MEng Membrane Lightweight Structure

Design of a Grid Shell structure with fabric formed concrete panels

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by

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Nixon Mosomi
Anthony Oloo

Abstract

Very few timber grid shells exist around the world, despite their many advantages. The knowledge of designing, building and erecting grid shell structures is concentrated in very few people worldwide. Form finding, analysis and optimization are difficult. Erection also has many challenges – 2D plans cannot accurately describe 3D doubly curved forms. It is no surprise therefore that many architects and building professionals shy away from this particular building task.

It is only in the last decade or so that computational tools for the design and analysis of grid shells have become relatively available. This has led to an increased interest by architects and engineers to investigate this building form again, as evidenced by the construction of the Downland and Savill Garden grid shells nearly twenty-five years after the construction of the Mannheim Multihalle.

Therefore the aim of this paper is to present what has been done in the past, present computational form finding strategies and cladding options in order to create a body of knowledge that may be useful to others who are in the quest to find additional information regarding this unique building form.

Contents

1.0 History of grid shell structures

1.1 Mannheim Multihalle

Built in 1975, the grid shell at Mannheim was designed by Frei Otto, a leading proponent of membrane architecture and lightweight structures. This radical building was the first multi-layer timber grid shell to be constructed in the world. The structural engineers were Ian Liddell and Edmund Happold from Ove Arup & partners.

Form finding was done by means of a hanging chain model. Chains hanging in tension form funicular geometries which when inverted act in pure compression. This is therefore an effective means of exploring structurally efficient geometries. This technique was also used by the Spanish architect Antonio Gaudi when doing form finding for the chapel at Colonia Guell.

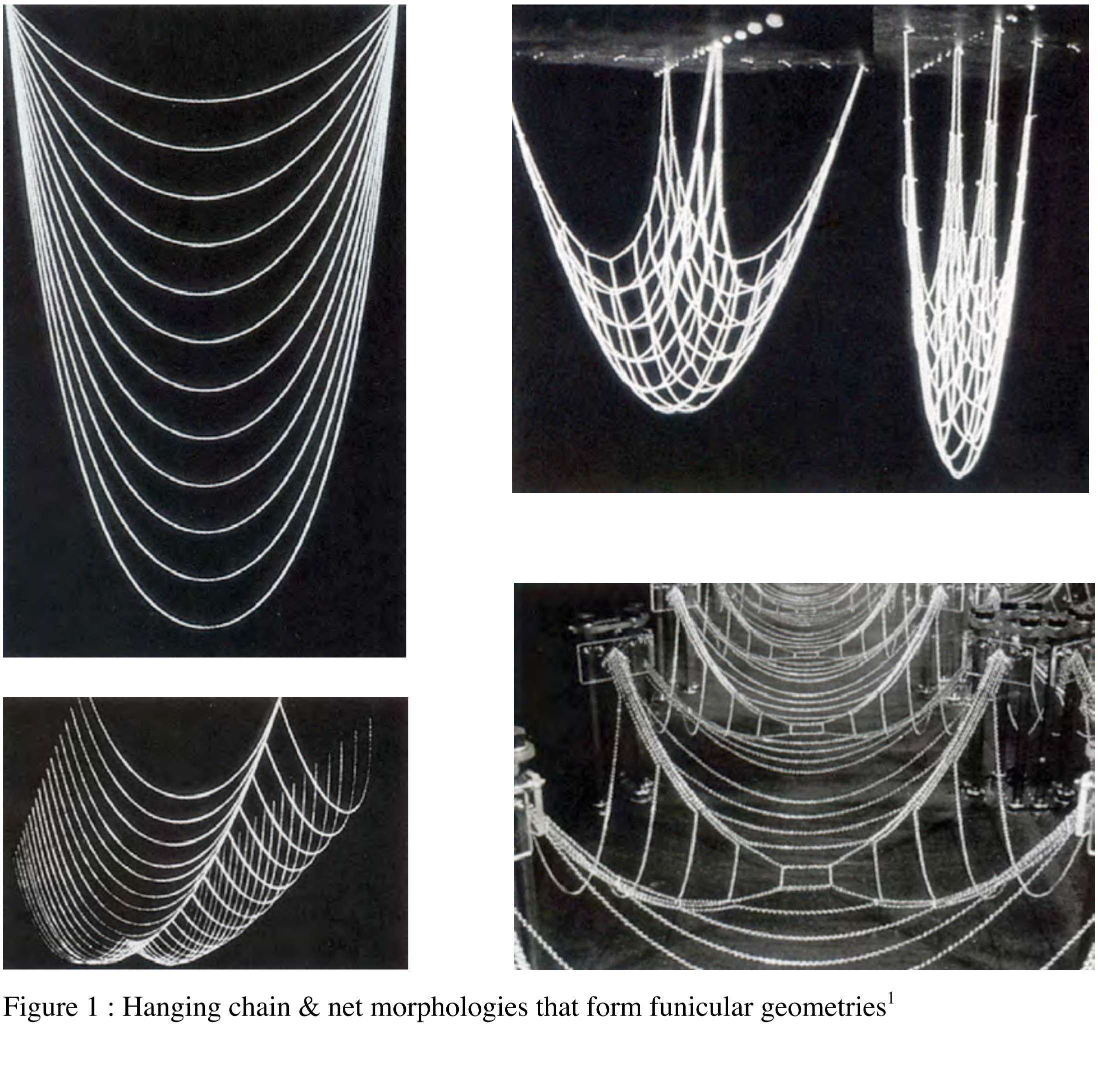


Figure 1 : Hanging chain & net morphologies that form funicular geometries[1]

[1] Frei Otto & Bodo Rasch, Finding Form (1995), Deutscher Werkbund Bayern

Figure 2 : hanging chain model for Colonia Guell[2]

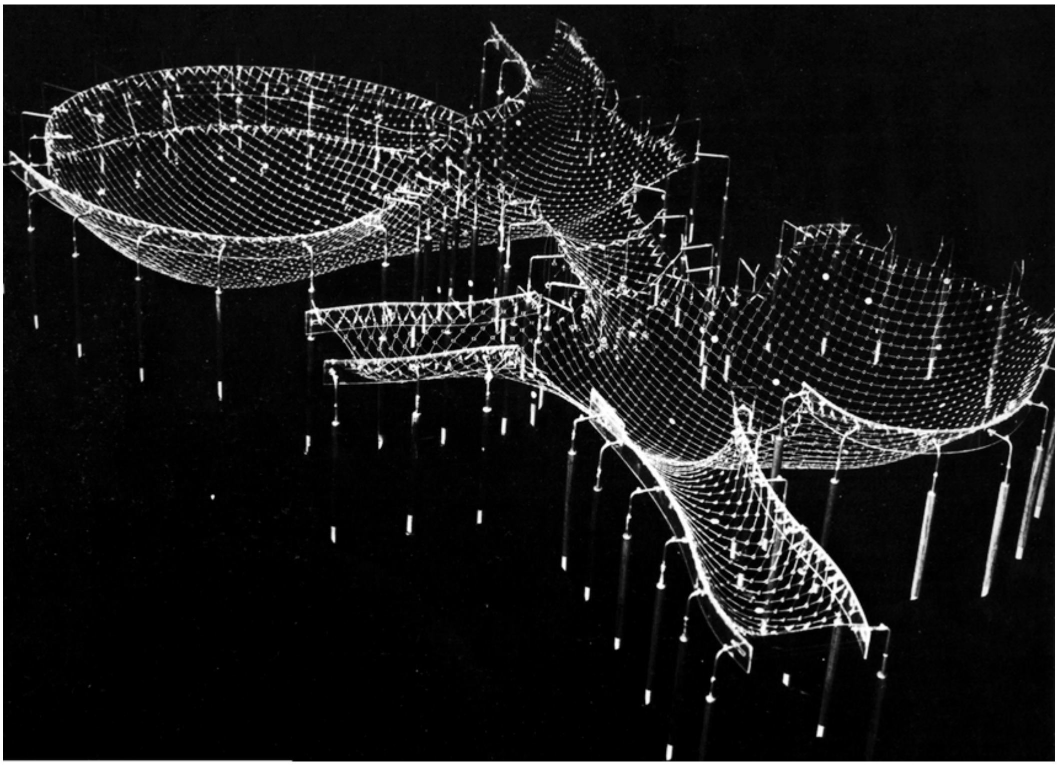


Figure 3 : hanging chain model Mannheim grid shell[3]

[2] Frei Otto & Bodo Rasch, Finding Form (1995), Deutscher Werkbund Bayern
[3] http://www.smdarq.net/case-study-mannheim-multihalle/

Form finding using the hanging chain method allows the designer a sculptural freedom and iterative feedback that paper drawings cannot match.

The building was constructed in response to a design competition that called for a temporary building for a federal garden exhibition that was to be held for six months. The building was so well received that the decision was made not to dismantle it after the exhibition.

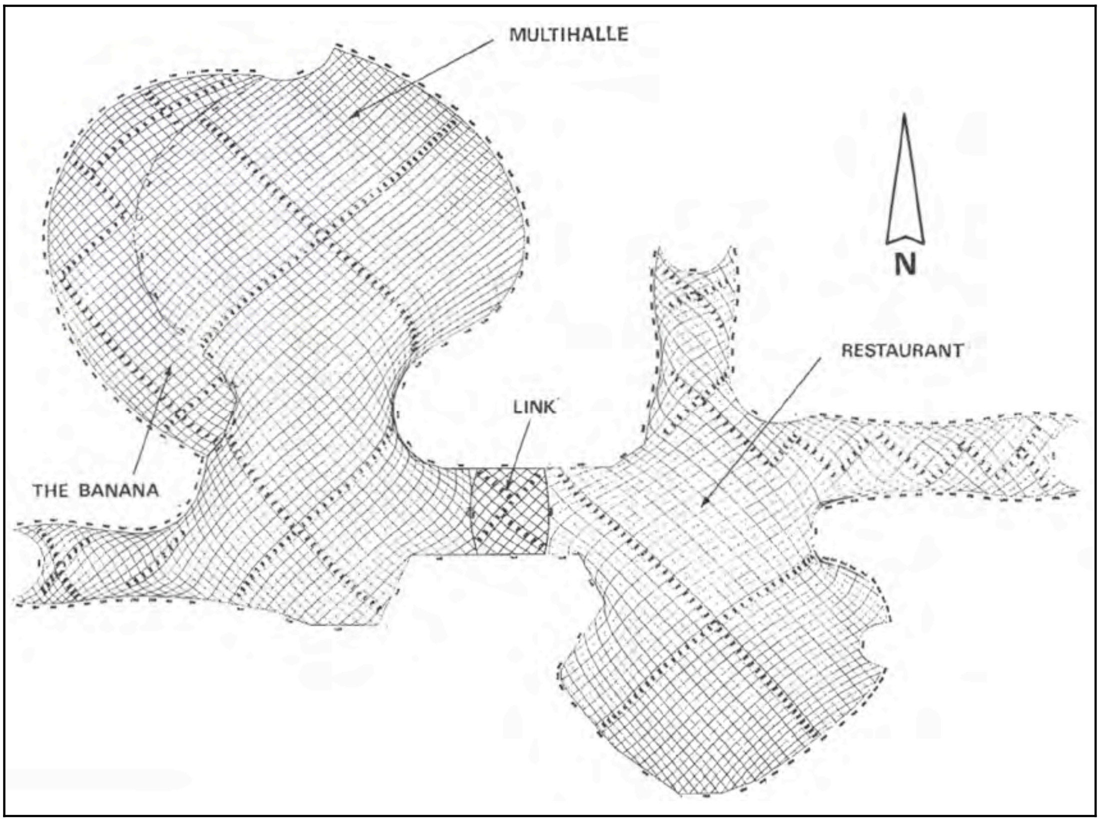


Figure 4 : Plan view of Mannheim Multihalle[4]

The hanging chain model was measured using a photogrammetric process and the model nodes input into a computer to do the non-linear structural analysis process and plot the plans and elevations of the model.

This building is remarkable due to the fact that the design and engineering was being thought out and designed literally as the project was underway – in short a new vocabulary of building form, structural analysis and connection details was invented for this project

[4] The structural engineer / March 1975 / No.3 / Volume 53

Figure 5 : exterior view of Mannheim Multihalle[5]

Figure 6 : interior views of Mannheim Multihalle

[5] http://www.smdarq.net/wp-content/uploads/2009/10/OttoMultihalle-ext_view.jpg

Nodes & support details

The grid shell at Mannheim was conceived of as a four-layer shell (2 lath layers in each direction). The laths were made from hemlock with a cross section of 50 x 50mm. The node connections were threaded rods that allowed in plane rotation of the laths during the erection process. Diagonal bracing was required to stabilize the structure after erection.

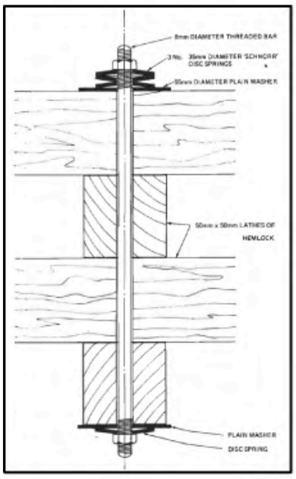


Figure 7 (a) : node detail[6]

Figure 8 (a) : photo of node

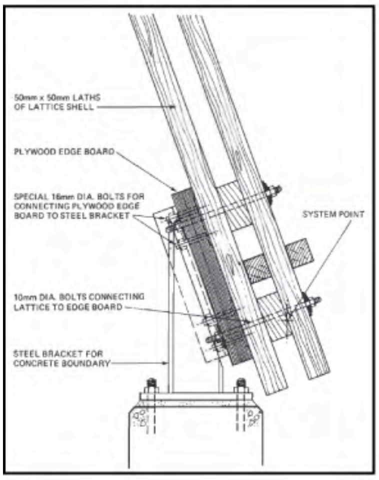


Figure 7 (b) : Concrete edge detail

Figure 8 (b) : photo of edge detail

[6] 7 (a), (b), (c) - The structural engineer / March 1975 / No.3 / Volume 53

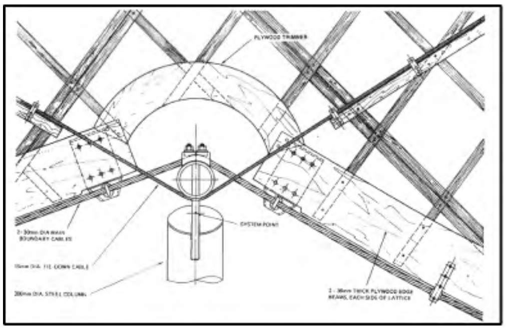


Figure 7 (c) : cable boundary detail

Figure 8 (c) : photo of cable edge

Erection process

The erection process was initially to be carried out using four two hundred ton cranes but on further thought many difficulties were found with this approach. One such difficulty was the fact that a large number of lifting points were required in order to get the correct shape of the shell, and that the cranes would be required to stay in position until all the nodes were bolted. It was also difficult to calculate the effects of the lifting points on the final shape.

Therefore it was decided that scaffolding towers with H-shaped spreaders would be more effective as the erection process could proceed at a slower pace thus giving more time and control to the contractor. This system worked well in the end, as this was the first time such an erection process was carried out.

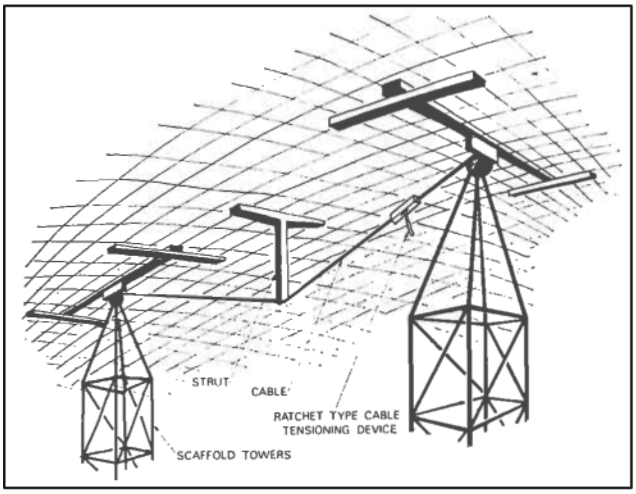


Figure 9 : scaffolding towers, H spreader & flying strut used to eliminate low points[7]

[7] The structural engineer / March 1975 / No.3 / Volume 53

1.2 Weald & Downland Museum

The construction of the weald & Downland Museum in West Sussex, England commenced in 2001 26 years after the completion of the Mannheim Multihalle. It was designed by Edward Cullinan Architects. The structural engineers were Buro Happold. The shell has a form resembling a triple bulb hourglass and is built over a concrete lower level buried into the chalk hillside below. The lower level functions as a storage area, workshop and offices. The plan area of the grid shell is 48 x 15 metres.

Form finding

Form finding was carried out by means of a computer software program using the dynamic relaxation technique. Models were also made to get a feel for the structural behavior of the shell and as a guide for the erection process.

Figure 10 : Views of the Downland grid shell[8]

[8] http://www.wealddown.co.uk/Buildings/Downland-Gridshell-Construction-Process

The building functions as a workshop where parts of buildings from the 15th to 19th century are restored. It is also meant to house offices and storage facilities for artifacts from this era.

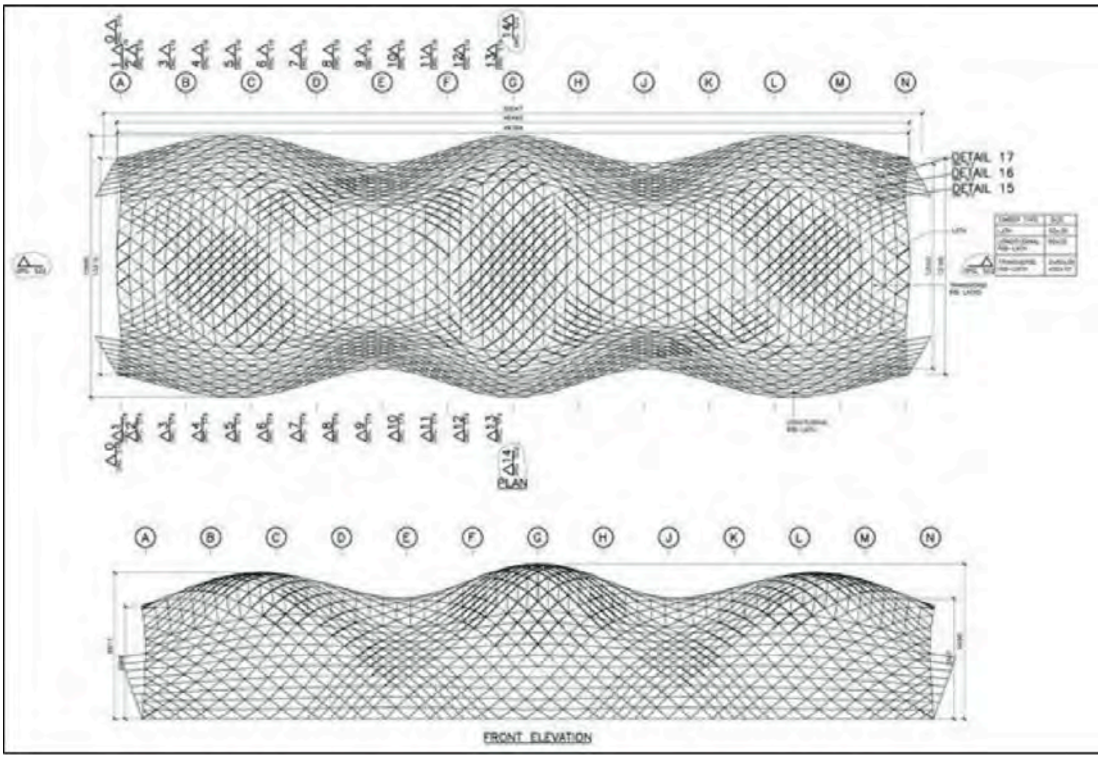


Figure 11 : plan and elevations of the Downland grid shell[9]

The shape of the grid shell is not funicular as it is not based on a hanging chain model, i.e. its members are not purely in compression under their own self-weight. With modern computer based form-finding techniques it is possible to produce non-funicular geometries. A funicular shape is advantageous but not essential.

Apart from computer based modeling, physical modeling was also used extensively in this project – a simple 1:100 wire mesh model was initially made to demonstrate to the client and the design team the 3D form. After this a 1:30 scale model using wood strips was constructed to give the whole build team a feel for how the structure would behave under asymmetric loading.

