NDSM wharf - a culture park

Application of ultra high performance concrete

Graduation thesis
Berend Bart Strijland
TU Delft, Faculty of Architecture
Julianalaan 134 2628 BL Delft
Tel. (015)2789111
informatie@bk.tudelft.nl

Berend Bart Strijland
Bagijnhof 119
2611 AN Delft
berendbart@gmail.com

Members of the graduation committee:

ir. Jan Engels (mentor Architecture)
prof. dr.-ing Patrick Teuffel (mentor building technology)
prof. Thijs Asselbergs
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Introduction

This thesis develops a new design for a parking structure spanning 50+ meters constructed in Ultra High Performance Concrete (UHPC). It explores history, development and future of the material UHPC. The design for spanning a large distance with concrete structures will be explored, and structural consequences implemented.

-Problem statement

The problem statement consists of three elements; the posed problem, the research questions and the design assignment.

The chosen technological fascination - Ultra High Performance Concrete in combination with innovative structures, based on precedents show great potential in architectural and structural design.

Design of construction will be the main field of research. The possibilities of a true plastic material in combination of the impressive mechanical statistics and prefab potential delivers an interesting challenge for the weeks ahead.

The problem stated is: What are possibilities of developments in Ultra High Performance Concrete in contemporary architectural construction forms?

-Design Assignment

The NDSM wharf in the north side of the Ij in Amsterdam, is a cultural hotspot. On this base of the old shipping dry-docks, numerous festivals - V ollt loves summer, War of the Words, 5D festival - take place every year. The factory building itself houses about 250 independent artists and graphic designers. Activities such as free markets, children markets, theatre shows and dance performances define the energy that wanders the NDSM wharf. The outdoor space that is vacant in between performances and festivals, is rented out as parking ground in order to keep the ‘stichting-NDSM’ financially viable.

The Amsterdam masterplan however designates this area as work/living by 2040. The development of the area is currently on hold due to the economic crisis, but the fact that it will be built with residential area is inevitable. In combination with this governments cultural budget cut by 50%, the immediate future for the NDSM wharf looks bad.

The architectural challenge in this design is the to utilize the potential of ultra high performance concrete in architectural design, and to explore its potential in large span constructions.

Relevance

Concrete is the most used building material in the world. Every year, seven billion cubic meter of concrete is produced, more than 1 cubic meter per person. The recent intensified research in concrete aggregates has led to developments in this field. The techniques that made this possible are amongst others electron microscopy, atomic force microscopy, nano indentation. These tools helped deliver a more precise way of producing high-tech concrete. Research question is: How can technical innovation in concrete be utilized to create long spans and more architectural innovation? Thanks to new understanding of the material, new design concepts can be researched.
Objective and approach

This thesis explores the current developments in the field of concrete, and its possible application in organic design. The analysed material will be transformed in a design and then tested on performance.

The objective therefor can be formulated as: ‘Develop a structural method or system for applying UHPC in innovative structures, based on graphic statics and then model it in an appropriate design software, where it can be described in a structural way.’

In order to reach the stated objective, the secondary objectives are formulated below:

a) Define a theoretical framework for current UHPC developments, stating methods of production, application

b) Define a reference framework (In Appendix)

c) Use the properties of newly developed material to form innovative design in construction elements

d) Illustrate the use of form finding methodology in the design

e) Implement the structure in finite element method analysis software (Oasys). Link results of the analysis and further develop the structural form

f) Evaluate performance and analysis method and form conclusions and recommendations.
Introduction Design and Urban Analysis

The NDSM wharf has been abandoned in the 1980’s due to bankruptcy of the industrial owner of the wharf. Since the mid 2000’s, the city of Amsterdam allowed natural expansion for the cultural sector. The main buildings of the wharf are now used as cultural office space, with the large open areas used mainly as festivals.

In the future the NDSM wharf changes a lot. There is approximately 240,000 square meters planned for the wharf before 2020.

In the municipality’s document on the future of Amsterdam, the program ‘Noordwaards’ states:

Important aspects of future development of the NDSM wharf

- Remaining of the rough and industrial character of the wharf
- Expanding the cultural centre to the largest in Europe
- Urban environment in very high density with maximum mix of program
The concept for the design is stacking the existing situation of cultural offices, parking, and event space.

Parking ground situation

Event area

Cultural offices
The program becomes the combination of parking, festival terrain and culture hotspot.
Entrance of the garage through the stairs
Fig. 11
Art Atrium.

