HYBRID PREFABRICATED SYSTEM FOR FABRIC FORMWORK FOR CONCRETE SHELLS

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ABSTRACT

Since their golden era in the Sixties, concrete shells gradually disappeared in favor of other kind of constructions. The cost of labor associated with the non-standard scaffoldings that are needed, due to their complex geometries, made shells unaffordable. With the use of computational form-finding techniques and the use of a flexible formwork, concrete shells can become, in some cases, a preferable alternative to traditional methods. Starting from the latest developments in the field, the paper presents a hybrid technique based on the combination of flexible formwork, computational form-finding, and prefabricated beams. The use of this hybrid technique allows to substitute the wooden temporary frame commonly used for the flexible formwork with a prefabricated concrete beam that will stay in place after construction. The method is particularly suitable in the design case that is presented making the construction cheaper, faster, innovative and finally appealing.

KEYWORDS: *Fabric formwork, Flexible formwork, Cable net, Concrete shell, Form finding*

I. INTRODUCTION

Although experiments on the use of flexible formworks for casting concrete have been conducted since the first half of the XX century, the method never reached a turning point where it could be implemented on a global scale. The re-discovery of flexible formworks have been fostered by the advent of advanced computer simulation tools and the widespread availability of high-strength fabrics (Hawkins et al., 2016). The worldwide presence of the ISOFF (International Society of Fabric Forming) and the IASS (International Association for Shell and Spatial Structures) have contributed in the last decades to foster the debate about flexible formworks and shells achieving interesting results. The structural efficiency of shells minimizes the bending stresses and loads are mainly transferred through membrane action reducing the amount of concrete that is used. Moreover flexible formworks are relatively cheap, they become especially competitive on large scale structures, and can be reused multiple times reducing the cost of labor for the manufacturing of the scaffoldings. Flexible formworks for specific applications outperform CNC milled foam or wood moulds especially in terms of cost. The combination of these advantages can bring to incredibly promising results, like in the case of the NEST HiLo roof which will be constructed in 2018 and has its roots in the research of flexible formworks for concrete shells.

2.1. Brief history

The first attempt in the direction of fabric formworks belongs to Louis Lilienthal. In 1899 he patented a method to build a fireproof ceiling, using fabric that spans over parallel wooden beams. The fabric naturally curves similarly to a hanging chain to form a catenary arch, then a wire netting is laid onto the fabric and concrete is poured on top. In 1934 James Waller patents his first construction method based on the use of fabric as a formwork, immediately followed by Dennis Farrar in 1937. Waller is probably one of the most prolific inventors in the field, his objectives are very clear from the beginning as stated in his first patent “One of the objects of the invention is to devise means for building structures which will be cheap and economical. Another object of the invention is to build structures which have great strength but at the same time are very light. A further object of the invention is to avoid the use of molds or shuttering when building such structures" (Waller, 1934). He gives examples of columns, walls, and floors built with the use of vegetable fabric, but despite the numerous advantages that he states in his patent the use of these technique was never implemented on a large scale. The first success of such structures comes during wartime shortages of steel (Veenedaal, West and Block, 2011), with the need of cheap, large-span and easy to build structures to serve as hangars or storages. His technique, later refined in two patents in 1952 and 1955, presents a method to build structures made of an array of steel supports with the profile of an inverted catenary arch covered with a textile membrane and then sprayed with concrete (shotcrete). The catenary shape ensures a maximized use of the capability of concrete to resist to compression only forces and thus resulting in very thin structures. But