[9]http://www.architectureweek.com/cgibin/awimage?dir=2003/0129&article=building_2-2.html&image=12029_image_10.jpg - accessed on October 14 2012

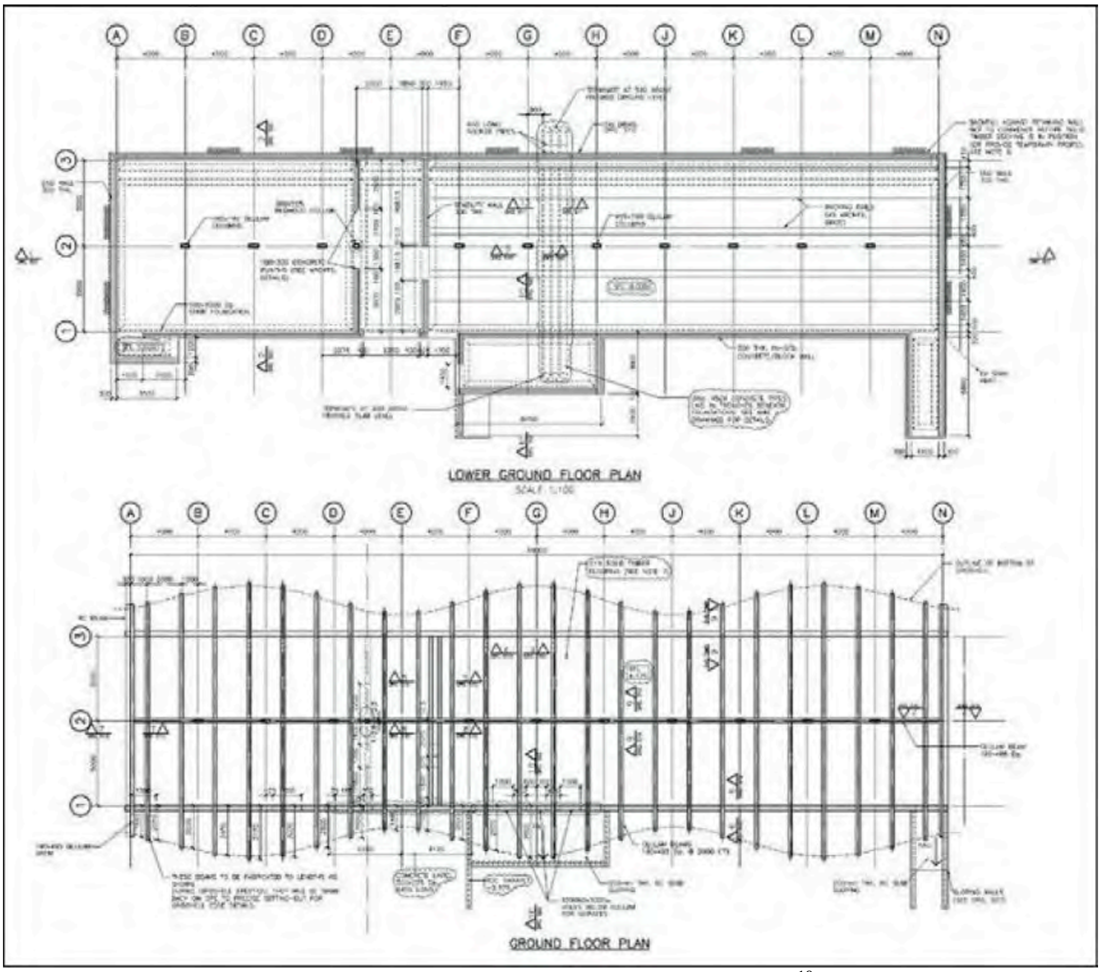


Figure 12 : lower and ground floor plans for the Downland grid shell[10]


Figure 13 : interior views of the Downland grid shell[11]

[10]http://www.architectureweek.com/cgibin/awimage?dir=2003/0129&article=building_2-2.html&image=12029_image_9.jpg

[11] http://www.wealddown.co.uk/Buildings/Downland-Gridshell-Construction-Process

Nodes & support details

The lath nodes for this project are made of 3 plates with the middle plate having locating holes to ensure that the correct geometry is achieved. The outer plates allow sliding and in plane rotation of the laths during formation of the shell

Volunteer curator Alan Old explains, "*After the diagonal bracing was in place, two of the four bolts on the plates were tightened just enough to provide stiffness throughout the shell. Once the structure had reached its final shape, all four bolts of each coupling were tightened to compress the wood together.*" (http://www.architectureweek.com/2003/0129/building_2-2.html - Don Barker, 29 January 2003)

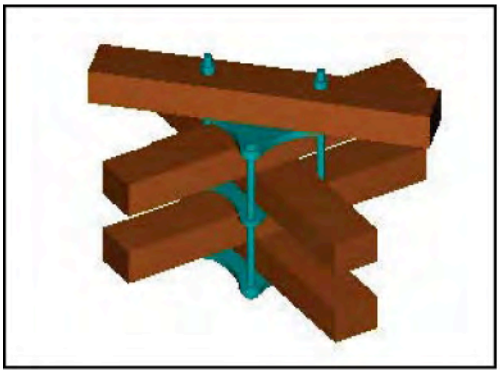
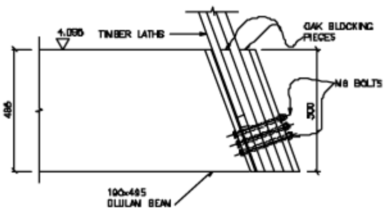


Figure 14 : Downland node[12]

Figure 15 : photo of the node[13]

At the boundary, sandwiching the laths between two plywood bands provided continuous support.



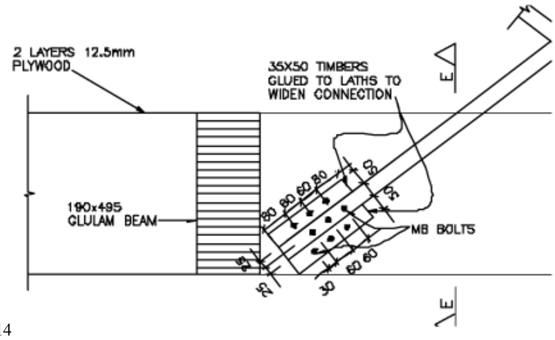


Figure 16 : Downland grid shell edge details[14]

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12 Harris et al. 2004 : 1005. http://ewpa.com/Archive/2004/jun/Paper_018.pdf

13 http://www.architectureweek.com/cgibin/awimage?dir=2003/0129&article=building_2-2.html&image=12029_image_8.jpg

Erection process

An important aspect of the construction of the Downland grid shell was that the flat lattice of laths was lowered downwards from a raised scaffolding platform towards the perimeter boundary. This was done in successive stages by removing the scaffolding to allow gravity to help deform the laths into their final geometry under their own self-weight.

In comparison the Mannheim grid shell was erected by pushing the lattice upwards from the ground using scaffolding towers and jacks.

Figure 17 : Lowering of the lattice to form the Downland grid shell[15]

[14] Harris et al. 2004 : 1006

[15] http://www.wealddown.co.uk/Buildings/Downland-Gridshell-Construction-Process

1.3 Savill Garden grid shell

Commissioned in June 2006, the Savill building sits at the entrance to the Savill Garden and acts as a gateway to the Royal Windsor Great Park. Designed by Glen Howells Architects and structural engineering consultants Buro Happold in conjunction with Haskins Robinson Waters (HRW), the structure houses all visitor facilities including a ticket office, shop, self-service restaurant, seminar rooms, offices and a small garden centre all under one gently undulating roof.

The grid shell roof is designed as a giant leaf that floats above the ground fixed to a tubular steel beam that rings the roof perimeter. Paired steel tubes carry the forces to concrete foundations that are linked to each other by below ground tie beams on both sides of the building.

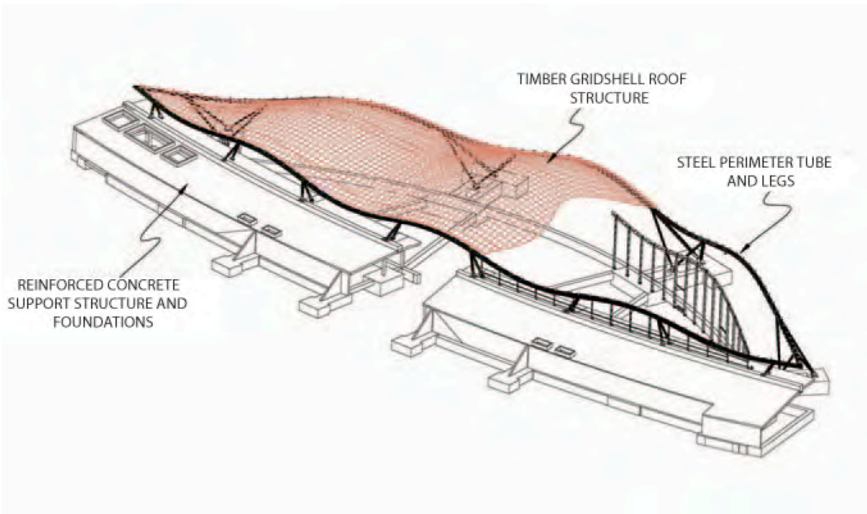


Figure 18 : structural layout of the Savill Building[16]

The roof shape is a symmetrical, 3 domed doubly curved sinusoidal shape with overall dimensions of 90 x 25 metres. The grid shell is comprised of four layers with a 1-metre grid of larch laths.

Form finding

The form finding process was carried out exclusively on the computer for this project using a parametric modeling process. Harris et al. [17] report that the perimeter shape on plan was set out using the arcs of two intersecting circles. The roof centerline (in section) was generated by a sine curve with its peaks

[16] Harris et al, The Structural Engineer 2 September 2008

and troughs at the tops of the domes and bottom of the valleys. The cross section is then set out across the sinusoidal centerline as a series of parabolic curves. A special program was written to define the roof surface shape as $z = f(x, y)$ with a damped cosine wave in the x direction and upside down parabolas in the y direction.

Figure 19 : photo of long elevation – Savill grid shell[17]

Once the roof surface shape had been created, the next step was the generation of an equal mesh grid over the surface using the chebyshev method.

Figure 20 : long elevations of the savill grid shell[18]

[17] http://www.glennhowells.co.uk/content/public/110/0/1 - accessed on may 5 2012
[18] http://www.glennhowells.co.uk/content/public/110/0/9 - accessed on may 5 2012

Figure 21 : interior view of the Savill building[19]

Nodes & support details

The lath nodes for this project are 80 x 50mm larch timber based on a four-layer grid shell. The lath size and spacing (of 1 mt intervals) was determined after three species of timber were sourced from the Crown Estates and tested for their suitability. Therefore the structural design process was informed by the structural tests carried out on the timber samples.

As the grid shell is carried by the perimeter steel tube, steel gusset plates have been welded onto the tube to transfer the load from the laths.

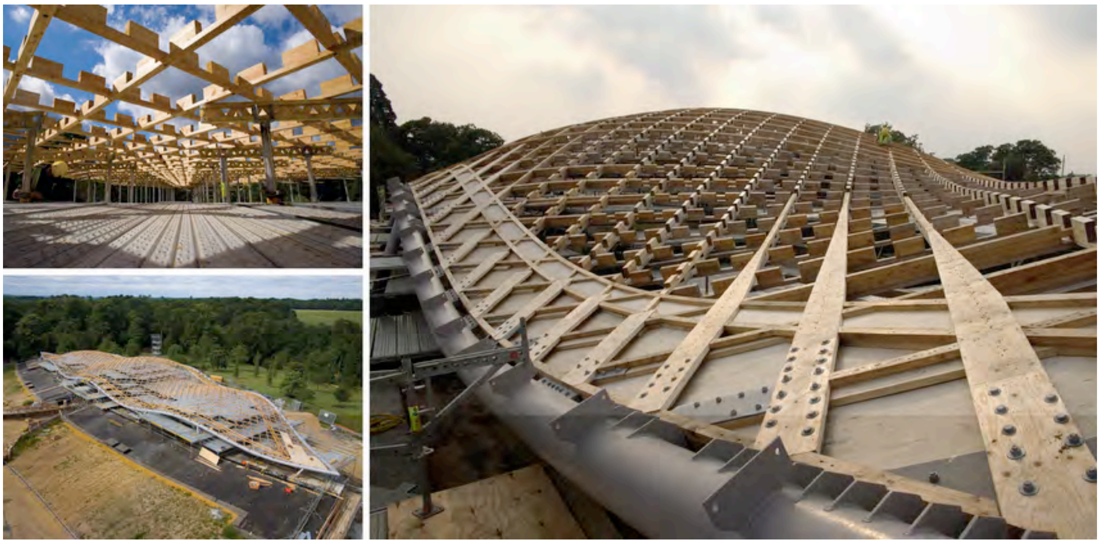


Figure 22 : edge details showing gusset plates and shear blocks[20]

[19] http://www.glennhowells.co.uk/content/public/110/0/4 - accessed on may 5 2012
[20] http://www.glennhowells.co.uk/content/public/110/0/6 - accessed on may 5 2012

Erection process

During the erection of the Mannheim and Downland grid shells, all four layers of the grid lattice were bent together. In the case of the Savill grid shell, two layers were bent as a first stage. Thereafter the shear blocks were screwed on and then the next two layers installed over the blocks.

Gridshell	Span	No. of layers	Lath Size	Material	Bracing
Mannheim	60m x 60m	4	50 x 50mm at 0.5m.	Hemlock	Twin 6mm cables every 6th node
Downland Gridshell	48 m x 15 m	4	50 x 35mm at 1.0 m.	Oak	Timber cladding rails, alternate nodes
Savill Garden Gridshell	90 m x 25 m	4	80 x 50 at 1.0 metre	Larch	plywood roof

Figure 23 : Summary of structural elements of the Mannheim, Downland & Savill grid shells[21]

Conclusion

Over the last three decades, computer technology and software development have progressed to the point where the difficulties faced by the first designers of grid shell structures can be overcome. In addition parametric computing has increased the search space for possible solutions for form and structural analysis and their attendant optimization far beyond what is possible with physical modeling.

Nevertheless the successful realization of a grid shell structure demands close collaboration between the architect, engineer, building owner and contractors. It is important to form a team at the outset of the building task and have regular interdisciplinary meetings.

[21] http://ewpa.com/Archive/2004/jun/Paper_018.pdf - accessed February 4, 2012

2.0 Form finding strategies

Introduction

Free-form architecture has become more popular in recent years. This has led to an increased interest by architects and engineers to develop improved methods of design and production. NURBS (non-uniform rational B-splines) modeling techniques now make it possible to create almost any surface and to generate a grid pattern on the surface.

There are two types of strategies that can be employed when form finding a grid shell structure – geometric and non-geometric modes of surface generation [1]. Geometric modes of surface generation produce the traditional classes of surfaces such as spheres, cones, surfaces of revolution and ruled surfaces. Therefore this mode of surface generation is somewhat limited in the form finding of grid shell structures. Non-geometric modes of surface generation produce the class of freeform surfaces. However here we are concerned with freeform surfaces generated by determinants such as gravity, pre-stress, air pressure and particle/spring systems, i.e. so called form-giving agents.

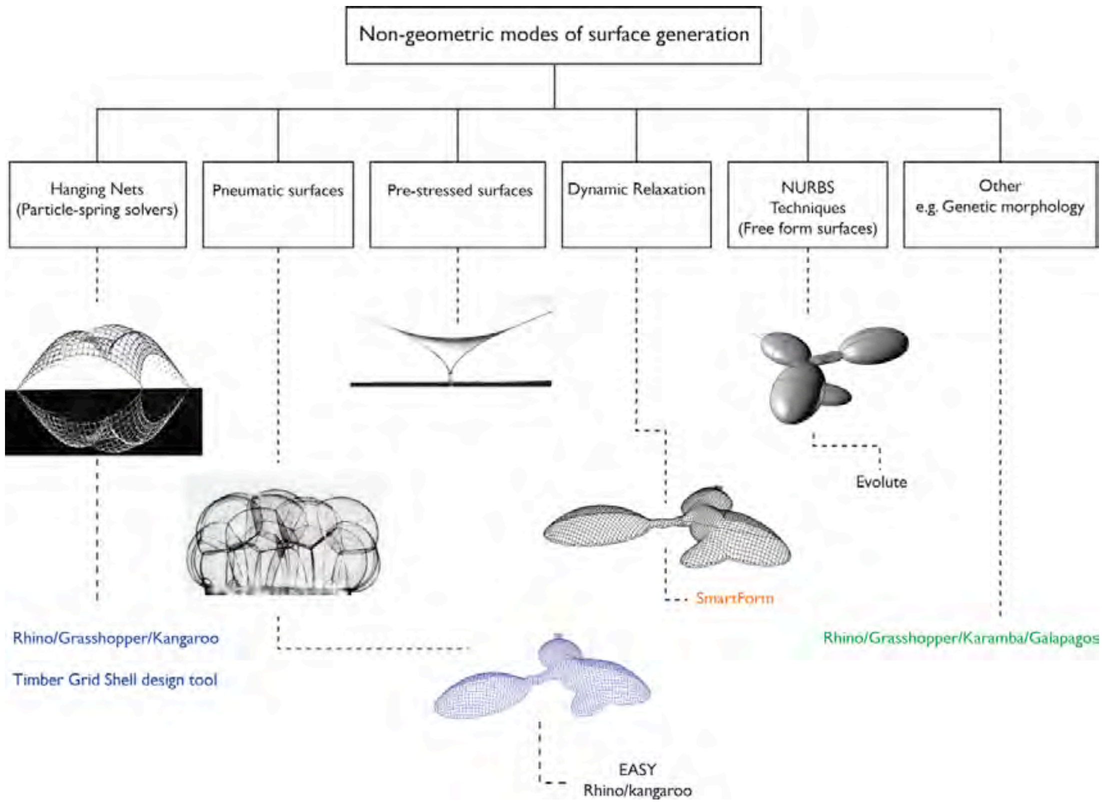


Figure 24 : different modes of surface generation

2.1 Definitions of grid shell structures

Timber or composite grid shell structures

Lienhard et al. state that timber or composite grid shells are structures that base their geometry on the elastic deformation of initially straight or planar elements. Bending is not avoided but actively used to create complex doubly curved geometries.

Bending can be considered as a process of self-formation for these structures. Therefore the physical properties of the chosen material must be taken into account when doing form finding.

The capacity of bending active structures to develop arch or shell properties in their final deformed state makes their load bearing behavior similar to that of form and surface active structures. In timber or composite grid shell structures bending is not avoided but systematized to create complex double curved geometries using commonly available building products [2].

Steel grid shell structures

Steel grid shell structures are mostly composed of single layer lattices with cable bracing systems. These structures differ from timber structures in that they have axially stiff members connected to nodes. Bending is not a process used in the formation of the final geometry.

Steel grid shells can be referred to as free-form reticulated surfaces. Steel grid shells must have a size, geometry and node details that are perfectly defined which is not the case for timber grid shells [3].

2.2 Bending resistance and its influence on form finding

Timber grid shells as defined above are bending active structures. Therefore the material properties of the timber species chosen for the project must be taken into account when doing form finding. According to [2], material dependant elastic bending radii are tabulated as :

Material	Youngs Modulus E [N/mm²]	tensile strength 60% fyc [N/mm²]	minimal radius as a factor of thickness
CFRP-HAT	165000	1680	49*t
GFRP-P	25000	144	87*t
Plywood	11000	30	183*t
Aluminium	70000	120	292*t
Steel	210000	213	493*t

Figure 25 : elastic bending radii of common grid shell materials[22]

According to the Euler Bernoulli law, a bending moment M is proportional to the change in curvature $\frac{1}{r} = \frac{M}{E \cdot I}$ [2]

For flat sections or plates the width has no influence on the bending stress, which can therefore be written as

$$\sigma = \frac{E \cdot I}{r \cdot w} = \frac{E \cdot t}{2 \cdot r} \quad [2]$$

For example, if cypress pine is the chosen material for the project with a trial section of 50 x 35 mm and E = 10^4 N/mm^2, the minimum radius as a factor of thickness can be estimated to be 166*t = 4980 mm. Therefore this information can be used to input control curves into the CAD system when carrying out the form finding process, as a visual check to see that parts of the grid shell do not have a radius of curvature tighter than the specified value. Alternatively the CAD system can be queried to check radii of curvature at different parts of the grid shell geometry.

2.3 Form finding with different software packages

A starting boundary condition as shown in figure 25 was used with all software packages as the basis for comparison of the results.

[22] Lienhard et al. (20110. Bending-active Structures – Research Pavilion ICD/ITKE research paper submitted to the International Association for Shell & Spatial Structures, p.2

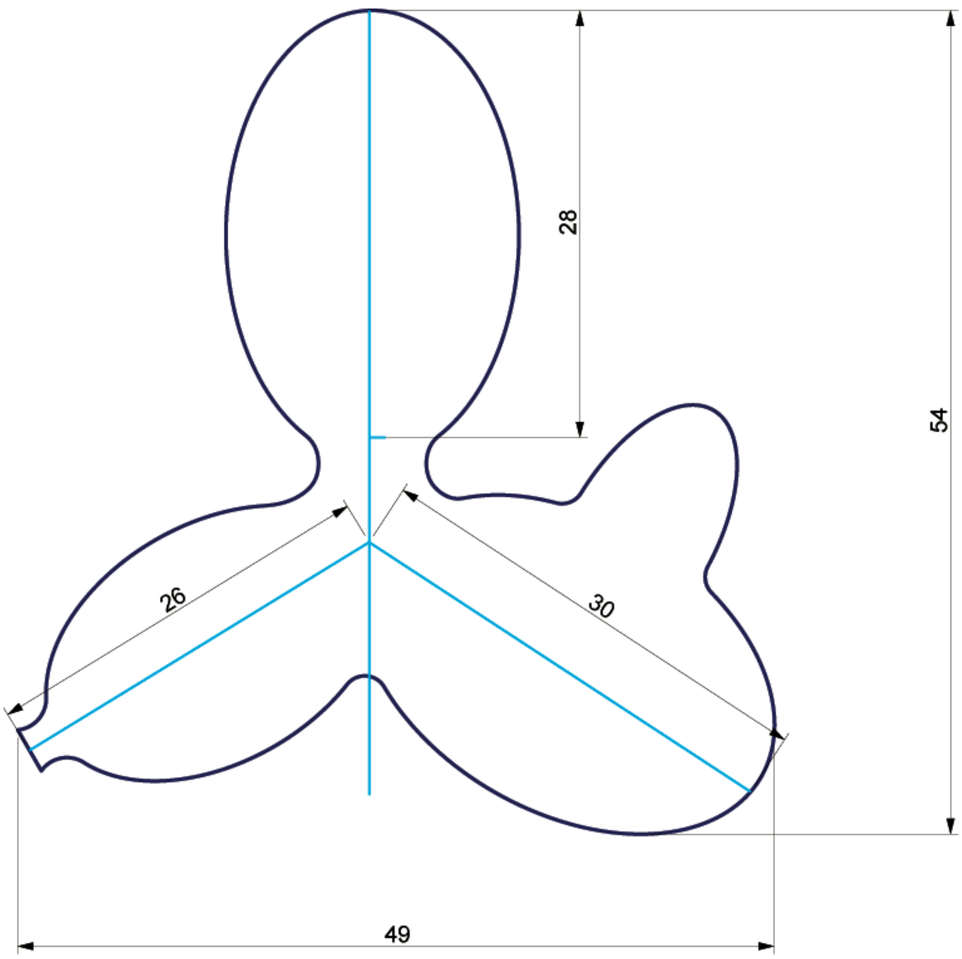


Figure 25 : initial geometry – boundary condition (dimension in metres)

Form finding with EASY (Technet)

The volume form finding component in EASY software was used to model the grid shell geometry using pneumatic pressure as a form-giving agent. The boundary condition was imported into the software and parameters set for form finding as follows :

1. Angle between U and X - 28^0
2. Angle between U and V - 90^0
3. Grid spacing 0.5 mt

Easy uses the force density method as the engine to find the form and equilibrium geometry under pre-stress or as in this case, inner pressure. Force density is a form finding concept based on force – length ratios (‘force densities’) for each link of a net or membrane field. The method is independent of the starting positions of the nodes in the initial geometry. The method transforms a system of non-linear equations to a set of linear equations, which can be solved. Different force density ratios will produce different equilibrium geometries. Therefore the force density method is used to identify the equilibrium shape associated with a specific pre-stress [6].

The equilibrium shape represents a minimal surface, which can also be defined as a minimum energy surface.

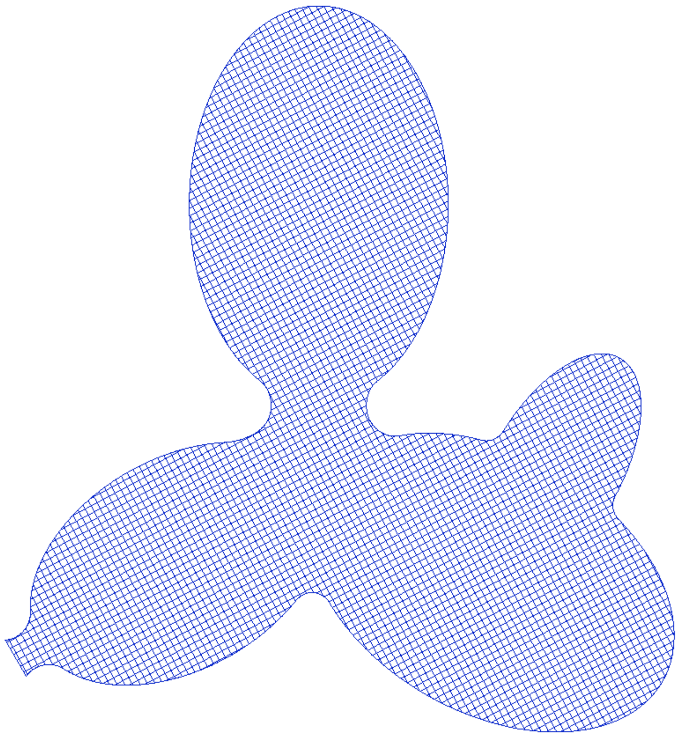


Figure 26 : intermediate mesh generated prior to inflation

There are several ways to control pneumatic structure, the main attributes that describe pneumatic structures are [4]:

- Pressure (P)
- Volume (V)
- Temperature (T)

The Boyle Marriotte`s law describes the relation between these values as follows:

$$(\mathrm{P} + \mathrm{P}_o) \bullet \mathrm{V} = m \bullet R \bullet T$$

With m = mass, R = constant value for gas.

