of surface, not all surfaces can be segmented with every grid generation method. The architectural design and the segmentation of the shell will be used for the structural analysis. On the basis of the results of this analysis the shape will be changed in order to get an improved force transfer and segmentation. The most optimal shape is a real shell structure, without any bending in the shell.

8.4.2 Structural analysis

For the structural analysis of the shell a finite element analysis program will be used. With this program the forces in the shell and the deflections of the shell can be calculated. To perform these calculations more information about the structure than only the shape and the segmentation is needed. The additional information that has to be known to perform a structural analysis is:

- The loads that act on the structure
- The construction material
- The type of connections between the elements
- The connection of the shell with the foundation or supporting structure

The loads on the structure can be defined using the regulations of the country in which the structure will be build.

The construction material is prefabricated concrete. The concrete composite that will be used can vary, but it is assumed that some sort of fibre reinforced concrete will be used. The strength properties and the regulations that have to be used for the calculation are different for the different concrete composites. When (ultra) high performance concrete is used an extra difficulty arises, because for these types of concrete still almost no regulations are made.

The connections between the different elements influence the force transfer in the shell and the stability of the shell. How the forces in the shell are influenced depends on the type of connection system and the stiffness and strength of the connection.

The foundation or the supporting structure of the shell determines the edge conditions of the shell and influences the forces in the edges of the shell.

The results of the structural analysis is an overview over the stresses and deflections of the shell. This information can be used to improve the shape and segmentation of the shell. If for example the deflection in a certain part of the shell is relatively large it can be tried to give this part a larger curvature to reduce the deflections in this part of the shell. The curvature of the shell can also be changed to reduce the bending moments in the shell and improve the membrane action of the shell. The segmentation can be improved, after the structural analysis has been performed, by placing the grid lines not in parts of the shell with high shell forces, because in general the joints are the weakest link of the shell structure.

With the results of the structural analysis some shell properties like the shell thickness and needed reinforcement can be calculated.

8.4.3 Segmentation and element generation process

On the basis of the architectural design the shell surface will be segmented. The segmentation process starts with the generation of a grid over de shell surface of the design. This grid defines the size, shape and arrangement of the elements. This grid will be used during the structural analysis of the shell to determine the positions of the connections.

When the grid is generated the grid lines are used to generate the elements. For each element the thickness and needed reinforcement is determined on the basis of the shell properties that are defined in the structural analysis. If the thickness and the shape of an element are known

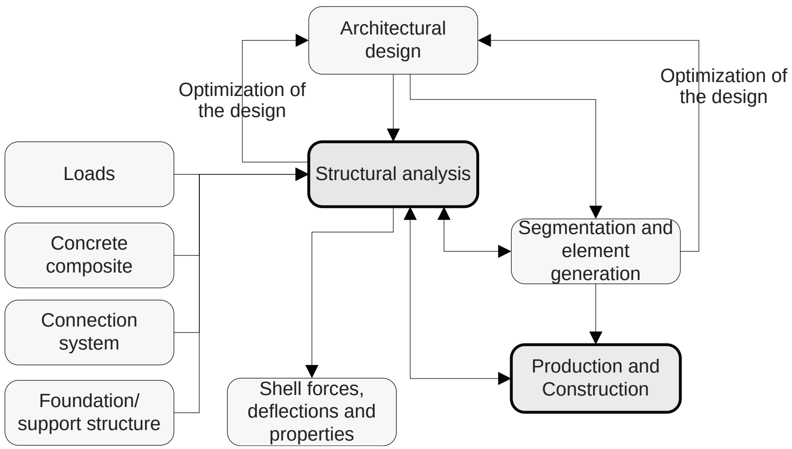


Figure 8.5 Relations of the structural analysis with the other aspects of the design-process.

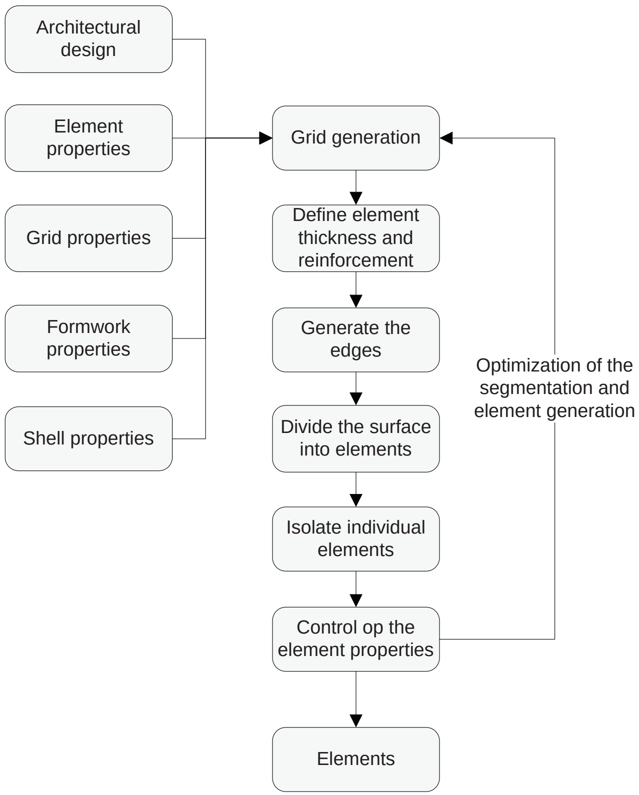


Figure 8.6 The different actions in the segmentation and element generation process.

the edges can be generated. With the design of the edges the type of connection system, the production of the elements and the construction of the shell are taken into account. In the segmentation process the edges of the elements are generated according to this design.

During the segmentation process the following properties of the elements, the grid, the formwork and the shell have to be taken into account:

Elements properties

- The shape of the edges of the elements should be compliant with the connection system, the production method of the elements and the construction of the shell.
- The angle between the edges in the plane and the angle between the edges in the cross-section of the elements may vary from 45^0 to 135^0, but angles around the 90^0 are preferred.
- A minimum size of the elements has to be defined to prevent that the elements become too small and there will be too much elements, this slows down the production and construction process of the shell.

Grid properties

- The grid should consist of double curved elements.
- The elements should all have about the same size.

Formwork properties

- The maximum curvature of each individual element is limited by the curvature that can be achieved with the formwork.
- The maximum size of the elements is restricted by the size of the formwork.
- The design of the edges should be is such way that they can be made with the flexible formwork and the chosen technique to create the edges.

Shell properties

- The thickness of the shell and the needed reinforcement is defined in the structural analysis.

When the segmentation process is complete the different elements of the shell surface have been defined. The generated elements are checked by the given requirements for the elements. These requirement can differ for each structure, here the following requirements are defined:

- Shape of the elements
- Element size
- Element curvature
- Shape of the edges
- Thickness of the elements
- Concrete cover
- Tolerances

When not all elements are designed according to the requirements and the desired optimization is not jet reached the segmentation and the architectural design of the shell have to be improved. When all aspects have reached the required optimization level the design can be considered as be complete.

8.4.4 Production and construction process

The production and construction of the shell are planned on the basis of the generated elements. The generated elements are already controlled during the segmentation and element generation process. So the production of the element in the chosen formwork should be possible. Here the production order of the elements in determined.

During the construction of the shell forces are induced on the elements that are often larger than the service loads. These construction loads have to be taken into account during the structural analysis of the shell carefully. The construction of the shell should be planned is such way that the forces in the element and the partly finished structure do not become too large and that the stability of the shell is ensured at all time. To ensure the stability of the shell the use of scaffolding might be necessary.

The shape of the element must be such that all element can be placed in the right position easily. When this is not the case the shape of the elements has to be adapted.

8.4.5 Optimization

In the design process different optimization loops can be seen. Optimizing the shell surface and the segmentation sounds simple but this is rather complex process.

Structural optimization of the design

Structural optimization is the optimization of the structural behaviour of the design for all load cases. In the case of a shell structure the most optimal structural behaviour is a pure membrane stress in compression for all load cases. This process of optimization is very complex because in most cases the most optimal shape is not obvious and there is a large amount of criteria that has to be taken into account.

In order to automate the optimization of the shell with the use of computers well defined parameters have to be defined that can be optimized. The definition of these parameters is not easy. The last years many computational optimization algorithms have been developed. The optimization of the shell can be performed with computational optimization algorithms, but thorough control of the found solutions is still essential.

Optimization the design for the segmentation

It might also be necessary to optimize the designed surface from the perspective of the segmentation of the shell. Not all surfaces are suitable for the generation of a grid of which the element are equally sized and not to skewed and twisted. When this is the case the surface has to be adapted to make the generation of a more optimal grid possible.

Optimization of the segmentation for the production and construction

The generated elements might not always be the most optimal elements for production and construction. When this is the case the segmentation has to be adapted. The aspects that have to be optimized in most cases are the element size, shape and curvature or the shape of the edges of the elements.

For optimization in the building industry there is most of the time not one solution that is the most optimal in all cases. This makes it even more difficult to automate the optimization processes.

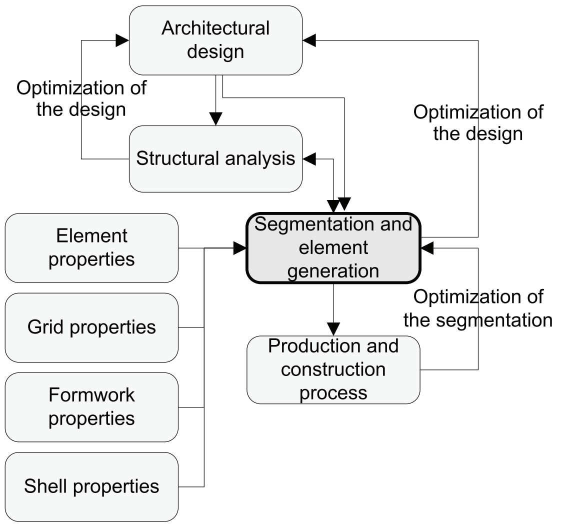


Figure 8.7 Relations of the segmentation and element generation process with the other aspects of the design-process.

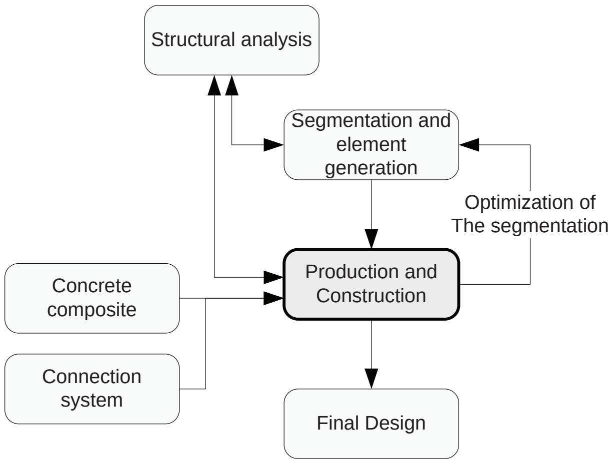


Figure 8.8 The relations of the production and construction process with the other aspects of the design process.

8.5 Conclusions

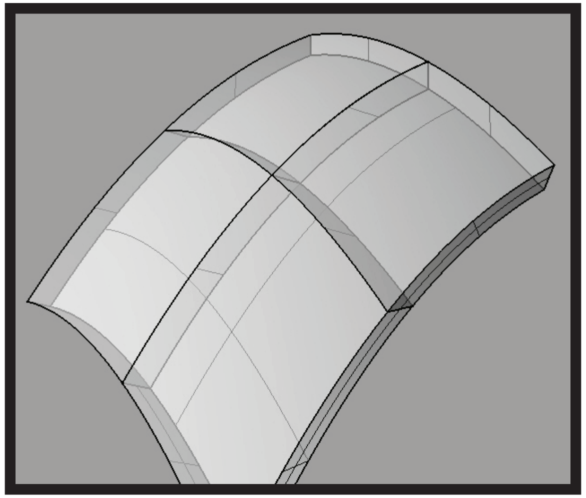
- The goal of performing the process from the initial architectural design to the final design as an integral process is to achieve a maximal optimization of the design with the minimum amount of effort.

- The complete design process can not be automated completely, there will always be some 'human' interaction needed.

- The automation of some parts of the design process can ease the design of complicated structures, but thorough control of the found solutions will always be necessary.

- For optimization in the building industry there is most of the time not one solution that is the most optimal in all cases. This makes it even more difficult to automate the optimization processes.

9. Geometry design tool



In this chapter the segmentation and elements generation process is discussed. The development of the design tool that can be used to generated the elements is based on this process.

A part of a shell that has been divided into different elements

9.1 Introduction

In this chapter the different aspects of the segmentation and element generation process will be discussed. This process considers the whole process from generating a grid on the surface to the detailing of the individual elements and checking the elements by the given requirements. First the different parts of the process that can be isolated are discussed and after this the design tool that has been developed is described.

Rhinoceros 4.0 will be used as the application with which the surface will de designed and segmented. The design tool has been written using Rhinoscript that is based on Visual Basic scripting.

In paragraph 9.2 the generation of the grid is discussed. As outlined in Chapter 3 there are a lot different methods with which a grid can be generated. All these methods have their own advantages and disadvantages. In Chapter 3 no final choice is made for the grid generation method that will be used for the segmentation process. Here a couple methods will be outlined and developed further for the use in the segmentation tool. After this a final choice for the segmentation method can be made. Beside these methods there are many other methods, that might give better results for the segmentation of surfaces, but these methods were not available during this thesis.

On the basis of the grid the surface can be divided in different parts, which will form the elements. After dividing the surface the elements will be given a thickness and the shape of the edges will be defined. The process with which this will be done is described in paragraph 9.3.

Paragraph 9.4 deals with the control of the elements. After generating all elements it has to be controlled whether they fulfil the requirements that are set for the elements. In this paragraph the elements are controlled only on geometrical constraints.

In paragraph 9.5 the designed segmentation tool will be discussed and evaluated. The segmentation tool consists of three different parts; the grid generation, the generation of the elements and the control of the elements.

9.2 Grid generation

9.2.1 Requirements

There are different requirements which the grid generation technique has to fulfil. These requirements ideally will be used as input for the grid generation method. If this is done this will directly result in an ideal grid where all requirements are met. For most grid generation method this will not be the case. Some requirement will be used as input, but others will be used to evaluate the quality of the grid and determine at which points the grid has to be optimized.

General

At first there are some general requirements, which consider the representation of the grid and the types of surfaces that can be described with the grid.

The grid generation method has to be able to describe irregular, double curved surfaces and define the geometry in a digital model. The data, of the generated grid, stored in the digital model should be interpretable by software used in later stages of the design process. For the representation of the surface NURBS are used.

All the grid generation techniques that are described in this chapter can generate a grid over an irregular double curved surface. The data of the grid generation method can all be stored in a digital model. Whether this data can be used easily by other software depends on how the data is stored in the digital model.

Element shape and size

Secondly there are also some requirements that are concerned with the shape and size of the elements.

The transport of the elements from the factory to the site and the size of the formwork limit the size of the elements. Beside the maximum size of the elements it is also preferred that there is not too much variation in the element size. As a result the element size needs to be controlled during the grid generation. In most grid generation techniques the element size can be controlled reasonably during the generation of the grid. After the generation of the grid the size of the elements has to be controlled to determine whether the size of the elements is within the set requirements.

For the production of the elements and the construction of the shell it is better that the elements are not too skewed or twisted and elements with low deformity and increasing uniformity are preferred. From the point of view of production the variation of the angle in the plane of the elements may for example vary from 45° to 135° degrees but angle of about 90° are preferred. Some grid generation techniques generate elements that are pretty equally shaped, but others generate elements with a large variation in shape. Therefore the shape of all elements has to be checked and optimized when necessary after the grid had been generated.

The surface should be divided in double curved elements and the grid generation technique should therefore generate double curved elements instead of approximating the surface with flat elements. The use of the flexible formwork gives some constraints to the curvature of the elements. With this mould it is not possible to create elements with a larger curvature than the maximum curvature of the mould. The grid generation technique should therefore create elements with a curvature that is smaller than the maximal allowable curvature. The minimum radius of curvature of the used mould is set on one meter. Most grid generation techniques can not generate elements with a certain maximal curvature, in this case the curvature of each elements has to be checked after the grid has been generated. When not all elements are curved within the limits the grid or the shape of the surface have to be changed until all elements are curved according to the requirements.

9.2.2 Approach

There are three different methods with which the grid generation over the surface can be approached. In the first method a grid, that is probably not an optimal grid, will be generated over the surface. After the generation of the grid this grid will be optimized in a couple optimization loops in order to get an improved grid, which fulfils the given requirements. With the second method an optimal grid is generated over the surface that just need little improvements after is has been generated. In the last method the surface is approached by an optimal grid that does not need optimization afterwards. This means that there will always be some deviation between the original surface and the generated grid.

These methods all have their own advantages and disadvantages. A less optimal grid can be generated rapidly, while improving this grid takes a lot of time. Generating a more optimal grid is more complicated and takes longer, but when this grid has been generated almost no time is needed to improve it. When the grid is approached with an optimal grid it will take some time to analyse with which grid the surface is approached best and the deviation between the surface and the grid is minimized.

9.2.3 Grid generation techniques

There are different grid generation techniques that can be used for the generation of the grid. On the basis of the evaluation in Chapter 3 four different grid generation techniques are chosen that are available, can be interpreted easily in practice and from which good result are expected. It is possible to find better methods than the ones used in this thesis, but those were not available and could therefore not be used during this thesis.

The different grid generation methods are all tested on three different surfaces. The resulting grids of all three surfaces can be seen in Appendix 3.

Projection

This technique is based on the isotope technique and consists of the projection of a flat grid onto the surface that has to be segmented. Every flat grid can be projected onto a surface, but here only a grid composed of equally sized squares or rectangles is concerned. The grids generated with this method are structured and the size of the elements is reasonably controllable by changing the cell size of the projected grid. A drawback is that when the free formed surface changes in height rapidly there can be a large variation in element size (See Figure 9.1). Another drawback of this method is that the elements at the edges of the surface can be small and badly shaped.

For the generation of a projected grid a simple script has been written that is based on the following steps:

- Define the needed variables.
- Ask the user the required length and width of the grid.
- Ask the user the number of tiles in both directions.
- Create the grid on the ground plane
- Ask the user to define the surface on which the grid has to be projected
- Project the grid on the surface.
- Delete the original grid.

The developed script does not work optimal jet, but gives a good idea of the advantages and disadvantages of the projection of a grid on a surface. To improve the script the size of the initial grid has to be based on the size of the surface, while this grid is now based on the size the user gives. It is also better when the user can give the required size of the cells in the initial grid in stead of the number of cells.

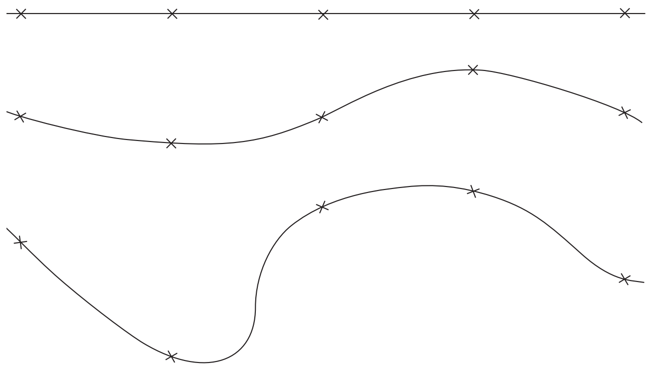


Figure 9.1 A rapid variation in the height of the surface results in a variation in the element size.

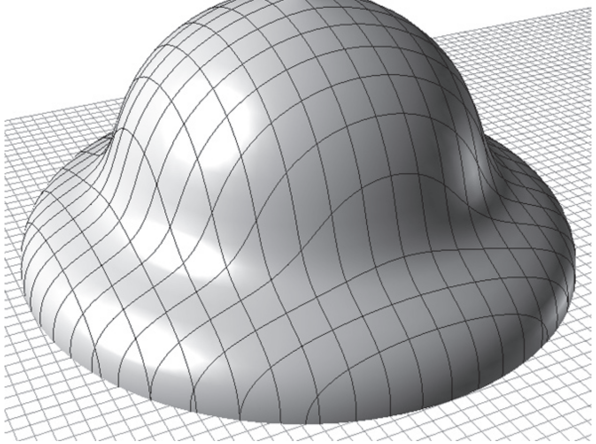


Figure 9.2 Surface of revolution with a projected grid.

These are some comments on the script as it is used here that have to be improved when this grid will be used for the final segmentation tool.

In the Figures 9.2 and 9.3 the script is used to generate a projected grid on two different surfaces. In the different figures it can be seen that the generated script is structured and the elements are equally sized when the surface deviation in height is not to large. When the height of the surface varies rapidly some very large elements are generated. On the edges of the surfaces some small bad shaped elements are generated. These elements have to be improved before the grid can be considered as a good grid. It might be possible to improve the generated grid, and make the elements more equally in size, by making the projected grid more dense in rapidly in height varying areas of the surface.

Rhino mesh

To generate this grid the Rhino command '_Mesh' was used. The result of this command is a polygon mesh that approaches the NURBS surface. The accuracy of this mesh depends on the mesh settings, like 'minimum edge length', 'maximum edge length' and 'maximum distance, edge to surface'. More detailed information about these mesh settings can be found in Appendix 4. These detailed render mesh options control the way in which the NURBS surface converts to the polygon mesh.

The fact that a polygon mesh is created means that the surface is covered with a mesh that has elements with straight edges. To create the desired double curved elements the mesh is projected onto the surface. In this way the grid is placed on the surface an the double curved elements can be generated from the grid.

To generate the grid on the surface the following procedure is used:

- Use the rhino command '_Mesh' to generate a mesh on the surface
- Use the script to extract the mesh wires
- Project the wires on the surface

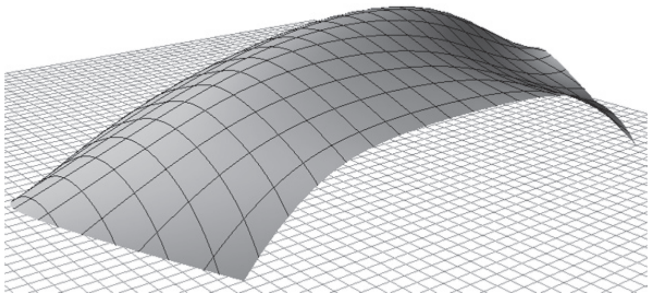


Figure 9.3 Surface 2 with a projected grid.

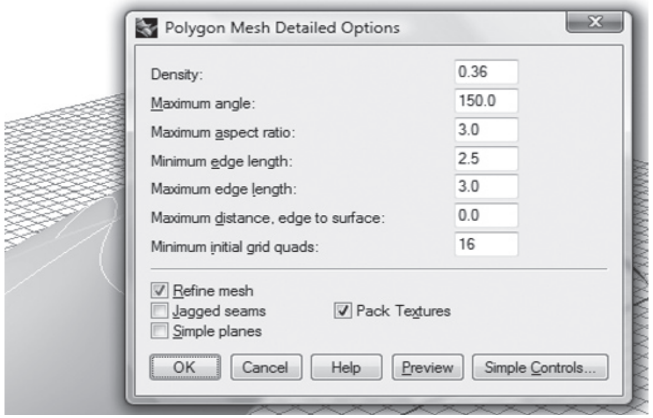


Figure 9.4 The option control box that is used to control the settings for the mesh generation in Rhino.