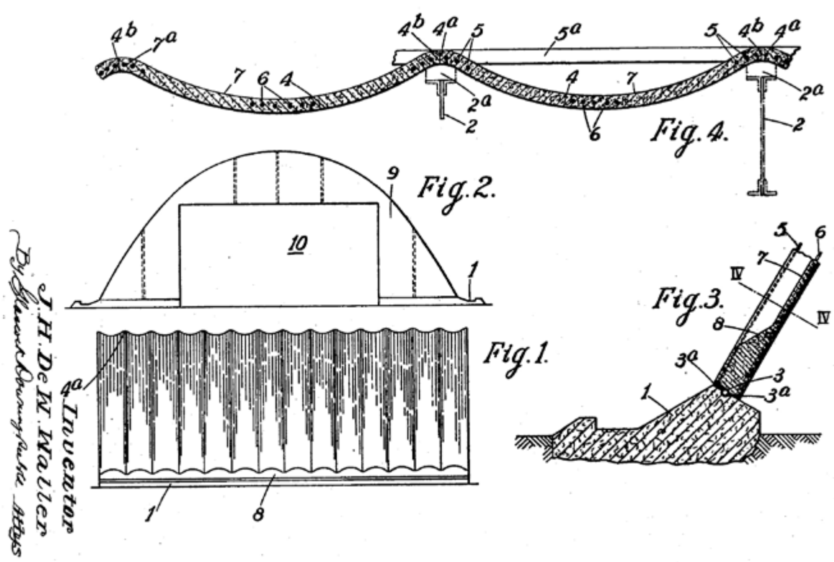


Figure 1. Ctesiphon system in Waller's patent of 1952

again the system is abandoned in favor of other techniques and "The disappearance of this building method may be related to the general decline of shell building, but specific criticism of the Ctesiphon system did arise, such as the likelihood of cracking at the top of the ribs and the poor thermal quality" (Veenedaal, West and Block, 2011). Even Candela, one of the greatest concrete shell engineers, before moving on to other geometries, in his first works used the Ctesiphon system patented by Waller.

In the 1990s the advent of new technologies allows an incredible advancement in the technique of form-finding, through the use of computational methods it is possible to determine and study the possibilities of flexible formworks and shells. Mark West of the University of Manitoba founds the Center for Architectural and Structural Technology (CAST) dedicating a great effort in developing new techniques of concrete casting and textile formworks.

In 2008 the ISOFF (International Society of Fabric Forming) is founded in order to promote the connection between research, education, building codes and investors in the field of fabric forming. In spite of the benefits that such a method introduces on the market, especially in regard to cost and construction speed, companies are reluctant to experiment with these methods since it involves a higher risk and they prefer to continue with traditional methods. Very few examples of flexible formworks for concrete shells exist, and the lack of case studies makes it difficult for building companies to price and calculate the risk of such interventions. More researches have been conducted in the last decades, and more will be needed in order to consolidate the use of flexible formworks in the open market.

2.2 Benefits of flexible formwork

The decline of concrete shell structures after the 1960s is often associated with the cost of formwork and the cost of labor. The problem of formwork is one of the reasons behind the constant presence of hyperbolic paraboloid (hypar) shapes in Candela's work, precisely the hypar is one of the few anticlastic shapes that can be constructed using straight pieces of conventional formwork (Van Mele and Block, 2011) but still allows to exploit the advantages of concrete shells. Shells indeed can be thin, elegant, and light thanks to their ability to carry loads mainly through membrane action.

On the other hand the advent of computational methods since the 1990s allowed for the automatization of the production line for non-conventional formworks. An extensive overview of the existing methods for casting double curved geometries can be found in Schipper (2015). Given the complex nature of double curved geometries, conventional wooden or steel formworks result in an incredible amount of on-site work or in a very high prefabrication cost due to the uniqueness of each single panel. The reuse of the same formwork is rare unless the same geometry is repeated multiple times. CNC-milling on foam, wax or timber have been used in several projects (Der Neue Zollhoff by Ghery or Rolex Center in Lausanne by SANAA), but the cost of such a technology is very high and the same goes for 3d printed formworks. None the less these techniques require high-tech machinery that are not available everywhere, and the cost may be economically prohibitive. Flexible formworks become a suitable alternative due to the low cost of material and ability to provide structurally efficient forms (Hawkins et al., 2016).