To control the form either the pressure or the volume can be held constant to calculate the other value.

These values can be edited with Easy’s VolEdit sub-program.

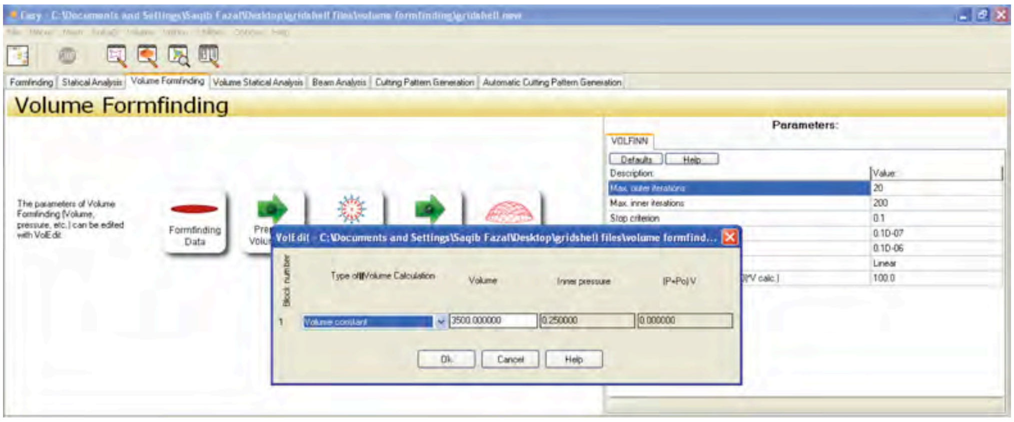


Figure 27 : VolEdit program set to volume constant option

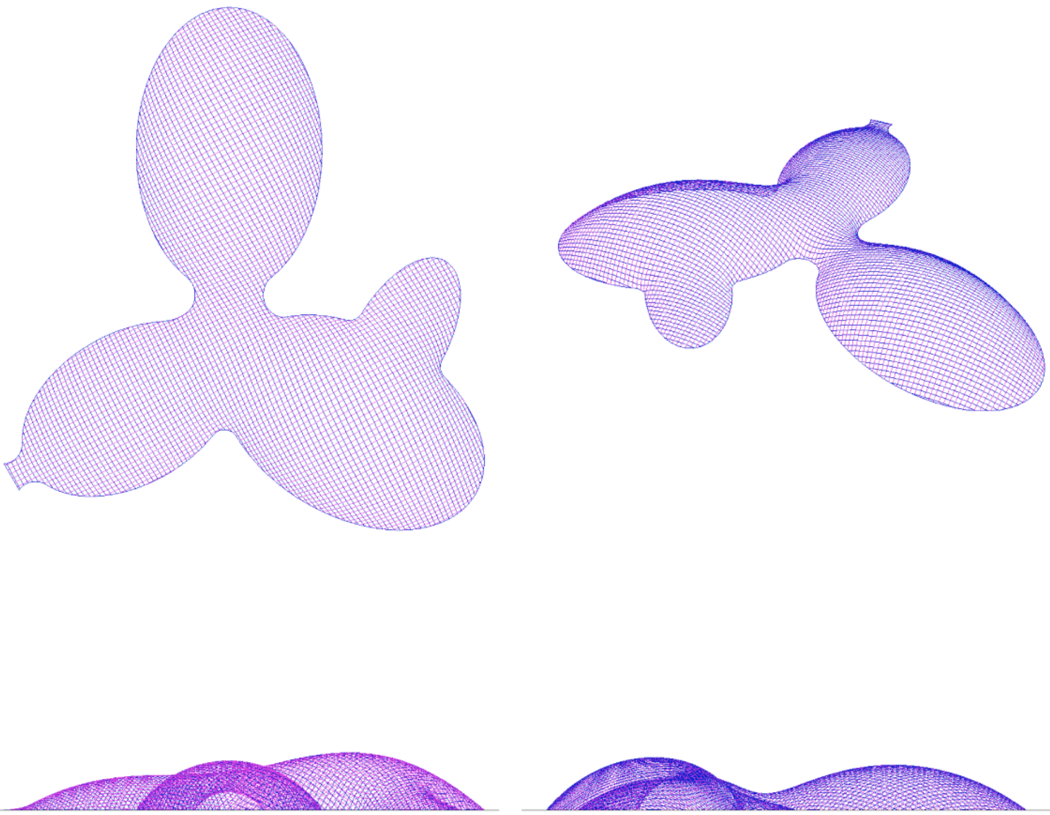


Figure 28 : result of the volume form finding process with EASY

This result can be exported in dxf format to a commercial FEA program such as Oasys GSA for structural analysis.

Form finding with Smart Form (Buro Happold)

Buro Happold has a developed a freeware plug-in that operates inside the Rhino 4 CAD environment. This plug-in uses dynamic relaxation as the engine to generate the equilibrium geometry [5].

Dynamic Relaxation is a numerical method originally developed to do form finding of membrane and cable net structures. The method is essentially a particle spring system. Mass is applied to the nodes of the starting geometry and the system oscillates to rest at an equilibrium position. Damping is applied to bring the particles to rest and increases the speed and efficiency of the computation process. It is an iterative process in which the geometry is updated at every time step.

A brief description of how the plug-in was used to generate the grid shell geometry follows :

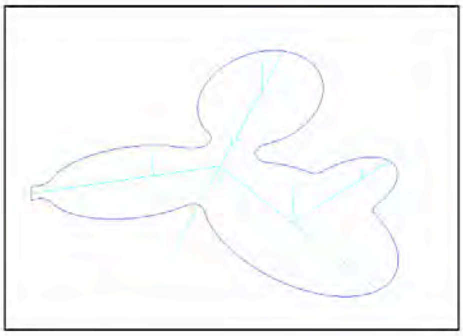


Figure 29 : Initial boundary

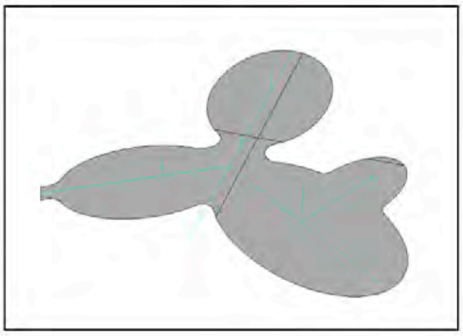


Figure 30 : Generation of surface

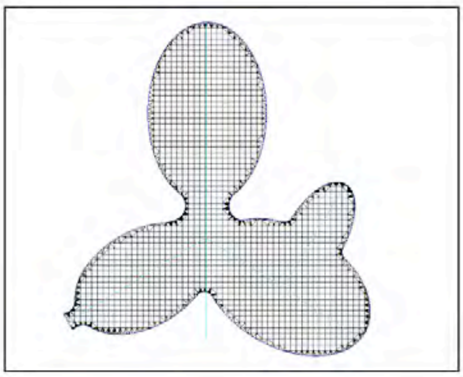


Figure 31 : Generation of mesh

The boundary curve is used to generate a surface using Rhino's _planarsrf command. Next a mesh is generated using the mesh from NURBS object command (_ Mesh). The mesh density can be set (in this example to 1.0 mt) inside rhino. The Smart Form plug-in relaxes the mesh to the equilibrium geometry. The boundary curve is set as a constraint.

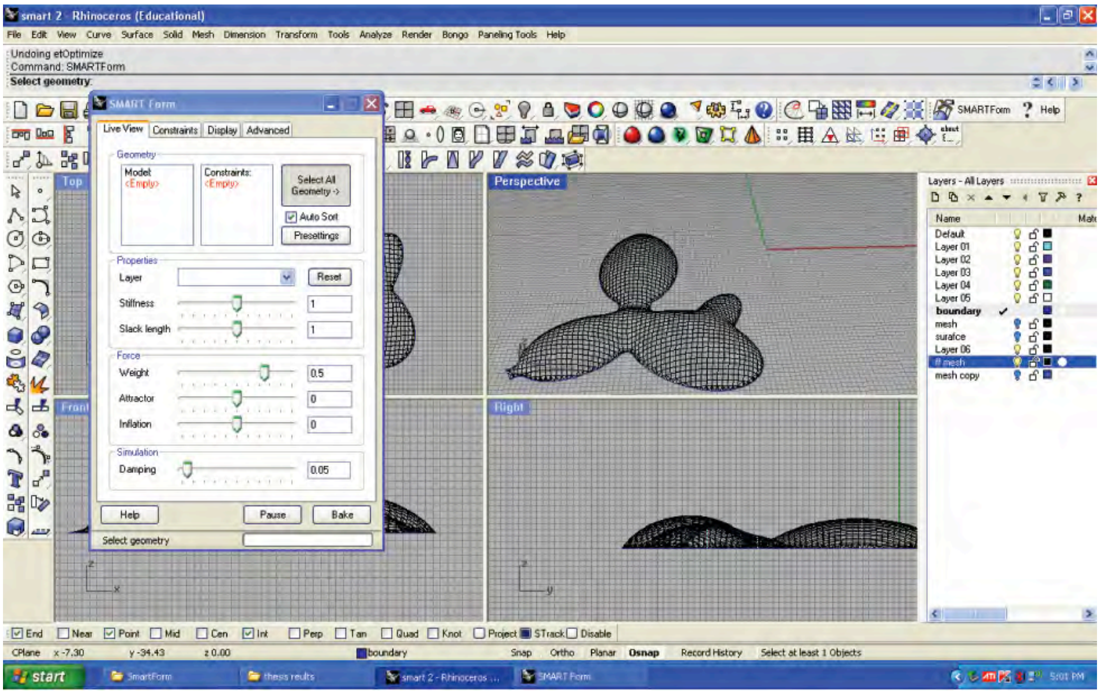


Figure 32 : The sliders allow real-time changes in geometry

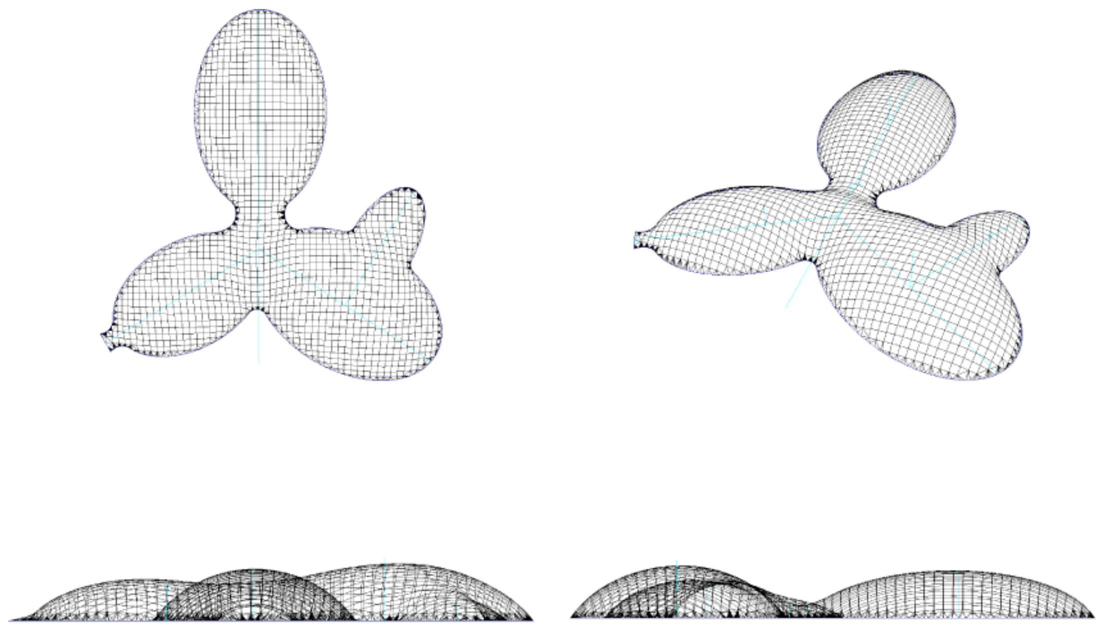


Figure 33 : Smart Form finding result

Form finding with the Timber Grid Shell Design Tool

Maarten Kuijvenhoven at the TU Delft developed a software tool to do form finding of timber grid shells, i.e. grid shells which use elastic bending of their component members as an integral part of the structural system.

The method used is based on a particle spring system built-up of both translational and rotational springs [7]. The grid configuration results from an approximation process, which generates a grid as close as possible to a target surface without exceeding the material's permissible stresses. The curvature of the profiles is controlled by the system of springs, which are linked to and migrate towards the initial target surface [8].

Dynamic relaxation is the method used to calculate the equilibrium geometry within the software. The tool has the following limitations :

1. Torsion and shear are not taken into account.
2. Only one grid orientation is considered by the tool, i.e. it is not possible to change the angle between U and X or U and V in the grid, U and V being the principal grid directions,
3. The Dynamic relaxation process migrates the initial grid towards the target surface only in the vertical direction.

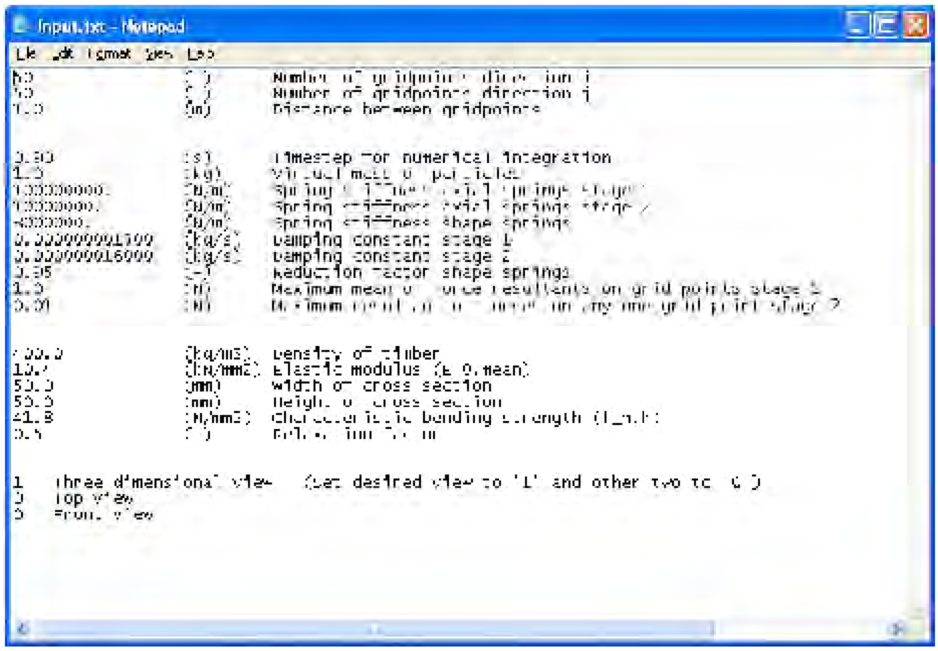


Figure 34 : input file of the design tool[23]

[23] Kuijvenhoven, M.: A design method for timber grid shells. Master's thesis, Delft University of Technology (2009)

Form finding with the program sofistik

Julian Lienhard at the University of Stuttgart in association with Christoph Gengnagel at the University of the Arts, Berlin have developed a new form finding methodology for bending active structures that uses the finite element approach to take into account the material's physical properties during the form finding and structural analysis process, using the software Sofistik.

Non-linear 3rd order large deformation theory is used to run the simulation process. In order to overcome convergence problems due to the large displacements and rotations during the form-finding process iterative deformation is used, where the deformation is split into smaller increments [2].

In order to overcome difficulties in the form finding process which occur as the complexity of the doubly curved form increase (large deformations lead to very high restraining stresses at the fixed nodes - too high for convergence to be reached during form finding) due to size or other design requirements, the use of elastic pre-stressing cables is introduced to temporarily reduce elastic stiffness, thereby enabling large deformations under constant pre-stress.

Form finding - Rhino/Grasshopper/kangaroo

Grasshopper is a well known plug-in for Rhino. It is a parametric modeling tool that is suited to the task of grid shell form finding. The physics based simulation engine Kangaroo is used in conjunction with Rhino and Grasshopper to provide the force based components needed for the interactive form finding.

The Grasshopper definition is split into three broad areas :

1. Grid creation
2. Removal of elements with no intersections on the grid
3. Definition of the supports
4. Connection to the Kangaroo engine.

This form finding method uses a particle-spring approach to find the equilibrium geometry.

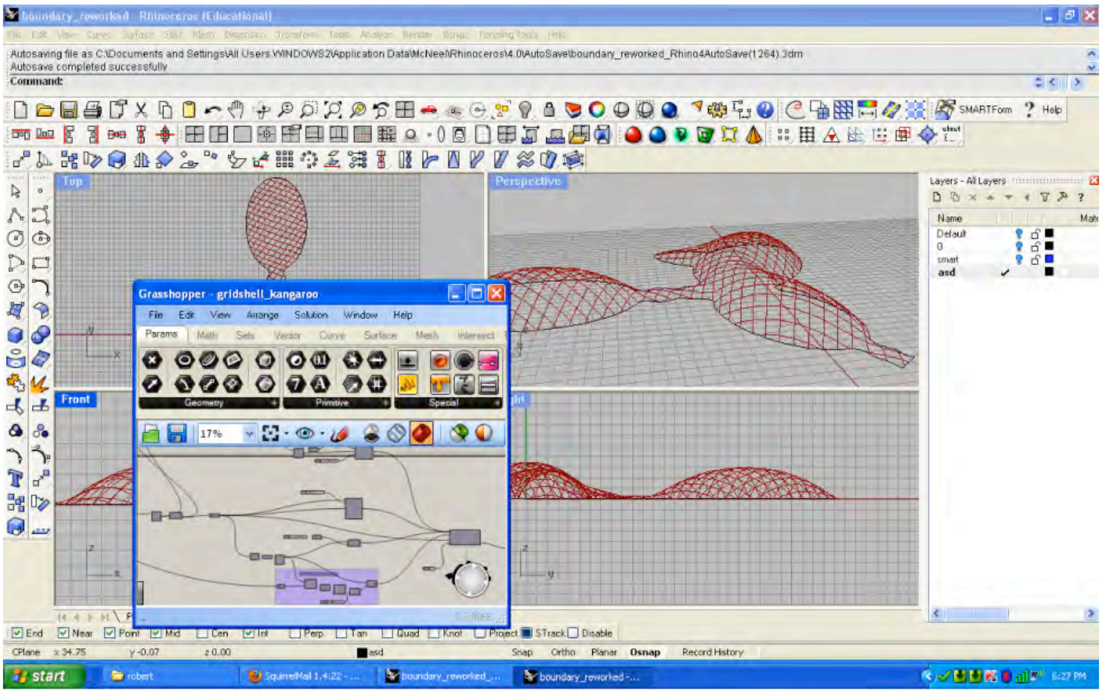


Figure 35 : interactive form finding with Rhino/Grasshopper/kangaroo

The grid shell geometry can be checked according to the minimum radius that the trial sections can be bent to, according to the table and formulas provided on page 21. Therefore basic checks can be carried out during the form finding process to try to minimize the breakage of laths during erection by ensuring that no part of the geometry has curvature tighter than the minimum bending radius.

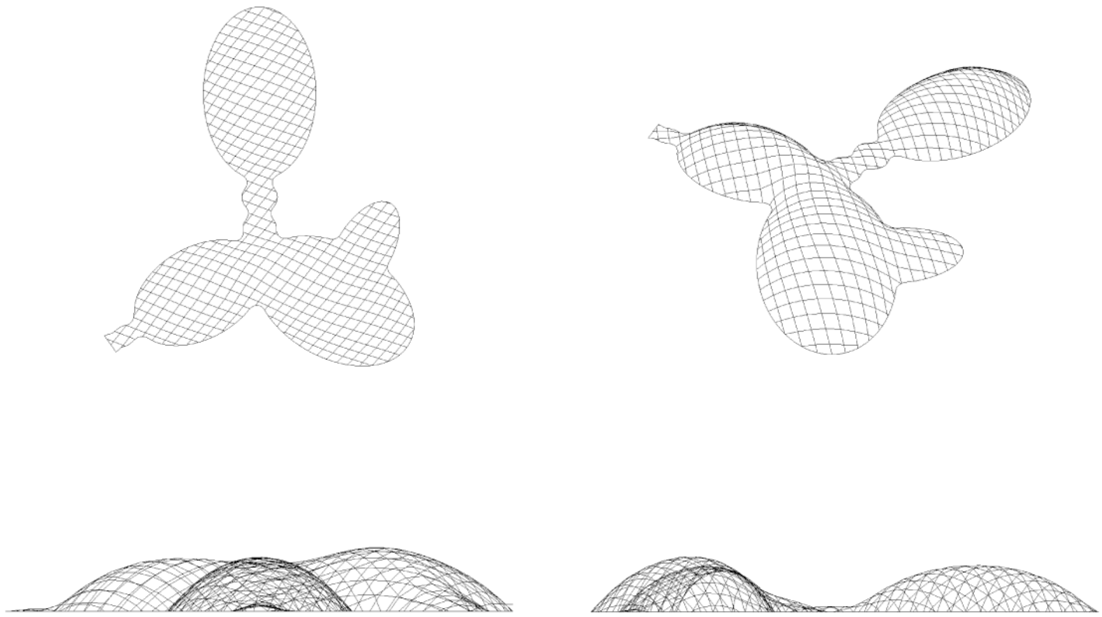


Figure 36 : form finding result of Rhino/Grasshopper/Kangaroo

2.4 Comparison of form finding methods

	Possibility to change grid orientation ?	Material properties considered during form finding ?	Form finding engine	Strengths / weaknesses (+/-)
EASY	Yes	No	Force density	+ good quality output + stable computation engine - not very interactive
SmartForm	No	No	Dynamic Relaxation	+ very interactive & intuitive form finding - output requires additional post processing
Grid shell Design Tool	No	Yes	Dynamic Relaxation + shape springs	+ Good output - Computation engine not stable
Sofistik	Yes	Yes	FEA	+ combines form finding & structural analysis in one tool - Time consuming process
Rhino Grasshopper Kangaroo	Yes	No	Kangaroo	+ good quality output + stable computation engine + very interactive & intuitive form finding

Figure 37 : Comparison of different form finding methods

2.5 Physical Modeling

A physical model was constructed on the basis of the Easy form finding geometry. The output was exported as a dxf file to rhino. The model was built to 1:25 scale using cypress strips. The grid shell geometry was flattened using Rhino's project to C plane command (ProjectToCplane), plotted onto waterproof blue back paper and fixed to the model ground plane to serve as an installation template for the model grid shell laths. The grid shell border geometry, being very curved, was exported as a 3D stereolithography file and output from a CNC shopbot.