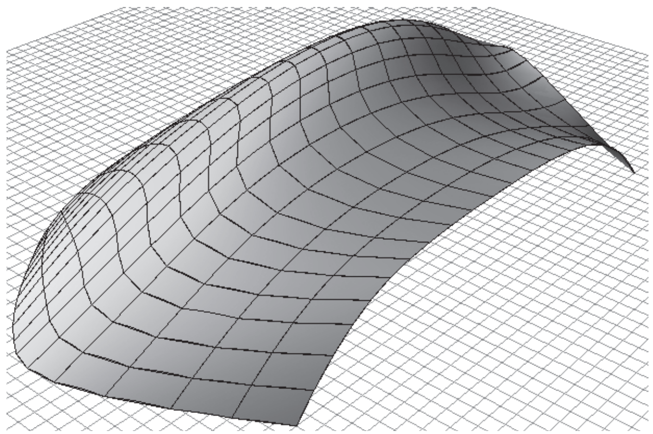


Figure 9.5 Surface 2 meshed with the Rhino meshing tool.

This grid generation method can be used to segment every surface. The quality of the resulting grid can be adapted by changing the mesh settings. This results in a grid of which most elements are quadrangular and equally sized. The generated grid is however not optimal for every surface. For some surfaces the parts that have larger or more difficult curvatures are meshed with triangular or smaller elements.
Another problem rises with the projection of the grid on the surface. This projection does not give a satisfying result for all surfaces. For some surface the projected grid line doe not form a smooth grid over the surface, see Figure 9.5.

Isocurve grid

This type of grid uses the isocurves of the surface to create the edges of the elements. An isocurve is a curved line that runs along the surface in the U and V direction of the surface. Each surface is made of NURBS curves is composed of isocurves.

In Rhino the command 'Extract.isocurve' can be used to find and isolate the isocurves of a surface.

To generate this grid on the surface the following procedure is used:

- Define the surface on which the grid has to be generated.
- Define number of elements in both direction.
- Extract the isocurves in the u direction.
- Extract the isocurves in the v direction.

This method generates a structured grid over the surface. Whether this grid generation method generates a grid with equally sized elements depends on the placement of the isocurves over the surface. When the isocurves are not equally divided over the surface the size of the element can vary a lot over the surface. The place of the isocurve can be influenced by 'rebuilding' the surface. The rebuild command can be used in Rhino to reconstruct a surface to a specified degree and a specified number of control

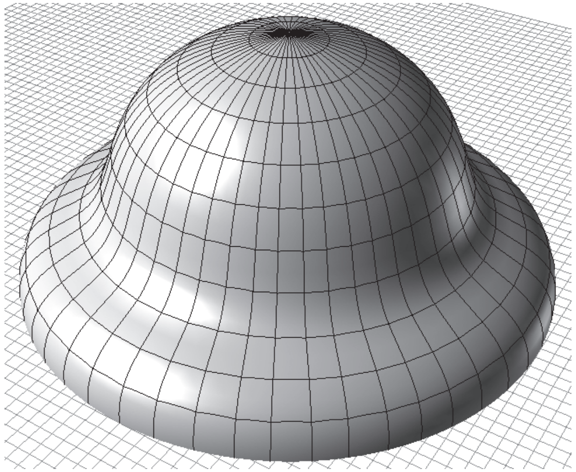


Figure 9.6 Surface of revolution meshed with the Rhino meshing tool.

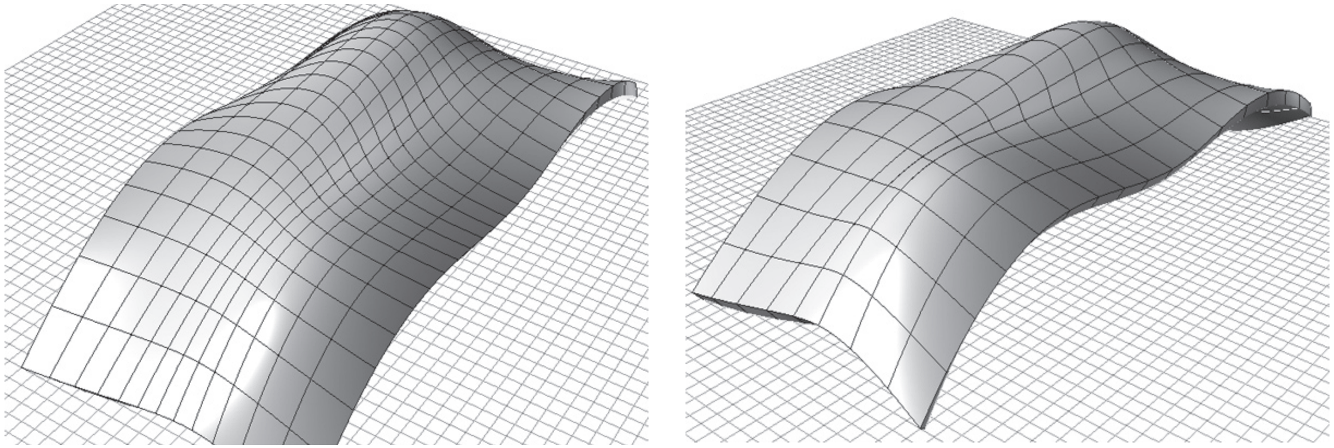


Figure 9.7 An isocurve grid generated over surface 1 before rebuilding the surface (left) and after rebuilding the surface (right). The maximum length of the edges is in both grids the same.

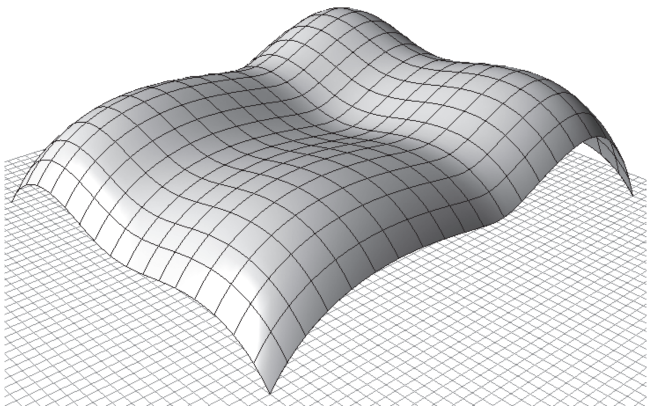


Figure 9.8 A translational grid generated over a surface.

points. This means that the number of isocurves in both directions can be changed and the isocurves are placed more equally spread over the surface. Due to the 'rebuilding' of the surface there might be some deviation between the original and the rebuild surface in some areas of the surface. The size of this deviation is in the order of a couple millimetres. It is assumed that this deviation should not cause any problems if it is performed in an early phase of the design process.

Translational grid

A translational grid is an almost optimal grid that consists of equally sized elements that also do not differ too much from each other in shape. Optimization of a translational grid is hardly possible, but most of the time not necessary.

The main problem with translational grid is that they can only be generated on a translational surface. This grid can only be used for a non-translational surface when this surface is approached with a translational surface. This is possible for a lot surfaces, but not very easy to achieve.

9.2.4 Evaluation

The different methods are evaluated on the basis of the requirement for the grid given in paragraph 9.2.1.

The projection method generates a structured grid that consists of quadrangular elements. The size of the elements can only be partially controlled. When the surface varies rapidly in height the element size may also vary over the surface. The shape of the elements is in general very nice, the elements are not too skewed or twisted. Only the elements at the edges of the surface can have irregular triangular shapes and can be very small.

The Rhino meshing method generates a hybrid grid over the surface. This makes that the generated grid can be composed of both quadrangular and triangular elements. These size of the elements can be controlled pretty well for most surfaces. The elements generated by the Rhino mesh tool approach the original surface with elements that have straight edges. The grid has to be projected onto the surface to get the desired grid. The only problem with projecting the grid lines is that they do not follow the surface nicely, but can have a kink at the edge of the elements.

The isocurve grid generates a structured grid that is based on the isocurves of the surface. This means that the quality of the grid depends on the placement of the isocurves over the surface. The placement of these isocurves can be improved by 'rebuilding' the surface. The element size and elements shape can vary a lot over the surface, but this can be improved by rebuilding the surface.

The translational grid is a structured grid that generates equally sized elements. The size of the elements can be controlled very well by varying the distance between the generator and the directrix. The shape of the elements varies a bit over the surface, but in general the elements are never to skewed and twisted. A large drawback it that this type of grid can only be used for the generation of a grid over translational surfaces.

The isocurve grid will be used for the development of the design tool. This grid is chosen, because it is an easy to implement method that generates a structured grid with reasonable equally sized elements that are not too skewed and twisted. The only major drawback of this grid is that is does not give a good grid for every surface. But there is no grid generation method available that is capable of generating an optimal grid for every surface.

9.3 Generation of the elements

When the grid has been generated over the surfaces. The next task of the design tool can start. This task is the generation of the elements. The process of element generation can be divided into four different parts. These parts are, in order of execution:

1. Generation of the edges.
2. Division of the surface into elements.
3. Creation of the inner surface.
4. Creation of the elements.

9.3.1 Generation of the edges

The generation of the edges can be divided in two different parts, the generation of the lines for the edges and the generation of the actual edges.

The edge lines are generated at each point on the surface where two grid lines cross each other. The edge lines are generated with the right angle to the surface and the length of the lines is equal to the thickness of the edge. When all edge lines are generated the edges can be made. The edges are made by creating a ‘sweep’ surface with two rails. The ‘sweep2’ is a Rhino command that creates a surface through a profile curve that defines the surface shape and two rail curves that define the surface edges. In this case the grid line is the profile curve and the edge lines are the rail curves that define the edges of the surface.

This type of edge generation makes that the edges always have the right thickness and corners of the different elements are always perfect aligned. Beside this the generation of the edges in this way can be used for all shell slicing methods, like perpendicular or horizontal. The different methods can also be combined by giving the different edge lines a different orientation with surface.

A point of attention with edges that are not perpendicular to the surface is that the length of the edge is larger than the thickness of the shell. So the length the generated edge line also has to be longer than the thickness of the shell.

9.3.2 Division of the surface into elements

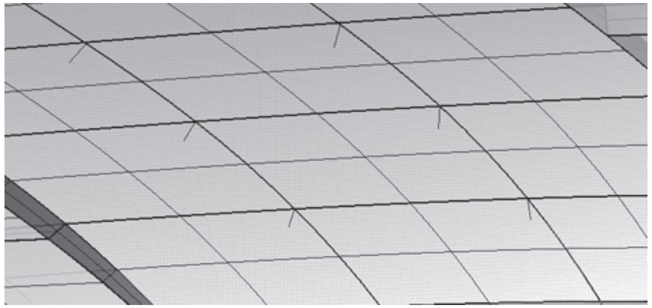
The surface will be divided into elements on the basis of the generated grid. The grid line mark the place of the edges of the elements. In Rhino script, that is used to make the design tool, there is no good method available for the division of the surface into elements. Therefore the Rhino command ‘split’ will be used to divide the surface into elements. A drawback of using this Rhino command is that there is some user interaction needed during the execution of the design tool. The user has to select the different objects that are needed to split the surface into elements.

9.3.3 Creation of the inner surface

There are two different methods with which the inner surface van be created. The first method is suitable for edges that are perpendicular to the surface and the second method is suitable for edges with a different angles to the surface.

For both methods the Rhino command ‘offsetsrf’ will be used to generate the inner surface. This command copies the selected surface in such way that the locations of the copied surface are at the same specified distance from the original outer surface. This distance is measured perpendicular to the original surface at every location and has to be equal to the element thickness.

In the first method an inner surface of the elements can be created by offsetting each individual element surface. In the second method the inner surface is generated by offsetting the complete outer surface. After the generation of the inner surface the surface can be divided into the ele-



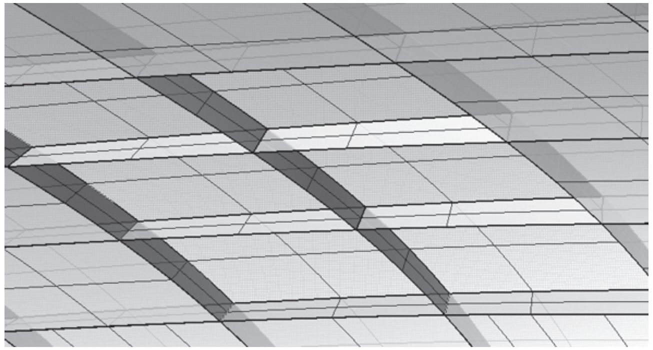


Figure 9.9 Edge generation by first generation the edge lines (above) and the creating the edges (below).

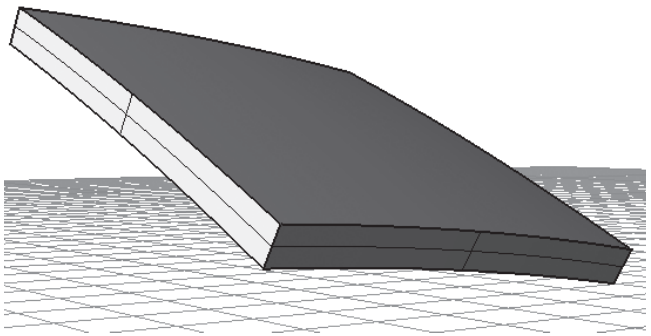


Figure 9.10 Element with edges generated according to the perpendicular edge generation method.

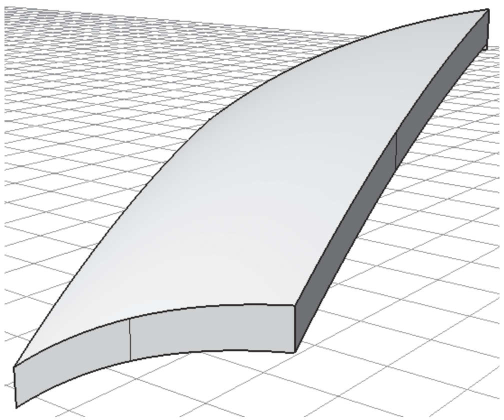


Figure 9.11 Element with edges generated according to the combination edge generation method.

ments. For the splitting of the inner surface the edges are used to determine the place of the edge on the surface.

The first method can only be used when the edges are generated perpendicular to the surface. When this is not the case the inner and outer surface of an element do not have exactly the same shape and the edges will not be aligned with the inner surface. The second method can be used in both cases, with the edges are both perpendicular or not perpendicular to the surface. Which method will be used depends mainly on the chosen angle between the edges and the shell.

9.3.4 Creation of the elements

After the generation of the different parts of the elements the elements can be created. This can de done by grouping the different parts, the four edges, the inner surface and the outer surface in one group. In this way each element can be isolated easily during the design process.

9.3.5 Method of slicing the shell

In Chapter 6 different methods for the generation of the edges are discussed. The two best methods are the combination method of horizontal and vertical slicing and the perpendicular method. Both methods are discussed with some special attention to the implementation of the method in the design tool.

Perpendicular

With the perpendicular edge generation method the edges are all perpendicular to the surface. So the angle between the edges in the cross-section of the element is always 90 degrees. A drawback of this method is that the edges can be in torsion.

To use this method the edge lines have to be oriented perpendicular to the shell surface. This can be done by determining the normal vector of the surface at the place of the edge line and the placing the edge line in the same direction. The length of the edge ling is equal to the thickness of the shell. The edges are created with the ‘sweep2’ command.

Combination

With the combination method the edges are always either horizontal or vertical. The choice for a horizontal or vertical edges is made on the basis of the angle between the edge and the surface. For each edge the orientation that gives the largest angle between the surface and the edge is chosen. The edges that are generated with this method always have an angle of minimal 45 degrees with the surface.

Determining the edge line that has the right orientation to the surface is a little more difficult that with the perpendicular method. First the line normal to the surface at the place of the edge line is determined. This line will be rotated to a horizontal or vertical orientation. The angle between the surface and the horizontal and vertical orientation of the edge line determines which orientation will be chosen. The edge line will always be rotated in such way that it is still perpendicular to one of the two grid lines at the surface.

Figure 9.12 The normal vector of the surface will always be rotated in the plane of a grid line to the horizontal or vertical direction. The rotated edge line is still perpendicular to the other grid line.

The length of the edge line has to be longer than the thickness of the element. The exact length of the edge can be determined with:

$$l = d/\sin\alpha$$

In which l is the length of the edge line, d is the thickness of the shell and α is the angle between the edge line and the surface.

Evaluation

With both slicing methods described above the edges of the elements can be generated very well. An advantage of the combination method is that the edges of the elements are flat instead of in torsion. This can give some advantages during the construction of the shell, but if this really is the case depends on the construction method and the used connection system. On the other hand the perpendicular method might have some advantages for the load transfer between the elements

The perpendicular method is easier to implement in the design tool, because the normal vector of the surface does not have to be rotated to get the right orientation of the edge line, as with the combination method. Beside this the length of the edge lines does not need to be adapted to the orientation of the edge. The generation of the inner surface of the elements is also easier to implement for the perpendicular method.

9.3.6 Evaluation

For the design tool the choice is made for the perpendicular edge slicing method for the elements that are not at the boundary of the shell. The edges of the elements at the boundary of the shell that are placed on the foundation are generated as a horizontal edge. This makes the construction of the foundation and the placement of the first row of elements a lot easier.

This choice for the perpendicular edge generation method makes that the inner surface of the shell can be generated by offsetting each individual element surface. Only the alignment of the boundary edges with the inner surface are a point of attention, because these elements are generated horizontal.

The generation method makes that the alignment of the edges at corners of the elements is always correct. And the perpendicular edges all have the right size.

For the isolation of the individual elements the edges have to be duplicated to make sure that the groups of each elements can contain all edges.

	Combination method	Perpendicular method
Angle between the edge and the surface.	$45 < \alpha < 135$	$\alpha = 90$
Shape of the edge.	Flat	In torsion
Orientation of the edge.	Horizontal or vertical	Perpendicular to the surface
Ease of implementation	A little difficult	Easy

Table 9.1 Overview of the properties of the different edge slicing method

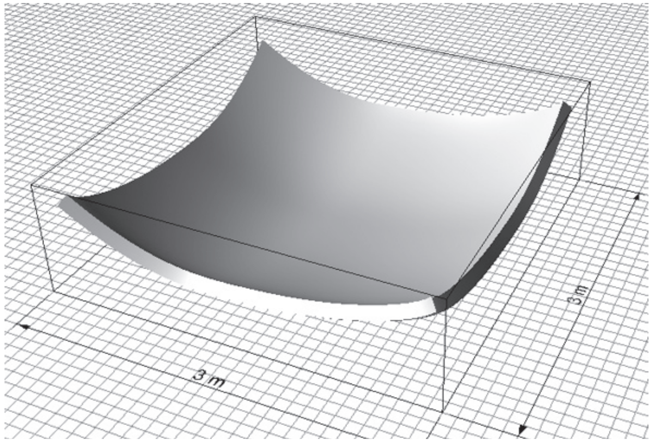


Figure 9.13 The elements should fit in a box with edge with a length of 3 meter.

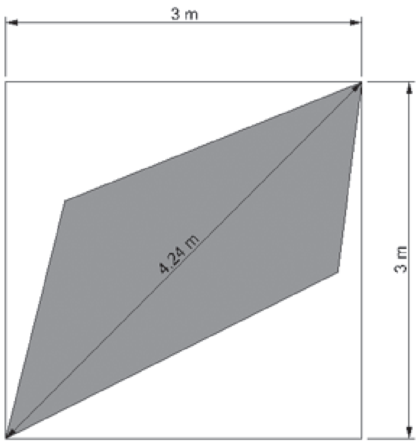


Figure 9.14 The maximum length of the diagonals of the projected element is 3√2 = 4,24 m

9.4 Element control

After generation all elements have to be checked to determine whether they fulfil the requirements that are set for the elements. In this paragraph the elements are controlled only on geometrical constraints.

9.4.1 Requirements

The requirement on which the elements will be controlled are:

- Element size
- Angles of the corners in the plane of the elements
- Element curvature

The maximum elements size is set by the size of the flexible formwork and the size of the truck with which the elements will be transported. It is defined that all elements should fit in a square box of which the length of the edges is maximal 3 m.

The minimum angle in the cross-section is set by the properties of the concrete, if the angles become to small the corners become to vulnerable. The minimum angle of the corners of the elements in the plane of the element have to be larger than 45 degrees.

The limits in the element curvature are set by the maximum curvature that can be made with the flexible formwork. In this case an adjustable formwork will be used for the production of the elements. The minimum curvature that can be made with this mould is $k = 1\ m^{-1}$.

The minimal angle of the corners of the edges in the cross-section of the elements was also set at 45 degrees. This value does not need to be controlled. The design tool does only generate angles that are larger than 45 degrees.

9.4.2 Control of the element size

The requirement for the elements size is that the elements should fit in a box with edges of 3 meter. When the angles between two edges of the element in the plane of the element are 90 degrees, this means the edges of the element should be maximal 3 meters. Because of the curvature of the edges of the elements the real width of the element is a little bit smaller than 3 meter. Only the generated elements do not all have angles between the edges of 90 degrees. When the angle is smaller or larger the maximum length of the edge of the element is also smaller.

The best method to determine wether the elements should fit in this box is to project the shape of the element on plane and measure the length of the diagonals. If the length of diagonals is smaller than 3√2 the element should fit in the box. This method is pretty complex to implement in the design tool. To make the method easier to implement the distance between two diagonal corners of each element is measured. This length can be longer, than the projected distance between the corners, due to the difference in height of the corners. This makes that the generated elements that are a little smaller than the actual maximal size of the elements.

The grid generation method is made in such way that the grid that is generated does always fulfil the size requirements. When not all elements are within the size limit a finer grid is generated until all element are within the size limits.

9.4.3 Control of the angles between the edges

The angle between the edges of the elements in the plane of the element has to be larger than 45 degrees. It is not necessary to measure all angles in the grid, because some angles have the same size due to geometrical rules. Figure 9.15 shows these rules. The angles marked with a always have the same size. The angle marked with be do also have the same size. Besides this the sum of the angles a and b is always equal to 180 degrees.

Due to these rules not all angles between the edges of the elements have to be measured. When only the angles marked with a * in the grid in figure 9.16 are measured all other angles can be calculated. In general it can be said that when the measured angle is between 45 and 135 degrees, the other angles in the square are also between 45 and 135 degrees. So if one measures angel does not fulfil the set requirements all the angles in that point to not fulfil the set requirements.

When not all angles fulfil the set requirements the segmentation or the shape of the surface has to be optimized until all angles do fulfil the set requirements.

9.4.4 Control of the element curvature

The curvature of the elements should be larger than 1 m^{-1}. The curvature of the elements can only be determined after the shell has been split into the different elements. When the radius of curvature of each elements has been measured, the data can be analysed to find whether the maximum radius of curvature is not exceeded.

In the case that some element do not fulfil the curvature requirements the surface of the shell has to be adapted. It is useless to change the segmentation of the shell, because the problem is in the curvature of the shell and the segmentation does not change this.

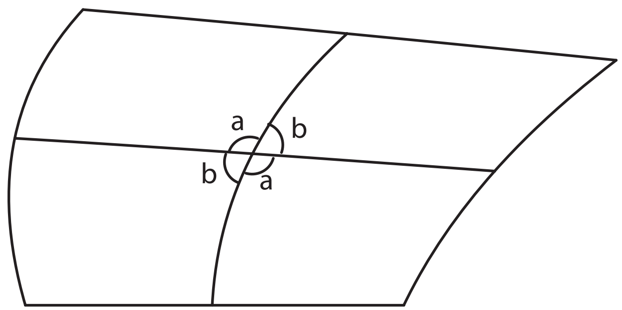


Figure 9.15 This section from a grid show that the angles a an the angles b are equally sized. Besides this the size of angle a + b is always equal to 180 degrees.