If we exclude freely curved geometries and only consider surfaces that can be controlled through a process of form-finding, the use of a flexible formwork based on fabric becomes inevitably the best choice (Schipper, 2015, p.21). Since form-finding techniques can result in very structurally efficient shapes, the combination with the fabric mould can lead to very thin shells, thus reducing the cost of material without adding labor cost. The structural optimization would also benefit the environment through the reduction of CO_2 emissions. Concrete is largely used in the construction field and a reduction of material use would also reduce the amount of CO_2 emission which is contained in Portland cement, and that until 2016 accounted for 6% of the total emissions of CO_2 (La Quéré et al., 2017).

While traditional formwork is assembled on-site through a laborious process, fabric can be prefabricated off-site, increasing quality control and precision on the final product. The fabric can

Figure 2. Mark West with a packed fabric formwork

be easily packed and transported to the site very efficiently due to its negligible weight (0.23 kg/m^2) when compared to a typical 18mm plywood formwork (10 kg/m^2) (Hawkins et al., 2016, p26).

Moreover flexible formworks can be reused several times significantly diminishing the price-per-structure since the cost of the temporary formwork is spread over the multiple uses. An example of the reusability of the formwork is the Landshape Wildlife Crossing project by ZJA, a bridge in the shape of a hypar thin shell.

2.3. Cost estimate

An important aspect to support the widespread use of fabric formworks is its cost. Since the perceived risk associated with the use of an unfamiliar construction method makes constructors reluctant to adopt such a technology, one of the incentives lies in the construction cost. Indeed the cost of a flexible formwork is 150-300 €/m^2 compared to traditional timber or foam CNC milled formworks that have prices that range from 300 to 800 €/m^2 and for this reason "conventional timber or milled foam formworks will not be able to bring back concrete shells. " (Veenendaal, 2017, p.410).

The following cost estimates are based on two case study. The Landshape Wildlife Crossing project (Torsing, 2012), and the prototype construction of a hypar shell (Veenendaal and Block, 2014). Further details about construction costs can be found in Veenendaal (2017, p.151, 345, 410).

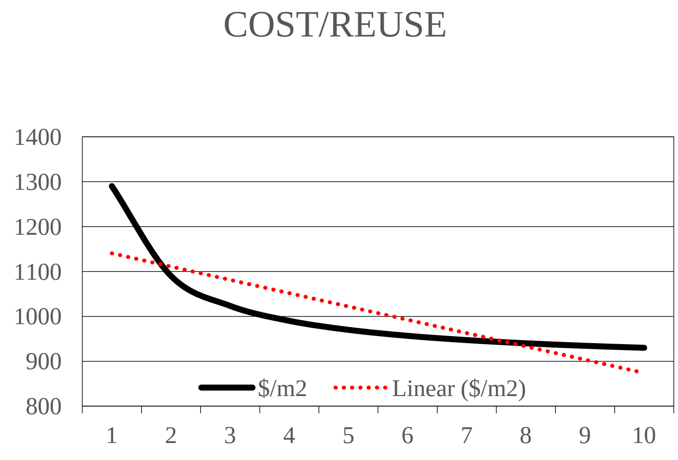
The cost for the construction of a shell can be summarized as follows:

Fixed cost: foundations, shell (an efficient shape would allow for a significant decrease of the shell thickness reducing the cost of material

Variable cost (according to possible reuse): geotextile, cable-net, temporary support structure

According to Torsing (2012) the cost of formwork (variable cost) consists of 31% of the overall cost of construction. In the worst case scenario where the formwork is used only once, the bridge would cost approximately 1100 €/m^2 which means the variable cost is 341 €/m^2, the cost for the formwork of the hypar prototype is around 140 €/m^2.

The findings match with the range provided in the most recent literature about the cost of flexible formworks (Veenendaal, 2017).



