Research Paper

How to use curved concrete panels, made with a flexible mould, in a structural manner.

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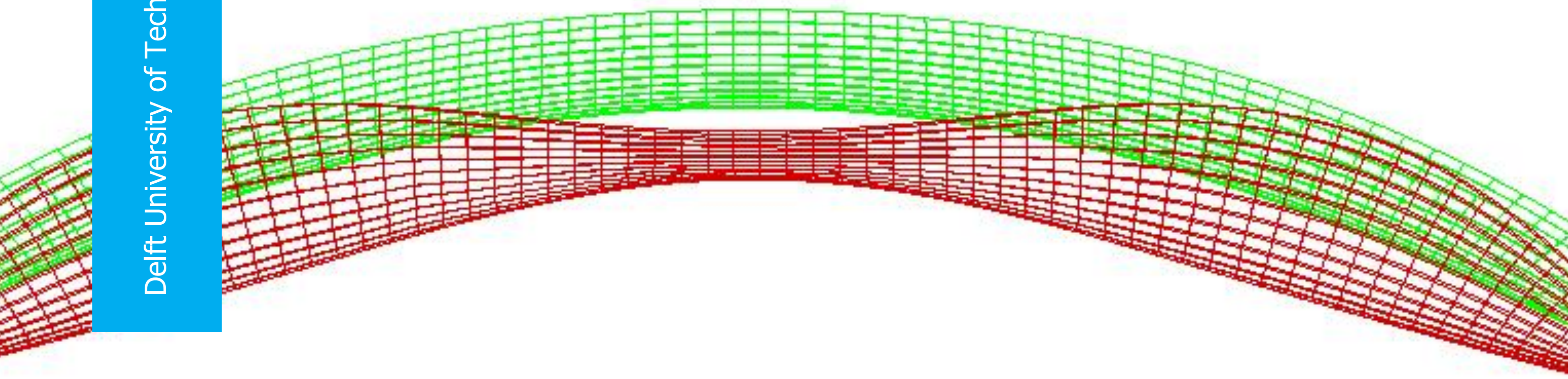

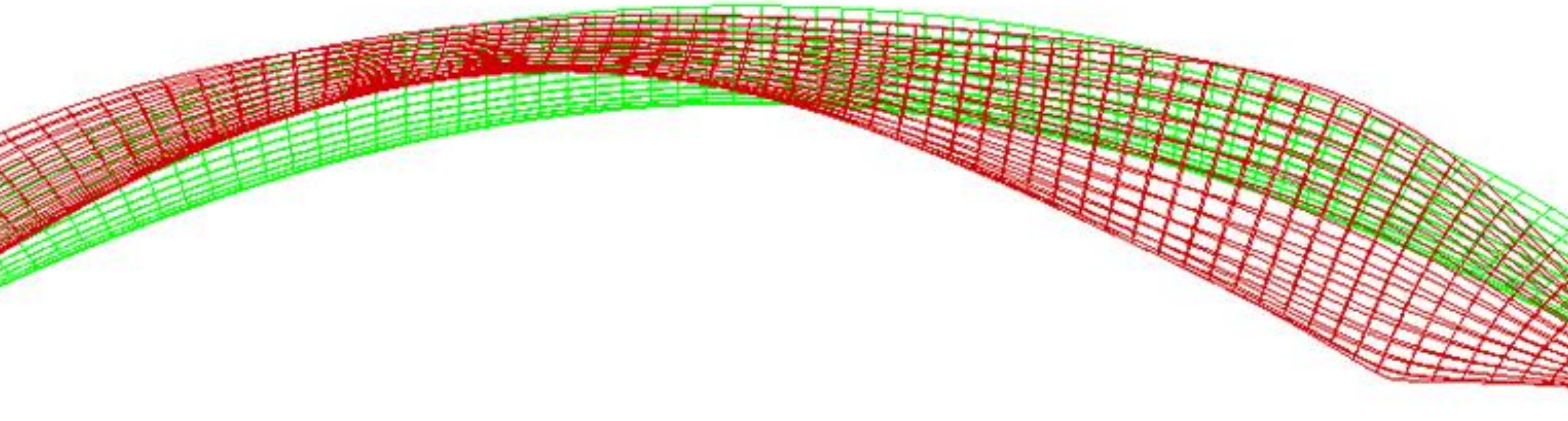

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Abstract

New digital fabrication techniques make it economically possible to mass-customize building elements, where economics dictate that mass-production is needed with conventional building techniques. A flexible mould give designers the possibility to create (double) curved panels. It is possible, with a carefully designed mould, to make very precisely shaped panels that come close to their digital reference model. The tolerances and deviations can often be controlled up to a couple of millimetres.

Using a computer to drive the flexible mould lowers the labour intensity of panel creation vastly. Reinforcing the concrete through post-tensioning or with mesh layers of textile improves the maximum tensile and bending stresses a panel can cope with. However, it takes a significantly amount of extra time to apply the reinforcement compared to the production of non-reinforced panels. In the case of textile reinforcement this can partly be overcome by using either 3D textile meshes or by edge clamping the textile layers before casting the concrete.

Presently, double curved panels made with flexible moulds have only been used in a non-structural capacity. This paper provides a case study in which multiple panels are connected and form one continuous shell structure. The results show that it is possible. Other case studies show similar results as the one provided in this paper.

Further research and calculations are needed to be able to give a decisive answer to the research question. Physically building a prototype would prove the hypothesis.

Keywords: flexible mould, post-tension, precast concrete panel, shell structure

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1. Introduction

Fascination

During my study period at the university my design philosophy has morphed quite significantly. At first I designed rational, easy to build and introvert buildings. This has progressed to more extrovert tectonic buildings with a key focus on the optimisation of their structure. Thin, elegant, curved and optimized structures tell a strong and inspiring architectural story. They ultimately show the frontier of human knowledge and capability. I, like most people, am often in awe when I see bridges, vaults, domes or shell structures.

