PRECAST DOUBLE CURVED CONCRETE PANELS

Koen Huyghe & Arnoud Schoofs
juni 2009

Delft University of Technology
Faculty of Architecture
Building Technology
Facade Master

Master's thesis committee:
Dr. Ir. Karel Vollers
Ir. Daan Rietbergen
Dipl.-ing. Steffen Grünewald

PREFACE

In front of you lies the report of the combined Master's thesis of Koen Huyghe & Arnoud Schoofs. It contains the research conducted during the spring semester of 2009 in the Facade Design Program at the Faculty of Architecture of Delft University of technology.

The thesis elaborates an innovative production method for precast double curved concrete elements. We would like to thank our supervisors Dr. Karel Vollers and ir. Daan Rietbergen for initiating and offering us this interesting graduation project.

An essential part of the research project was to carry out experiments and to build prototypes, so we could evaluate the principles of the production technique. We deliberately and intensively united knowledge and expertise from various faculties and companies to present a viable and convincing end result. We would like to thank Giel Hermans, Faculty of Electronics, for his assistance on the electronics of the actuators. Many thanks to Y. 'Wolf' Song, Faculty of Industrial Design, for his support on 3D-scanning. Within the Faculty of Civil Engineering we would like to thank Edwin Scharp and Ton for their guidance and patience during the many concrete experiments and Kees Baardolf for his practical knowledge and cheerfulness.
We would like to thank everyone at Hurks Beton for their cooperation and especially Dr. Steffen Grünewald for his valuable remarks and impressive concrete knowledge.

Doing research in the Netherlands was an interesting opportunity and learnful experience. We want to thank our parents, family, friends and partners, Annelies and Ellen, for the support they provided. You all contributed to this result.

Koen Huyghe
Arnoud Schoofs
june 2009

TABLE OF CONTENT

1. INTRODUCTION

There is nothing more difficult to take in hand, more perilous to conduct or more uncertain in its success than to take the lead in the introduction of a new order of things. (Niccolo Machiavelli)

1.1. PROBLEM DESCRIPTION

The potential for double curved concrete precast elements is enormous. The big break-through is in sight but for now, still fragile. A working principle describing an adjustable formwork can tip the balance. This new production process can significantly reduce the production time and costs of complex elements and through this establishes the introduction of free form architecture in our daily environment. Before reaching this 'tipping' point, many problems need to be resolved in advance.

The idea of an adjustable formwork is not new: the bigger idea is yet presented and sketched many times in the last decades. However, the exact construction and coherence between its parts is never presented before. Several research institutes and companies have solved particular components, but none managed to produce accurate, convincing concrete elements so far.

The process layout described by Dr. K. Vollers & PhD candidate D. Rietbergen serves as datum in this thesis. The unknown and unsolved issues, present in the process description, can be divided in two fields; computation and product development. A clear process layout describing the exchange of information between computer and physical setup is not at hand. Also it is expected that a certain amount of pre-and post-processing should take place when producing complex elements. Materialisation of the flexible formwork and related components, (e.g., edges, positioning concept, reinforcement, etc.) is not defined yet.

1.2. RESEARCH OBJECTIVE

The aim of this Master's thesis is to formulate and materialise a feasible production technique for double curved precast concrete elements.

The formulation of the process and its individual components is described in this report. The main topics are:

- Accumulating knowledge on the behavior of concrete in fresh as well as in hardened condition. A description of the desired behavior linked to the production technique should be the aim.

- Description of the pre-and post processing applications necessary to produce and evaluate complex concrete precast panels. The treated topics can be classified under computational research.

- Development of a working principle for a flexible formwork.

The materialisation of the production process takes place during the entire research period and is continuously fed with the conclusions of the theoretic part. Formulated concepts are tested in mock-ups that together with time progression, grow in complexity, refinement and size. The main focus points are;

- Testing of several concrete compositions on their behavior in fresh and hardened state.

- Experimenting with several methods to materialise a flexible formwork.

- Construction of a convincing concrete element at the end of the research period to demonstrate the feasibility of the proposed technique.

1.3. RESEARCH STRATEGY

The research can be divided in four parts; the diagram below (figi1.1)shows the components. Part 1 focuses on the relevance of the process and investigates aspects related to the production process. Part 2 contains two individual elaborated research tracks and presents solutions for a flexible formwork and an overview of the necessary pre-and post-processing to fabricate the panels. In part 3 two different panel configurations are designed and materialized. Part 4 lists the conclusions of the research and formulates recommendations for future research.

PART1: GENERAL ASPECTS
Literature is consulted to gather relevant information on aspects related to the process.

Chapter 2 ' relevance & context', will discusses existing production techniques for double curved elements and weigh their importance. Possibly methods or approaches can be extracted and integrated in the new technique. The variety in techniques is discussed with the help of case studies. At the end, the principle described in the patent acquired by Dr. K. Vollers & PhD Candidate D. Rietbergen is summarized to mark the datum of this thesis.

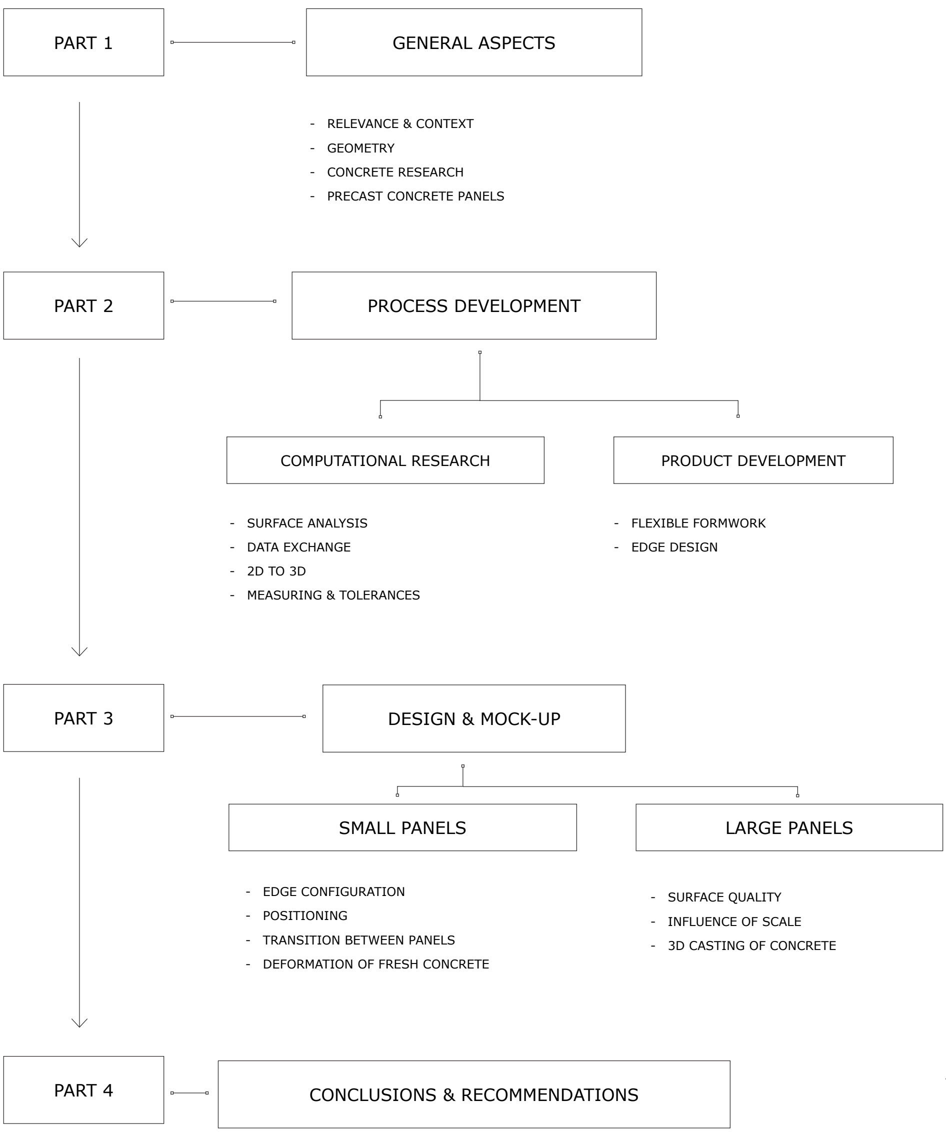


fig.1.1 scheme of the research stragtegy

In **Chapter 3** 'geometry', the most important geometrical aspects of free form shapes are listed and described.

The importance of concrete developments, in particular fibre reinforced concrete, are discussed in **Chapter 4**. This review of literature is supplemented with several experimental concrete tests to asses the desired behavior of the concrete for this particular production technique.

Chapter 5 'concrete precast elements' lists the phenomena affecting concrete panels and its components. In this chapter 'precast' as mentioned in the thesis' title is elaborated and guidelines for design are presented.

PART 2: PROCESS DEVELOPMENT
Based on personal interest, two research tracks are presented. Each students individually pursues his track. At certain time intervals findings are exchanged and panels are constructed to consolidate the gained knowledge.

'Computational research' is the emphasis in **Chapter 6** and elaborated by Arnoud Schoofs. The exchange of data between virtual and physical model is discussed as well as several proposals to control the deformation from 2D to 3D. Additionally, an evaluation method for produced panels is presented and tested.

Chapter 7 'formwork development' , pursued by Koen Huyghe addresses the principle and materialisation of a flexible formwork.

PART 3: DESIGN & MOCK-UP:
The acquired knowledge of the previous chapters is implemented in two mock-ups.

Chapter 8 'design & mock-up describes the design of the two completely different setups. The construction method and evaluation criteria are deliberately diverse.

PART 4: FINAL REMARKS
The process and the developed components are evaluated. The produced concrete elements serve as a frame of reference.

In **Chapter 9** 'conclusions and future perspectives' the findings of the research are summerised and areas in which future development is useful are indicated.

2. RELEVANCE & FRAME OF REFERENCE

Concrete has a cultural history and an identity of its own. Since its invention it always had a characteristic building culture. It's a culture of simplicity and experiment, a culture of every day building and the artistic avant-garde. The identity of the material lies in its unmistakable authenticity and its universal character.
For more than hundred fifty years the material has inspired designers, artists and architects to explore yet many of the endless possibilities that concrete provides. But throughout these years the trick has always remained: how to produce or construct it? New or updated production techniques always opened up a way to explore a new range of applications.

fig.2.1   Volcan cultural centre, Oscar Niemeyer

2.1. INTRODUCTION

This chapter aims to describe the frame of reference we are working in and tries to capture the relevance of our main research questions stated in the previous chapter. Conclusions will be formulated to close off this initial research period.

Just a few decades ago concrete was often misunderstood, disliked and captured by its image fixed due to the rapid urbanization of the 1960s. But since that time, concrete has made considerable progress, not only in technical terms, but also in esthetic terms. It is no longer the heavy, cold and grey material of the past; it has become beautiful and lively. Thanks to research and innovation, new concretes have been created: more resistant, lighter, white or colored, etc. Concrete has learned to adapt to almost all new challenges that appeared. Translucent concrete can be seen as a recent answer to the architects call for more transparent architecture. (fig.2.2)

As one can notice in the reference book we edited there is a great demand for freely curved elements. But the designers of those projects still turn towards steel, glass or composites when materializing their buildings. Those who dare using concrete still encounter an expensive and time consuming production technique with double moulds that drastically increases the building cost and therefore leaves many of these projects unexecuted or accomplished with a discrete representation of these smooth curves. If the concrete industry want's to broaden it's market range, it's inevitable that a new production technique for freely curved concrete panels is developed.

fig.2.2 translucent concrete panels produced by Litracon www.litracon.hu

The drawback in this production process is not so much the concrete mixtures or how to analyze force flows throughout such a panel. It is however, the adjustable mould puzzle that never seems to get solved.
And as today's great demand for double curved surfaces exceeds the technological innovation, the industry reverts to known formwork methods.

2.2. CASE STUDIES

The reference book we edited, provides a general overview to convince one of the great demand for double curved elements in contemporary architectural projects. Here we will examine four projects more in depth to focus on their respective production techniques and merit them on several parameters.

The following projects were selected because they differ in scale, complexity and construction processes :

1. Philips Pavilion, Le Corbusier, Brussels(1958)
2. Mercedes Benz Museum, UN Studio, Stuttgart (2006)
3. Spencer Dock Bridge, Future Systems, Dublin (2008)
4. Villa NM, UN Studio, New York (2007)

Villa nm	Spencer dock bridge	Mercedes Benz Museum	Philips Pavilion	
v	v	v		on site
			v	prefab
v			v	size s
v	v			size m
		v		size l
v		v		radius < 10m
	v	v		radius < 50m
		v	v	radius < 100m
	v	v		structural
		v		interior
v	v	v	v	exterior

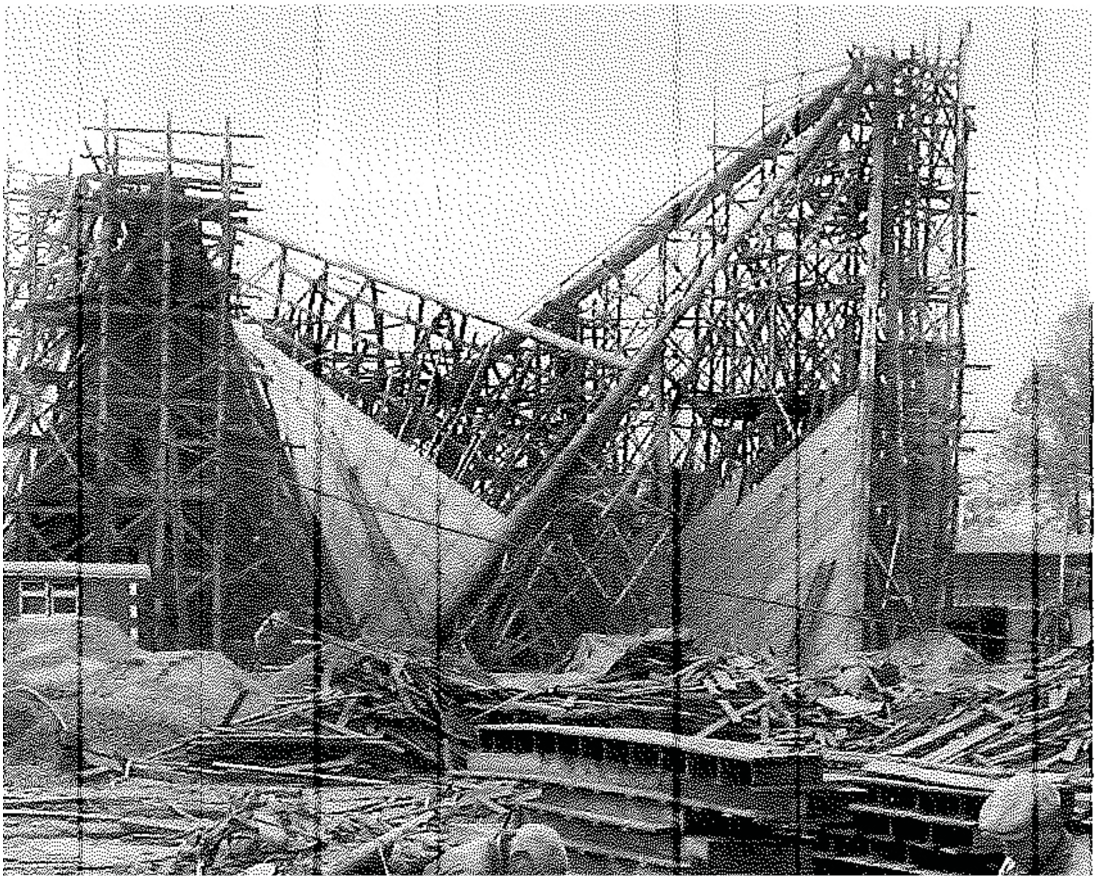


fig.2.3 construction site of the Philips pavillion in 1958

PHILIPS PAVILION

After a visit in Ronchamp to the Chapelle notre Dame du Haut, L.C. Kalf , the art director of Philips, was convinced that Le Corbusier was capable of composing their new pavilion.
Le Corbusier's main design concern was the overall experience of the visitors. He specifically requested that he would be in charge of the interior as well. Within 2 years Le Corbusier and his team composed and constructed the Philips Pavilion for the World' Fair in Brussels in 1958 as a 'gesammtkunstwerk' with a perfect symbiosis between architecture, graphic design and music. It attracted over 300 000 visitors and became most famous among architects because it epitomized the modern architecture movement.

The organic form of the outer shell, curved surfaces composed of straight lines, is based on the composition Metastasis, which premiered in 1955. The form consist out of several hyperbolic paraboloids and conoids. Nine hyperbolic paraboloids and two conoids are placed asymmetrically to create dynamically-angled contours. The surfaces are composed out of 2000 unique and prefabricated concrete elements which are brought on site to place into a primary steel structure. Steel tension cables on both sides of the panels clamp the panels together to form monolithic surfaces.

The concrete elements measure on average 700 x 700 mm with a thickness of just 50 mm. They were produced off site on piles of stabilized sand that represented the actual geometry. These piles were subdivided by wooden girders into smaller element. Before constructing the final elements stress tests and overall construction tests were performed by using full scale mock up elements.

This project shows the following :
Complex geometry can be generated with low-tech means. A pile of sand and some common sense approved to be sufficient to produce such a large number of double curved elements on a relative short notice. This can truly be seen as a pioneer project.
On the other hand it was undoubtedly a labour intensive production process for this rather small building volume.
The question also remains whether or not they actual produced the intended design. Without a doubt they had to incorporated high tolerances on the actual geometry.

fig.2.4   construction site of the Mercedes Benz Museum, UN Studio

MERCEDES BENZ MUSEUM
Less then 3 years went by for the construction and planning of this 35 000 m² of museum. One of the main focusses in the project are two intertwining circulation routes that curl up around a central triangular atrium. These paths guide you towards column free spaces, some with clear spans of 30 m, that display heavy fire trucks and buses. The heavy loads are transferred from the facade towards the cores through the sculptural floor elements that vary in section as they get closer to the cores. Inside these twisting elements service areas and duct work are integrated as a 'negative ' of the building.
Before constructing the museum, full scale mock ups were produced as a warm-up for the contractors. This way they could determine the right concrete mixture , the right type of formwork and focus on the connection between two or more elements. The structural elements of this museum include vertical cores, ramps, twists and four legged steel columns that all had to connect in some way.

During construction lots of attention was focussed on the concrete work. Most of this poured in place concrete is exposed inside the building and therefore requested a high standard workmanship.
Specialists from Züblin and Wolff & Mueller worked very closely with PERI engineers to survey the whole building process.
Customized wooden formwork was delivered by Peri GmbH. At peek times they worked with 50 highly trained carpenters and 30 design engineers on site to manage an efficient coordination of the work and to cope with high demands on scheduling the enormous quantities of materials (fig.2.4).

Crucial during the whole building process was an accurate 3D model of the total geometry. This 3D model was the medium between the various contractors and architects. Because of the extreme geometry common 2D drawing became insufficient when calculating for example the amount of steel reinforcements in a twisting element or to position one of these twisting elements. According to Van Berkel, co-founder of UN Studio, the day when a project will be executed without any 2D drawings " is not so far away. "

Resuming we can say that tests and full scale mock-ups, prior to the actual construction, are a sine qua non in such innovative building projects. Dealing with such a complex geometry requires a knowledge upgrade from all parties (contractor, engineer ,client, etc.) to assure a fluent communication.
These innovative projects request for new techniques (e.g. gps positioning of elements) and call for new tolerances. (e.g. how much deviation is granted from a certain curvature?)

VILLA NM
Just outside of New York Un Studio designed a single family house onto a sloping site.
The slope became the leading element in the concept and served as device for both volumetric and programmatic organization. One of the two box volumes leans on the slope while the other rises up and twists to create a split level. This volumetric transition is generated by a set of five parallel walls that rotate along a horizontal axis from vertical to horizontal. The ruled surface maintaining this transition is repeated five times in the building. From inside the huge window strips from floor to ceiling allow a fluid continuity between interior and landscape. From the exterior the reflective glass seams to become one with its surroundings.

The construction consist out of a steel framework with primary and secondary profiles. At the "twist" five double curved surfaces are formed of approximately 3m by 4 m each. The surfaces are rotated 90° along their horizontal axis. This results in a low curvature radius of approximately 5m The structural frame was filled up with insulation and the whole construction was concrete sprayed.

We can conclude that spray applied concrete can easily cope with complex curvature but it requires a secondary structure.
Another conclusion is the fact that complex geometry is slowly finding its way to the private real estate market. The quantities of double curved elements are far less compared to a public building. This calls for an economical production line.

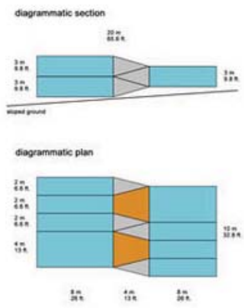
SPENCER DOCK BRIDGE

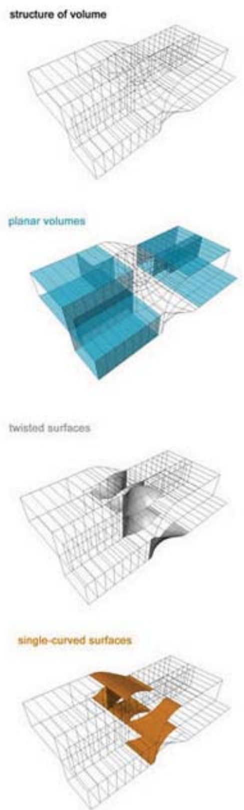
Future Systems partner Amanda Levete compares the bridge's shape to a manta ray:'In plan view, the center points of the north and south sides bow out some 16 feet to form cantilevered decks over the water, offering pedestrians views up and down the canal. From west to east, the main deck slopes up like a fin, rising by some six feet along its length. The 62-foot to 95-foot-wide, shallow deck—just two feet thick—is supported at its center by two piers. At night, the bridge's white concrete-clad underside will be illuminated with vibrant colored light.'

Nedcam, an Apeldoorn based shaping technology company provided the formwork for this spectacular design.

The bridge's geometry was divided into elements that fitted the milling process. EPS foam blocks served as the 3d mould to cast the concrete into. The EPS foam blocks were machined in shape and covered with a thin layer of polyurethane. These blocks were then numbered and provided with a basic connection profile to ensure a quick installation.
On site a narrow toleranced scaffolding, covered with plywood was built up to act as a supporting structure for the EPS blocks. Next steel reinforcement was put into place and the concrete was cast into the 3d shape. A double mould was unnecessary because the top layer would remain horizontal.

This project shows the logistical complexity of such a building process. A simplified building process could be achieved by introducing precast double curved elements that could serve as lost formwork. Moreover the prefabricated elements would reduce the total building time, which is precious in such an urban environment.





a

c

b

fig.2.6   villa NM, UN studio different surfaces : a) planar b) single-curved c) double curved

fig.2.5   villa NM, UN studio upstate New York

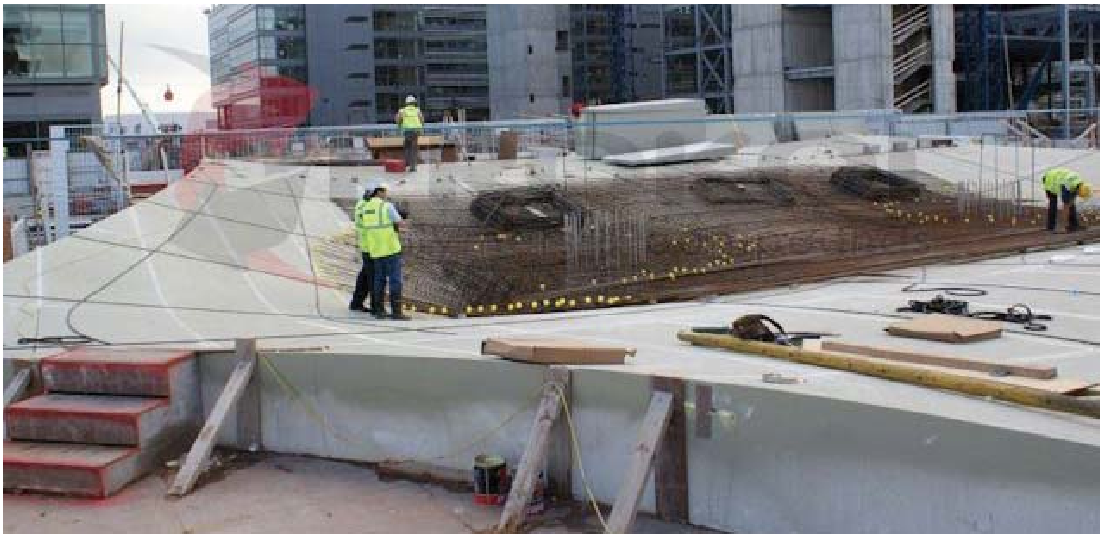


fig.2.7 EPS foamwork for the Spencer Dock Bridge

2.3. TYPES OF FORMWORK

Most of the formwork that was applied in the previous examples can be categorized among two types of formwork : milled formwork or permanent formwork. We will explain these construction methods more in detail and introduce new emerging production techniques.

2.3.1. MILLED FORMWORK

The milling technique is used to shape a solid material as formwork. The computer numerical controlled (CNC) milling is a subtractive manufacturing process where the raw material, often in a primitive shape (like a cube or cylinder) is altered into the requested 3d solid shape. The drill moves around the material in a continuously growing number of axis.
The general (economical) limitations of CNC milling are prototype size, axis movement, and the inability to bore square-edged holes into a material.

One of the most common materials to mill is EPS foam. The expanded polystyrene foam is mainly used because of its low price and easy handling in a 3d milling process. It's lightweight and offers sustainable qualities because it can partially be recycled an reused.
Depending on the geometry, a single or double sided mould is shaped out of EPS foam. Then the EPS is covered with a thin polyurethane layer on which the concrete is then cast or injected.
Another widely used material is wood. Instead of using solid blocks, the geometry is sliced in the x and y direction to create a 'waffle-structure'. The wooden ribs are milled or cut by laser and put into position. Next this 2 way structural grid is covered with plywood or steel plates to form a closed surface to cast the concrete upon.

These production types require high material investments and are only economical when the mould can be reused several times. Moreover this process requires a high amount of initial embedded energy. *EPS consumes 117MJ/kg as to 10.4 MJ/kg for plywood*[1]. (fig. 2.8)
Recycling EPS and plywood is off course possible but still requires additional processes and energy. Nevertheless this production technique is still mostly used in today's construction work.

fig.2.8 numbers obtained from a report of the centre of Building Performance Research department at the Victoria University of Wellington, New Zealand; website: www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf

2.3.2. PERMANENT FORMWORK

The surface's geometry is now constructed as lost formwork out of sand, steel or wood. To ensure the concrete's fixation, the top layer of this setup must be rough textured. Often a wired steel mesh is implemented. Next, the concrete is applied onto the surface by hand or by a pressured hose.

Spray-applied concrete uses this technique since it's first use now 70 years ago in civil engineering applications, such as roadway repairs and tunnels, and in commercial projects. The most common residential uses are swimming pools and skate parks. Because of its flexibility in application over complex surfaces, it also has been used extensively in creating simulated natural objects and environments, such as rock-shapes in zoo exhibits, and ornamental water features in private gardens.

Some savings can be achieved because there is less formwork. However, material savings may be offset by higher labor and equipment costs.

The economical savings are also countered by high embodied energy coefficient. Because the formwork is nor reused nor recycled the process consumes too much energy.

2.3.3. INFLATED FORMWORK

In this case the geometry is reconstructed by using hollow inflated formwork elements of elastic material which may be either covered with a concrete layer or filled with a concrete mixture. Often the formwork can be reused but still every sheet of the formwork has to be cut down to the right size and mounted together precisely. One of today's most successful example of this technique is the Neal bridge on Route 100 in Pittsfield, USA. (fig.2.9)
Here they used inflatable carbon fibre tubes that were placed on site to act as the permanent formwork of the bridge. Once inflated the tubes were infused with a vinylester resin. Once fully hardened these tubes were filled with fibre reinforced concrete through a hole at the top of the arches and the bridge supporting structure is realized.

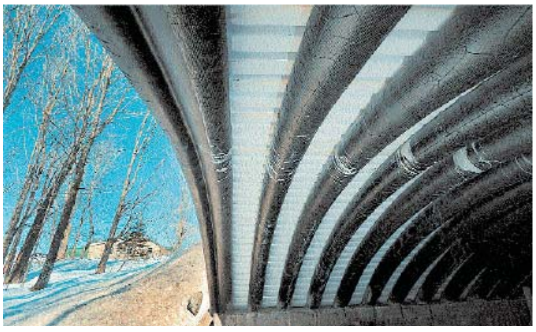


fig.2.9 an example of inflated permanent. bangor daily news photo by Gabor Degre

2.3.4. FABRIC FORMWORK

Currently there has also been a significant progress in using prestressed fabric as formwork for curved concrete panels. These flexible textile membranes are allowed to deflect under the weight of the concrete they contain.
A key-role is given to a finite-element method that predicts the expansion of the fabric due to the concretes weight. The centre for Architectural Structures and Technology of the University of Manitoba can be seen as a leading research group in this field. More information on: *http://www.umanitoba.ca/cast_building*

2.3.5. ADJUSTABLE FORMWORK

The quest towards adjustable formwork is not just a contemporary one. In the sixties of the previous century Renzo Piano already invented an innovative solution with vertical pistons for the construction of a free form shell structure. There is no indication that interest is abating since new patents keep on appearing. But today's developments are still based on this vertical adjustable pistons covered with a flexible mat. Mostly they differ by the distance in between these vertical pistons and their matter of operation.

A production technique that incorporates a flexible mould is however still favoured. This adjustable mould transcends the previously cited formwork techniques because it potentially greatly reduces the overall production time and costs. The possible applications of this pin-type tooling isn't limited to architecture. It can applied in the automotive, aerospace, transportation and marine industry.

RECENT DEVELOPMENTS
In the last years several institutes are focusing on the development of a working principle. It feels like the solution is at hand but for now nobody proposed a solid solution. In Eindhoven a mould is under development by Sebastiaan Boers. He started his research based on the idea of the pin-art toys and mainly focuses on the development of high resolution surface for shaping car and medical industry related products. Also at the TU/e another adjustable mould specifically for the use with concrete is under way. M. van Roosbroeck created and tested a mould with soft adjustable pins. Here the soft pins (spaced 3cm in grid) are covered by a thermoplastic layer, later covered with concrete. Although these examples are all situated in the Netherlands we have to anticipate a global interest and research effort.
In the meantime it is generally accepted that the mechanical operation of an adjustable mould is within reach. What remains unknown is the accuracy of the mould, a realistic edge solution and a sound cost-benefit analysis. This last argument may be the decisive factor to claim the first working principle.
In the work of Sebastiaan Boers a dense set-up (0.5mm in grid) in combination with a single positioning mechanism is proposed. This implies relative low operation costs but on the other hand a vast amount of material costs. When enlarging the mould-for now the FLexmould

is only 20cm x 30cm- thousands of pins have to be constructed and correctly operated in a fairly short period of time.On his turn, M. van Roosbroeck spaces the actuators at 3cm while operating them with individual drivers. The lower amount of actuators results in a lower construction cost, while the individual operation mechanism may lead to increased cost and possible failure.

At the TU Delft Dr. Karel Vollers and PhD Candidate Daan Rietbergen are working since 2006 on their own preposition. Initially developed for shaping free form glass sheets they foresee wide-spaced (200mm in grid) actuators with a continuing flexible profile on every line of actuators. These are then covered cross-wise with thinner, secondary steel rods. This principles aims at relative low construction costs and minimal chance of failure while introducing sufficient accuracy.

fig.2.10 prototype of a double curved window that can be opened. A cooperation between Dr. K. Vollers, Alcoa, Bruining Glasatelier en Tetterode Glass Voorthuizen

Significant results are already achieved with this set-up. In cooperation with Alcoa and Tetterode Glass they produced the first double curved window that can be opened. (fig.2.10) To maintain a leading position in the field, and acknowledging the importance and huge potencies of a similar process for concrete panels, they applied for a patent. At the end of 2008 the patent was granted and the build-up of the project was subsidized by a STW Valorization Grant.

The translation/transformation of the glass set-up for the use with concrete is the main focus of thisMaster thesis period. The patent describes the desires and rough outlines of the research but it does not bring up balanced solutions for the individual components.

PATENT DESCRIPTION

At the basis of the process progress lies a predetermined scheme expressed in the patent that runs through the steps in the development. In front of this overview some important guidelines-credo's-are stated to stress some 'concerns' ;

- Only invest in mechanization if the technique is tested and approved.
- The dimensions of the mould are increased gradually.
- The development is divided in separate modules; these modules can be researched in parallel.
- Manual-labour introduces errors and have to be monitored and minimized if possible
- Small measurement deviations will be tolerated.

The saying - practice makes perfect - suits to represent the evolution in the development. This does not mean that every achievement is a matter of hit-or-miss. In the early stages concepts and physical models are constructed then evaluated and eventually optimized. This loop is repeated several times with an increasing level of complexity and accuracy. The patent distinguishes 4 types of modules:

1. **height regulating-module**: The shape of the support surface on the pins is defined by their respective position. The pins can be statically by parallel wooden or steel line supports or dynamically by electronic actuators.

2. **mould-module**: This module fixates the positions of the pins on a specific height. Each line of pins is interconnected with a primary 'girder' that creates a smooth curve on a single line. This module enables the possibility to detach the mould-module and together with this the formwork and edge module from the height-regulating-module. This significantly speeds up the production and allows the creation of numerous unique panels on the same height regulating-module.

3. **formwork-module**: The formwork is laid on top of the primary support and is composed out of narrow spaced steel rods. These foresee the necessary stiffness in the second direction while allowing smooth curvature. The rods are embedded or positioned under a flexible surface; the actual formwork's underside.

4. **edge-module:** the contours of the concrete element are indicated on the formwork. Hereby special attention is paid to the difference in shape of the 2D and 3D dimensions. The edges, connected to the boundary of the mould-module are installed. The concrete is poured and deformed.

The original and complete description can be consulted in the patent. We will focus on the alterations (fig.2.11) we introduced to the process to make it suitable for the use with concrete.

2.4. CONCLUDING REMARKS

There is consistent interest in the topic to pursue its commercialisation. This interest goes beyond architecture and even stretches out to the aerospace industry.

The patent as described by Dr. Karel Vollers and Daan Rietbergen offers a good framework and will be regarded as a starting point for further modification and interpretation.

The second module of the patent (mould-module) will be neglected since this has more to do with optimizing an actual production technique.

Sufficient prototyping and testing is inevitable to develop a comprehensive production technique.