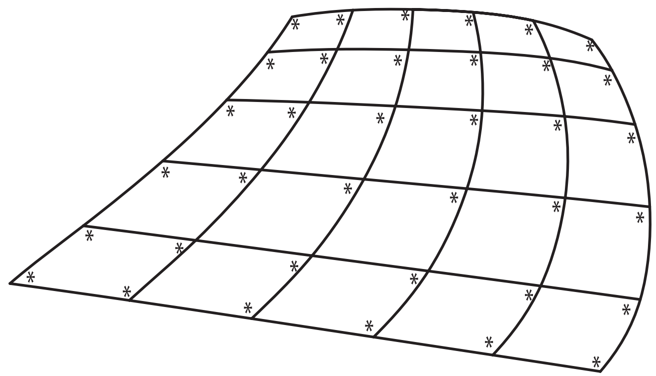


Figure 9.16 In a grid only the angle marked with a * have to measured to know the size of all angles between the edges of the elements.

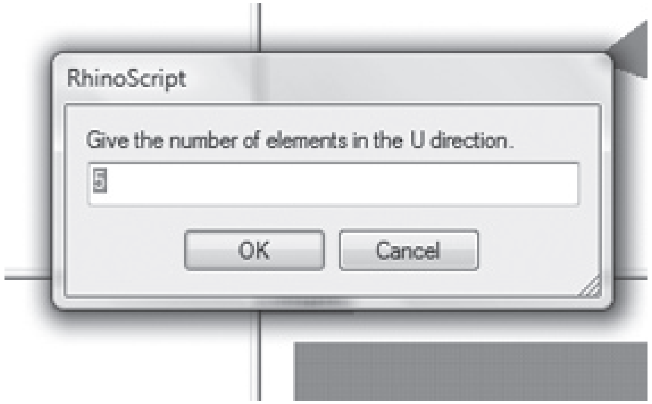


Figure 9.17 The option box in which the user has to give the initial number of elements for the generated grid.

9.5 Design tool

To for the design tool the different parts described in the previous paragraph are combined. The global execution procedure of the design tool can be seen in Figure 9.17. In this paragraph the total process of the complete design tool is discussed, tested and evaluated.

9.5.1 Description

Input

To determine the surface that has to be segmented and divided into elements, the surface has to be selected by the user. The user has to give the initial number of elements, the thickness of the shell and the maximum length of the edges in control boxed like the one in Figure 9.17.

Grid generation

The first grid is generated with the number of elements that is given by the user. The isocurves are divided over the surface by a division made on the basis of the domain of the surface. As a result for some surfaces elements with a large variation in size are generated. To improve the division of the grid lines over the surface the can be rebuild before the generation of the grid. The user has the choice to rebuild the surface before the grid will be generated. This rebuilding can cause some deviation of the new surface with the original surface.

Measure diagonal length

To determine whether the generated grid has the right element size the length between two diagonal corners of all elements is measured. When the length of this diagonals is longer that the maximum diagonal length the generated grid is removed and a new grid is generated in which the number of elements is increased. This process will be repeated until all edges are within the limit for the edge length.

Generate edges perpendicular to the surface

The edge lines are created at the crossing points of the grid lines. At first all edge lines are generated perpendicular to the surface. The edges are created by sweeping the grid line on the surface along the two matching edge lines. The edges created in this way are perfectly aligned at the corners of the elements and have the right thickness, when the edge lines have the right thickness.

Create horizontal edges

The edges of the boundary elements that will be placed on the foundation or supporting structure should be horizontal. So for these edges the perpendicular edges have to be replaced by horizontal edges. This can be done by rotation the edge lines of these edges in the right direction to the horizontal plane. The length of these also has to be adapted. After this rotation of the edge lines the new horizontal edges can be created. This replacing of the boundary edges is not implemented in the design tool.

Split the outer surface and create the inner surface

The inner surface is created by offsetting the already in elements divided outer surface. This means that each individual element of the outer surface is used to create the inner surface of that elements.

Determine length of the edges

The data of the length of the edges will be exported to a .txt-file to make analysis of the data possible.

Determine angles

The angle between the edges of the elements is measure by measuring the angle between to grid lines. The measured angles are also exported to a .txt-file to make analysis of the data possible.

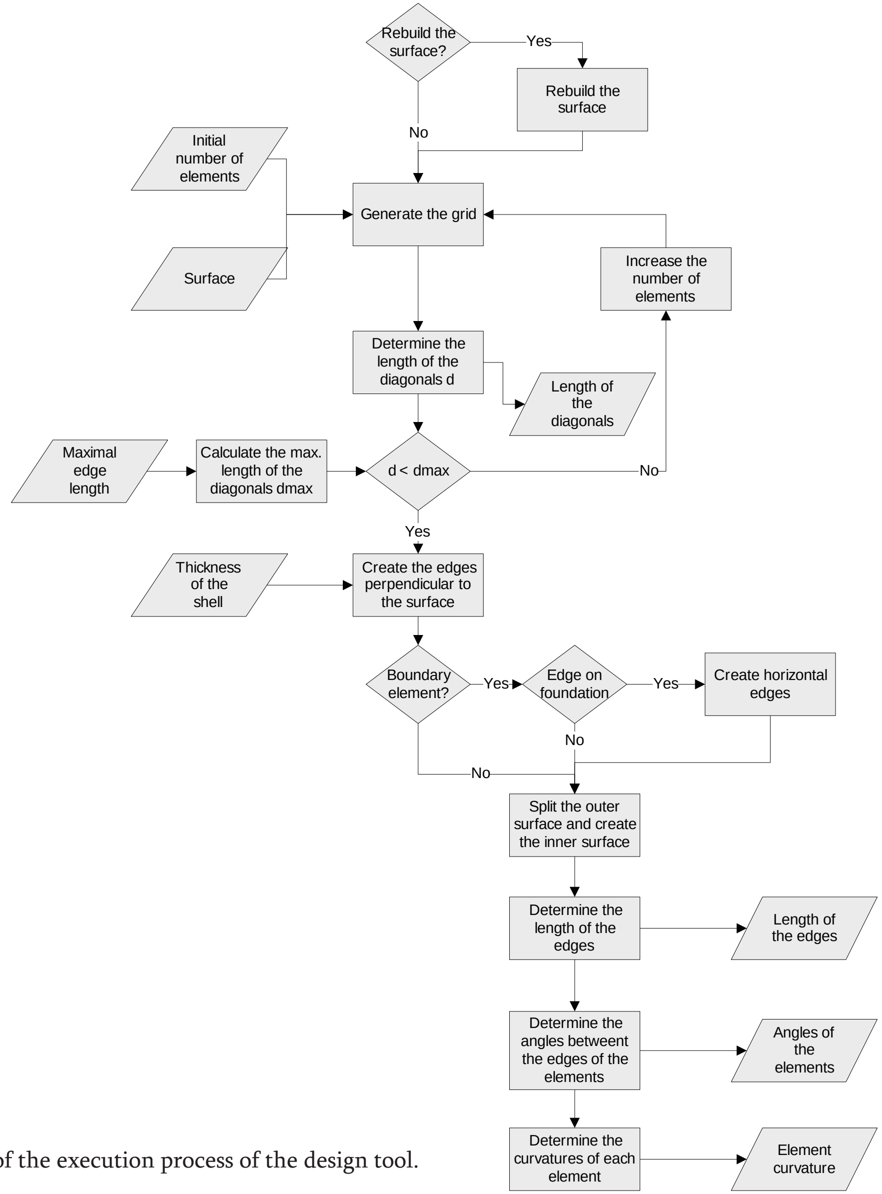


Figure 9.18 Diagram of the execution process of the design tool.

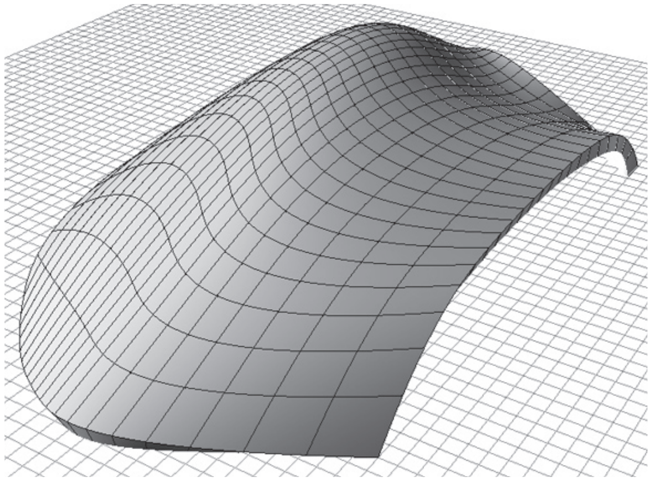


Figure 9.19 Surface 2 with an isocurve grid.

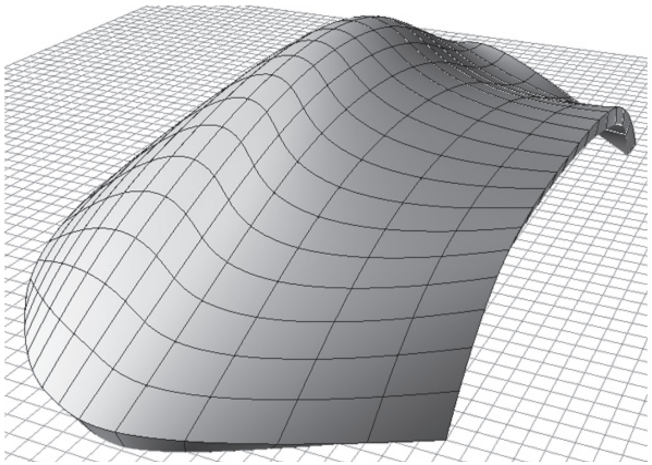


Figure 9.20 Surface 2 with an isocurve grid, after the surface has been rebuild.

The colour of the grid lines of the angles that do not met the requirement is changed to visualize the angles that do not fulfil the requirements for the angle between the edges in the plane of the surface.

Determine curvature

The curvature of the element is measured for each element. The results are exported to a .txt-file to allow further analysis of the element curvature.

9.5.2 Testing and evaluation

The three test surfaces are segmented twice, for both the original and rebuild surface, with the design tool to test the tool and evaluate the results. Results of generated grids can be found in appendix 3.

Grid generation

The used grid generation method is the iscurve grid. The test surfaces show that the grid can be improved by rebuilding the surface. In the rebuild surface the average elements size approximates the maximum element size better and less very small elements are generated. This rebuilding however gives some deviation in the shape of the new surface compared to the original surface.

The average angle between the edges for the different surfaces is between 80 and 110 degrees, but almost for every surface there are some angles that are not within the set requirements. A large drawback of the chosen grid generation method is that the angles between the grid lines cannot be changed or improved, because the grid is based on the isocurves of the surface.

The curvature of the elements is not really influenced by the rebuilding of the surface. When the curvature of the surface is too small to be made with the flexible mold the surface has to be adapted or the choice has to be made to cast these particular elements with another type of mould.

Element generation

The generated edges are nicely aligned in the corners of the elements. The length of the edges is also generated correctly. Due to the generation of the edges perpendicular to the surface the edges can be in torsion. The inner surface of the shell is nicely aligned with the edges of the elements.

The shape of the boundary edges should be dependent on the shape of the foundation. The edges of the elements that are placed on the foundation should be horizontal. This is not implemented in the design tool, so these edges are still generated perpendicular to the surface.

The outer surface is divided into elements using the Rhino command split. For the division of the outer surface into element some user interaction is needed. The user has to define the outer surface and the grid lines that will be used to split the surface. It is better that no user interaction is needed to split the surface. But in the rhino scripting language no good alternative was found that could replace the Rhino command and does not require any user interaction.

Element control

The size of the elements is controlled by measuring the distance between two diagonal corners of the elements. By analysing this distance it can be determined whether the element fits in the box with the prescribed size. This control work good, it can only result in elements that are a little smaller than the prescribed size when the difference in height between the corners is larger. The control of the angles between the edges of the elements does work properly. The control for the element curvature does also work properly.

Optimization

The optimization for the element size works very well, all generated elements are within the given requirements.

The optimization of the grid with respect to the angles between the edges is not possible due to the type of grid generation method that has been chosen.

To optimise the curvature of the elements the shape of the surface has to be optimized. The adaptation of the grid does not change the curvature of the surface.

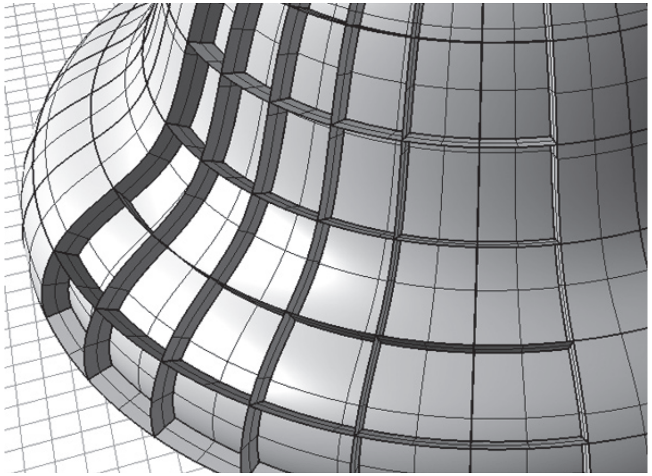


Figure 9.21 Detail of the generated elements of the surface of revolution.

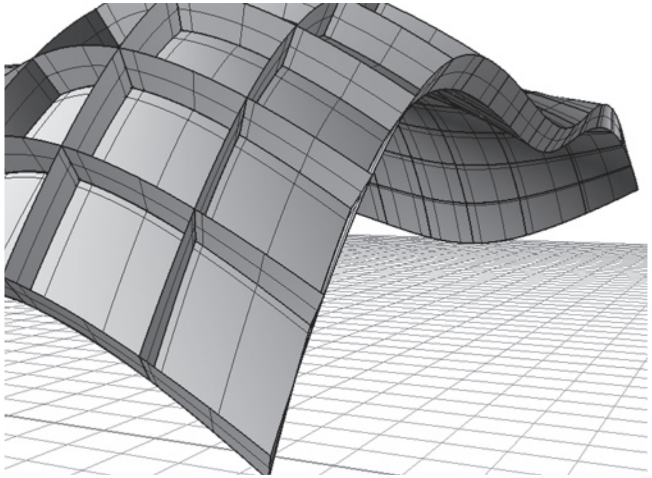


Figure 9.22 Detail of the generated edges of surface 1.

9.6 Conclusions

- The used grid generation method is the iscurve grid. The grid can be improved by rebuilding the surface. This rebuilding however gives some deviation in the shape of the new surface compared to the original surface.

- The average angle between the edges for the different test surfaces is between 80 and 110 degrees, but almost for every surface there are some angles that are not within the set requirements.

- A large drawback of the chosen grid generation technique is that the angle between the edges of the elements cannot be changed. This means that optimization of the elements shape is not possible.

- All elements of the grid are different. This is not a problem when the adjustable formwork will be used for the production of the elements. It is no problem to change the shape of the mould for every element. However, the production of the elements can faster when some elements have the same shape and the mould does not need to be adjusted for each elements.

- The edges are generated perpendicular to the surface. This means that the edges can be in torsion.

- The shape of the boundary edges, that are placed on the foundation, should be horizontal. This is not implemented in the design tool, so these edges are still generated perpendicular to the surface.

- For the division of the outer surface into elements some user interaction is needed. It is better that no user interaction is needed to split the surface.

- The size of the elements is controlled by measuring the distance between two diagonal corners of the elements. This control work good, it can only result in elements that are a little smaller that the prescribed size due to the difference in height between the corners is larger.

- The control of the angles between the edges of the elements does work properly.

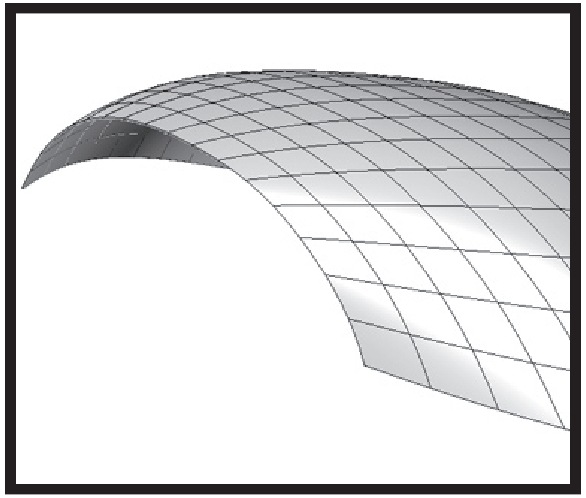
- The control for the element curvature does work properly.

- The optimization for the element size works very well, all generated elements are within the given requirements.

- The optimization of the grid with respect to the angles between the edges is not possible due to the type of grid generation method that has been chosen.

- To optimise the curvature of the elements the shape of the surface has to be optimized. The adaptation of the grid does not change the curvature of the surface.

10. Case study



In this chapter the case study that is performed is described. To see if the chosen design process describes the relations between the different aspects correctly and to further test the design tool a preliminary design is made for the designed shell surface.

10.1 Introduction

In this chapter the performed case study is described. To see To see if the chosen design process describes the relations between the different aspects correctly and to further test the design tool a preliminary design is made for the designed shell surface.

First the design and the design concept of the shell are introduced in paragraph 10.2. After this the structural analysis of the preliminary design is performed in paragraph 10.3. In paragraph 10.4 the shape of the elements, the connections and the foundation of the shell are discussed. After this the generated elements and the production and construction of the shell are discussed in the paragraphs 10.5 and 10.6. In the last paragraph some concluding remarks about the case study are given.

10.2 Architectural design

10.2.1 Concept

Before the shape of the design is introduced the design conditions will be set that function as a starting point from which the design will be developed.

The following points will be considered during the development of the architectural design:

- The building will have a irregular double curved geometry
- The structure will be designed using 3D modelling software.
- The design will be a shell structure and should structurally work as a shell.
- The design will be constructed in prefabricated concrete and must be suitable for this construction method.

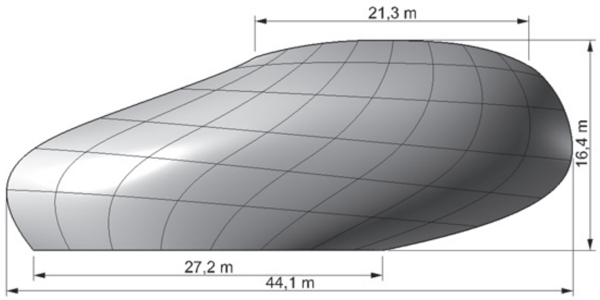


Figure 10.1 Top view of the shell design with some dimensions.

10.2.2 Model

The design that will be analysed in this case study is presented in the figures on this page. The size of the shell can also be seen in Figures 10.1 and 10.2.

In arch of the shell a glass facade will be placed. It is assumed that this facade is self supporting and does not carry any load to the shell surface.

The shell will be constructed as a prefabricated concrete structure. The foundation of the shell will be made of in-situ concrete. The design of the connection system will be defined during the design of this shell.

The elements will be made with a flexible formwork as defined earlier in this Master's thesis. The concrete that will be used for the production of the elements will be a high performance fibre reinforced concrete. The fibres in the concrete are steel fibres with different sizes. The average compression strength of the concrete will be about 100 N/mm^2.

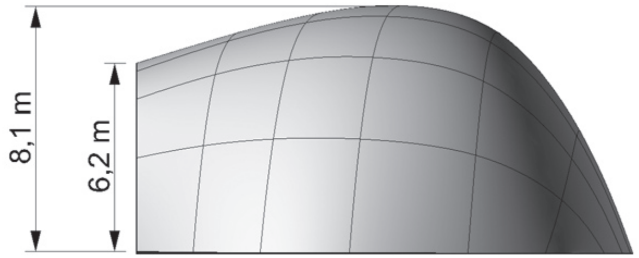


Figure 10.2 Side view of the shell design with some dimensions.

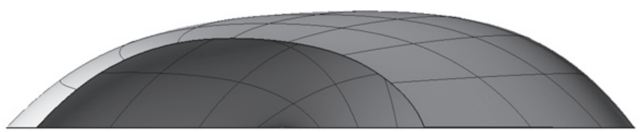


Figure 10.3 Side view of the shell design.

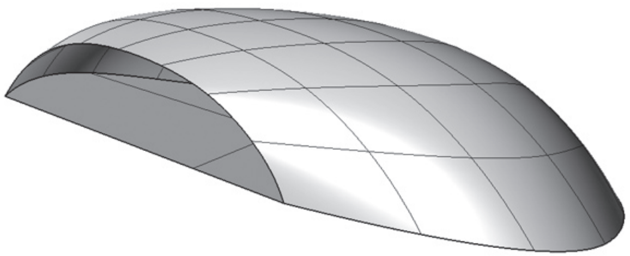


Figure 10.4 Perspective view of the shell design.

10.3 Structural analysis

For every structure that will be build the strength, stiffness and stability have to be verified according to the valid building codes. In Europe the valid building code is the Eurocode, but every country can add some local regulations to the Eurocode.

The shell will be analysed with the help of Diana, a finite element analysis program. To perform this analysis the loads, load cases an the shell properties have to be known. With the results of the calculations the performance of the designed shell can be analysed and improved

10.3.1 Load definition

There are different types of loads that have to be taken into account during the design of a structure. The most important types of loads are listed below.

Gravity loads

Gravity loads include both dead and live loads. Dead loads may be defined as the self-weight of the permanent construction, they include the structural, non-structural elements and the permanent installations that are present in the building. Live loads are not permanent in nature and vary depending upon the usage of floor area in the building. These include people loading, furniture loading and vehicle loading.

In this case the design concerns a shell structure that forms the roof of a building. Here only the dead loads are taken into account. The live loads are left out of consideration in the structural analysis of the design. This is because the live loads on a roof structure are not very large due to the shape and function of the roof. Beside this taking the live loads into account, during the analysis of the preliminary design, would make the analysis unnecessary complicated.

The size of the dead load depends mainly on the material used for the shell, in this case a fibre reinforced concrete composite, and the thickness of the shell.

Snow loading

With the design of a roof of a structure snow loading has to be taken into account. The way in which the snow falls on the roof depends on the shape of the roof, the roughness of the roof, the thermal conditions of the roof, the presence of other buildings and the local climate.

In the Netherlands the size of the characteristic snow load on the ground is $s_k = 0{,}7$ kN/m^2. The actual design loads depends on the shape of the roof.
The snow load on the roof can be calculated with:

$$s = \mu_i \, C_e \, C_t \, s_k$$

In which μ_i is the snow load shape coefficient, C_e is the exposure coefficient and C_t is the thermal coefficient. According to the Dutch attachment to the Eurocode the exposure coefficient and the thermal coefficient are $C_e = C_t = 1{,}0$. The size of the snow load shape coefficient depends on the shape of the roof and is in this case $\mu_i = 0{,}8$. With the factors that take into account the shape op the roof, the snow load becomes:

$$s = \mu_i \, C_e \, C_t \, s_k = 0{,}8 * 1{,}0 * 1{,}0 * 0{,}7 = 0{,}56 \text{ kN/m}^2.$$

Wind loading

The wind loading on a structure also depends on different factors. These factors are the presence of other buildings in the surrounding of the building, the shape and height of the building and the local climate.