Problem & Relevance

Over time there has been a shift in building costs, switching from high material costs to expensive labour. Cheap labour and high materials costs gave designers once the option to design custom and detailed elements. It also gave people like Nervi, Isler and Candela the option to put a lot of labour resources into the creation of moulds for shell structures and double curved surfaces. Today, most of the products used in the building trade are standardized and mass-produced to limit labour intensity per unit fabricated. It has become unrealistic to design double curved structures with a high rate of mass-customization in the traditional fashion. In contemporary architecture the free-form is often only accomplished for non-loadbearing façades supported by a generic structure. The explosion in computing power and the introduction of digital fabrication techniques provide new tools for designers. These tools have the potential to reintroduce mass-customization. Digital fabrication is still relatively new, therefore it is an interesting field for further research.

The digital fabrication technology that this paper focusses on is the flexible mould. A flexible mould is a mould that is flexible itself. The mould surface can be adapted and curved to the designer desired specification. With a traditional mould there is a requirement to mass-produce elements, in order to be economically viable. With a flexible mould this requirement is dropped, because the mould is adaptable for any desired shape. It can theoretically be reused infinitely. By driving this flexible mould automatically via a computer the shape of the mould can be set with great accuracy, without any need for manual labour. This gives designers the possibility to create customized (double curved) panels or shell structures once more.

Research question

- How to use curved concrete panels, made with a flexible mould, in a structural manner?

Sub-questions

- What is a flexible mould?
- What are the limits of existing flexible moulds?
- What is the quality of the panels made from these moulds?
- How to connect panels together into a continuous surface?
- What are the requirements for this connection detail?
- How to use the panels in a structural fashion?

Sign-posting

Chapter 2: Methods, describes the methods used during this technical research. All these methods are placed in a conceptual framework to guide the research process. In Chapter: 3 Results, all relevant products and results are given. The sub-questions will also be answered. Intermediate steps and results are left out of this paper to keep it readable. The last chapter of this paper is Chapter 4: Conclusion & Discussion. This chapter gives the main conclusion of this research, with a summary of all the results, the scope of this research and will provide advice for further research. The paper ends with a reference list. An abstract is provided at the beginning of this paper.

Acknowledgments

I would like to thank Annebregje Snijders, my first tutor and main supervisor, for providing me with general inspiration, vital criticism and feedback. I also would like to thank Peter Eigenraam for his time and insight during consult sessions. His technical knowledge and enthusiasm helped me to overcome technical problems during this research.

2. Methods

Before the actual technical research started, a process framework was designed (see Figure 2.1). This framework shows which methods to follow and the interaction between these research methods. All applied methods for this research form rings around each other, like an onion. The inner layer is the most exact and is fed with information from the more general outer layers. There is a constant exchange between the different layers of the framework. These exchanges and an iterative work process let each cycle to more specific and detailed answers.

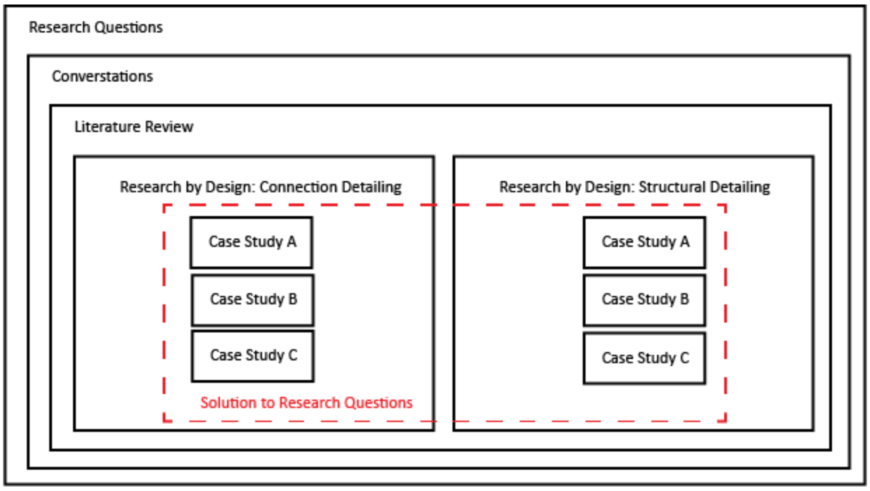


Figure 2.1: Process framework

<u>Conversations</u>
During this research project I have had conversations, discussions and consults sessions. The conversations with my fellow students about architecture in general, my project and their projects helped to further spark my interest. It also helped to see my project and problems from another perspective. Consult sessions helped to structure my process, overcome problems and find new relevant literature. Without success I tried to get in contact with relevant companies and researchers. My inquiries were either declined or ignored.

<u>Literature Review</u>
Before any design or research can start it is vital to have a general overview of the research topic and its wider field. There is already a vast amount of knowledge available. By getting familiarized with the body of knowledge the researcher makes sure no time gets wasted by reinventing something which is already known. By starting a literature review early in the process it can also help to focus the designer and sharpen the research question(s).

By reading literature new insights will be gained. The more technical and specific knowledge will lead to deeper understanding of the problem and its roots. This will potentially lead to new and original answers to the research questions. Literature can also identify completely new questions.

Normally the literature review also includes a review of presidents. The flexible mould technology is researched actively. So far the panels made with this production method have not been used in a structural capacity. Therefore it is impossible to review shell structure made with this technique. Presidents of individual panels made by flexible moulds and general concrete structures have been studied.

There are three main sources of literature used for this technical research. To get familiarized with the research field books and magazines from the university library and my own bookshelf were used. This body of literature is also used to find answers to post-tension technical problems. Reviewed and published research papers found in magazines and online were used to gain knowledge about the more experimental flexible mould technology. At our university a lot of research has been done on flexible mould technology (and concrete shell structures in general) by researchers, professors and graduation students. Therefore the TUDelft repository with the reports of their work has been significant for this technical research.

<u>Research by design</u>

The research by design has been split up into two tracks. The first track focused on the connection detailing between the individual panels. The second track focused on the structural capacity of the shell structures as a whole. This is done through finite element analysis. Multiple case studies were done, each varying in size and applied load conditions. These two topics were studied side by side with constant interaction between the two, giving each other relevant parameters. By integrating these two tracks a cohesive design can be made and the research question can be answered.

3. Results

This chapter provides the outcome of the literature review and the research by design. This will answer the sub-questions as formulated in the introduction.