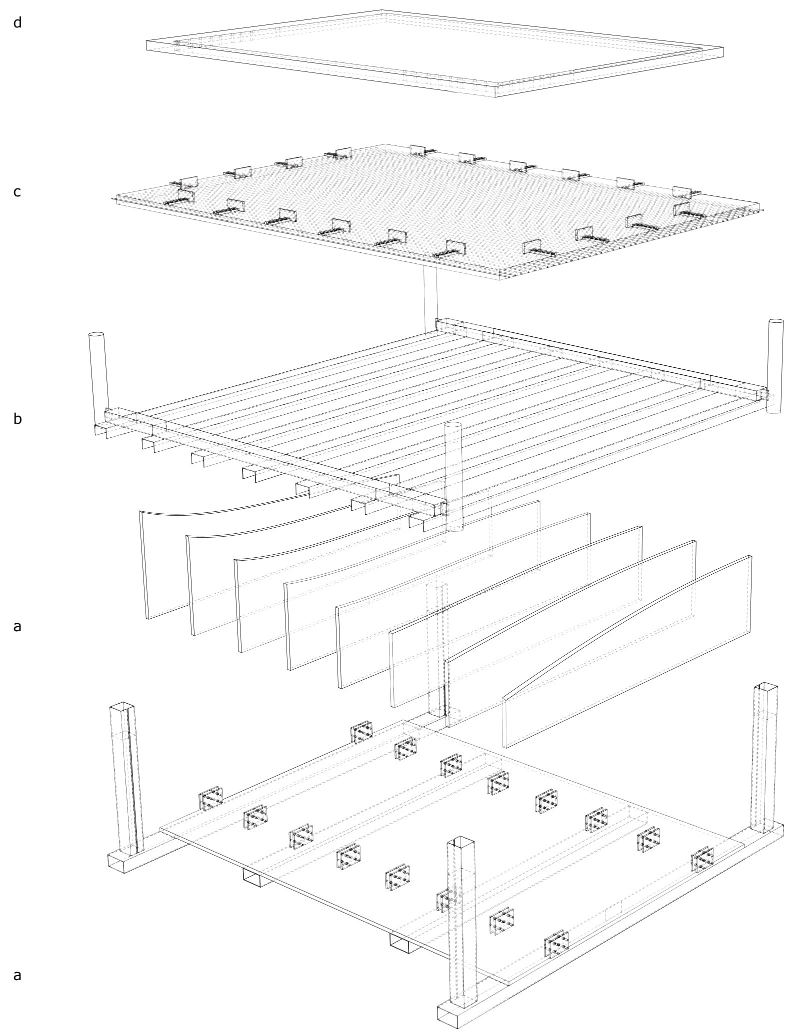


fig.2.11 Our first interpretation of the patent description. It consist out of 4 modules. a) height regulating module of static wooden ribs, 8mm MDF b) lowering device, 40mm by 65mm wooden girders c) form-work module, polyurethane with feather steel reinforcement perpendicualre to the wooden girders d) flexible edge module

3. GEOMETRY

Geometry lies at the core of the architectural design process. It is omnipresent, from the initial form-finding stages to the final construction. Modern geometric computing provides a variety of tools for the efficient design, analysis, and manufacturing of complex shapes. On the one hand this opens up new horizons for architecture. On the other hand, the architectural context also poses new problems to geometry. Around these problems the research area of architectural geometry is emerging. It is situated at the border of applied geometry and architecture. (Axel Kilian)

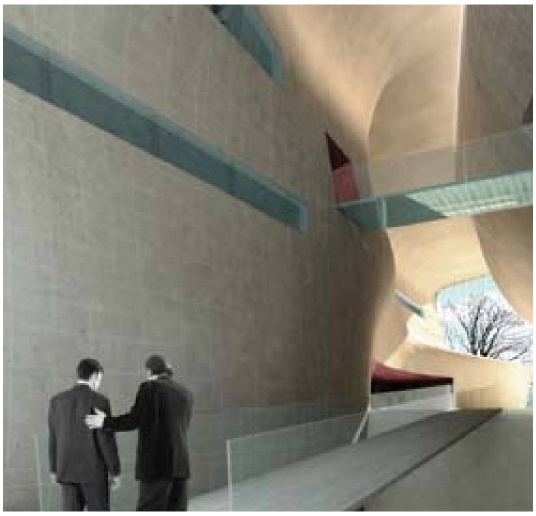


fig.3.1 The Museum of the history of Polish Jews in Warshaw by Rainer Mahlamaeki

3.1. INTRODUCTION

A profound knowledge on complex geometry is indispensable to be engaged in this targeted research. This chapter will therefore provide a general overview of those geometrical features that relate to ourMaster thesis period on freely formed surfaces. As the discussion on curves will naturally lead to a discussion on surfaces we will start by defining curves. The chapter will close off by recommendations towards the actual production process.

The book *Architectural Geometry by Helmut Pottman, Andreas Asperl, Michael Hofer and Axel Killian, 2007 Bentley Systems* was as a most helpful resource to summarize and to sort out the relevant features.

3.2. CURVES

3.2.1. CURVES REPRESENTATION

The most basic definition of a curve in two dimensions is $y=f(x)$. This definition can be used to draw simple curves but yet we remain restricted to simple 2d geometry that is hard to manipulate. We are interested in more complex curves and there are mainly three different mathematical approaches to describe these curves :

- parametric representation
- explicit representation
- implicit representation

To describe spatial curves, a parametric representation is the most commonly used approach. One reason is that drawing a curve based on its parameterization is very simple, whereas the same task is more difficult to achieve with the implicit or explicit representation.
In the following we will explain the parametric representation of a curve and all concepts about curves in thisMaster thesis period will be based on a parametric representation.
Using the parametric representation, the coordinates of a point p of a parametric curve c are expressed as functions of a variable t. This means that a spatial curve c can be represented by $c(t)= (x(t), y(t), z(t))$, where t is some parameter assuming all values in an interval I. We could consider a curve as the result of a continuous mapping of an interval I into a plane or three-dimensional space. Thereby , every parameter t is mapped to a curve point $p(t)$. Often it is helpful to think about t as time, although t need not be time. The functions $x(t)$, $y(t)$ and $z(t)$ are called the coordinate functions and $c(t)$ the parameterization of c.

3.2.2. DIFFERENT CURVES

There are three types of free form curves that are mainly used in design :

- Bézier curve
- B-spline curve
- NURBS curve

The Bézier curves are among the most widely used free form curves. They possess an intuitive geometric construction which is based on repeated interpolation. They are completely determined by their control points. A Bézier curve with n+1 control points is of degree n. This results in two major limitations of Bézier curves.

First, a Bézier curve with a large number of control points becomes impractical for design. The degree of the curve increases and the curve shape resembles less and less the shape of the control polygon. Second, the control points have global control on the shape of the curve. This means that if we add a new control point or if we modify the position of one single control point the shape of the entire curve changes.

B-spline curves are free form curves that consist of multiple Bézier curve segments of the same degree and that are knotted together at their endpoints with the highest possible smoothness. It provides local control and allows for very complicated free form curves. But there is however one major drawback. With B-spline curves it is not possible to represent such simple curves as a circle or an ellipse. Because these curves are often used in design the following curve type is introduced: nurbs curves.

NURBS curves are nonuniform rational B-splines. The new thing about these curves is that they have an additional shape parameter, the so called *weights*. These weights w are associated with the control points d of a NURBS curve c. These weights simply represent the z-coördinate of the control points d. Increasing the weight w of a control point d drags the curve towards the control point, and decreasing the weight moves the curve away from that control point.

To conclude we can summarize the degrees of freedom (fig.3.1) that are related to the type of curve. Instinctively we recommend NURBS curves as they offer more freedom to the user.

	control points	degree	weights
bézier	v	x	x
B-spline	v	v	x
NURBS	v	v	v

fig.3.2 scheme of the different degrees of freedom between the three curve types. In the scheme v means that this design handle can be set by the user.

3.2.3. CURVE FEATURES

The curve tangent T is used to locally approximate a smooth curve *c* at a point *p* by a straight line. The curve tangent can be found by the following limit process. On the curve *c,* take any point *q* that is close to the point *p* and connect points *p* and *q* by a straight line *l*. This line *l* is also called a chord of *c*. Then move the point *q* on the curve *c* closer and closer to *p*. In the limit , the point *q* coincides with *p* and *l* assumes a limit position; namely, the tangent T of the curve *c* at *p*.
We can now prove that the first derivative vector of the parametric representation $c(t)= (x(t), y(t), z(t))$ defines the direction of the curve's tangent. A parametric representation of the curve tangent at point c(t) can be found with $T : x(u) = c(t) + u. c'(t)$ Here, u is the parameter for describing the points of T. The normal of a planar curve is the normal of the tangent in the touching point p. A space curve has a normal plane at each point p.

Discrete curves can be seen as a approximation of a smooth free form curve. If we have a smooth curve *c* with vertices *c1, c2*,... that lie on *c.* We can now connect these vertices with a polygon line P and form an approximation of the smooth curve *c*. It is not necessary that all polygon edges have the same length. We simply need to consider sufficiently uniform refinements towards a smooth curve. Three consecutive vertices of this polygon *P* possess a circumscribed circle which is called the **osculating circle** of the curve *c.* The locus of centres of all osculating circles is called the evolute *e* of the curve *c*.

The **curvature radius** *r* is used to generate the curvature *k* of a curve *c* at a point *p.* The radius r is equal to the radius of the osculating circle, which is explained above. The **curvature** k is now defined as the reciprocal value of this radius *r* ($k = 1/r$)
For every point p1 p2 ,... a respective curvature value k1, k2,... can be deducted. This leads to a maximum and minimum value among these values. These values are called the **principle curvatures** *k1* and *k2*.
The product of the principle curvatures *k1* and *k2* is referred to as the **Gaussian curvature K**.
$K = k1 * k2$

Other interesting points are the **inflection points**. At these points, the osculating circle degenerates into a straight line, namely the tangent *T* of *c.* The curvature at this point is reduced to zero and the curve *c* changes the side of the tangent.

3.3. SURFACES

3.3.1. FREE FORM SURFACES

Free form surfaces do not have rigid radial dimensions, unlike regular surfaces such as planes, cylinders and conic surfaces.
Initially developed for the automotive and aerospace industries, free form surfacing is now widely used in all engineering design disciplines from consumer goods products to architecture and ship design.
The difference with regular surfaces lies in the degree of the surfaces.
For example, a surface with a degree of 1 would be a flat cross section surface. A surface with degree 2 would be curved in one direction, while a degree 3 surface could (but does not necessarily) change once from concave to

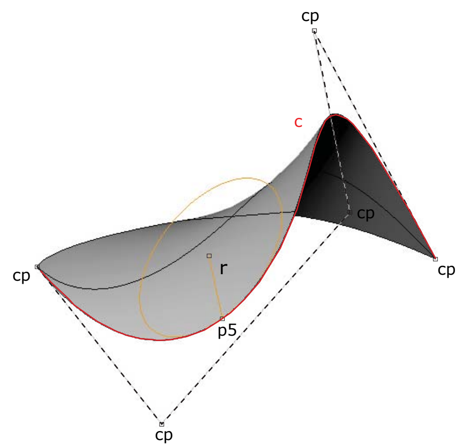


fig.3.3 A NURBS curve c with five control points is located at the edge of a surface. The curvature *K* at point *p5* can be derived from the radius *r* at that point

convex curvature.

The free form surfaces are categorized by the types of curves that serve as primary input for the surfaces. That is how free form surfaces can be divided in the following types :

- Bézier surfaces
- B-spline surfaces
- NURBS surfaces

A Bézier surfaces can be constructed by using two Bézier curves. Here again NURBS surfaces offer the most control over the surfaces due the weight that is attached to each control point.The effects of changing a weight are the same as for NURBS curves.
A complete mathematical description will not be discussed in thisMaster thesis period. As our production process will start with a given surfaces, we will highlight only these features that seem important for the production process.

3.3.2. CURVATURE OF SURFACES

The Gaussian curvature K determines whether a surfaces is developable, synclastic or anticlastic. (fig.3.3) A *k* value of zero in all the points on the surfaces signifies that the surface is developable. That means that the surface can be flattened onto a plane without distortion. These surfaces are also called single curved surfaces. A cylinder or a cone are frequently used examples of developable surfaces.

A positive K value is found on a synclastic surface, whereas a negative K value determines anticlastic surfaces. The color-coded mapping of these K values are a frequently used tool for surface analysis

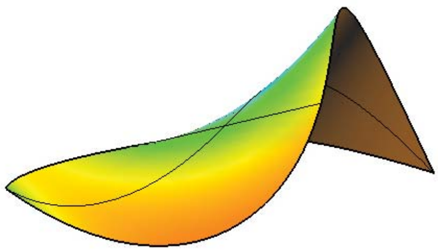


fig.3.5 analysis of the gaussian curvature K of a surface

Mean curvature H is another important measure of a surface's curvature. H is the arithmic mean of the principle curvatures, $H = (k1+k2)/2.$ (fig.3.4) If H equals zero we have defined a minimal surface, which appear (for example) as shapes of soap circled by a closed wire. The term "minimal surface" is because these surfaces originally arose as surfaces that minimized the total surface area as well as minimizing the forces appearing in the surface. These and related equilibrium shapes of surfaces are discussed in a following chapter in relation to shape optimization problems.
Every location on a smooth surface has two circles that best approximate the curvature at that location. The circle with a biggest radius is

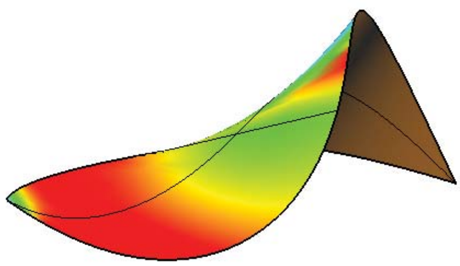


fig.3.4 analysis of the mean curvature H of the surface

always orthogonal to the circle with a smallest radius.

The maximal and minimal principle curvature are inverse of the radii of these arcs. (fig.3.5) The Gaussian curvature is positive when both half circles point the same way, negative when the circles point opposite ways, and zero if one of the half circles degenerates into a line.

3.4. MESHES

Throughout thisMaster thesis period mesh generation will be used as a tool to divide freely curved geometry into elements that can be prefabricated. The aim of this mesh generation is to describe a geometrical complex continuous surface in a discrete way that is sufficiently accurate to represent a given geometry.
We will start by describing some essential terminology of grids and continue with an overview and explanation of different categories of grids.

3.4.1. TERMINOLGY

Roughly speaking a mesh is a collection of points (vertices) arranged into basic elements called faces. These faces are bounded by polygons. Typically one type of polygons dominates. They fit together along common edges and roughly describe the shape of a smooth surface.

When dealing with meshes we should first discuss their connectivity, also referred to as mesh typology. This means that we have to label the vertices of the mesh and know in which way they are joined to form edges and faces. This leads to two fundamental classes of meshes : structured and unstructured.
A mesh can be categorized as structured when the organization of the vertices and the form of the faces do not depend on their position, but are defined by a general rule. They are lack the required flexibility for handling complex surfaces. Their faces are obliged to have one standard shape. This can cause severely skewed or twisted faces if the geometry becomes to complex.
Unstructured grids can provide a solution for rendering faces in regions with complex geometry. Here the connection of neighboring vertices varies from point to point. An example of a widely used unstructured mesh is the Voronoi diagram (fig.3.6). For a random set of points the Voronoi diagram marks off the region of space that lies closer to each point that the other points. This way a region is formed surrounding the various points. Each of this Voronoi regions consist of the region of the plane that is closer to that point than to any other point

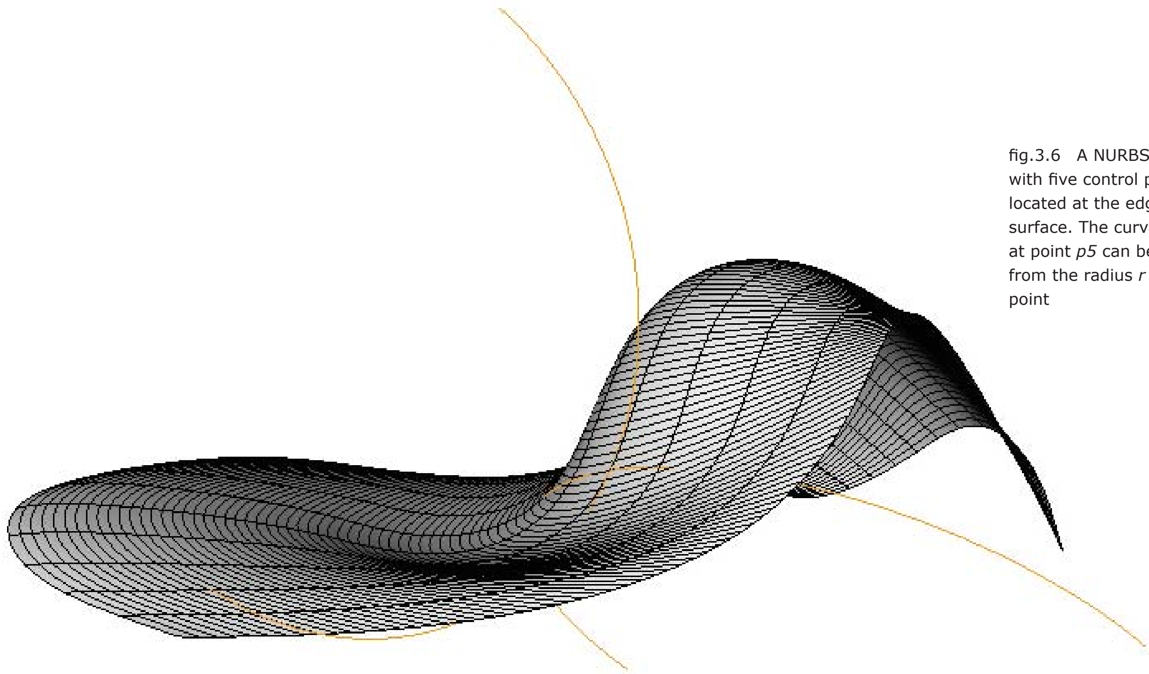


fig.3.6 A NURBS curve c with five control points is located at the edge of a surface. The curvature *K* at point *p5* can be derived from the radius *r* at that point

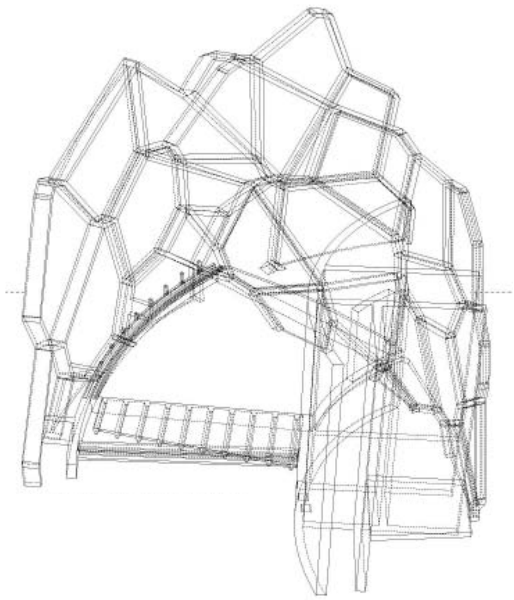


fig.3.9 wire frame view of a 3d voronoi diagram. Here the voronoi diagram serves as a primary structural element.

3.4.2. MESH GENERATION

Projection is a technique based on the isotope technique and consists of the projection of a flat grid onto the surface that has to be segmented (fig.3.7). 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. Another drawback of this method is that the elements at the edges of the surface can be small and badly shaped.

Another type of grid uses the **isocurves** of the surface to create the edges of the elements (fig.3.8). An isocurve is a curved line that runs along the surface in the U and V direction of the surface.
Each surface that is made of NURBS curves is composed of a number of isocurves.
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 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 millimeters.

More types of grid generation are developed every day, mostly depending on the purpose they serve. For example the meshes in game industry require a lot of flexibility for animation and a low number of polygons for a low render time. Constructing these meshes can be a time consuming procedure. When a mesh is rejected in a later design stage often the mesh has to be rebuild from scratch. Nowadays software like Generative Components and Grasshopper offer a parametric interface that allows for quick adaptations and variations.

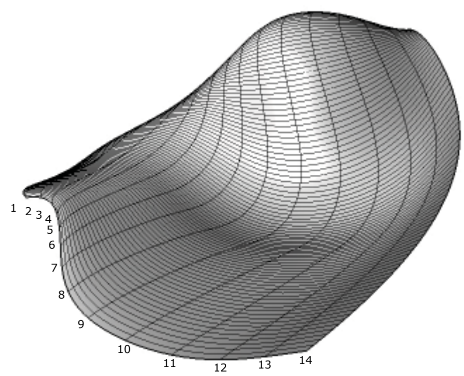


fig.3.8 grid generation by using the isocurves of a surface. (14 isocurves in u direction and 32 in the v direction, this causes unequally sized elements)

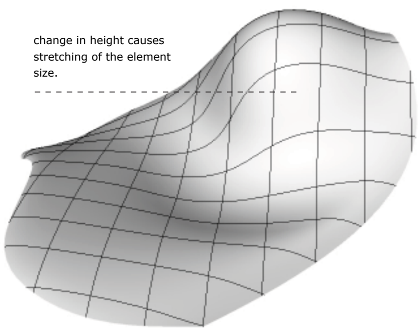


fig.3.7 the projection of a 2d grid onto a 3d surface.

3.5. CONCLUDING REMARKS

Extensive knowledge on geometry and proper computational skills are a prerequisite to proceed in this investigation. Proper use of the right terms is essential for a good communication between different parties.

Every problem calls for a different computational approach and often there is more than one way to formulate your solution. First think of what you want to achieve, then use the right tools to accomplish the result.

When joining two or more surface the curve tangency is an important factor to determine whether or not a curvature is constant.

When developing a mesh the isocurve generation is still favorable. It offers enough flexibility and can act as the basis for a more complex grid generation technique.

4. PRECAST CONCRETE ELEMENTS

I've always felt that if one was going to take seriously this vocation as an artist, you have to get beyond that decorative facade. (Anish Kapoor)

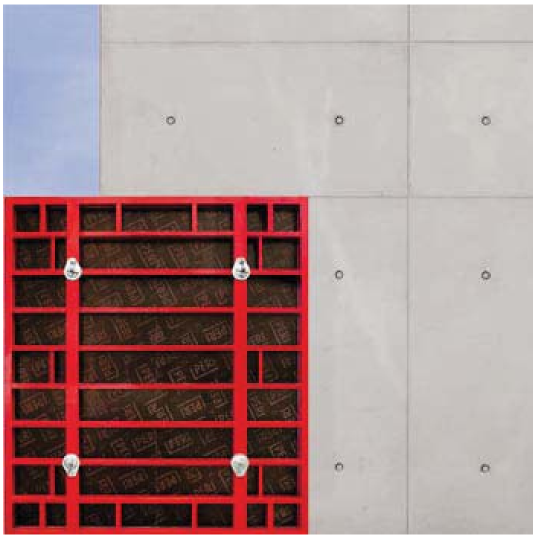


fig.4.1 Maximo formwork by PERI

4.1. INTRODUCTION

The renewed interest in exposed concrete as surface material has led to numerous developments in the precast concrete industry. At the same we notice a changing attitude towards precast elements. The precast concrete industry got rid off his negative image of uninspiring, simplistic and non-innovative. This research is the best example of the enormous potential that lies in this field.

This chapter discusses topics related to precast concrete elements. Before designing a new type of production technique for the precast industry, one needs to be acquainted with today's production techniques, design parameters and the range in end-products.

Zoomed in on facade elements we distinguish several types of construction principles common for 2D panels. The cold-facade principle with open joint configuration is compared to the principle of a warm-facade with closed joints. They are both explained briefly and evaluated in terms of performance, complexity and construction. The phenomena affecting both principle facade types are described to assess their importance. The related components, e.g., edges, joints, anchors are described separately. The most common configurations, materials and defects are listed.

At the end, a section is devoted to the transformation of the principles to 3D elements. This is done by logic reasoning to indicate preliminary issues and points of attention for the development of the technique later on.

4.2. FUTURE APPLICATIONS

Before narrowing down the research field to facade elements and forces acting on them, it is recommended to summarize the possible end-products of this new production technique. This rundown helps to assess the range of applications and improvements ahead.

4.2.1. STRUCTURALLY PERFORMING

This first group of possible end products is populated exclusively with concrete elements that perform in a structural way. Subsequently we divide this group in two categories: architectural related structures and others.(fig.2)

Under structural elements we understand autonomous components that are applied with an additional load next to the evident dead load. Once the structure is loaded, the separate elements have to interact and exchange forces through their connections. The forces acting on a connection are compression, tension and shear forces ass well as bending and torsion.

The demands on these type of elements are high. Especially the edges and connections to other panels are subjected to several influences. The need for movement in a structural system, due to the concrete's 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 connections zone.
The connection's area is often reinforced with bars, plates or other inserts and leaves few room for the concrete. To ensure a minimal concrete covering and room for appropriate reinforcement, it is important to take into account these parameters in the design phase. Furthermore it is preferred that the connections behave in a ductile manner. With this large plastic deformations can take place before failure of the structure. This ensures a structural buffer to encounter unexpected or once-only load cases.

Wall-systems, as inside leaf of a cavity construction or as combined structure in for instance a sandwich panel are perfect examples of structural interacting panels. They have to fulfil strong stability and strength requirements and have few margin in error.
Also in roof construction, often shell-like, free form shapes are more and more applied. Roofs have been used throughout history to express

a building's appearance with a growing trend towards lighter and more complex shapes. They address the same principles as wall-systems with a different load case as main difference.
A third future possible application related to architecture is the so called 'lost formwork'. A thin layer of reinforced concrete is positioned on site and covered or filled (as sandwich construction) with concrete. This method does not only speeds up construction time but at the same time reduces significantly the cost of a building. The advantages of this method are acknowledged and the flat variant is nowadays applied worldwide. Imagine what advantages a double curved version of this widespread system can bring. Their development could herald a new era in free form design.
The second category has a direct link with infrastructure. Structures like bridges, noise reduction barriers and complex embankments can benefit from this technique ass well. In fact these structures require enormous investments and their design is function-performance driven. One can imagine that these massive infrastructures are the ideal catalyst for development of this new production technique. Abutments and bridges can be better integrated in their surroundings and so minimize their visual impact on the environment. Besides the visual aspect, noise reduction barriers can benefit from the almost unlimited geometric possibilities. Nowadays, the level of complexity is limited to single curved elements (fig.4.3) Further optimization inevitably leads to more complex geometry.

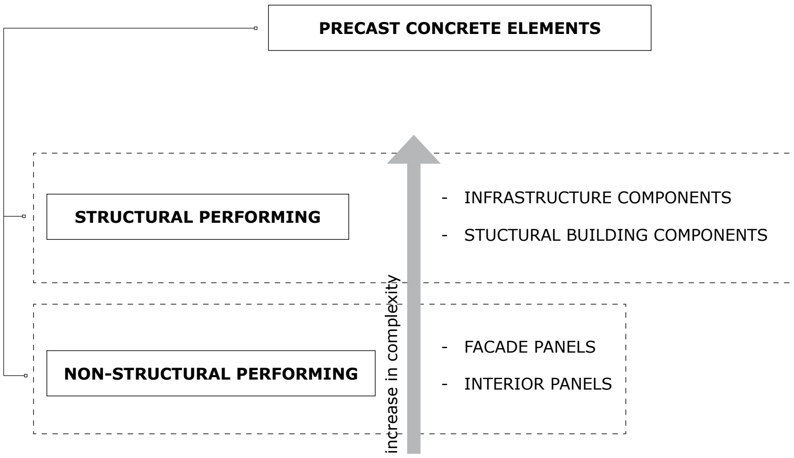


fig.4.2   possible end products with new technique

4.2.2. NON-STRUCTURALLY PERFORMING

In the non-structural category we find facade panels and interior panels. Both of them allow greater freedom in design and room for experimentation due to a lower degree of complexity. They do not transfer forces from one panel to another, so the edge conditions are less demanding. They are hanged or pinned to a secondary construction. Despite this simplification there are some important design & construction parameters that have to be taken into account. The size of the panels, quick change of surface temperature, water infiltration, fire retardancy and aging of the concrete (e.g. creep) all have their effect on the resulting panel, its surface and its edges.

fig.8.1   Freimann noise reduction barrier, Munich 2005 by Schmitt Stumpf Frühauf und Partner Ingenieurgesellschaft im Bauwesen mbH

This will be elaborated further on. For initial development of this new production technique we will start with the application of the system for facade panels. In general they share the same issues as their more advanced relatives. The greatest simplification lies in the lack of structural reinforcement, the absence of structural connections and a smaller size and weight. Once all the uncertainties and defects for facade elements are solved, the process can be transferred to more complex load bearing structures.
In the following sections we will discuss in detail the forces acting on the panels and the physical phenomena influencing them. Also a more detailed description of its components e.g., edges and anchors is given to assess their importance. This discourse will help to determine design parameters that can be injected into to the development of the flexible mould later on.

4.3. DEFINING THE TYPE OF FACADE

The facade industry is rapidly changing and gains importance since more demands in its 'ensemble' of functions is requested.
Until the seventies facades were merited on their rigidity, strength, fire retardancy, water-and airtightness. Since the seventies greater interest and much more design effort is reserved for the thermal properties of a facade to reduce the environmental load and energy consumption. And since the mid-nineties this interest turned in a trend towards reactive and anticipating facades. We acknowledge and stand by this irreversible evolution but this research will not contribute to this matter (yet). We will work with simplified models to grasp the key elements influencing the concrete panels.

COLD VS. WARM FACADE
In broad terms and with no respect to the material applied, two types of facades are constructed; cold and warm facades. Both have their own characteristics and field of application. The description of both principles follows the definition formulated by Renckens, J.

A cold facade works like an aesthetic raincoat and together with the interior shell, forms an air space ventilated by ambient air. This space contains outer air. The facade's insulation is located at the exterior of the interior shell. This type is often used in front of a building with load-bearing facade panels or a concrete wall shell. The interior shell is thus insulated and the entire construction is completed with weatherproof, non-insulated exterior shell which is anchored to the interior shell at shell distance. The panels of the exterior shell can be installed with open joint. (Renckens,J.)

The second principle is a warm pre-set facade that has a warm shell closed against the outside air.

The panels contain the facade's insulation and are installed to the load-bearing building structure at shell distance. One advantage, compared to the cold shell facade, is that this type of composition is much more suitable for buildings by means of panels and super-panels (building of larger units). This is a complete facade in front of a normally load-bearing facade. Disadvantages are: higher building costs, a limited accessibility in case of water or air leakage and few flexibility for replacement or adjustment of the facade. Water and wind tightness are dealt with in the exterior shell. Also, for this type of construction, the interior shell must be as airtight as possible in order to avoid leakage of humid interior air into the air space: this leads to loss of heat and brings about the danger of formation of condensation water within the shell. (Renckens,J.)

Although these definitions were initially formulated for the use with aluminum/glass facades we can adopt them for the use with concrete. No choice or preference for one of the principles is outspoken. The distinction is merely important to understand the array of requirements and configurations of joints, anchors and edges. As the precast elements do not have to take up additional loads , we are particularly interested in deformations due to dead-and wind-load, the movement of the joints and a valid solution for water-and airtight sealing of the joints.
For completeness it is mentioned that the presence of glass infill panels or framed windows is neglected and thus the facade is envisaged as a complete concrete paneled construction.

4.4. PHENOMENA AFFECTING A CONCRETE ELEMENT FACADE AND ITS JOINTS

With the description of the facade in mind we can examine its static and chemical behavior in detail to formulate design parameters. In the following sections we will make use of specific terminology, which might not be recognized by every reader. To avoid confusion the most important expressions are listed and shortly described below;

- **element**: one of the prefabricated concrete panels from which the facade is composed.
- **joint**: the space between two element or between one element and another facade part, which contours the tolerances in construction or allows the movement of the elements
- **joint's edge**: the part of the surface element that forms the boundary of one side of the edge
- **joint's width**: the distance between the edges of two adjoining elements.
- **initial joint width**: the joint's width, as measured, immediately after the elements are positioned onto the construction
- **joint's movement**: the movements that the edges of the joint undergo in relation to the elements
- **movement percentage of the joint**: the movement of the edge, expressed in percents of the initial width of the joint
- **non-constructive joint**: a joint that can't (or nearly can't) transfer forces and in general is not designed to do so
- **joint sealan**t: a plastic or elastic material that closes of the complete width of the joint
- **sealing the joint**: taking measures to close a joint watertight, vapourtight and/or gastight
- **open joint**: a joint where no sealant is applied

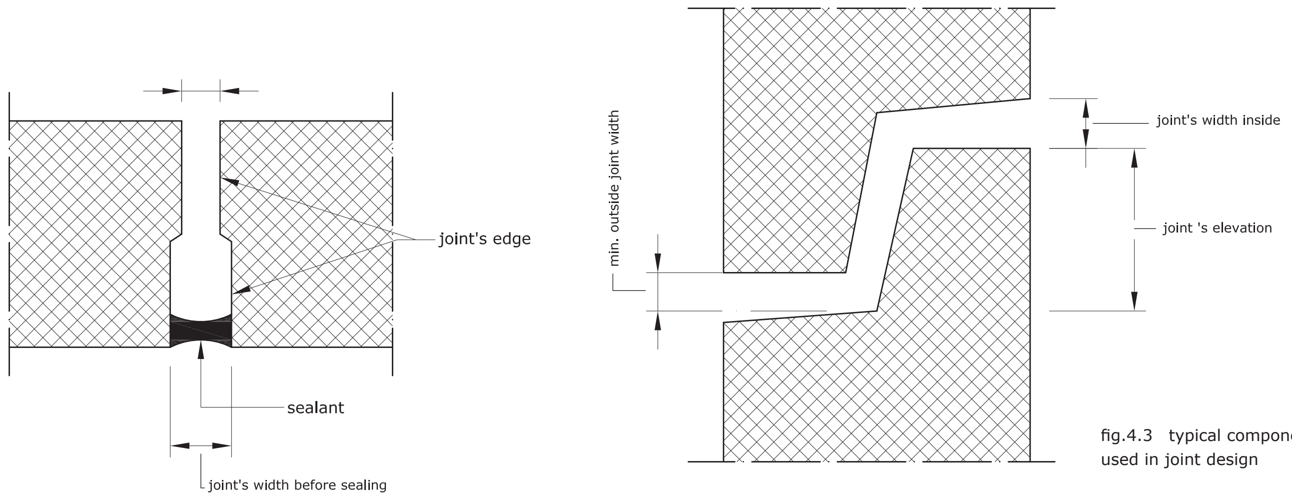


fig.4.3 typical components used in joint design

4.4.1. INFLUENCE OF OUTDOOR CLIMATE

INTRODUCTION

Besides the vertical definition of a space, facades have the important task of shifting the weather situation. Rain, wind, too low and sometimes too high temperatures must be kept outside the sheltered space. When a facade is composed out of separate concrete elements, the omnipresent joints in between the panels have to offer sufficient resistance against weather attacks. When exposed to weather conditions, the concrete elements undergo change in form and composition. The main consequences are;

- deformations of the elements and with this the joints
- erosion
- corrosion

Change in outside temperature results, although with some delay, in an extension-shortening and sometimes warping of the panels. Change in atmospheric humidity has roughly the same outcome through the absorption and emission of water. These deformations are of great importance when determining the maximum size of the concrete panels and when dimensioning the joints.
Except for the panels themselves it is clear that climatic changes influence the sealant between the elements. In cold conditions almost all plastic and elastic sealants loose their abilities to take on large deformations, while in warm conditions they have tendency to sag. The durability of sealants is also liable to the weather conditions (aging), with solar radiation as main factor. Rain or fog can lead to freezing of the saelant, while rainwater itself, through its resolution abilities, can have disastrous results for the sealants.
In the Dutch climate special attention has to be paid at the retention of rainwater. The wind hampers this, as the wind pressure forces the water particles to move horizontal or even vertical upwards. When designing the joints one has to consider all these factors to prevent future failure of the facade. To understand the resulting behavior and estimate the influence of each factor we will discuss them in detail.

TEMPERATURE

The maritime climate influences West-Europe weather and flattens out the temperature differences. Nevertheless considerable extreme values are measured. In the Netherlands this happens in the eastern part of the province Gelderland;

- highest temperature: 39°C
- lowest temperature: -27,5°C

These extreme values are hardly never reached. But temperatures of -20°C are often registered and values of +30°C are exceeded almost every summer. Changes in temperature alter gradually. The biggest changes in the shortest time span occur in a period between early morning and afternoon. In about 10 hours the air-temperature can rise a maximum of 10°C.