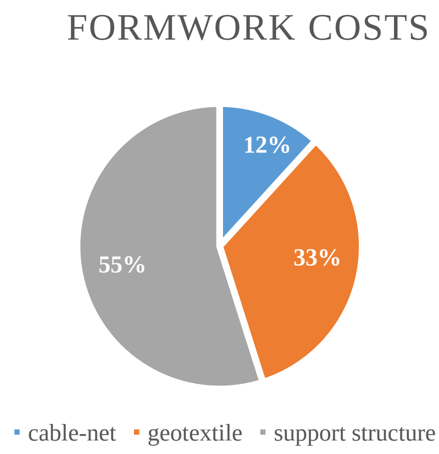


Figure 3. $/$m^2$ decreases very rapidly when the formwork is reused

Figure 4. Proportions of the cost of flexible formwork

The reuse of the same formwork would make the variable cost decrease very rapidly since it would be spread over multiple constructions. In the case of the Landshape the reuse of the formwork for a total lifespan of ten times would make the formwork cost drop from 31% to 4% (44 €/m^2). Slight variations in the shape of the formwork from time to time are also possible by changing the prestress of the cables each time in a different way. However the repeated removal of clamped nodes can cause fraying in the cables after multiple uses, thus limiting the life span of the formwork.

The Landshape bridge spans almost 90m. The cost of a conventional construction (standard formwork, prefabricated beams and slabs) that spans the same length would be in a range between 2500-3500 €/m^2 and the cheaper version with two spans of 45m would be between 1300-2500 €/m^2 (Torsing, 2012). This means that using a flexible formwork in this case results in a construction which is approximately 35% cheaper. The cost of flexible formwork in the Landshape project is composed by geotextile (12%), cable-net (34%) and support structure (54%). A similar proportion has been found in the table of the costs presented in the hypar prototype's research paper (Veenendaal and Block, 2014, p.48).

In the construction method that will be presented later in this paper, the support structure consists in a net of prefabricated beams instead of the more commonly used wooden frame. Since the cost of the support structure already accounts for 60% of the cost of the formwork, the use of a prefabricated beam will probably slightly increase this number, while maintaining the overall cost of the formwork within a reasonable price.

II. DESIGN PROCESS

3.1. Context

In order to understand the reasons behind certain choices and make clear the objectives of the research, it is necessary to introduce the context of the project.

Within the context of an existing building, its renovation requires the construction of a single surface that covers a market and at the same time caters to the needs of a walkable roof. The Hennebique building has a plot area of about 38x213m and the market roof that has to be designed measures 15x213m. Since the renovation should occur mostly in a very narrow space surrounded

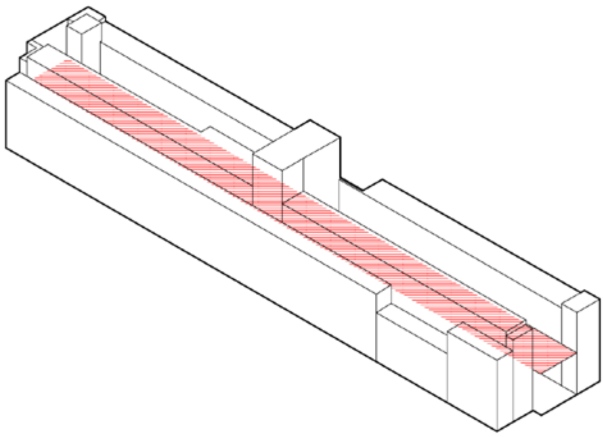


Figure 5. Axonometric view of the existing building, highlighted in red the area of the intervention

by an existing building the choice of a flexible formwork is strategic. It allows to keep most of the space at the ground level unoccupied by support structures during construction and also it is easily transportable inside the building due to its small size when packed.

When using a flexible formwork the concrete is sprayed onto the tensed fabric (shotcrete), but casting 3000 m^2 all at once would be an enormous effort and it would expose the structure to a higher risk of cracks, moreover one unique cast would not allow for repetition and reuse of the formwork in order to build a cost-effective structure. At the same time the control over a shape that is entirely form-finded is very little and some of the requirements to make a walkable roof would not have been fulfilled due to the lack of flat or semi-flat areas and paths.

A system of flat prefabricated beams splits the area in different sectors, where each sector is a form-finded shape on its own, independent from the adjacent one. This also means that the formwork from one sector can potentially be reused for a sector with a similar shape hence reducing costs. The beams also act as a supporting frame and scaffolding for the workers during construction and ensure flat spaces for people walking on top later.