The model laths were immersed in water to keep them pliable during the model building process, and to prevent breakages as the laths dried quickly. The laths were fixed with miniature nails known as panel pins at the intersections. This connection allowed in plane rotation of the laths when necessary during the model building. The finished model had a good match to the computer model, with a maximum discrepancy in height of 25 mm, which works out to 625 mm at real scale.

Figure 38 : ShopBot outputting model boundary

Figure 39 : close up photos of the model

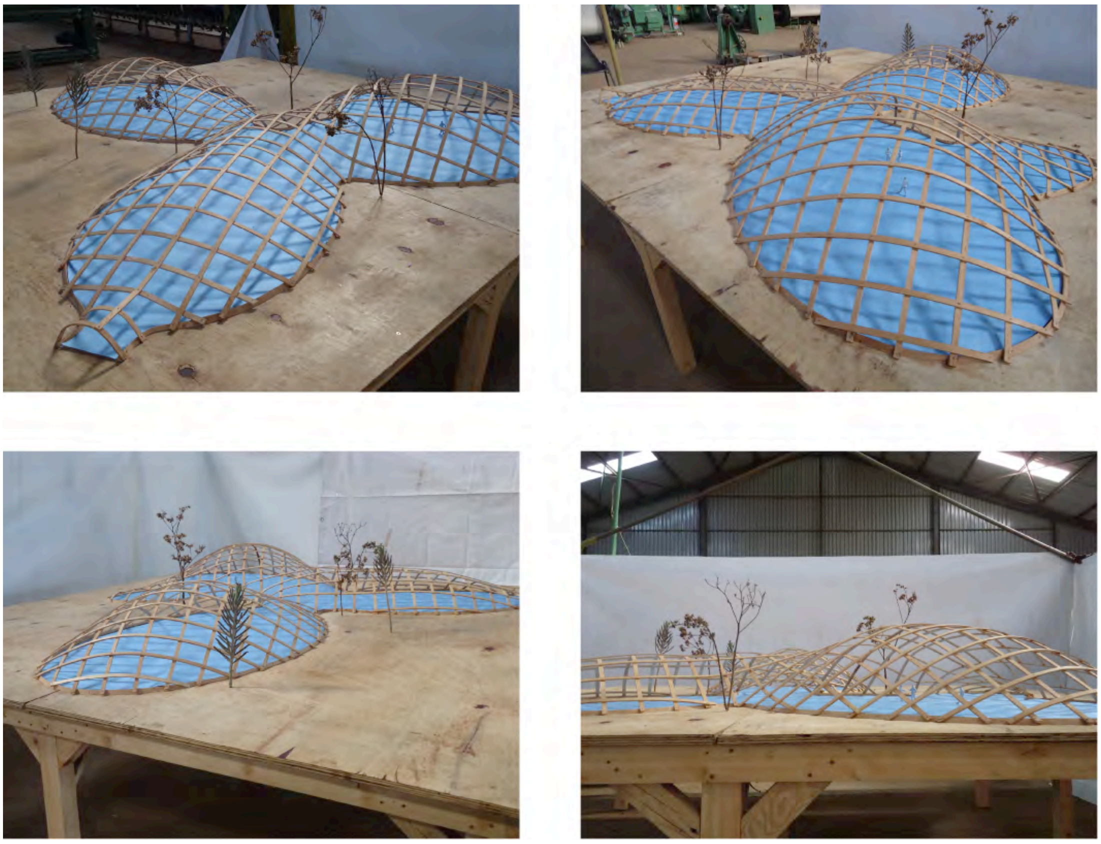


Figure 40 : selection of photos from the physical model

3.0 Ultra High Performance Concrete (UHPC)

Ultra high performance concrete is a new class of concrete that represents a leap forward in concrete technology. It represents the state of the art in concrete design and material capabilities in terms of strength and resistance to environmental degradation. This material is increasingly being used in the construction industry, for example in the construction of bridges – or anywhere where lightweight and high strength is required.

3.1 Composition and properties of UHPC

UHPC is a cementitious composite material characterized by a compressive strength in excess of 150 Mpa and a post cracking tensile strength greater than 5 Mpa. It is made by the combination of Portland cement, quartz flour, silica sand, super plasticizer, fibre reinforcement and silica fume.

The material derives its strength from the controlled particle size in the composite matrix – it has a very dense microstructure due to the fine particle sizes, and this improves the bond between the cement and aggregates. The excellent characteristics of UHPC are obtained by physical, chemical and adhesion optimization. This is mainly obtained by the absence of gravel within the mixture and the increase of the amount of cement. Therefore a dense, non-porous solid structure is produced that attains a high performance very rapidly due to the short diffusion paths at hydration, pozzolanic reactions and other physical-chemical reactions [9].

The fact that very little water is required for the physical and chemical reactions needed to bond UHPC means that there are much smaller capillary pores and hydration paths left when the water evacuates the cementitious matrix upon setting of the concrete. Therefore the ingress of water and other harmful chemicals and gases is prevented. This means that UHPC is a very durable material, with a lifespan of between 50-100 years.

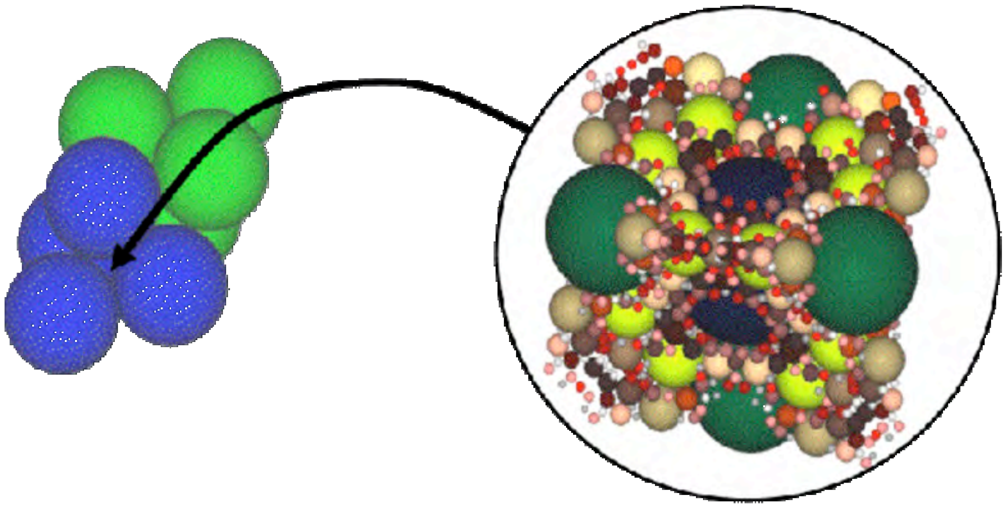


Figure 41 : fine particles fill the voids between the larger particles, increasing the packing density[24]

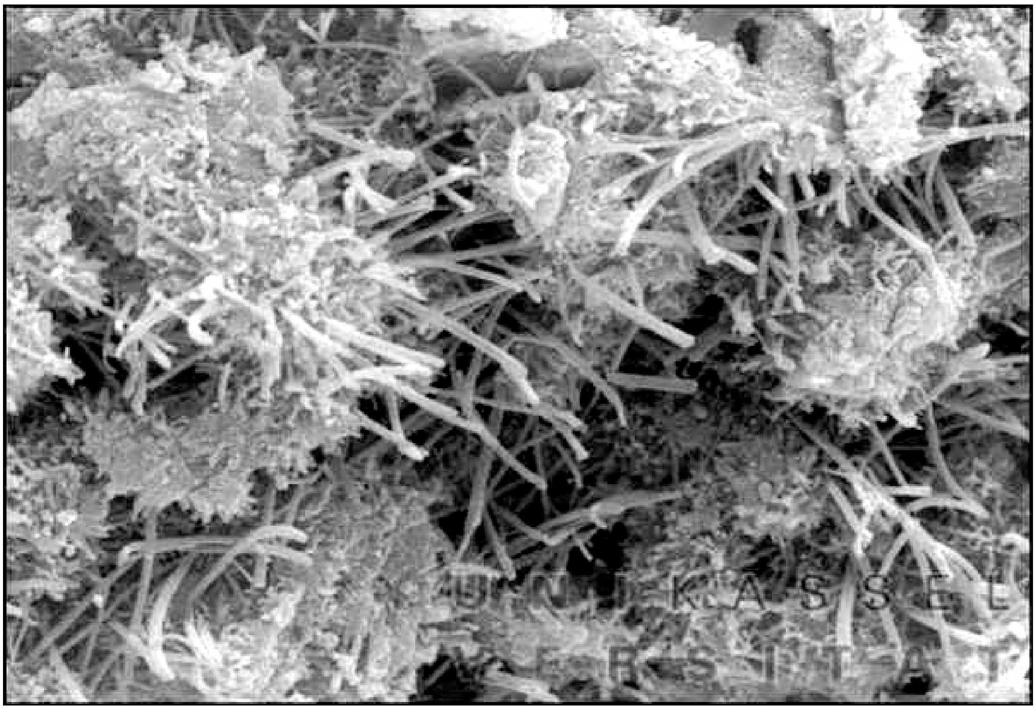


Figure 42 : SEM image of normal concrete showing its porosity and permeability

[23]http://www.uni-kassel.de/hrz/db4/extern/wdbubc/index_was_ist_uhpc_en.php accessed may 2012

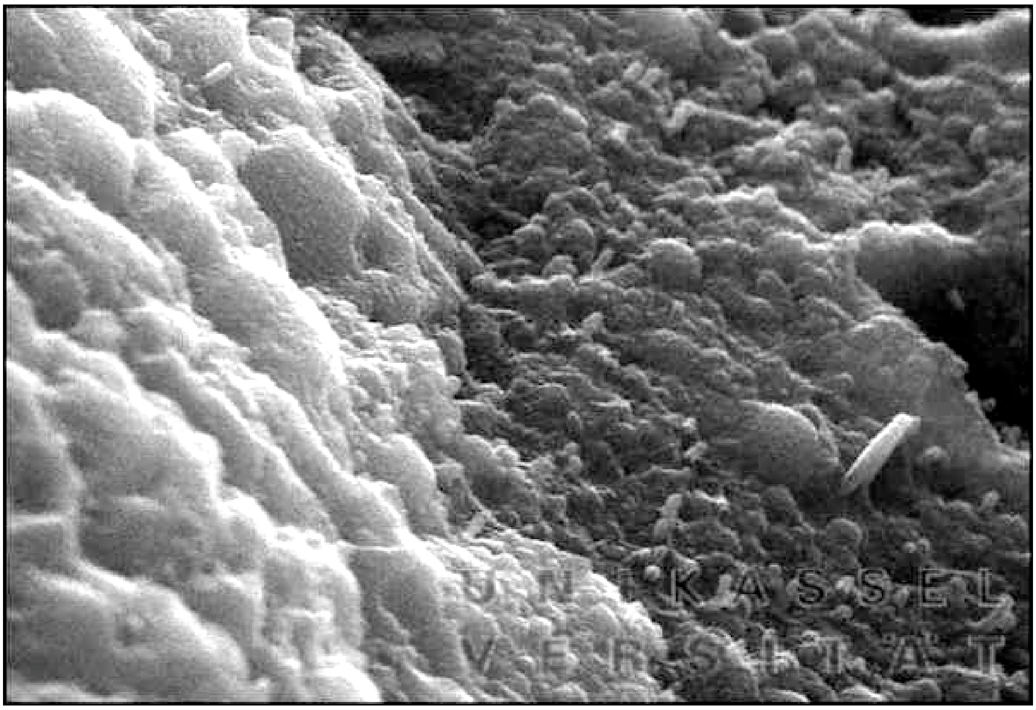


Figure 43 : SEM image of UHPC showing its dense microstructure

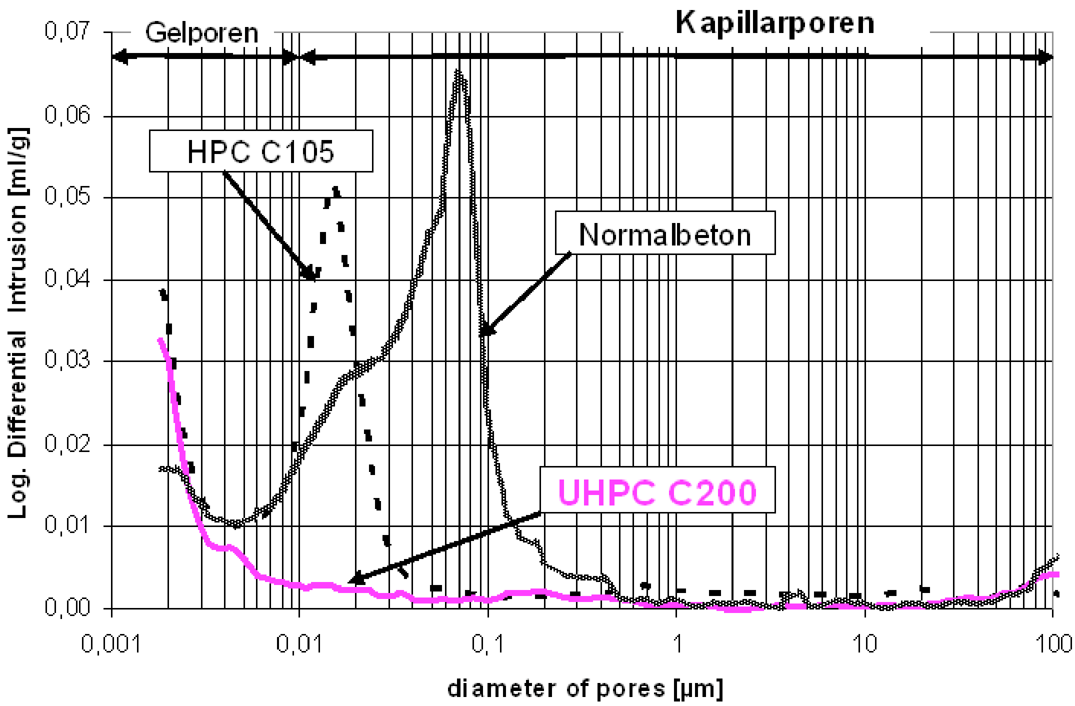


Figure 44 : pore size distribution of normal concrete compared to HPC & UHPC

In summary the compressive strength and durability of UHPC is based on four principles :

1. High packing density due to controlled particle size leading to dense microstructure of the composite cementitious matrix. Creates stronger pozzolanic, chemical and physical bonding. This reduces the possibility of brittle failure of the concrete.
2. A very low water to cement ratio of 0.2 to 0.25 means much smaller capillary pores are formed in the concrete.
3. Large amounts of superplasticizer are required to adjust the workability of the concrete.
4. Addition of steel or fibre reinforcement to increase the tensile strength and ductility of the concrete

Component	Density per component per material (kg/m3)			
	B45	B85	B200	B800
Cement	360	475	1075	980
Silica Fume	-	25	165	225
Sand	790	785	1030	490
Gravel	1110	960	-	-
Steel Fibers (13mm)	-	-	235	-
Micro Fibers (3mm)	-	-	-	615
Quartz flour	-	-	-	380
Super plasticizers	0.5	4.6	39	18
Water	145	150	200	185
Total density	2400	2400	2750	2895
Water / binder ratio	0.4	0.3	0.16	0.14

Figure 45 : mix design of conventional concrete B45, High performance concrete B85 and Ultra high performance concrete B 200[25]

[25] Maten Ter, R.N.: Ultra High Performance Concrete in Large Span Shell Structures. Master's thesis, Delft University of Technology (2011)

3.2 Advantages of UHPC

UHPC has many times the compressive and tensile strength of normal concrete. That makes it possible to reduce the weight and thickness of structural elements significantly and predestines it as a material for future construction applications. It is eminently suitable for a cladding application due to its inherent characteristics (light weight, strength and durability)

Therefore the central research question is whether UHPC can be adapted for use as cladding for grid shell structures, in a constructive and economic manner.

3.3 Existing research on UHPC Cladding panels

A research study was conducted by the Belgian Building research Institute (BBRI) and the Vrije Universiteit Brussels (VUB) on the flexural behaviour of fibre reinforced ultra high performance concrete and the application in cladding panels. This study is of particular relevance to the proposed use of fabric formed UHPC as cladding elements for grid shell structures. Therefore the important parts of this research as it pertains to the thesis will be reported here [10].

The research was commissioned to investigate the choice of admixtures and (micro)fillers, aggregate grading and fibre cocktail with regard to the suitability for its application in thin plate elements for use as cladding or façade panels.

Composition	Material Density [g/cm³]	[kg/m³]	vol. [%]
Porphyry 1/3	2.70	789	29
Quartz sand 0/0.5	2.65	363	13
CEM I 42,5 R HSR LA	3.10	833	26
Superplasticizer (polycarboxylate based)	1.06	20	2
Silica Fume (dry)	1.40	167	12
Water	1.00	179	18

Figure 46 : composition of the reference mixture[26]

[25a, b, c] Remy et al, flexural behaviour of fibre reinforced ultra high performance concrete and the application in cladding panels, research paper, Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, 2008

2 days		7 days		28 days		91 days	
AVG [MPa]	stDEV [MPa]	AVG [MPa]	stDEV [MPa]	AVG [MPa]	stDEV [MPa]	AVG [MPa]	stDEV [MPa]
99	1.2	138	0.5	172	3.5	188	3.8

Figure 47 : compression strength test results of the reference mixture[25 b]

Fibres [%]	Fr [kN]	fr [N/mm²]	Fu [kN]	fu [N/mm²]	B150 [kNmm]	B300 [kNmm]
0%	97	13	97	13	4	4
2%	95	13	107	14	8	104
4%	123	16	136	18	13	144

Fr: force at first crack
fr: tension at first crack
Fu: ultimate force
fu: ultimate tension

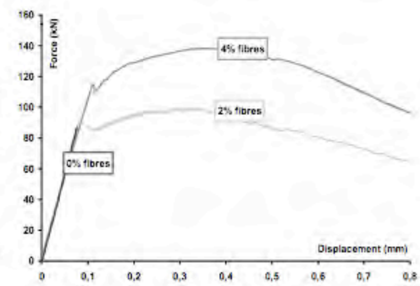


Figure 1: Displacement vs. force curves for fibre reinforced UHPC

Figure 48 : flexural behaviour of fibre reinforced UHPC[25 c]

The flexural behaviour of thin UHPC panels was also investigated relative to wind loading and the local stresses created at the attachment points to the primary support structure. A hybrid reinforcement consisting of a combination of PVC coated glass fibre mesh and random steel fibres were placed in the cementitious matrix to investigate the increase in tensile strength and ductility.

Cladding elements with a length of 2 mt and thickness of 4mm were built and tested using the four point bending test. The research study concluded that there were positive indications for the possibility of manufacturing thin plate fibre reinforced UHPC panels for cladding applications.

25 b

25 c see page above

Another study was conducted by BBRI in conjunction with VUB to research the formation of doubly curved thin concrete shells using pre-stressed fabric formwork. The fabric used was A PES textile, PVC coated, with an elastic modulus of 0.1 GPa and a stiffness of 150 kN/m [11, 12]. The fabric was pre-stressed to 1.5 kN/m and was made up from 3 separate pieces to ensure a wrinkle free doubly curved shape for the shell. Computer generated cutting patterns are used to derive the correct shape.

Four types of fabric and two types of concrete reinforcement (steel and glass fibre mat) were tested. 10 shells were made. The size of each shell was 2 x 2 mt, with a height of 1 mt at the arches. The recorded deviation at the center of the shell was 15 mm.

The case study concluded that for slender small span shells designed according to the euro code, flexible glass fibre mat reinforcement was more advantageous over steel reinforcement in that it was easier to make slender shells with flexible reinforcement, thereby leading to a significant reduction in thickness. Shells made with steel reinforcement require a minimum cover of concrete according to code requirements.

Shells made with both types of reinforcement were loaded up to failure by a gradually increasing load in the middle of the shell. The flexible glass fibre mat reinforced shell failed at 62 kN, while the steel reinforced shell failed at 70kN.

In conclusion this study provides positive information that the manufacture of slender small span shotcreted shells is possible using a prestressed fabric formwork. Further it also provides the direction that flexible reinforcement (in comparison to steel) is a better option as it allows for shell optimization (slender sections) and ease of manufacturing. Therefore this information will be used in the design and manufacture of the proposed sprayable UHPC cladding panels for grid shell structures.

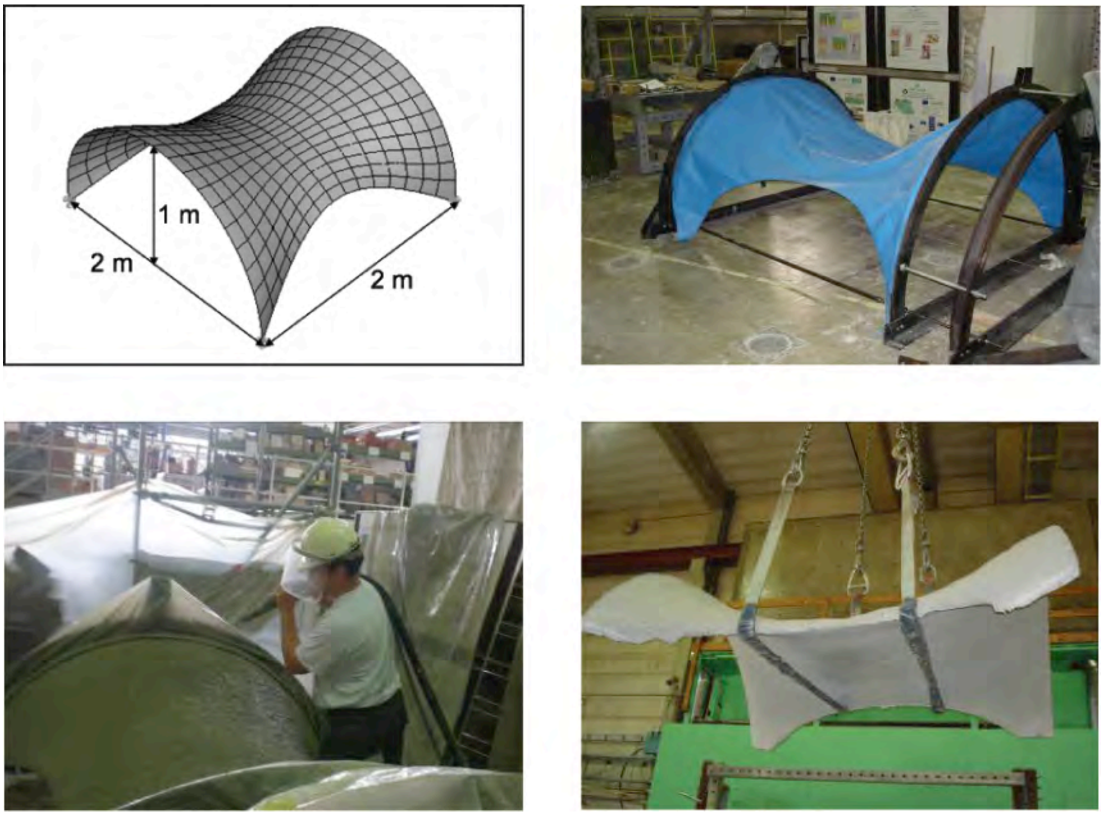


Figure 49 : clockwise from top left, shell shape, pretensioning arrangement, shotcrete application and demoulding of the shell[27]

Figure 50 : Load test[26b]

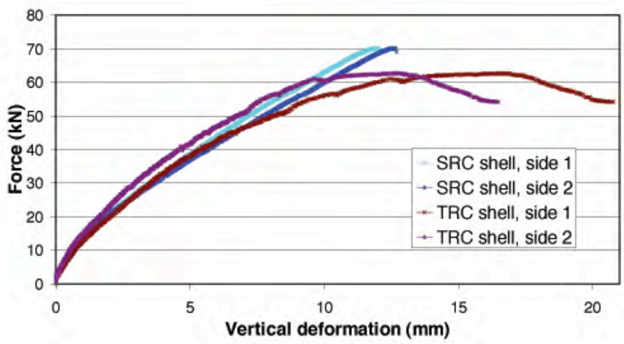


Figure 51 : vertical deformation of shells under load[26c]

[26, 26b, 26c] Cauberg et al, Fabric Formwork For Flexible, Architectural Concrete (part 1 & 2), Belgian Building Research Institute and Vrije Universitat Brussels, research paper submitted to the International Society for fabric Forming, http://www.fabricforming.org/, accessed may 3, 2012

3.4 UHPC built structure – case study

Commissioned in the year 2003, the world's first pre-cast, thin shelled, doubly curved UHPC roof system was installed at the Shawnessy Light Rail Station in Calgary, Canada. It was designed by Enzo Vicenzino, CPV Architects & engineers Ltd [13]. Twenty four shell structures each measuring 5 x 6 mt x 2 cm thick are each supported on one single column.