Equally important as the outside temperature is the effect of solar radiation to the facade elements. Without become to technical, one has to understand that through direct solar radiation, the surface temperature of the concrete elements can achieve notably higher values then expected. The parameters triggering this are:

- intensity of the radiation
- travelled distance of the radiation
- level of cloudiness
- orientation of the facade

Considering a well insulated facade panel with a dark colored surface finish, you can expect surface temperatures of around 85°C on a sunny, clear day. For a cold-facade, with the insulation at the inner leaf of the cavity wall and a ventilated cavity, you can expect average temperatures of the outer leaf of around 55 à 65°C, depending on the color of the outside surface.

Concluding we remember that when designing a concrete facade panel, we foresee a maximum outdoor temperature of +35°C and a minimum temperature of -20°C, keeping in mind a possible increase up to 60°C due to solar radiation. This difference in temperature has to be implemented in the linear expansion coefficient to asses the deformation in mm/m.

ATMOSPHERIC HUMIDITY
Air contains a certain level of water vapor. The amount in grams per mass unit is called water vapor concentration. Air of a certain temperature can contain a certain amount of vapor; higher temperature allow a higher vapor concentration. If the air contains the maximum level of vapor, the air is saturated. The ratio between vapor present in the air and maximum concentration for the same temperature is referred to as relative humidity.

Air of 20°C is thus saturated when 14,8 gram water vapor per kilogram dry air is present. If 7,4 gram is present, relative humidity is equal to 50%. A quick way to find these values is by interpreting a psychrometric chart (fig.4.5)

Unsaturated air can be saturated through:

- adding water vapor at constant temperature
- lowering temperature at constant water vapor concentration
- combination of these two

The **dew point** is referred to as the the temperature at which the air with a certain water vapor concentration reaches maximum concentration. If the temperature drops below the dew point, condensation appears.

If the water vapor concentration in concrete is stable, relative humidity will fluctuate strongly due to temperature graduation per day, season and per year. The amount of moisture of the concrete of the facade element will be influenced by these fluctuations. Water vapor diffusion affects the exchange between outdoor air and the air in the pores of the concrete. In stationary condition every relative humidity of the surrounding air relates to a certain humidity of the material (hygroscopic level of humidity)
Some values for concrete are mentioned below

The water vapor transport through diffusion happens analogue to heat transport. The main difference is that the adaptation of the **hygroscopic level** of humidity to the relative humidity takes more time than with heat transport.

Resuming it is important to keep in mind that a concrete element has to perform in the range between 45% and 100% of relative air humidity. In addition rising of the temperature decreases the chance for simultaneous occurring of high temperature and high relative humidity. The effect of change in hygroscopic level in the concrete element is not of that big of importance when compared to the effect of temperature changes

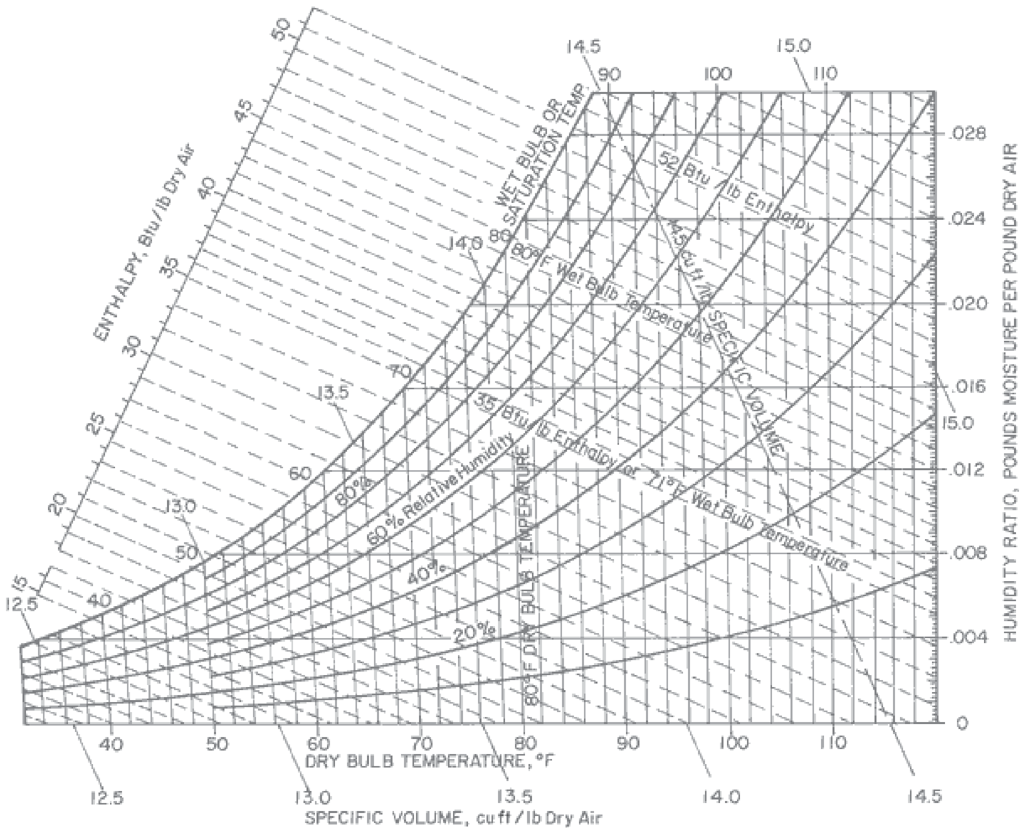


fig.4.4 psychrometric chart

WIND
Wind itself has no direct negative effect on the panels in terms of internal composition. It rather has to be taken into account as a (mostly) horizontal load case causing bending and thus stresses in the panels. Therefore it will be discussed in the section 5.4.3

RAIN
Rain alone does not harm a vertical facade. Only long-lasting rainfall can influence the humidity level in the element causing small deformations. The actual danger lies in the combination of water and wind. Wind can create draft and so drag rainwater through the joint, with leakage as a result.

The combination of rain and wind is thus a dominant factor in the design of the joint.
The angle from which the rain hits the facade, depends on wind speed and size of the drops. Fine drops are carried along more easily then large ones. The amount of rain hitting the facade varies according the position on the facade, the approximity and type of surrounding buildings and the orientation of the facade.

In experimental test it is observed that the raindrops tend to follow the streamlines of the wind. The movement of the drops becomes more vertical under influence of air friction and gravity when getting closer to the surface because the speed perpendicular to the facade sharply reduces in this area. Once the rain reaches the surface, the movement of the water itself is characteristic.

Under intense rainfall a water film develops on the concrete. The speed at which this originates depends on the surface's texture. A somewhat porous surface will retard the formation of this film slightly but eventually will not prevent it. The water film will thicken downwards and drip at horizontal ridges or be blown of later on. The thickness and flow pattern of the water film is influenced by the wind and can vary from location to location. Accumulation of water, horizontal flows and even upward flows of water are some of the issues appearing under rain 'load'. To design a proper joint we need to have understanding of the phenomena procuring water infiltration.

- **capillary action**: It is generally accepted that a joint width of 2mm or wider no longer is affected by capillary action. However attention has to be paid to the surface's smoothness. The smoother a surface is, the less capillarity occurs. So keeping in mind the average roughness of concrete panels, it is recommended to work with 5mm joint width (at least to tackle this effect)

- **gravity**: Water flowing downwards, will try to penetrate the facade at each horizontal edge, while water drops falling of suchlike edge can splatter to the inside. By equipping the horizontal edge with an upward slope, this infiltration can be avoided. Vertical edges have the same issues as horizontal ones. Key is to prevent the vertical flow from penetrating deep in the joint. This to avoid extra loading of the horizontal joint at intersections with the vertical. The maximum length of the vertical joint should thus be limited to prevent accumulating water. An outward drainage at certain distance is essential.

- **kinetic energy**: At strong wind speeds raindrops, falling more or less perpendicular on the vertical joint, will permeate to the back of the joint. While raindrops falling under an angle will splatter in the back and thus deliver possible moisture behind the joint. The best solution is to foresee a water retaining closure at the front of the joint.

- **airflow through the joint**: Difference in air pressure in front and behind the joint can cause an airflow through it. The joint has to be designed in a way that the air present in the joint is widely connected to the outside air. This intervention flattens the effects of overpressure & underpressure acting on the facade. Another smart measure is to close of the ventilation and relaxation inserts or the cavity wall at certain distance. Pressure differences developing along the surface can then no longer propagate in the facade construction. These closed of areas are maximum 6m x 6m. Finally the velocity of the air in the joint can always be lowered by locally widening it. (relaxation gap)

- **pumping-effect**: Insufficient and non-ventilated joints enhance the pumping-effect. This will happen when a closed water film flows over a joint and is sucked inside due to an under pressure. This sudden movement will break the film from which the process starts all over. The correct solution to this is foreseeing a wide relaxation gap.

Resuming the effects of rain on a facade we acknowledge the presence of rain on a facade. When taking the necessary precautions (e.g., upward directed horizontal edge, zoning of airspace behind the panels, implementing of relaxation gap,..) no lasting problems are expected.

4.4.2. INFLUENCE OF CONCRETE COMPOSITION

CREEP
Creep in concrete is understood as the growing deformation of the element under long-lasting loading. It is generally accepted that the stresses in facade elements caused by dead-load or wind load are low or applied for a short period of time, so the creep can be neglected.

SHRINKAGE
Shrinkage of concrete occurs in the transition between fresh and hardened state. The shrinkage continues at a decreasing rate for several months after the concrete is poured. The outcome is twofold; the element shrinks/swells and possible cracks appear. This last effect is most problematic with structures that are rigidly connected and where the elements cannot contract freely to undergo the shrinkage of the concrete through hardening or thermal effects.

The effect is thus limited for unrestraint facade panels as they are not interconnected, but can not be ignored, as cracks of 0.1mm or wider can yet allow water infiltration. Measures to minimize the formation of shrinkage cracks are;

- a low water cement ratio in the mix to achieve strength and workability
- proper curing techniques
- reinforcement to counteract the shrinkage and to distribute the cracks evenly. Fibres (plastic or steel) can contribute to this as well.

The effect of creep and shrinkage in the main structure, supporting the panels, is acknowledged but ignored in this research.

4.4.3. INFLUENCE OF LOAD

Roughly, a facade element has to deal with two load cases; dead load and wind load. Both are discussed in this section.

DEAD LOAD
The weight of the panel is determined by the dimensions and the composition of the concrete. When designing a panel, priorities have to be stated in advance. The maximum dimensions or the weight can both act as determining parameters.

The stresses generated in the material by dead load will hardly ever cause problems. The weight of flat concrete panels cause in-plane loading where double curved panels can cause out of plane loading and accompanying moments. Sufficient reinforcement and an appropriate concrete composition can deal with this.
The weight of the panel can only generate problems if the supports or principal structure is too weak. This is sketched in(fig.4.6). The joints are compressed/elongated in certain areas. A stretchable sealant has to cope with this as the adhesion between sealant and concrete edge must remain intact.

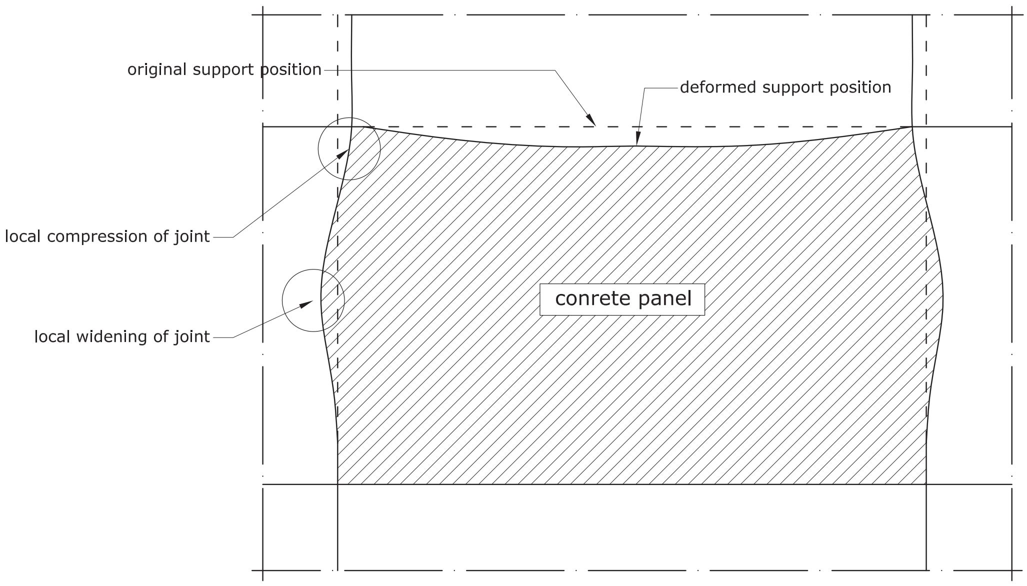


fig.4.5 diagram explaining bending of a support line under deadload of a concrete panel

WIND LOAD
Wind is air in movement. When this air bumps into a building, the movement is tempered. According Bernouilli's law:

½ρv² + p = constant

ρ = air density (kg/m³)
v = air velocity (m/s)
p = air pressure (N/m²)

If for instance the outdoor temperature is 15°C, then ρ = 1,25 kg/m³. If the velocity is completely blocked, p will grow with speed ½ρv² and the resulting overpressure on the facade is 0,625 v². The air movement is hardly ever reduced to 0, because the air tends to flow around the building while changing direction. Around corners and cantilevering parts, the velocity of the air can easily exceed the initial attacking wind speed.
At the lee side of the building streamlines can not instantly regroup; a wake develops where the streamlines detach from the building's edge.(fig4.7) The so created underpressure amounts half of the overpressure. The pressure distribution over the facade is dependent on:

- situation of the building
- wind direction
- geometric shape of the facade
- roughness of the facade

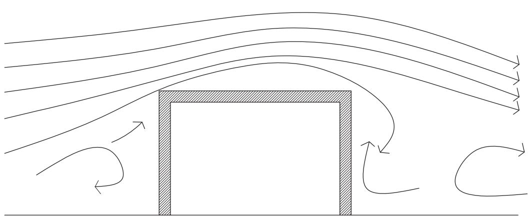


fig.4.6 wind flow around building

When calculating the wind load on parts a building, the unfavorable condition of simultaneously occurring wind loads, Prep must be taken as basis. This is expressed in the following formula;

Prep = Cdim x Cindex x Ceq x Φ1 x ρw

- **Prep** : the wind load caused by wind pressure, suction, friction, and pressure above atmospheric or depression in kN/m²;

- **Cdim** = the factor by which the dimension of the building is integrated

- **Cindex**: the wind load factors (Cpe for external pressure or suctions on surfaces, Cpi for internal pressure above atmospheric or depression)

- **Ct**: combination of the C-factors mentioned above, meaning that the total wind load is considered as a whole

- **Ceq:** pressure equalization factor

- **Φ1**: the enlarging factor by which the dynamic influence of the wind directed on the building is considered

- **Pw**: extreme value of impact pressure

When calculating facade elements, the value 1 can be determined for several factors. This is true for the factors Cdim, Ceq and Φ1. If considering this simplification the following formula based on combined wind load factors appears;

Prep = Ct x Pw

To determine the impact pressure,Pw, on a facade the following factors have to be taken into account;

- the location of the building in the Netherlands (or any other country)
- the surroundings of the building: with or without neighbouring buildings
- the ratio between height and width of the building

In the Netherlands the guidelines are assembled in the NEN 6702 standards. (fig4.8)
Concluding we can deduce the following wind load factors for closed facades.

- wind pressure: Ct = 1.1
- wind suction: Ct = -1.1

This value may increase to Ct = -11.5 in the case of small surfaces or at the corners and edges of a building. This extreme value should be carefully determined as we want minimal vibrations in the facade's corner elements. If occurring they will cause large tensionshifts in the elements and practice large forces on the anchors. At the same time vibrations affect the movement of the element en so the deformation of the joint, which can be problematic when using rather stiff joint fillers.

Tabel - Waarden voor de stuwdruk P_w als functie van de hoogte boven het aansluitende terrein

h m	P_w kN/m²		
	Gebied I onbebouwd	Gebied II onbebouwd	Gebied III onbebouwd
≤ 2	0,64	0,54	0,46
3	0,70	0,54	0,46
4	0,78	0,62	0,49
5	0,84	0,68	0,55
6	0,90	0,73	0,59
7	0,95	0,78	0,63
8	0,99	0,81	0,67
9	1,02	0,85	0,70
10	1,06	0,88	0,73
11	1,09	0,91	0,76
12	1,12	0,94	0,78
13	1,14	0,96	0,80
14	1,17	0,99	0,82
15	1,19	1,01	0,84
16	1,21	1,03	0,86
17	1,23	1,05	0,88
18	1,25	1,07	0,90
19	1,27	1,09	0,91
20	1,29	1,10	0,93
25	1,37	1,18	1,00
30	1,43	1,24	1,06
35	1,49	1,30	1,11
40	1,54	1,35	1,15
45	1,58	1,39	1,19
50	1,62	1,43	1,23
55	1,66	1,46	1,26
60	1,69	1,50	1,29
65	1,73	1,53	1,32
70	1,76	1,56	1,34
75	1,78	1,58	1,37
80	1,81	1,61	1,39
85	1,83	1,63	1,41
90	1,86	1,65	1,43
95	1,88	1,68	1,45
100	1,90	1,70	1,47

fig.4.7 wind impact values in the Netherlands; source, NEN 6702

CONCLUSION
Loads occur in every part of the building. Because this research concentrates on facade panels, we only take into consideration dead weight and wind load. Both loads cause movements of the panel that have to be restrained by the supports & further absorbed by the joints. Wind load has the biggest influence on facade elements. For regular buildings (<20m), no additional measures need to be taken to assure a safe behavior of the facade panels. With increase in height (>20m) and in areas with exceptional high wind speeds, extra reinforcement in the panels or tension anchors will counter the wind load.

4.5. ANCHORS & FIXATION

A concrete facade panel has a substantial weight compared to for instance a wooden or aluminum panel. This weight is transferred to the load bearing structure with the help of supports. This transfer can take place with point-supports or line-support. The division between warm and cold facade is reused to explain the two most common methods of anchoring facade panels. A contemporary warm-facade is conceived as sandwich panel. Optimally, both leafs are connected in the factory and the whole is installed as a complete wall on site. With the help of 4 anchors, fixed to the floor slabs, the panel is placed in position. Adjustments in three directions are possible.

In comparison with a warm facade, a cold facade is constructed out of smaller panels. The connection with the load bearing structure can take place in two ways. The first method is a fixation with the help of point-like anchors. Here, stainless steel anchors connected to the outside leaf, cross the ventilation gap, perforate the insulation layer and connect to the secondary structure behind. In this configuration we distinguish three types of anchors; retaining, supporting and torsion anchors. (fig 4.9) While the horizontal loads (wind pressure and suction) are carried by all anchors proportionately, the rigid supporting anchor transfers the vertical load downwards. The supporting anchor is preferably placed above the centre of gravity of the panel. The retaining anchors are placed around the edges. Their design allows them to follow deformations in length without any resistance. Torsion anchors, rigid in one direction but movable perpendicular to the rigid connection counter possible twisting of the In the same way as for large panels, adjustability in vertical, horizontal and lateral direction is feasible by slotted holes in the anchors.

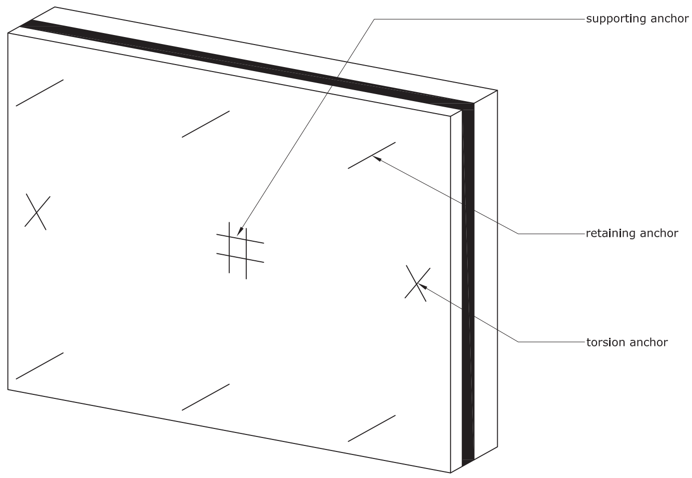


fig.4.8 diagram explaining different anchors and their respective position

Instead of using point supports there is the alternative of fixating small panels to a secondary structure with a post and beam structure. When dealing with very small panels this can result in reduced installation times, reduction of errors. A disadvantage is the decreased flexibility & adjustability.

4.6. JOINT

Now that we have understanding of the factors influencing concrete precast elements we can derive possible consequences and present design solution concerning the joints. Description of the joint's behavior incorporates the concrete's edges and the sealant filling the space between two elements. When regarding the previous sections, we can state that the joint's main function is to close of the inside from the outside and through this counter and absorb wind, water and loading influences. After installment the prescribed influences are mostly converted into a separate or combined movement. It is exactly this movement of the panel that is absorbed by a proper joint.

In this section, the movement's frequency, its origin and degree are discussed. Following, the two main types of joints are sketched and several design coefficients are derived. Also a preference for an optimal edge configuration is presented. Lastly, several types of sealants and their intended properties are discussed.

4.6.1. JOINT'S MOVEMENT

MOVEMENT'S FREQUENCY & SPEED
The frequency at which movement takes place is divided in two categories;

- movements occurring after installment. (e.g. hardening shrinkage and creep of the concrete)

- movements occurring repeatingly after installment. These movements cause the most problems and will be monitored closely.

The movement's speed can be divided in three levels. **Quick**; where the duration of the movement is measured in seconds or shorter. (e.g., traffic vibrations, wind gusts,...) **Slow**; where the duration of movement is measured in minutes and hours. A typical example is thermal deformation. And finally **very slow**, where the duration of the movement is measured in days, months and years. (e.g., shortening of the elements under hardening shrinkage, creep in the concrete and length-deformations caused by altering level of humidity)

MOVEMENT'S ORIGIN
The movement's origins largely corresponds with the phenomena described in (4.4), but are resumed here for their specific relation to the joints. We distinct two main categories;

- origins of **physical** nature; creep, temperature changes, shrinkage due to hardening or swelling of the elements

- origins of **mechanical** nature; altering external loads on the elements and/or load bearing construction through which elastic deformations happen. (wind load and loading of the main-construction). Also movements caused by vibrations due to traffic, local setting and earthquakes belong to this category.

MOVEMENT' DEGREE
The degree of movement in the joint is dependent on a number of factors, partly of physical, partly of mechanical nature. The main factors are;

- dimensions of the elements; Large elements cause bigger joint movements then small elements. The thickness has a reverse influence on the movement; increased thickness results in less shrinkage and a slower adaptation to altering air humidity and temperature.

- outside climate conditions; Areas with large changes in max and min temperatures cause bigger deformations in the panels then areas with a stable temperature. The same is true for indoor conditions.
- orientation & color of the elements; elements with direct solar radiation and elements with a dark surface finish cause larger deformations than others.
- composition of the concrete; Physical and mechanical properties of the concrete depend on type of cement, aggregates, w/c factor, method for consolidation,...
- reinforcement of the elements; length-deformations can be countered with the use of reinforcement along the considered direction.
- period of installment
- stiffness of the elements; A lower stiffness will enhance deformations of the elements and so the joint's width.
- stiffness of the load-bearing construction; Deformations occurring in the main construction due to altering or constant loads can influence the joint between two elements.
- stifness of the anchors;

4.6.2. TYPE OF JOINT

Joints between panels are of open or closed type. The open type is characterized by an inner membrane seal and an outer flexible mastic seal on the inner leaf. The closed type has a single outer seal of flexible mastic. These general principles count for both vertical and horizontal joints.

Open joints are internally drained and ventilated. An open joint allows windblown rain to pass through the outer gap between two panels. A baffle strip is placed in a continuous slot formed in the edges of two adjacent panels. Water entering this 'inner chamber' is led away from the slot through the horizontal joint below. The interior face of the joint is closed with an air seal using silicone. The most basic configuration lacks the baffle strip, thus water can actually reach the ventilated area behind the facade panel. This technique is less applied these days because unrepairable damage of the inner leaf can occur.

Closed joints are sealed on the outside face with a wet applied sealant. Water penetrating the outer seal can still be drained in the void behind. Small weep holes in the horizontal joints release the water in the voids.

4.6.3. DESIGN COEFFICIENT

A list of design coefficients helps to determine joint dimensions. They they may not be interpreted as absolute numbers but rather as helping hand in the initial design phase.

The inaccuracies and maximum tolerated deformations for an element between 2 and 5 meter can be approximated by working with the following coefficients;

- minimal joint width at installment: **2,7mm à 3,0mm/m ≥ 8mm**
- normal joint width: **4,0 à 4,5mm/m ≥ 10mm**
- maximum movement of the joint in one direction (26%): **0,7 à 0,75mm/m**
- maximum expected total movement of the joint: **1,25mm/m**

4.6.4. EDGE PROFILING

The edge profile can have a positive influence on the behavior of the facade. It is generally accepted that a more complex profile performs better than a simple one. But together with a growing complexity of the edge, the production costs and fragility sharply increases. The thickness of the sample also plays a key role. The criteria thus have to be compared and selected based on priority.

Commonly used profiling configurations are: flat, stepped, overlapping, tong and groove, (fig 4.10) To avoid redundant water infiltration, a stepped, sloped horizontal edge is preferred. The horizontal edge's function is then twofold; preventing horizontal water infiltration and drainage of water coming from the vertical joints. .

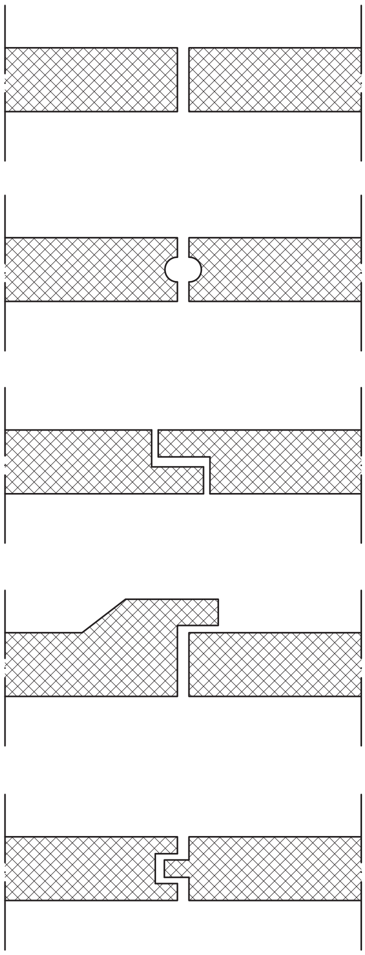


fig.4.9 different edge configurations, from top to bottom; flat, hol & dol, stepped, overlap, tong and groove

4.6.5. JOINT SEALANT

Both open and closed joints make use of elastic sealants. The sealant has to fulfill a number of functional demands such as excellent workability at varying conditions, solid fastening, large elasticity without occurrence of stress cracks, low creep, indifferent to low or high temperatures, low dirt adhesion, fully waterproof, non-corrosive with metals, invulnerable to micro-organisms, long durability,...
The last decades huge progress is made in the development of sealants. The introduction of silicones as building material is considered a breakthrough in the field because it tackles most of the above described criteria. For completeness we mention other materials that can be used to seal a joint. Based on the installation method we distinguish;

- preshaped profiles, when closing the gap after installment:
- preshaped packings , when sealing takes place together with installment
- plastic or metal strips, if incorporated in the design of the edges at fabrication level. These can be glued or soldered together after positioning of the panel on site takes place to create a fully sealed joint.

In reality however, most of the sealants are wet applied silicons. When applied on site, correct installment is subject to weather conditions and skilled workers. Minimizing the risk of these unknowns is the task of the designer. Therefore it is important to discussed the two most critical criteria of the sealant; sufficient adhesion and proper cohesion.

ADHESION & COHESION
The combined action between adhesion and cohesion is necessary to guarantee the sealing of the joint. (fig 4.11) Adhesion is understood as the bonding between sealant and concrete. This can only be obtained if the edges are clean and dry. Cement or dust particles decrease the effect of adhesion. Possibly, the concrete edges have to be pretreated to assure sufficient adhesion. This pretreatment also prevents infiltration of constituents of the sealant into the concrete edge.
Cohesion is understood as the internal bonding of the sealant. Movement in the joints cause stresses in the sealant that result in constriction of the silicon and ultimately rupture.

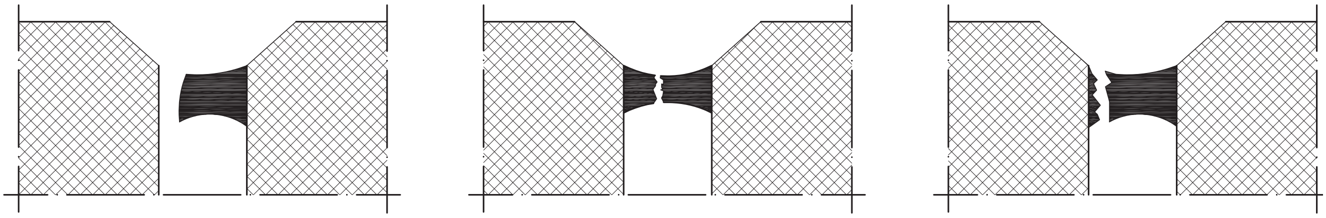


fig.4.10 from left to right; lack of adhesion, lack of cohesion, lack of adhesion and cohesion at the same time

The complex interplay between adhesion and cohesion must be balanced as it determines the durability of the joint, the panel and thus the appearance and life span of the facade. The durability is influenced by;

- quality of installment
- maximum movement in the joint
- shore-toughness of the sealant
- frequency of the joint's movement and related resistance to fatigue of the material
- the shape of the sealant
- protection of the sealant through advanced edge profiles
- adhesion quality of the concrete's surface.

OPTIMAL SEALANT CONFIGURATION
Literature learns us that under elongation, the stresses in the sealant increase together with growing depth of the sealant in comparison to a sealant filled to a lower depth. The ideal condition is thus when a joint is filled with sealant in a way that a large adhesion surface is combined with a thinner section in the area of maximum constriction. An estimation of this situation is established by installing a soft round profile behind the sealant. (fig 4.12) Foam strips of any kind are suitable to be squished into the gap and allow joint movements at the same time.

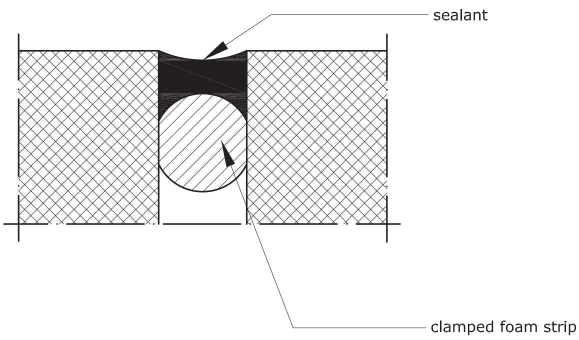


fig.4.11 layout of an optimal sealant construction

4.7. 3D RELATED ISSUES

All the topics discussed and every solution presented is suitable for 'flat' 2D panels. The scope of this research however focuses on double curved concrete elements. It is expected that several beforehand accepted solutions will conflict when applied to free form panels. The author's acknowledge the importance of solid solutions for edge-and joint configurations. Therefore findings and considerations on this topic are listed. The list contains no in depth researched topics but rather findings and comments that appeared together with the development of the production process. The remarks indicate areas in which further research is desirable.

- Through experimental tests, it is concluded that the preferable orientation of the edges is normal to the surface. By doing this, the transition between two panels is established in a smooth and correct manner. As each point of the edge finds its 'brother' point of the next panel perpendicular to itself, the fitting of two panels becomes easy. Next to the advantages, it must be said that the edge is in torsion and thus becomes more fragile.

- In free form design, possible inward directed elements occur. When thinking of water running down the facade, problems can be expected. Although this can be countered in terms of building science, stains or imprints on the elements might disturb the appearance of the building.

- Positioning on site of concrete free form panels is significantly more difficult. The demands on the adjustability of the anchors are higher than with 2D panels. Next to a linear adjustability in x, y and z-direction a possible rotation around the three axis's has to be considered.

4.8. CONCLUDING REMARKS

Facade panels are relatively uncomplicated compared to load bearing structures. The requirements concerning connections, anchors, edges and joints are clearly lower than their more complex relatives. However, weather influences combined with wind load and dead loads determine to a large extent the design of the above components and limit the dimensions of the panels.

For this reason, facade elements are the perfect building components to start the development of the new production technique. Contemporary solutions for 2D precast facade elements will act as starting point and should be adapted for the use with free form panels. In the beginning it is advised to experiment with flat edges for the panels. Together with the progression made in the development of the mould, extra features and design effort can be assigned to the panel's boundaries.

Stepped edges, a slotted water drainage inside the panels' thickness or embedded anchors are just a few of many additions that could enhance the trustworthiness of the technique in a later stage.

5. CONCRETE EXPERIMENTS

No amount of experimentation can ever prove me right; a single experiment can prove me wrong. (Albert Einstein)

fig.5.1 mixing of ECC concrete

5.1. INTRODUCTION

A new production technique for double curved concrete panels is implicitly connected to the material properties of concrete. Due to the innovative nature of thisMaster thesis period new testing methods and specific properties were tested. Therefore we will not focus on general properties and applications but zoom in on those qualities relevant for the graduation project. Basic understanding of concrete as a building material is expected.

We will take of by summarizing relevant properties and discuss the studied types of concrete. Subsequently an overview of the various conducted experiments is given. We conclude this chapter with the description of two different approaches concerning the behavior and processing of concrete suitable for this production technique. The description of both types of concrete will then act as starting point in the design & mock-up chapter later on.

5.2. CONCRETE PROPERTIES

5.2.1. MECHANICAL PROPERTIES

Concrete is a well known construction material capable of taking large compression forces and composed of a mixture of cement, sand, gravel, water, additives and admixtures in specific proportions. This mixture hardens by the chemical reaction between cement and water. The ratio in which the water and cement are mixed is also known as the w/c factor. It influences the strength of the concrete, the higher the water-binder ratio the lower the concrete strength.
The tensile strength of normal strength concrete is very low, only 1/10 to 1/15 of the compression strength (according to Betonpocket 2008). So in most calculations the tension strength of the concrete is neglected.
In order to be able to take tension forces, steel reinforcing elements are added to the concrete members. The tension force in the concrete members is almost completely carried by its 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 carries the compression force and the reinforcement transmits the tension force, after the development of some micro cracks.

Today steel reinforcement bars are a standard component when designing concrete structures like plates beams and columns. Mostly a mesh of reinforcement is positioned in the concrete. Recently a new development in concrete, the addition of fibres, gains importance. Different types of fibres (e.g., steel, glass or synthetic) are used to improve the concrete’s characteristics.
They don’t fully replace steel reinforcement and offer less performance when coping with tensile stresses. But they do offer more control towards local crack prolongation. This is due to the fact that they are so closely spaced and randomly distributed in the concrete matrix.

The concept of the production process conflicts with the idea of traditional reinforcement. Positioning of a steel mesh in a free form mould is technically challenging and problems can be expected. To avoid this we will aim for a concrete mix that withstands the applied forces without traditional reinforcement. We will use the properties of self compacting fibre reinforced concrete to the utmost. SCFRC is characterized by high maximum pressure strength (possibly >65 N/mm²), high tension strength in comparison with traditional concrete, good local crack control and excellent flowing capacities. The expertise of Dr. Steffen Grünewald (PhD on performance based design of self compacting fibre reinforced concrete, 2004) is addressed to develop suitable compositions and to evaluate the results.