In a similar way the first patent from Lilienthal (1899) featured a fabric supported by wooden beams. This hybrid method can see its generative premises in the work of the pioneers of fabric as formwork, and the latest developments that implement the use of a cable-mesh in combination with fabric and form-finding

3.2. Requirements

The roof needs to cater to the needs of the program: market roof (light, water tightness, sheltering, atmosphere, climate efficiency) and elevated courtyard (walkability, connection, playfulness, relax, shading).

The shape obtained by the form-finding process needs to be complementary with the architectural and environmental requirements necessary to obtain a meaningful project. The space for the market underneath needs clearance overhead, and at the same time the funnel-shaped columns divide the spaces. The peaks act as solar chimneys by extracting exhaust air and by letting light through, illuminating the space. On the other hand the surface functions as a courtyard where people walk, connecting the two wings of the building. This means that a certain amount of flat or semi-flat areas have to be provided, moreover the roof can collect rainwater by means of the funnels that can later be reused in the greywater system.

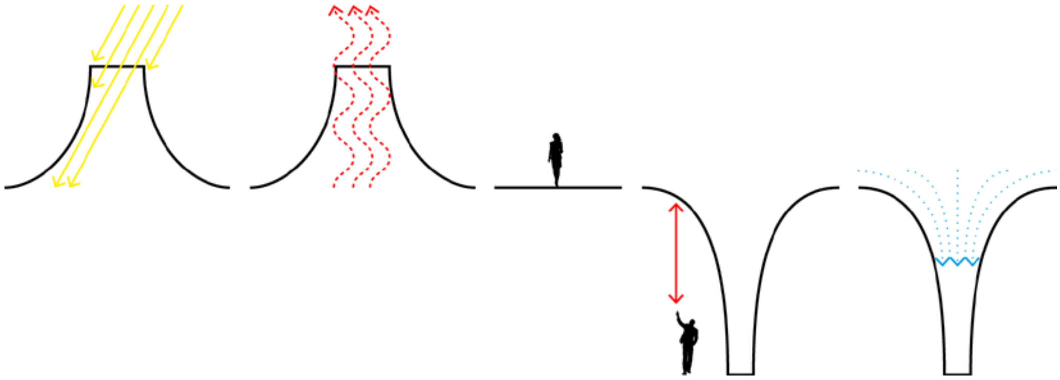


Figure 6. Diagram showing the functions of cones and funnels

The perfect balance between all the functions relies upon a construction method that is flexible enough to control the final shape of the design while maximizing structural efficiency and construction costs.

3.3. Modelling and testing

Back in time physical modeling was the only way to test these kind of structures. Isler, Gaudi, Otto, Musmeci, all experimented with soap-film, hanging chains and other methods to gain a better understanding of the structural behavior of their designs. Computational form-finding nowadays allows to test multiple geometries very quickly and optimize the shapes.

Both the physical model in nylon and the digital simulation showed that the stretch of a material with a constant stiffness (that correspond to equal tension in U and V direction) didn't allow for a semi-flat transition area between a high and a low point. Moreover the profile of the conical shapes can be changed only by means of different prestresses in the elements of the cable-net.