Fig. 12
The concept is similar as Toyo Ito’s Mediatheque. A set of rigid floors penetrated by a more organic and non linear structure. In the construction analysis a GSA analysis was made of a truss, a set of columns working as a core and a calculation of a segment of the building.

Fig. 14

Fig. 15
The structure (green colour) is made of UHPC concrete. The large truss, indicated in red, will make the span covering the ramp.

Abstract diagram of the truss spanning the ramp.

The mesh above represents the truss of the construction. The mesh was modelled in GSA Oasys, FEM software, to be able to find maximum stresses in beams. These divided loads and stresses will then be transferred to a biological structure.
The biological structures found in nature will be an example of free form structure applied in the truss system. The structure picked comes from cracks in paintings, which in theory will always exist of lines drawing up exactly in between two points.

Thee structures found in nature. Often optimized ways of making a 3 dimensional structure with the least amount of material.
Initial GSA test.

Identifying the stresses (compression and tension).

Apply biological structure.

Overlay.

Identify stress maximum.

Added and changed mesh.

Mesh after initial calculation. Further optimization process in GSA elaborated hereafter.
The properties of UHPC by German firm Gtecz (gtecz.com). For this model the Qauntz Q250 properties are used, a next model the more experimental Q500.

Material properties GSA.

Load cases. Extended load cases in appendix.
The stresses in elements with diameter of 150mm and UHPC properties.

Deformation of truss elements up to 900mm(!)
Beams of top and bottom enlarged to 400x400 square beam with post tension cable. Idea is to compensate all tensional force in the concrete prestressed reinforcement.

Precedent: UHPC bridge in Amsterdam which works with tendon cables to compensate tensional force.
Prestressed cables in lower beam.

Axial forces in beams - tension in a few elements is problem.
Prestressed cable in both beams. The tensional force in a few beams have to be solved and 700 MPa is too high.

Deformation in elevation. Max deformation is 125mm
A single truss with axial stresses.

Facade elements by architect Ricoti imitating natural structure in UHPC elements.
A GSA analysis was made of a part of the building. The trusses are set up as three parallel sets and loaded on the extended load of event area and parking. Wind load was modelled for the location Amsterdam as a free standing structure with no surrounding buildings.

Mesh set up.

Loads of columns and q-load of floors.
Wind load on facade. See appendix excel load sheet attached.

Deformation on facade as result of wind load.
Q-loads of floors and wind load.

The stresses in the beams. Values range from 100 N/mm² to -400 N/mm², well within the property reach of UHPC.

Deformation of trusses on the Z direction. The truss of 54 meter span shows a deformation of -30 mm maximum with a section of 200-300 and prestressed tendon beams on the bottom.
**Columns**

Since UHPC does not need ‘conventional’ reinforcement the properties can mainly be utilized in the field of free form. This makes very efficient manufacturing possible in combination with tensile fabric form work.

The concept for the building is a sharp set of floors penetrated by a very organic looking structure that follows biological form. The columns are based on the structure found in wool, where wires form a certain

Exploded view of the structure. The set of columns indicated with red is described below.

The fabric is analysed and split up in certain ways that they split up. A matrix is developed to find possible combinations for the ‘mesh’ of columns. The columns won’t work if placed separately, but are connected to work as a more rigid construction. This also allows the columns to be much thinner.
The concrete consoles of the floor allow the mesh to be connected to them on variable places. This way, if seen in section through the construction, the mesh makes a more ‘random’ appearance. Also this makes the columns look like an organic element growing through the building.
The columns as set up in the model. The red lines indicate the way the structure works as a set of direct lines transferring load. Therefore, the curved appearance of the beam does not compromise its strength.

The set of columns as seen in the building.
GSA Analysis

Input GSA described. The model was set up in AutoCAD and exported to GSA. The material properties are similar as the ‘truss’ with data supplied by Gtecz Germany. The nodes are pinned on the end’s of the beam on top and the bottom of the columns.

The load was set up as a q-load on the beam on top at -875 kN/meter. This is based on the excel load sheet, see appendix.

The section of the columns is set up at 100 mm. The beam on top is animated as a beam of 300 x 200 mm

In the right image, it becomes obvious that once there is a straight column in the set, all loads go through that one and it will break.
The beam stresses in the columns are maximized at 120 N/mm². This is well below the 500 N/mm² the material can take.

Deformation in the z direction. The deformation is maximized at 125 mm, which is still unacceptable.
A changed setup for columns. No column is now unconnected to another one to improve on stiffness of the structure.

Deformation is now acceptable.
A set of columns set up as a mesh that can act as a core. The columns now can take up the rotational moment.
The construction principle detail.
Regarding the performance of UHPC in design, compared with existing construction, the following can be stated:

- UHPC has unique properties that have the ability to change the way concrete is used entirely.