5.2.2. WORKABILITY

The amount of water also influences the workability of the concrete mixture; more water improves workability. With a large water/binder ratio not all water is used to react with the cement grains. Some water is left in the pores of the concrete. Additionally pressure builds up because of decreasing size of the pores. This phenomenon is also known as shrinkage and can cause micro cracks in the concrete. An optimum between strength and workability has to be found for each mixture. In traditional compositions a water/cement ratio of 0,5 is used. Most of the water then reacts with the cement and the mixture has still a good workability. High strength concrete has a lower w/c factor; possibly as low as 0,4. To preserve a certain degree of workability a superplasticifier is added to the mixture.

After casting the concrete needs to be compacted with vibrating energy to remove air from the mixture, and minimize the air bubbles that stay in the concrete.
Self compacting concrete makes this extra procedure redundant in the casting process. This comes at hand in 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.

5.2.3. CONCRETE MIXTURES

As we stated before the number of different concrete mixtures is innumerable due to concrete's wide application range. We acknowledge that a more profound research towards an ideal mixture is preferable. But as our time frame is limited and with the focus on the development of the process itself we experimented with 5 varying concrete types. This returns us basic understanding of the possibilities of today's mixtures and helps to define the desired behavior of a final mixture. The studied concrete types are;

- traditional lean mixture
- ECC
- Holchim canoe mixture
- Hurks beton stable mixture
- concrete cloth

TRADITIONAL MIXTURE

	materiaal	hoeveelheid	eenheid
cementsoort	CEM 1 52,5 R	2,768	kg
toeslagmaterialen	zand 0.125-0.250	1,104	kg
(droog)	zand 0,250-0,500	1,657	kg
	zand 0,500-1	1,657	kg
	zand 1-2	1,104	kg
totaal water		1,395	kg
	totaal	4,5	liter
	gewicht element droog	+/-5,4	kg

HOLCHIM MIXTURE

	materiaal	hoeveelheid	eenheid
cement	CEM 1 52,5 LA	580,452	kg
vulstof	Micro Silica	217,669	kg
toeslagmaterialen	Poraver 0,1- 0,3 mm	54,708	kg
	Poraver 0,25- 0,5 mm	86,778	kg
	Poraver 0,5- 1 mm	43,389	kg
	Poraver 1,0- 2,0 mm	3,773	kg
toevoegingen	Tillman accrytec	10	kg
	Tillman injex	1,412	kg
	Plastic fibres	0,350	kg
	Tillman ONS 2000-P	0,470	kg
	Tillman betonvertrager Type K	1,000	kg
	totaal	1000	kg

fig.5.2 composition of two used concrete mixtures. left; traditional mixture right; holchim mixture

fig.5.3 (left) composition of ECC mixture

ECC			
	materiaal	amount	eenheid
cementsoort	CEM 1 52,5 R	1,818	kg
vulstof	vliegas	3,384	kg
	quartzand	1.521	kg
hulpstof	glenium 51	0,157	kg
toeslagmaterialen	zand 0.125-0.250	0,581	kg
toevoegingen	PVA 8mm/0,004	0,117	kg
totaal water		1,227	kg
	totaal	4,5	liter

TRADITIONAL MIXTURE

A simple mixture with no additives or admixtures is composed and will be used as a reference point for comparing the more evolved mixtures. Few is expected from this lean mixture. Low compression failure strength, almost no tensile strength and brittle behavior are the characteristics. We used this composition only once hereby focusing on workability and hardening process.

ECC

'Engineered Cementitious Composites' (ECC) are strain hardening composites with a normal strength matrix (the complete range of compressive strength can be produced) and a moderate fibre content of about 2% by volume. They contain synthetic fibres with a high elastic modulus that have a maximum lenght 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/mm2 and 7 N/mm2, while the PVA-fibre (Polyvinyl alcoholic fibre) content is still controlled around 2%-3% by volume. The water-binder ratio is set on 0,45. The result is a strain hardening, multi-cracking and ductile material.

HOLCHIM CANOE MIXTURE

This mixture is originally developed for the concrete canoe race, which is a held every year and attended by Universities and colleges from several European countries. The mixture, composed by Holcim beton and TU Delft contains CEM 1 52,5 LA white, light weight poraver glass particles and plastic fibres. The mixture is premixed by Holcim, only water needs to be added; 2,8 -3,3 litres of water for 10 kg of dry mortar results in w/c ratio of 0,35 - 0,41. The result is a very strong and light concrete.

The aimed thickness for the canoe is 6mm. This is the minimum thickness to cover the steel mesh, acting as reinforcement. The atypical use of this concrete triggered our imagination and led to a quick first test. The dry substance allows clean processing and immediate deformation, while the lack of flow creates compacting problems. Only by applying the concrete in thin layers, sufficient compacting of the concrete appears. Another method to improve workability is to increase the water part. The characteristic pressure strength is not retrieved, but is expected to be above 45 N/mm².

HURKS BETON MIXTURE

A high strength concrete is prepared at HURKS beton. The aim is to come up with a self-compacting fibre reinforced concrete with a high plastic viscosity and a low yield value. These two factors can be combined but conflict with the original definition of self-compacting concrete as this prescribes a rather low viscosity to prevent slowing down of the concrete during casting and a high yield value to enhance the mixture to start flowing . The reason to create such an atypical mixture is dictated by our desire to cast and shape the fresh concrete directly onto a 3D surface. The fresh concrete thus have to be stable (minimal flow) and self-compacting at the same time. The used mixture contains PVA fibres (26 kg/m³), plasticifier, stabilizer and limestone powder. The exact composition cannot be displayed as it is still under development and no publishing permission from Hurks is granted. The compressive strength was not determined, but is expected to be above 45 N/mm². The fully developed strength (after 28 days) is not known at the moment of this writing. More information on the casting of this type of concrete and the encountered issues are explained in chapter 8.

CONCRETE CLOTH®
Concrete Cloth (CC) is a proprietary material developed and manufactured by Concrete Canvas Ltd. CC consists of a 3-dimensional fibre matrix containing a specially formulated dry concrete mix of for us unknown composition. A PVC backing on one surface of the cloth ensures the material is water proof. Hydrophilic fibres on the opposite surface aid hydration by drawing water into the cement. When water is added the material remains flexible for 2 hours and then sets rapidly. It can be hydrated either by spraying with water or by immersion. Once set, the fibres reinforce the concrete preventing crack propagation and providing a safe plastic failure mode. Furthermore, the manufacturer claims that the hardened concrete is hard wearing, durable, water proof and fire proof. It is very easy to work with and can be cut to shape with conventional hand tools, stapled or nailed through.

The available thicknesses are 4, 8 and 13mm. A compressive failure strength of 40 N/mm² and Young's modulus of 1500 N/mm² are indicated by the manufacturer.

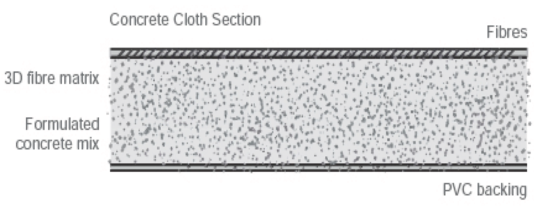


fig.5.4 concrete cloth; section and composition. source: Concrete Canvas Ltd.

5.3. EXPERIMENTS

During theMaster thesis period period we conducted various tests that focus especially on concrete properties related to deforming fresh concrete. No sound or scientific test describing the deformability and preservation of bonding under deformation of fresh concrete was found. Therefore the experiments, except for the compression strength cube test, cannot be categorized under scientific research. They are established through logic reasoning and mainly help us to asses the behavior and hardening of fresh concrete mixtures. The performed test are the following;

- deforming various types of fresh concrete
- monitoring hardening and slump of fresh concrete
- compression / tension failure
- concrete cloth experiment

5.3.1. DEFORMING VARIOUS TYPES OF FRESH CONCRETE

Three different concrete compositions are cast and deformed in fresh state. Their behavior is observed and described below

COMPOSITION 1
The first mixture is traditional concrete. This is considered the utmost basic form of concrete and so complications are expected due to its llow tensle strength. The matrix is mixed carefully in a small scale bucket in the following order: sands, cement and finally the water. The mould is smeared with mould release oil and bordered with PS foam attached to the mould with double adhesive tape. This boundary is kept as simple as possible, thus no profile is applied. This is done to have a clear view on edges in semi-dry and hardened state . The overall thickness of the sample is 2cm.

The matrix is poured into the mould ten minutes after the mixing begun. Within ten minutes the entire mould is filled and the concrete is spread evenly. Important to the process is a thorough consolidation of the matrix to prevent air bubbles being trapped causing minor cracks later on. Based on our empirical judgement, we decided to remove the PS border after one hour. At this point the concrete had sufficient internal bounding and strength to remain its shape. After this the 2D mould is positioned above the 3D surface and lowered until it rests on top of it. The final shape is now obtained and the

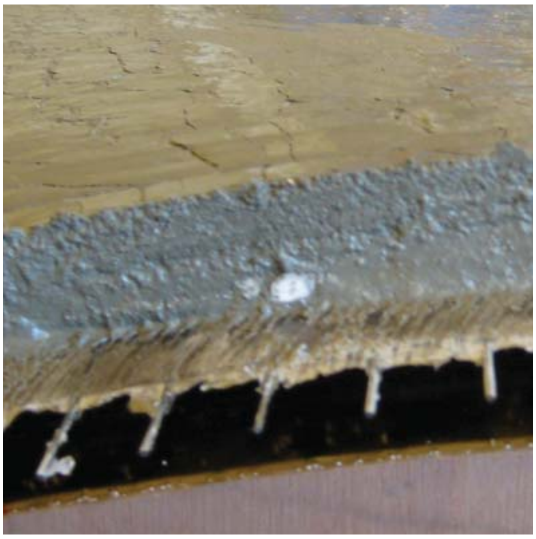


fig.5.5 composition 1 deformed in its final 3D shape. Edge disturbance and surface cracks are visible.

fig.5.6 corner failure in hardened composition1

hardening process continues.
Due to the curvature of the shape, bulging of the edges occurs. Mainly water decomposed itself. After two hours hair cracks were formed in areas subjected to tensile stresses (fig.5.5). This was expected but unfortunately led to rupture of one corner. (fig.5.6) After 12 hours the concrete was sufficiently strong to remove the sample from the support and inspect the bottom of the panel. This underside was surprisingly smooth and contained no cracks what so ever. Overall the edges withstood the subjected curvature well as most of the circumference edges were pointing in a direction normal of the mat.

COMPOSITION 2
This is the above described ECC mixture with quartz-sand and PVA fibres (SCFRC). We have no experience with this type of concrete so the processing is unknown to us and the result unpredictable. Hardening duration and dehydration properties are also unknown to us. Just to point out that this is rather an experiment than a well-prepared test. This is a totally different matrix with entirely different properties in fresh and hardened state than the previous traditional concrete. To use the self compacting properties to a maximum we decided to introduce a profiled edge border. This boundary is composed out of two plywood frames, where the upper has an offset to the inside creating a basic stepped profile. Again the mould is oiled in the same way as with mould nr.1.

As the matrix contains several additives and admixtures it has to be mixed more carefully and in a specific order. First the sand and quartz-sand are mingled. Then the cement is added, followed by a gradual adding of the water and superplasticifier, glenium 51. This specie is then mixed thoroughly to obtain a homogenous matrix. This last mixing takes surprisingly long. Probably due to the superplasticifier that has to bound with the cement and sand. At the end, we gradually add the fibres. The matrix is then poured into the mould. Immediately we recognize a different pouring behavior: the fresh concrete pours, looks and feels more sticky than the first one. It almost behaves as a liquid plastic. To prevent dehydration of the sample we cover it with a plastic foil.

The dehydration of the concrete is retarded due to the plastic foil on top of the sample. After +/- 02:00h the concrete had not hardened at all, so we decided to remove the foil in the assumption that this would stimulate the hardening process positively. At 02:35h we tried to remove the boundary shape to evaluate the edge condition. Unfortunately this was done to early. The concrete had gained no stiffness and bounding yet. As a result the specie sagged down, diminishing the required profile. Recognizing that the sample was already failing, we put it on the 3D surface after 03:25h. (fig.5.7) Within minutes the complete profile disappeared. Another remark is that the top surface was bumpy and white stained due to the presence of the fibres. Later, the same corner (the one with the largest curvature) as with the first composition, broke off. Reason for failure: a lack of internal bonding in the composition! We simply transferred the sample too early from the 2D mould to the 3D surface.

COMPOSITION 3
This mixture is similar to composition 2. It is a slightly modified version of the ECC. The main

fig.5.7 composition 2; profile sagging

fig.5.8 composition 3; forming of hard top layer due to uneven dehydration

difference lies in the presence of another filler, e.g. fly ash instead of limestone. Next to that the amount of cement is smaller (1.818 kg vs 2.367 kg). The amount of water, superplasticifier and fibres is comparable.
The edge mould is strongly clasped to the PU to prevent penetration of the specie as we saw with the second composition. The concrete is mixed in the same order as the previous one. The mixture looks promising. When pouring it, we immediately noticed a more homogeneous flowing compared to the second batch, which poured rather flaky. Due the unpredictable result of the foil in last experiment we decided to leave this sample uncovered.

After three hours we noticed a thin hard top layer on the sample. (fig.5.8) As we were not able to judge the material below and were convinced that the concrete was stable enough, we transferred the sample to the 3D surface. Seemingly the transfer was initiated too early and only the top layer had bonded. Once the concrete took the shape of the 3D mould, the whole thing sled downwards and fell apart.

EVALUATION
Composition 1 is evaluated as the best. It is satisfying to see that the edges are directed normal to the surface. This is promising, considering a future connection of panels. Setback in this test was the cracking of the panel in areas with large internal tensile stresses.

The specie of the two self-compacting reinforced concretes behaved as expected. Its excellent flowing capacities help to fill a more advanced mould without having the risk of air bubbles being trapped and through this weakening the concrete. However we can pose that the hardening duration and the duration for which the concrete remains deformable is not under control at all at this point. Much research lies ahead to deal with this topic.

The size of the panels and related curvature is of big importance to maintain a meaningful research. For now we worked on a scale sample of 45x45x2cm. In reality this would be a panel of 225x225x8cm. The question remains: Is it possible to work with scaled samples and extrapolate the results? This matter is discussed with ir. Roel Schipper of the Civil Engineering Faculty. He pointed at the relation between the elongation ε under curvature and the thickness *d* of an element.

$\varepsilon = \kappa \times 0.5 \times d$ (*with κ = curvature = 1/R*)

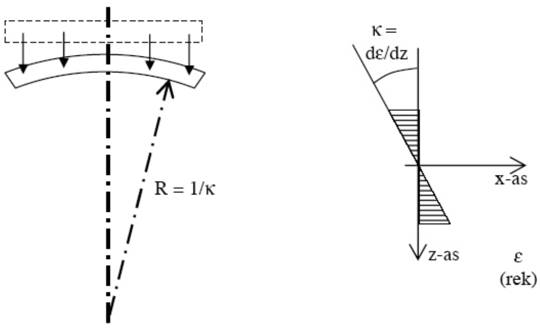


fig.5.9 linear stress accumulation under bending in a structural section

fig.5.10 setup of the test; showing 12 poured concrete samples

Larger curvature creates higher stresses in the concrete. The thickness of the concrete relates to the maximum stress in the concrete. The strain ε in a material increases linear with the distance away from the neutral line. (fig.5.9) An experiment with a specific concrete matrix can thus be successful in a scaled version but when producing the same element in full-scale, the required elongation *ε* might result in large stresses at the outer surfaces that can cause failure of the element. Therefore we decided to experiment with full-scale elements instead of scaled versions from now on.

5.3.2. MONITORING HARDENING AND SLUMP OF FRESH CONCRETE

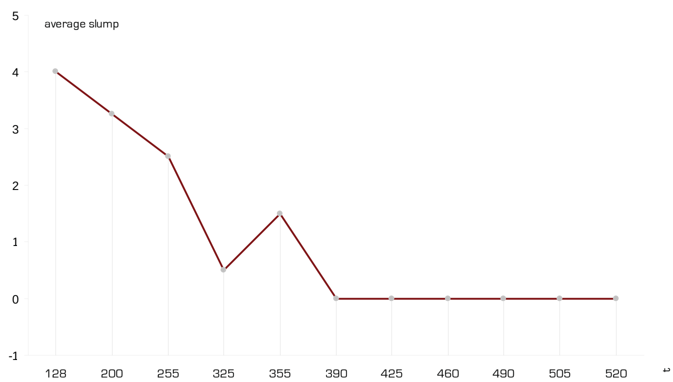
Among the conclusions that were listed after the first experiment, it became clear that the moment where the concrete matrix reaches the right plastic/elastic balance is of utmost importance in this process. Therefore we formulated an alternative 'slump test' as a first step to empirically determine the right moment of the deformation.

SETUP & APPROACH

A standardized slump test is known as the Abraham's cone. Briefly the result of this test is the variation in height (how much the concrete cone sags down). This defines the flow capacities of the concrete and is an indicator for workability. We performed a similar test but decided to use a cylinder shape mould (12 cm x 4 cm height), to verify whether or not the edges remain vertical and to what extent the sample sags. Both criteria are measured in certain time intervals.

A PVC drainpipe is sliced into 12 identical cylindric sections to form the moulds. Next we placed the moulds on a 18 mmplywood board. (fig.5.10) Both theplywood and the pvc pipe remain untreated. (without release agents)

fig.5.11 sagging of the samples over time



Following 4.5 liter of ECC concrete is prepared and poured into the moulds. The samples are carefully flattened out and each mould is covered with a plastic foil to prevent dehydration. Because we presume that the hardening process will proceed slowly in the beginning and faster towards the end of the day, we agreed on the following intervals to measure the slump and evaluate the edges: 120-180-240-300-360-390-420-450-480-520.

After the beginning of the first time interval the mould is released and the sample's slump is measured. At the end of the interval the slump is measured again to determine an average flow over time. This is done for all the samples. The results are shown in fig.5.11

EVALUATION

The goal for this experiment was to determine a time interval in which the concrete gained sufficient strength and stiffness to stand on itself but at the same time still has the capacity to be deformed without loss of bonding. For this ECC mixture the optimal moment is recorded after 8h of hardening.

This value only applies to the ECC mixture and with a considered thickness of 40mm. Other compositions follow another hardening process. Next to this, additives in the mixture can speed up the hardening process and stabilize the mixture at the same time. With their aid, it becomes feasible to reach a prescribed behavior at the desired moment in time. We conclude that it is more important to define a moment in time based on the necessary preparation time of the mould or speed of the production line, than focusing on the initial 'ideal' deformation moment of the concrete. As this last one can easily manipulated by concrete experts.

5.3.3. COMPRESSION TEST

After 28 days we tested the mechanical properties of the self compacting ECC concrete mixture. Three cubes are tested on compression strength and two cubes on tension failure strength using the split test.

The cubes measure 150 x 150 x 150 mm and were kept in a conditioned room for 28 days. At day 28 the cubes were removed from the room en wept dry.
The specimen is now placed centrally in the compression bench and applied with a constantly rising load of 13.5 kN/s. This process is automatically stopped when the pressure bench notices a lower resistance from the specimen which is an indication of internal bonding failure. The magnitude of this load is called the critical pressure f'_c. The compression strength f_c now results from dividing the critical pressure f'_c [N] by the total surface area A [150 x 150 mm²].

60.21 N/mm² was the average compression strength with a maximum of 61.63 N/mm².
The ECC mixture is thus a nearly high strength concrete mixture. High strength concrete have to withstand a minimal compression strength of 65 N/mm².
Typical in fibre reinforced concrete is the formation of small cracks at f'_c instead of destruction of the sample. (fig.5.12) When compressing traditional (no fibres) concrete, part of the specimen tears off and a minimal surface is formed. (fig.5.13) Due to the high amount of fibres in ECC concrete, cracks cannot prolong easily, with a ductile behavior as result.
Since the concrete panels will undergo bending, tensile stresses will occur throughout the panel. To asses the maximum tolerated tensile stresses in the sample a splitting test is performed. The same cubes measuring 150 x 150 x 150 mm and hardened in a conditioned room for 28 consecutive days are tested. The samples are placed in the compressing machine and a strip of wood is placed on both sides of the specimen. The wooden slats are in between the concrete sample and the compression machine and generate tensile forces in the material.
The force is constantly increased with 1.1 kN/s untill the samples fails. The tensile splitting force f_b can be found via the following formula (betonpocket 2008):

$$f_b = 2F / \Pi \times l \times d$$

where

fb = splitting tensile force (N/mm²)
F = critical force (N)
l = specimen height (mm)
d = length in between wooden slats (mm)

We measured an average result of 6.23 N/mm² which lies well above the average tensile strength of concrete.

fig.5.12 surface cracks appear at *f'c*

fig.5.13 typical failure of traditional concrete under compression.

5.3.4. CONCRETE CLOTH EXPERIMENT

The remarkable thin canvas and the promised properties interested us, so we ordered 3m² of canvas to do tests on. The ordered sample comes on a 1.1m wide roll. A small piece is cut out and positioned in the silicon formwork. The fabric is sprayed extensively and dried overnight at room temperature. The sample is inspected; the concrete is not fully hardened and the bonding cracks when loaded. Unfortunately there is no time left to determine what went wrong.

fig.5.14 concrete cloth on silicon formwork

5.4. CONCLUDING REMARKS

We do not pretend to be concrete technologists, but through the conducted experiments and by casting numerous panels ourselves, we feel acquainted with concrete as material in every stage of its processing. We have understanding of the relevant properties of concrete in fresh and hardened condition.

More important is that the experiments helped defining two approaches to deal with the deformation. The first one describes the deformation of semi-hardened concrete after a predetermined period in time. This approach is studied in section 4.3.2. The improvised experiment gave us the optimum moment for deformation off the ECC mixture; 8 hours. The relevance of this value is relatively low, as the hardening process of every mixture can be accelerated or decelerated easily with the help of additives. It thus becomes important to assess the necessary time at which deformation can take place after casting. The preparation time for the mould, the speed of the production line or the transportation time from the mixer to the mould are good examples of this interval. From here, the concrete composition has to be designed backwards.
The second approach is to cast the concrete immediately on a 3D shape. Therefore a stable mixture with low yield value and high viscosity is preferred. This is tested at Hurks beton (chapter 8, design & mock-up). The biggest disadvantage is that an overall equal thickness is difficult to obtain. On the other hand, no extra loading of the fresh concrete, as seen in approach 1 where forces are applied on the freshly bonded concrete, takes place.

Both approaches are feasible and the trustworthiness will be tested in the two mock-ups described at the end of this report.
Next to the specific requirements we conclude with several general recommendations on concrete compositions;

- Self-compacting concrete is preferred. This makes it possible to embed complex edge profiles or surface textures in the mould. Besides, the fragility of the setup does not allow vibrating energy to compact the mixture.
- Fibres in the concrete can make traditional reinforcement redundant. The concrete behaves ductile (safer) and thickness of the panels can be minimized.
- Light-weight concrete (Holcim mixture) is preferred in facade panels to limit dead weight.

6. COMPUTATION Arnoud schoofs

Like all new tools that are brought into a scientific process, computational models confront a variety of universal concerns : Can these tools generate new and useful insights? How robust are they? How far developed are they?
For any tool we employ, it is always important that we remember the relevant issues surrounding its appropriate use, regardless of its current level of acceptance. (Neri Oxman)

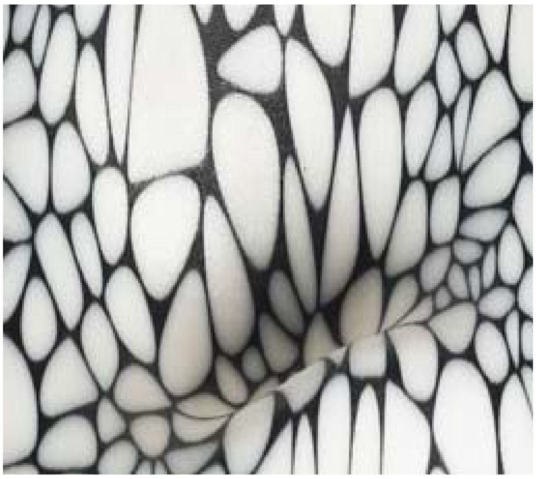


fig.6.1 Neri Oxman

6.1. INTRODUCTION

The adjustable mould system is specifically reserved for those architectural projects that are almost completely computer generated. Therefore it becomes indispensable to create a correct and constructive data interface.
The influence of computation throughout this process can be subdivided into two elements : the support of the production process and monitoring of the results.
This personally motivated research will formulate the computational influence based on these two elements and will tackle the most problematic issues encountered. The progress and findings are then injected in the production of the mock-ups along the way. The generated feedback is then re-entered in the themes and further optimized.

6.2. PROCESS SUPPORT

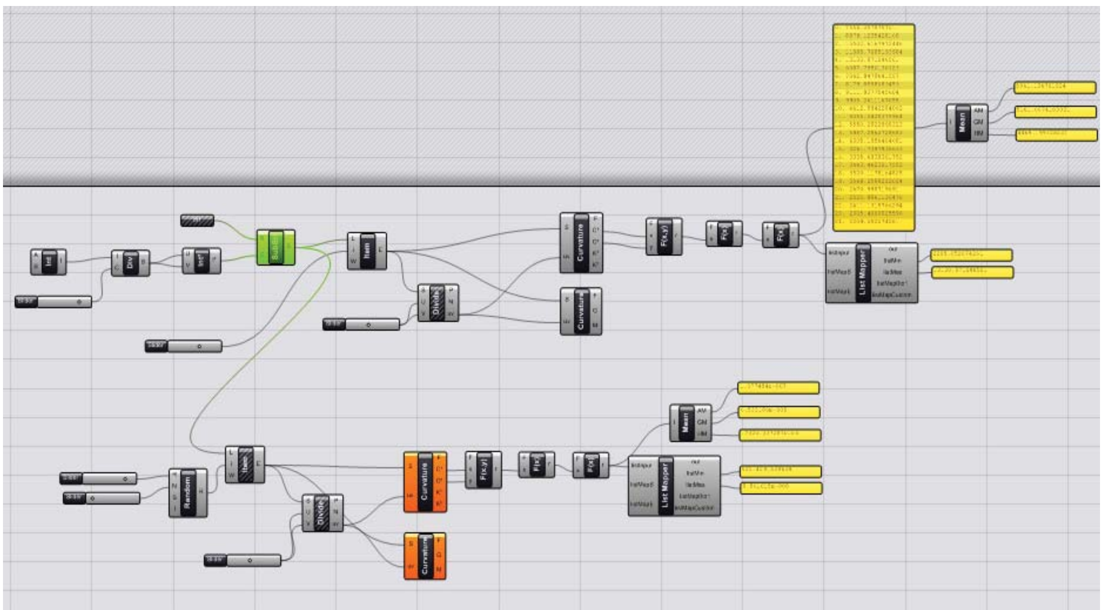
Today's free form geometry is almost completely computer generated. One is expected to have a profound knowledge of geometry. The most occurring types of curves, surfaces and meshes are studied in the beginning of the research and summarized in the chapter geometry.
Understanding of the principles and control over these geometric shapes in the computer is one thing, bringing them in practice and relate them to the flexible formwork is another.

6.2.1. SURFACE ANALYSIS

A fluent interaction between computer and mould set-up is vital. This can only be established when the required properties of the geometry are known. Think of dimensions of the panels, principal curvatures, max displacement out of plane, etc.
To deal with this in a smart way, a generative model is introduced to extract the necessary values and evaluate if further processing of the geometry is feasible.

A tool is developed in Rhino's Grashopper. (fig.6.2) This is a generative plug-in closely linked to Rhinoceros as surface modeling software. The interface works intuitive and operation requires no in depth knowledge of scripting. However knowledge of the basic principle of scripting enhances quick results.
Why generative? Well, the greatest power of generative computer models lies in the definition of objects with the help of parameters. This link enables quick alterations in an almost intuitive way. Another advantage is that the underlying structure of every model is constructed in steps and fully originates from the builder's mind. The parameters can exist as mathematical functions, simple slider values or geometric objects. Also a great number of prescribed functions, initially developed for Rhino, as there are; extrusion, boolean operations, trim,... are integrated in Grasshopper. This leaves us with a very powerful tool to design smart computer models.

fig.6.2 The Rhino grasshopper interface showing the analysis tool. The script can be read from left to right.



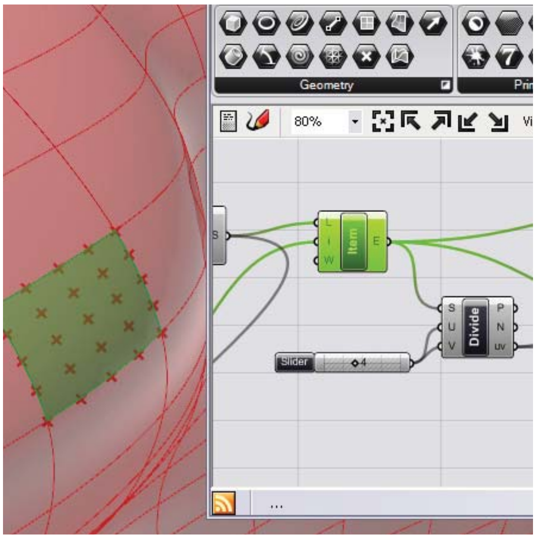


fig.6.3 (l) The Museum of the history of Polish Jews in Warshaw by Rainer Mahlamaeki

fig.6.4 (r) The Rhino grasshopper tool with the selection of a desired panel. and the number of points for curvature analysis.

The software is in this case used to evaluate the geometry presented by architects or engineers. As a result of the limitations of the production process in terms of size of the panels and principal curvatures the need for a first evaluation system forces itself on.
The created tool reads the selected geometry (mostly surfaces). If an unknown or unusable type of surface or mesh is handed over, it will have to be rebuilt first keeping in mind the formulated tolerances and allowable dimension alterations. Change in shape is a not negligible factor when rebuilding geometry. Mostly there is room for minimal distortion but certain design cases foresee tolerances in the order of 0.5mm.
After selecting the surface, the software runs through the programmed functions. The variables that can be altered to find optimization are:

- **grid size**; the size of grid can be altered with U and V settings

- **type of grid**; so far the script is only capable of building rectangular grid patterns based on the isocurves of the surface.

- **panel number**; the panels are a list of numbers. With -*extract number out of list function* - attached to a slider, we can run through the complete list of ‘panels’ and extract the panel needed(fig.6.4).

- **number of points** for curvature analysis; a selected surface can be evaluated at X number of points. As average values have no meaning in curvature analysis, a sufficient number of points, evenly spread on the surface, have to be checked.

The numeric results are subsequently streamed as a text file and can be quickly evaluated in Excel. The extracted values are;

- mean curvature
- principle curvature 1 & 2
- max value of principal curvature
- maximum movement out of plane
- length of edges
- area of surface

This information will provide us with a first feedback to the actual production process. The curvatures can for instance influence the chosen flexible formwork and can also determine the amount of stabilizers that has to be applied in the concrete mixture.

To simulate a realistic approach we reference our production technique for thisMaster thesis period to an already realized project : the Museum of the history of Polish Jews in Warsaw by Rainer Mahlamaeki (fig.6.3). Inside this museum two grand double curved walls form a cave like experience. They are build up out of limestone elements which are attached to a secondary steel frame. At this stage we are dealing with realistic curvatures and panel sizes.
The geometry of Warsaw Museum for Polish Jews is imported in Grasshopper and evaluated. The boundary conditions dictated by the adjustable mould are in this case:

- maximum dimensions: 1000mm x 1000mm
- ultimate curvature in formwork: 1.5m

The result is 249 panels, from which 89% can be made with this type of formwork.

6.2.2. INTERACTION BETWEEN ACTUATORS AND COMPUTER MODEL

In an optimal solution a fluent streaming of data between computer and actuators is established. Both an accurate computer model and reliable actuator operation are needed to reach this optimum. The word 'reliable' is key in this section.

As described in the previous section we are able to stream data from the generative model as text file. We will now extend the generative model started in the previous chapter. After selecting a specific panel, it is extracted and optimally positioned; meaning as horizontal as possible.(fig.6.6) This minimizes the maximal movement out of plane and thus the amount of concrete poured under inclination.
Next a grid, representing the actuators, is projected on the panel. With the help of the command - *line with start point and direction*- a set of lines is constructed with starting point on the surface and end point on a horizontal plane underneath the free form surface. Each line in the set has a unique length representing the position of each actuator in z-direction (fig.6.5).

The output is utterly simple. A list of numbers- precision 0.001m- is streamed as a text file. The order of them numbers is related to the set-up of the actuators, so number 1 corresponds with actuator 1 and so on. Not completely true this last thing, as grasshopper considers 0 a number as well. To counter this we transform the list to correlate the numbers and actuators.
Once the generative computer model is built, it becomes feasible to attach any surface to it and extract the respective height of the actuators. The system is tested, approved and can be labeled both reliable and productive.

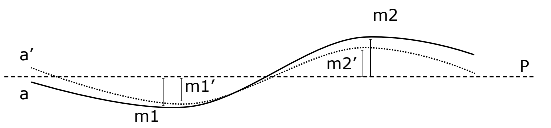


fig.6.6 The original curve a is rotated to its position a' to minimize the amount of displacement out of plane P. (m1'<m1 & m2'<m2)

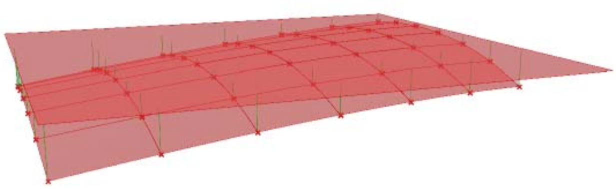


fig.6.5 Optimizing the element by reducing the displacement out of plane

Operating the actuators on the other hand behaves rather capricious. The actuators are dug up, midway the research period, and tested at numerous occasions and in different configurations. Before discussing the encountered defects, a brief explanation on the operation of the actuators is given.

The actuators and control unit is constructed following the specifications of Vollers/Rietbergen in the Faculty of Electronics at the TU Delft in 2008. (fig.6.8) It is originally designed for the use with plastics and the production of concrete panels in mind. Most important parts in the actuators are:

1. electro-motor
2. spindle
3. homing positioner
4. protecting frame
5. data retriever
6. threaded end

We have 36 actuators at our disposal. They are lined up in rows of 6, with the possibility to equip each line with 10 actuators. The configuration and operation is executed with Labview. A small interface panel allows different operation modes and alterations in settings. The following items can be regulated:

- **individual actuator positioning**: controls every actuator individually
- **general positioning**: the text file can be uploaded to provide the exact positioning of every actuator in a single instance.
- **speed**: in mm/s
- **height**: accuracy up to 1mm
- **speed error delay** : a build in safety to bridge the difference between the theoretical speed and the actual speed (fig.6.7)
- **time error delay**: a build in safety to bridge the difference between the a speed 0 and the maximum set speed(fig.6.7)
- **homing**: command to lower the actuators back to their original position, can be controlled individually or as a general command for the whole surface.

Ideally the set-up works fluent. Unfortunately extensive testing has brought up several defects. In order of importance they are;

- individual refusal: when attaching a text file as general position command, it often occurs that one or more actuators stagnate at there 0 position. This causes severe friction in the actuators when a flexible formwork is attached to them.

- proportional moving malfunctions: Due to individual differing friction in the spindle, no trust can be hold in the proportional moving of the spindles. This is most unhandy, as we will see later on.