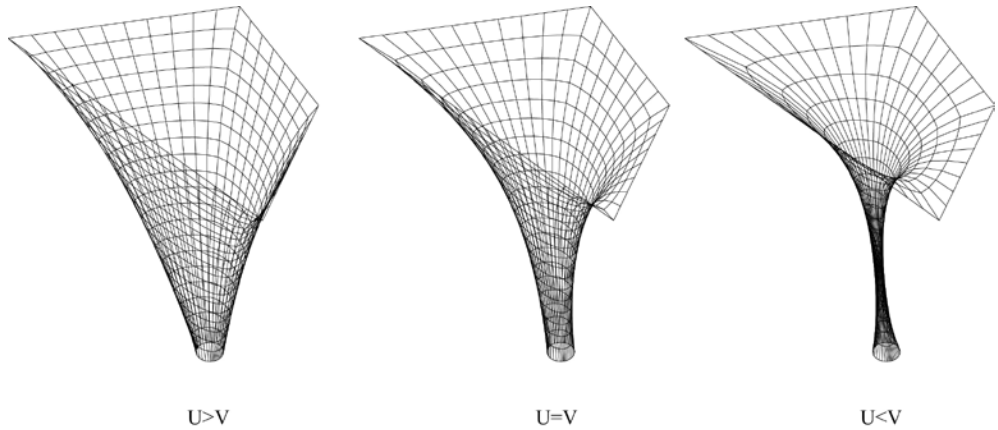


Figure 7. Variation of prestresses affecting the overall shape of the formwork

A variation in the prestresses is the first way of controlling the final result and it would allow to satisfy almost all requirements except for the control of flat areas. Moreover the alteration of the shape does not compromise the result since in the end the outcome of any form-finding process is a tensioned surface in static equilibrium (Torsing, 2012).

The major problem of obtaining these flat areas lies in the physical principles of form-finding itself: when a force is applied to a node it moves accordingly and it stabilizes itself in a static equilibrium with the surrounding nodes. A flat area would require multiple nodes to lie on the same plane, hence creating bending moment stresses which contrast the principles of form-finding. The need of a hybrid method that relies on form-finding process, flexible formwork, and traditional construction methods needs to be implemented to reach a satisfactory result.

3.4. Hybrid system of prefabricated beams and flexible formwork

Flexible formworks are composed by a support structure, a cable-net and a fabric. The support structure is usually a wooden beam with holes where the steel cables are attached and prestressed, and it defines the boundary of the shell. On one side the need to split the surface into smaller parts, on the other the need to gain more control over the shape of each conical shape, led to the choice of splitting the area of the intervention by means of a series of interconnected structural prefabricated beams.

By observing the cable-net layout of HiLo NEST roof project (Veenendaal, Bakker and Block, 2017) it is possible to notice that vertices B and S form a line along which the mesh patches encounter. The HiLo shell presents a wooden support structure only along its perimeter (along B vertices), and the S vertices are obtained through an optimization process for the study of the cable-net layout, so in this case it represents only an imaginary line.

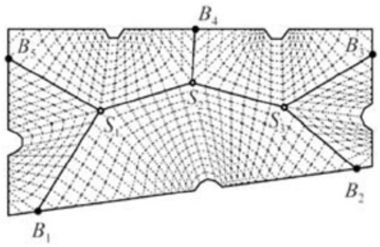


Figure 8. Optimization of the mesh for the HiLo NEST (Veenendaal, Bakker and Block, 2017)

Starting from this optimized layout of the cable-net the idea is to transform the line along the boundary of each patch into a prefabricated beam. Each prefabricated beam would act as a support structure substituting the more common wooden support and dividing the area of 15x213m into smaller cells according to a Voronoi pattern. Each cell contains only one mesh and a center point that will later become the center of the conical shape, mesh edges are respectively in a radial or concentric direction in relation to the center point.

The net of prefabricated beams, that forms a “backbone”, only has to cover a span of 15m in one main direction and the section of the beam is mainly wider than higher resulting in a flat beam. The perfectly flat top surface of the supporting structure will ensure comfortable paths along the backbone while being perfectly integrated in the thickness of the on-site casted conical shapes.