3.1 Literature review

This technical research started with my fascination for structurally optimized free-form architecture and a lecture given by Pieter Stoutjesdijk on digital fabrication [1]. In his lecture he showed various new fabrication techniques. Each has their own unique potential to solve traditional building and/or connection problems.

The flexible mould was one of the promising digital fabrication methods I came across. Two short movie clips published by a Danish company called Adapa inspired further research [A][B]. Adapa develops and produces flexible moulds. Their technology can be used to create double curved panels. The shape of the surface of their mould is controlled by computer driven actuators. The smallest curvature radius that can be achieved with this technology is a curvature radius of 400 millimetres (see Figure 3.1). Adapa claims that their moulds can create unlimited number of panels without any waste of production materials [2]. The materials which can be used are concrete, thermoplastics, gypsum, glass, fiberglass and carbon fibre. This technical research paper focusses on the use of concrete.

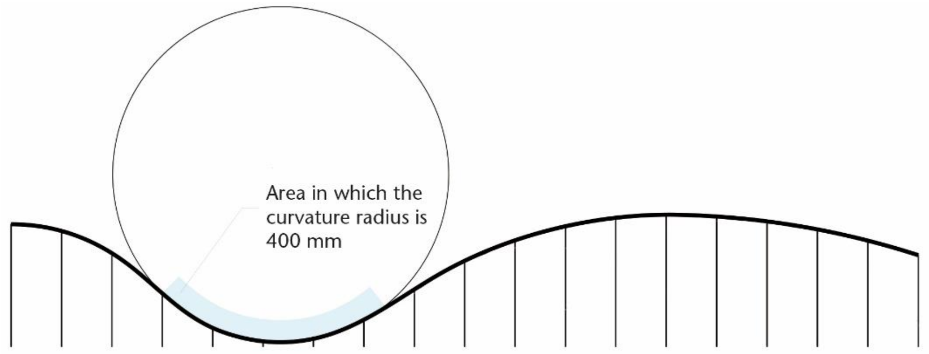


Figure 3.1: Maximum achievable curvature radius with (Adapa) flexible mould technology

Figure 3.2 shows the process from design to the creation of a double curved panel. The first step is to design a panel, or surface, in Rhino 3D. It is possible to use other computer programs, but Rhino 3D allows the designer to work with NURBS-surfaces. NURBS-curves and surfaces are highly accurate and fluent. Therefore it is possible to create the panels very accurately. The second step is to apply the material (concrete) for the panel on the mould. In the third step the computer drives the actuators of the mould. This shapes and curves the surface of the mould into the desired shape. When the panel is hardened it can be removed from the mould and stored until the concrete is hardened completely. The process can now be repeated. If holes, recesses or specific edge details are required in the final panel, temporary objects with that shape must be placed on the mould before the application of concrete is done. After the panel is hardened these temporary objects can be removed. The result is a panel with holes or recesses in the desired locations. It is also possible to attach connection brackets or other elements directly on to the panels. This must be done when the panel is still wet. After the concrete is hardened these objects have become an integral element of the panel.

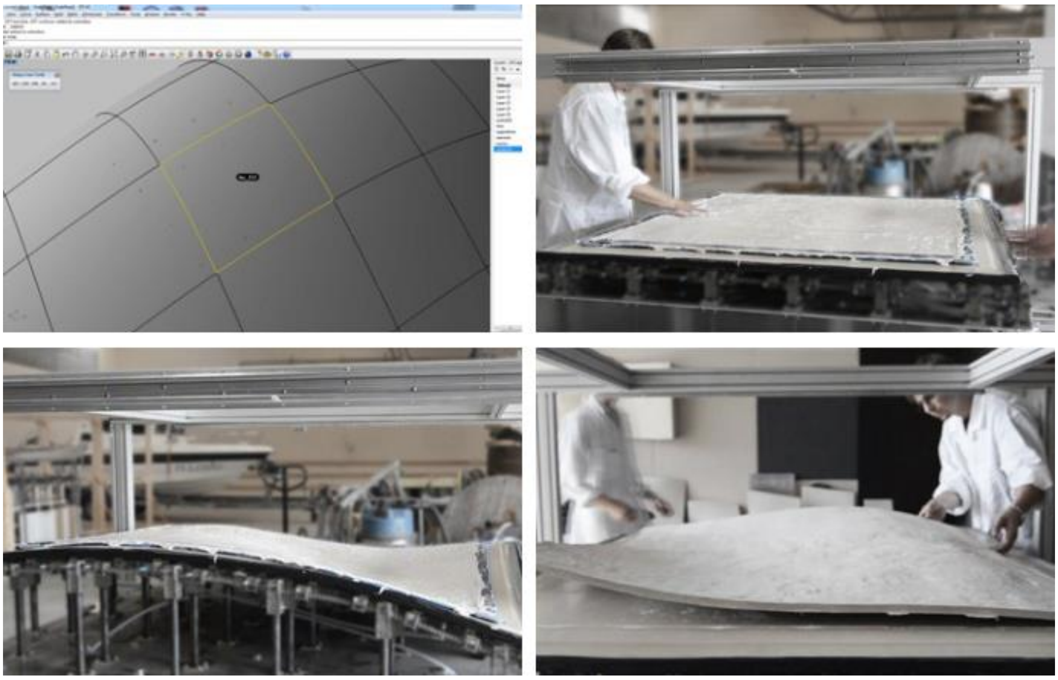


Figure 3.2: digital design of the panel, application of material, reshaping of the mould, final panel

Eline den Hartog worked for her master thesis on the prefabrication of concrete shells structures [3]. She describes the use of a flexible mould to produce the prefabricated panels. Two topics in her thesis are the quality of the edges of the panels and possible connection methods between panels. She lists six principle connection methods, namely:

- Wet connection
- Bolted connection
- Post-tensioning connection
- Welded connection
- Glued connection
- Fibre joint

Two from these six methods are used for the 'research by design' done for this paper. The post-tensioning connection provides a strong connection between the panels and is very suited to be used in combination with concrete elements. The second connection method to be used is the wet connection. This also provides a strong connection between the panels and will provide extra space for more reinforcement.