Individual refusal is caused through loss of data when streaming from computer to actuators. Giel Hermans, designer of the configuration, also mentions lack of power as a possible reason for failure. Cause of the friction is an eccentric loading of the top end of the spindle. At first this has to be minimized by allowing the top of the spindle to move freely in all directions. So no fixed surface may be attached to all actuators at the same time. At most one actuator may be fixated to the above formwork.
Besides this basic principle it is necessary to lubricate the spindles from time to time with teflon spray to lower the motion friction and to keep away dirt and dust. But even with these two measures in mind, the proportional moving does not perform as intended.
A redesign of the actuators is required. With the help of a new part (spacer clip) more space is created in the vast part of the spindle. This allows larger movement at the top of the actuator. Together with this, the friction is lowered and the spindle runs smooth.

We can conclude that the electronic operation of the adjustable mould is still in its infancy. Much improvement lies ahead but progression is hindered by an enormous cost. We acknowledge the temporality of this system and its defects but find it important to describe the properties of an 'ideal' system based on the experience to enhance future development . In a later stage, manufacturer as for instance Festo, can enter the process and sponsor materials and know-how to build the perfect mould.

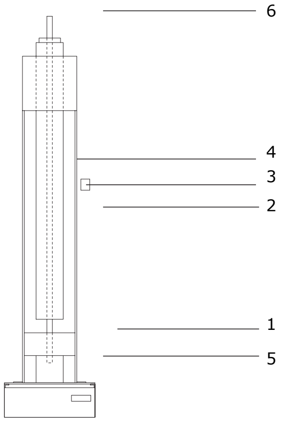


fig.6.8   The actuator and its various components

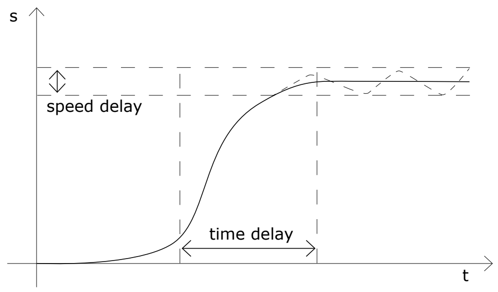


fig.6.7   The graph explaining the actiators speed and error delay

6.2.3. FROM 2D TO 3D

The great challenge of the new production technique lies in the transformation from 2D to 3D. The formwork is prepared and the concrete is poured in horizontal position. After short hardening and at the critical point in time, the formwork is pushed into a 3D shape. A sandwich-mould thus becomes redundant as the overall constant thickness is guarantied in the 2D stage. To make the technique accurate and present it as a working principle one needs to know how the surface behaves between 2D and 3D state. So what happens when a flat surface is deformed into a 3D surface?

The answer can be divided in three subjects;

- geometric & mathematical issues
- concrete behavior
- properties of the formwork

Only the first subject, will be discussed in depth here. The formwork and its abilities are researched by Koen Huyghe in chapter 7. The concrete behavior and desired properties are discussed chapter 5.

GEOMETRIC & MATHEMATICAL ISSUES
The influence of curvature on surfaces can be best explained with the help of a simplified single curved element. The overall elongation of the element is explained with the help of a simple setup described by ir. Roel Schipper. An arc (b) representing a concrete panel, extended over 2 floors, with varying curvature is compared with its flat variant (k). (fig. 6.9)
It becomes clear that with decreasing curvature-radius the elongation sharply increases. In the table (fig.6.10) we read R=11m gives an elongation of 6,4%. This corresponds with an actual extension of 40cm on top of the initial 640cm. Although this a rather extreme situation, neglecting the flattening effect caused by the stretch in the formwork, it points at a not negligible factor in the process.

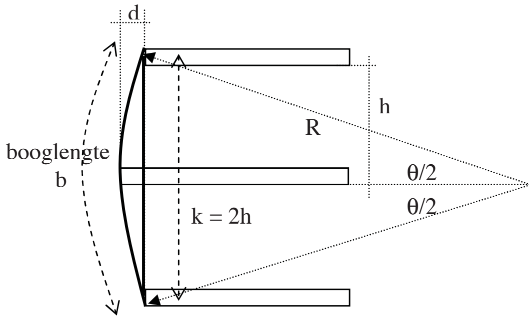


fig.6.9   Scheme representing a concrete panel extended over two floors.

To detect the issues involved we focus on the geometric aspects. The approach in this section searches for a convincing method to transform the free form surfaces into planar surfaces.
The 3D version is the starting point and the planar surface is in demand. What happens in between is the question at hand. Three different techniques are proposed:

- flattening
- projected planar
- no deformation

Their pros and cons are considered and linked to the production set-up to evaluate their potencies.

FLATTENING
In geometry developable and non-devevopable surfaces are distinguished. Single curved objects, for instance a cylinder, belong to the first group and can be developed into a planar surface. Double-curved surfaces, for instance a sphere, can not be developed straight away. Thanks to modern techniques they can be estimated. This type of technique is widely applied in ship design, where double curved elements are constructed out of flat steel sheets. Another industry benefitting from this is shoe-industry. Textiles, leathers,... are cut out in 2D and mounted as free form surfaces. Important to mention is that not every free form surface can be flattened in one part, as the strains become to big. A split in separate parts is then inevitable.

d	**[m]**	**0,10**	**0,20**	**0,30**	**0,40**	**0,50**	**0,60**	**0,70**	**0,80**	**0,90**	**1,00**
k	[m]	6,40	6,40	6,40	6,40	6,40	6,40	6,40	6,40	6,40	6,40
R	[m]	103	51	34	26	21	18	15	14	12	11
omtrek	[m]	644	323	216	163	132	111	96	85	77	71
hoek □	[°]	3,6	7,2	10,7	14,3	17,8	21,2	24,7	28,1	31,4	34,7
boog b	[m]	6,40	6,42	6,44	6,47	6,50	6,55	6,60	6,66	6,73	6,81
verlenging	[‰]	0,7	2,6	5,8	10,4	16,2	23,3	31,6	41,2	51,9	63,9

fig.6.10   Table showing the relationship between cruvature radius and elongation.

Rhinoceros comes with a plug-in named *squish* which estimates the flattening of free form surfaces. It has additional settings to control the way it flattens surfaces:

- stiff boundary: yes/no
- deformation = free/stretch mostly/stretch only/ compress mostly/ compress only/
- material: floppy/rigid
- decorate: yes/no
- outside: up/down

A free form surface, with a rectangular boundary (in top view) of 2400mm x 1800mm is studied. We foresee a free movement - stretch/ compression - of the formwork and are focusing on the flattening of an abstract concrete surface to find an outline of the panel that can be positioned on the 2D formwork later.
The used settings are;

- stiff boundary: yes
- deformation: compress only - aims at minimal expansion as possible when the 2D pattern is deformed into the 3D shape. This is necessary as we work with concrete that allows almost non tension stresses.

Evaluation of the flattening (fig.6.12) tells us more on the transformation that took place:

- new length of edges: 2402mm x 1809mm
- new area of surface: + 37 mm²
- compression average & maximum: 1.7
- stretching average & maximum: 1.2

This method approximates the behavior of the plane the best. In practice this method can be applied by projecting the flattened shape with the help of a beamer on the 2D formwork.
The deviations compared to the initial plane are rather low. Next to that several physical tests showed that the total error created with formwork, actuators and edge positioning grows bigger than the error in neglecting the shape deviation. Thus the question presents itself if the small deviations may be neglected. Therefore a simpler projection-method is researched.

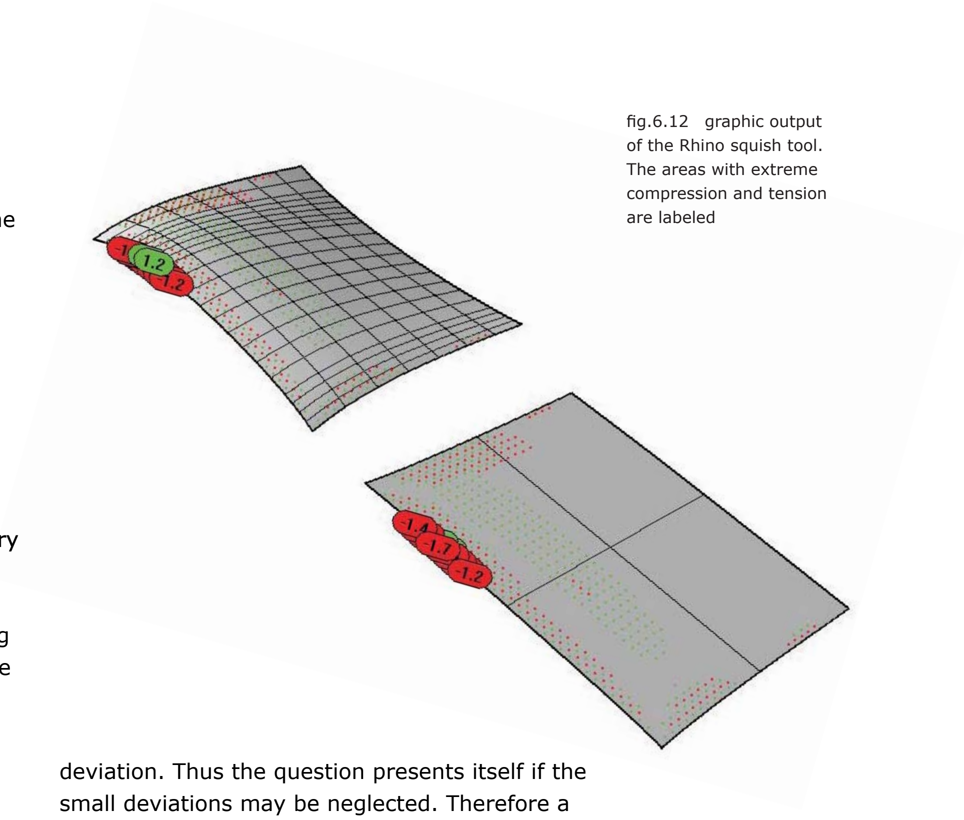


fig.6.12 graphic output of the Rhino squish tool. The areas with extreme compression and tension are labeled

PROJECTION
A second way to interpret the deformation is to start from a projection. A free form surface is projected along on axes onto a horizontal plane. The change in dimensions (edge length, area,..) is neglected. This method again foresees a free deformation inside the formwork and in addition to this a substantial loading of the unhardened concrete. Tests will reveal the feasibility of the additional loading of the fresh concrete and measuring the panels can take away doubts concerning tolerances.

Several test have been performed to check whether this method works or not. The deviations between computer model and actual panels are minimal. For the smaller test samples measuring 1m x 1m the largest deviation was only 4mm. The results are promising but to clear all doubts we need to scale up the panel dimensions.

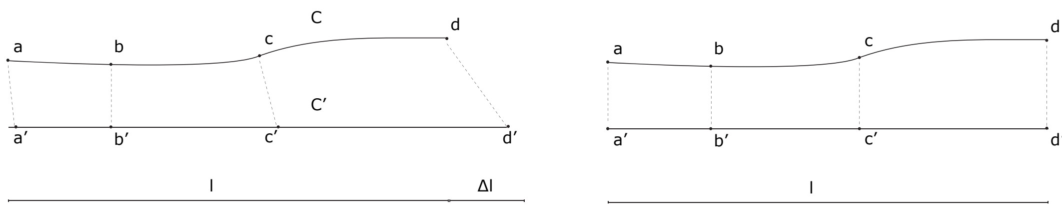


fig.6.11 (l) sketch illustrating the elongation of a flattened curve C′

fig.6.13 (r) sketch illustrating the projection of a curve

NO DEFORMATION
The third method that can describe the 2D-3D transformation is an outsider. It goes against the idea of switching from planar to free form surface. For completeness and acknowledging its potency it is mentioned. The process is simplified here and the transformation part is canceled. The actuators are brought in position, the edges are attached and the formwork is filled with a stable concrete mix. In this solution the exact position of the edges is extracted from the computer model and thus no dimension error is present. During discussions with Jan Dekkers, CEO of Hurks beton, it was brought up as an alternative.

Against accurate dimensions and no positioning errors, stands a possible inconstant concrete thickness. This does not have to be a problem, especially when the inside surface of the panels has no strict demands. A large panel (2400mm x 1800mm) will be constructed at Hurks according to this principle

EVALUATION
The criteria to evaluate these three solutions are:

- dimension accuracy
- edge accuracy
- constant thickness of concrete
- possibility of cracks in concrete
- chance of errors on site

The criteria are listed below and graded from 1 (negative) to 5 (positive)

	dimension accuracy	edge accuracy	constant thickness	cracks occuring	errors on site	total
flattening	4	2	4	3	3	16
projection	2	3	4	3	3	18
no deformation	5	5	3	4	4	21

fig.6.14 evaluation of the various options.

6.2.4. POSITIONING & REFERENCE SYSTEM

Deforming the geometry to planar surfaces and back to 3D is one thing, controlling their exact position on the actuator field is another. Clearly the positioning is related to the formwork that on his turn is related to the actuators. The solution of a reference system and a following position method evolves out of the actuators x & y position. They are the only vast elements of the mould.

FORMWORK POSITIONING
Based on the two methods described in the previous section; flattening and projection a study on positioning is undertaken.
Flattening leaves no control between 2D and 3D state. A point in 2D (actuator midpoint for instance) is moved under deformation to another X,Y and Z location. The start and end point are both known but the movement in between is differently for each point on the surface. An error is inevitable.
Dr. Karel Vollers suggest a restraint line (set of actuators) that keeps the formwork in position. This would create additional stresses but no test has been done so far to prove this idea.

The projection method makes positioning much easier. The z-values of the actuators can directly be extracted from the generative model. The position of the panel is then derived. Possibly a larger panel needs to be used as projection base to ensure correct curvature in the panel. Although the projection errors are present here, it might work for several types of elements.
We propose the following solution. Only a single point of the formwork will be fixed right above an actuator and serve as a reference point (with zero degrees of freedom), his two adjacent edges will have a degree of freedom according to their proper X or Y orientation and the other two edges remain freely positioned on the actuators. (fig.6.15)
By using this technique the formwork undergoes a controlled deformation from its 2D to its final 3D position.

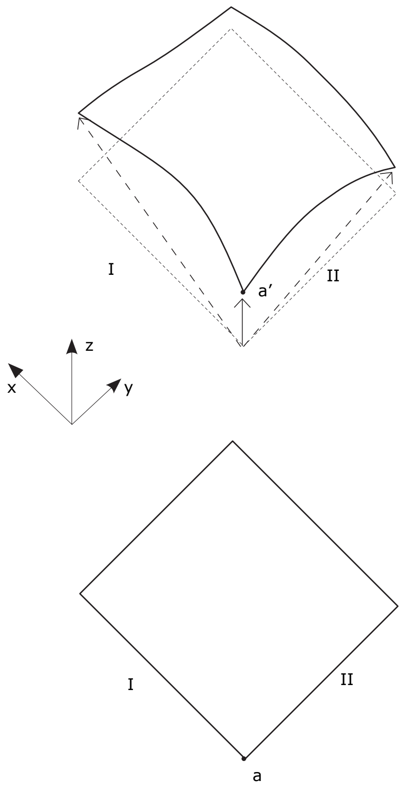


fig.6.15 Illustration of the fixed point a and two edges I and II that can freely move over the X (I) and Y(II) direction.

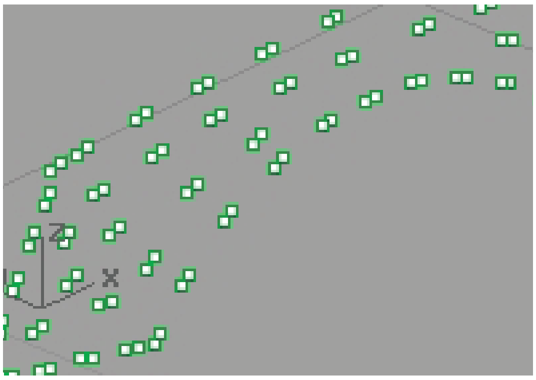


fig.6.16 example of Rhinophoto. The green dots represent the according marks on the actual surface.

6.3. MEASURING AND TOLERANCES

A persuasive production technique can present strict tolerances. They can only be established through extensive testing. The physical samples we created are not sufficient to describe meaningful tolerances yet. However, they can indicate an order in which deviations are expected. Also it is vital to think about methods to measure physical models and compare them with the initial geometry in the computer. Simple properties (e.g. edge’s length) can be evaluated manually. When it comes to curvature and overall dimensions (e.g. area, volume) we need computational aid to evaluate them properly. Photogrammetry and 3D scanning are two techniques suitable to deal with this. They both allow relative quick digital replication of the physical model.

6.3.1. PHOTOGRAMMETRY

Photogrammetry is a digitizing technique that uses photographs as the fundamental medium for measuring surfaces. It extracts information from target points applied onto the surface and uses it as a reference system for reconstructing the surface by triangulation or point clouds. Evidentially the quality of photographs determines the accuracy of the result. For instance highly reflective materials can cause errors due to the reflected image inside the photograph and your camera needs to be calibrated properly to avoid distortion.

Rhinophoto (fig.6.16), provides an easy setup for this technique. The software calibrates your camera automatically and generates the correct target point to attach onto your surface. When the pictures are taken, they are uploaded into Rhino and a 3d point cloud is formed that can be altered into a surface with standard commands.

6.3.2. 3D SCANNING

The purpose of a 3D scanner is usually to create a point cloud of geometric samples on the surface of the subject. These points can then be used to extrapolate the shape of the objects.

3D scanners are very analogous to cameras. Like cameras, they have a cone-like field of view, and like cameras, they can only collect information about surfaces that are not obscured. While a camera collects color information about surfaces within its field of view, 3D scanners collect distance information about surfaces within its field of view. The "picture" produced by a 3D scanner describes the distance to a surface at each point in the picture. If a spherical coordinate system (fig.6.17) is defined in which the scanner is the origin and the vector out from the front of the scanner is φ=0 and θ=0, then each point in the picture is associated with a φ and θ. Together with distance, which corresponds to the r component, these spherical coordinates fully describe the three dimensional position of each point in the picture, in a local coordinate system relative to the scanner.

For most situations, a single scan will not produce a complete model of the subject. Multiple scans, even hundreds, from many different directions are usually required to obtain information about all sides of the subject. These scans have to be brought in a common reference system, a process that is usually called alignment or registration, and then merged to create a complete model. This whole process, going from the single range map to the whole model, is usually known as the 3D scanning pipeline.

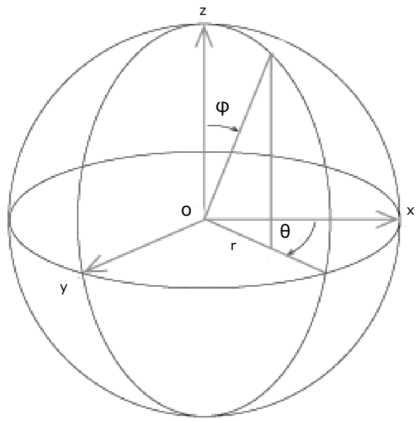


fig.6.17 illustrating the spherical coordinate system

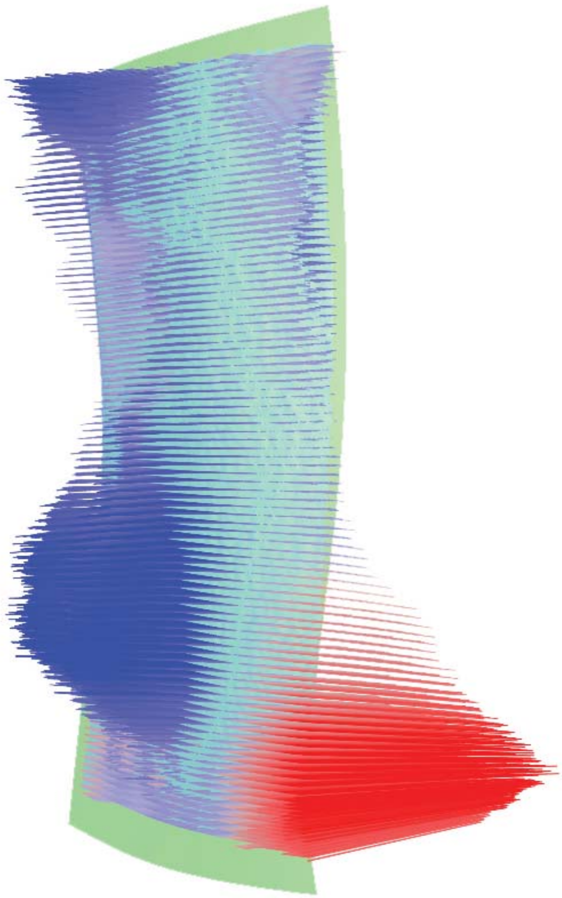


fig.6.18 illustrating the deviation of two elements. scale x 1000

As a case study we decided to 3D scan one of the produced elements to judge whether or not we fabricated the actual digital model. We chose to compare just the top surface of the selected panel since creating a solid volume is still far more complex than generating a single surface. First our concrete element was placed in front of the 3D scanner and a 'picture' was taken. Because of the laser process we encountered some distortion at the edge of our element (fig.6.19). This is apparently always the case. So an offset of 50 mm inwards now determines our focus area.

As noticed the 3d scanned model is highly accurate. Bad compacting of the concrete makes that surface panel is not smooth. The original virtual model however has an infinitely smooth surface. So a first tolerance is built in to rule out this difference in accuracy. Next the original virtual model and the 3d scanned model need to be aligned to each other to start the analysis. This alignment is achieved by pointing out 3 reference points on each of the surfaces and an algorithms aligns the two surfaces. (fig.6.20) At this point the Rapidform software is able to compare both surfaces. There was only an average deviation of 3 mm with a maximum of 12mm (fig.6.18). This maximum deviation value was expected due to an error during fabrication.

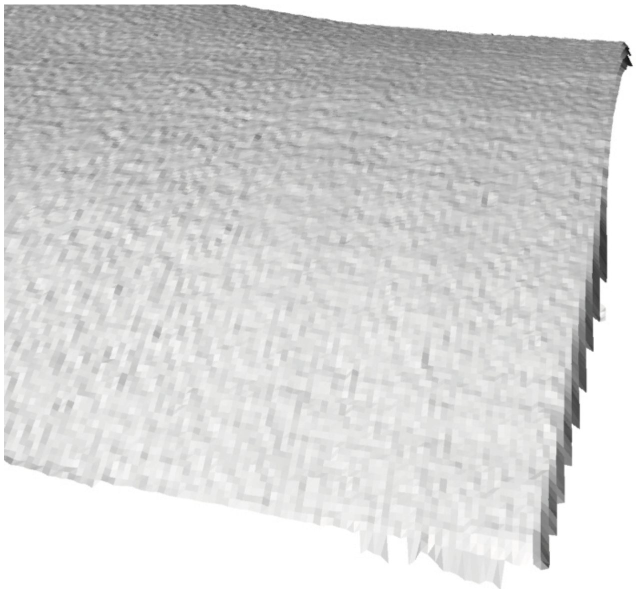


fig.6.19   edge distortion

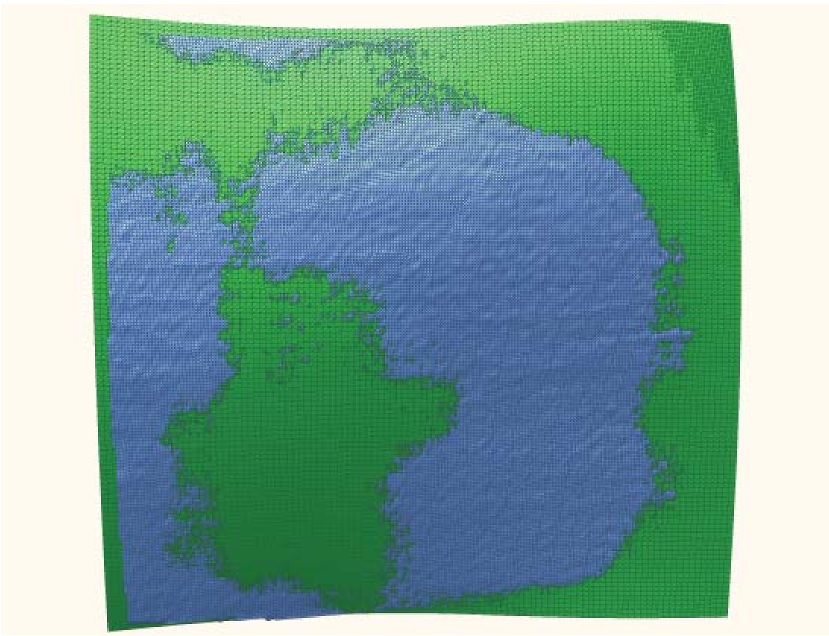


fig.6.20   aligning two surfaces

6.4. CONCLUDING REMARKS

As mentioned above the analysis tool in Rhino Grasshopper can be labeled reliable and efficient. During theMaster thesis period period it served its purpose. Further development of this tool would include an even more advanced mesh generation and could incorporate an optimization script to adapt the given geometry instantly at critical points. (e.g. extreme small curvature)

With access to a suitable, stable concrete mixture the ‘no deformation approach’ is considered the most favorable as no size deviations nor loading of the unhardened concrete occurs. For smaller elements (1000mm x 1000mm), projection flattening can be used as an alternative to the first method. The deviations then remain within a reasonable range as long as the panels size and minimum curvature are small.

3D scanning is the most optimal method to evaluate fabricated panels. The ease and accuracy are superior and it will enable future researchers to come up with a new set of tolerances in double curved panels.

7. PRODUCT DEVELOPMENT (Koen Huyghe)

*"I believe that quality level is determined primarily by the actual design of the product itself, not by quality control in the production process" (*Hideo Sugiura)

fig.7.1 rigid carved formwork

7.1. INTRODUCTION

The formwork is just a small part in the production technique, but holds the key to its success. Its paradoxical function: being flexible and stiff at the same time prevents a straightforward solution. This requirement is the key of my research and will be elaborated in this chapter.

As the underlying concept is already described in the patent, analysis of its functioning and parts makes more sense than to come up with a complete new system. It is also expressed by Dr. Vollers that an evolution and optimization of the glass principle should be the focus. The approach taken in this optimization process is best described with the expression: Reverse Engineering.

Reverse engineering (RE) is the process of discovering the technological principles of a device, object or system through analysis of its structure, function and operation. It often involves taking something apart and analyzing its workings in detail to be used in maintenance, or to try to make a new device or program that does the same thing without copying anything from the original.

The principle of the glass production and the version in the concrete patent are based on the same idea. The 'formwork' for the glass process is constructed out of bear steel rods, supporting the glass sheet. Once in the oven, the sheet is heated and at the exact moment in time, the supported sheet is lowered and sags over a secondary set of supports that shape a predetermined free form surface. Glass is a 'clean' material in a way that a vast sample is imported in the oven. The glass is then carefully heated, where it looses its stiffness but not its bounding. Once deformed in its new shape, it is cooled down and it regains its original stiffness. This technique works for glass but is never displayed successful with concrete. Therefore, interpretations and modifications of the system and its components are considered from the beginning.

7.2. FORMWORK DEVELOPMENT

The development of the formwork is supported by numerous physical samples produced during the research period. Each of them is tested, evaluated and later on optimized/dismissed. The following types of formwork evolved;

- reinforced flexible formwork
- restrained flexible formwork
- rigid carved formwork

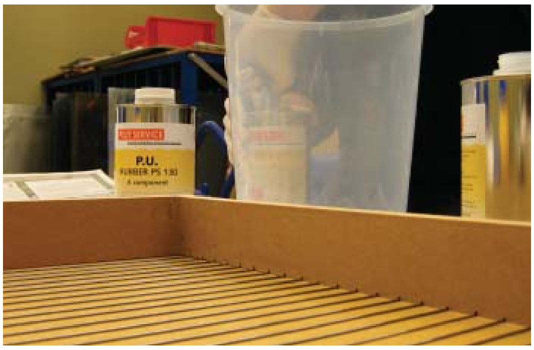
7.2.1. REINFORCED FLEXIBLE FORMWORK

As a first attempt, a small (450mm x 450mm) flexible formwork (formwork A) is constructed to test the adaptation of the glass principle. Following to that and with the remarks of the first sample in mind, a mid-size formwork (600mm x 1000m, formwork B) is produced.

FORMWORK A

With the deformation procedure of the glass setup in mind, an adapted setup is constructed. A flexible rubber (PU) acts as bottom of the formwork and holds the fresh concrete. As few stiffness is present in the polyurethane, reinforcement is necessary to ensure the load bearing abilities of the formwork. The assessment of required stiffness and flexibility is the trickiest part in this type of formwork. The fresh concrete has a substantial dead weight but no stiffness yet. To withstand the weight of the concrete the formwork is supported by embedded steel rods. On the other hand a certain flexibility has to remain in the formwork as it is deformed later in a free form shape. The rods will individually bend but as a whole establish sufficient support to hold the concrete's weight. A worksheet in Excel, helps to converge both requirements. Based on a simple beam-model, it is possible to calculate the resulting bending under dead load of each stiffening rod. The following parameters can be altered;

- **span** of the stiffening rods and thus the distance in between deflection takes place
- **E-value** or Young's modulus indicating the resistance to deformation of the rods and the rubber
- **diameter** of the stiffening rods
- **spacing** of the stiffening rods



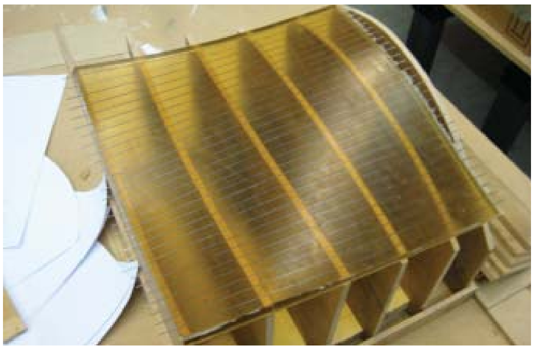


fig.7.2 top left; stiffening rods embedded at the bottom side of the contra mould

fig.7.3 bottom left; pouring from the PU from one corner

fig.7.4 top right; finished formwork on the free form surface

fig.7.5 bottom right; polystyrene edge in 2D state and application of the release agent

The chosen properties of the formwork are;

dimensions	450 x 450 x 12	mm
PU - shore 30	14	mm
span	100	mm
spacing of stiffening rods	10	mm
diameter of stiffening rods	12	mm
static plywood support	12	mm

A contra mould is constructed from wood. The stiffening rods are positioned at the bottom. They will be enclosed with a thin layer of PU. The wood is enameled to prevent the PU from sticking to it. The PU is a two component rubber with a mix-ratio 1/1. Pouring of the PU happens from the corner inwards to dismiss air bubbles. (fig.7.1 & fig.7.2) The PU is released from the mould after 24 hours and tests with concrete are performed.

The results are suprisingly good. The two requirements; overall flexibility & rigidity in the secondary direction are established. Several concrete samples are cast on this formwork.

Considering only the formwork we can conclude;

- PU can be applied as a surface material as no adhesion of the concrete occurs. Re-usability of the formwork is an important criteria. After 4 samples, the rubber remain unaffected

- the stiffening rods, positioned on the bottom side of the formwork, have the tendency to detach after multiple test. Deeper embedding is necessary.

- intense curvature of the supports result in hovering of one corner. The reinforcement is thus too stiff here. However it must be mentioned that the curvature radius of the surface reaches an extreme value of 1.2 m. This magnitude is rather unusual for building envelops.

A simple edge configuration is used. In fresh state, the concrete is bordered with a PS (polystyrene) or wooden edge. When lowered, the edge is removed. Because the critical point of the hardening concrete has not been determined yet, the resulting edges are distorted.

FORMWORK B

A bigger mould based on the same principle is constructed. The goal is to test the critical point of deformation determined with the experimental tests (section 5.3.2). To have better control over the edges of the panel then with formwork A, a profile is embedded in the mould. This complicates the construction of the mould but facilitates the deformation to 3D state. Also a first attempt to control the position of the element in deformed state is elaborated.

The properties of the formwork are;

dimensions	1000 x 600 x 10	mm
silicon - shore 10	10	mm
span	100	mm
spacing of stiffening rods	15	mm
diameter of stiffening rods	18	mm
static chipboard support lines	12	mm

The contra mould is again built up out of wood to keep the costs as low as possible. The shape of the formwork's bottom is derived with the help of the squish command in Rhino. (section 6.3.2) This means that the initial rectangular shape is slightly distorted. (fig.7.6) While constructing the mould, it became clear that the error in sawing the panels might be bigger than neglecting the deformation of the squished surface. Accurate sawing of a marginally curved element by hand is almost impossible. Next to that an additional error in transferring the printed surface to the wooden surface occurs. Only atomization and CAM-related techniques can dismiss these errors. Incorporating the shape deformation between 2D & 3D state does not ad up at this stage of the development. But for this formwork the errors are recognized and memorized for future improvement.

The mould is enameled and the reinforcement is fitted. (fig.7.7) To counter the previous ripping of reinforcement, the rods are embedded deeper.

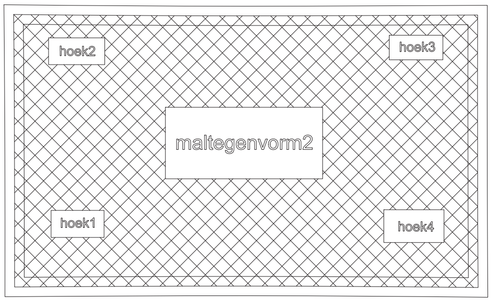


fig.7.6 top right; squished surface print out

The edges and openings of the contra-mould are sealed with silicon sealant to prevent dripping of the fluid silicon. (fig.7.8)

Again the mould is filled from the corner inwards. 10 liter of orange silicon flows into the edge profile. The sagging of the reinforcement under dead-weight is countered with an additional support in the middle. Looking back a hanging support would do a better job.

After two days, the hardened silicon is released from the contra-mould. The outcome is a very smooth surface and an accurate edge profile. The reinforcement is not sufficiently covered in the middle, due to deformation of the stiffening rods. The immense cost of the silicon rubber (24€/kg) forced us to purchase less silicon than initially calculated.
At the same time as the formwork the support structure is constructed. The wooden line supports are connected to a base panel with the help of custom made steel brackets. Spaced 100mm they describe a proper free form surface. The idea behind the positioning is straightforward: the location of the 4 corners is extracted from the computer model and indicated on the supports. 4 guiding brackets are constructed and set at each corner to determine the final position of the formwork in 3D state. (fig.7.9) The formwork will be lowered with the help of a crane to simulate the workflow in an actual production process. (fig.7.10)

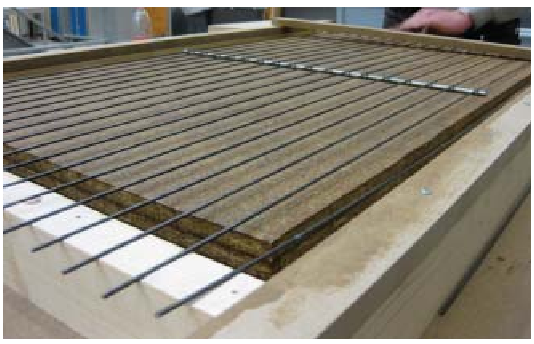


fig.7.7 left; layout of the stiffening rods with a middle support to counter deflection under dead weight

fig.7.8 right; embedded rods sealed with silicon sealant

Several tests with formwork B gave us the following insights;

- The shore value (indicating resistance against deformation for rubbers) of silicon - 10 - is too low for the purpose. In between the reinforcement sagging occurs. This can not be tolerated, because it will negatively affect the smoothness of the concrete's surface.
- The lack of internal stiffness in the silicon also affects the edges. In 3D-state the weight of the sloped semi-hardened concrete produces buckling of the edges. Deviations in the panel are the result and can not be accepted.
- The edge profile looks promising. Several panels are shaped in this mould and came out smooth. By simplifying the setup and embedding the profile in the mould few errors can be made. A great disadvantage is the uniqueness of the mould. Only numerous replication of the same element can make this principle pay off. But we are looking for an adjustable edge configuration.
- Fitting the formwork in the positioning brackets works fine in this setup. This is considered a good starting point to connect formwork and supports. But again improvement is necessary because this is a one-panel solution that allows no shape adjustments.
- Silicon rubber as formwork material is not as suitable as PU. The higher possible level in detail of silicon rubber is higher than the level of detail of PU, does not counter balance the cost difference. (24€/kg vs 14€/kg) The concrete elements only necessitate a limited level of detail, especially in the begin stage.