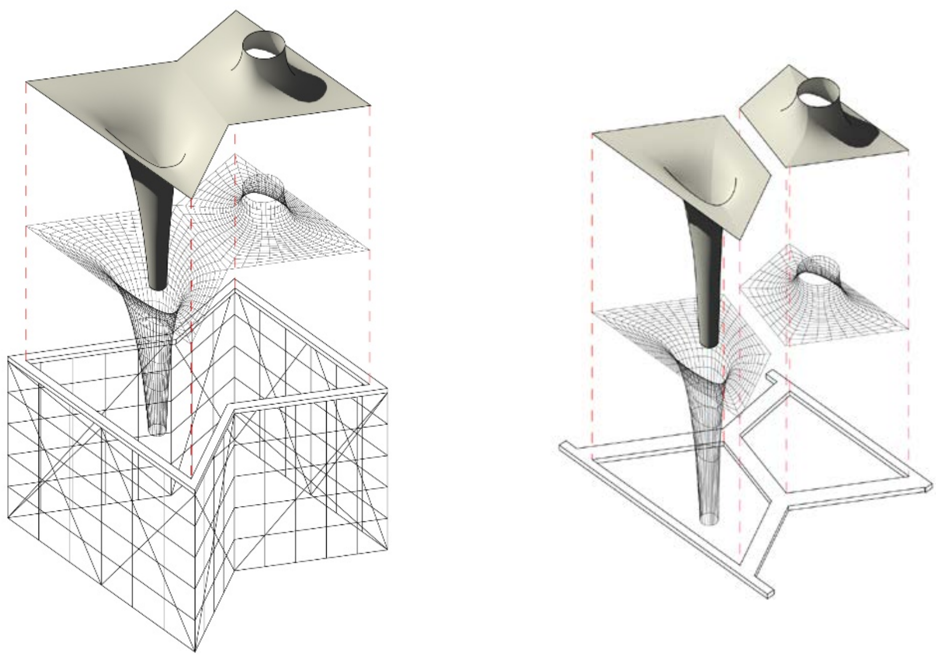


Figure 9. Common flexible formwork (left) and hybrid flexible formwork with prefab beams (right)

Since each Voronoi cell has to be casted individually, the same cable-net and geotextiles can be reused for multiple cones reducing the cost for the formwork. Although fabric can serve only the cast of an individual shape, the adjustable nature (through length and prestress control) of the cable-net allows its reuse for shapes that are different.

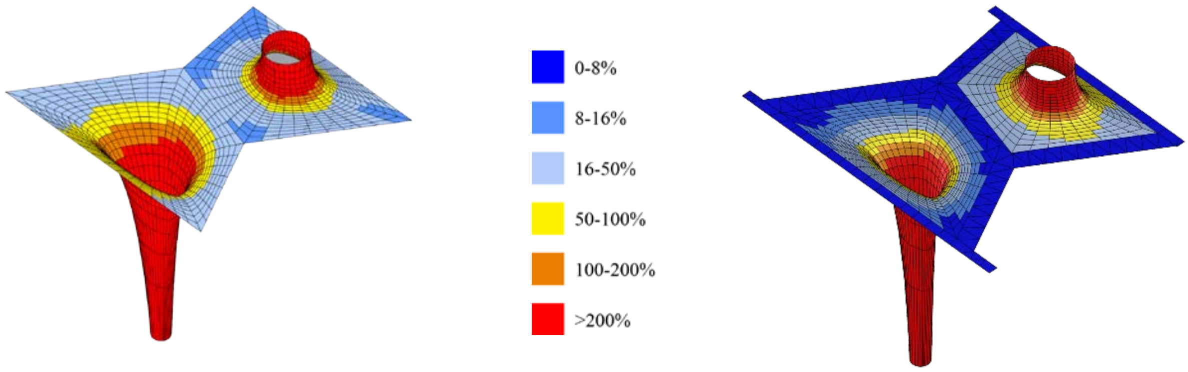


Figure 10. The model on the right shows how the prefab beam support forces the shape to flatten

III. Construction

4.1. Process

After the demolition of the concrete silos the building is split into two halves along its longitudinal direction. The outer facades of the building are maintained and the only way to fit large construction elements is from the top. A crane transports the prefabricated beams into place from above. Once they are in place the crane is not needed anymore and the beam system serves as a scaffolding for the workers, it is the platform from which they can attach the cable-net and pretense it. This sort of floating scaffolding allows to maintain the ground floor completely unobstructed and workers to freely move underneath it.

The flexible formwork is very compact when packed and can be easily transported on-site through the existing openings in the building, and then assembled.