The wind pressure on the outside of a building can be calculated with:

$$W_e = q_p(z) \, C_{pe}$$

The wind pressure on the inside of a building is:

$$W_i = q_p(z) \, C_{pi}$$

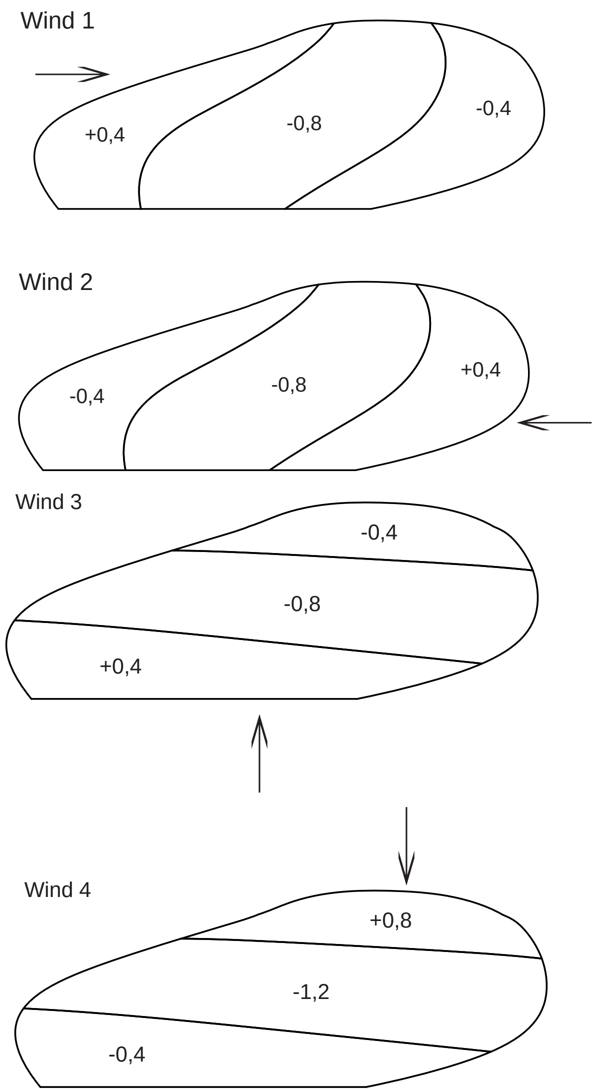


Figure 10.5 Compression coefficients on the surface for the different wind directions.

In which $q_p(z)$ is the extreme wind pressure at a certain height z and C_{pe} and C_{pi} are the compression coefficients of respectively the outer and inner pressure.

The total wind pressure on a building is:

$$W = W_e + W_i$$

With the compression coefficients of the outer pressure the building shape and wind direction can be taken into account. The coefficients for a wind load on the shell from different directions are shown in figure 10.5.

The compression coefficient of the inner pressure can have two different values, over pressure or under pressure. The size of the coefficients is then respectively C_{pi} = + 0,3 or C_{pi} = - 0,3.

The extreme wind pressure $q_p(z)$ = 0,62 kN/m^2. This pressure is defined for a building with a height of 8 meter in a surrounding with buildings in wind area two.

Thermal loading

Daily and seasonal changes in shade, air temperature, solar radiation and re-radiation, will result in variations of the temperature distribution within individual elements of a structure. The magnitude of the thermal effects will depend on local climatic conditions, together with the orientation of the structure, its overall mass, finishes, and in the case of building structures, heating and ventilation regimes and thermal insulation.

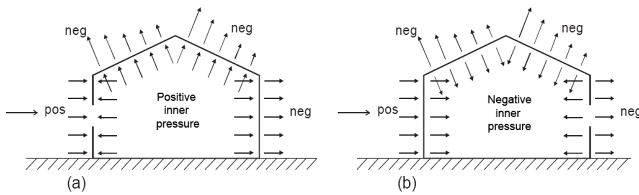


Figure 10.6 Coefficients of the inner pressure on the surface. [15]

This type of loading on the shell structure will not be taken into account during the preliminary design of the shell. But it is important to find out the effect of these loads in the next phase of the design.

Load cases

The different loads that have to be taken into account during the structural analysis of the shell structure lead to different loads cases. The following loads cases are taken into account during the processing of the structural analysis:

- Load case 1: Dead load
- Load case 2: Dead load + snow load
- Load case 3: Dead load + wind load 1 + negative inner pressure
- Load case 4: Dead load + wind load 1 + positive inner pressure
- Load case 5: Dead load + wind load 2 + negative inner pressure
- Load case 6: Dead load + wind load 2 + positive inner pressure
- Load case 7: Dead load + wind load 3 + negative inner pressure
- Load case 8: Dead load + wind load 3 + positive inner pressure
- Load case 9: Dead load + wind load 4 + negative inner pressure
- Load case 10: Dead load + wind load 4 + positive inner pressure

According to the Eurocode the maximum wind load and the maximum snow load do not occur at the same time. This means that there is no load case where both the wind load and the snow load act on the structure at the same time.

Limit states

Design for limit states is based on the use of structural and load models for relevant limit states. It needs to be verified, for all relevant design situations and load cases, that no limit state is exceeded.

The limit state that concerns the safety of people and the safety of the building can be classified as ultimate limit state. The limit state that concerns the functioning of the structure or structural members under normal use, the comfort of people and the appearance of the construction works can be classified as serviceability limit state. Usually the serviceability requirements are agreed for each individual project.

For both limit states all the previously defined load cases are taken into account during the calculations. The size of the loads are not the same for both load cases. The difference in size is defined by the safety factors. For the ultimate limit state the safety factors are 1,2 for the dead and live load and 1,5 for the variable loads, like the wind and snow load. The safety factors for the serviceability limit states are 1,0 for all loads. These safety factors are taken into account during the calculation with Diana.

10.3.2 Shell properties

There are different properties of the shell that have to be know before the structural analysis can be performed. These properties are the concrete composition, the thickness of the shell, the strength of the connections, the supports of the shell and the type of meshing of the shell.

Concrete

The type of concrete composite that will be used in the first calculations is hybrid fibre concrete, as defined before. The properties of this type of concrete composite are:

- Young modulus (uncracked): 35000 N/mm^2
- Poisson's ratio: 0,18
- Density 24 kN/m^3
- Compression strength: 100 N/mm^2
- Tension strength: depends on the amount of fibres added to the mixture

Thickness

In the calculations it is assumed that the shell has an equal thickness over the whole shell surface. When necessary the thickness of the shell can be changed locally in a later phase of the design process.

- Thickness 100 mm

Connections

In the these first calculations the shell is not divided into elements jet and so the place of the edges is not known. The calculations are therefor made for a solid shell where all connections are rigid and have the same strength as the shell.

- Connections rigid

Supports

The supports of a shell structure influence the force transfer in the shell. Here the supports are assumed to be pinned.

- Supports pinned

Meshing

Before the calculation can be performed in Diana the surface has to meshed and divided into elements. This is a different mesh than the mesh that will be used to divide the surface in different prefabricated elements. The mesh that is applied determines the type of forces the surface can transfer. The number of elements determine the accuracy of the calculations.

- Mesh type: QU8 CQ40S
- Mesh division: 40 x 40

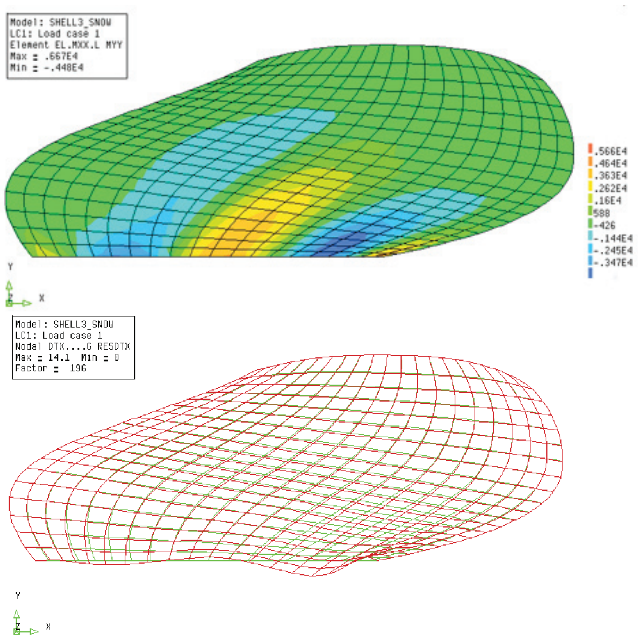


Figure 10.7 The places with the largest deflections are also the places where the largest bending moments are present in the shell.

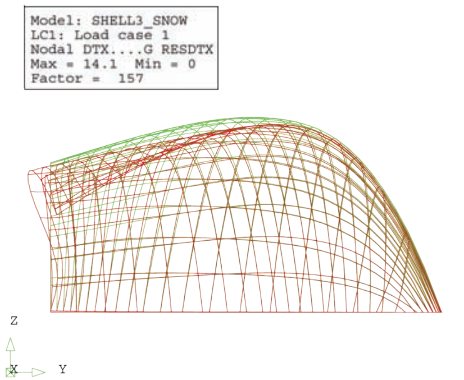


Figure 10.8 Side view of the shell with the resulting deflections of the shell surface due to both the dead load and snow load.

10.3.3 Analysis

The loads and other properties will be inserted in Diana, the finite elements program that will be used to analyse the structural performance of the designed shell. The results of the calculations with Diana will be analysed here.

Deflections

The maximum deflections that are allowed to exist in the shell in the serviceability limit state are:

- $u_x \leq h/300 = 8$ m/300 = 27 mm
- $u_y \leq h/300 = 8$ m/300 = 27 mm
- $u_z \leq 0{,}004l = 0{,}004 * 16$ m = 64 mm

The maximum deflections are present in the load case where both the dead load and the snow load act on the shell. These maximum deflections are:

- $u_x = 2{,}91$ mm
- $u_y = 6{,}08$ mm
- $u_z = 14{,}00$ mm

These deflections are all smaller than the maximal allowed deflections.

The largest deflections are present in the arch of the shell. In Figure 10.7 it can be seen that the largest deflections are present in the place where also the largest bending moments M_{yy} are present in the shell. To decrease the deflections in the arch the bending moments in the shell have to be minimized. There are two methods to decrease these bending moments. The first method is to improve the shape of the shell in the area of the arch. The arch does not really follow the compression line. When the shape of the arch and the shell is improved and follows the compression line better the bending moments and the deflections of the shell can be decreased. The second method is to strengthen the arch with for example extra reinforcement or a some sort of beam at the place of the arch. This will also reduce the forces and deflections in the arch. It is recommended first to try to improve the shape of the shell, before the shell or the arch will be strengthened.

	Top (N/mm²)		Bottom (N/mm²)	
	Tension	Compression	Tension	Compression
σ_{xx}	2,67	4,62	1,77	2,59
σ_{yy}	6,22	4,78	2,91	4,14
σ_{xy}	2,55	3,64	1,48	1,95

Table 10.1 The maximum stresses that are present in the shell surface for all load cases.

Strength

The largest stresses in the shell are present in load case 2, where both the dead load and the snow load act on the surface. In the load cases where the dead load is combined with wind loads the stresses in the shell are smaller.

The maximum stress that is allowed in the shell depends on the type of concrete that is used and the applied reinforcement. In this case hybrid fibre concrete will be used. This type of fibre reinforced concrete that the following strength properties:

- Compression strength: 100 - 120 N/mm²
- Tension strength: 4 - 8 N/mm²

The tension strength in the concrete depends on the amount of fibres that are added to the concrete. The more fibres are added the larger the tension strength of the concrete.

The maximum stresses that are present in the shell are presented in table 10.1. These stresses all occur in load case 2 in which the dead load and the snow load are combined. This table shows that the maximum compression stresses in the surface are much lower than the maximum compression strength of the concrete. The maximum tension stresses in the shell are also lower than the tension strength of the concrete. Although for these maximum stresses some further investigation has to be performed whether some reinforcement might be necessary. At first it will be assumed that no additional reinforcement is needed in the shell. The application of steel reinforcement makes the production of the elements and the construction of the shell more complicated.

The maximum stresses in the shell all can be found in the area of the arch of the shell. The stresses that are found in the arch are both tension and compression stresses. The variation of the stresses will probably be caused by the varying bending moments in the arch. So some optimization of the shape of in the area of this arch can reduce the tension stresses in this part of the shell and improve the structural performance of the shell.

In the overview of the stresses σ_{xx} in the surface it can be seen that the largest part of the surface is in compression. But in some parts of the surface some small tension stresses are present. In general it is not favourable that there a tension stresses present in concrete shell structure, even not when the stresses are very small. For load case 8 even in almost the whole shell surface tension stresses are present. This means that structural optimization of the shell surface is advisable.

The overview of the stresses σ_{yy} in the surface show that in all the whole shell compression forces are present for most load cases. Only in some small parts of the top of the shell some small tension forces are present.

The overview of the stresses σ_{xy} shows that the largest parts of the surface the tension forces are governing. Only in one lower part of the shell some tension forces are present.

The principal stresses are used to get a better idea of the force transfer in the shell. The directions of the principal stresses in the shell can visualize the load-carrying mechanisms of the shell. The directions of the principal stresses σ_1 show the directions of the largest tension forces in the shell. The directions of the principal stress vector σ_3 show the directions of the smallest or compression stresses in the shell. The figures in which the directions of the principal stresses are visualized show that there is a compression area in the top of the shell from the middle of the arch to the lower back of the shell.
The tension forces in the shell are for a large part distributed to the arch and the sides of the shell. Trough the arch they are carried down to the foundation.

In Figure 10.15 the resultants of the reaction forces in the shell are show. It can be seen that these resultants are all in the direction of the shell. The largest reaction forces are present in the bottom of the arch. Beside this it can be seen

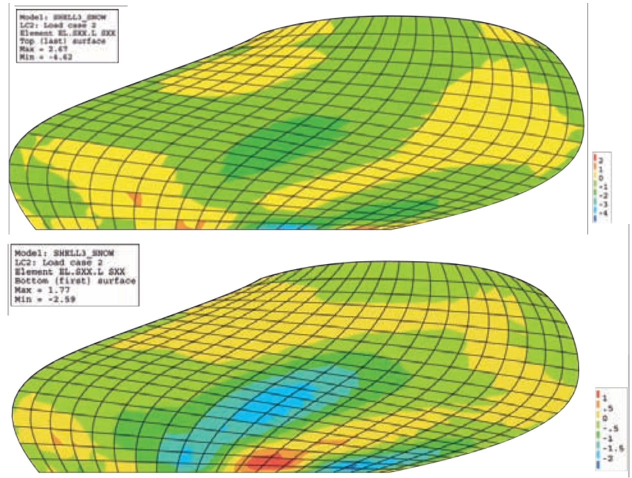


Figure 10.9 The stresses σ_{xx} in the top (above) and bottom (below) of the shell surface due to load case 2 dead load and snow load.

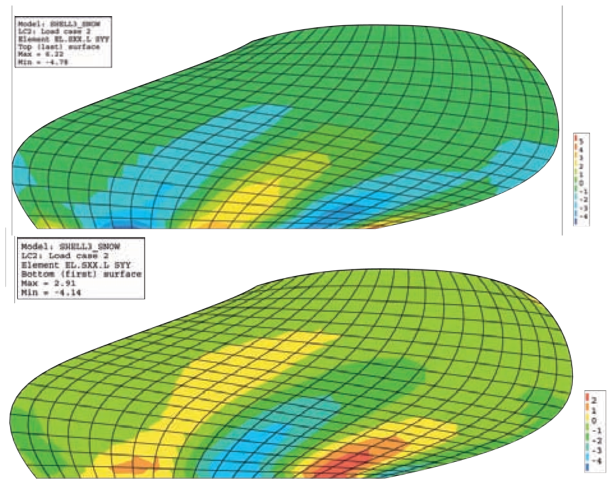


Figure 10.10 The stresses σ_{yy} in the top (above) and bottom (below) of the shell surface due to load case 2 dead load and snow load.

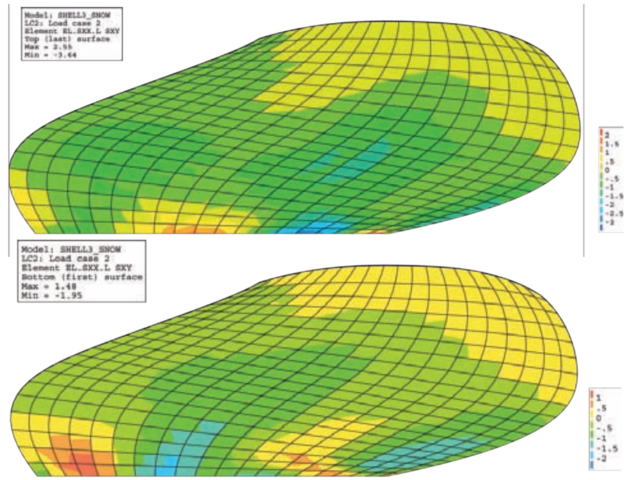


Figure 10.11 The stresses σ_{xy} in the top (above) and bottom (below) of the shell surface due to load case 2 dead load and snow load.

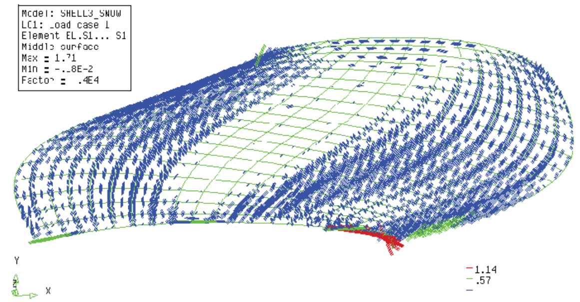


Figure 10.12 Principal stresses in the direction σ_1 displayed with the vector representation for load case 2.

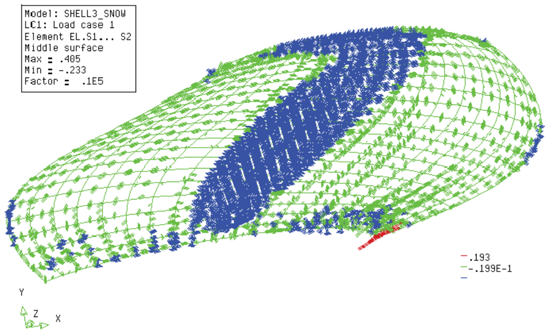


Figure 10.13 Principal stresses in the direction σ_2 displayed with the vector representation for load case 2.

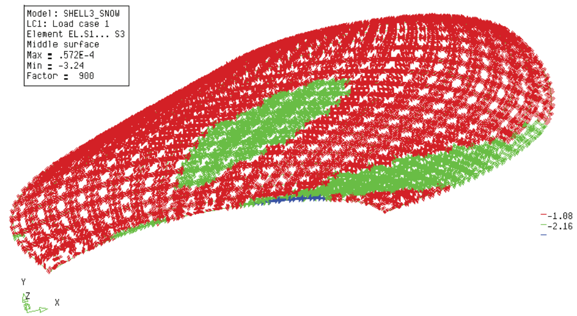


Figure 10.14 Principal stresses in the direction σ_3 displayed with the vector representation for load case 2.

that most forces are carried down to the sides of the shell.

The torsional moments M_{xy} in the arch are balanced by the development of effective shear forces in the edges of the elements. The principal of the development of effective shear forces due to torsional moments is shown in Figure 10.16.

10.3.4 Conclusions

The analysis of the result of the finite element analysis show that the defections of the shell are smaller than the maximal allowable deflections of the shell. The largest deflections are present in the arch of the shell.

The stresses in the shell are all smaller that the maximal allowable stress of the concrete. The largest tension and compression stresses are present in the arch of the surface. In some parts of the surface tension stresses are present, but the largest parts of the surface are in compression.

The assumed thickness of the shell is 100 mm. The only reinforcement that will be applied is the fibre reinforcement.

To improve the force transfer and the deflections of the shell the shell surface has to be optimized. When the bending in the shell can be reduced the tension forces in the shell will probably also reduce. When this structural optimization is performed properly, and no tension forces are present in the shell surface, the shell thickness might even be reduced.

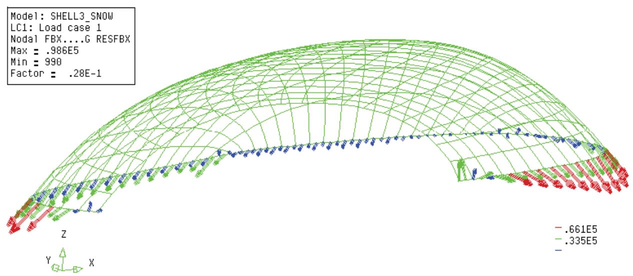


Figure 10.15 Resultants of the reaction forces of the shell for load case 2.

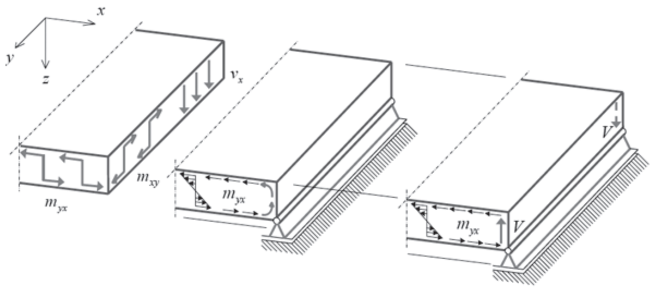


Figure 10.16 The development of local shear forces due to torsional moments M_{xy} in the shell.

10.4 Detailing

10.4.1 Shape of the elements

With the shape of the elements is meant, whether the surface of the elements is flat or has some kind of rib structure. There are different shapes that can be used for the elements.
The most simple one is a flat surface. Both the upper and lower surface of the elements are flat. This type of elements is the easiest to cast on an adjustable formwork.
The second type is the cassette element. In this type of elements the edges of the elements are thicker than the middle surface of the element, creating some sort box.
The last type is a ribbed elements where the ribs are not only placed at the edges of the elements, but also in the middle of the element surface.

The benefit of adding ribs to the elements it that the strength of the elements increases. Beside this less concrete might be needed for the element because of the strength of these ribs.

A drawback is that ribbed or cassette elements are a lot more difficult to cast, due to the ribs on the inner surface of the elements, especially using the adjustable formwork. The adjustable formwork cannot be adjust in such way that the vertical edges of the ribs can be formed with the mould. To form these edges some sort of inserts have to be placed on the mould to form the ribs. This makes it very complicated to cast ribbed or cassette elements on the adjustable formwork. The benefit of the fast adjustment of the adjustable formwork will disappear when it will be used to cast ribbed elements.

This leads to the conclusion that for this shell the surface of the elements will be flat without any ribs.

10.4.2 Connections

In Chapter 6 three connection systems have been chosen to be developed further during the case study. These systems are:

- The wet connection.
- The bolted connection.
- The glued connection.

Here the choice for the connection system for this particular shell will be made. To do this first the properties of the shell are described and then the different connection systems are discussed.

Shell properties

The properties of the elements are determined on the basis of the generated elements and the production method.

- Thickness shell:	100 mm
- Shape of the edge:	Can be in torsion
- Angle edge-surface:	90 degrees
- Inserts in the edges:	Possible
- Ridge/valley in the edges:	Possible

On the basis of the structural analysis the different forces and the size of these forces in the shell can be determined. Table 10.2 shows the stress distribution for a couple places in the shell surface. These stress will be used as the decisive stress for the design of the connections between the elements.

Wet connection

The wet connection is a connection where the seam between the elements is filled with some sort of concrete mortar and some reinforcement. The combination of the mortar and the reinforcement gives the connection its strength. The benefits of the wet connection is its strength

Figure 10.17 Detail of the ribbed elements used for the canopy at sanatorium Zonnestraal.