The columns are supported by the steel rebars found in normal reinforced concrete construction. The UHPC used for this project is known as 'Ductal', a commercially available premixed product manufactured by Lafarge. The structural engineers, Strudes Inc. modeled the structural system using the FEM method. The analysis was run on connected modules of three canopies with fixed column base connections and an expansion joint every three canopies [14].

A great deal of testing and load tests on full scale prototypes was carried out to confirm that the behaviour under load of the shell and column conformed to the design calculations and building codes. Concrete was a natural material choice for this product as it has great flexibility in shape formation, and therefore lent itself to the realization of the architect's vision.

The design and realization of this structure was a milestone for UHPC construction and is further evidence of the capabilities of this material.

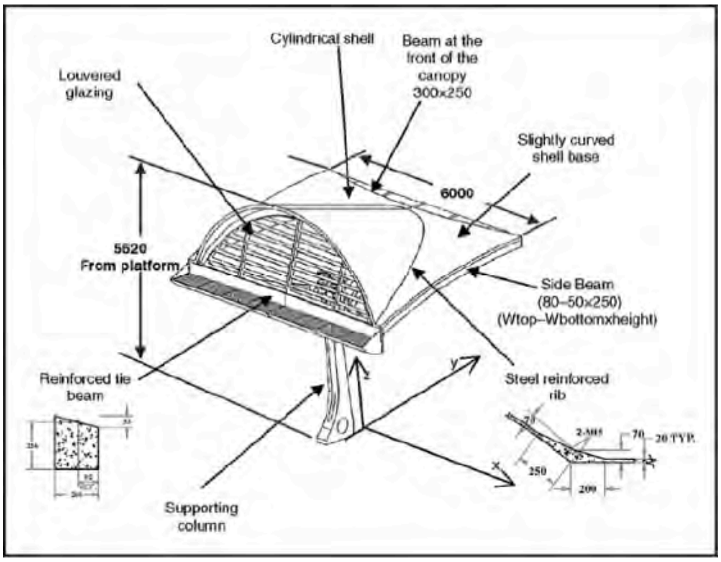


Figure 52 : schematic of one shell[28]

[28] http://www.ductal-lafarge.com/ - accessed September 2012

Figure 53 : Shawnessy LRT[29]

Figure 54 : selection of photos – Shawnessy LRT[28b]

[28, 28b] http://www.ductal-lafarge.com/ - accessed September 2012

3.5 Different Strategies to make UHPC cladding panels

1. Static moulds made with timber formwork

The simplest method of constructing a cladding panel is to make a timber frame onto which a flat fabric sheet is fixed and allowed to hang to form a funicular compression geometry. When the sheet is tensioned with the dead weight of concrete, load produced buckling occurs at the corners. This provides buckling-resistant sections aligned with the principle lines of compression force in the shell [15].

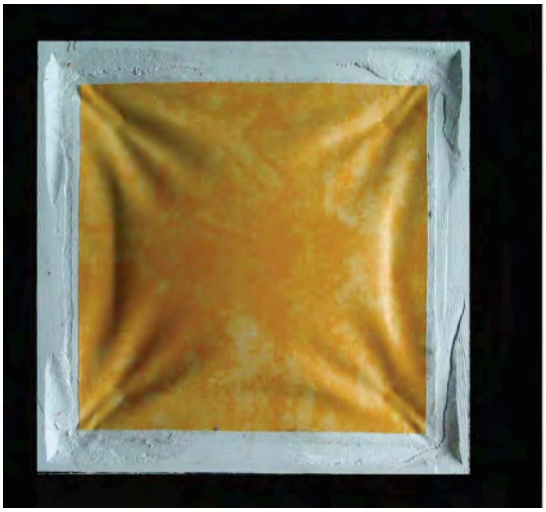


Figure 55 : load produced buckling at the corners[30]

2. CNC milled moulds

Grid shell cladding panels can be milled directly from the CAD environment onto styropor material using the subtraction milling process. However this would be a time consuming and expensive process as each shell produced would require a male and female component of the mould. The shells would have to be produced using the injection casting process. When considering a doubly curved form the size of the Mannheim Multihalle requiring thousands of panels each with a unique geometry, this would require a substantial investment in time and energy.

[30] http://www.umanitoba.ca/cast_building/assets/downloads/PDFS/Fabric_Formwork/Thin-Shell_Concrete_From_Fabric_Forms_SCREEN.pdf - accessed December 29, 2010

Figure 56 : CNC subtraction milling process[31]

3. Kinetic (form active) moulds

Free form architecture with its complex computer generated geometry is becoming increasingly popular and socially acceptable. Form active mould systems have been developed as a response to the need to manufacture cladding panels for doubly curved structures. This technology is a means to realize complex geometries in concrete.

The system consists of a bed of actuators that are attached to a flexible membrane that creates the doubly curved shape. The actuators receive shape instructions directly from the computer, for example from the Rhino / Grasshopper CAD environment.

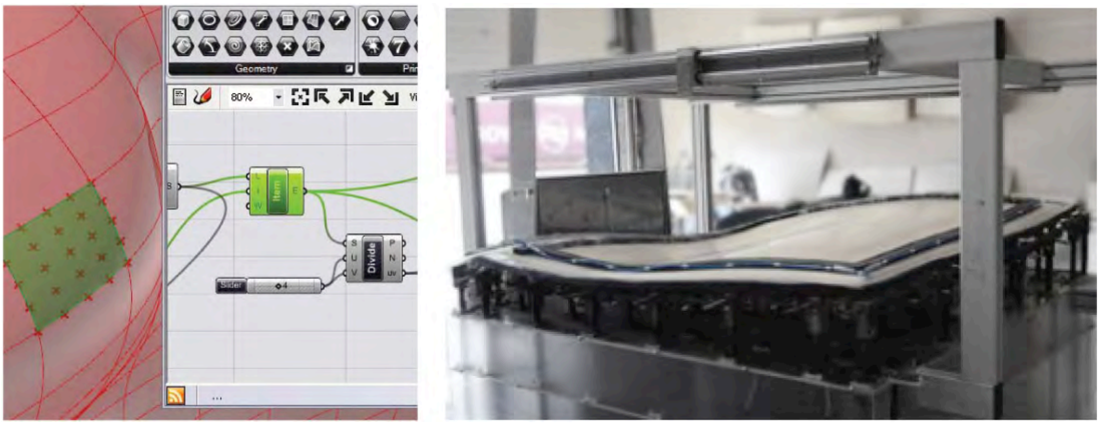


Figure 57 : curved panel in Rhino/GH and kinetic mould system[32]

[31] repository.tudelft.nl/assets/uuid.../186_483_110_2_Schipper_Le.pdf – accessed April 20, 2012

[32] left image, Koen Huyghe & Arnoud Schoofs, Precast Double Curved Roof Panels, Master's thesis, TU Delft 2009, right image, www. Adapa.dk – accessed October 21, 2012

4. Shotcreting of fabric fixed on grid shell structure

UHPC can be made in a special spray formulation and sprayed onto fabric which has been fixed directly to the grid shell primary structure, as is the case with the Mannheim Multihalle. This fabric can be a geotextile fabric with a rough surface texture to ensure good adhesion of the fabric to the concrete. An alternative would be PVC coated PES fabric as commonly used for membrane structures. These fabrics are designed to be pre-stressed to levels in the range of 1.0 – 1.5 kN/m.

In order to prevent the fabric from hanging or drooping between the grid shell laths due to the dead load of wet concrete, the fabric would need to be inflated. This measure alone will however not suffice in preventing the deflection of the fabric. It is therefore suggested that in addition to pre-stressing the fabric, a very thin initial layer of UHPC is sprayed and allowed to harden – this first layer will then be capable of carrying the load generated by subsequent layers of sprayed concrete.

In order to ensure that an equal thickness of concrete is sprayed over the surface of the fabric, pins normal to the surface of the fabric would have to be fixed to the fabric surface in a regular grid pattern.

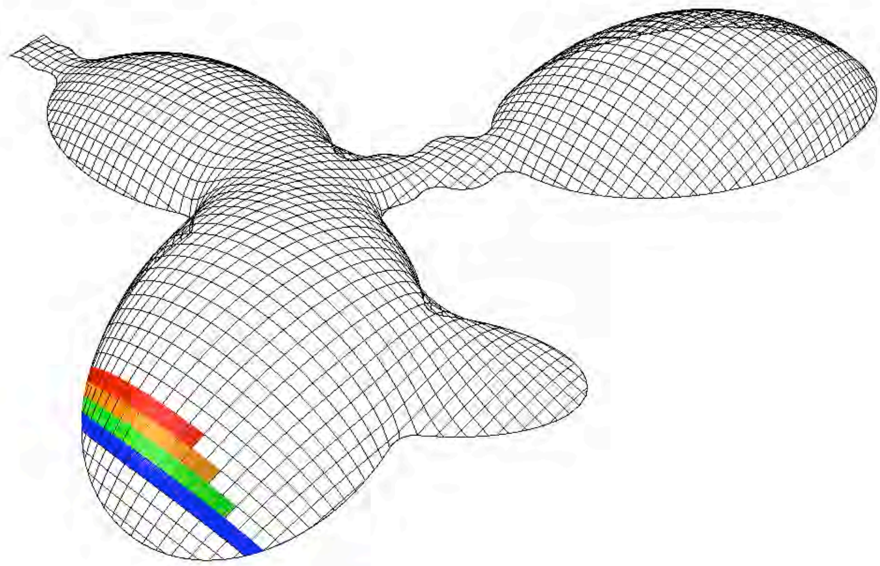


Figure 58 : strips of fabric fixed to grid shell structure

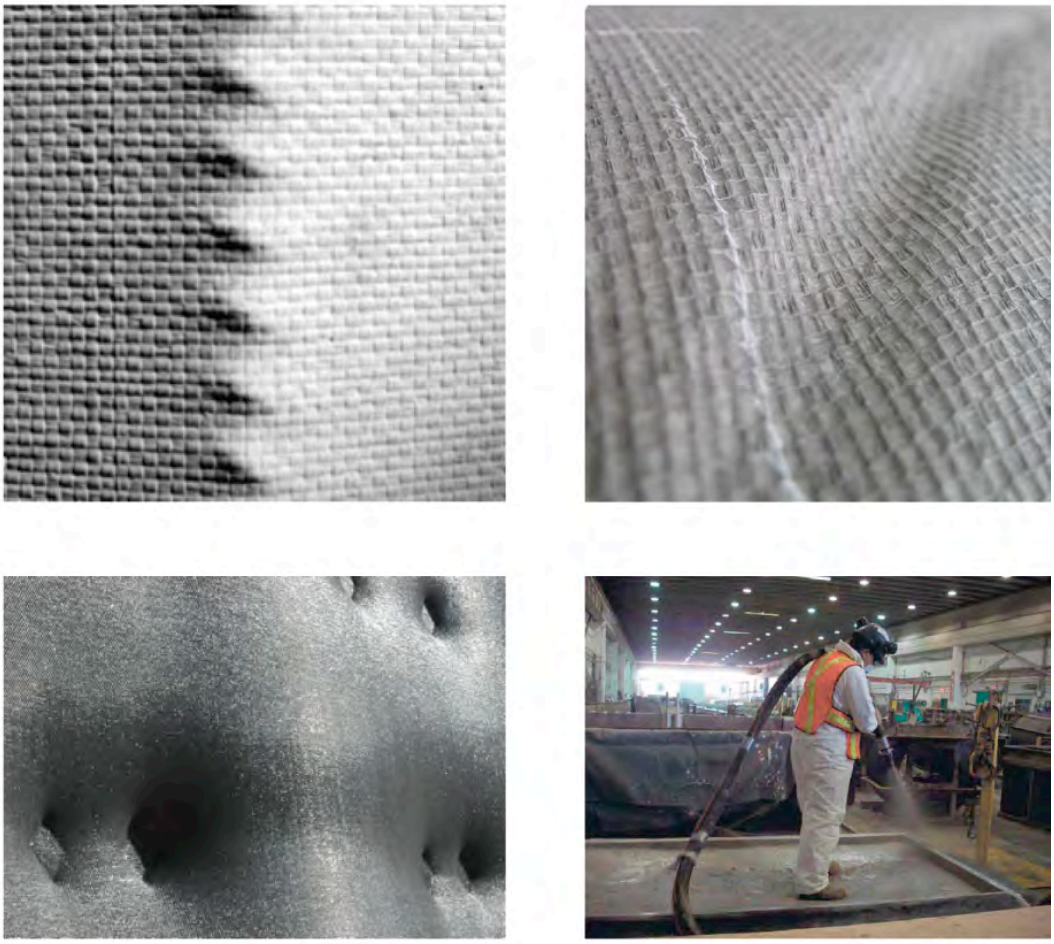


Figure 59 : geotextile fabrics used for fabric formed concrete at CAST[33]

5. Inflated cladding panels

The fabric can be fixed to the grid shell primary structure and inflated in a process similar to inflating an air hall. When the design inflation pre-stress is attained the cladding panels can be sprayed with concrete This method has a number of advantages when compared to the other methods presented :

1. There is no need for a separate mould system as the inflated panels act as in-situ moulds.
2. The process would be fast.

An alternative to spraying UHPC on inflated fabric panels would be to inflate a composite concrete impregnated fabric. This possibility will be investigated in the next chapter.

[33]http://www.umanitoba.ca/cast_building/assets/images/fabric_formwork/Surface_detail_of_a_fabric-cast_panel.jpg - accessed October 2012

As with the previous method presented, a system of pins normal to the surface to the fabric would have to be used to ensure that an equal thickness of concrete was sprayed on the fabric. It would also be prudent to spray an initial thin layer of concrete and allow it to harden.

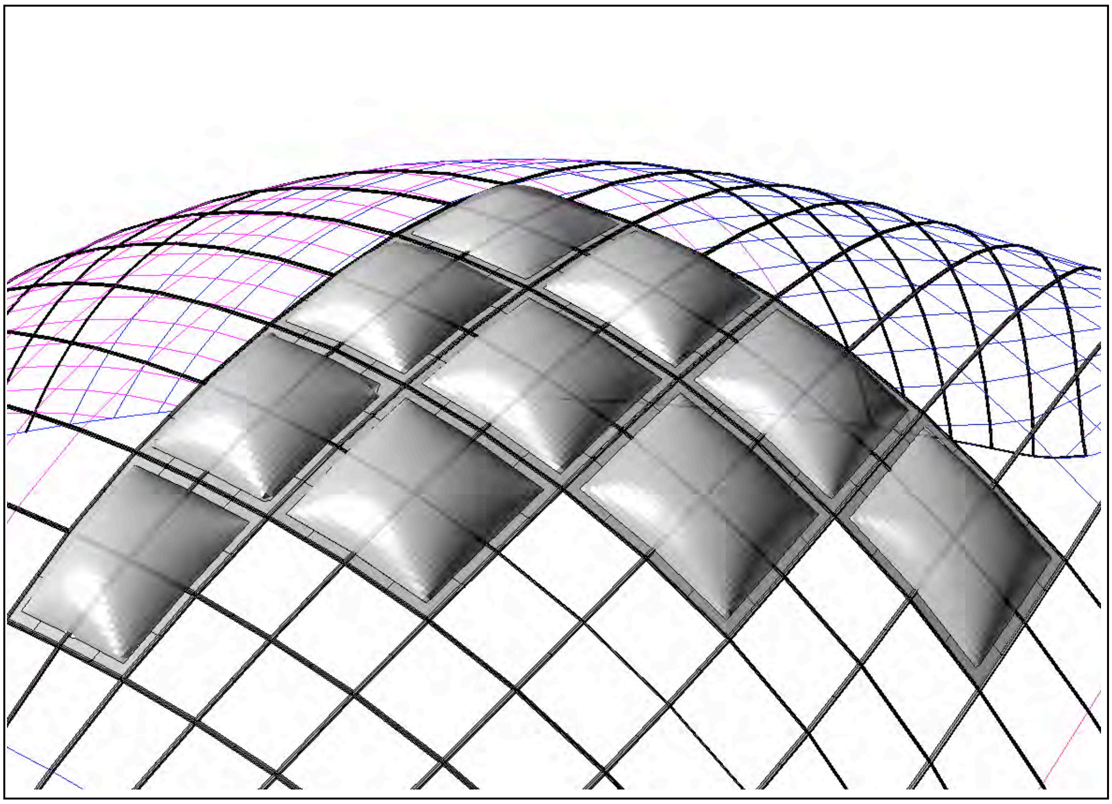


Figure 60 : graphic showing inflated fabric formed concrete cladding panels

3.6 Experimental work

In order to test the practicality of using sprayed UHPC shells as cladding elements, some experimental shells were made at the Institute of Building Construction and Technology at TU Vienna. This is a center for building materials research, material engineering and fire protection.

Three shells were made, 2pcs of size 1 x 1 mt, and 1 pc of 2 x 2 mt. The shells were made by hanging fabric from a timber frame and allowing the weight of the concrete to form load produced folds at the corners. The timber frames were fixed to uprights to allow space for the fabric to hang.

The fabric chosen was a PVC foil. As this is an extruded film, its behaviour under load can be assumed to be orthotropic and linear-elastic.

In addition to the formulation of a UHPC mixture suitable for spray application, PVC coated glass fibre mat was used to provide reinforcement. The cladding element was conceived of as a composite, in which the glass fibre mat was sandwiched between layers of concrete. In general 1 cm of concrete was sprayed followed by placing of the mat, This was repeated three times in the case of the 2 x 2 mt shell, and two times for the 1 x 1 mt shell. A photo based description of the work follows :

Figure 61 : prepared UHPC components, computer controlled cement mixer and fabric on frame prior to spraying

Figure 62 : spraying of 1 x 1 mt shell

Figure 63 : placing the first layer of glass fibre reinforcement

Figure 64 : close up of the glass fibre mesh

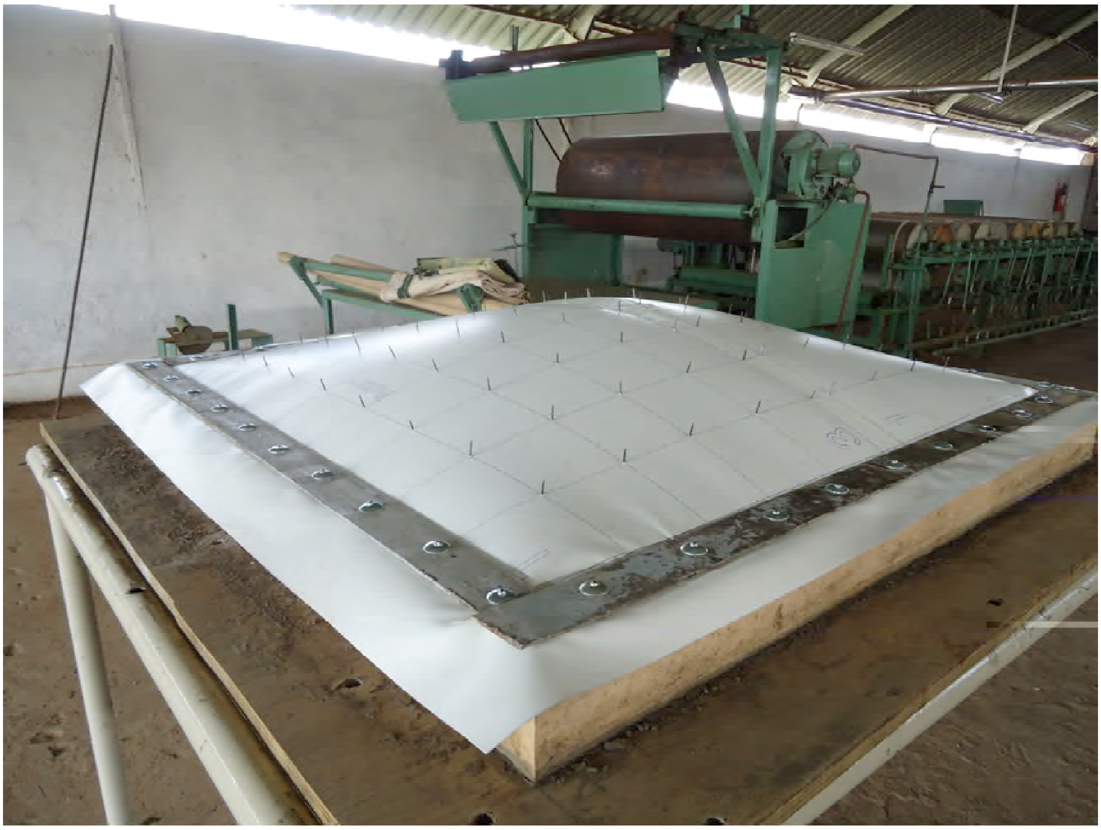


Figure 65 : system of pins normal to the fabric surface orientation

Sprayable UHPC formulation

Mischungsberechnung für UHPC	
durchgeführt von:	DI Johannes Kirnbauer
Ort:	Labor 1030, Adolf-Blamauergasse 1-3
Datum:	6/12/2012
Zweck:	**Sprayable UHPC**