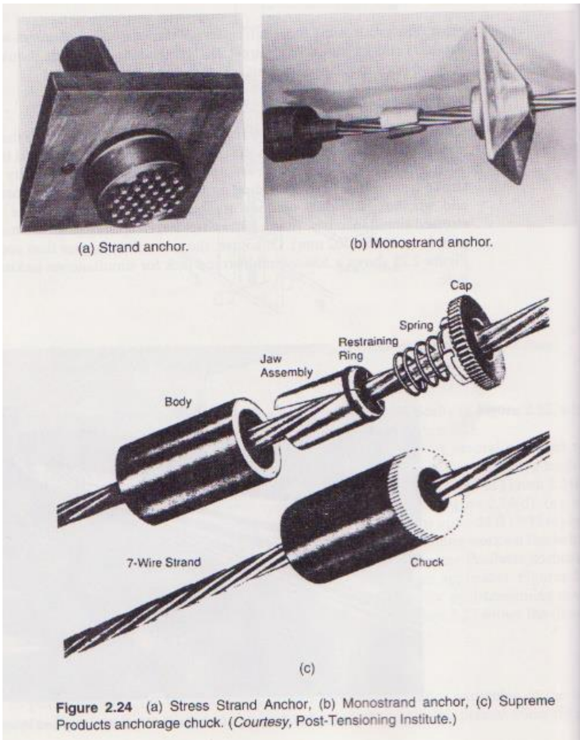


Figure 3.3: different types anchors

Post-tensioning is a form of prestressing concrete, which is used in already hardened or precast concrete elements. Post-tensioning can be used in complex and curved geometry because it makes use of a tension cable and not a rigid steel bar. A cable is pulled through ducts inside concrete elements and is locked in tension with an mechanical anchor (see Figure 3.3). The duct does not only provide a path through the construction for the cable, it also provides protection against damage done to the cable due to the mechanical handling of it during installation. A complete post-tensioning system of cables, ducts and anchors is called a tendon. The locked tension stress in the tendons causes compression stress in the concrete. This new compression stress counteracts tensile forces, created by load conditions. Effectively, the prestressing will improve the capability of concrete to cope with tensile stress at the cost of extra compression stress. A tendon can be designed as a bonded system or an unbonded system. With a bonded system the ducts are filled with grout after stressing, this introduces stronger compatibility between the concrete and the tendon. Strain experienced by either material is also experienced by the other. With an unbonded system the ducts are not filled with grout after stressing. This keeps the compatibility between the materials lower, the strains on either material is not directly transferred to the other [4][5].

Concrete can take a lot of compression stress compared with its capability to take tensile stress. Therefore it is important to apply reinforcement in concrete structures. With the use of a flexible mould the deformation of the panel takes place after the concrete is cast. Traditional iron reinforcement bars are not flexible enough to deform sufficiently and therefore do not stay in the desired place after deformation. There are ways to apply traditional steel reinforcement bars, but the preparation and the awkward manner of placing them makes this unpractical and uneconomical.

Marijn Kok studied the strength of double curved panels made from textile reinforced concrete for his master thesis [6]. The maximum tensile and bending stress a panel can cope with greatly increases when concrete is reinforced with layers of textile during the casting procedure. The applied layers of textile consists of bundles of fibre yarns in a mesh pattern. More than one layer of textile is needed in a panel to exceed the tensile strength of the concrete. The layers of textile meshes should be around 5 millimetres spaced apart. His research shows that the textile meshes, after deformation of the mould, stay within a millimetre of their desired location in the panel. A textile reinforced concrete panel has around 20% of the tensile and bending strength of the applied textile. This is significantly higher compared to panels made from concrete without (textile) reinforcement. The lamination and casting process is labour intensive. This labour intensity can be reduced by either using 3D textile meshes or by edge clamping all the individual mesh layers before casting the concrete.