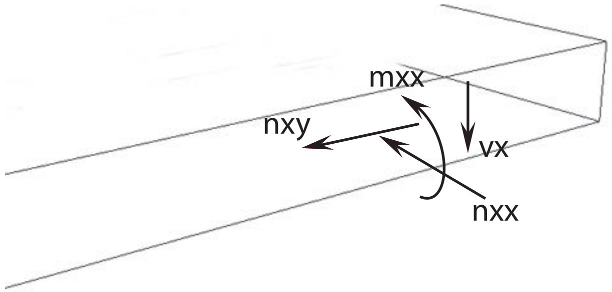


Figure 10.18 The different types of forces that are present in the connection.

	Top (N/mm²)			Bottom (N/mm²)		
	σ_{xx}	σ_{yy}	σ_{xy}	σ_{xx}	σ_{yy}	σ_{xy}
1.	1,0	-1,0	0,5	0,5	-1,0	0,5
2.	-1,0	-1,0	-1,0	-1,5	0	-1,0
3.	1,0	-1,0	-0,5	0,5	-1,0	-0,5
4.	-3,0	-1,0	-2,5	0,5	0	0,5
5.	-2,0	-3,0	-2,0	-2,0	2,0	0

Table 10.2 Stresses that will be used for the analysis of the connection strength.

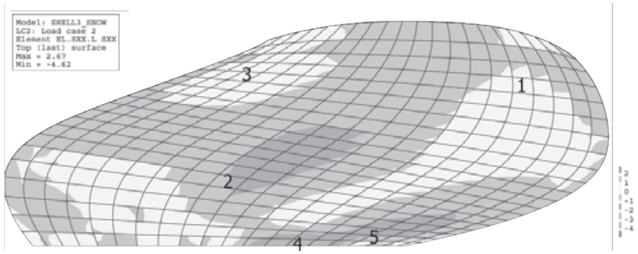


Figure 10.19 The places where the average stresses in the shell are determined are marked with a number.

and the large tolerances. The drawbacks of the wet connection are that it is labour intensive to place the mortar and reinforcement. Beside this the placement of the mortar is weather dependent and the mortar needs some time to harden and gain strength.

The compression strength of the wet connection depends mainly on the strength of the used mortar. In this case the elements are made of a high performance fibre reinforced concrete. So the mortar that will be used for the wet connection should also have a high compression strength in the order of 70-100 N/mm². The tension and shear capacity of the connection depends more on the applied reinforcement. It should not be a problem to achieve the required strength for this shell with a wet connection. The major point of concern is the bonding between the mortar and the UHPC elements.
It might be necessary to place protruding steel reinforcing bars in the elements. These bars will strengthen the connection between the elements in cooperation with the additional stitching reinforcement. These protruding bars complicate the production, transport and placement of the elements.

The thickness of the joint between the elements will be large enough to allow easy placement of the elements. This means that the torsion of the edges does not cause any problems during the assembly of the elements. After the placement of the elements the stitching reinforcement can be placed in the joint between the elements. To cast the mortar in the joint it might be necessary, depending on the design of the edges, to place some temporary formwork under the joint between the elements.

Bolted connection

The bolted connection connects the elements by means of bolts. In the elements special provisions have been made, like holed or inserted plates or bolts, that will be used to connect the elements permanently. Large benefits of the bolted connection are the fast assembly, that is weather independent, and the strength of the connection that is present directly after assembly. The weaker points of the bolted connection are the durability, fire proofing, cost and ease of design.

The strength of a bolted connection can be very high. The strength of the steel bolts is much larger than the forces that are present in the concrete. The main problems with a bolted connection are the load introduction of the connection forces into the concrete elements and creating a connection with enough stiffness and bending capacity.
When the loads are introduced into the concrete locally high peak force develop in the concrete element, which can cause failure of the connection.
Because shell structure a very sensitive for buckling the connection should have a minimum stiffness. Because bolts are point connections it is hard to reach this stiffness with a bolted connection, while keeping the connections simple.

Making a good design for a bolted connection that is applicable for all elements in the shell is very complicated. Over the shell surface different forces are present and more important the torsion of the edges varies over the surface.

It is almost always necessary to use some provisions that are inserted into the elements to make the connection. These inserts have to be placed on the mould correctly during the production of the elements and complicate the production.

The fact that the elements are bolted together makes that there is not very much space between the elements. This makes the tolerance are small and the placement of the elements can be complicated. When the elements are placed the bolt can be applied and the strength of the connection is directly on the final level.

Glued connection

With the glued connection the elements are connected to each other by means an epoxy resin. This is a adhesive that hardens by chemical or physical processes. The benefits of the glued connection is its strength and the evenly over the surface spread the load introduction. Possible drawbacks are that it is labour intensive to make the connection and that no large amount of data is present about the long term performance of the connection.

The used epoxy resin will be Sikadur-30 [65], this is a two component system that can also be used to secure reinforcing bars in concrete elements. The same resin is used for the glued connections in the Gartnerplatz bridge in Kassel. Some properties of this resin are:

- Maximum layer thickness: 30 mm
- Shrinkage: 0,04 %
- Compression strength: 70-80 N/mm^2 (for a hardening temperature of +10 °C after 7 days)
- Shear strength: 14- 17 N/mm^2 (for a hardening temperature of +15 °C after 7 days)
- Tension strength: 24-27 N/mm^2 (for a curing temperature of +15 °C after 7 days)
- Bonding strength: concrete fracture (> 4 N/mm^2)
- Processing temperature: +8 °C - +35 °C

For the application of the epoxy resin as structural connection some test were performed on the strength and durability of glued UHPC connection. The test results show that the tested prisms have a tensile strength of 6-7 N/mm^2 and a flexural tensile strength of 10-13 N/mm^2 in all weather conditions. The specimens failed in the concrete structure adjacent to the epoxy layer. The thickness of the used epoxy layer was varied between 3 and 6 mm. The long therm performance shear tests gave a shear strength of 12-16 N/mm^2. [6]

These test results give a connection strength that is larger than the stresses that are present in the designed shell. So no problems are expected with the strength of this type of connection. The only thing is that the glued connection is still in an experimental phase of design, and more testing has to be done to make sure that it is also a reliable connection for the whole lifetime of the structure.

There are no requirement to the shape of the edges simple flat edges without any ridges can be used. Some sort of ridges can be used to increase the shear strength of the connection, but this might make the assembly of the elements a little more difficult. For this reason it is chosen to use edges without any ridges. The assembly of the element is already complicated due to the possible torsion of the edges. Another advantage of the glued connection is that no extra provision have to be inserted into the mould for the connection. This makes the production of the elements a lot easier.

To obtain optimal bonding between the elements and the adhesives the surface of the edges has to be roughened and loose particles and other impurities have to be removed before the epoxy resin can be applied. After the subsequent element has been placed vibration can be used to make sure the right thickness of the joint is reached. This roughening and cleaning of the edges make the assembly of the edges more complicated and labour intensive.

The thickness of the concrete layer that will be used is 5 mm. This size is used to maximize the ease of assembly of the elements. With this thickness the epoxy layer does not sag with application on vertical surfaces. For the more difficult to place elements it might be better to used a thicker epoxy layer, to create more room for placing the element.

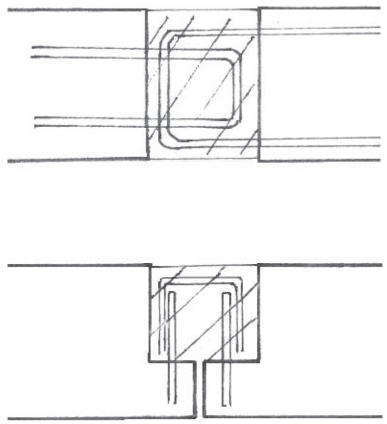


Figure 10.20 Two different options for the design of the wet connection.

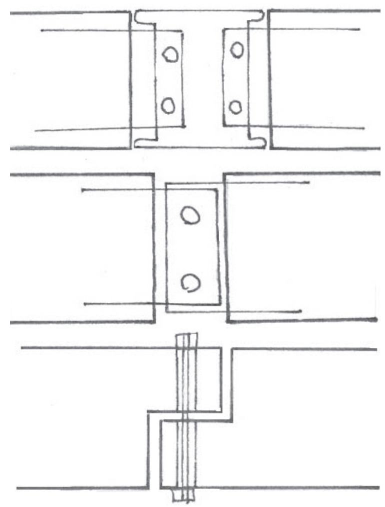


Figure 10.21 Three simple design ideas for a bolted connection.

	Wet connection	Bolted connection	Glued connection
Strength	Good	Good	Good
Durability	Good	Point of attention	Point of attention
Load introduction	Equally spread	Local	Equally spread
Design	Easy	Difficult	Easy
Difficulties due to torsion	No	Yes	Yes
Reinforcement in the elements	Possible	Possible but difficult	Not possible
Allowable tolerances	Large	Small	Small
Placement	Easy	Difficult	Difficult
Labour intensive assembly	Yes	No	Yes
Strength development	Very slow	Direct	Slow
Weather dependent	Yes	No	Yes

Table 10.3 Evaluation of the properties of the connection systems.

Evaluation

The properties of the different connection systems are summarized in Table 10.3. On the basis of properties of the connections the glued connection will be used as connection systems for this shell structure. The main drawback of this system is the fact that it is still an experimental connection system and the long term performances is not jet fully known. So in the next phased of the design of this shell special attention has to be paid to this aspect of the connection system.
Another aspect that has to be looked at closely is whether the relative small joints between the elements give problems with the placement of the elements.

10.4.3 Foundation

The foundation is a very important part of the construction. The complete shell is supported by the foundation. All induced forces on the construction are carried down to the foundation.

The supports of the shell are designed as pinned supports. The maximal reaction forces for the different load cases that are calculated with Diana are:

- F_x = 105,0 kN
- F_y = -38,8 kN
- F_z = -100,0 kN

The largest horizontal forces are present in the bottom of the arch. In the other parts of the shell the horizontal reaction forces are smaller. With the design of the foundation of the shell care has to be taken that these horizontal forces can be taken by the foundation.

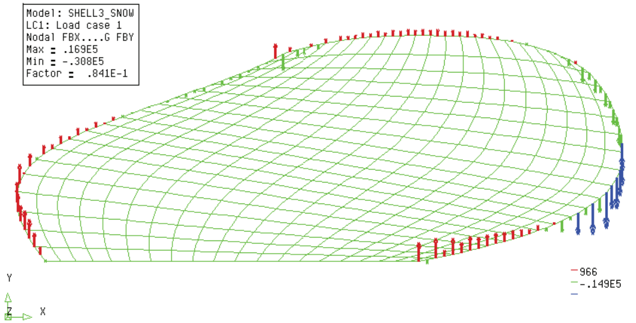


Figure 10.22 Horizontal support reactions in the y direction for load case 2.

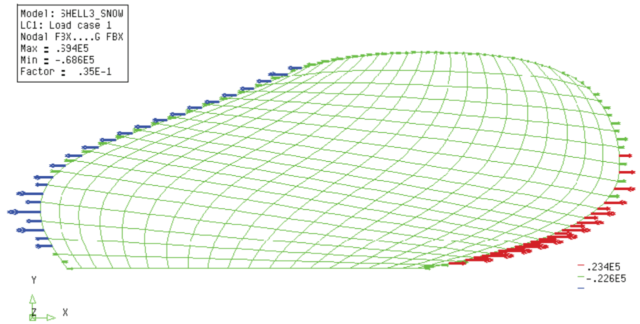


Figure 10.23 Horizontal support reactions in the x direction for load case 2.

10.5 Segmentation an geometry definition

The design tool is used to generate the grid over the case study design. The following length of the edges and thickness of the shell are used:

- Maximum length of the edges: 3,0 m
- Thickness of the shell is: 100 mm.

10.5.1 Element size

All generated element are with the criteria for the size of the elements. The size of the different elements does not differ a lot for large parts of the surface. There are only two areas where very small elements are generated. These areas are marked with two circles in Figure 10.26. The shape of these elements is also not very optimal. This means that these elements have to be improved during the optimization of the generated grid.

10.5.2 Angles

The results show that there are a lot angles between the edges of the elements in the plane of the elements that do not fulfil the set requirements:

- Angles between the edges has to be: $45^o \leq \alpha \leq 135^o$
- Number of angles < 45 degrees: 70
- Number of angles > 135 degrees: 4

The elements of which an angles is measured as incorrect are marked in Figure 10.25. This figure shows that in a large part of the surface the angles are too small.

When the size of the angles is inspected further it can be seen that

- Number of angles < 35 degrees: 4
- Number of angles > 145 degrees: 3

This means that when the requirements for the angles are changed, there are only 7 angles that do not met the set requirement in stead of 70 angles. It is assumed 35 degrees is also an angle that would not cause very large problem during casting and transport of the elements. But of course it is better when the elements are less skewed. The 7 remaining incorrect angles can all be found in the areas of the surface that were already marked as problem area with the analysis of the elements size.

10.5.3 Curvature

The analysis of the measured curvature of the elements shows that there are four elements where the minimum radius of curvature is smaller that 1,0 m. These minimum radii for these elements varies between 3 mm and 379 mm. These radii are too small to be able to cast these elements with the flexible formwork. The elements of which the curvature is larger than the maximum radius of curvature can all be found in the areas that are marked as problem area in Figure 10.26.

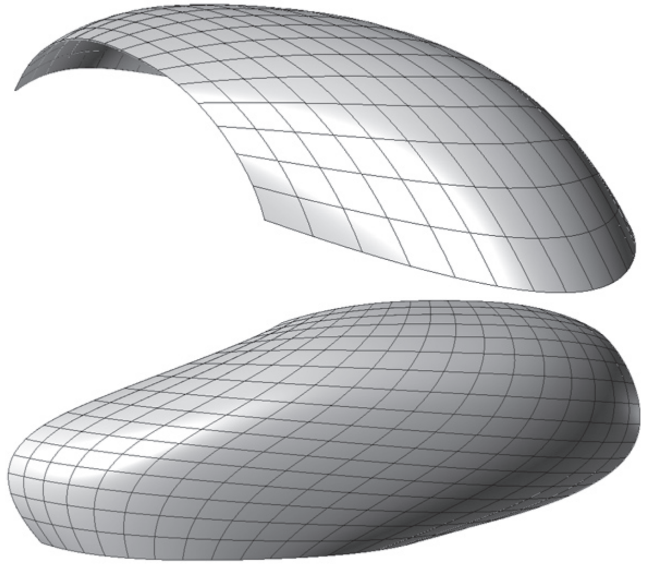


Figure 10.24 The generated grid over the surface.

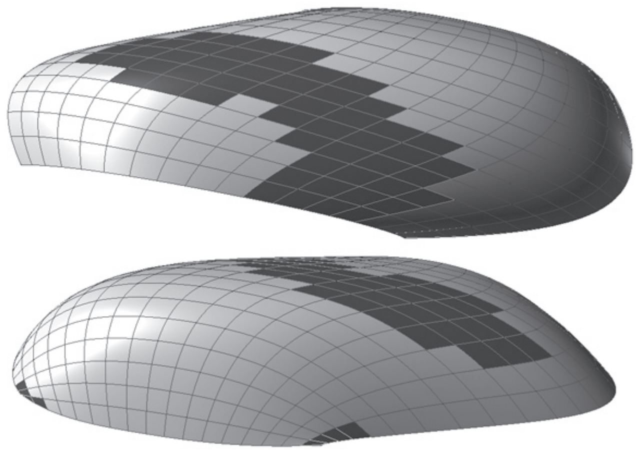


Figure 10.25 The elements of which an angle is determined as to small or to large are marked.

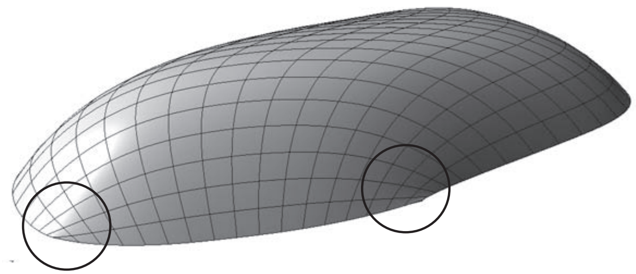


Figure 10.26 The problem areas of the grid the element size and element curvature are marked with the two circles.

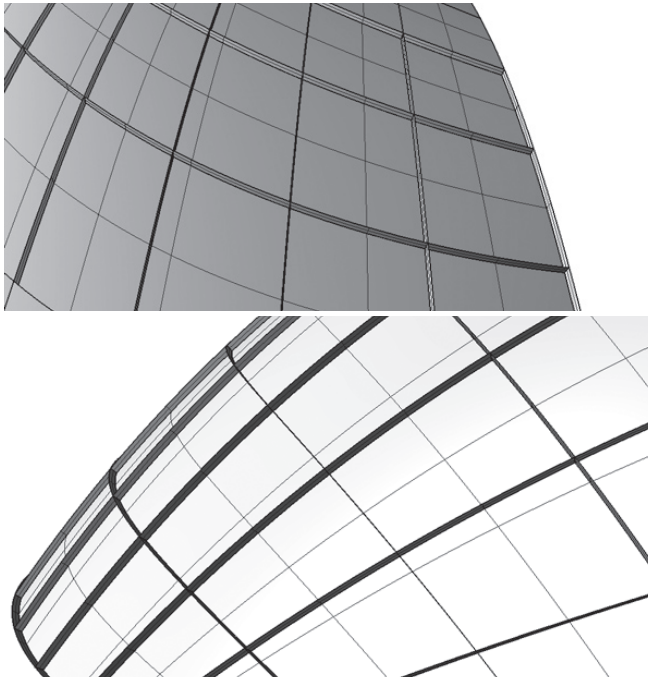


Figure 10.27 Details of the generated element in two places of the surface

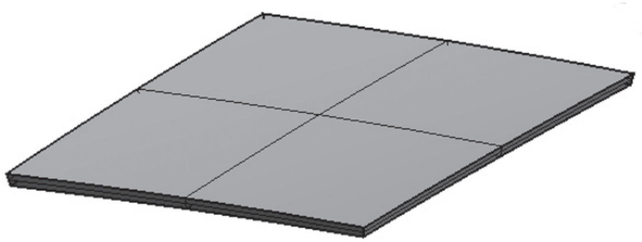


Figure 10.28 One isolated elements.

10.5.4 Geometry definition

The elements are generated correctly. The edges are perpendicular to the shell surface and the inner surface is aligned correctly with the edges. The corners of the elements are also aligned perfectly.

The only thing that has to be considered is the boundary edges that will be placed on the foundation are not generated horizontal, because this is not implemented in the design tool. This means that the shape of these edges still has to be changed.

10.5.5 Optimization

The optimization of the element size is already implemented in the design tool. This means that all elements are within the criteria for the elements size. There are however some elements that are a lot smaller than the average element size. The size of these elements can only be improved by changing the placement of the isocurves. This can only be done by changing the shape of the surface..

It is not possible to improve the size of the angles between the edges with the chosen grid generation method. This means that there are only two options to improve the angles between the edges of the generated grid these are to change the shape of the surface or use the changed requirements for the size of the angles.

The elements of which the curvature is too small can not be made with the flexible formwork. Optimization the grid does not change the curvature of the shell at the place of these elements. To improve the curvature of the elements the shape of the shell surface has to be optimized. Another option is to use another type of mould for the elements that cannot be cast with the flexible formwork. Whether this is a feasible solution depends mainly on the amount of element that can not be made with the flexible formwork.

10.5.6 Evaluation

The design tool has generated 289 elements. All elements fulfil the requirements for the length of the elements. There are 77 places where the angles do not fulfil the requirements for the angles in the plane of the elements and the average angle is only 66 degrees. This means that the elements are pretty skewed. There are there are 4 elements that do not fulfil the requirements for the minimal curvature of the elements.

There can be two problem areas found in the shell with respect to the generated elements. The shape of the shell has to be improved for these elements.

A large drawback of the chosen grid generation technique is that the angle between the edges of the elements cannot be changed. This means that optimization of the elements shape is not possible. To make the elements less skewed the shape of the surface has to be changed.

All elements of the grid are different. This is not a problem when the adjustable formwork will be used for the production of the elements. It is no problem to change the shape of the mould for every element. However, the production of the elements can faster when some elements have the same shape and the mould does not need to be adjusted for each elements.

10.6 Production and construction

10.6.1 Production process

The production process consists mainly of the production of the prefabricated elements. The elements will be cast in a factory and transported to the building site after hardening. The elements will be cast using the adjustable mould as it is defined in Chapter 5 ‘Adjustable formwork’. The used concrete composite is hybrid fibre concrete.

Casting sequence

The casting sequence of the elements can be determined on the basis of the construction of the shell. The order of production of the elements will be the same as the placing order. With this production sequence it is least likely that the construction will be delayed due to problems with the production of the elements.

Casting process

Mould will be brought in the curved shape after casting, to prevent sag and flow of the wet concrete. The deformation of the partly hardened concrete may cause some extra stresses in the elements. The strength development of high performance concrete is relatively fast, but due to the large amounts of superplasticizer that are added to the mixture the strength developments is slowed down on the first day. Before the elements will be produced some testing has to be done to find the right combination between the amount of superplasticizer in the concrete, the workability of the concrete and the moment the mould will be deformed that will give the least extra stresses in the concrete and the fasted production speed.
The fact that the mould will be deformed after casting of the concrete makes that it is not possible to add any steel reinforcing bars to the elements.

Inserts

Because the concrete is cast before the mould is deformed the inserts that form the edges of the elements also have to be placed before the mould is brought in the deformed shape. This works very well for the edges in the middle of the shell, that are perpendicular to the surface. But the edges at the boundary of the shell are more difficult to form. These edges are flat and orientated horizontal. This means that the strips of these edges have to be in torsion before the mould is deformed. In this way the inserts become flat when the mould is brought into the curved shape. The orientation of the inserts with the flat mould also has to be calculated accurately to get a correct orientation of the edge of the cast element.

For the connections no inserts have to be placed into the elements. The only inserts that might be needed are some provision to lift the elements.

10.6.2 Storage

For the storage of the elements the frame introduced in Chapter 7 ‘Production and construction’ will be used. This frame ensures that no unnecessary deformation of the elements occurs during storage of the elements.

This frame can also be used to transport the element from one location to the next. For example from the storage area in the factory on the truck and from truck to the storage area on the building site. When the frame is used to lift the elements no extra lifting loads are induced on the elements, these loads are all taken by the frame. Besides this the frame also protects the elements during transport.

This shell consists of 289 elements. When all elements are produced before the construction the shell starts there are also 289 storage frames needed. These frames can be re-used for different projects, but prefabricated shell structures will always be specials projects that are not built very often. So the construction of these special frames will increase building costs.

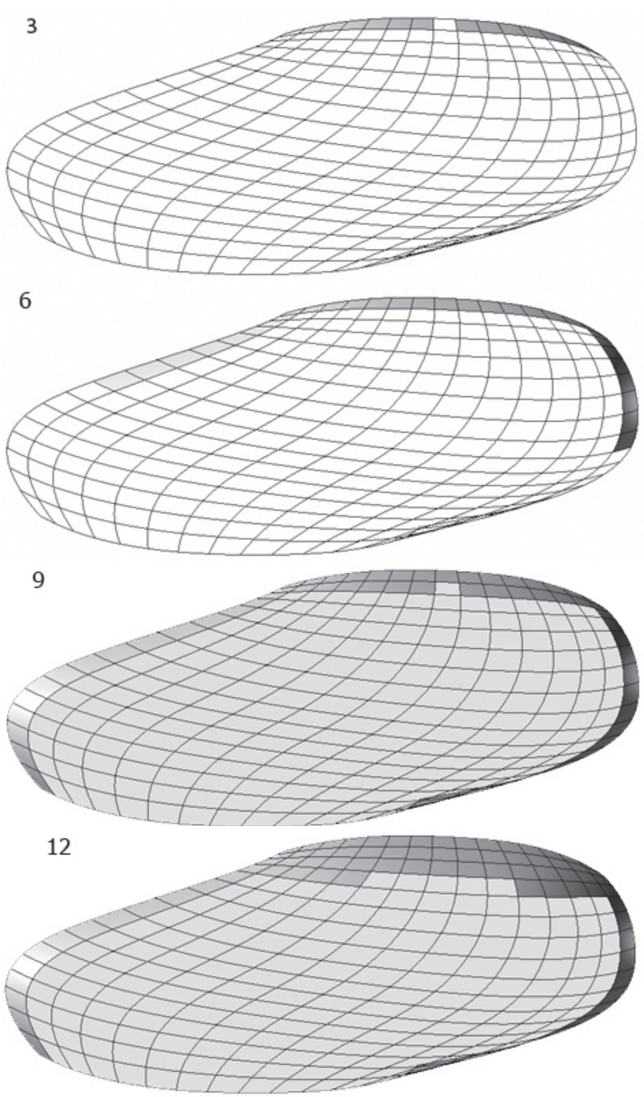


Figure 10.29 Building sequence of the shell.