7.2.2. RESTRAINED FLEXIBLE FORMWORK

The high costs and the amount of labour related to mould construction made me reflect on alternative solutions that originate from standard materials. The idea of a homogenous semi-rigid formwork instead of a complicated composite is the first step in this new approach. The shift in approach is also enhanced by the introduction of the adjustable pin bed. Instead of having line supports, a point grid now shapes the 3D surface. Although the initially described process was already equipped with these adjustable pins and knowing that the wooden line supports were abstracted actuators, new ideas emerged when testing the pin bed setup.

Instead of integrating reinforcements in primary and secondary supports, the concept of a plate-like support is elaborated. A single semi-rigid material will be connected to the actuators and act as formwork bottom at the same time. In this concept, simplification, standardization and low-costs are key aspects. Before setting up a complete surface (800mm x 800mm) a sample piece is constructed to test the load bearing capacity and the connection to the pins.

A standard support foot that allows rotation around two axis' is purchased. It is mounted directly onto the actuator with help of a threaded connector. The flat upper side, supporting the formwork, is modified and equipped with thread screw at the inside. A bolt sealed with an O-ring ensures the connection of formwork and actuator. (fig.7.11) A 3 mm gap at each side of the protrusion allows in plane sliding of the formwork. The formwork itself is a rubber slab (14mm) with shore 60. Holes, 150mm in grid, are drilled and milled to hold the O-ring. The test setup is deformed in different ways to evaluate it performance under curvature. The drilled holes are widened to allow more movement in deformed state.

fig.7.9 left; steel positioning bracket mounted on the wooden support lines

fig.7.10 right; lifting of the formwork and lowering device with a crane

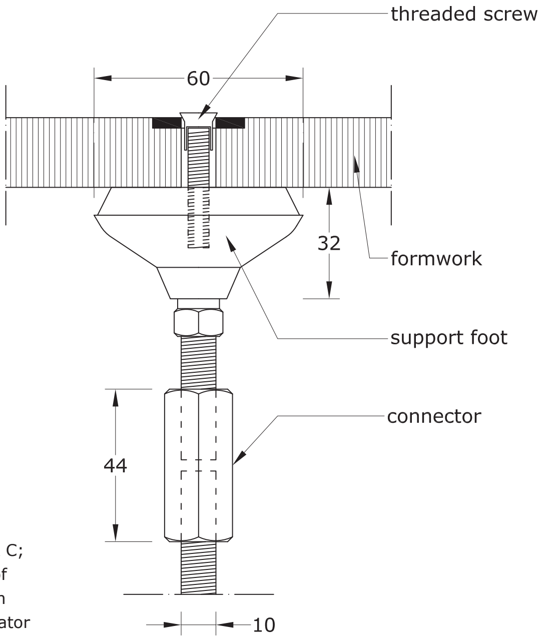


fig.7.11 formwork C; technical drawing of connection between formwork and actuator

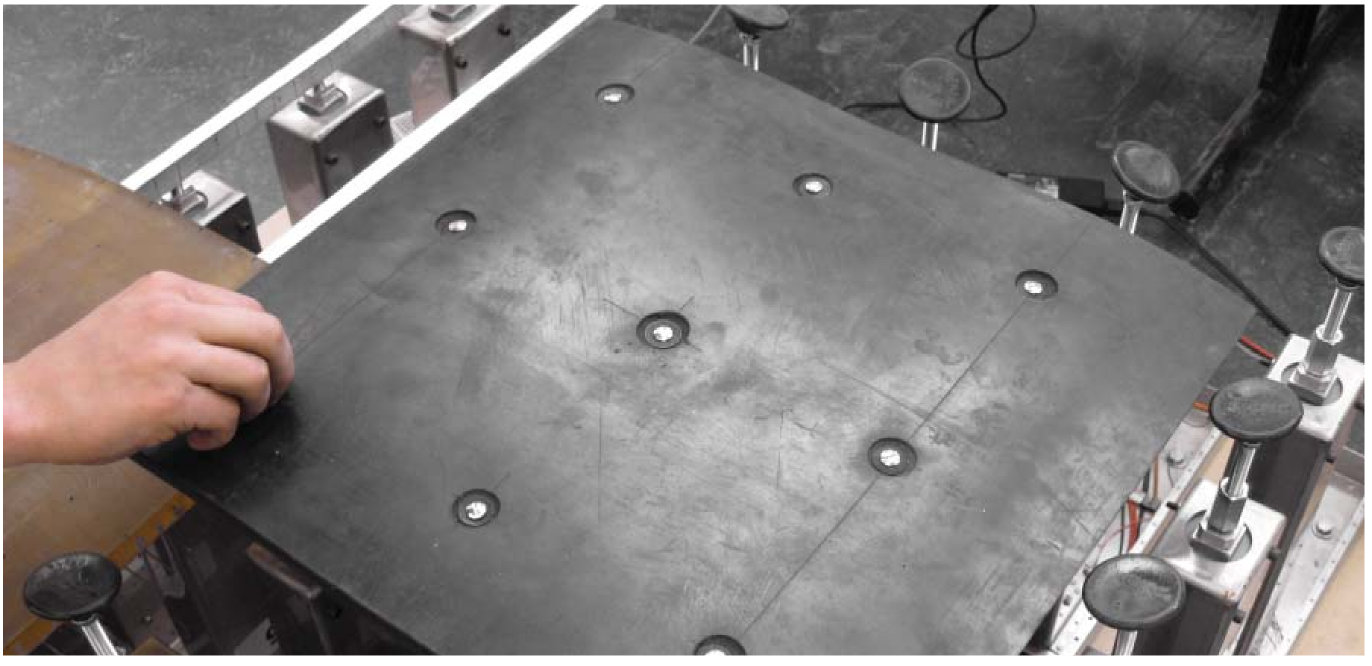
FORMWORK C
Once the sample is approved, a complete slab (800mm x 800mm) is prepared and attached to the actuators. Rubber strips form the edges. (fig.7.13) They are cut to size and pasted onto the rubber with adhesive tape. The formwork's properties are;

dimensions	800 x 800 x 14	mm
rubber - shore 60	12	mm
spacing of actuators	150	mm
edges - rubber strips	30 x 20	mm

Several panels are shaped with this type of formwork. Following conclusions can be drawn;

- fluency of the panel's curvature is good, however a small deformation arises around the connections. The area between two connections wants to stretch when curvature increases. This is due to the elongation of the surface under curvature.
- the internal stiffness of the rubber slab prevents free elongation/shortening under curvature. This is problematic as it puts a lot of pressure on the actuator mechanisms. The friction of the spindle is increased and possible failure of actuators occurs. This has to be prevented as much as possible!
- The wax filling of the drilled holes sticks onto the hardened panel, leaving an imprint at the surface. This might not be desirable for certain applications.
- The pasted edges perform well in the tests. Sometimes the adhesion of the tape is rather low due to dust or dirt on the formwork. The biggest advantage of this solution is an easy mounting and the variety in shapes that can be formed this way. The edges of the resulting panels are all directed normal to the surface. No profile is applied yet and increase in concrete thickness might produce the same buckling of the rubber as seen with formwork B.

fig.7.12 test setup examining the possibilities of formwork C



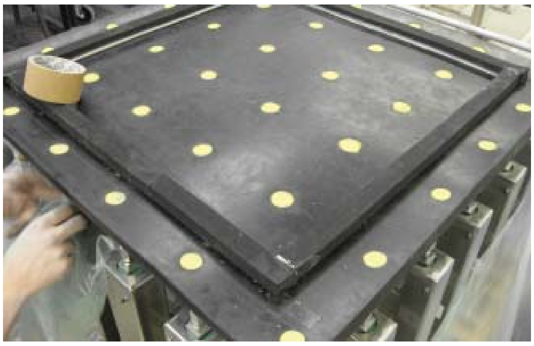


fig.7.13 complete setup including flexible edges and wax fillers around connection area

The tests brought up new possibilities. The idea of a plate-like support is evaluated positively. However, a fixed connection of the formwork on all actuators is not necessary and causes too much stress on the electro-motors and spindles. The elongation/shortening of the formwork may not be restrained to ensure the life-time of the actuators and to generate smooth surface curvature of the elements.

7.2.3. RIGID CARVED FORMWORK

At this point the progression of the research was presented to Jan Dekker, CEO of Hurks betongroep and participant in the patent. From his part, a preference for wood as base material for the formwork was articulated. He argued that the concrete industry is used to process wood in many ways to build moulds and that it is a cheap and omnipresent material.

To make wood suitable for taking on free form shapes a weakening of the material is necessary. The idea of weakening a solid material was already tested on the solid rubber slab before and turned out very effective in terms of increasing flexibility. Not much attention was given to this tryout until the meeting with Jan Dekker. The weakening idea is now applied to a wooden panel. Standardized one-directional weakened MDF panels are yet for sale in every home depot. They are carved at equal intervals in one direction to fit for instance around columns. This carving method is used as the basis for a new type of formwork; rigid carved formwork.

FORMWORK D

To enable free form deformation in a stiff wooden panel a carving test is undertaken. a MDF 9mm sheet is carved (3mm) in two directions to a depth of 6mm with spacing of 50mm. (fig.7.14) These incisions are applied at both sides of the panel, where the one side is offset 25mm compared to the other. By carving both sides, the panel becomes remarkably flexible without losing its bonding. To hold the concrete a stretchable thin rubber layer (3mm) is connected to it. This simple laminate delivers a fairly cheap but durable formwork. Also it can be manufactured easily by concrete factories themselves as they are used to work with wooden moulds. A setup for concrete testing on the adjustable mould is prepared. The properties of the formwork are;

dimensions	850 x 850 x 12	mm
MDF	9	mm
rubber	3	mm
spacing of actuators	150	mm
edges - rubber strips	30 x 20	mm
one edge profile	12	mm

The formwork is no longer rigidly connected to the actuators to prevent eccentric loading of the spindles and electromotors. Another reason is to minimize the chance in failure of the formwork. Often several actuators rise slower than the others. If connected rigidly, rupture of the formwork happens. To control the position of the formwork in relation to the actuators, the outer incisions at the bottom side are lined up with the actuators center points. The flexible edges of the formwork are also positioned on this 'reference' line and again put in place with the help of adhesive tape.

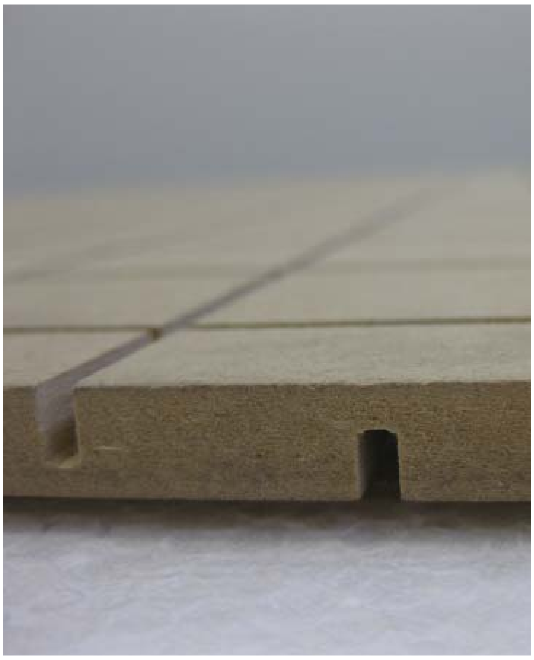


fig.7.14 detail of double sided two-way carved 9mm MDF sample

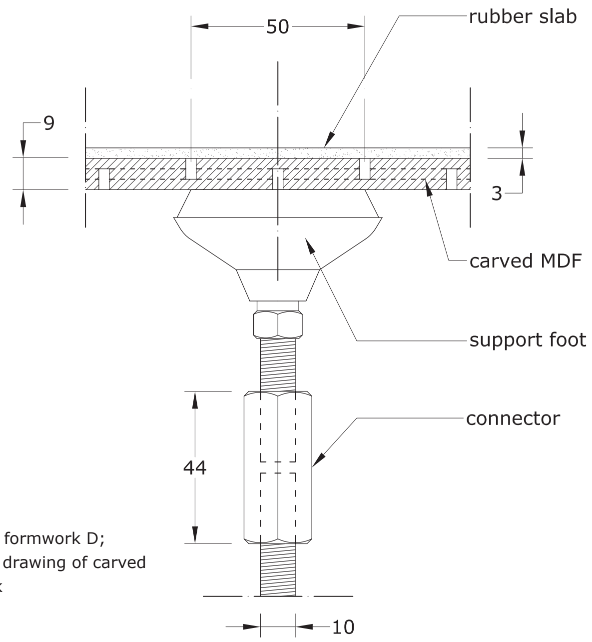


fig.7.15 formwork D; technical drawing of carved formwork

A set of two 200mm thick panels is cast in two periods. The mutual edge of the panels has a stepped profile. The connection between two independently and differently oriented cast panels is hereby tested. The Holcim mixture is used for its clean processing and interesting workability (smearing rather than pouring) Also a reinforcement mesh is pressed in the fresh concrete halfway filling the mould. Evaluation of formwork D revealed the following;

- The curvature of the panels is almost perfect. It is the first type of formwork that establishes a sufficient smooth upper surface. The concept of carving a solid stiff material generates the necessary smoothness of curvature, while the rubber layer levels out possible imprints of the squares. The idea of a laminate formwork is thus evaluated positively.
- The present curvature of the panel is in some areas too high, meaning that the formwork remains hovering above certain actuators under dead load of the concrete. (fig.7.16) This can be interpreted in three ways: the formwork is too stiff, the concrete load is too low or the demanded curvature radius is too small.

Because certain areas of the formwork were not at their intended positions at the time the hardening process initiated, the two panels did not line up correctly. It becomes clear in this stage of the development that the solution is at hand, but that accuracy and positioning of the formwork is not yet trustworthy.

7.3. EVALUATING THE FORMWORKS

The different proposals are listed and evaluated in fig.7.17 . Each formwork is tested by the list of criteria and valuated with a number from 0-5. Additionally, a factor is assigned to each criteria to assess its importance in the development. This factor is multiplied with the initial number after which all values are summed, resulting in a total score for each formwork. The criteria processing cost, material cost, surface accuracy and reusability are considered average

fig.7.16 formwork D in deformed state; several actuators to do not touch the formwork

				importancy factor							
				2	2	2	3	1	2		
	dimensions L x W x H	type of formwork		processing cost	material cost	surface accuracy	surface smoothnes	edge's accuracy	reusability		final score
formwork A	450 X 450 X 12	RFF		1	2	3	2	1	4		27
formwork B	1000 x 600 x 10	RFF		1	1	2	2	4	4		26
formwork C	850 x 850 x 14	RSFF		2	4	2	2	3	2		29
formwork D	850 x 850 x 9+3	RCF		3	4	4	4	3	2		41
topics are merited on a scale from 0-5 and multiplied with the priority factor. **RFF**= reinforced flexible formwork, **RSFF** = restrained flexible formwork, **RCF** = rigid carved formwork											

fig.7.17 evaluation of the formwork

important. The most defining criteria in this evaluation is the surface's smoothness. The least important is the edge's accuracy. The values for the criteria are mostly assigned through empirical judgement as no sound evaluation frame per criteria exists at the moment.
The material and processing cost is roughly calculated. And the surface's accuracy can be measured with the 3D-scanning technique described in (section 7.3.2)

Interpreting the evaluation table, one can conclude that formwork D is the most performative, especially in the area of surface smoothness, surface accuracy and material cost. The reusability of formwork D is rather low, as rupture of the MDF occurred several times in the test setups. The development of flexible adjustable edges is still in the begin stage. There is the belief that further development for an adjustable edge can only be meaningful if the problems with the formwork are solved.

Concluding it is accepted that RSFF, in this configuration, is not viable as too much pressure is exerted on the actuators, which are the most expensive component in the setup. In a good research climate, RFF could be reconfigured and elaborated towards a working principle. But due to higher costs, high mould preparation times and less accuracy it is dismissed and RCF formwork is chosen for further development.

7.4. OPTIMAL FORMWORK

Formwork D yet delivered satisfying results. The required smoothness in the surface's curvature is a boost for the research and a motivation to pursue this technique. The optimization of the rigid carved formwork will focus on three topics.

- calculation model
- reusability
- positioning

A calculation model assessing the deformation of the panel under an equally distributed load is a must to get rid of untouched actuator tops as seen in the previous experiments. They cause large inaccuracies in the hardened panels. Secondly, the reusability of the formwork must be improved to assure a longer life-span. Possibly the rough laminate solution can be upgraded. Finally, positioning of the formwork comes to the fore and needs a clear solution to produce accurate concrete panels. A first attempt to accomplish this is described.

7.4.1. CALCULATION MODEL

First of all the spacing of the actuators is reconsidered. Instead of 150mm, a spacing of 200 mm is proposed. So now, a larger formwork can be supported with the same amount of actuators.

With the help of FEM software, Diana, a calculation model to predict the deformation is constructed. The intention behind it is that the deformation of any wooden panel (e.g., MDF, plywood, chipboard) with a specific thickness and a specific incision depth and spacing can be calculated under predetermined load case (read: concrete thickness). Parameters in this setup are;

- thickness of the concrete layer (N/mm²)
- weight of the concrete (kg/m³)
- incision spacing (mm)
- incision depth (mm)
- Young's modulus (E) (N/mm²) of the wooden panel; orthotropic materials (plywood) can be divided in layers with different E-values
- weight of the wood (kg/m³)
- spacing of the actuators (mm)

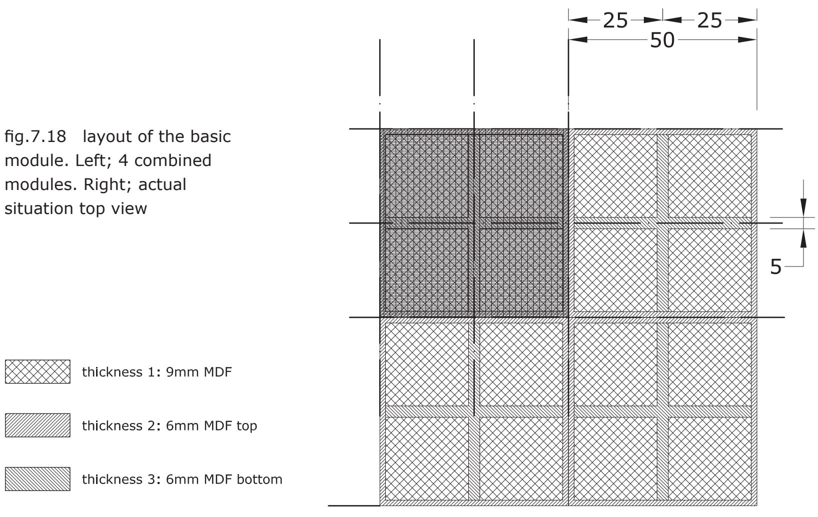
For completeness, it is mentioned that the contribution of the rubber slab (3mm) on top of the formwork is not taken into account. The principle is tested with a small (40mm x 40mm) MDF panel setup. The drawing part is done in rhino and later on imported in Diana. The incisions on both sides presented a modeling challenge. Knowing that at the end the carved areas (6mm) are assigned different geometric properties than the full areas (9mm), I deconstructed a single square (50mm x 50mm) in 4 modules. (fig.7.18) The three hatch types represent the three different thickness's of the panel. . The properties of the computational model are;

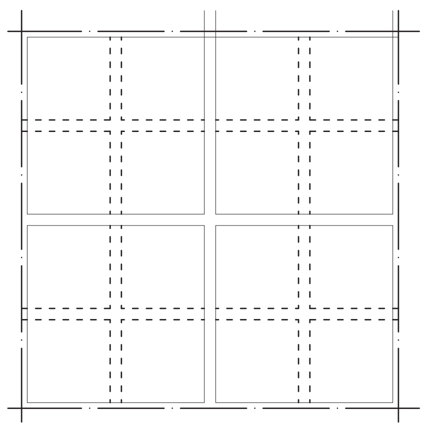
dimensions	400 x 400	mm
spacing of actuators	200 x 200	mm
thickness MDF	9	mm
thickness concrete	60	mm
incision depth	6	mm
incision spacing	50	mm
offset of the grid	25	mm
spacing of actuators	200 x 200	mm
Young's modulus MDF	2800	N/mm²
density MDF	800	kg/m³

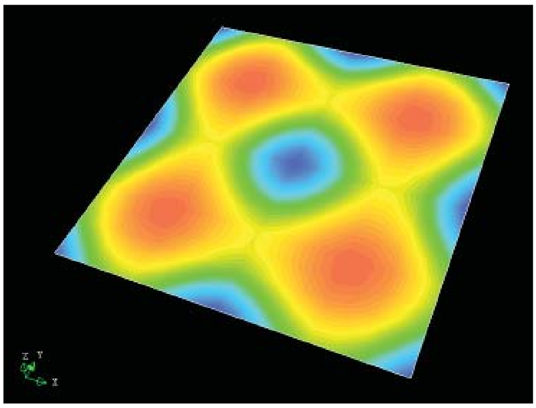
After importing the model in Diana, the above values are assigned. The trickiest part is determining a correct method to represent the incision area. With the help of mesh type; CQ40S, a valid representation is found. This mesh type has the possibility of layering the material. The MDF properties are then the above values and the incised part is represented by a Young's modulus of almost 0. Almost 0 because 0 would result in a fatal crash of the calculation. The .dat file is sorted, the load case is applied and the calculation is rendered. The graphic output is shown in fig.7.19 & fig.7.20. The deformation in between the actuators is clearly visualized. Interpretation of the numeric output learns that the maximum deformation is as small as 1,4mm. This a satisfying outcome and tells us that the weakened MDF plate

With a working principle set up, it becomes easy to alter the thickness of the concrete,

fig.7.18 layout of the basic module. Left; 4 combined modules. Right; actual situation top view







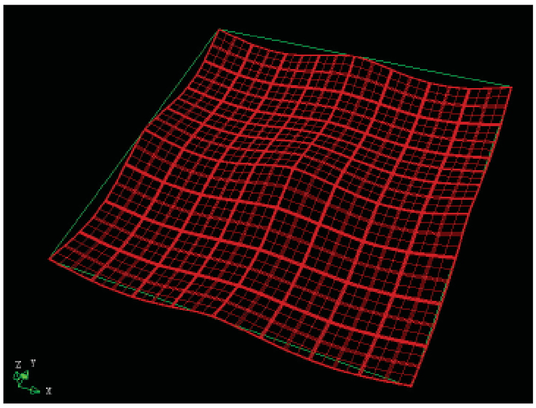


fig.7.19 right; shape deformation of carved formwork

fig.7.20 left; deformation of carved formwork in colour values

incision depth and material properties. Due to time shortage, this is not elaborated. In future developments this can be a starting point for further optimizing of the formwork. Next to the deformation under dead weight it is desirable to have a tool to disposal that calculates if the carved formwork touches all the actuators.

A start on the development of this tool is made, but incomplete at the moment of writing I will limit myself to its description. Optimally, a script runs through the setup and determines whether or not an actuator touches the formwork. If so, it recalculates the span made by the formwork. The calculation then starts again until the following actuator is touched. This is continued until the formwork sits on all actuators or until the deformation of the formwork halts. This iterative process is a challenging approach and difficult to set up. Besides the difficulty in constructing such a tool, one can question its relevance. Small physical samples applied to extreme curvatures can rapidly indicate areas in which a specific carved panel performs.

7.4.2. REUSABILITY

The rigid carved formwork turns out to be rather fragile in use. After several tests rupture and the MDF occurred. Next to that it became clear during the experiments that the improvised laminate of loosely connected MDF and rubber should be enhanced in a later stage. A solution for both issues is found in the development of an advanced laminate.

By filling the carved formwork with a soft rubber (PU or silicon) and adding an additional top layer with the same rubber at once, the formwork becomes more resistant to dirt and wearing while maintaining its excellent flexible behavior. A tryout to materialise this optimization is undertaken at the end of the research. The carved formwork is bordered and filled with Polyurethane rubber - shore 30. (fig.7.21) After 2 days the mould is released and the sample inspected. Some remarks;

- Every incision is filled completely with the rubber due to the excellent flow capacities of the PU.
- The sample seems to be 'lifted' minimally, as a thin layer of PU is present at the underside of the sample. By this, the whole sample is completely packed with a PU coat.
- When deforming the sample constriction of the PU in the carved areas occurs. This is adverse for proper functioning as formwork bottom. By increasing the top layer's thickness this shortcoming can be countered.
- The allowed level of deformation in the optimized sample is bigger than in the original sample. The PU contributes to the flexible behavior of the rigid carved formwork.

fig.7.21 rigid carved formwork enclosed with a thin PU layer

7.4.3. POSITIONING SYSTEM

To produce accurate panels, a smart but uncomplicated positioning system has to be attached to the formwork. The principle to obtain this, is already explained in section 7.2.4. The idea behind it is straightforward; by fixing a single corner point and only allow movement along the X-and Y-axis, starting in the fixed point, the elongation or shortening of the formwork is controlled. This idea is applied to the rigid carved formwork. The existing incised grid of the formwork is very opportune to guide the orthogonal movement of the formwork.

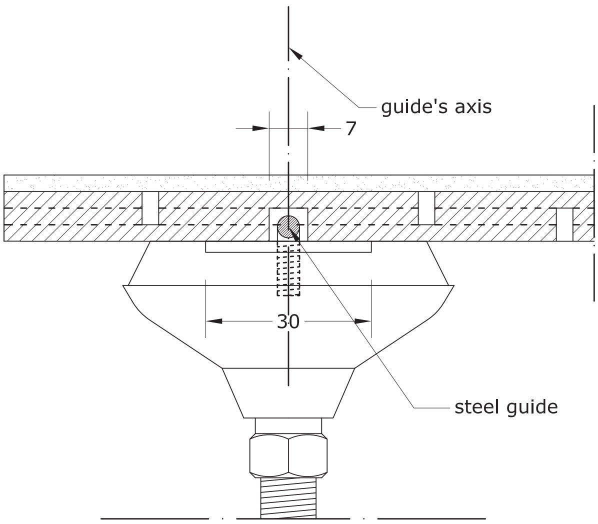
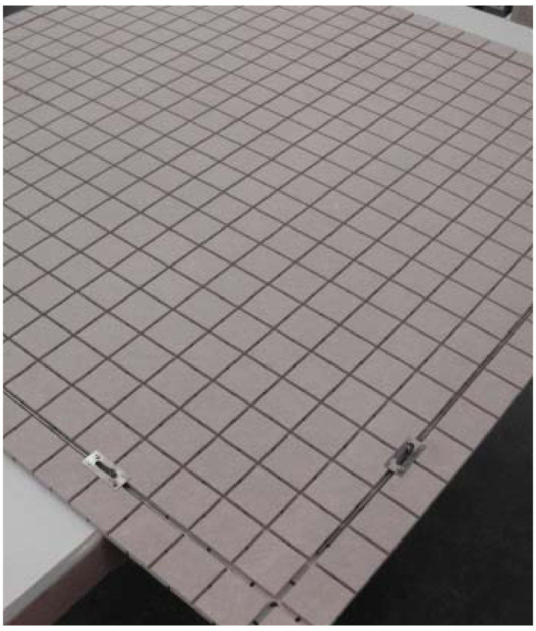


fig.7.22 detail of the embedded guide at the border of the formwork

A setup is prepared to test the principle. The most outer incision at the bottom side of the formwork is widened to 7mm. In here, a steel guide is inserted to ensure the orthogonal movement. Three short screw threads are welded to the guide at 200mm distance from each other. The free end of the thread is tapped in the respective support foot. A thin steel cover plate (30mm x 48mm) is mounted at the underside of the formwork to prevent the guide from 'derailing'. Next to that, the fixed point is connected to the corner actuator. Several surfaces are created to evaluate the positioning system. The most important are;

- The setup is convincing as both guides restrain the formwork in a simple but effective way.
- As the guides are rigidly connected to the actuators, only limited curvature radii can be reached. A future connection should operate as a roller nest for both the formwork and support feet.
- For now, there is still slack in the guides' position. A more advanced embedding of the steel rod can eliminate this.
- When producing multiple panels on the same formwork, one has to adjust the movements' origin and direction to each other. At this point it is unknown if this causes large dimension issues at the end.



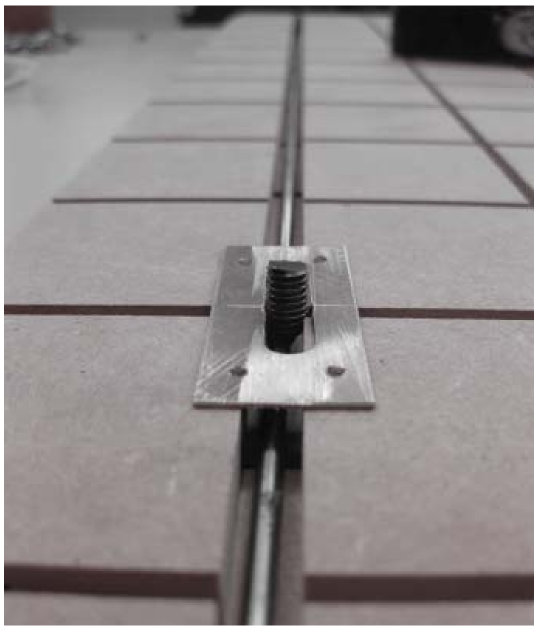


fig.7.23 left; mounted guides in X and Y direction

fig.7.24 right; mounted retaining bracket

7.5. CONCLUDING REMARKS

The emphasis in this chapter was on the development of a working solution for the formwork. The formwork is considered one of the most important components in the production process. Starting from the description in the patent and the experience gained with the glass process, several types of formwork are developed and tested extensively. The practical approach is the strength of this research and allows profound evaluation of the proposals. As a result of this approach, only a limited amount of proposals is researched. But each one of them is developed and materialized to its limits.

Formwork D, rigid carved formwork, is evaluated as the most suitable formwork for further application. The restrained flexible formwork does not qualify for further development and reinforced flexible formwork can lead to a working principle if someone persists in its maturation.

The principle of rigid carved formwork is chosen for further development as it returns a smooth surface with a very simple technique; carving of a rigid wooden plane. The formwork is thus easy to produce and cheap in its processing. Furthermore,it allows alterations in the carving's depth and spacing to obtain the desired level of flexibility for different surfaces.

A first set of improvements to RCF are undertaken. A calculation model returns the deformation between the supports under a certain concrete load. The description of a more advanced 'curvature-calculating' model is formulated to complete the pre-processing part of this production technique. Unfortunately, this last step is not at hand for now.
The reusability of the original RCF is fragile. A sound proposal to improve this, is by encasing the formwork with a thin Polyurethane layer. Next to enhanced reusability it allows more extreme deformations of the formwork.
The last improvement deals with the positioning of the formwork. The incised grid is used as starting point.

The next step in the development of the formwork is the introduction of adjustable edges connected to the formwork. They can be linked to the carved grid of carvings or evolve as a separate component.

8. DESIGN & MOCK-UP

"*instead of using the innovation process to come up with finished prototypes, the prototypes themselves drive the innovation process*"
(Michael Schrage)

fig.8.1   mould of mock-up1 at Hurks Beton in Veldhoven

8.1. INTRODUCTION

This chapter consists out of the description and evaluation of two full scale mock-ups. They can be seen as the materializing of the findings as described so far. The research that was conducted during the past months converges into the design and production of these elements in order to display the efficiency of the developed production system.

The geometry of both elements is again extracted from the Museum for the History of Polish Jews to reference to actual curvature.

8.2. MOCK-UP 1

8.2.1. DESCRIPTION AND RELEVANCE

This first mock-up represents a panel that can be structurally applied as in a sandwich construction. So far we only dealt with small elements (max 1200mm x 600mm) with a maximum thickness of 40mm.
The idea behind this panel is based on the warm facade principle. A warm facade has a thermal insulation layer applied directly to the outer surface of the building. The detail below shows the setup for this panel. Here two panels are attached to each other and a floor slab to form a rigid connection of building components. (fig.8.2)

Producing this entire sandwich construction is favorable but lies not within the reach of this Master's thesis period. We will therefore focus on the outer part of the sandwich construction to tackle the first scale related issues. A 1400mm by 2400mm panel will be produced.
We are no longer working within standardized sizes of building components now and the forces and weight of a 60 to 100 mm thick element increases the complexity of the production process. Because of this, edge profiles and detailed connections will be faded into the background. The evaluation will focus on the behavior of the formwork and the idea of casting in 3D.

Producing the element will take place on the grounds of Hurks Beton Groep for logistical and practical reasons.

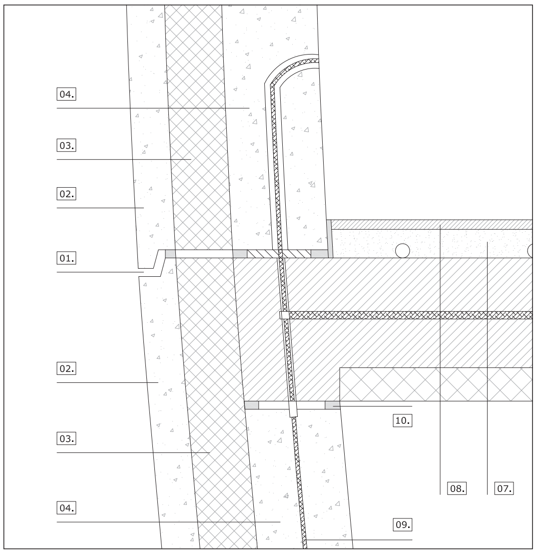


fig.8.2 representative detail

LEGENDE

01 voeg
voorzien van drie rubberen afsluitingen
vangt uitzettingen op
02 buitenschil, ECC beton
d 40 mm
03 isolatie
d 60 mm
04 binnenblad, ECC beton
d 100 mm
05 vloer als dragend element op geveldeel
06 leidingen

8.2.2. FORMWORK SETUP

The formwork is composed out of 3 components;

- 2 way grid structure
- plywood layer
- rubber layer

2 WAY GRID STRUCTURE
Since this will is the first attempt in producing a large scale element this try-out will not make use of an adjustable mould. Plans were drawn up to construct a manually adjustable mould out of RVS steel elements. This configuration is under construction at the moment of writing. But as many scale related unknowns are present we decided to test on a static, cheaper version first. The static version is conceived as rigid 2 way grid structure that will represent the desired double curved shape.
The grid is composed of 15 mmplywood ribs, spaced 200mm. A 200mm spacing optimally uses the expensive actuators and opens up more possibilities towards the curvature that has to be met.

The outer ribs received a 100 mm offset in the z-direction to provide and edge to cast the concrete against. As mentioned earlier the flexible edge profiles are not within the focus of this mock-up.