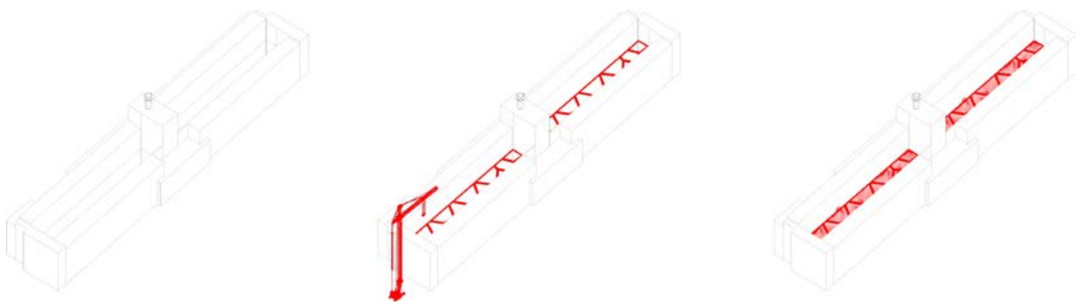
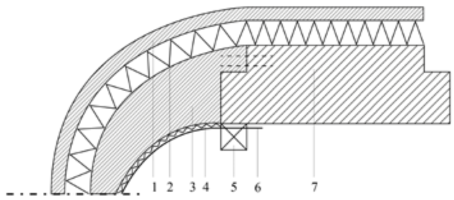


Figure 11. Steps for the construction: demolition, net of prefab beams, flexible formwork and casting

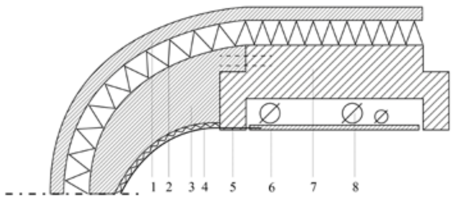
Cable-net is attached to the beams and the fabric is laid on top. Once the reinforcement mesh grid is set the concrete is sprayed in a very thin layer in order to cover the formwork with a homogenous layer. Each cell can be cast individually and the formwork can be reused. This means that in order to speed up the construction process during the casting of the second shell, the finishing of the first one can start and so on.

4.2. Detailing

One of the most important developments of this hybrid method is the connection between the prefabricated beams and the flexible formwork. Comparing to the original method, where the wooden support structure was only temporary, here the beam stays in place and needs to be firmly connected to the casted shell. The advantage of the prefabricated system is the complete customization of the pieces that have to be designed in order to achieve a complete integration with the flexible formwork. Several ideas for the detailing of the structure are investigated and only further analysis can reveal the most efficient connection.



1. Concrete finishing
2. Insulation
3. On-site casted concrete
4. Fabric
5. Wooden support for the cable-net
6. Cable-net
7. Prefabricated concrete beam



1. Concrete finishing
2. Insulation
3. On-site casted concrete
4. Fabric
5. Cable-net
6. Precast concrete lid for inspection
7. Prefabricated concrete beam
8. Piping

Figure 12. Detail with a small temporary wooden support for the cable-net (left), and a fully integrated system which includes also piping within the space of the beam (right)

IV. CONCLUSION

The development of a hybrid flexible formwork with the introduction of the prefabricated beam element is particularly useful within the context of the design problem that was faced. The solution remains very specific and is an answer to the problems and objectives that were set during the preliminary design phase where a method had to be developed to meet the desired requirments. A particular effort was made in order to be able to control the amount of flat surface that was required to make a usable roof with paths connecting the different zones of the building. Conditions such as the possibility to attach the prefabricated beams to the existing building to form a frame, and the decision to position the form-finded surface at a height of 15m above the ground played a crucial role in the deifnition of a method. The system could be replicated where the conditions are similar and a cost-effective solution is required. Further developments of the method could study a way to integrate the beams with the existing building and a more efficient way of connecting the prefabricated system with the cast on-site surface. A more in-depth analysis of the costs would be required to investigate the economical potential of the prefabricated frame instead of the wooden support structure.

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