10.6.3 Transport

The elements will be transported from the factory to the building site by road. The elements are loaded with the storage frames on a truck. Depending on the exact size of the frame and the size of the truck between 6 to 12 elements can be transported on one truck. This means that for the 289 element between 24 and 48 truck loads are needed to transport all elements from the factory to the building site.

10.6.4 Construction process

Before the construction of the actual shell can start the foundation of the shell has to be made. The foundation forms the basis of the shell and will be made out of in-situ concrete. When the construction works on the foundation are finished and prepared for the placement of the elements the construction of the shell can start.

The elements are placed one row at a time from bottom to the top of the shell. When the placement of the elements of one row is finished the placements of the elements of the next row can start. The construction of one row starts in the two ‘corners’ of the shell. Form that point the elements are toward the middle of the back of the shell and to the arch in the front of the shell. The complete construction process is visualized in appendix 5.
By choosing this construction sequence in each row only one element has to be placed in between two other elements on an element of the previous row. All other elements can be placed on the element of the previous row next to one other element. This means that in each row there is only one element with which the torsion of the edges might give some difficulties with the placement. The element that might give these problems is located in the part of the shell which is least curved, and the edges of the elements are there also not to much in torsion.

Before the elements can be placed the surface of the edges has to be roughened and cleaned carefully to ensure a good bonding between the element and the epoxy resin. After the epoxy has been applied on the edges of the already placed elements the next element can be placed. Vibration can be used to achieve the required thickness of the epoxy joint.

During the placement of the elements the stability of the shell has to be ensured at all time. So each elements will be placed on a temporary scaffolding. This scaffolding makes that the elements are supported at all time and the crane time of each elements is minimized.

When all elements are placed and the connections have reached their final strength the scaffolding can be removed. At this moment the construction of the shell is almost finished, but the building process of the shell is not. At this time the glass facade in the arch can be placed and the work on finishing the building can start. This means that the electricity, isolation, floors etcetera can be installed.

10.7 Conclusion

Structural analysis

- The analysis of the results of the finite element analysis show that the defections and stresses of the shell are withing the requirements. The largest deflections and stresses are present in the arch of the surface.

- To improve the force transfer in the shell and approach the ideal of pure membrane action for all load cases the design has to be optimized.

Detailing

- The glued connection will be used as connection systems for this shell structure. The main drawback of this system is the fact that it is still an experimental connection system and the long term performances is not jet fully known. This means that in the next phased of the design of this shell special attention has to be paid to this aspect of the connection system. Another aspect that has to be looked at closely is whether the relative small joints between the elements give problems with the placement of the elements.

- The foundation has to be able to transfer the forces form the shell correctly. The horizontal forces on the foundation are relatively large.

Geometry definition

- A large drawback of the chosen grid generation technique is that the angle between the edges of the elements cannot be changed. This means that optimization of the elements shape is not possible.

- There can be two problem areas found in the shell with respect to the generated elements. The shape of the shell has to be improved for these elements.

Production and construction

- Mould will be brought in the curved shape after casting, to prevent sag and flow of the wet concrete. This means that the inserts should be able to deform during the deformation of the mould. This production process makes the production of the inserts for the horizontal boundary edges more difficult.

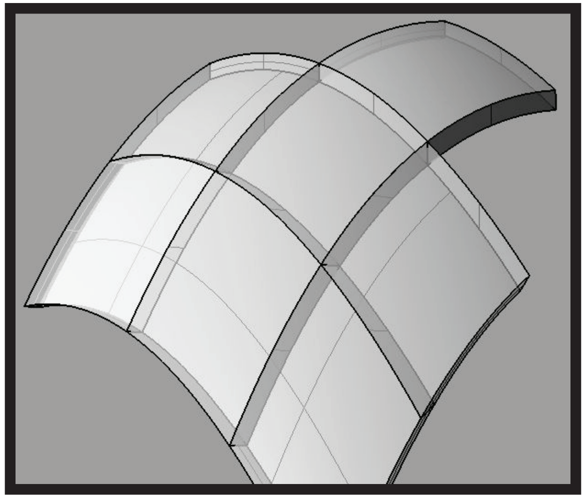
- The used connection system and the casting method of the elements do not allow the application of steel reinforcing bars in the elements.

- All elements of the grid are different. This is not a problem when the adjustable formwork will be used for the production of the elements. It is no problem to change the shape of the mould for every element. However, the production of the elements can faster when some elements have the same shape and the mould does not need to be adjusted for each elements.

- For the storage and transport of the elements special frames will be used. The benefit of these frames is that they protect the elements against damage and unnecessary deformation, but the production of these frames is pretty expensive.

- In the construction process of the shell there are some elements that will be more difficult to place. It might be necessary to take some special measures in the design of these elements, like increasing the thickness of the epoxy layer. Whether this is necessary has to be determined in the later phases of the design.

Conclusions & Recommendations



In this chapter the conclusions and recommendations of this Master's thesis are given.

Conclusions

In the following the general conclusions of this thesis are given. The conclusions are discussed point wise and are ordered corresponding to their occurrence in the thesis.

- The structural analysis of thin shells is quite complex due to the three dimensional shape of the shell and the combination of in-plane and bending stresses in the shell. The introduction of finite element methods made the analysis of shells easier, but to the structural behaviour of prefabricated concrete shells and the influence of the connections and the place of the connection on the structural behaviour still much research has to be done.

- From a theoretical point there is no optimal grid generation technique that results in the best grid for every surface. The most suitable grid generation technique for a surface depends on the geometry of the surface, the architectural design and the structural layout.

- The high performance fibre reinforced concrete composites form a good solution for the use in prefabricated concrete shell structures. But more research has to be done to define regulations for the design of constructions in high performance fibre reinforced concrete composites.

- At the moment large steps in the development of the adjustable formwork are made by the construction of a large scale testing model.

- There are different types of connection systems for the connection of the elements in the structure. There is no system that is the most optimal in all cases so the best connection system has to be chosen for each individual design.

- The integral design process of a prefabricated concrete shell is quite complicated due to the many different aspects that have to be taken into account at the same time and the many different possibilities to optimize the design. For most aspects there is not one solution that is the most optimal design choice for every design.

- The developed design tool is capable of generating a grid over a lot of different surfaces. However not for every surface an optimal grid is generated. A large drawback of the used grid generation technique is that the angle between the grid lines cannot be optimized.

- To make a next step in the development of prefabricated concrete shell it is advised to really build a prefabricated shell structure of which the elements are made with the adjustable formwork.

Recommendations

In the following the recommendations of this thesis are given. The recommendations are discussed point wise and are ordered corresponding to their occurrence in the thesis.

- More research to the structural behaviour and the stability of prefabricated concrete shell structures and the influence of the connections has to be performed.
- For the increase of the application of high performance fibre reinforced concrete composites it is advised that a design code is developed for these type of concrete composites.
- More research has to be done to the development of the adjustable formwork.
- More research has to be done to the development of connection systems for prefabricated concrete shell structures with elements made of high performance fibre reinforced concrete.
- The segmentation of the shell is now made without interaction with the structural analysis of the shell. A research has to be performed to with whether the structural performance might be improved when the segmentation is based on the structural analysis of the shell.
- More research has to be done to the construction of the prefabricated concrete shell. The advised method to do this research is with the construction of a real prefabricated concrete shell.

References

References

Books and reports

[1] Bentur, A. & Mindess, S.; *Fibre reinforced cementitious composites 2nd edition*; Taylor & Francis Group London and New York; 2007

[2] Bennenk, H.W., Kuik, M.E.M.E. van, Waperom, H.H.; *Prefab beton, deel 1*; BFBN; Woerden; 2003

[3] Blauwendraad, J en Hoefakker, J.H.; *Theory of Shell, Course CT5143*; Delft University of Technology; September 2004

[4] Bruijn, H.J. de; *Literatuur- en voorstudie: hogere sterkte beton nader belicht*; Master's Thesis; TUDelft; December 2005

[5] Diks, M.E.; *Translucent sandwich systeem voor dubbel gekromde toepassingen*; Master's Thesis; TUDelft; January 2005

[6] Fehling, E., Schmidt, M., Stürwald, S.; *Ultra High Performance Concrete (UHPC), Proceedings of the Second International Symposium on Ultra High Performance Concrete*; Structural Materials and Engineering Series, Heft 10; Kassel, Germany; 5-7 May 2008

[7] Grunewald, S.; *Performance-based design of self-compacting fibre reinforced concrete*; TUDelft; 2004

[8] Haas, A.M.; *Design of thin concrete shells, volume 1*, positive curvature index; John Wiley & Sons New York & London; 1962

[9] *Handboek uitvoering betonwerken; Stubeco/ betonvereniging*; 1e druk; Gouda; 2005

[10] Jansen, H.; *Prefabricage bij blobconstructies, een civiele kijk op blobarchitectuur*; Master's Thesis; TUDelft; november 2004

[11] Lappa, E.S.; *High strength fibre reinforced concrete, static and fatigue behaviour in bending*; Phd Thesis; TUDelft; 2007

[12] Liseikin, V.D.; *Grid Generation Methods*; Springer; Berlin; 1999

[13] Markovic, I.; *High-Performance Hybrid-Fibre Concrete, Development and Utilisation*; Phd Thesis; TUDelft; 2006

[14] Nederlandse norm *NEN-EN 1990 Eurocode* – Grondslagen van het constructief ontwerp; December 2002

[15] Nederlandse norm *NEN-EN 1991-1 Eurocode 1*: Belastingen op constructies; December 2002

[16] Nederlandse norm *NEN-EN 1992-1-1 Eurocode 2*: Ontwerp en berekening van betonconstructies –Deel 1-1: Algemene regels en regels voor gebouwen; April 2005

[17] Peerdeman, B; *Analysis of Thin Concrete Shells Revisited: Opportunities due to Innovations in Materials and Analysis Methods*; Master's Thesis; TUDelft; June 2008

[18] Pressley, A.; *Elementary Differrential Geometry*; Springer Undergraduate Mathematics Series; London; 2001

[19] Roosbroeck, van M.K.H.M.; *The Construction of prefab concrete shells, morphology-segmentation-material-production method*; Master's Thesis; TUDelft; February 2006

[20] Ruhle, H.; *Raumliche Dachtragwerke Construction und Ausfuhrung*, Band 1; Verlagsgesellschaft Rudolf Muller; Koln-Braunsfeld; 1969

[21] Schmidt, M., Fehling, E., Geisenhanslüke, C.; *Ultra High Performance Concrete (UHPC), Proceedings of the International Symposium on Ultra High Performance Concrete*; Structural Materials and Engineering

Series, Heft; Kassel, Germany;13-15 September 2004
[22] Schodek, D.L.; *Structures fifth edition*; Pearson Prentice Hall; 2004
[23] Thompson, J.F., Soni, B.K., Weatherill, N.P., editors; *Handbook of grid generation*; CRC press; 1999, online version
[24] Vambersky, Prof. dipl.-ing J.N.J.A., Wagemans, Prof. ir. L.A.G., Coenders, Ir. J.L.; *Structural Design-Special Structures, course CT5250*; Delft University of Technology; April 2006
[25] Yuguang, Y; *Bending behaviour of a High Performance Concrete overlay on an orthotropic steel deck*; Master's Thesis; TUDelft; August 2007

Articles

[26] Adeeb, S.M., Scholefield, B.W.J., Brown, T.G., Shrive, N.G., Kroman, J., Perry, V.H. and Tadros, G.; *Modelling, testing, and construction of the first Ductal® canopy in the world*; Canadian Journal of Civil Engineering; volume 32 2005; page 1152-1165
[27] Bayasi, Z. & Zeng, J.; *Flexural behaviour of slurry infiltraded mat concrete (SIMCON); Journal of materials in civil engineering*; November 1997; page 194-199
[28] Detail; *Flugzeugmuseum in Duxford*, England; Volume 38; 1998; number 6; page 988-991
[29] Fielt, R.; *Creatief met beton*, Folly in Hilversum laat vorderingen constructietechniek zien; De ingenieur; jaargang 117; nummer10/11; 10 juni 2005
[30] Haas, Ir. M. de; Comeback voor betonnen schaalconstructies? Stijve verbindingen voor prefab schalen; Cement; 2008; number 3
[31] Huijben, R.N.J.; *Geen brug te ver, Diverse prefab betonsoorten*; Cement; 2002; number 4; page 34-39
[32] Kaptijn, N.; *Toekomstige ontwikkelingen van zeer-hogesterktebeton, De visie van Rijkswaterstaat*; Cement; 2002, number 2; page 56-63
[33] Kempkes, M.; *Das Neue Tempodrom am anhalter Bahnhof in Berlin*; Stahlbau; volume 71; 2002; number 3; page 165-170
[34] Markovic, dr.ir.I.;Hybride Vezelbeton (1) Ontwikkeling en toepassingsrichting;Cement; 2007; number 4
[35] Medwadowski, S.J.; *Concrete thin shell roofs at the turn of the millennium; Current and emerging technologies of shell and spatial structures*; proceedings of the colloquium held on 28-30 April 1997 in Madrid; edited by J. Abel, R. Astudillo and N.K. Srivastava; 1997; page 9-22.
[36] Rossi, P.; *Ultra-High-Performance Fiber-Reinforced Concretes; a French perspective on approaches used to produce high-strength, ductile fiber-reinforced concrete*; Concrete International, December 2001
[37] Rossi, P.; *Development of new composite materials for construction*; Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications; Volume 219; no. L1; Februari 2005; page 67-74
[38] *Shawnessy LRT station award press release*; Lafarge North America, Canada, 2006
[39] Slaich, J. and Schober, H.; *Glass roof for the Hippo House at the Berlin Zoo*; Structural Engineering International; Volume 7; 1997; number 4; page 252-254
[40] Vicenzino, E., Culham, G., Perry, V.H., Zakariasen, D., Chow, T.S. ; *First use of UHPFRC in thin precast concrete roof shell for Canadian LRT station*; PCI journal; sept/oct 2005; page 50-67

[41] Walraven, prof.dr.ir. J.; *Waar gaan we naartoe met ons beton? Beton als conventioneel bouwmateriaal*; Cement; 2002; number 4; page 6-13

Interviews

[42] Interview with Daan Rietbergen about his PhD-thesis.

Internet pages

[43] en.wikipedia.org/wiki/Finite_element_method date 14-4-2008
[44] en.wikipedia.org/wiki/Finite_element_method_in_structural_mechanics date 15-4-2008
[45] en.wikipedia.org/wiki/Finite_element_analysis date 14-4-2008
[46] en.wikipedia.org/wiki/NURBS date 5-3-2008
[47] en.wiki.mcneel.com/default.aspx/McNeel/RhinoScript.html
[48] picasaweb.google.com/rs.tulipmed/HastaEspana/photo#5064723626394534210
[49] www.asce.org/pressroom/news/display_press.cfm?uid=2650 date 24-4-2007
[50] www.bouwwereld.nl/web/EenProjectUitgebreid.htm?contentid=648&jumpto=intro&showall=true#intro date 16-11-2007
[51] www.bsieiffage.com/ date 24-8-2007
[52] www.ductal-lafarge.com
[53] www.fibretech.org date 7-02-2008
[54] www.franken-architekten.de
[55] ww.gmp-architekten.de/2projects/tempodrom/tdrom.html date 6-6-2007
[56] www.grca.org.uk date 7-02-2008
[57] www.imagineductal.com date 4-6-2007
[58] www.lafargenorthamerica.com/wps/portal/!ut/p/kcxml/04_Sj9SPykssy0xPLMnMz0vM0Y_QjzKL N4p3CwbJgFjGpvqRyCIG8Y5wAV-P_NxU_SB9b_0A_YLc0IhyR0dFAKjZGbQ!/delta/base64xml/L3dJdyEvd 0ZNQUFzQUMvNElVRS82XzJfRlM!?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/LNA/Library/ Project/Product/Ductal/Shawnessy+LRT+Station/Shawnessy_LRT_Station date 24-4-2007
[59] www.mero.de/uploads/tx_cwtcartoongallery/free_ret_stru_e.pdf date 8-2-2008
[60] www.nookindustries.com
[61] www.peri.de/ww/en/projects.cfm?fuseaction=showreference&reference_ID=449 Date 5-6-2007
[62] www.rdw.nl/tet
[63] www.rhino3d.com/nurbs.htm date 5-3-2008
[64] www.structurea.de
[65] www.reconstructivism.net/
[66] www.website.hurksbeton.nl/main.php?cm=79%2C80%2C122_1cCgGh1_oupxnHp7g1WQOV_588&cm_ wfs=589.1063&prid=92 date 24-4-2007
[67] http://www.sika.nl/tds_sikadur30_nl.pdf

Appendices

Appendix 1 Personal data and graduation committee

Personal data

Name: Eline den Hartog
Student number: 1014277
Adress: Frank van Borselenstraat 44, 2613 NM Delft
Telephone: 06-14277450
E-mail: elinedenhartog@gmail.com

Graduation committee

Prof. ir. L.A.G. Wagemans
Faculty of Civil Engineering am Geoscience
room 1.60 ST2
T: 015- 2784752
E: l.a.g.wagemans@tudelft.nl

Ir. J.L. Coenders
Faculty of Civil Engineering am Geoscience
room: 1.60 ST2
T: 015-2785711
E: j.l.coenders@tudelft.nl

Ir. A. Borgart
Faculty of Architecture
T: 015-2784157
E: a.borgart@tudelft.nl

Dr. ing. S. Grunewald
Faculty of Civil Engineering am Geoscience
room: 1.04 ST2
T: 015-2784580
E: s.grunewald@tudelft.nl

Appendix 2 Gaussian curvature

At any point A (See Figure 2.1) on a surface a vector that is normal to the surface can be defined. A plane that intersects the surface and contains a normal is considered to be normal to the middle surface at that point. The plane curve formed by the intersection of the plane, that contains a normal of the surface, with the surfaces is called normal section of the surface at that point. Every point has an infinite amount of normal sections and they all have a local curvature k and a radius of curvature r. The local curvature is defined as the inverse of the radius of curvature. The two plane curves, with the minimal and maximal value of curvature, are called the principal sections and their curvatures at point A are denoted as k_1 and k_2. These principal sections are orthogonal to each other. With these principal sections two properties of the surface at that point can be determined. The first one is the mean curvature:

$$H = ½ (k_1 + k_2)$$

The second one is the Gaussian curvature, the product of the two principal curvatures:

$$k_g = k_1 \cdot k_2$$

The sign of the Gaussian curvature can be used to characterise the local shape of the surface. The classification of surfaces by Gaussian curvature results in four classes:

Plane

The Gaussian curvature is equal to zero. In this case both principal curvatures are equal to zero; $k_1 = 0$, $k_2 = 0$. This means that in both principal directions the radius of curvature is infinite and the surface is flat.

Simply curved

The Gaussian curvature is equal to zero. In this case only one of the principal curvatures is equal to zero; $k_1 = 0$, $k_2 \neq 0$. These surfaces are single curved and developable.

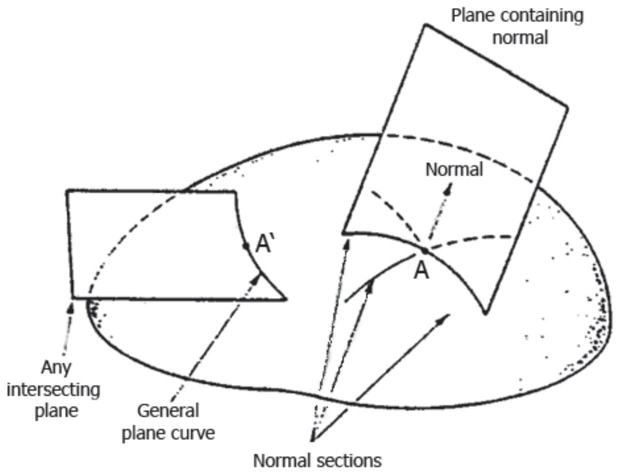


Figure 2.1 Intersection of different planes with a surface. [3]

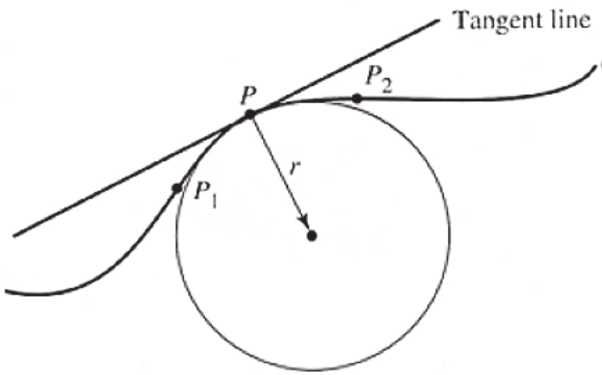


Figure 2.2 Radius of curvature r of a general curve C. [59]

Figure 2.3. The Jahrhunderthalle Hoechst (Frankfurt, 1963) is an example of a sinclastic curved structure. [64]

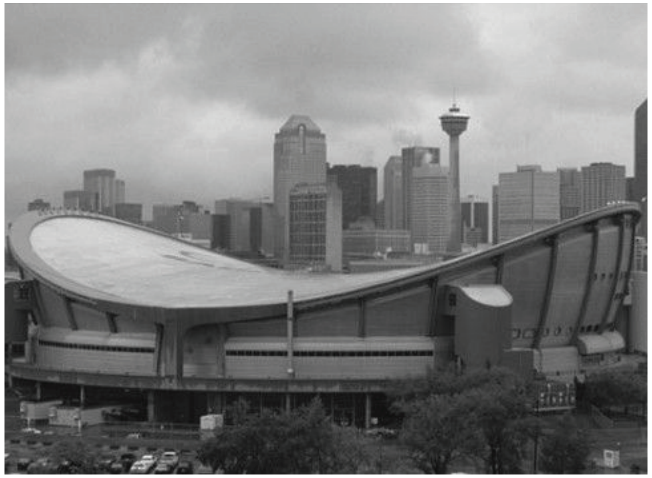


Figure 2.4 The Saddledome (Calgary, 1983) is an example of an anticlastic curved structure. [64]

A developable surface is defined as a surface that can be developed into a plane form without cutting and/or stretching their middle surface. An example of this type of surface is the cylindrical shell.

Synclastic

The Gaussian curvature is positive. This means that both principal curvatures have the same sign. This results in a double curved surface. Examples of synclastic structures are domes or elliptic paraboloids.

Anticlastic

The Gaussian curvature is negative. This means that the principal curvatures have different signs. This results in a double curved surface. Examples of anticlastic surfaces are for example found as sable shape surfaces or in tensioned membrane surfaces.