- The main reason UHPC has potential especially in architecture is the absence of reinforcement. The fletching of steel reinforcement makes complex structures very tough to execute.

- The biological structures explored are just one way of showing the potential in construction in combination with textile formwork. The need for rectangular beams and trusses gets less certain because of form freedom and possible structural alternatives.

- Structure can be created analysing adapting structural activity in construction.

- The main disadvantages of UHPC material in thin construction design is frigidness of the construction.

- Disadvantage of UHPC is that due to limited production, cost of material are still very high and uneconomic
Light analysis

The design was modelled in Velux sun simulation to test the light penetration in the structure. Velux software is created by the foldable window manufacturer and produces realistic light calculations for the building industry.

Three representative locations of the interior space were identified and calculated. In this calculation, the date was set at July, at noon in Amsterdam. The glass had a standard transparency for glass of 68%.

The Art-City space equipped with separate office space delivers light at the borders of 500 lux, office quality. However, more towards the center artificial lighting will be necessary for office work or other activities.
2. The Art-City space equipped with separate office space delivers light at the borders of 500 lux, office quality. One of the office boxes are the border. The analysis shows great gain of light at the borders of the construction. The light intensity reaches 500 lux even on the inside of the office, which would theoretically enable work with no artificial lighting.

3. A typical office space. The glass on both sides allows for maximum light entrance. The entrance is very bright, further into the office artificial light is needed.
Mechanical engineering

The atrium is naturally ventilated with ventilation rafts on the sides. The offices are also naturally ventilated. Mechanical ventilation is there for the toilets and kitchen area.

The mechanical canals are all rounded up in the floor alongside the interior.
The air system is mechanical for toilets and for the night venue.

The water from the Ij acts as a heat exchanger for the heating system.
The interior spaces are set up with sprinkler installations. The Dutch law does not enforce sprinkler systems in above-ground parking garages.

The fire compartments. The flight escape routes are the ramps, the main staircase and the stairs on the right.
A series of calculations show improvements on concrete properties applied in structural components. The comparison here is a basic calculation of C28/35 concrete with conventional material and a C170/200 UHPC construction.

For these tests following materials were used:

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<th>Name</th>
<th>C28/35 concrete</th>
<th>UHPC 170/200 Ductal</th>
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<td>Compressional strength:</td>
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**Beam**

Results bend able moments:

Beam: 400mm x 600mm
Usable height: 0.9 x h = 540mm
Reinforcement Maximum

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<td>Moment</td>
<td>6392 mm²</td>
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Concluded can be that in a beam, the difference between concrete and high performance concrete is not very large. The only big difference is that UHPC can contain much more reinforcement through which its bending moment can be much larger.
Beam

Beam: 400mm x 600mm
Usable height: 0,9 x h = 540mm
Reinforcement 2128 mm² (0,8%)  
Med 500 kNm

Results shear force:

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Using fibres in construction will greatly improve its shear existence.
Column

Beam: 400mm x 400mm x 4000 mm
Reinforcement 4% = 6400 mm²

Results:

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<td>Normal force N</td>
<td>1405 kN</td>
<td>5435 kN</td>
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<td>Second order moment</td>
<td>442 kNm</td>
<td>1068 kNm</td>
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The ultra high performance concrete shows a normal force of 5435 kN where regular concrete can only take 1405 kN on a similar 400x400 section. Very high compressional forces can be achieved with UHPC.

Excel sheets in appendix.
Final Reflections

Reflecting on the main objective of this thesis it can be said that it has been successfully achieved within this project scope and research question: What are possibilities of developments in Ultra High Performance Concrete in contemporary architectural construction forms?

The method used, while it still has limitations, shows interesting possibilities in the construction design optimization. The structure tries to find the optimal shape regarding load transfer. This method is done with graphic form finding, computer programmed structural optimization is needed to finish really optimise.

The outcome of the project shows a continuation of the urban landscape into the sky through a set of very rigid floors. The structural system designed is in big contrast with this system, which makes it very interesting and intriguing architecture. Parking structures almost embody or reflect the history and continued progress of concrete technology through the in-situ age, the rise of prefabrication and pre-stressed and post-tensioned structures.

The results is an exaggerated view of how technological fascination and urban analysis comes together.
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Cover: Hut of Laugier
Appendices
Load cases GSA analyses

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| total load column facade | | | | | | | | | |

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## Thesis - Ultra High Performance Concrete

### Table: Loads

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