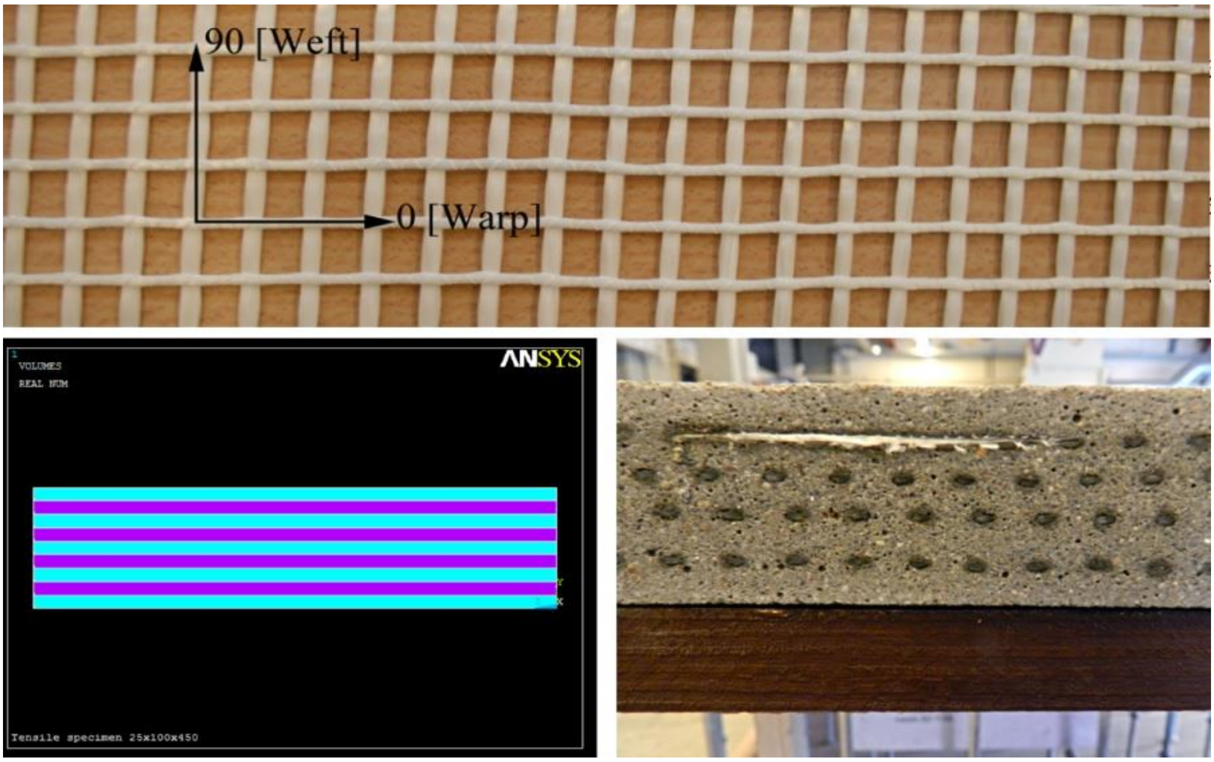


Figure 3.4: textile mesh, a textile reinforced concrete panel in finite element analysis software shows the layers, a concrete test panel with textile meshes spaced 5 millimetres vertically apart

Research done at the Vrije Universiteit Brussel [7] on the topic of textile reinforced concrete has shown comparative results as Marijn Kok's results. Their shell structures made from textile reinforced concrete only needed a thickness of 8 millimetres for a span of 2 meter and a thickness of 40 millimetres for a span of 10 meter. Another way to strengthen the panels is to use short glass fibres added to the concrete mix before casting. However, only a limited amount of fibres can be added to preserve compression strength. It is also impossible to finely control the distribution of fibres in the concrete mix, which can lead to local weak spots. Using textile meshes therefore is preferable over the use of short fibres.

Peter Eigenraam worked for his master thesis on the improvement of the accuracy of the panels made by flexible moulds to match the reference geometry as close as necessary [8]. With his new concept for a flexible mould he has found ways to reduce uncontrolled and unwanted displacements and rotations of the mould surface. At the moment his thesis is still under embargo, therefore I cannot explain how his new flexible mould works in-depth.

I visited the faculty of Civil Engineering together with Peter Eigenraam. Here he showed me his work on flexible moulds and some of the test panels he made with them. The panels showed that flexible moulds have the capacity of creating accurate double curved panels, with a high surface quality. It also showed that it is possible to create sharp edges, which is important for the connection detailing.

The size limit of the panels is determined by the size of the flexible mould. A maximum panel size of 1,2 by 1,2 meter is a common size used by researchers. This is a workable size for prototypes, for commercial moulds the maximum panel size can be larger. Adapa has moulds ranging up to a size of 1,2 by 3,6 meter. Eline den Hartog has in her thesis a theoretical mould of 3,0 by 3,0 meter.

From the literature review we have learned what a flexible mould is and how it can be used. The limits in size and the quality of the panels vary between different companies and researchers. Over time the maximum size of the panels may grows, by the creation of larger flexible moulds. Another aspect that improves is the accuracy of the panels through the development of better flexible moulds. Using textile reinforced concrete increases the loadbearing capacity of the panels and makes structural behaviour more predictable.

3.2 Research by design

For a continuous curved surface on a useful architectural scale, multiple panels must be connected to each other. Therefore multiple connection details need to be designed. Important parameters for the panels, details and construction methods are:

- the ability for the connection to allow for tolerances in the panels
- the ability to transfer forces from one panel to the next panel
- the aesthetics of the connection joint
- during the construction the panel must be kept in place by a temporary support structure
- the ability to lift panels into the air to their position
- an efficient way to transport these panels

The most relevant case study done this semester is described in this research paper. The limited size of this paper does not allow full description of all the case studies.

3.3 Case Study A

This case study is a simple shell structure made from three double curved panels. The concept behind the design is the possibility to actually build and test it at the university.

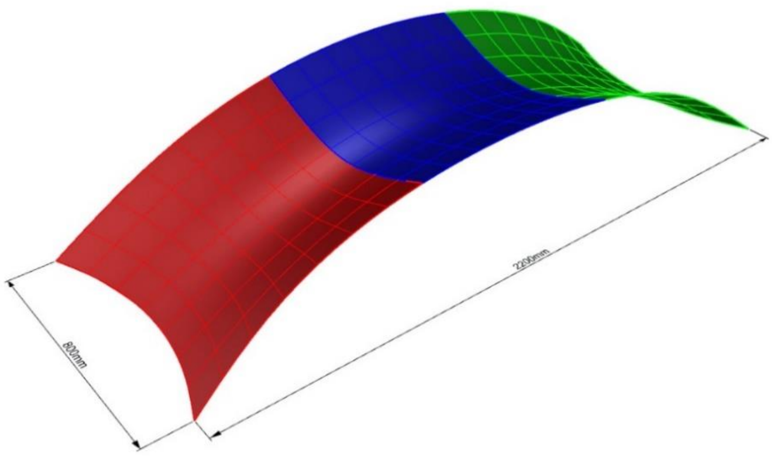


Figure 3.5: Case Study A, three double curved panels forming a single shell structure

Figure 3.5 shows the shell structure designed for Case Study A. The individual panels have a dimension of 850 by 850 millimetres before deformation. After deformation their combined size, measured in on the horizontal plane, becomes 800 by 2200 millimetres.

The shell structure is designed in Rhino 3D. The curvature is generated with the help of Grasshopper and Kangaroo. This ensures an almost structurally optimized shape. The shape of the geometry is tweaked a little afterwards to eliminate sharp local curvature radii.

The panels are connected to each other with a post-tensioning connection. At this size it is probably easier to use adhesives to join the panels together. However this case study is intended as a mock-up towards larger structures, in which applying post-tension to the structure becomes more vital. Applying three tendon in such a small structure is excessive. This decision has been made to be on the safe side in case something goes wrong with a tendon, or one of the clamping details, in the prototype.

After the panels are placed and are temporarily supported by tripods, steel cables are pulled through the panels and are locked in tension. This makes the shell structure stable. The holes and the placement of flexible ducts for the cables in the panels must be planned before production (see Figure 3.6).