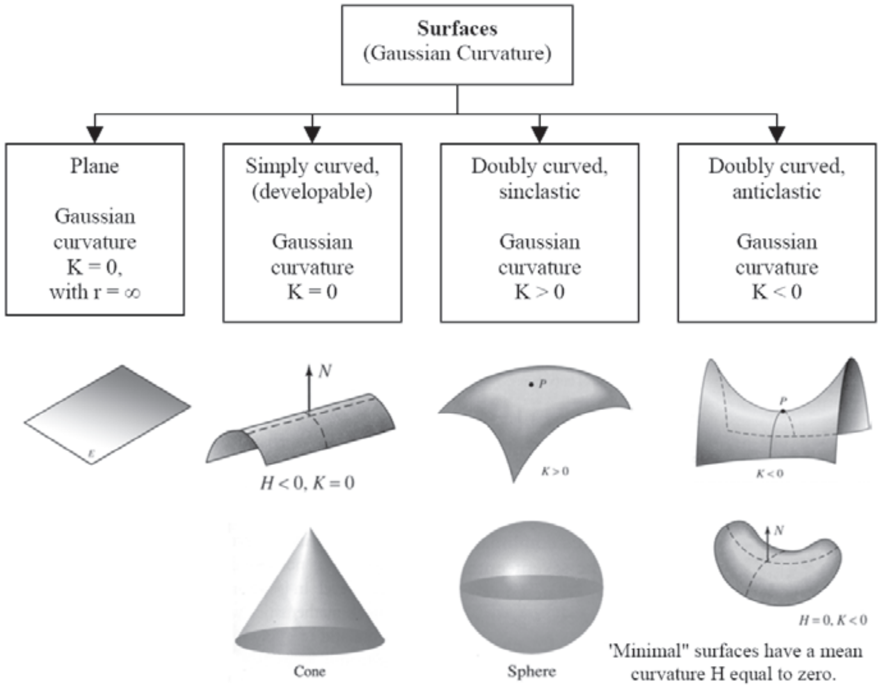


Figure 2.5 Surface classification by Gaussian curvature. [59]

Appendix 3 The test surfaces

The three test surfaces with a projected grid.

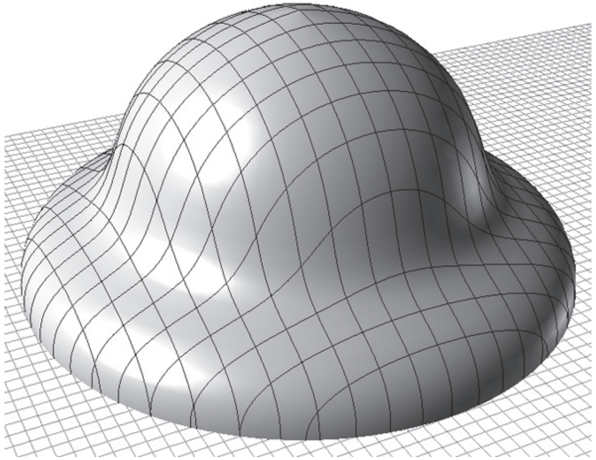


Figure 3.1 Surface of revolution with a projected grid.

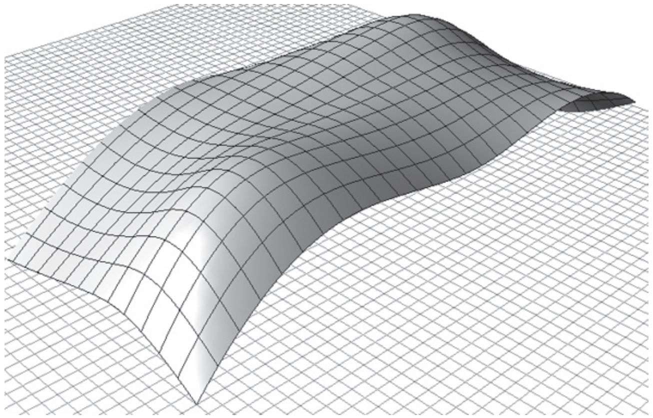


Figure 3.2 Surface 1 with a projected grid.

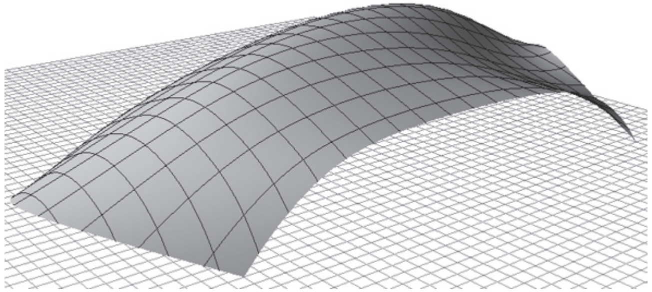


Figure 3.3 Surface 2 with a projected grid.

The three test surfaces with a Rhino mesh.

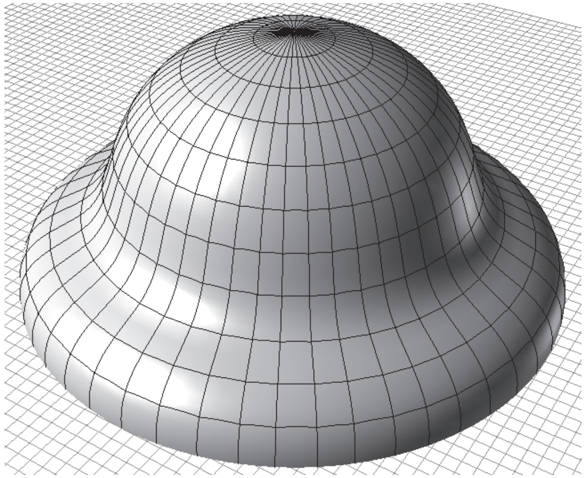


Figure 3.4 Surface of revolution with a Rhino mesh.

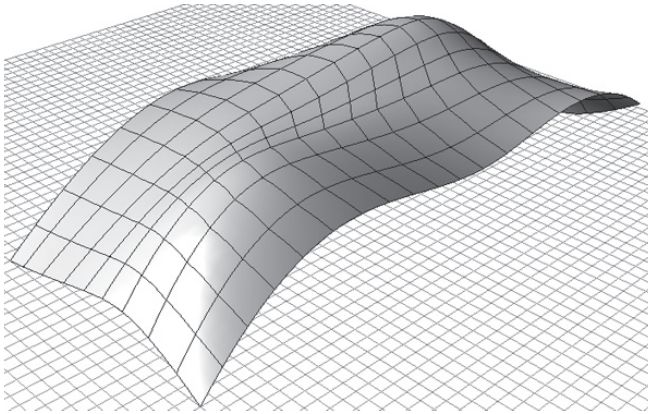


Figure 3.5 Surface 1 with a Rhino mesh.

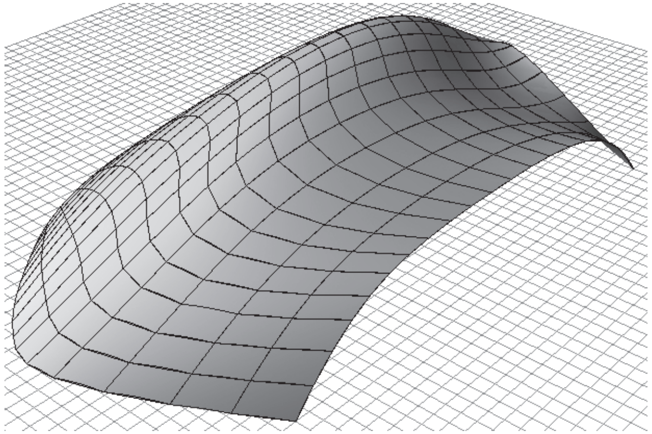


Figure 3.6 Surface 2 with a Rhino mesh.

The three test surfaces with a isocurve grid, before rebuilding.

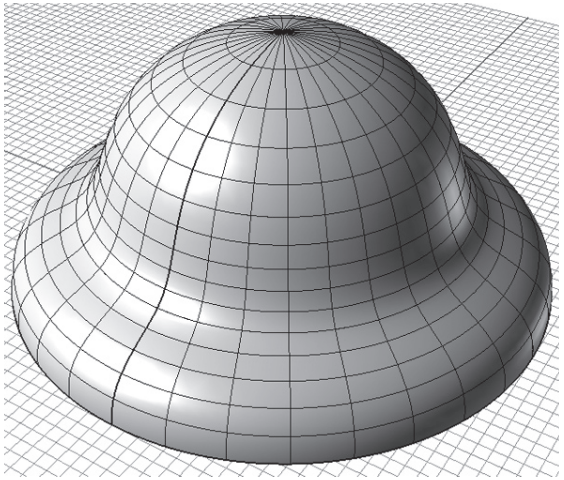


Figure 3.7 Surface of revolution with an isocurve grid.

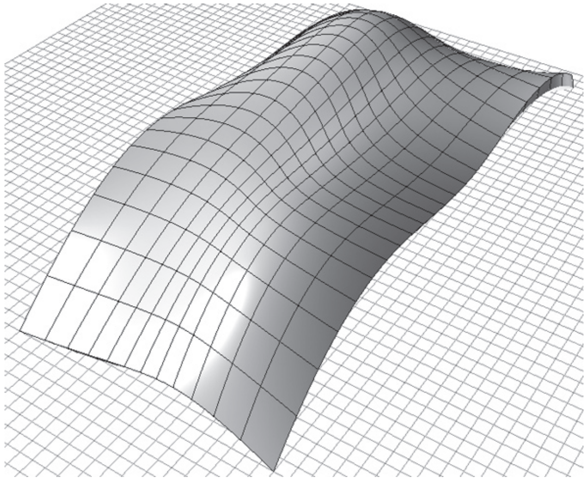


Figure 3.8 Surface 1 with an isocurve grid.

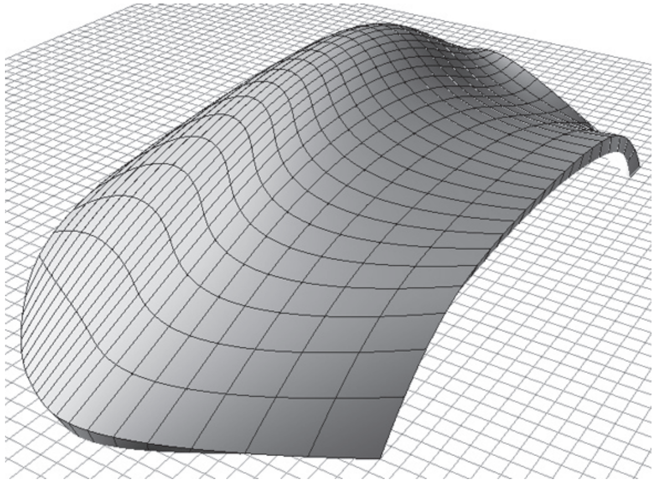


Figure 3.9 Surface 2 with an isocurve grid.

The three test surfaces with a isocurve grid, after rebuilding.

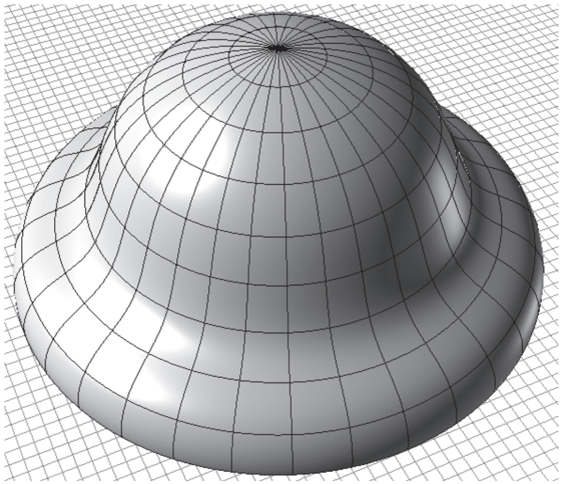


Figure 3.10 Surface of revolution with an isocurve grid. Maximum deviation with rebuilding is 0,00894 m

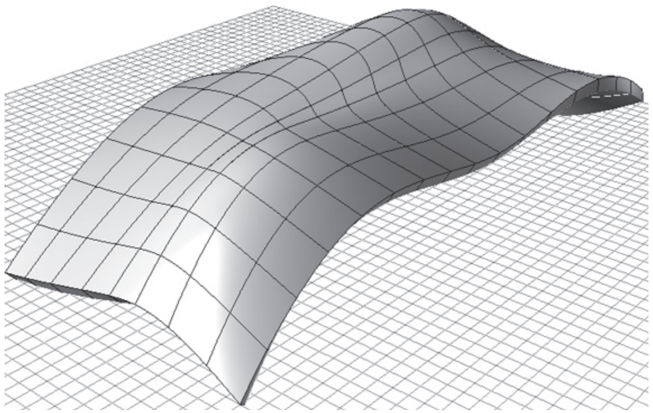


Figure 3.11 Surface 1 with an isocurve grid. Maximum deviation with rebuilding is 0,00693 m

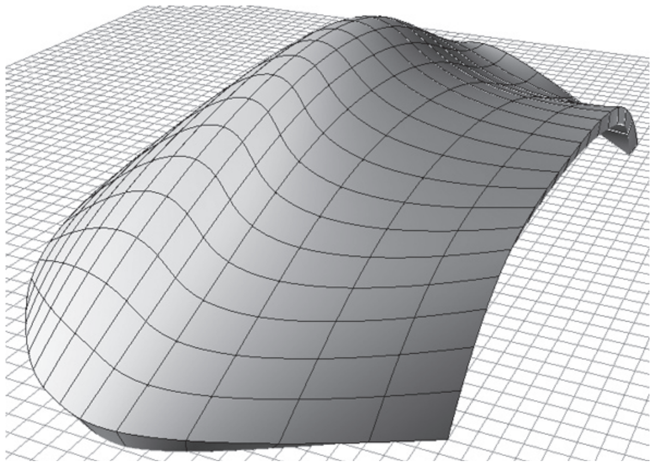


Figure 3.12 Surface 2 with an isocurve grid. Maximum deviation with rebuilding is 0,00589 m

Testing of the design tool

The three test surfaces are segmented with the design tool to test the tool and evaluate the results. Each surface is segmented twice, both the not rebuild and the rebuild surface are segmented. The maximum length of the edges is 4 m, for all surfaces and the thickness is 1 m.

The resulting grids are presented in figures 3.7 to 3.12 and the results of the control of the elements is presented in table 3.1.

This table clearly shows that grid is improved for the surfaces that have been rebuild, compared to the not rebuild surfaces. There are less elements in these grids and the average elements size is closer to the maximum elements size. This means that the there are less very small or very large elements.
The rebuilding however gives some deviation in the shape of the surface compared to the original surface. This deviation is in the order of a couple millimetres. It is assumed that this deviation does not give any major problems, because the rebuilding of the surface is executed in an early phase of the design process.

The average angle between the edges for the different surfaces is between 80 and 110 degrees. But almost for every surface there are some angles that are not within the set requirements. A drawback of the chosen grid generation method is that the angles between the grid lines cannot be changed or improved. This means that when the grids consists some too small or too large angles the grid cannot be improved till all angles are within the requirements. The only options are to accept the too small angles or change the shape of the surface. Especially with the surface of revolution the elements in the top have very small angles and are actually more triangles that quadrangulars. From this it can be concluded that the chosen grid generation method is not especially suited for the generation of a grid on a surface of revolution.

The curvature of the elements is not really influenced by the rebuilding of the surface. When the curvature of the surface is too small to be made with the flexible mold the surface has to be adapted or the choice has to be made to cast these particular elements with a another mould.

The generated edges are nicely aligned in the corners of the elements. The length of the edges is also generated

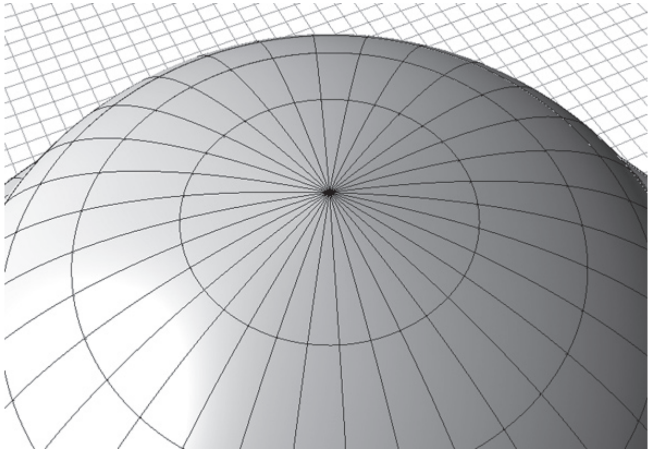


Figure 3.13 The elements in the top of the surface of revolution are generated as triangular elements, with very small angles in top of the surface.

	Rebuild-ed	Max. deviation (m)	Number of elements		Average edge length (m)		Average length of the diagonals (m)	Average angle in plane	Incorrect angles	Minimum curvature (m)
			U	V	U	V				
Surface of revolution	No		32	15	2,5	2,0	3,3	84°	33	0
	Yes	0,00894	32	9	2,2	3,3	4,0	90°	0	0
Surface 1	No		12	22	1,9	2,1	2,9	95°	0	3,9
	Yes	0,00693	8	16	2,8	2,9	4,0	91°	0	4,0
Surface 2	No		21	22	1,7	2,1	2,7	109°	23	0
	Yes	0,00589	13	18	2,6	2,5	3,6	107°	12	0

Table 3.1 The result of the tested surfaces.

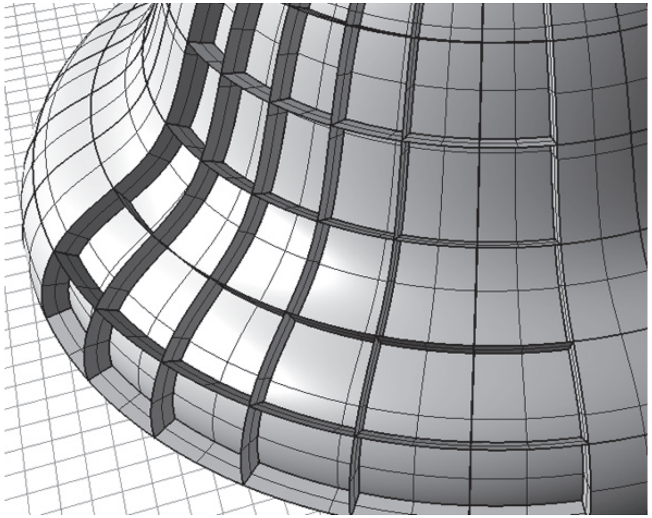


Figure 3.14 The edges of the surface of revolution are almost not in torsion probably due to the regular change of the curvature of the surface.

correctly. Due the generation of the edges perpendicular to the surface the edges can be in torsion. The torsion of the edges is influenced by the amount of curvature in the shell. The the curvature of the shell changes rapidly there is more torsion in the edges than when the curvature of the shell changes only slowly or regularly. Also the fact whether the surface is synclastic or anticlastic might influence the torsion in the edge. It is expected that the amount of torsion in the edges is smaller for a synclastic surface than for a anticlastic surface.

The shape of the boundary edges should be dependent on the shape of the foundation. The edges of the elements that are placed on the foundation should be horizontal. This is not implemented in the design tool, so these edges are still generated perpendicular to the surface.

The inner surface of the shell is nicely aligned with the edges of the elements. Because the boundary edges are generated perpendicular to the surface and not horizontal at this point not problems with the alignment of the edges with the inner surface occur. When the boundary edges are generated horizontally the shape of the inner surface of these elements has to be adapted to the horizontal edge.

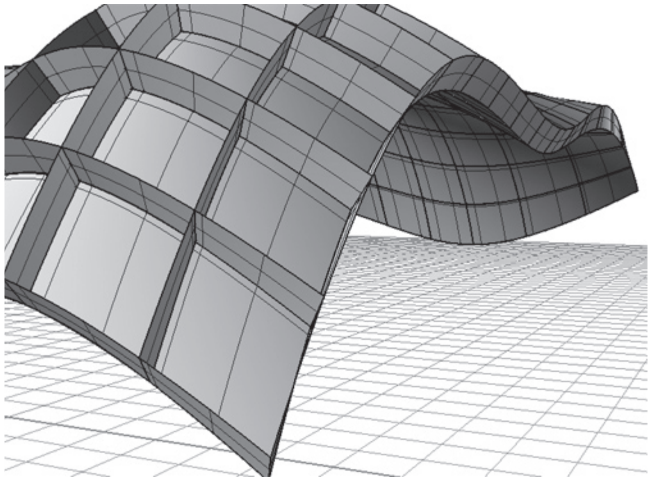


Figure 3.15 This detail of surface 1 shows that the edges of the elements are in torsion.

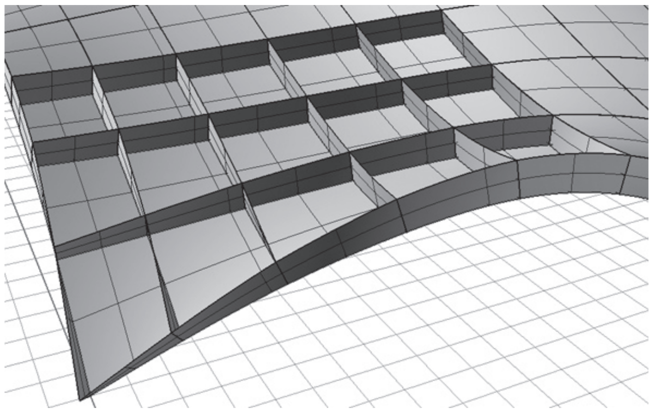


Figure 3.16 This detail of surface 1 shows that the torsion of the edge is larger when the curvature of the surface is larger.

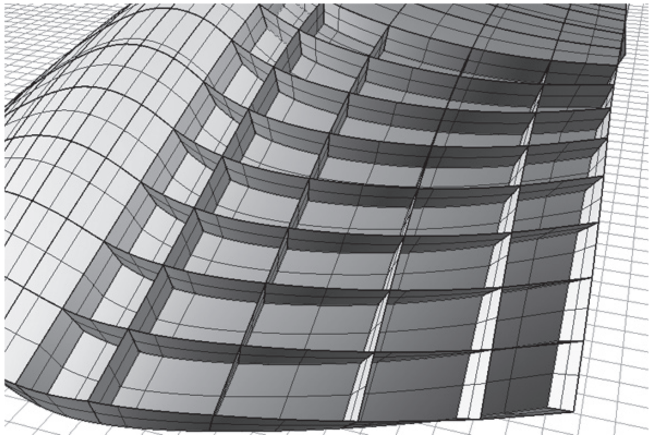


Figure 3.17 This detail of surface 2 shows that these edges are also in torsion.

Appendix 4 Rhino mesh tool

In this appendix the process with which the mesh is generated and the different control options are explained.

The rhino mesh tool creates polygon meshes from NURBS surfaces or polysurfaces. Surfaces are meshed in a two step process. First a regular quad mesh is created and then that mesh is refined by splitting some quads into 4 smaller quads. The ‘maximum aspect ratio’, ‘maximum edge length’ and ‘minimum initial grid quads’ settings control the generation of the initial mesh. The ‘maximum angle’, ‘maximum edge length’, ‘minimum edge length’, and ‘maximum distance, edge to surface’ settings determine which initial quads get split up into smaller quadrangles.

Density

This option uses a formula to control how close the polygon edges are to the original surface. Values between 0 and 1 can be used, larger values result in a mesh with a higher polygon count.