◊ Grau hinterlegte Felder müssen eingetragen werden ◊

Anforderungen

W/C-Ratio	W/B-Ratio	0.246	0.30	Superplastizicer [M.% v. cem]	4.00
Sand dry [dm³/m³]			350.00	Superplasticizer [M% v. fines]	2.26
Air content (estimated) [V.%]			2.00	w/Fv	0.479
Anti-foamer [kg/m³]			0.00	Relative density calculated	0.849

Matrix

	Description	Portion [M. 1]	Portion [V. 1]	Mass [kg]	Density [kg/dm³]	Volume [dm³]		
Superplasticizer	Sika FM 209	4.00	3.67	26.84	1.09	24.63	30.00	Solid part [M.%]
Water incl. SP-part liquid	Water	30.00	30.00	201.32	1.00	201.32		
SP solid part		1.20	0.87	8.05	1.38	5.84		
Cement	CEM I 42,5 R	100.00	32.26	671.07	3.10	216.47		
Admixture 1	Microsilica Elkem 940 U	22.00	9.57	147.64	2.30	64.19		
Admixture 2	Quartzpowder 3600	55.00	20.75	369.09	2.65	139.28		
Admixture 3	na	0.00	0.00	0.00	2.65	0.00		
Anti-foamer	na	nb	nb	nb	1.06	nb		
		208.20	93.45	**1397.17**	**2.23**	**627.10**		

Zuschläge

	Description	Portion [%]	Dry-M. [kg]	Dry density [kg/dm³]	Stoffraum tr [dm³]	Water content [M. %]	Water content [l]	Wet mass [kg/m³]
Sand 1	ME 0,1-0,5	100	927.5	2.65	350	0	0.00	927.50
Sand 2	na	0	0	2.65	0	0	0.00	0.00
Sand 3	na	0	0	2.8	0	0	0.00	0.00
***		**100**	**927.50**	**2.65**	**350.00**		**0.00**	**927.50**

Fasern

	Description	Portion [M.%]	Addition [kg/m³]	Density [kg/dm³]	Volume [dm³]
Fibre 1	AR Glassfibres 12mm	50.00	2.00	2.85	0.70
Fibre 2	Polypropylen fibres 3,0mm	50.00	2.00	0.91	2.20
Fibre 3	na	0.00	0.00	7.85	0.00
		100.00	**4.00**	**1.38**	**2.90**

Stoffraum

	Portion [V. %]	Portion [M. %]	Mass [kg]	Density [kg/dm³]	Volume [dm³]
Air	2.00	0.00	0.00	0.00	20.00
Matrix	62.71	60.00	1397.17	2.23	**627.10**
Sand	35.00	39.83	927.50	2.65	350.00
Fibres	0.29	0.17	4.00	1.38	2.90
		Fresh concrete density	**2328.67**	4.878	1000.00
		Water addition total [l/m³]:	**182.53**		

Mischung

	Volume of mixing batch		30.00	dm³	V Kontrolle
	Description	Mass			[illegible]
Water	Water		5475.9	g	[illegible]
Cement	CEM I 42,5 R		20132.1	g	[illegible]
Admixture 1	Microsilica Elkem 940 U		4429.1	g	[illegible]
Admixture 2	Quartzpowder 3600		11072.7	g	[illegible]
Admixture 3	na		0.0	g	[illegible]
Superplasticizer	Sika FM 209		805.3	g	[illegible]
Anti-foamer	na		0.0	ml	[illegible]
Sand 1	ME 0,1-0,5		27825.0	g	[illegible]
Sand 2	na		0.0	g	[illegible]
Sand 3	na		0.0	g	[illegible]
Fibre 1	AR Glassfibres 12mm		60.0	g	[illegible]
Fibre 2	Polypropylen fibres 3,0mm		60.00	g	[illegible]
Fibre 3	na		0.0	g	[illegible]

Mischreihenfolge und Dauer

Type of mixer:	Eirich R 08				
Method of mixing:	Counterflow				
Type of mixing tool:	Bolt tool		**Mixing pan speed**	**Mixing tool speed**	
Mixing sequence:	[s]	[min]		[U/min]	[m/s]
1) Cem, MS,QP, QS, Fibres	90.0	01:30		1250	7.9
2) Water+SP+AF	30.0	00:30		1250	7.9
3) Mixing	120.0	02:00		1250	7.9
4) Mixing break	0.0	00:00		0	0.0
5) Mixing	0.0	00:00		0	0.0
6) SP addition	0.0	00:00		0	0.0
7) Postmixing	180.0	03:00		300	1.9
8) Vacuum [60 mbar]	0.0	00:00		0	0.0
Sum	420.0	07:00			

Fresh concrete test Date:			Hardened concrete test Date:
Slump flow:		cm	Bending tensile strength:
Density:		kg/m³	Compression strenght:
Air content:		%	Density:
Fresh concrete Temp:		°C	
Curing:			

3.7 Load testing

The 2 x 2 mt shell was too large to fit onto any of the Institute's testing equipment. It was therefore decided to carry out a load test by placing cement bags on the shell and measuring the deflection on the shell. For this a digital deflectometer was used. Deflection was also measured on unloading the shell. The shell was loaded in increments of 100 kg and time steps of 3 minutes before the next load increment was applied.

Test Object :

Size of shell in plan area – 2 x 2 mt

Thickness – 3 cm

Estimated surface area – 4.637 m^2

Estimated weight – 4.637 * 0.03 * 2400 = 330 kgs

Note : As the form for the shell was found by loading concrete onto the fabric, and not modeled in the computer first, it was difficult to know the exact surface area of the shell. However an estimate was made by measuring the rise of the shell at its center point. A shell was then modeled in the computer using inflation pressure as the form-giving agent. The surface area of the digital shell was then taken as the estimate for the physical one.

Figure 66 : 2 x 2 mt shell load test setup

Figure 67 : shell with maximum test load of 2000 kg

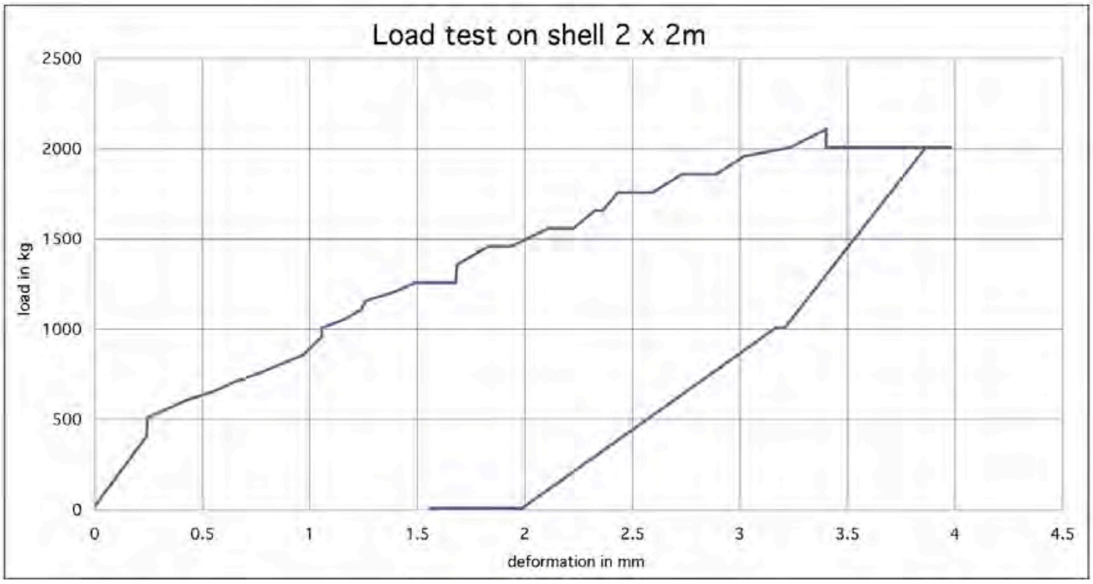


Figure 68 : plot of load test on 2 x 2 mt shell

Result : The maximum deflection is 3.984mm. After the test the shell is permanently deformed by 1.567 mm

Load test on 1 x 1 mt shell

Description of test :

As the shell was too big to fit directly into the test equipment, it was placed on a massive steel beam. On top of the shell at the center, a reinforced concrete pad area of 30 cm x 30 cm x 5 cm height was made (10.8 kg). A steel plate of 30 cm x 30 cm x 1 cm thick was placed on top of the pad (7.1 kg). A second steel plate of 20 cm x 20 cm x 2 cm thick was placed on top of the first plate (6.3 kg). Over this was placed a steel cylindrical shaft of diameter 50 mm x 50 cm length (7.7 kg).

A steel beam IPB 160 (h = 160 mm, b =160 mm, g = 35,2 kg/m) with a length of 2000 mm was used (70,4 kg) to load the shell. These items as used in the test are summarized as initial load, are 102,3 kg (ca. 100 kg)

Two steel angle profiles were used to support the sides of the shell as it was too big to fit in the test rig (see photos). A separate load cell was used between the steel beam IBP 160 and the hydraulic machine. The force was applied with a computer controlled hydraulic test machine with a maximum load of 500 kN on the right side. The load speed was with 1 mm/min. Two strain gauges were fixed to the shell, one at the bottom edge of the shell, and one near the center at the top.

Test Object :

Size of shell in plan area – 1 x 1 mt

Thickness – approximately 2 cm

Estimated surface area – 1.15 m^2

Estimated weight – 1.15 * 0.02 * 2400 = 55.2 kgs

compression strength on 10 x 10 x 10 cm: 143,73 - 137,47 - 166,59 - 150,05 N/mm^2; average: 149,5 N/mm^2

Measurements :

1. The vertical force on the right side of the shell with a separate load cell (and the load cell of the test machine).
2. strain at two points on the shell, using strain gauges
3. The deflection under load, at the center of the shell, in 1/100 mm. The device was installed on a separate frame.

Because of the test scheme the values of force have been doubled.

Results :

1. The maximum load was 12,848 N
2. The maximum deflection 5,13 mm
3. The maximum strain on the bottom (direction parallel to edge) 69,8 μm/m
4. The maximum strain on the upside (direction vertical to edge) 4,8 μm/m
5. The first crack occurs about 10.000 N (near the edge), the second at about 4,3 mm deflection (see photos and deflection plot).
6. After the test the cracks had a width of 2,5 mm and 4 mm (see photos).

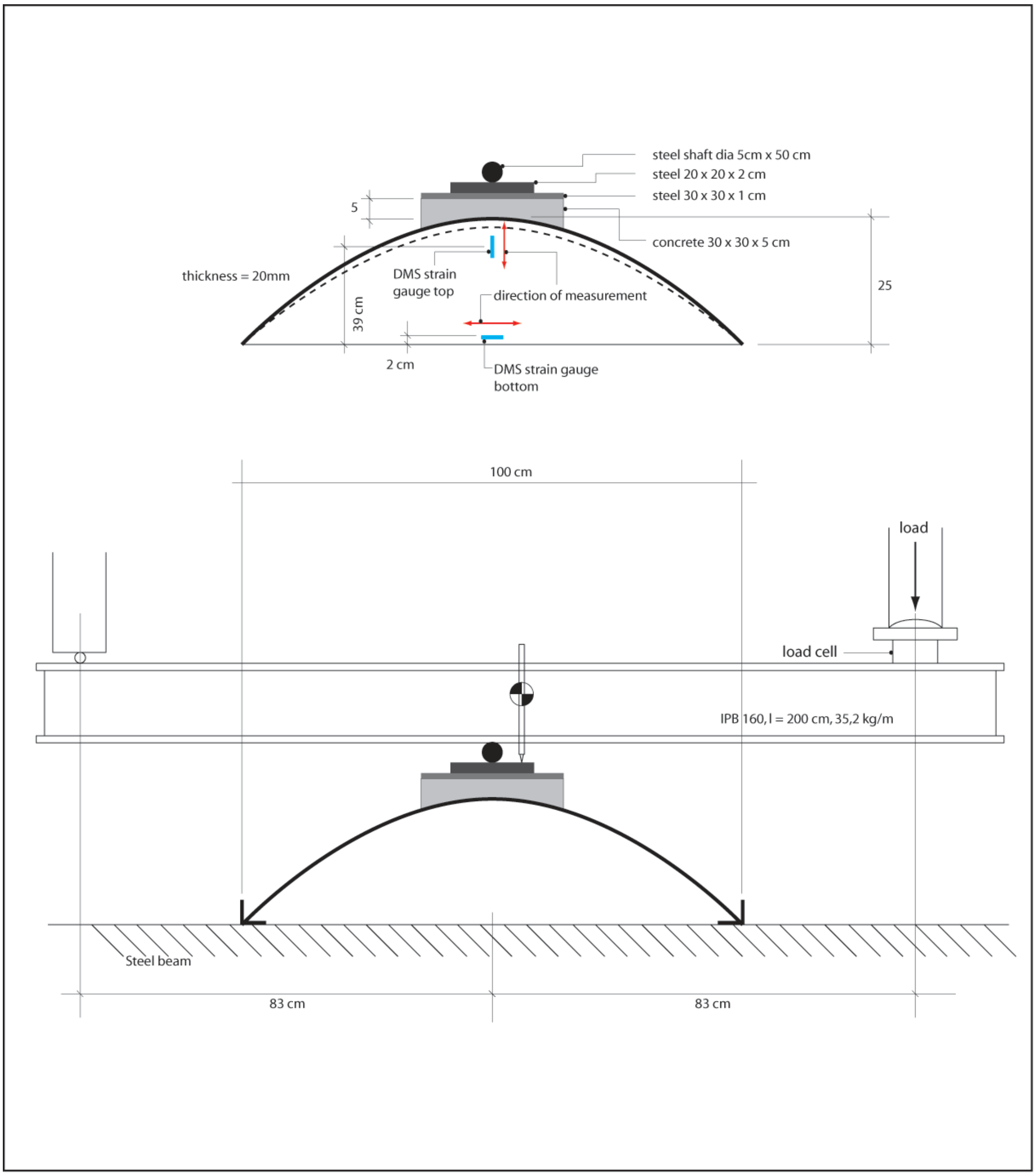
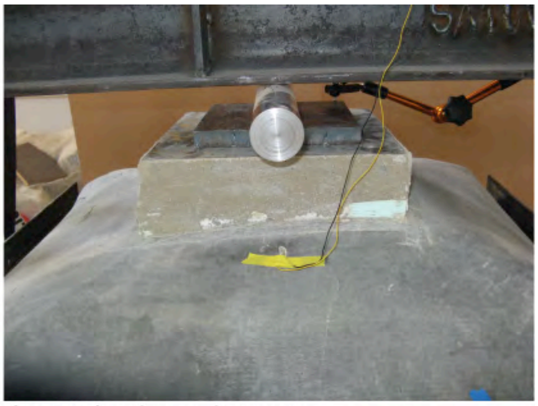


Figure 69 : Test scheme

Test setup



closeup showing strain gauge

Test setup - view from the side

Load cell

Crack measurement

Crack after test

Figure 70 : selection of photos from the load test of 1 mt span shell

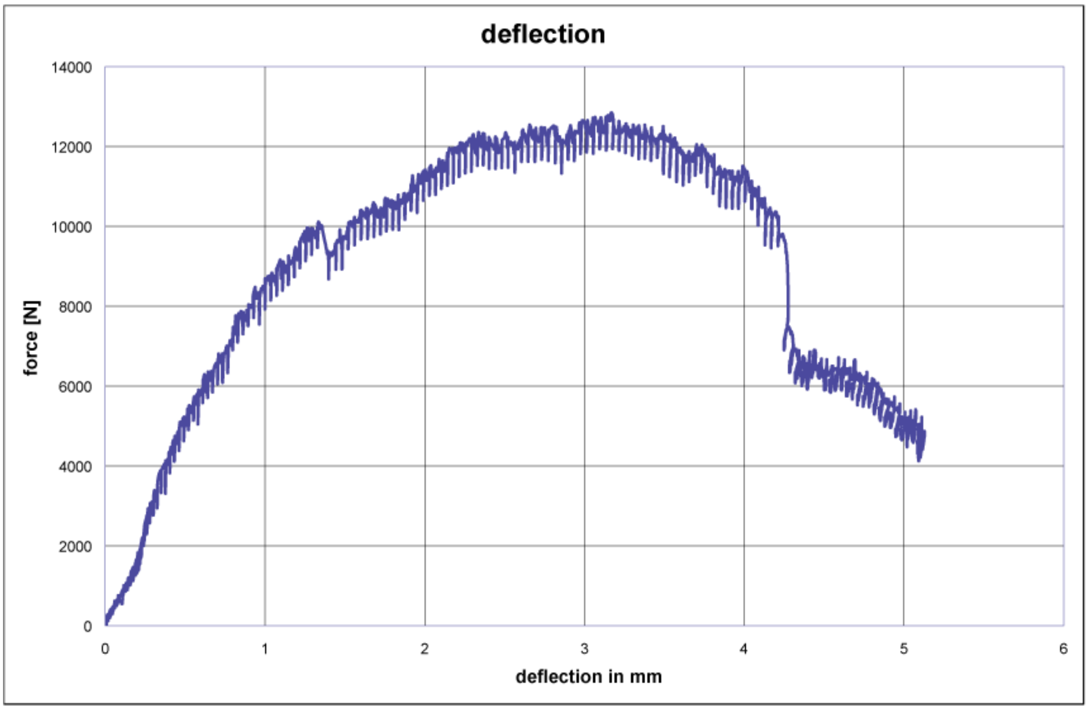


Figure 71 : deflection plot

Positive values for deflection is in the downwards direction

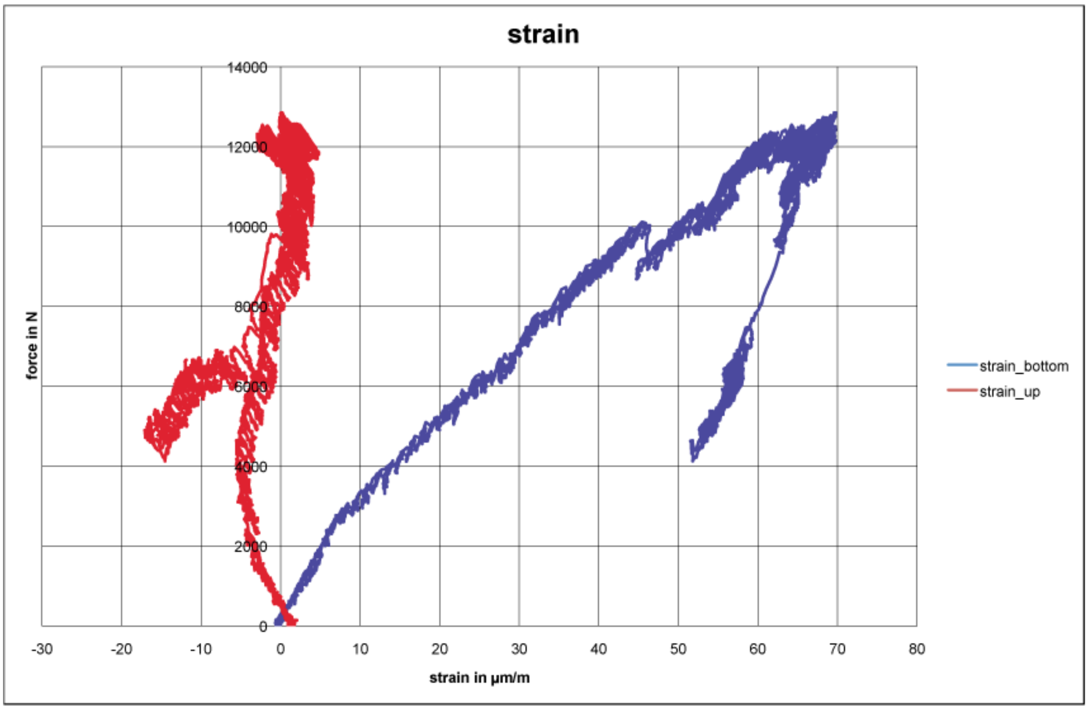


Figure 72 : strain plot

Positive values of the strain is tension.