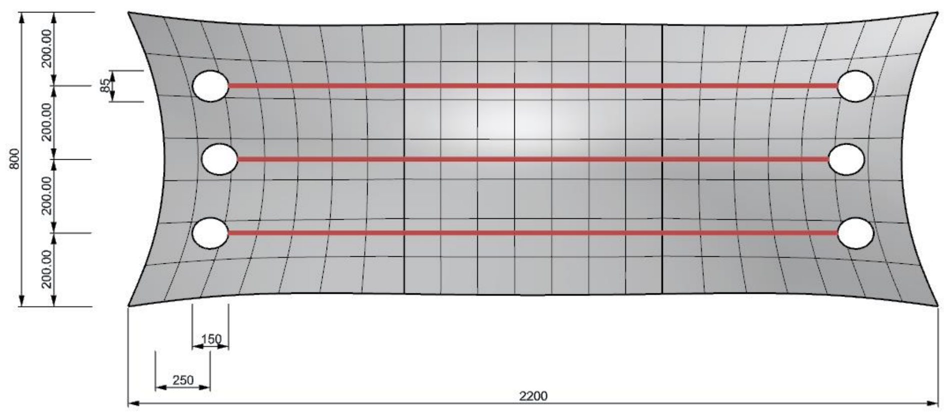


Figure 3.6: Location of the cable ducts and access holes through the structure.

Local peak forces arise when the cables are pulled in tension. The forces can partly be spread out over a larger area in the panels by the placement of a steel h-profile. This reduces the risk cracks, or other types of damage, forming in the concrete.

The placement of steel tension cables in the panels depend on the application and shape of the structure. Another important factor is load condition. In the cross-section of the panels, tensile stresses in (curved) slabs are maximum in either the top or bottom surface, or partly in top and partly in bottom surface. It is therefore wise to run tension cables along the top and/or bottom of the cross-section of the panels. It is also possible to run a tendon partly along the top of the cross-section and partly along the bottom (see Figure 3.7)

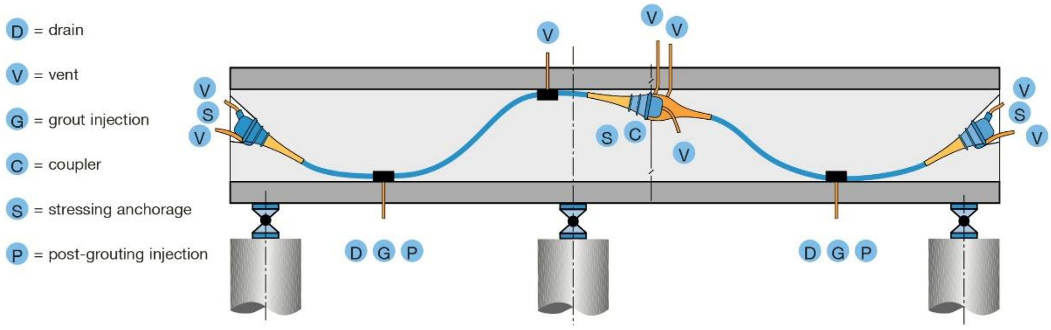


Figure 3.7: Tendon, with connection joints, running along the top and bottom of the cross-section.

Case Study A is only a small and thin prototype structure. In this case the steel tension cables run, for practicality, through the middle of the slab. The cross-section of Case Study A is 20 millimetres. The flexible tension cable ducts have a diameter of 10 millimetres, which leaves 5 millimetres towards both the top and bottom surface. The ducts can have a smaller diameter, but 10 millimetres is a size that is commercially widely available. The extra width in diameter makes it also easier to pull the tension cables through the ducts.

Deviations in panel shape compared to the reference design are small. However, the connection details have to allow for these tolerances. During the production process, due to the deformation of the mould and the hardening process of the concrete, some strain in the concrete occurs. The estimated in-plane deviations near the edges of the panel are at maximum 10 millimetres. Tolerances in the local Z-axis of the panels are at maximum 2 millimetres.

Construction felt is applied in the connection details to compensate for these construction tolerances. Construction felt is normally applied between two precast concrete elements, for example between a wall and an hollow-core concrete slab. With an adhesive strip the felt can be connected to one panel. The construction felt between two panels compresses under strain when the post-tension is applied. The production tolerances between the panels will be overcome by the compression of the felt. This ensures a tight connection between panels. It also lowers local peak forces, by distributing forces more equally along the panels edge. Construction felt is available in various thicknesses and compression strengths up to 18,0 N/mm^2 [9].

<u>Calculation</u>

The designed surface has been exported from Rhino 3D to FX+ for Diana and to iDiana Femview for calculation purposes. Table 1 shows the model properties which were used to make the calculation model. Figure 3.8 shows the placement of the point load for Load Case

2. This point load is placed in the middle of one of the outer panels to create an asymmetrical load condition.

Table 2 shows all the calculation results from iDiana Femview. The values in columns below 'in surface' are all the highest absolute values found somewhere in the surface. The values in columns below 'on edge' are all the highest absolute values found specifically on the edge between the two panels near the point load (see Figure 3.8). Hereby, I made sure not to miss the highest tension stress which is the most crucial stress in the structure.

Model Properties	
dimensions shell	800 mm x 2200 mm
panel thickness	20mm
property	hyperbolic
supports	hinged
mesh quality	1.000 = 34% > 0,933 = 61% > 0,867 = 5%
material	concrete
elastic modulus	22,3 GPa
Poisson's ratio	0,2
mass density	$2,4 \times 10^3$ kg/m^3
Load Case 1	body weight
Load Case 2	body weight + 1 kN point load (Z-axis)

Table 1: Model properties

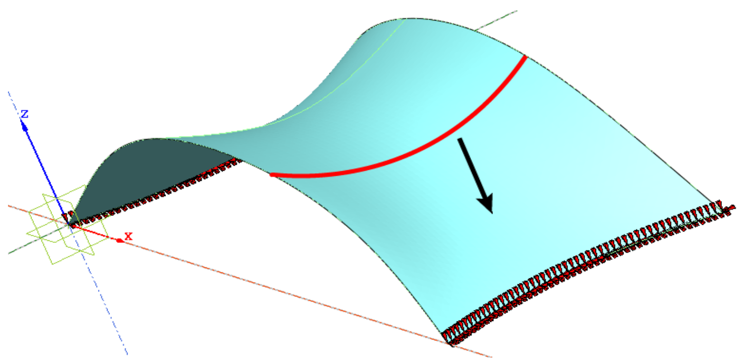


Figure 3.8: Point load (arrow) and (red) edge line.