Maximum angle

This option controls the maximum allowable change between the surface normal at any point and the mesh vertex. Two vertices are neighbors if they are at the ends of a facet edge. Smaller values result in slower meshing, more accurate meshes, and higher polygon count.

Maximum aspect ratio

Surfaces are initially tessellated with a regular quadrangle mesh, which is refined after generating. The initial quad mesh is constructed so that on average, the maximum aspect ratio of the quads is less than or equal to Maximum aspect ratio.

Smaller values of the aspect ratio result in slower meshing and a higher polygon count with more equilateral and nicely shaped polygons.

Minimum edge length

If any edge is shorter than the Minimum edge length, no further division of the mesh faces occurs. This length is, approximately, the minimum edge length of the quads in the initial mesh grid.

Maximum edge length

The polygons are divided until all polygon edges are shorter than the maximum edge length. This length is, approximately, the maximum edge length of the quads in the initial mesh grid.

Maximum distance, edge to surface

Polygons divide until the distance from a polygon edge midpoint to the NURBS surface is smaller than this value. This distance is also the approximate maximum distance from polygon edge midpoints to the NURBS surface in the initial mesh grid.

Minimum initial grid quads

With this value the number of quadrangles per surface in the initial mesh grid can be set. Bigger values result in slower meshing, more accurate meshes and a higher polygon count with more evenly distributed polygons. Setting this value to zero turns off the option.

Refine mesh

After its initial meshing, Rhino uses a recursive process to refine the mesh until it meets the criteria defined by ‘maximum angle’, ‘minimum edge length’, ‘maximum edge length’, and ‘maximum distance, edge to surface’ options. No refinement results in faster meshing, less accurate meshes with a lower polygon count

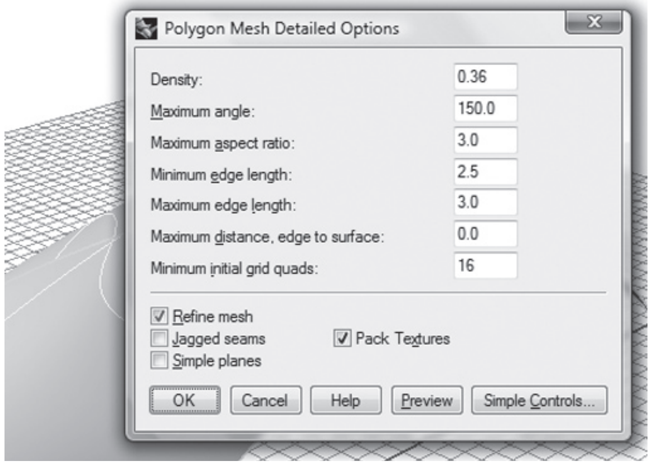


Figure 4.1 The option control box of the Rhino mesh tool.

Jagged seams

All surfaces are meshed independently and Rhino does not stitch the edges of joined surface edges together. If Jagged seams is not checked, watertight meshes are created. This causes faster meshing, a lower polygon count and cracks between joined surfaces in the rendered image.

Simple planes

All planar surfaces are meshed by meshing the surface edges and then filling the area bounded by the edges with triangles.

Pack textures

When polysurfaces are meshed, the packed texture coordinates are created. A packed texture is a partition of the unit square into disjoint sub-rectangles so that one bitmap can be used to apply independent textures to each face of the polysurface.

Appendix 5 Case study

Segmentation and element generation

The design tool is used to generate the grid over the case study design, for both the original and the rebuild surface. The results of the generated elements are given in table 5.1.

- Maximum length of the edges: 3 m
- Thickness of the shell is 100 mm.

The first thing that can be seen on this results is that the difference between the original and the rebuild surface is much smaller than with the test surfaces of Chapter 9. This makes that the grid of the rebuild surface is not absolutely better than the original grid. Because the small difference between the two grids only the grid of the rebuild surface will be shown and discussed here. This grid will be used, because the number of elements in this grid is smaller and the number of elements with wrong angles is also smaller than in the original surface.

Element size

The results in table 5.1 show that the length of the edges in the U-direction is smaller than the length of the edges in the V-direction. This means that the shape of the edges is more rectangular that square.
The size of the different elements does not differ a lot for large parts of the surface. There are only two areas where very small elements are generated. These areas are marked with two circles in Figure 5.4. The shape of these elements is also not very optimal. So these elements have to be improved during the optimization of the generated grid.

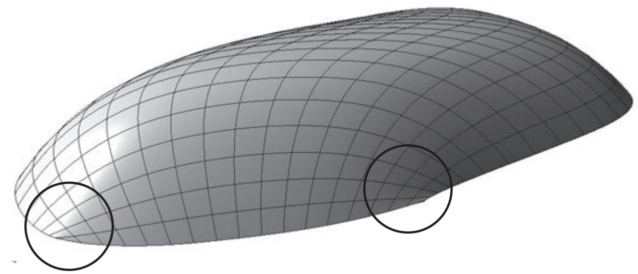


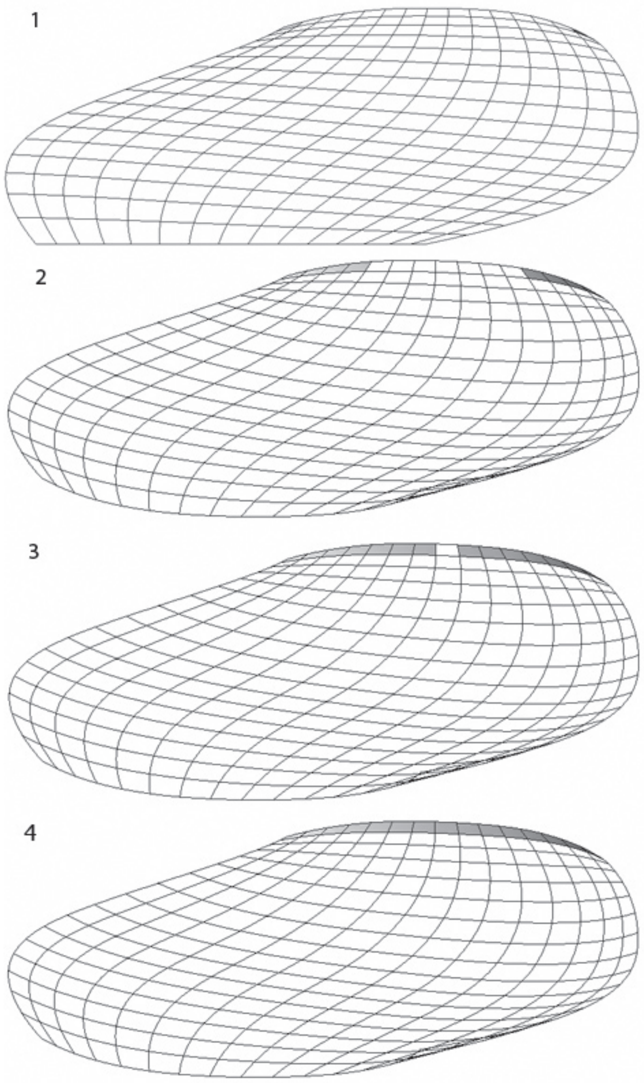
Figure 5.1 The problem areas of the grid the element size and element curvature are marked with the two circles.

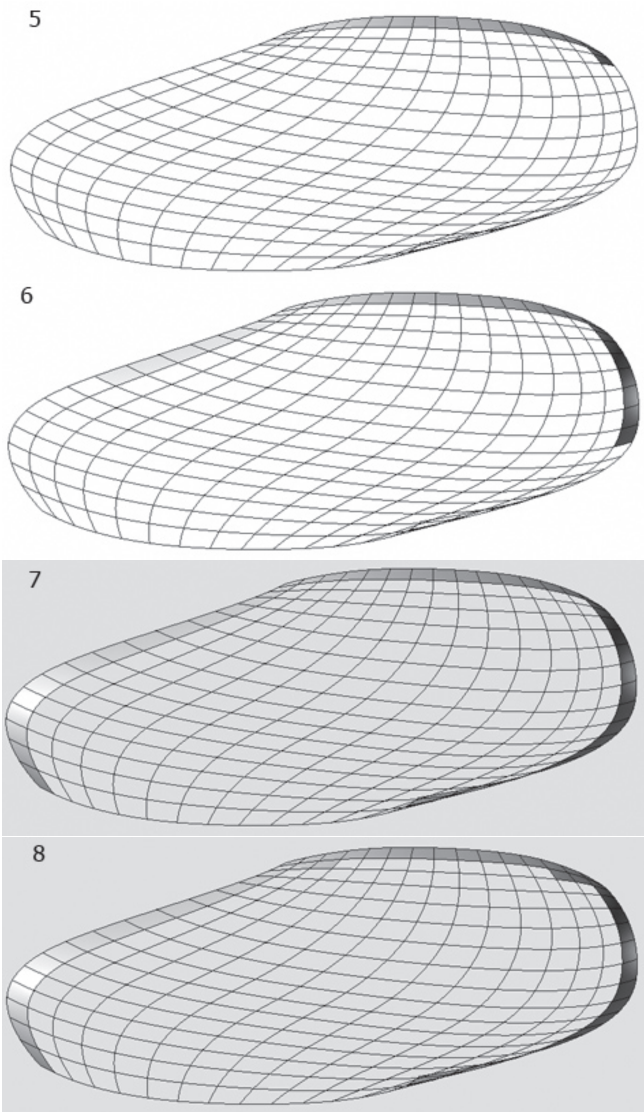
		Case study design	
Rebuild		No	Yes
Maximum deviation (mm)			0,688
Number of elements	U	18	17
	V	17	17
Maximum edge length (m)	U	3,00	2,95
	V	2,64	2,63
Minimum edge length (m)	U	0,68	0,39
	V	1,25	1,24
Average edge length (m)	U	1,49	1,58
	V	2,16	2,10
Average length of the diagonals (m)	dir1	2,02	1,98
	dir2	3,15	3,14
Average angle in plane		64^{o}	66^{o}
Incorrect angles		77	70
Minimum curvature (m)		0	0

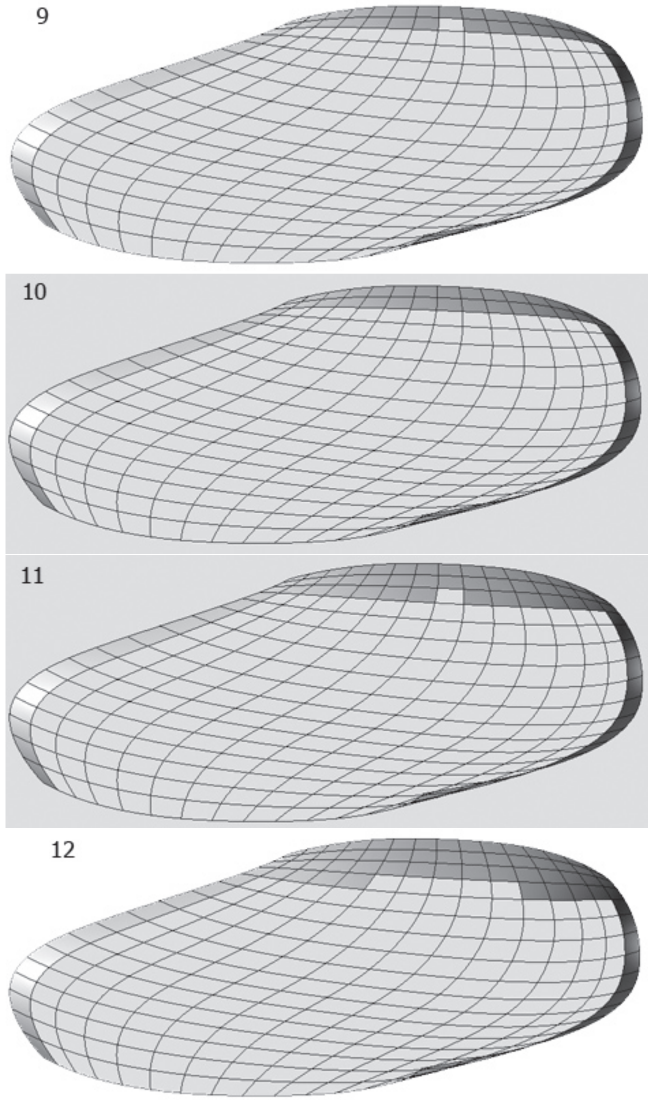
Table 5.1 Results of the generated grid of the case study design

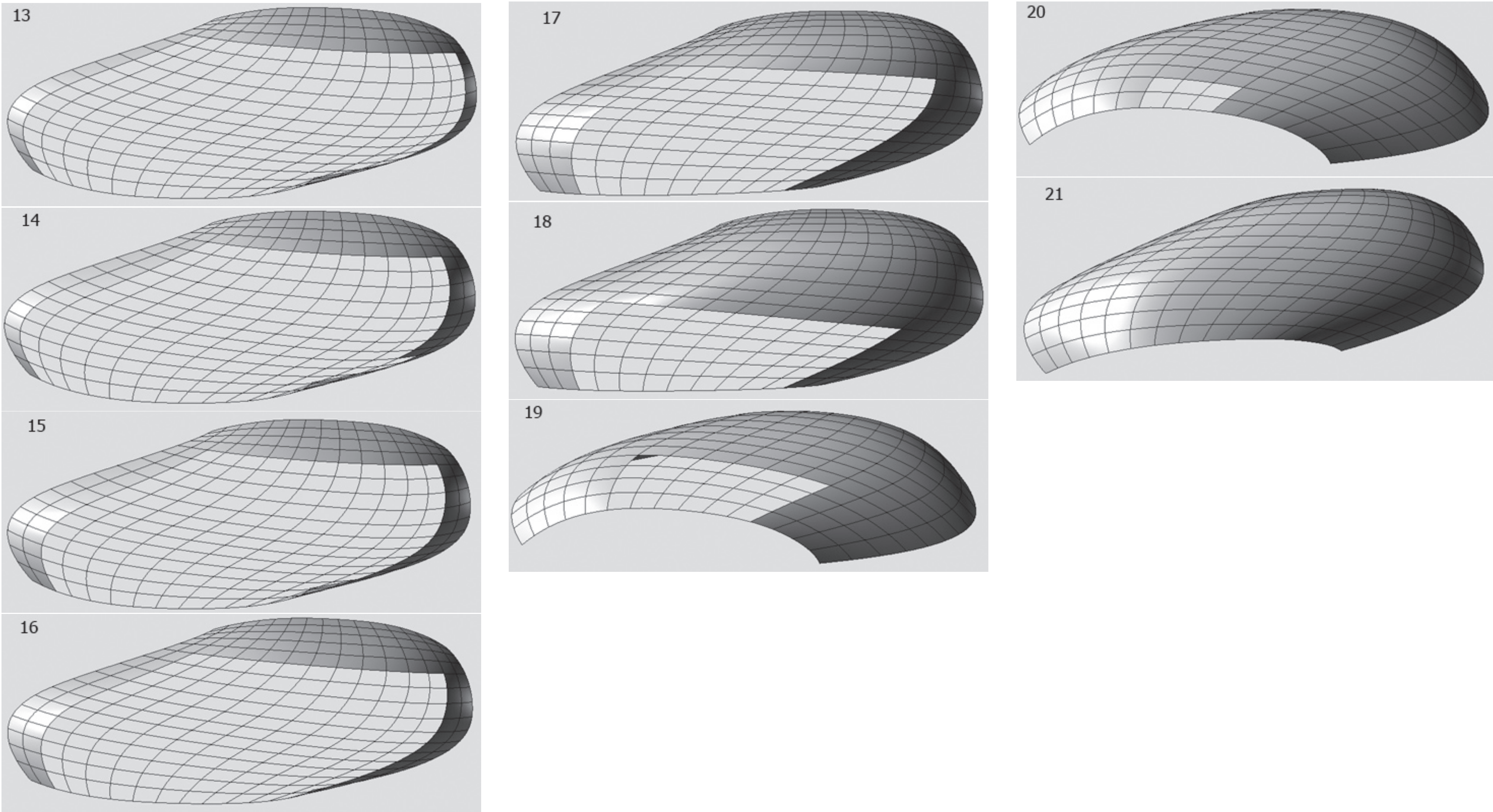
Construction process

In the following figures the placing sequence of the elements is visualized.








13
14
15
16
17
18
19
20
21

Appendix 6 Functional and technical roof aspects

6.1 Water proofing

The outside of a roof needs to be water tight, this mean that the seams in the water carrying surface need to be made as water tight connections. This can for example be done with bitumen or plastic foils. The water resisting layer needs to be very reliable, because a small leak can cause large damage in the building.

The rainwater that falls on the roof needs to be drained of the roof as fast as possible. The design of the roof must be made in such way that no water will be collected or stays at any place on the roof.

The moist balance in roofs is hard to control. Because the outer layer is completely water tight, moisture from leakage or condensation has to be drained inwards.

6.2 Heat transport or insulation

Another aspect of a building is the insulation, which makes sure that no excessive heat loss occurs during cold periods. Beside temperature of the inner surface of the roof has to have a minimal value to prevent to much condensation in the construction. The present building code requires some sort of insulation in almost all buildings. The quality of the insulation depends on the type of building.

Requirements of the insulation

In the building code minimum values for the thermal insulation are set. The minimum value specified heat resistance (R_c) of a facade, roof or floor for residence areas is 2,5 m^2K/W. This is a minimum value that has to be applied in practice the used value will be often higher due to the energy performance standards. The specified heat resistance can be calculated as follows:

$$R_c = \sum R_m$$

And:

$$R_m = d/\lambda$$

In which R_m is the specified heat resistance of a single layer in the structure, d is the thickness of the layer and λ is the heat conduction coefficient or thermal conductivity. Thermal conductivity is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions. The thermal conductivity of some often used materials is shown in table 6.1

When it is assumed that the thickness of the concrete is 70 mm a layer of about 100 mm of mineral wool layer or a layer of 70 mm of cotton wool is needed to come to a specified heat resistance of 2,5 m^2K/W. In this calculation it is assumed that the package of the construction only consists of two layers (concrete and an insulation material) and it gives only an indication of the needed thickness of the insulation material.

6.3 Package composition

There are different methods that can be used to design the roof package, that consists of the concrete elements, an isolating layer and a water tight layer.

Insulation on top of the concrete elements

In the first method the package composition from the outside to the inside is:

- Water tight layer;
- Insulation;
- Concrete elements

In this way the concrete is not visible from the outside, but can be visible form the inside of the building. But the concrete elements are protected against moisture, large changes in temperature and frost.

Material	Thermal conductivity λ (W/m.K)
Reinforced concrete	2,3
Unreinforced concrete	2,2
Cement mortar	1,73
Rock wool insulation	0,045
Cotton wool insulation	0,029
Mineral wool blanket	0,04
Fibre insulation board	0,048
Foam glass	0,042
Foamed plastics	0,03

Table 6.1 The Thermal conductivity of concrete and different types of insulation material.

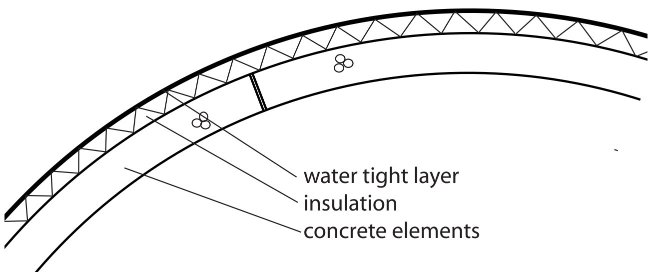


Figure 6.1 Roof package with the insulation on top of the elements.

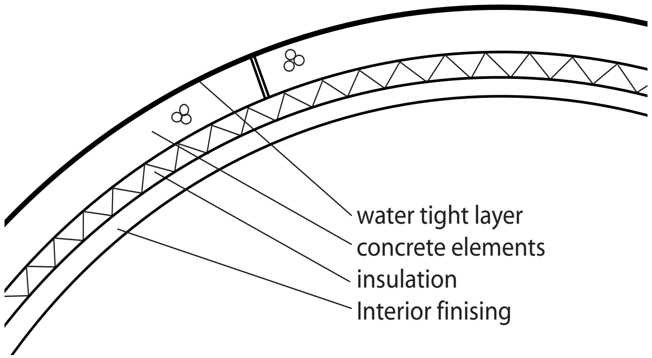


Figure 6.2 Package composition with the insulation under the elements.

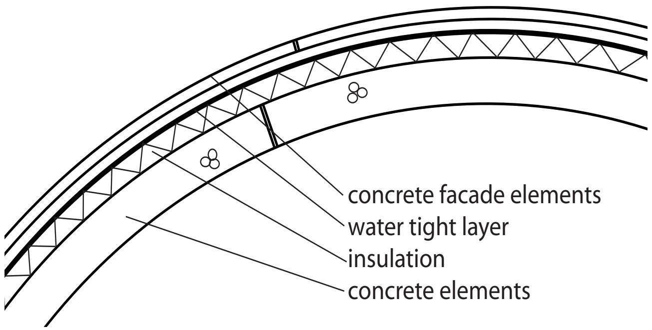


Figure 6.3 Package composition with concrete elements on the inside and outside.

Insulation under the concrete

In this method the concrete forms the outer layer of the structure and the insulation is placed under the concrete elements. The concrete element can be covered with a water tight layer or can be constructed in such way that they form water tight layer. The inside of the insulation is covered with some finishing layer. With this method the elements are visible on the outside of the structure. But the concrete elements are exposed to temperature changes, what can damage the concrete. Beside this the moist balance in this type of package is not very optimal.

Double concrete layer

In this last method the following package composition from the outside to the inside is used:

- Concrete facade elements;
- Water tight layer;
- Insulation;
- Load bearing concrete elements.

In this way the concrete can visible on both the outside and inside of the shell and at the same time an optimal roof package composition can be used. A drawback of this method is that it is more expensive due to the concrete facade elements.

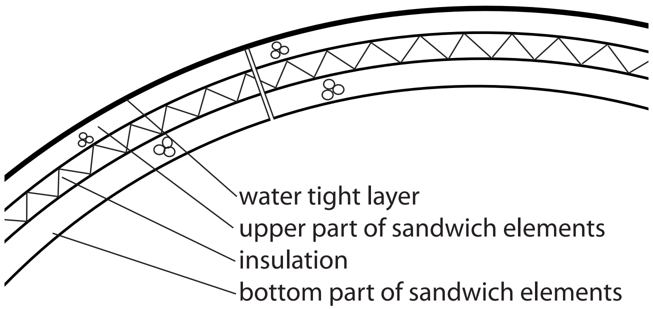


Figure 6.4 Package composition of the shell composed of sandwich elements.

Sandwich element

A sandwich element is composed of two layers of concrete with an insulation layer in between. The three layers are attached to each other to form a composed element. The benefit of this type of element is that the inner and outer layer of concrete can work together. This makes that the thickness of these layer might be reduced due to a more optimal distribution of the material.
The production of these sandwich elements is a lot more complicated than the production of the normal double curved elements. This makes the production of the elements also a lot more expensive. A benefit of the use of sandwich elements is that the insulation is integrated into the element and does not need to be placed on the structure on site.

6.4 Evaluation

From the point of view of moist balance in the roof, water tightness and insulation the first and the last two methods can have the same performance quality.
The second method performs a lot worse from the aspect of building physics, and it is not advisable to use this method.
A drawback of sandwich elements is that the production is more complicated, but this might be compensated by the better mechanical performance due to a better material distribution. But in general it is better to use sandwich element as facade element, that do not have a load bearing function. Because it is very hard to connect the two concrete layers of load bearing sandwich element in such way that they work together properly.

Whether the first or the third method is used depends mainly on the aesthetic wishes from the architect and future owner of the building and budget of the project.