E-MOD_Prismen_2012-07-24.ZSE **26.07.12**

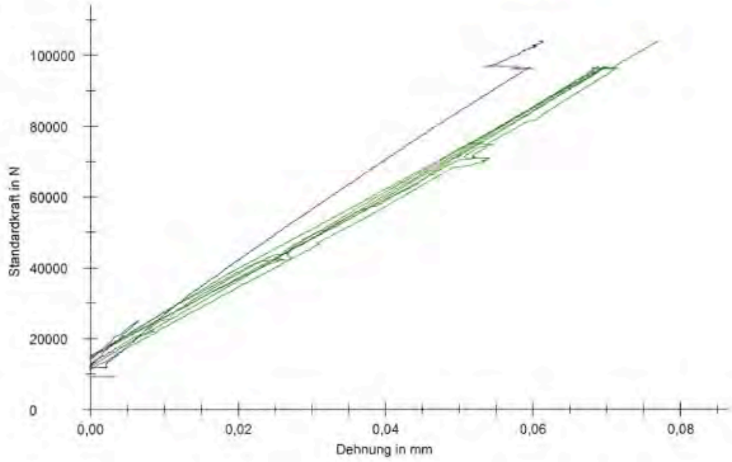
Ergebnisse:

Nr	F_{max} kN	σ_m N/mm²	F_b N/mm²	A mm²	EMod N/mm²	σ_u N/mm²	ε_u mm	σ_o N/mm²	ε_o mm
1	104,06	65,04	-	1600	65113,32	17,14	0,01	60,13	0,07
2	104,04	65,03	-	1600	57615,13	7,54	-0,00	60,10	0,07
3	104,03	65,02	-	1600	71285,42	7,56	0,00	60,05	0,06
4	104,06	65,04	-	1600	67659,50	7,25	0,01	60,10	0,07
5	104,05	65,03	-	1600	72896,63	7,33	0,00	60,07	0,06

averg: 66914

Prüfgeschwindigkeit 3 N/mm²s

Seriengrafik:



Statistik:

Serie n = 5	Probennummer	EMod N/mm²
$\bar{x}$	3	66914,00
s	1,581	6024,29
v	52,70	9,00

Figure 73 : plot of elastic modulus – 1 x 1mt UHPC shell

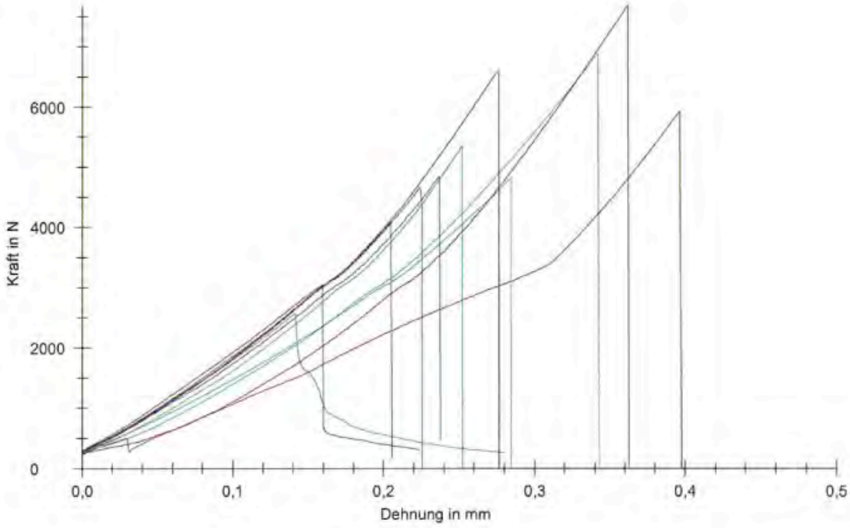
Biegezug_Spritz-UHPC_2012-07-25.ZSE

Ergebnisse:

Nr	Probennummer	A mm²	Probendicke a0 mm	Probenbreite b0 mm	σ N/mm²	FMax N	Datum	Uhrzeit
1	1	1697	40,3	42,1	13,00	5924,06	25.07.2012	12:21:43
2	~~2~~	~~1656~~	~~40,3~~	~~41,1~~	~~5,77~~	~~2567,03~~	~~25.07.2012~~	~~12:24:05~~
3	~~3~~	~~1648~~	~~40~~	~~41,2~~	~~6,89~~	~~3029,21~~	~~25.07.2012~~	12:25:54
4	4	1635	39,6	41,3	11,14	4811,62	25.07.2012	12:27:43
5	~~5~~	~~1648~~	~~40,4~~	~~40,8~~	~~9,20~~	~~4082,53~~	25.07.2012	12:29:10
6	6	1640	40,2	40,8	15,04	6610,15	25.07.2012	12:30:56
7	7	1644	40,5	40,6	12,04	5343,66	25.07.2012	12:32:36
8	8	1656	39,9	41,5	10,60	4668,31	25.07.2012	12:34:16
9	9	1788	39,9	44,8	14,47	6878,86	25.07.2012	12:36:03
10	10	1754	40,6	43,2	10,20	4842,07	25.07.2012	12:38:00
11	11	1803	40,8	44,2	15,66	7679,60	25.07.2012	12:39:49

Prüfgeschwindigkeit : 0,4 mm/min avg.: $\overline{12{,}77}$

Seriengrafik:



Statistik:

n = 11	Probennummer	A mm²	Probendicke a0 mm	Probenbreite b0 mm	σ N/mm²	FMax N
x	6	1688	40,23	41,96	11,27	5130,65
s	3,317	63,09	0,3524	1,454	3,20	1578,06
v	55,28	3,74	0,88	3,47	28,41	30,76

Figure 74 : plot of bending strength

Splitting tensile strength test spray-UHPC 25.7.2012 TU Wien

load increase 200N/s

prism ca. 4*4*6,9cm

shim: hard fiber wood board stripes 8mm wide 4mm thickness

number of specimens is the same like at bending tensile (but one half prism was cut on both ends for this test). The bending tensile test is a 3-point, span 100mm, single load in the middle, prism size is 40 x 40 x 160 mm

Nr.	d [mm]	L [mm]	F [kN]	splitting tensile [MPa]	bending tensile Mpa
1	40.3	69.1	36.06	8.24	13.00
2	40.3	68.9	33.01	7.57	5.77
3	40.0	69.0	50.24	11.59	6.89
4	39.6	69.1	52.02	12.10	11.14
5	40.4	69.1	44.39	10.39	9.20
6	40.2	69.2	42.61	9.75	15.04
7	40.5	69.2	23.62	5.37	12.04
8	39.9	69.5	57.84	13.28	10.60
9	39.9	68.8	52.83	12.25	14.47
10	40.6	69.5	49.84	11.24	10.20
11	40.8	69.4	52.33	11.77	15.66
			Mean	**10.23**	**11.27**
			Min	5.37	5.77
			Max	13.28	15.66

compressive strength on sprayable UHPC cubes 100mm

load increase 3 Mpa/s

Nr.	mass [g]	a1 [mm]	a2 [mm]	b [mm]	compressive strength [Mpa]
1	2410.30	103.50	100.60	100.00	143.73
2	2415.20	100.80	103.50	100.80	137.47
3	2350.10	99.90	99.90	100.00	166.59
4	2398.50	100.00	102.30	101.20	150.05
			Mean		**149.46**
			Min		137.47
			Max		166.59

Young’s modulus on prism 40 x 40 x 160mm

Nr.	Mpa
1.	65113
2.	57615
3.	71285
4.	67659
5.	72896
Mean	**66913.60**
Min	57615.00
Max	72896.00

3.8 Analysis of results

From the results of the tests it is clear to see that UHPC has material properties that are suitable for use as building cladding. The shells made during these tests were too heavy to be considered as cladding for grid shells with timber or composite laths such as GFRP. The 2 x 2 mt shell had a weight of 330 kg, and the 1 x 1mt shell 55 kg. In order to carry the dead load of the cladding, the timber or composite members would have to have much larger sections. This would impact on their ability to form self-stabilized doubly curved form through the process of elastic bending. The energy required to bend larger section sizes would be much higher. However, that being said, the experience of making them has shown that great room exists for optimization – the shells as sprayed were too thick.

Optimization can bring the shell thickness to between 4-7mm, leading to a reduction in weight of approximately 75%. Therefore a 2 x 2 mt shell (4.64 m^2) would weigh 77 kg and represent a dead load of 16.6 kg/m^2. Optimization strategies are not just limited to a reduction of the thickness :

1. The density of the polypropylene and glass fibre in the UHPC mixture needs to be researched by further testing in order to find the optimum value. Generally an increase in density will lead to increased tensile and flexural strength.
2. Shells can be made with steel reinforcement mat instead of glass fibre mat.

3.9 Conclusion

During the tests, the choice of fabric for making the forms was a PVC foil. This foil is an orthotropic film and had a very large distortion under the load of the concrete. This caused strain cracking on the surface of the shells (this can be seen on the photos of the shells on page 53). The deformation forced us to spray the shells a bit thicker than we would have liked to. A more suitable fabric for the formwork would be a PVC coated PES, as commonly used for membrane structures. These fabrics are designed to carry pre-stress. Their distortion under load is well documented and can be factored into the cutting patterns for the forms.

In regards to the possibility of using sprayable UHPC for building cladding, the experience of making the shells brought to light some potential difficulties :

1. The formulation, mixing and batching of UHPC is a precise task and needs to be done under controlled conditions in order for its material parameters to be attained. It would be difficult to achieve these conditions on a building site.
2. Spraying UHPC is a physically demanding task. The concrete pump, accelerant dosing pump and hose need to be accessible to the operator. To spray fabric forms at height, a lift platform would be required. In order to achieve reasonable production speeds, several operators and lift platforms would be required to spray the UHPC simultaneously. This would add considerable time, expense and complexity to the building task.
3. As mentioned earlier in the document, a system needs to be devised to ensure that a uniform thickness of UHPC is applied onto the fabric surface. A system of pins normal to the surface orientation glued to the fabric in a grid pattern was proposed.

4.0 Concrete Canvas

Further to the work done with UHPC and the results noted therein, further tests were proposed – the manufacture and testing of cladding panels suited for grid shell structures using a concrete impregnated composite fabric known as Concrete Canvas.

This product is composed of two layers of fabric – the top layer is a fabric woven with hydrophilic (water absorbent) fibres. The bottom layer is a PVC coated PES waterproof fabric. Between the two layers of fabric is a high performance concrete mixture and a fibrous mat designed to keep the concrete mix distributed uniformly. In essence the two layers of fabric and fibre mat traps dry concrete powder in a 3-dimensional fibre matrix. The product is flexible and is manufactured in roll format. In order to activate the concrete, water must be applied. CC will achieve 80% strength at 24 hours after hydration.

This fabric was chosen as it has obvious advantages that are relevant for building cladding :

1. The product is pre-made – there is no need to spray UHPC on site – simply fix to the primary structure and hydrate.
2. CC has values for compressive, tensile and bending strength that are not as high as UHPC but are nevertheless acceptable for the proposed building task.

The relevant material properties have been extracted from the manufacturer's data sheet and are presented. The full data sheet is included in appendix 1.

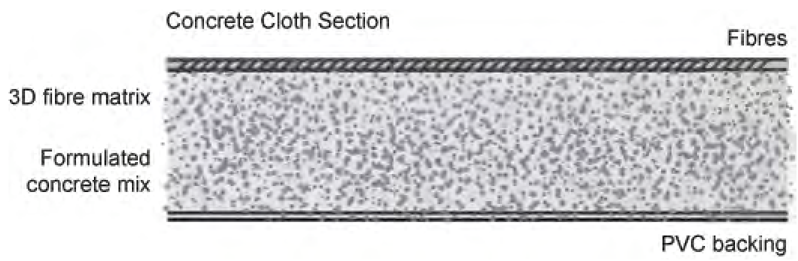


Figure 75 : concrete cloth section[34]

[34] http://.concretecanvas.co.uk/Download.html - accessed May 2012

Figure 76 : photo of CC 13 showing its composite structure

4.1 Material properties

Strength Values

Compressive tests based on ASTM C109 – 02

- 10 day compressive failure stress (MPa) 40

Bending tests based on BS EN 12467:2004

- 10 day bending failure stress (MPa) 3.4
- 10 day bending Youngs modulus (MPa) 180

Tensile data (Initial crack)

	Tensile strength (kN/m)	
	Length direction	Width direction
CC5	6.7	3.8
CC8	8.6	6.6
CC13	19.5	12.8

Figure 77 : tensile strength values[33]

Abrasion Resistance :

Similar to twice that of OPC Max 0.10 gm/cm^2

MOHS hardness 4-5

CBR Puncture Resistance EN ISO 12236: 2007 (CC8 & CC13 only)

Min. Push-through force 2.69kN

Max. Deflection at peak 38 mm

Freeze-thaw testing (BS EN 12467:2004 part 5.5.2) passed

Water impermeability (BS EN 12467:2004 part 5.4.4) passed

Fire Euroclass B certification

BS EN 13501-1:2007+A1:2009 B-s1, d0

CC	Thickness (mm)	Batch Roll Size (sqm)	Bulk Roll Size (sqm)	Roll Width (m)
CC5	5	10	200	1.0
CC8	8	5	125	1.1
CC13	13	N/A	80	1.1

Figure 78 : roll formats & available thicknesses[33]

CC	Mass (unset) (kg/m2)	Density (unset) (kg/m3)	Density (set) (kg/m3)
CC5	7.0	1500	+30-35%
CC8	12.0	1500	+30-35%
CC13	19.0	1500	+30-35%

Figure 79 : physical properties of CC before & after hydration[33]

Pre-set CC properties :

Working time 1-2 hours subject to ambient temperature

Method of hydration

Spray the surface with water until it feels wet to the touch for several minutes after spraying.

Figure 80 : one application of CC – rapid deployment hardened shelter[35]

[35] http://www.concretecanvas.co.uk/Images/ccsgallery/index.html - accessed October 2012

4.2 Manufacture of inflated shells

CC8 and CC13 were the fabric weights chosen to make the cladding panels. The decision was made to use pneumatic pressure to create the form. The shapes were modeled in the computer and cutting patterns generated for the production of the shells. In contrast, the sprayed UHPC shells were made by a physical form finding process.

Test regime

Two sizes were made – 0,5 x 0,5 mt, and 1,0 x 1,0 mt. The reason for these sizes is that the grid shell at Mannheim had a 0,5m spacing between the laths, while the shells at Downland and Savill Garden had a spacing of 1,0 mt. Therefore it was felt that these were the most appropriate sizes, given the history of grid shell buildings and the current state of the art. The shells were made by attaching the fabric to a 75 x 50mm timber boundary fixed to 20mm thick marine board. See graphic showing test setup.

Two inflation systems were tested :

1. Standard air line from a compressor fitted with a pressure adjustment mechanism, gate valve and pressure gauge (see figure 82).
2. Air supply from a blower powered by a 1.5 Hp motor, fixed to a 100mm diameter supply hose. At the inlet to the marine board was a gate valve and air pressure gauge.

The reason for two inflation systems was to compare how each worked. In addition, at the time of designing the test setup it was felt that inflation pressure from a standard compressed air line might not be sufficient to satisfactorily form the CC 13 shell which had a weight of 19 kg/m^2.

Some shells were made with a joint in the middle. This was due to the computer modeling and cutting pattern generation process – in order to get a cutting pattern, the doubly curved surface has to be unrolled or ‘developed’. Doubly curved surfaces are undevelopable without distortion. Splitting the surface along a theoretical geodesic line lying on the surface of the shell and then using a flattening algorithm to generate a cutting pattern was the method used to obtain the cutting pattern. This process is done automatically by the volume form finding module of the software Easy.

One shell was made at first using the CC8 fabric. The shell had a satisfactory shape upon inflation and hydration. An initial point load test was done, and failure occurred at a load of 2.5 kN. The joining of the fabric is not easy as it is a composite matrix. Therefore at this point it was decided to make some shells without joints. It was felt that they would be stronger, and the production process simpler. A way would have to be found to minimize the distortion of the cutting patterns.

	With joint	Without joint
CC8	1,0 x 1,0 - 1 pc	0,5 x 0,5 - 2 pcs
CC13	1,0 x 1,0 - 1 pc	1,0 x 1,0 - 2 pcs

Figure 81 : summary of shells produced

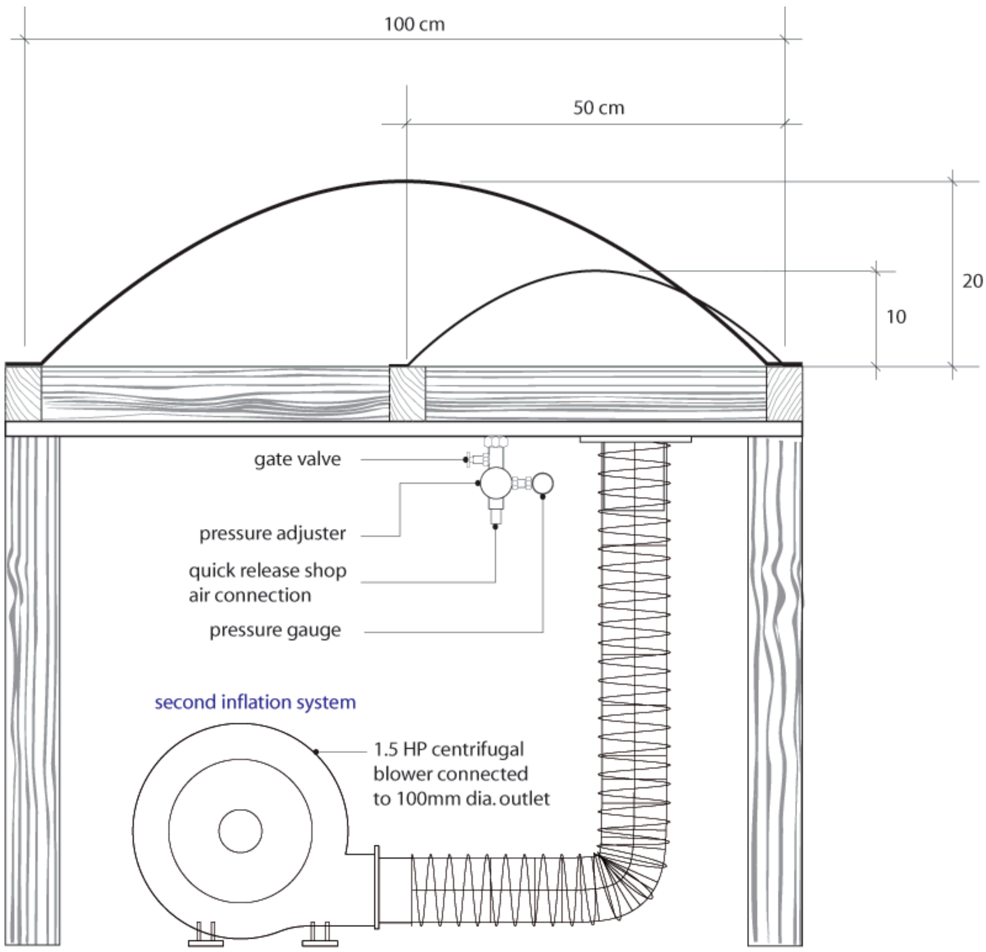


Figure 82 : Graphic showing inflation setup

Modeling, patterning & fabrication

The cladding panels were modeled in the computer using the Volume form finding module of the program Easy (Technet), and cutting patterns were generated after setting seam allowances.

The cutting patterns were output from a cutting plotter onto roll format paper. The patterns were used to cut the CC fabric by hand.

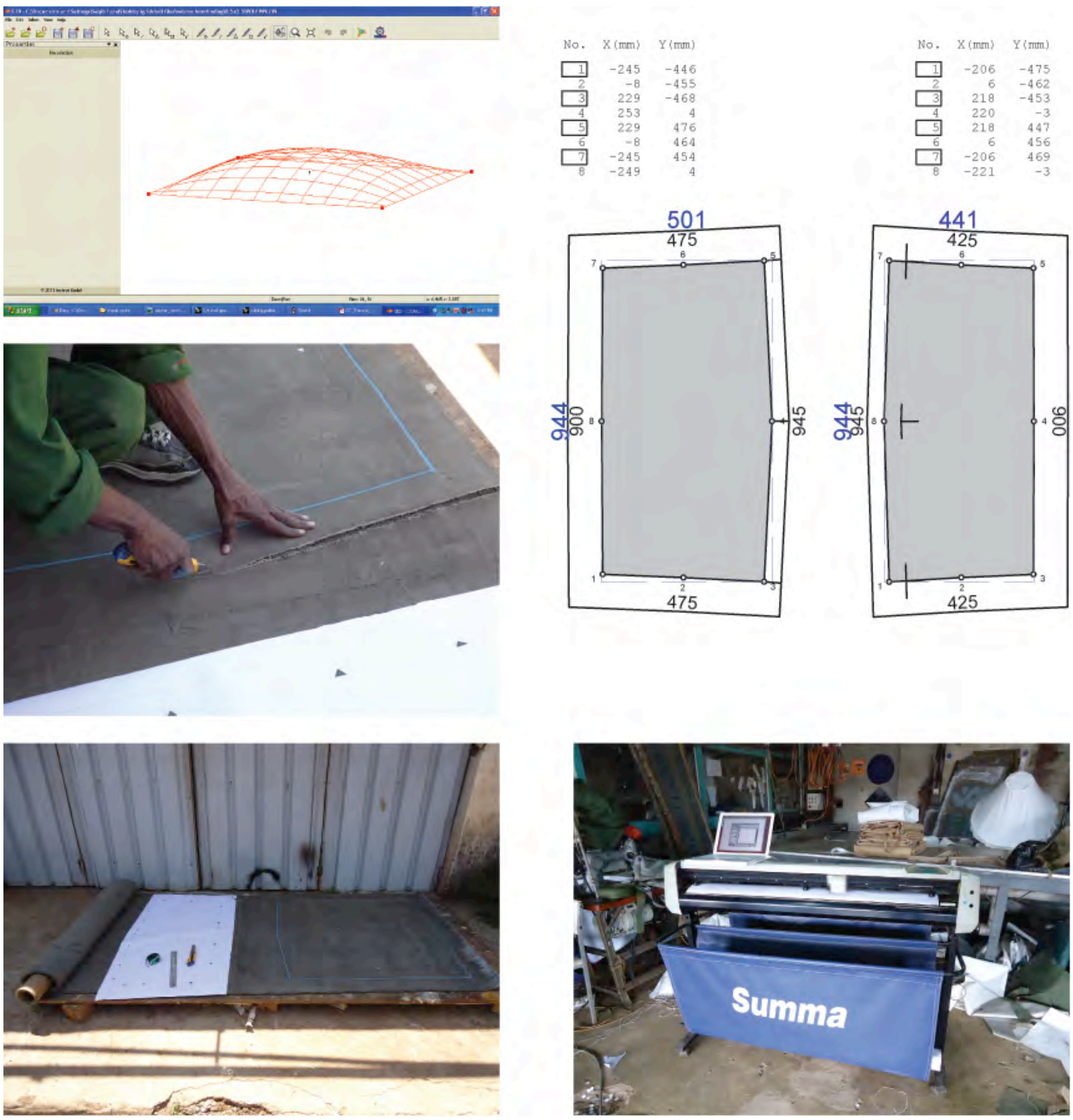


Figure 83 : pictorial of the modeling and patterning process clockwise from top left – modeling, patterning, plotting, tracing onto fabric and cutting

Cutting patterns for cladding panels without joints

The cladding panels are doubly curved surfaces which cannot be unrolled, flattened or developed into cutting patterns without distortion. Therefore the following strategy was employed in order to obtain a cutting pattern with a minimum of distortion. A geodesic line was defined on the surface of the panel, near the middle . The geodesic line was defined as the warp direction. The panel was split into two discrete pieces at the defined geodesic line.

The next step was to re-join the two separate shapes into one in order to obtain the cutting pattern. The software produces a report showing overall distortion from the original shape.

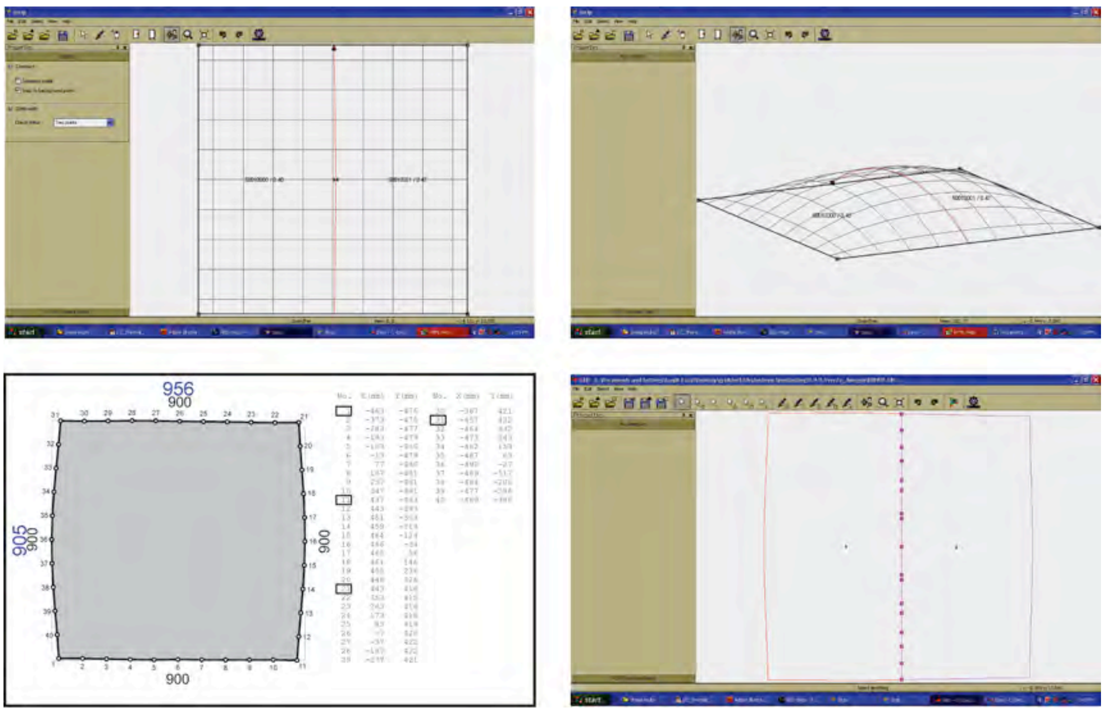


Figure 84 : clockwise from top left, definition of the geodesic line & warp direction, joining of the two discrete shapes and the resultant cutting pattern.