Calculation results				
	In surface		On edge	
	Load Case 1	Load Case 2	Load Case 1	Load Case 2
RESDTX	$0,673 \times 10^{-2}$	0,151	$0,468 \times 10^{-2}$	$0,856 \times 10^{-1}$
DTX			$0,706 \times 10^{-3}$	$- 0,438 \times 10^{-1}$
DTY			$- 0,281 \times 10^{-3}$	$0,27 \times 10^{-1}$
DTZ			$- 0,462 \times 10^{-2}$	$- 0,748 \times 10^{-1}$
MXX	- 2,61	- 259	1,06	- 19,7
MXY	0,771	- 23,4	- 0,508	- 12,5
MYY	- 1,4	- 313	- 0,755	- 27,5
S1 (bottom surface)	$0,209 \times 10^{-1}$	5,39	$0,958 \times 10^{-2}$	0,429
S1 (top surface)	$0,18 \times 10^{-1}$	1,13	$0,605 \times 10^{-2}$	0,272
S2 (bottom surface)	$- 0,161 \times 10^{-1}$	4,94	$- 0,696 \times 10^{-2}$	0,157
S2 (top surface)	$- 0,213 \times 10^{-1}$	-4,15	$- 0,114 \times 10^{-1}$	- 0,229
S3 (bottom surface)	$- 0,578 \times 10^{-1}$	- 0,955	$- 0,552 \times 10^{-1}$	- 0,328
S3 (top surface)	$- 0,734 \times 10^{-1}$	- 4,66	$- 0,457 \times 10^{-1}$	- 0,545
SXX (bottom surface)	$- 0,578 \times 10^{-1}$	4,64	$- 0,551 \times 10^{-1}$	0,241
SXX (top surface)	$- 0,693 \times 10^{-1}$	- 4,34	$- 0,457 \times 10^{-1}$	0,146
SXY (bottom surface)	$0,102 \times 10^{-1}$	0,543	$0,849 \times 10^{-2}$	- 0,173
SXY (top surface)	$+/- 0,173 \times 10^{-1}$	- 0,546	$- 0,66 \times 10^{-2}$	- 0,204
SYY (bottom surface)	$0,209 \times 10^{-1}$	5,26	$0,761 \times 10^{-2}$	0,445
SYY (top surface)	$- 0,213 \times 10^{-1}$	-4,2	$0,41 \times 10^{-2}$	- 0,501
Total mass	82,15 kg			
Cells contain highest absolute values. Units are N, mm, Nmm or N/mm^2				

Table 2: Calculation results

The deformation of the geometry under both load cases stay well below a millimetre. Therefore the deformation due to loading is insignificant compared to the estimated production tolerances. It seems unlikely that there is so little deformation, but a 2 meter span shell structure designed and tested at the Vrije Universiteit Brussel also deformed less than 1 millimetre [7]. Their structure was made from textile reinforced concrete. However it was only 8 millimetres thick so it was less than half the thickness of Case Study A.

All the stress values under Load Case 1 stay below the strength of B15 concrete [10]. No extra reinforcement is needed to cope with the body weight of the geometry. None of the compression or shear forces, in either of the load cases, are a problem for B15 concrete. However, the point load of 1kN in Load Case 2 causes a local spike of tensile stress, which is more than B65 concrete can cope with. The application of a post-tensioning connection makes sure the structure is strong enough.

There is still a risk that a condensed point load will be able to smash through one of the panels and thereby damage the shell structure severely. Marijn Kok's research [6] shows that his panels with three layers of textile reinforcement are capable of handling almost all the tensile stresses found in Table 2. Panels with five layers of textile reinforcement are strong enough for all the calculated stresses.

The choice for the type of reinforcement and the type of concrete depends on which sort of load conditions are applied on the structure. A singular point load of 1kN is quite extreme for this geometry, it is more than the total body mass. It is not completely farfetched, it is possible that somebody falls or jumps on the structure causing such a force. For testing purposes applying the post-tensioning cables should be enough. For more permanent usage it is recommended to use a combination of stronger concrete, textile reinforcement and post-tensioning. A fourth way is to lower the stresses by increasing the panel thickness.

Connection details.

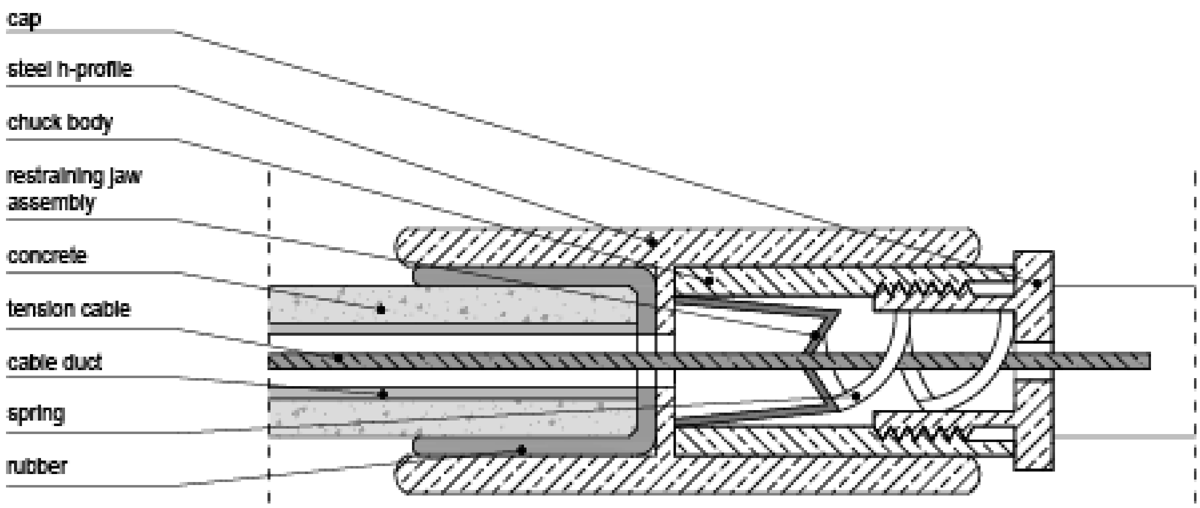
Originally a half lap splice joint connection was designed. The small overlap of the panels ensured a tight and secure connection. However the cross-section of 20 millimetres in this case study is too slim to allow for this type of connection.