MULTIPLEX LAYER
Based on the rigid carved formwork principle, developed in chapter 7, two 18 mmplywood panels (2400mm x 1400mm) are carved to 12mm depth. To assure its position and to minimize the chance in errors, they are screwed onto the support ribs. (fig .8.4)

RUBBER LAYER
On top of thisplywood layer a 2mm rubber slab is placed to protect theplywood layer and to ensure a smooth surface. The surface consists out of two separate slabs since common

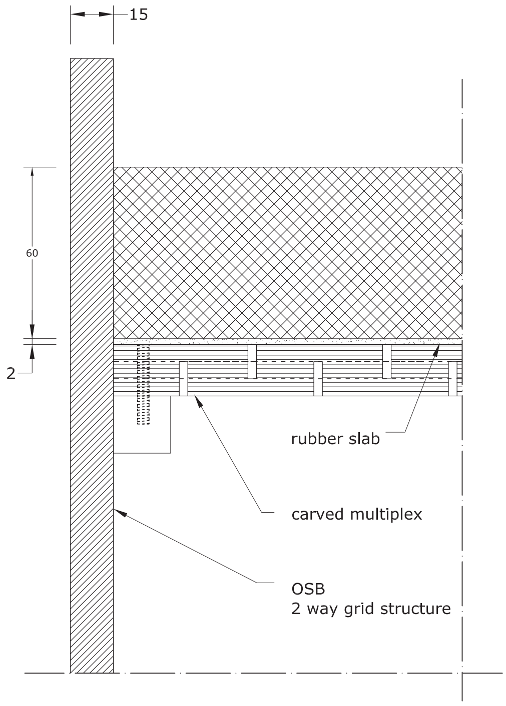
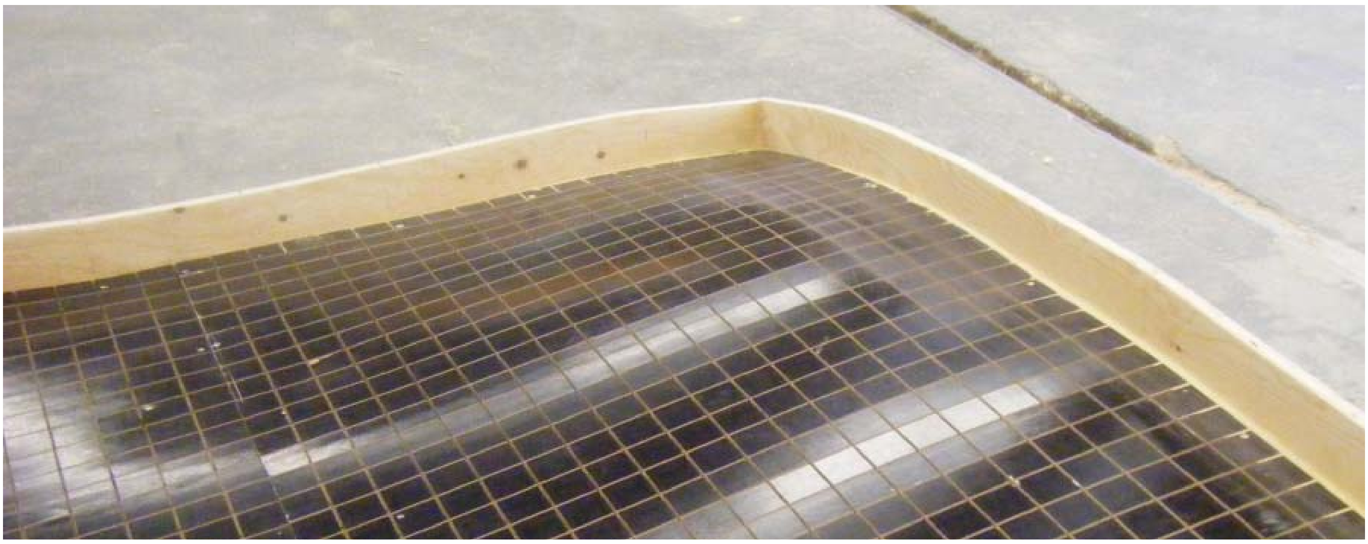


fig.8.4 corner detail of the formwork

fig.8.3 theplywood formwork. The light reflection emphasises the continous curvature



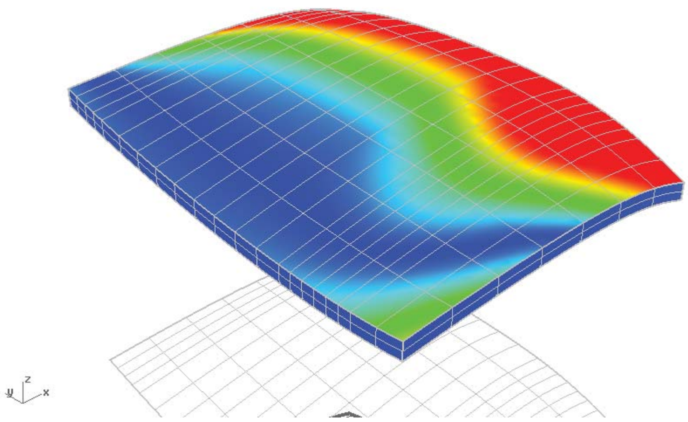
production sizes have a max width of 1200mm. The edge between both slabs is sealed with epoxy filler to provide a continuous surface.

8.2.3. SURFACE PROPERTIES

The surface geometry is a double curved element nr. 145 with a vertical deviation of approximately 400mm. (fig.8.5) The surface generates gaussian curvatures between -1 and 6 which signifies that we are not working with a developable surface. The surface contains both anticlastic and synclastic areas.

properties	nr. 145	
dimensions	2400 x 1400 x 60	mm
surface area	3.4	m^2
volume	0.204	m^3
max radius	5077	m
min radius	1.1	m
mean curvature	0 to -9.88	
gaussian	-1.4 to 6.8	

fig.8.5 analysis of the surface's mean curvature



8.2.4. CONCRETE MIXTURE

The concrete mixture that will be used is a stable fibre reinforced high strength mixture developed by Hurks to cast directly onto a 3D shape. The mixture should have a moderate yield value (> 40 PA) in order to remain within a slope after casting and not too high viscosity to prevent that a high vibration energy has to be applied to compact the concrete. Otherwise its not able to remain in the desired slope.

The total volume of concrete is 0.204 m^3 which brings the total weight of the panel on approximately 600 kg. This volume will be cast in the 3D mould and the top layer will be 'sculpted' by hand according the geometry. In coordination with Hurks Beton anchoring points are placed along the longest edges to transport the element when hardened. Within the facilities of Hurks Beton Groep there are opportunities to treat the surface afterwards.

A first test returned an undesired behavior of the concrete. The mixture had the intention of leveling each time 'sculpting' took place. Even after 3 hours, stabilization of the mixture had not set in. A more stable mixture is necessary to prove the feasibility of the technique. Therefore the mould is reconstructed and an adapted mixture with an increased amount of stabilizer, is prepared.

This time the concrete behaves as intended. Once poured on the formwork, it stopped flowing. Even on the steepest side of the formwork, no flowing occurs. However, once vibrated or 'sculpted' by hand, the mixture shortly regains a certain flow. This allows sculpting of the panel and strengthens our belief in the technique.

concrete mixture	
CEM I 52,5 R CEM III/B 32,5 N Kalksteenmeel Plastificeerder Stabiliseerder Water Fijn zand PVA-vezels (26 kg/m3), Lf=8 mm	for confidental reasons we do not publish the exact composition
compression	37.7 MPa (24h)

fig.8.6 table of the mixture composition

8.2.5. CONCLUDING REMARKS

As mentioned before we narrow the evaluation of this mock-up down to two factors; the performance of theplywood panels as formwork and the feasibility of the 3D cast technique.

FORMWORK
The principle of rigid carved formwork is successfully transferred to a bigger scale. The surface is reproduced smooth and accurate. However, several points of attention are mentioned to improve the performance of the formwork in the future;

- The stiffness of theplywood is too high at this moment. We assessed its thickness and incision depth for now. As a result the formwork had to be screwed to the support ribs to prevent lifting in the strong curved corner areas. When using an adjustable mould in the future, a rigid connection between formwork and supports is not tolerable. Therefore, a more suitable rigid carved formwork is desirable. This can be calculated with the model described in section.7.4.1

- The transition between theplywood panel is minimally reflected in the surface. A more advanced joining of theplywood panels can solve this issue.

- The durability of the setup is limited. Some of the carved squares are destroyed when the concrete is released form the formwork. The rubber leveling layer is also pulled of . A more advanced laminate described in section 7.4.2. can counter this.

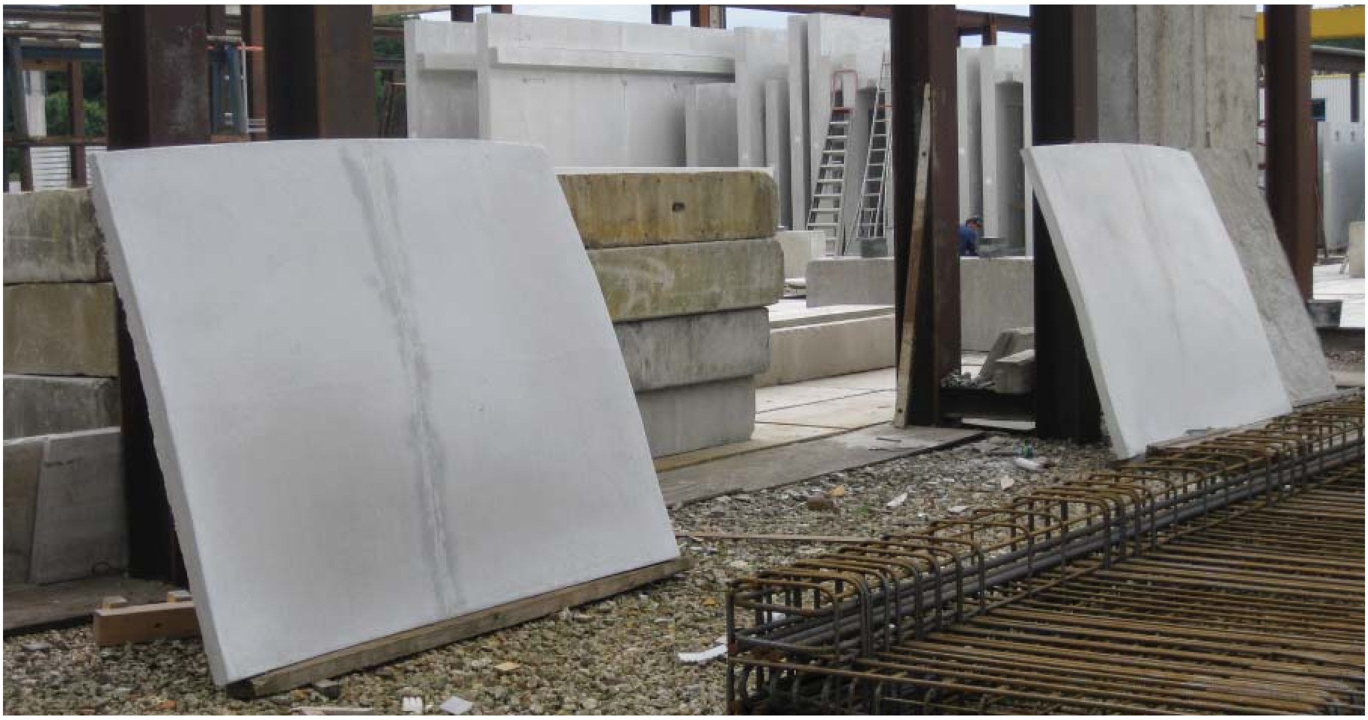
- The processing of the rigid carved formwork is done ourselves. Carving of bothplywood panels took 3 hours and can thus be labeled cheap. The cost can even be lowered when processing takes place on a CNC-operated machine.

fig.8.8 embedded anchor in the thickness (60mm) of the panel

CONCRETE MIXTURE

The second mixture convinced us of the fact that it is possible to cast directly onto a 3D shape. First half of the entire amount is cast into the 3D shape and vibrated to assure compacting on the exposed side of the element. Due to vibrations, the mixture tends to level itself horizontally. The other half of the mixture is now cast into the mould and sculpted by hand. The biggest disadvantage of the technique is the uncertainty about the constant thickness throughout the panel. But as long as there is enough coverage around the anchor points and a minimal thickness of 40 mm is maintained throughout the entire panel, the deviations can be tolerated.

fig.8.7 both cast panels at Hurks beton groep, Veldhoven



8.3. MOCK-UP 2

8.3.1. DESCRIPTION AND RELEVANCE

The second mock-up will represents a series of 2 contiguous smaller panels (1000mm x 1000mm). Here the underlying construction principle is based on the cold facade principle (section 4.3). Such a facade is characterized by the presence of an internal ventilated cavity between the outer layer and the thermal insulation (fig.8.9).

These elements will display the feasability of the production process. Both the product development research and the computational research find their way towards this mock-up.

The first focus in this mock-up is on geometrical aspects. The resulting panels should present a continuous curvature, joints have to match seamlessly and the panels need to represent the exact geometry. Both panels are fabricated autonomous and the mutual edge is constructed at a different side of the formwork. This to prove that adjoining panels can be fabricated accurately, indepedent of its position on the formwork.

Another focus point will target the formwork. Both the edges and the flexible mat have to deal with the curvature of the panels in an accurate way.

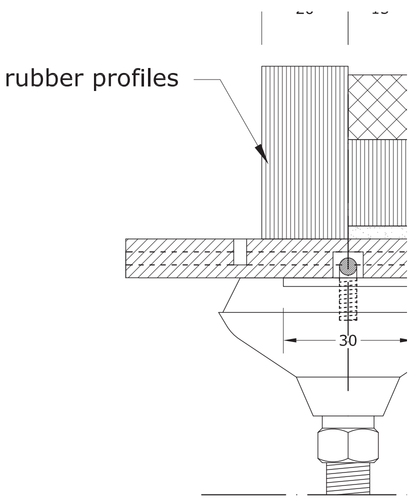


fig.8.10 detail of the rubber edge profiles positioned on the formwork

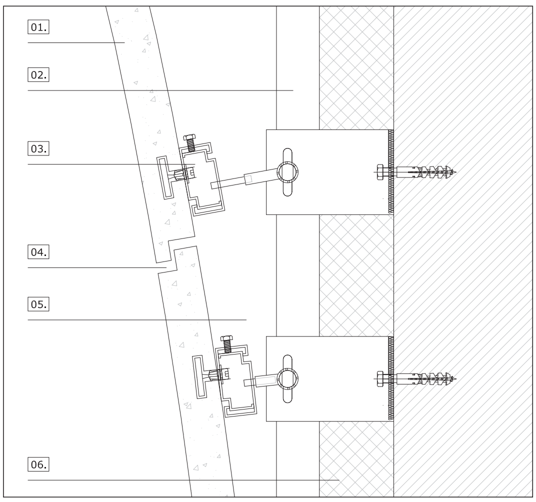
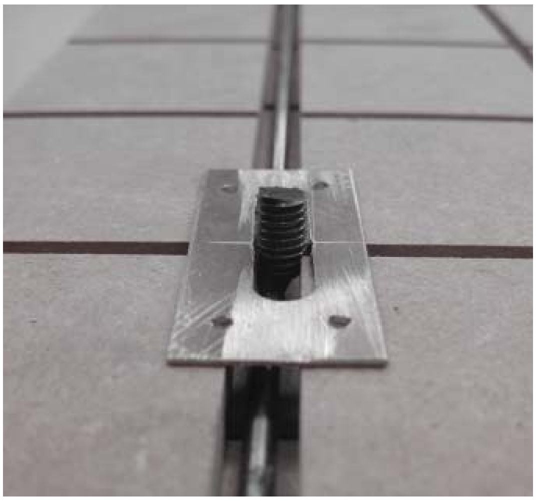


fig.8.9 representative detail for mock-up 2

LEGENDE

01 ECC gevelpaneel
d 40 mm
ca. 1100 x 1100 mm
02 secundaire structuur
03 ankers
rotatie
translatie
04 voeg met rabat
05 geventileerde spouw
06 isolatie
07 primaire structuur



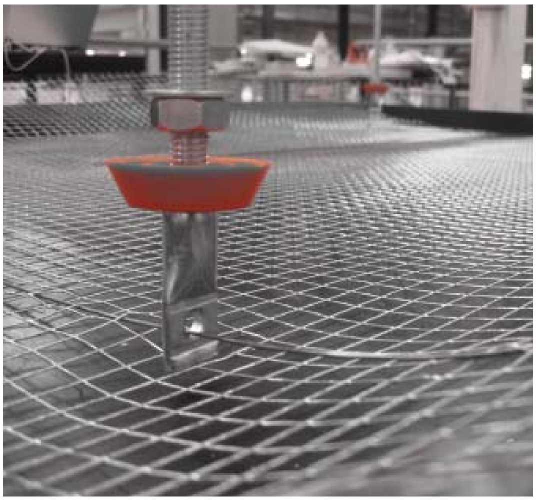


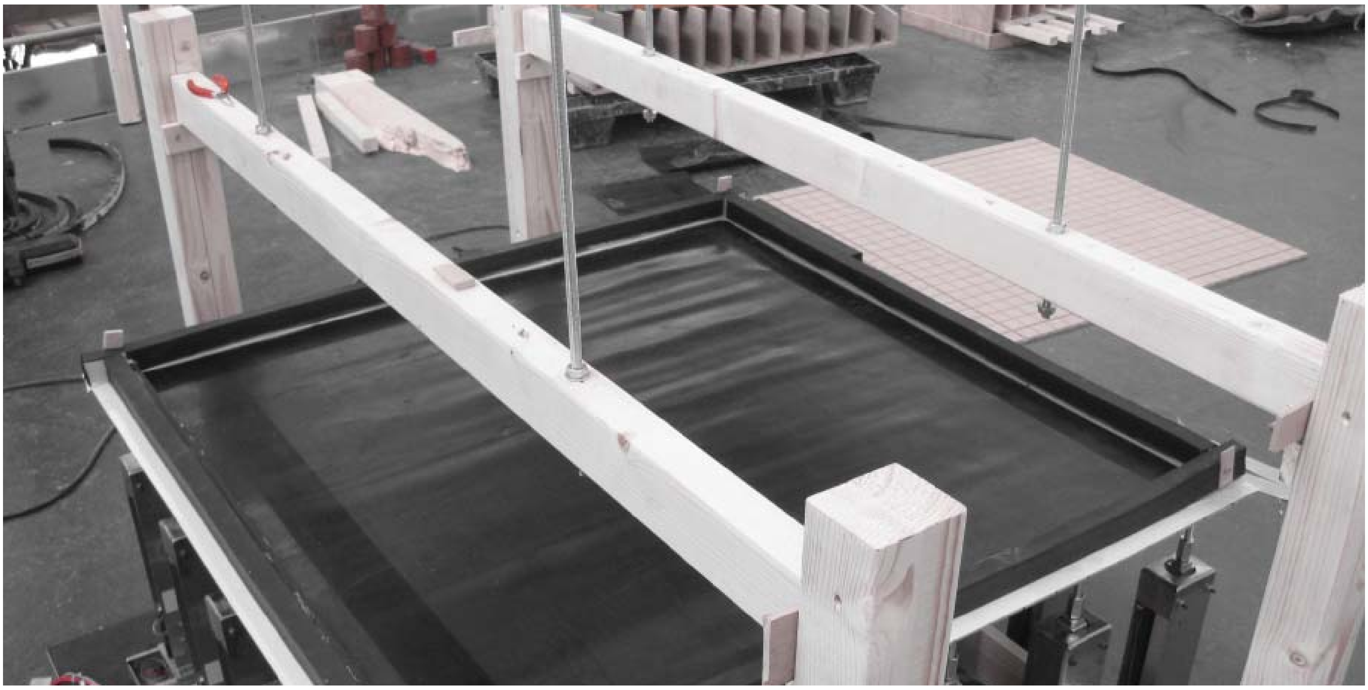
fig.8.11 (l) bottom side of the formwork; edge I with 1 degree of freedom

fig.8.12 (r) reinforcement mesh connected to anchor

8.3.2. FORMWORK SETUP

As stated above the panel will be produced on the adjustable mould. For this setup the actuators of the adjustable mould are rearranged to provide a 200 mm span between each actuator. The pin bed is covered with a carved 9 mm MDF board with 6 mm incisions every 50 mm and this in 4 directions (two on the top surfacaca end two at the bottom). This leaves us with a suffucient flexible formwork to cast upon.
The formwork is fixated in one corner to an actuator (actuator nr.1) while its two adjacent sides can freely move according to their proper X and Y direction (fig.8.11).
Next, double sided adhesive tape is used to attach the rubber to the rigid carved panel (fig.8.13) to generate a usable surface and to provide edge profiles. The edges are screwed to each other at every corner.
Now, a wooden structure is positioned above the actuator field to position the anchors (M10 x 45) correctly above the element. These anchors will be interwoven with a steel reinforcement (10mm x 10mm x 0.5 mm) mesh that is placed in middle of the concrete. (fig.8.12)
This wooden structure already forms the secondary structural elements to position the elements when fully hardened.

fig.8.13 overview of the entire setup



8.3.3. CONCRETE MIXTURE

We use the fibre reinforced lightweight Holchim mixture described in section 5.2.3. This mixture does not compact sufficiently but its workability is appreciated and it is present at the TU. In the future we would recommend the adapted ECC concrete mixture that is used in mock-up 1.

8.3.4. SURFACE GEOMETRY

From the museum for the History of The Polish Jews elements nr. 278 and nr. 279 are extracted to be produced. They represent average values of the entire wall. Other properties of the elements are listed below.

properties	nr. 278 + 279	
dimensions	2000 x 1000 x 37	mm
surface area	2.02	m²
volume	0.08	m³
max radius	141	m
min radius	1.1	m
mean curvature	0 to + 6.78	
gaussian	+ 3.6 to - 4.3	

The proper values are extracted again and loaded into the LabView interface. After the concrete is cast, the adjustable mould takes on the required form and the anchoring points are connected to the wooden structure.

8.3.5. CONCLUDING REMARKS

The adjustable mould works as a principle. In practice the unreliable operation of the actuators still causes much trouble and loss of time. The general control command still lacks reliability. This way certain options of fixing the formwork to the actuators cannot be tested yet.

The rigid carved formwork performs optimal in this mock-up. The weight of the concrete is sufficient to push the formwork down at every actuator. However, small deviations occur. For instance, in the mutual edge a curvature deviation is noticed. It points at the neccesity of a retaining device, ensuring the position of the formwork in the area of the actuator top.

Most problemetic in this mock-up is the behavior and performance of the edges. The total height of the element reaches 37 mm which causes buckling in the edges due to the weight of the concrete. Next to that, insufficient adhesion of the tape, results in released edges. In further development a more stiff custom designed profile should be integrated in the formwork to assure accurate panels.

The proposed anchors are evaluated negatively. No sufficient fixation is established. It is better to foresee anchors at the edges of the panels as shown in mock-up 1.

The attempt to incorporate the secondary structure for on site mounting is interesting and evaluated positively. It guarantues a correct anchor position.

fig.8.14 overview of the entire setup when concrete is cast.

9. FINAL REMARKS

In the middle of every difficulty lies opportunity.
(Albert Einstein)

fig .9.1 mixing ECC concrete at Hurks Beton, Veldhoven

9.1. CONCLUSIONS

Developing an innovative production process for precast concrete double curved elements is complicated due to the many different aspects that have to be taken into account.
However, we are strengthened by the progress we have made throughout the past months to proclaim a strong believe in the opportunities offered by an adjustable formwork. The final mock-ups demonstrate that both approaches, deforming fresh concrete as well as 3D casting, lead to convincing results that can accomplish curvatures up to 1m. We achieved to formulate and materialize all aspects related to an adjustable mould.

The computational development now shows a clear and user friendly process layout that describes the necessary exchange of information between a computer model and a physical setup. The research on materializing the form work resulted in the preference for a rigid carved form work. It returns sufficient surface smoothness, offers a sound solution for its positioning and the addition of an embedded polyurethane layer greatly increases the durability of such a form work.
We also manage to describe the properties of a suitable fibre reinforced concrete mixture that serves our purpose. Important factors are a correct yield and viscosity value.

To deal with the 2D to 3D transformation of concrete, we prefer the 3D casting method because at this point it provides more accuracy than the technique of deforming fresh concrete. It has less problems to overcome and will therefore lead to a convincing production technique within a short period of time.

9.2. FUTURE PERSPECTIVES

A quick follow-up of the acquired results and information is vital. Many of the components are close to their maturation. We mention that the combination of academic research and the experience and common sense of companies like Hurks Beton can really speed up the progress.
A collaboration with a plastics developer will encourage the completion of the hybrid flexible form work. Other companies, like Festo, can enter the research to assist on developing the ideal adjustable pin bed.

We encourage future research on a computational finite element analysis tool that supports the future research on the flexible form work. This can create a connection between requested curvatures and the carving method of the form work.

The real future challenge is situated in the research and development of a large scale adjustable mould with the integration of a sound edge configuration and optimized carved formwork.

When a solution for every component is presented and all main problems are tackled, and every component should be looked over again to allow further optimization and attuned.

REFERENCES

BOOKS AND REPORTS

Bakkker,S.(Ed.);.*Concrete Design book on Robustness*; 's Hertogenbosch;ENCI Media; 2004

Bakker,S.(Ed.);2007;*Concrete Design book:Plastic-Opacity*; Bundesverband der Deutschen Zementindustrie E.V.;2007

Bennett,D.; *exploring concrete architecture*; Birkhäuser,2001

Bloch,J; Bridge to the future?, Bangor daily news, p A6-a8, february 21-22 2009

Brabander, C.; *Een dubbelgekromd dragend gevelelement voor een twister in zelfverdichtend hoge sterkte beton*; Master's Thesis; TUDelft;November 2004

Diks, M.E.; *Translucent sandwich systeem voor dubbel gekromde toepassingen*; Master's Thesis; TUDelft; January 2005

Domeison,O.;*The Quest for ornamen*t.Detail,vol.6,574-582,2008

Den Hartog, E.; *Prefabrication of concrete shells*; Master's Thesis; TUDelft; December 2008

Fehlhaber, J.M.;*Plastic-Opacity, International Concrete Design Competition*; Bundesverband der Deutschen Zementindustrie; 2005

Grafe,C., Pimlott,M.& Stuhlmacher,M.,(Eds.);*Ornaments.Oase*;vol65;2004

Grünewald, S.; *Performance-based design of self-compacting fibre reinforced concrete*;PhD thesis TUDelft; 2004

Kind-Barkauskas, **F., Kauhsen, B., Söffker, G., Polonyi, S., Thrift,P., Brandt, J.**; *Concrete Construction manual*; Birkhäuser; 2002

Knaack U. , Klein T., Bilow M., Auer T.; *Facades : Principles of construction*; Birkhäuser Verlag AG; 2007

Krikhaar, H.M.M.; edited by J. van Eldik & P. de Vries; *Betonpocket 2008;* 's Hertogenbosh; 2007

Krause,JR.; *fibre cement, technology and design*, Birkhäuser, 2007

Kubo,M.,& Moussavi,F.(Eds.);*The function of Ornament;*Barcelona;Actar D.;2006

Lok G.; *Praktijkhandboek kunststoffen*; POLYSERVICE BV; 2007

Peerdeman, B; *Analysis of Thin Concrete Shells Revisited: Opportunities due to Innovations in Materials and Analysis Methods*; Master's Thesis; TUDelft; June 2008

Ponce de Leon,M.,& Tehrani,N.;*Versioning:Connubial Reciprocities of Surface and Space*;Architectural Design,vol.72,18-25;2003

Pottman H., Asperl A., Hofer M., Kilian A.; *Architectural Geometry first edition* ; Bentley Systems; 2007

Rahim,A.,& Jamell,H;*Elegance in the age of digital techniques*.;pp.6-9; Architectural Design,2007

Renckens, J.; *Facades & architecture : facination in aluminium and glass*, TUDelft VMRG VAS FAECF, 1998

Roosbroeck, van M.K.H.M.; *The Construction of prefab concrete shells, morphology, segmentation, material-production method*; Master's Thesis; TUDelft; February 2006

Scalbert,I.;Ornament.In Wingardh,G.,& Waern,R.(Eds.),*Crucial Words: Conditions for contemporary architecture* (pp.137-144).Sweden;Birkhauser;2008

Schoofs A., Huyghe K.; *Reference book on double curved surfaces*, TUDelft; 2009

Schutter,De G.,&Bartos,P.J.M.,&Domone,P.,&Gibbs,J.;*Self-Compacting Concrete*.Scotland;Whittles Publishing;2008

Van Doosselaere,P.,Van Gastel,J.;*Zelfverdichtend staalvezelbeton*.Katholieke Universiteit Leuven, België;2003

Watts, A.; *Modern Construction facades;* Springer-Verlag; Wein; December 2004

INTERNET PAGES

b sieiffage
www.bsieiffage.com

concrete canvas
www.concretecanvas.co.uk

construction in vivo
www.constructioninvivo.com

Ductal Lafarge
www.ductal-lafarge.com

FUR Barbeton
www.f-u-r.de

Grasshopper
en.wikipedia.org/wiki/Grasshopper

hyposurface
hyposurface.org

rieder smart elements, Austria
www.rieder.cc

University of Manitoba
Centre for Architectural Structures and Technology, CAST
www.umanitoba.ca/cast_building/

APPENDICES

APPENDIX 1 : PERSONAL DATA AND GRADUATION COMMITTEE

APPENDIX 2 : CAST ELEMENTS

APPENDIX 3 : PATENT VOLLERS/RIETBERGEN

APPENDIX 1 : PERSONAL DATA AND GRADUATION COMMITTEE

PERSONAL INFO

students
Koen Huyghe
1799992
Rotterdamsedijk 274
3112BT Schiedam
the Netherlands
e huyghe.k@gmail.com
t +31 (0) 63 000 22 12

Arnoud Schoofs
1380818
Rotterdamsedijk 274
3112BT Schiedam
the Netherlands
e arnoud.schoofs@gmail.com
t +32 (0) 496 44 52 97

GRADUATION COMMITTEE

main mentor
Dr. Ir. Karel Vollers
Faculty of Product Design
e K.J.Vollers@tudelft.nl
t + 31 (0) 65 31 19113

second mentor
Ir. Daan Rietbergen
Faculty of Architecture, Building Sciences
e d.rietbergen@tudelft.nl
t +31 (0) 15 27 81279

third mentor
Dipl.-Ing. Steffen Grünewald
Faculty of Civil Engineering & Geosciences
e S.Grunewald@tudelft.nl
t +31 (0)15 278 7438

lab coordinator
Ir. Arie Bergsma
Faculty of Architecture, Building Sciences
e A.C.Bergsma@tudelft.nl
t +31 (0) 15 27 82867

APPENDIX 2 : CAST ELEMENTS

PANEL AA01

	AA01
DATE OF CONSTRUCTION	19-12-2008
SIZE	40 X 40 X 2 CM
TYPE OF FORMWORK	REINFORCED FLEXIBLE FORMWORK A
TYPE OF EDGE	POLYSTYRENE FOAM
SUPPORTS	STATIC WOODEN LINE SUPPORT
TIME BETWEEN POURING AND DEFORMATION	2 HOURS
CONCRETE TYPE	TRADITIONAL LEAN MIXTURE
SURFACE EVALUATION	HAIR CRACKS IN TENSIONED AREAS / FAILURE OF SAMPLE

PANEL BB02

	BB02
DATE OF CONSTRUCTION	22-01-2009
SIZE	120 X 60 X 4 CM
TYPE OF FORMWORK	REINFORCED FLEXIBLE FORMWORK B
TYPE OF EDGE	SILICONE
SUPPORTS	STATIC WOODEN LINE SUPPORT
TIME BETWEEN POURING AND DEFORMATION	5 HOURS
CONCRETE TYPE	ECC MIXTURE
SURFACE EVALUATION	EDGE SLIGHTLY BULGE OUT / GLOSSY SURFACE

PANEL BB03

	BB03
DATE OF CONSTRUCTION	29-01-2009
SIZE	120 X 60 X 4 CM
TYPE OF FORMWORK	REINFORCED FLEXIBLE FORMWORK B
TYPE OF EDGE	SILICONE
SUPPORTS	STATIC WOODEN LINE SUPPORT
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	NOT FULLY COMPACTED

PANEL BB03

	BB04
DATE OF CONSTRUCTION	15-02-2009
SIZE	120 X 60 X 2 CM
TYPE OF FORMWORK	REINFORCED FLEXIBLE FORMWORK B
TYPE OF EDGE	SILICONE
SUPPORTS	STATIC WOODEN LINE SUPPORT
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	NOT FULLY COMPACTED/SURFACE REVEALS LINE SUPPORTS

PANEL CC04

	CC04
DATE OF CONSTRUCTION	22-02-2009
SIZE	100 X 100 X 4 CM
TYPE OF FORMWORK	RESTRAINED FLEXIBLE FORMWORK A
TYPE OF EDGE	RUBBER
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	NOT FULLY COMPACTED/REINFORCEMENT BULGES OUT

PANEL CC05

	CC05
DATE OF CONSTRUCTION	02-03-2009
SIZE	100 X 100 X 4 CM
TYPE OF FORMWORK	RESTRAINED FLEXIBLE FORMWORK A
TYPE OF EDGE	RUBBER
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	OK

PANEL CC06

	CC06
DATE OF CONSTRUCTION	10-03-2009
SIZE	120 X 60 X 4 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK A
TYPE OF EDGE	RUBBER
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	COMPACTED/ DETAILED EDGE PROFILE

PANEL CC07

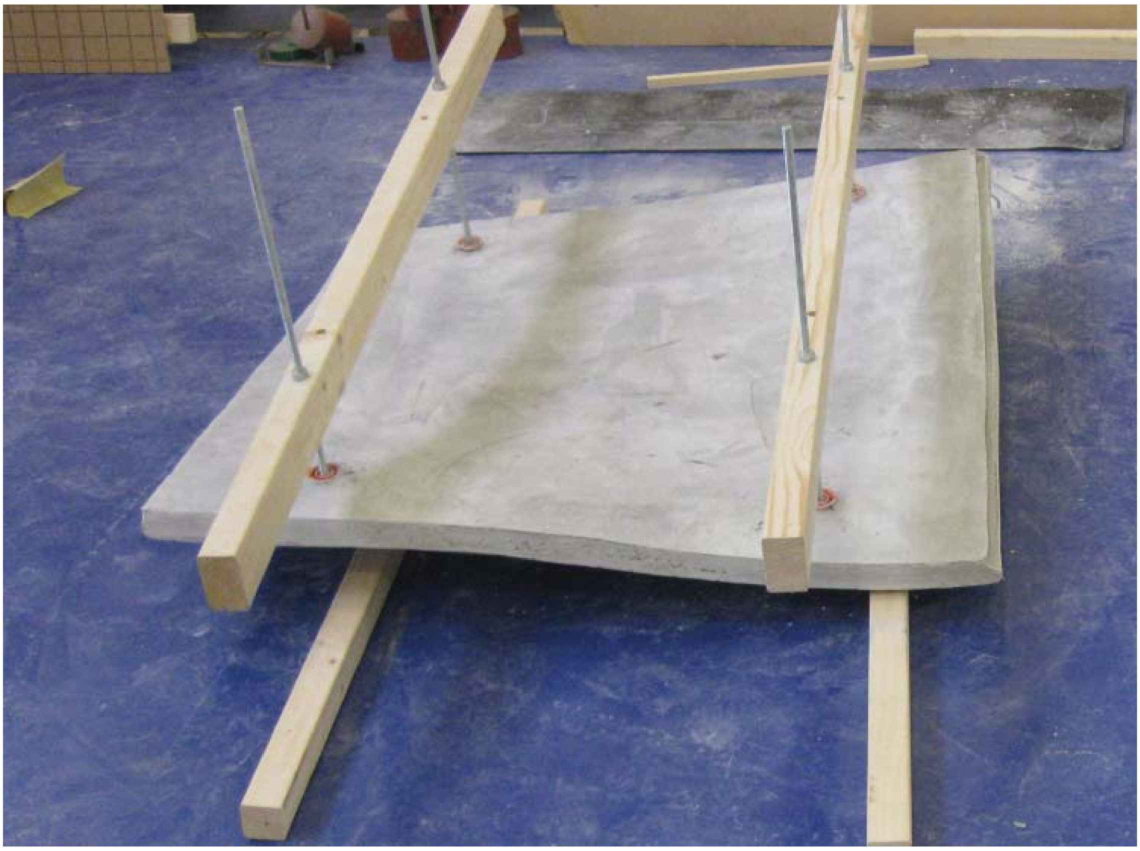
	CC07
DATE OF CONSTRUCTION	20-03-2009
SIZE	120 X 60 X 4 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK A
TYPE OF EDGE	RUBBER
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	HOLCIM MIXTURE
SURFACE EVALUATION	COMPACTED/ DETAILED EDGE PROFILE