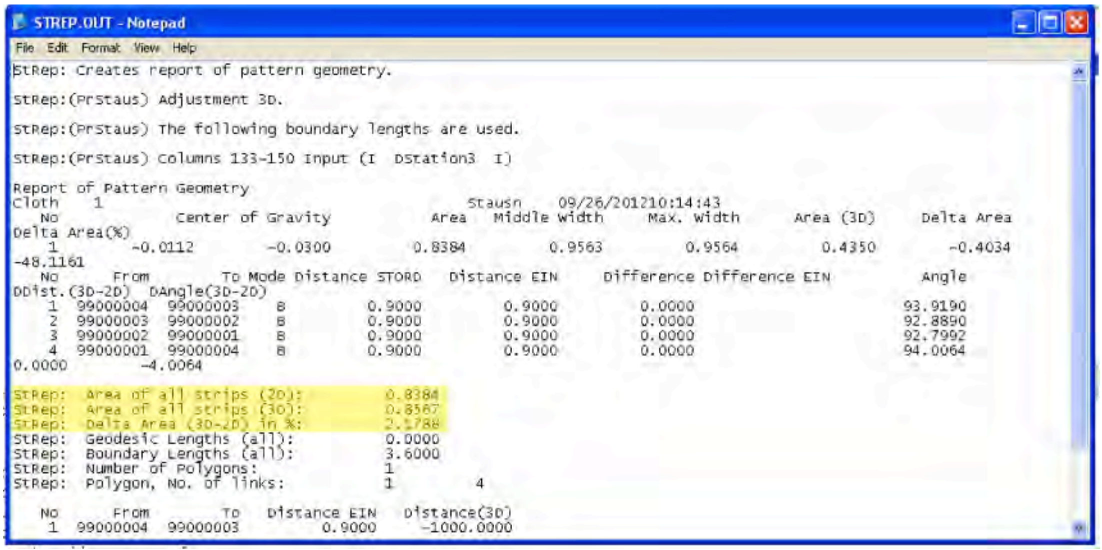


Figure 85 : software report summarizing distortion of the cutting pattern

The software report shows a distortion of 2,18% (Delta area 3D – 2D). This level of distortion is acceptable for this size of cladding panel.

Thermal welding of the panels

The backside of CC fabric is a PVC coated PES fabric. Therefore it can be thermally welded. A hand held hot air welding tool was used to join the fabric panels. Prior to welding the PVC side must be cleaned with a damp cloth to remove concrete dust. After the welding process the fibre side of the panels were stitched by hand to help them to lay flat, and to increase the mechanical strength of the joint.

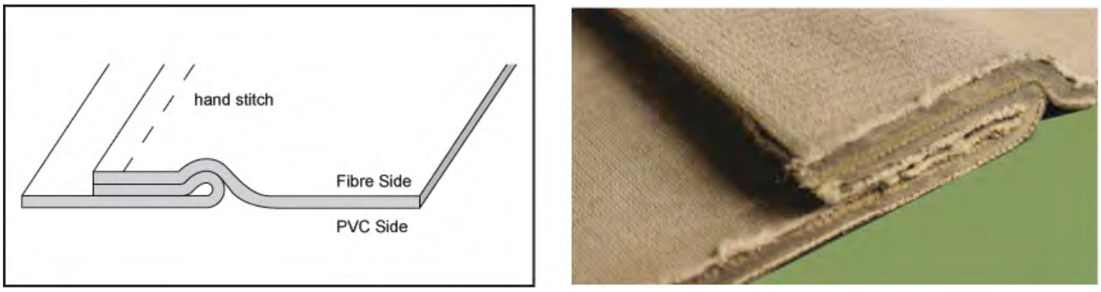


Figure 86 : seam overlap for CC[36]

[36] http://www.concretecanvas.co.uk/downloads - accessed May 14, 2012

Figure 87 : right to left, welding and hand stitched CC fabric

Manufacture of the shells :

Photographs are presented of the work done in making the shells :

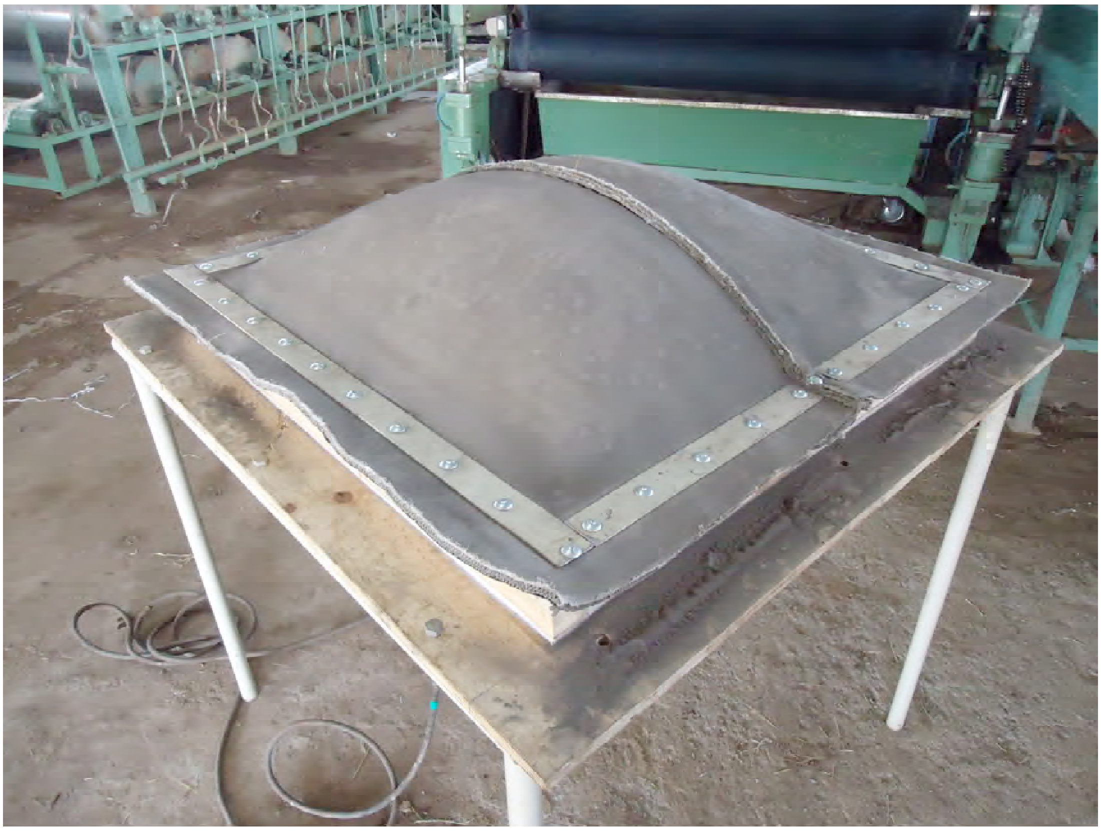


Figure 88 : Inflation of the first CC 8 shell with joint (prior to hydration)

Figure 89 : Hydration of CC 8 shell

Figure 90 : cutting off the excess material before removal of the shell from the timber frame

Figure 91 : CC 8 shell size 0,5 x 0,5mt

Figure 92 : photo shows both types of inflation systems used (CC13 shells)

4.3 Load Testing

Load test for CC 8 shell size 1,0 x 1,0 mt with joint.

This was the first shell made to test that the patterning, welding and inflation systems worked satisfactorily before the other shells could be made. The shell was subjected to a load test 7 days after completion. The shell was re-hydrated once a day for three days after the initial set to increase its strength.

A point load (cement bags, each of 50 kg) was placed at the center of the shell in 50 kg increments. Failure occurred at 250 kg (2,5kN). The failure was caused by a separation of the thermally welded PVC backing fabric, rather than a failure of the concrete component of the composite matrix. This test led to the decision to make shells without joints.

Figure 93 : failure mode of CC 8 shell with joint size 1,0 x 1,0mt

Load tests for CC 8 shells size 0,5 x 0,5 mt without joint.

The shells were subjected to two kinds of tests – a point load test and an area load test.

Point load test

The shell was subjected to a 3 point test, single load in the middle. The shell was supported at the edges. The load was applied hydraulically by a test machine. Failure (buckling of one side of the shell) occurred at 2,814 kN.

Figure 94 : point load test on 0,5 x 0,5 mt shell

Area load test

The shell was subjected to an area load by placing 50 kg cement bags in 100 kg increments on the shell. The bags were placed so as to cover as much of the surface area of the shell as possible.

The aim of the test was to measure deflection of the shell under load. A dial gauge deflectometer with 0,01mm divisions was used to measure the deflection. The maximum load considered for the test was 500 kg (5kN). The surface area of the shell is 0,2625m^2. The maximum load represents a load factor of 19,05 kN/m2, which is higher than any environmental load that can be imposed on the structure.

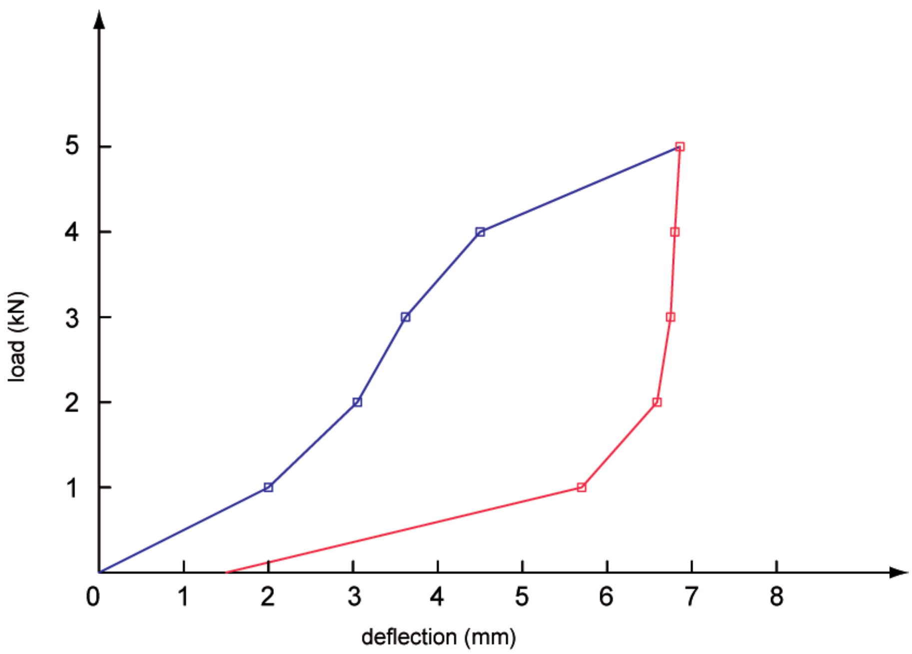


Figure 95 : deflection plot for CC 8 0,5 x 0,5 shell

Figure 96 : test setup showing dial gauge deflectometer

Figure 97 : test in progress

Result :

The maximum deformation was 6,86mm at 5,0 kN load. The shell was permanently deformed by 1,5mm after the test.

Load test for CC 13 shell size 1,0 x 1,0 mt without joint.

The same procedure for the area load test for the 0,5 x 0,5 shell was carried out with the CC 13 1,0 x 1,0 mt shell. Load was applied in 200 kg increments up to a maximum load of 1200 kg (12 kN). The deflectometer was used to measure deflection under load, and reverse deflection on removal of the load.

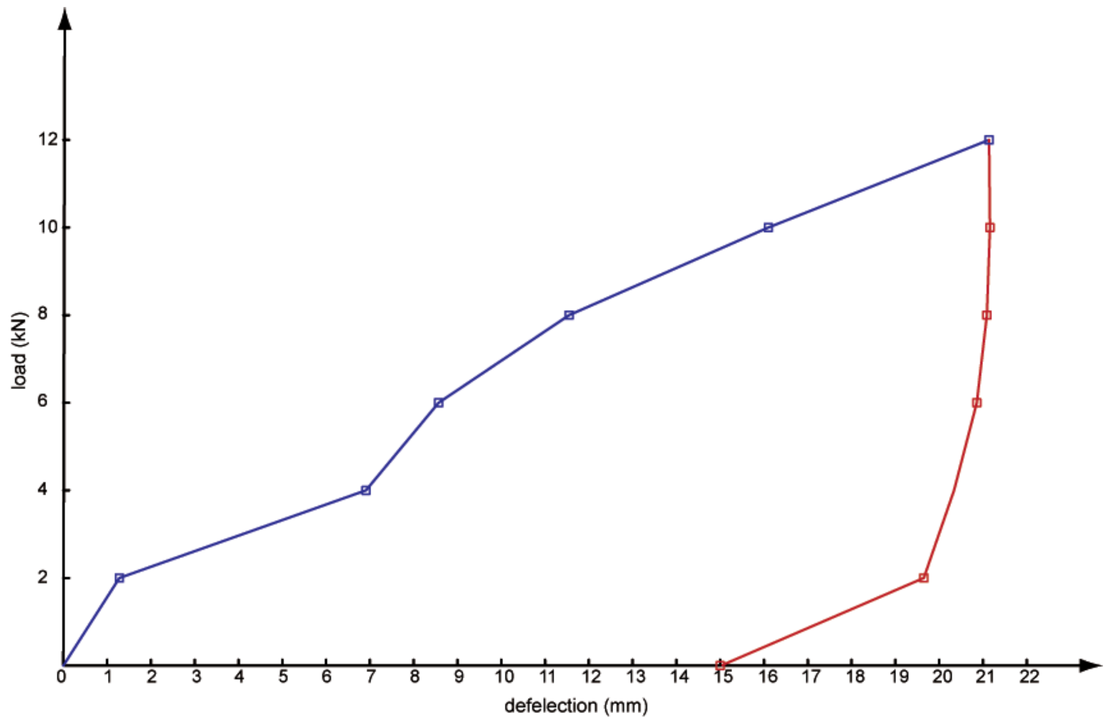


Figure 98 : deflection plot for CC 13 1,0 x 1,0mt shell

Result :

The maximum deformation was 21,14 mm at 12,0 kN load. The shell was permanently deformed by 15,02mm after the test.

Comparison of inflation systems :

The inflation system using the centrifugal blower connected to a 100mm diameter outlet hose was discontinued after the production of one CC 13 1,0 x 1,0 shell. The reason for this was that there was no way to adjust or control the air pressure with this system. The air pressure output was much higher with this system as compared to the system which had air supply from a compressor. The high air pressure caused the PVC backing fabric to tear when the shell was inflated. As a consequence, the concrete mix fell out of the fibrous mat, creating a weak spot.

During hydration, a lot of air bubbles were seen coming out of the affected area. Two hours after hydration, the area remained soft and flexible when the rest of the shell had begun to harden. Refer to the photos :

Figure 99 : high concentration of bubbles seen coming from shell during hydration

Figure 100 : Left to right, cement mix falls onto board and torn PVC backing fabric

Load test on damaged shell :

A test was carried out on the damaged shell produced from the inflation system with the centrifugal blower. The aim of the test was to see how much load the shell would take before failure or a permanent deformation of the doubly curved shape occurred. Deformation was not measured quantitatively.

If this cladding system was used in a real building and one of the panels got damaged, the results of this test might provide some information on the behaviour of a damaged panel under load. The shell was loaded with 50 kg cement bags up to a maximum load of 1500 kg (15 kN). The shell was under maximum load for a duration of 30 minutes.

Figure 101 : damaged shell loaded with 15 kN

Figure 102 : Damaged area of shell marked in red

Result :

The shell did not lose its doubly curved shape. There was permanent deformation as with the other CC 13 shell subjected to the load test described on page 78. The shell stood up to the load remarkably well despite its damaged condition. It can still function as a cladding element.

Shell weights :

Shell description	Weight
CC8 0,5 x 0,5 (without joint)	5,4 kg
CC8 1,0 x 1,0 (with joint)	18,2 kg
CC13 1,0 x 1,0 (with joint)	29,8 kg
CC13 1,0 x 1,0 (without joint)	27,4 kg

Figure 103 : summary of shell weights

4.4 Analysis of the results :

Concrete Canvas has a lot of potential for use as cladding for a grid shell structure or any other building :

1. The test results show it can withstand high loads.
2. The product is a composite. This protects the concrete mix from environmental degradation and increases its flexural and tensile strength.
3. CC is a ready product and is easy to work with.
4. CC achieves 80% of final strength 24 hours after hydration. This means that the speed at which a building can be clad is very high, which is of interest to the building designer, owner and contractors.

5.0 Conclusion and recommendations

Form finding

Advances in computer technology and software products in the last decade have made the task of form finding grid shell structures a relatively straight forward task. The designer has many options in their digital toolbox.

Caution is however advised in dealing with the output of some of the tools. Does the tool generate output that represents an equilibrium geometry taking into account the physical properties of the selected material ? – if this capacity is not present in the tool the designer must take additional steps to make sure that the chosen material can conform to the represented geometry.

Cladding solutions

Sprayable, fabric formed UHPC offers a good potential for grid shell cladding panels, given the strength, light weight and durability of the material. However some problems were noted during the tests :

1. UHPC needs to be produced under controlled conditions. These conditions are difficult to replicate at a building site. Therefore in situ spraying of inflated fabric panels on a grid shell structure would be require pre-mixed batches of material to be brought to site.
2. The spraying of UHPC is a physically demanding task. The pump, hose and nozzles need to be near the operator during the spraying process. Work at height would require a lift platform. This solution would need to be scaled up in order to complete the building task in a realistic timeframe – multiple operators and equipment sets would be required to complete a building the size of Mannheim Multihalle.

Concrete Canvas offers distinct advantages :

1. CC is flexible, ships in roll format and therefore is easy to bring to site.
2. CC can be cut, welded and fixed to the primary building structure with basic hand tools. In comparison with UHPC it requires no controlled conditions.
3. The concrete mix is encapsulated between two layers of fabric and requires only water for activation. The task of cladding a grid shell

structure would be completed very fast – fix to primary structure, inflate to create the doubly curved cladding panels, and hydrate.

4. It would also be a more economical solution than sprayable UHPC as much less labour, time and resources are required.
5. CC has strength values that are not as high as UHPC, but are nevertheless sufficient for the envisaged building task.
6. Further scope for testing and optimization remains as only CC 8 and CC 13 were tested. There is a 5 mm thick product (CC 5) which was not included in the testing regime.

Abbreviations

BBRI	Belgian Building Research Institute
CAST	Center for Architectural Studies & Technology, University of Manitoba
CC	Concrete Canvas
DR	Dynamic relaxation method
FDM	Force density method
GRFP	Glass fibre reinforced plastic
TRC	Textile reinforced concrete
SRC	Steel reinforced concrete
UHPC	Ultra high performance concrete
VUB	Vrije Universiteit Brussels

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Appendix 1 :

CONCRETE CANVAS
Concrete Impregnated Fabric

For further information or technical support contact
+ 44 (0) 845 680 1908 | info@concretecanvas.co.uk | www.concretecanvas.co.uk

Concrete Canvas™ Material Data

CC Physical Properties*

CC	Thickness (mm)	Batch Roll Size (sqm)	Bulk Roll Size (sqm)	Roll Width (m)
CC5	5	10	200	1.0
CC8	8	5	125	1.1
CC13	13	N/A	80	1.1

CC	Mass (unset) (kg/m2)	Density (unset) (kg/m3)	Density (set) (kg/m3)
CC5	7.0	1500	+30-35%
CC8	12.0	1500	+30-35%
CC13	19.0	1500	+30-35%

Pre-Set CC Properties

Setting

Working Time 1-2 hours subject to ambient temperature

CC will achieve 80% strength at 24 hours after hydration.

Method of Hydration

Spray the fibre surface with water until it feels wet to touch for several minutes after spraying.

Re-spray the CC again after 1 hour if:
- Installing CC5
- Installing CC on a steep or vertical surface
- Installing in warm climates

Notes:
- CC cannot be over hydrated and an excess of water is always recommended.
- Minimum ratio of water:CC is 1:2 by weight.
- Do not jet high pressure water directly onto the CC as this may wash a channel in the material.
- CC can be hydrated using saline or non-saline water.
- CC will hydrate and set underwater.
- CC has a working time of 1-2 hours after hydration. Do not move CC once it has begun to set.
- Working time will be reduced in hot climates.
- CC will set hard in 24 hours but will continue to gain strength for years.
- If CC is not fully saturated, the set may be delayed and strength reduced. If the set is delayed, re-wet with a large excess of water.

Contact Concrete Canvas UK

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Post Set CC Properties

Post set data is based on CC hydrated in accordance with the CC Hydration Guide.

Strength

Very high early strength is a fundamental characteristic of CC. Typical strengths and physical characteristics are as follows:

Compressive tests based on ASTM C109 – 02
- 10 day compressive failure stress (MPa) 40

Bending tests based on BS EN 12467:2004
- 10 day bending failure stress (MPa) 3.4
- 10 day bending Youngs modulus (MPa) 180

Tensile data (Initial crack)

	Tensile strength (kN/m)	
	Length direction	Width direction
CC5	6.7	3.8
CC8	8.6	6.6
CC13	19.5	12.8

Abrasion Resistance (DIN 52108)
- Similar to twice that of OPC Max 0.10 gm/cm2

MOHS hardness 4-5

CBR Puncture Resistance EN ISO 12236: 2007 (CC8 & CC13 only)
- Min. Push-through force 2.69kN
- Max. Deflection at Peak 38mm

Resistance to Imposed Loads on Vehicle Traffic Areas
EN 1991-1-1:2002 (CC8 & CC13 only)
- Category G compliant
- Gross weight of 2 axle vehicle 30 to 160kN
- Uniformly distributed load not exceeding 5kN/sqm

Standard Test Method for **Impact Resistance of Pipeline Coatings** ASTM G13 (CC13 only) Passed

Other

Freeze-thaw testing (BS EN 12467:2004 part 5.5.2) Passed

Soak-Dry testing (BS EN 12467:2004 part 5.5.5) Passed

Water Impermeability (BS EN 12467:2004 part 5.4.4) Passed**

Reaction to Fire

CC has achieved Euroclass B certification:
BS EN 13501-1:2007+A1:2009 B-s1, d0

CC Patent Information

Patent Protected
Pat Pend/Granted: [illegible] and other patents pending

Concrete Canvas Ltd
CF37 5SP United Kingdom
11
EN12467:2004
Concrete Canvas
Fibre cement sheet
NT
Oversize sheets
Class 1, Category A
Reaction to Fire B-s1,d0

* Indicative values

** For containment applications where a 100% waterproof seal is required, it is recommended to use CC as a protective overlay in combination with an appropriate sealed membrane liner. CC is not recommended as the sole barrier layer where 100% impermeability is critical.