The post-tensioning cables are anchored in tension via a mechanical chuck anchorage (Figure 3.9). It is designed in similar fashion as the Supreme Products chuck (see Figure 3.3), but adapted for the smaller scale. The steel h-profile keeps the chuck body in place and spreads the compression force, caused by the tendon, over a larger area.

Detail: anchorage chuck detail

Section

Figure 3.9: anchor detail (scale 1:1)



Detail: connection between two panels

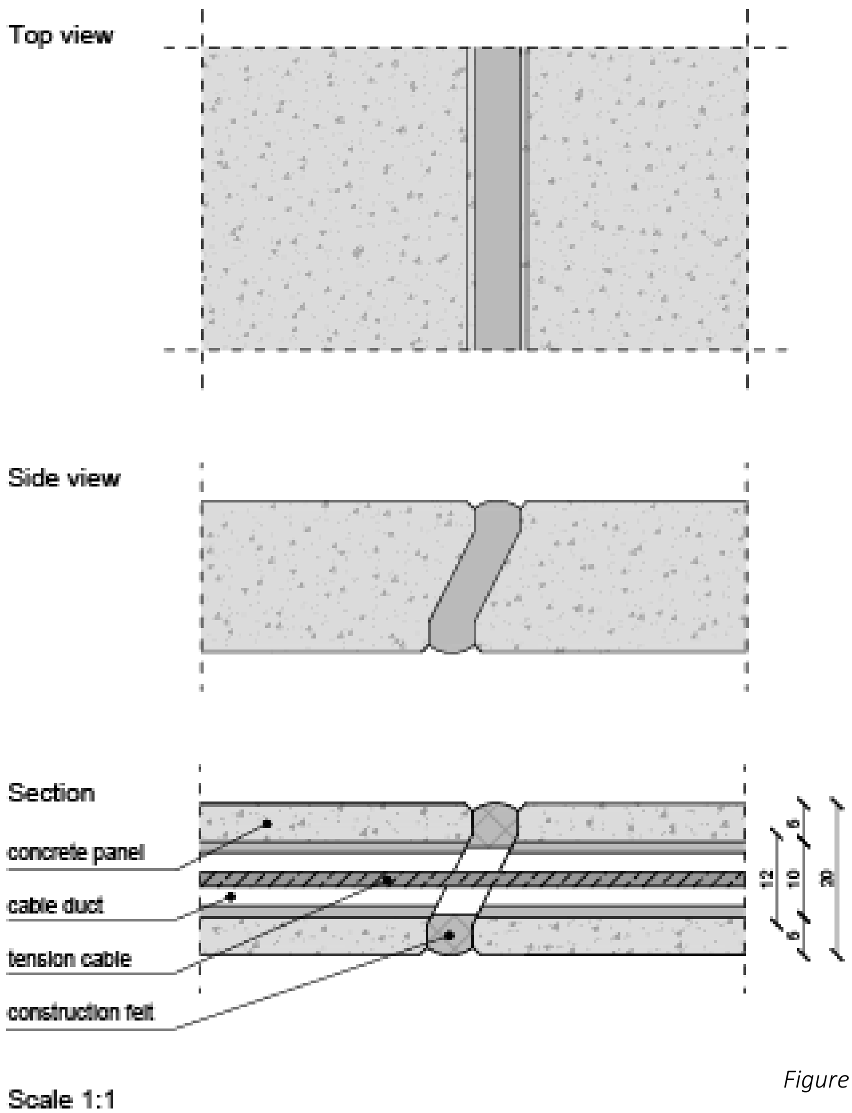


Figure 3.10: connection detail (scale 1:1)

4. Conclusion & Discussion

The literature review and a visit to Civil Engineering has shown what flexible moulds are, how they work and what their possibilities are. Prototype flexible moulds are often hand driven and for practical reasons around 1,2 by 1,2 meter big. Flexible mould technology is still relatively new. Therefore there are globally not many companies providing flexible mould production services to customers. Adapa does provide these services with computer driven moulds which have a size up to 1,2 by 3,6 meter. With enough financial investments these moulds could be scaled up further in size.

The surface quality of the panels made by flexible moulds is high. Deviations in the shape of the completed panels are limited to millimetres when compared to the digital reference model.

It is possible to structurally reinforce the panels made with a flexible mould. This gives the designer the possibility to make very slender structures. Another viable option of adding reinforcement is to post-tension stress the structure.

This technical research has been done in one semester. The scope of this research has been limited to an extensive literature review and the design of multiple case studies. The study explored the possibility of concrete panels, made with a flexible mould, being used in a structural manner. The case studies show that this should be possible. Further research and more precise calculations are needed to be able to give a decisive answer to this research question.

Physically building a mock-up would have proven the hypothesis. Time with a flexible mould and help with building and testing a prototype were offered to me. It would take an estimated two or three weeks to build and test the structure. It has not been possible to do this within the timeframe of this technical research. This is something that can be done in a future study.

This research focussed on concrete panels. With flexible moulds it is also possible to make panels from other materials. Using these other materials will probably provide different design challenges.

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[B] Adapa - Adaptive Moulds - https://www.youtube.com/watch?v=3CmmYjNaGDo - watched September 2014

Figures:

Figure 3.1: Adapa (2014) Adaptive Moulds, A New Paradigm In Moulds, Aalborg (Denmark)

Figure 3.2: http://adapa.dk

Figure 3.3: Nawy, E.G. (2010) Prestressed concrete, New Jersey. Pearson Education

Figure 3.4: Kok, M. (2013) Textile reinforced double curved concrete elements, Delft

Figure 3.7: DYWIDAG-Systems International (2014) Bonded Post-Tensioning Systems