PANEL DD08

	DD08
DATE OF CONSTRUCTION	02-06-2009
SIZE	140 X 240 X 6 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK B
TYPE OF EDGE	WOOD
SUPPORTS	WOODEN LINE SUPPORTS
TIME BETWEEN POURING AND DEFORMATION	30 MINUTES
CONCRETE TYPE	ECC MIXTURE
SURFACE EVALUATION	COMPACTED/ BAD CURVATURE

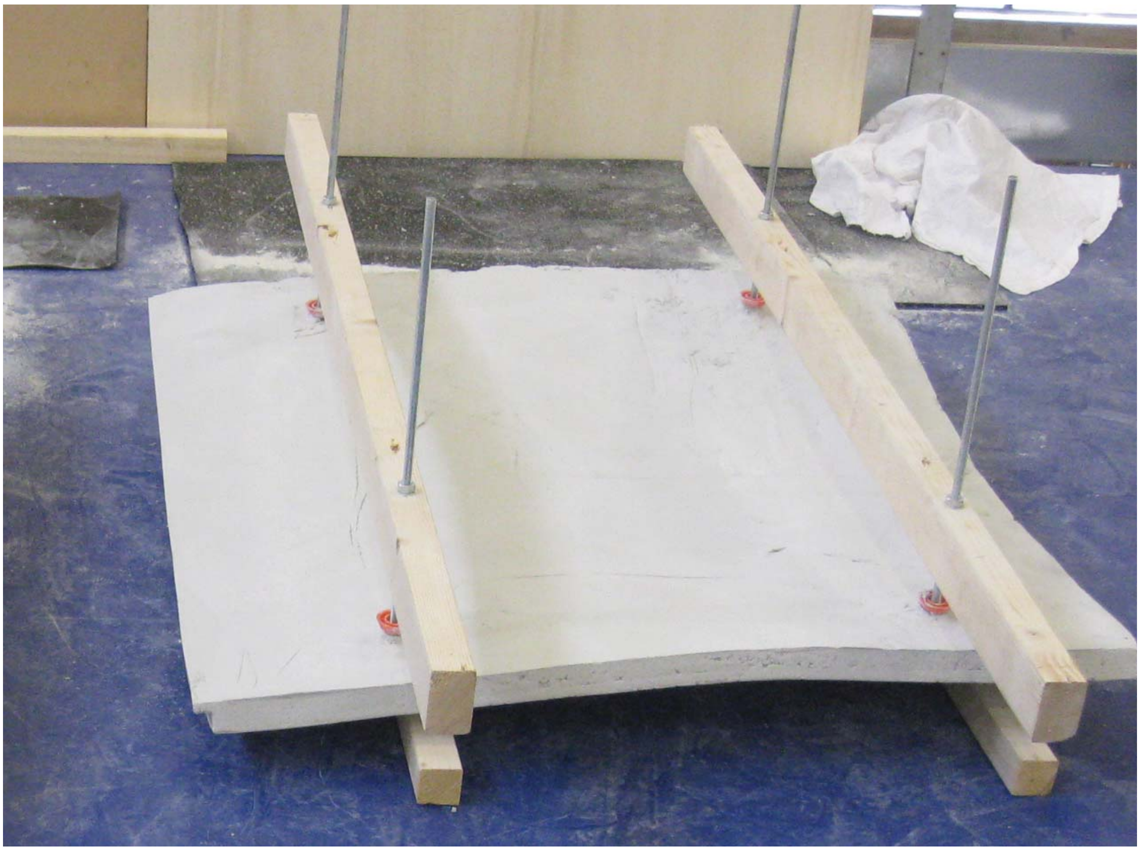
PANEL CC09

	DD09
DATE OF CONSTRUCTION	16-06-2009
SIZE	140 X 240 X 6 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK B
TYPE OF EDGE	WOOD
SUPPORTS	WOODEN LINE SUPPORTS
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	ECC MIXTURE
SURFACE EVALUATION	COMPACTED/ IMPRINT OF RUBBER LAYER/CONSTANT THICKNESS



PANEL CC10

	CC10
DATE OF CONSTRUCTION	16-06-2009
SIZE	100 X 100 X 4 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK A
TYPE OF EDGE	WOOD
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	30 MINUTES
CONCRETE TYPE	ECC MIXTURE
SURFACE EVALUATION	COMPACTED/ BAD CURVATURE



PANEL CC09

	CC11
DATE OF CONSTRUCTION	18-06-2009
SIZE	140 X 240 X 6 CM
TYPE OF FORMWORK	RIGID CARVED FORMWORK A
TYPE OF EDGE	WOOD
SUPPORTS	ADJUSTABLE PIN BED
TIME BETWEEN POURING AND DEFORMATION	20 MINUTES
CONCRETE TYPE	ECC MIXTURE
SURFACE EVALUATION	COMPACTED/ DETAILED EDGE PROFILE

APPENDIX 3 : PATENT VOLLERS/RIETBERGEN

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 December 2008 (31.12.2008)

PCT

(10) International Publication Number
WO 2009/002158 A1

(51) International Patent Classification:
C03B 23/025 (2006.01)

(21) International Application Number:
PCT/NL2008/050243

(22) International Filing Date: 24 April 2008 (24.04.2008)

(25) Filing Language: Dutch

(26) Publication Language: English

(30) Priority Data:
2000699 12 June 2007 (12.06.2007) NL

(71) Applicant (*for all designated States except US*): TECH-NISCHE UNIVERSITEIT DELFT [NL/NL]; Stevinweg 1, NL-2628 CN Delft (NL).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): RIETBERGEN, Daan [NL/NL]; Prof. Krausstraat 138, NL-2628 JV Delft (NL). VOLLERS, Karel Jan [NL/NL]; Overtoom 433-1, NL-1054 KE Amsterdan (NL).

(74) Agent: VAN BREDA, Jacques; Weteringschans 96, NL-1017 XS Amsterdam (NL).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(54) **Title:** A METHOD AND APPARATUS FOR FORMING A DOUBLE-CURVED PANEL FROM A FLAT PANEL

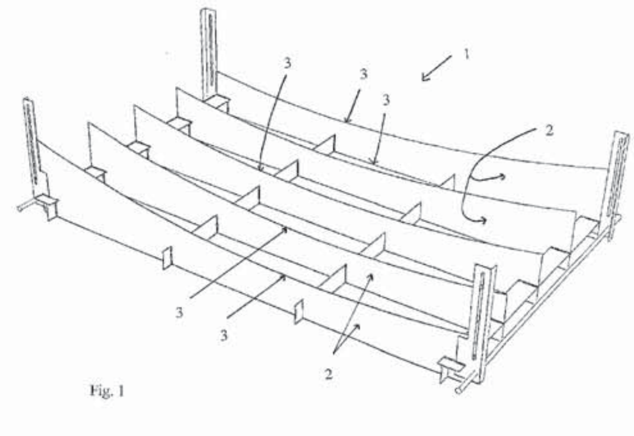


Fig. 1

(57) **Abstract:** A method for forming a double-curved panel from a flat panel, which comprises processing a plastically deformable flat panel or rendering the flat panel plastically deformable to enable it to mould itself to a predetermined shape, wherein the shape is obtained by a primary supporting construction cooperating with a secondary supporting construction, wherein the primary supporting construction may or may not be adjustable to an invariant position that determines the shape, and the secondary supporting construction is adjustable between a starting position in which it supports the flat panel, and a finishing position in which the secondary supporting construction supports the double-curved panel, while said supporting construction rests on and is shaped in accordance with the shape of the primary supporting construction, wherein the adjustment from the starting position to the finishing position occurs at least subject to the distribution of the gravitational force exerted on the secondary supporting construction by the panel while this is plastically deformable.

WO 2009/002158 A1

A method and apparatus for forming a double-curved panel from a flat panel

In the first place the invention relates to a method for forming a double-curved panel from a flat panel, which comprises processing a plastically deformable flat panel or rendering the flat panel plastically deformable to enable it to mould itself to a predetermined shape.

From the European patent publication EP-A-0 440 884 a method is known for forming a single-curved glass panel from a flat glass panel, wherein after heating, the flat glass panel moulds itself to a plurality of curved rods that support the glass panel. Heating provides the glass panel with the desired plastic deformability.

The method known from the European patent publication EP-A-0 440 884 is not suitable for forming a double-curved glass panel.

It should be noted, that the invention may be employed with glass panels, but also with panels made of a different material such as, for example, plastic, a composite material or metal, or any other material that might be intended now or in the future to be subjected to the deformation process referred to herein.

In order to provide a method for forming a double-curved glass panel, it is usual practice to use moulds that have been shaped in accordance with the shape eventually desired for the glass panel. As the glass panel before it has moulded itself to the mould starts out flat, the manufacture of the double-curved glass panel involves particular problems, with breakage being a frequent occurrence. In practice it happens regularly that a pane has to be made anew up to ten times before the resulting double-curved glass panel is acceptable.

One of the objects of the invention is to provide a reliable method for forming a double-curved panel from a flat panel, and by which the desired double-curved panel can be made available at lower costs than is the case with the prior art technique.

To this end the method according to the invention is characterized by one or several of the appended method claims.

In a first aspect of the invention, the method for forming a double-curved panel from a flat panel is characterized in that the shape is obtained by a primary supporting construction cooperating with a secondary supporting construction, wherein the primary supporting construction may or may not be adjustable to a fixed position that determines the shape, and the secondary supporting construction is adjustable between a starting position in which it supports the flat panel, and a finishing position in which the secondary supporting construction supports the double-curved panel, while said supporting construction rests on the primary supporting construction and is shaped in accordance with the shape of the primary supporting construction, wherein the adjustment from the starting position to the finishing position occurs at least subject to the distribution of the gravitational force exerted on the secondary supporting construction by the panel while this is plastically deformable. If desired, the adjustment of the secondary supporting construction may be aided in another way, for example, by additional pressure means, or by providing a partial vacuum under the panel being supported by the secondary supporting construction.

When the finishing position is reached, the plastic deformability of the panel may be terminated or reduced by a suitable process. This process may involve, for example, terminating the heating at a glass panel, or fixing a flexible plastic panel by means of UV radiation. However, which process and which material is used is of minor importance as long as the essence of the invention, being embodied in the cooperation between the primary supporting construction and the secondary supporting construction, is employed.

The method proposed according to the invention facilitates an efficient production method for shaping the double-curved panel and making a mould, as in the prior art, becomes superfluous while less glass is being used in the manufacture of a double-curved glass panel because glass breakage is significantly reduced.

The invention is also embodied in an apparatus with which this production method for forming a double-curved panel from a flat panel can be executed effectively.

To this end the apparatus according to the invention is characterized by one or several of the appended apparatus claims.

In a further aspect of the invention, the apparatus is therefore characterized in that it comprises a primary supporting construction that may or may not be adjustable to a time-invariable form that corresponds to a desirable double curve of the panel, as well as a secondary supporting construction that is designed to rest on the primary supporting construction and, subject to a distribution of gravitational force from a panel resting on the secondary supporting construction, is deformable into a shape that corresponds to the time-invariable shape of the primary supporting construction.

The effectiveness and the simple realisation of the desired double-curved shape is obtained in particular by the fact that the primary supporting construction and the secondary supporting construction define cross-wise intersecting supporting lines.

The above described starting points provide a basis for various ways in which to realise both the method and the apparatus in a simple and suitable manner.

In a first embodiment, the primary supporting construction may be provided with a plurality of additional construction elements, which at the upper side define a plurality of first supporting lines, and that all of these first supporting lines determined by the construction elements lie in an imaginary plane having the predetermined shape.

This primary supporting construction is then formed, for example, by a number of steel plates manufactured manually or computer-controlled, which are placed at some distance from each other and together fulfil a supporting function for the secondary supporting construction described above.

The secondary supporting construction in turn is then preferably formed like a mat comprised of a plurality of flexible rods disposed next to each other. These rods are kept at a distance from each other, for example, by coupling them to each other or by lodging each rod in grooves provided at the top side of the primary supporting construction. This mat of flexible rods has to be constructed such as to allow the rods to readily deform under the influence of the thermo-plastically deformable panel resting on the secondary supporting construction, allowing the same to shape itself to the desired double-curved shape.

In order to be able to assume the desired double-curved shape embodied in the construction elements of the primary supporting construction, it is desirable for the plurality of flexible rods of the secondary supporting construction to be placed cross-wise (preferably orthogonally) on the plurality of first bearing lines of the construction elements of the primary supporting construction, which rods thus form a plurality of second bearing lines, which serve to support the panel.

The invention, whose essence is embodied in the appended claims, will be further elucidated below, with reference to the drawing.

The drawing shows in:

- Fig. 1, a primary supporting construction as can be used with the method according to the invention;
- Fig. 2, the primary supporting construction according to Fig. 1, above which is placed a secondary supporting construction in a starting position, supporting a flat glass plate,
- Fig. 3, the primary supporting construction and the secondary supporting construction with the glass plate resting thereon, while these have been moved to the finishing position, and
- Fig. 4, the apparatus shown in Fig. 3, wherein the glass plate is shown to be transparent.

Fig. 1 shows that the primary supporting construction 1 is formed by steel partitions 2 whose upper sides define bearing lines 3 that all lie in an imaginary plane exhibiting the predetermined desired double-curved shape. To this end each of the separate partitions 2 is provided with a single-curved top side 3, derived from the desired double curve created by all the partitions 2 together. Alternatively it is also possible to embody this primary supporting construction 1 to be adjustable for obtaining the bearing lines 3 that correspond to the desired double-curved shape. It is then also possible - as opposed to what is shown in the figures - to begin with a flat starting position of the primary supporting construction 1 with the same supporting the secondary supporting construction with the (glass) panel and, after the panel is sufficiently heated, to adjust the primary supporting construction so as to obtain the above-mentioned bearing lines 3.

In Fig. 2 a flat glass plate 4 rests on a likewise still flat mat 5 formed by the flexible rods 6 of a secondary supporting construction 5 located above the primary supporting construction 1. In this position the glass plate 4 can be heated and, when the glass plate 4 has become sufficiently bendable, the secondary supporting construction 5 may be lowered such that the rods 6 defining bearing lines for the glass plate 4, come to rest on the orthogonally oriented bearing lines 3 that are determined by the partitions 2 of the primary supporting construction 1. It will be obvious that instead of lowering the rods 6 with the glass plate 4 resting thereon, the primary supporting construction 1 may also be moved upward.

Deformation of the rods 6 of the secondary supporting construction 5 occurs subject to the distribution of gravitational forces exerted on the rods 6 of the secondary supporting construction 5 during heating of the glass panel 4. This distribution of gravitational force makes that, as show in Fig. 3 and even more clearly in Fig. 4, these rods 6 come to rest on all of the partitions 2 of the primary supporting construction 1. The rods 6 of the secondary supporting construction 5 will over their length assume an orientation that lies almost completely in the plane of the predetermined double-curved shape embodied in the primary supporting construction 1. Accordingly, the glass panel 4 also substantially assumes this desired double-curved shape.

If it is desirable to optimise the accuracy of the double-curved shape of the panel 4, it is possible to increase the density of the bearing lines of the primary 1 and secondary 5 supporting construction.

Within the scope of the invention it is also possible for a tertiary supporting construction to be added to the apparatus or to be used with the method, respectively, which cooperates with the secondary supporting construction in a manner corresponding to the one explained above regarding the primary and the secondary supporting construction.

CLAIMS

1. A method for forming a double-curved panel from a flat panel, which comprises processing a plastically deformable flat panel or rendering the flat panel plastically deformable to enable it to mould itself to a predetermined shape, **characterised** in that the shape is obtained by a primary supporting construction (1) cooperating with a secondary supporting construction (5), wherein the primary supporting construction (1) may or may not be adjustable to an invariant position that determines the shape, and the secondary supporting construction (5) is adjustable between a starting position in which it supports the flat panel (4), and a finishing position in which the secondary supporting construction (5) supports the double-curved panel (4), while said supporting construction (5) rests on the primary supporting construction (1) and is shaped in accordance with the shape of the primary supporting construction (1), wherein the adjustment from the starting position to the finishing position occurs at least subject to the distribution of the gravitational force exerted on the secondary supporting construction (5) by the panel (4) while this is plastically deformable.

2. A method according to claim 1, **characterised** in that the primary supporting construction (1) and the secondary supporting construction (5) substantially define cross-wise intersecting supporting lines (3, 6).

3. A method according to claim 1 or 2, **characterised** in that the primary supporting construction (1) may be provided with a plurality of additional construction elements (2), which at the upper side define a plurality of first supporting lines (3), and that all of these first supporting lines (3) determined by the construction elements (2) lie in an imaginary plane having the predetermined shape.

4. A method according to one of the claim 1-3, **characterised** in that the secondary supporting construction is a mat comprising a plurality of flexible rods (6) disposed next to each other.

5. A method according to claim 4, **characterised** in that the plurality of flexible rods (6) are placed cross-wise on the plurality of first bearing lines (3) of the construction elements (2) of the primary supporting construction (1), thus form-

ing a plurality of second bearing lines (6), which serve to support the panel (4)

6. An apparatus for forming a double-curved panel from a flat panel, **characterised** in that the same comprises a primary supporting construction (1) that may or may not be adjustable to a time-invariable form that corresponds to a desirable double curve of the panel (4), as well as a secondary supporting construction (5) that is designed to rest on the primary supporting construction (1) and, subject to at least a distribution of gravitational force from a panel (4) resting on the secondary supporting construction (5), is deformable into a shape that corresponds to the time-invariable shape of the primary supporting construction (1).

7. An apparatus according to claim 6, **characterised** in that the primary supporting construction (1) is provided with a plurality of additional construction elements (2), which at the upper side define a plurality of first supporting lines (3), and that all of these first supporting lines (3) determined by the construction elements (2) lie in an imaginary plane having the predetermined shape.

8. An apparatus according to claim 6 or 7, **characterised** in that the secondary supporting construction is a mat (5) comprised of a plurality of flexible rods (6) disposed next to each other.

9. An apparatus according to claim 8, **characterised** in that the plurality of flexible rods (6) are placed cross-wise on the plurality of first bearing lines (3) of the construction elements (2) of the primary supporting construction (1), which rods thus form a plurality of second bearing lines (6), which serve to support the panel (4).

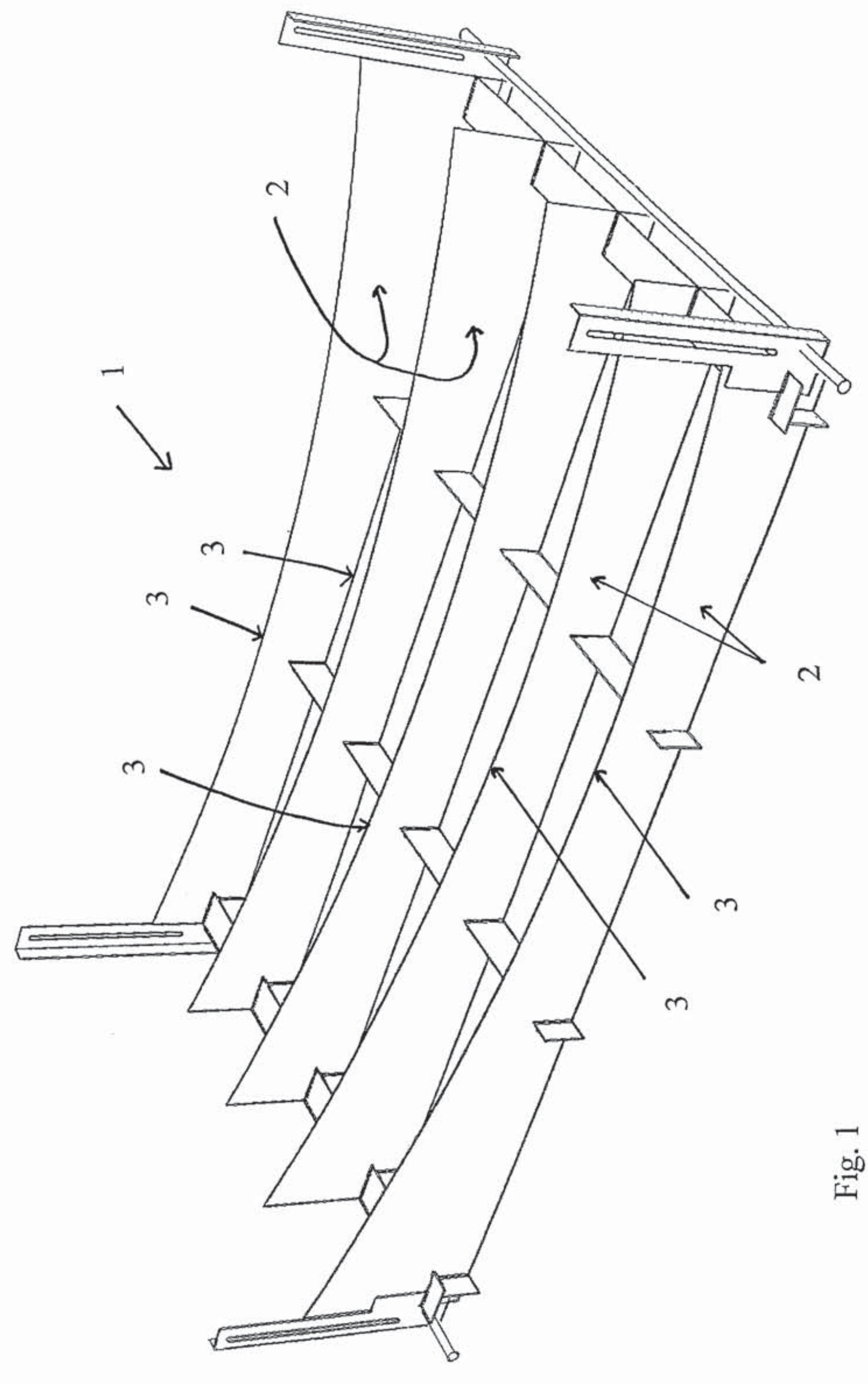


Fig. 1

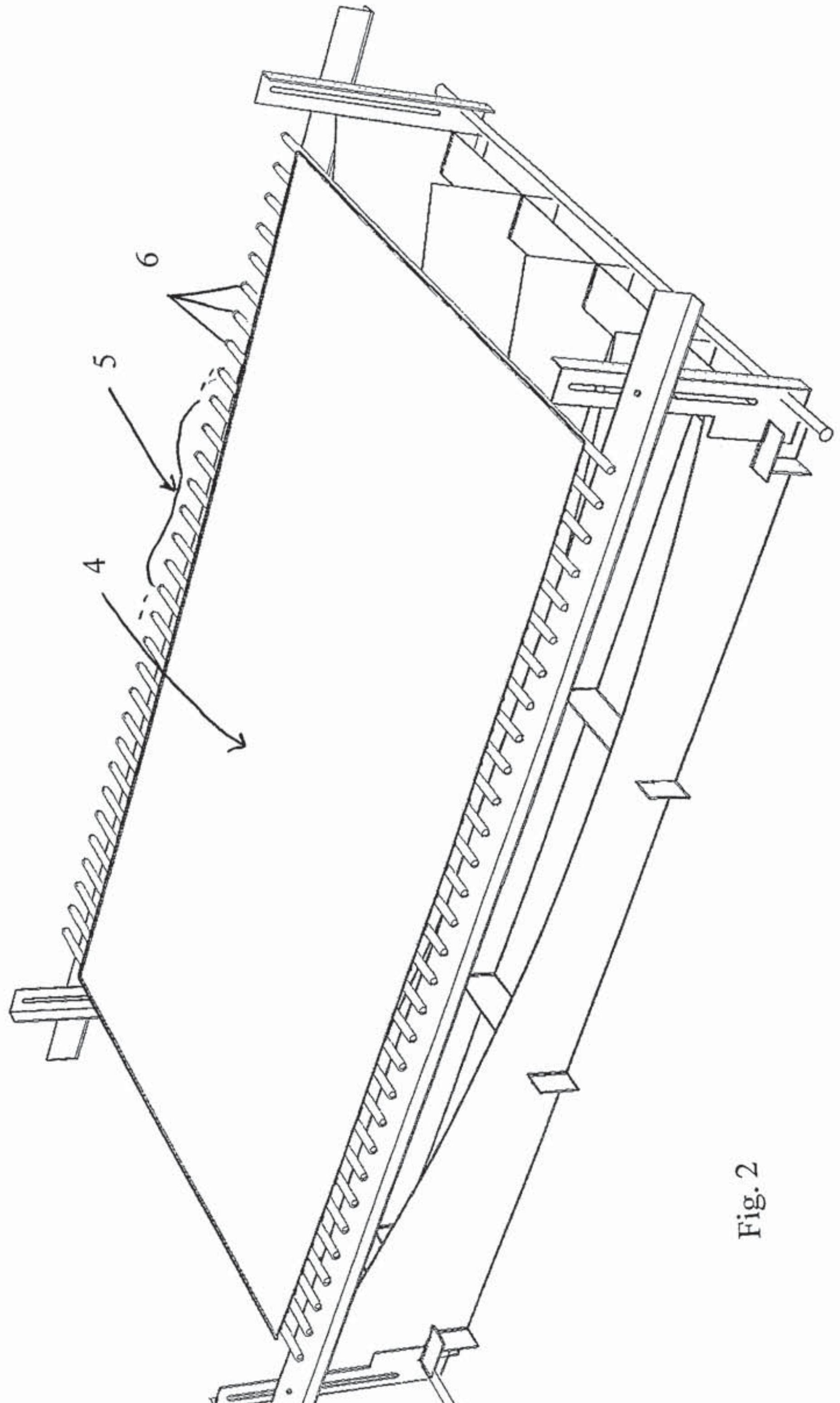


Fig. 2

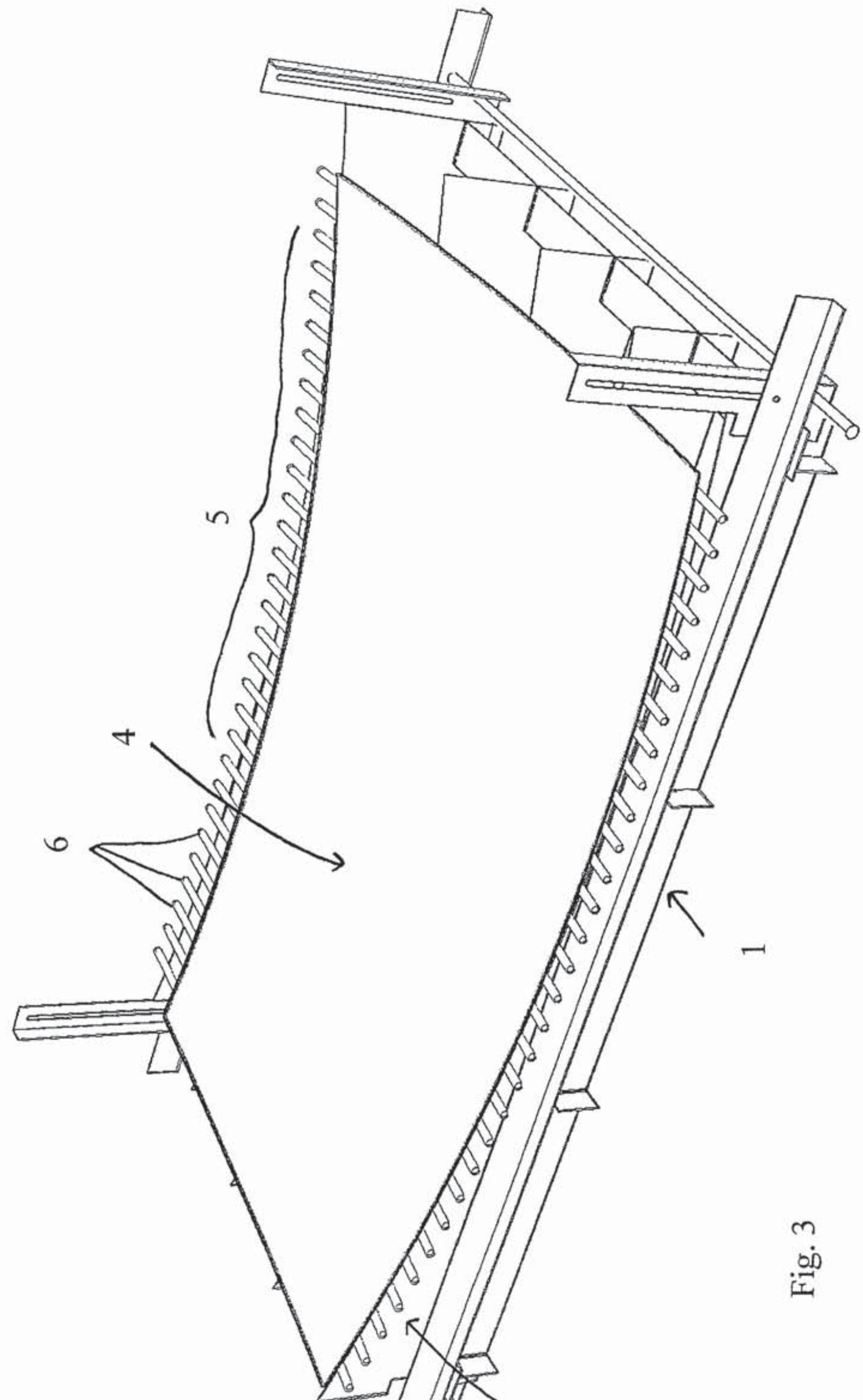


Fig. 3

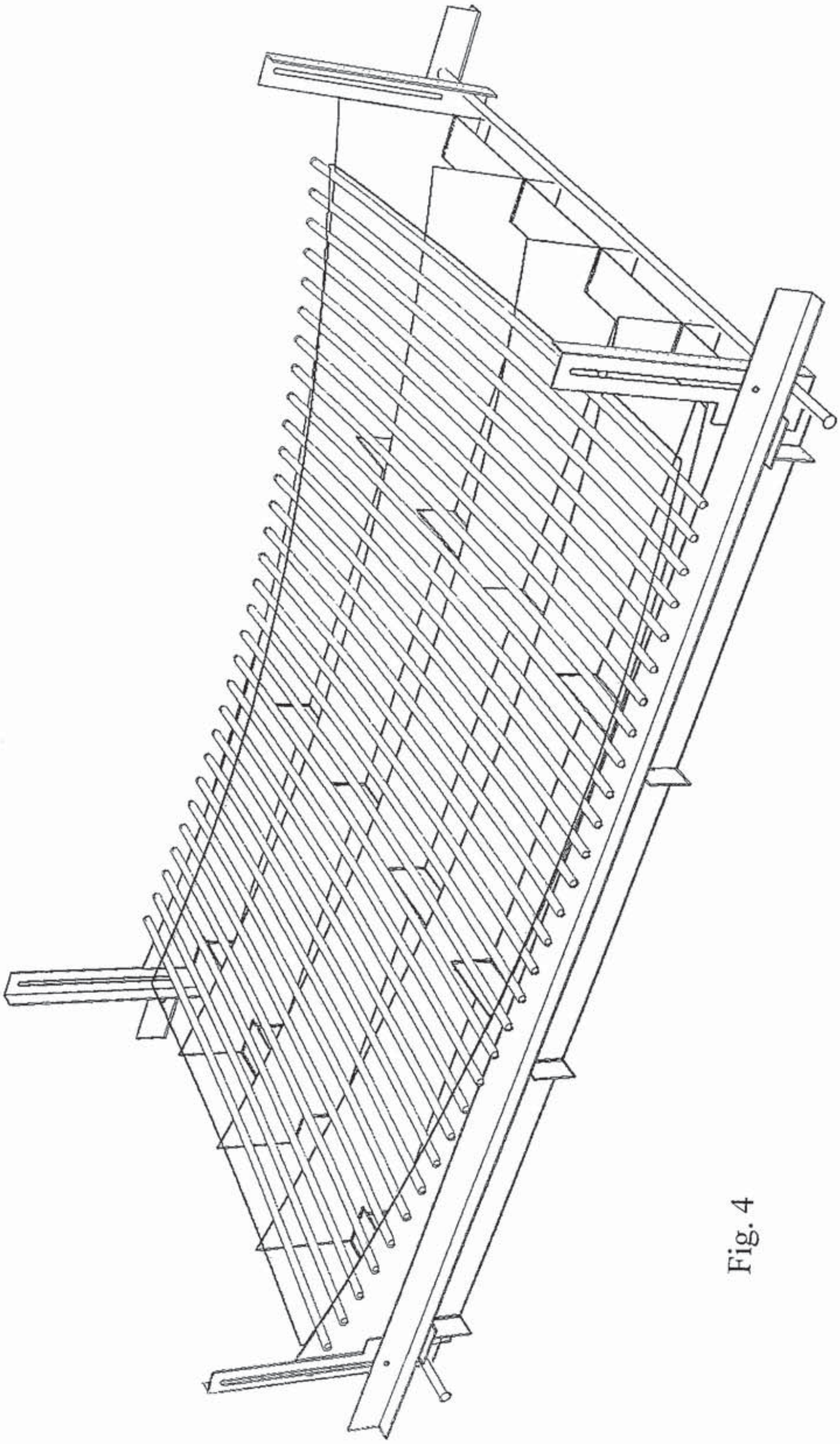


Fig. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2008/050243

A. CLASSIFICATION OF SUBJECT MATTER
INV. C03B23/025

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 440 884 A (WSP INGENIEURGESELLSCHAFT FUER [DE]) 14 August 1991 (1991-08-14) cited in the application figure 2	1-9
A	GB 04680 A A.D. 1910 (ROBIER DESIRE JEAN BAPTISTE [BE]) 23 June 1910 (1910-06-23) figure 2	1-9
A	EP 0 885 851 A (PPG INDUSTRIES INC [US] PPG IND OHIO INC [US]) 23 December 1998 (1998-12-23) figures 3,7	1-9

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 August 2008	12/08/2008

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Marrec, Patrick

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2008/050243

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 0440884	A	14-08-1991	AT	139754 T	15-07-1996
			DE	4003828 A1	14-08-1991
			ES	2088939 T3	01-10-1996
GB 191004680	A	23-06-1910	NONE		
EP 0885851	A	23-12-1998	CA	2235447 A1	16-12-1998
			DE	69836603 T2	20-09-2007
			ES	2277367 T3	01-07-2007
			JP	2889877 B2	10-05-1999
			JP	11060256 A	02-03-1999
			US	6076373 A	20-06-2000