Large-scale designs for mixed fabric and cable-net formed structures.

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This paper presents two recent projects from the design practice of Zwarts & Jansma Architects: an entry for the ARC Wildlife Crossing Design Competition and a preliminary design for the Extended Waal Bridge in Nijmegen, the Netherlands. In both cases, the design has been informed by the construction method of using a large cable-net formwork with a secondary system of geotextiles. This new concept builds upon existing architectural vocabulary, ideas and advantages found in fabric formwork technology, cable-nets and tensioned membrane roofs, to allow for large-scale, long-span structures. The resulting designs demonstrate how both thin shell and volumetric concrete structures can be made with this system. Both physical and digital, parametric design models were used during development of these designs. However, doubts surrounding the constructability of these designs have surfaced. The jury for the ARC competition has praised the use of well established construction techniques in its winning entry. Similarly, the contractor of the Extended Waal Bridge will likely use conventional methods in favor of the flexible formwork that originally informed the geometry of the design. Insights into the feasibility and viability of this method are discussed based on these and other experiences during the design process.

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1   Introduction

In two recent designs for concrete structures by Zwarts & Jansma architects, in cooperation with Iv-Groep structural engineers, the use of fabric formwork was considered and investigated as a construction method. In this paper the design of both these projects and how they are different from each other is discussed. The role of physical models and digital, parametric models during the design process will be discussed as well as the way they influenced each other.

In the first project, the Landshape Wildlife Crossing, an entry for the ARC competition, the proposed method was carried through to the end. This resulted in a detailed technical design and building strategy. For the second proposal, the Extended Waal Bridge, it has not been decided yet which method will be used for its construction. Reasons why this is so are described, suggesting directions in which further research might be needed.

2   Cable-net supported formworks

The architectural shapes that seemed appropriate for both these projects overlap with the forms that are naturally being generated by membrane structures. This suggested using such membranes as their formwork.

To date, large-span structures using fabric formwork have only been realized in the form of James Waller's Ctesiphon system (Veenendaal, 2011). The largest of such examples was perhaps the Chivas Distillery Warehouse in Paisley, Scotland, featuring three ca. 100m spans. However, the main loadbearing structure relied on steel arches with the fabric only spanning the distance of ca. 2.5m between the arches (Anon., 1959), Contemporary high-strength polymers allow fabrics to carry larger loads, exemplified by 4 to 12m fabric formed beams, cast by the University of Manitoba (West, 2006) and the University of Bath (Orr, 2011), However, to cope with larger scales the authors propose combining fabric formwork with a cable-

network. The cable-net not only adds strength to the fabric mold but also means to control the geometry.

In the past, especially in the 1960's, large scale cable-net supported structures such as the Olympic Stadium by Frei Otto have been built. Today, apart from a few recent examples such as the London Olympic Velodrome, this type of structure is no longer widely used. A possible cause might be the introduction of affordable, high-strength fabrics. By contrast, the construction of large-scale tensioned membrane structures is a well understood and widely used technique.

Recently a broad range of software tools that can predict the geometry and behavior of such cable networks have become available. At the same time the interface between design and manufacturing has seen a shift towards digital workflows. This allows for rapid prototyping of designs and more freedom to use components tailored for specific projects. These developments combined might eliminate some of the practical objections for using such cable-nets.

The authors are convinced that the combination of these two technologies into a hybrid structure of cable-nets that support a fabric formwork can make it economically feasible to create large-scale curved structures and surfaces.

Using these methods has the potential to reduce waste of materials and energy. It provides a vocabulary of shapes that would otherwise be hard to build. This form language has the flexibility to adapt to a wide range of sites and circumstances.

3   Landshape Wildlife Crossing

3.1   Project description

The objective was to design a wildlife crossing in the Southern part of the Rocky Mountains near Vail, United States, as part of a more generic design strategy for the construction of 25 crossings at other sites in the surroundings. The design brief encouraged designs that were that were technically innovative while at the same time being constructible, efficient and cost-effective. They had to be context-sensitive, attractive and ecologically responsible.

3.2   Design concept

A hypar surface was chosen as the main theme for the authors' solution (Fig. 1). Seen from the road it creates an inviting arch spanning 81.5m for the traffic passing underneath while extending the flowing lines of the landscape. In cross section the upward facing

Figure 1: Rendering of the Landshape Wildlife Crossing.

arc protects the wildlife against noise and lights from the highway.

Together these two perpendicular organizing curves define a double curved, anticlastic surface, the hyperbolic paraboloid, or hypar. Initially chosen for its architectural and functional qualities, this shape also has good structural potential. By executing it as a thin concrete shell a large span can be realised, efficiently carrying the required loads with minimal material usage.

The hypar as a thin shell structure is an idealised surface. It is completely symmetrical and has very low stress. Reality is not so neatly organised. Applied in the non-symmetrical and irregular nature of the site topology, this idealised geometry is transformed into a shape that is context specific.

The curves in the landscape serve as an outside influence. They combine with the internal logic of the flow of forces in the shell to shape the bridge into a natural form; a 'Landshape' is created.

3.2.1 Physical modeling

To quickly test the initial idea, a physical model was made by pouring gypsum over a latex sheet (Fig. 2).

Figure 2: Plaster sketch model

This model not only showed some characteristics of the overall shape, but also the esthetic possibilities of the hard to avoid creases.

It was soon clear that the tensions in the membrane during casting would become too high for the fabric on its own. To solve this, a supporting steel cable-net was proposed. This grid of steel cables, along with its supports, formed a temporary structure that carried the fabric formwork. Splitting the formwork in a primary, steel network and a secondary fabric layer allowed for greater control over the geometry of the bridge.

A wire model of the cable-net was made to get a feeling for credible geometries (Fig. 3). After digital modeling a final model was created to tangibly demonstrate the principles of the construction method (Fig. 4).
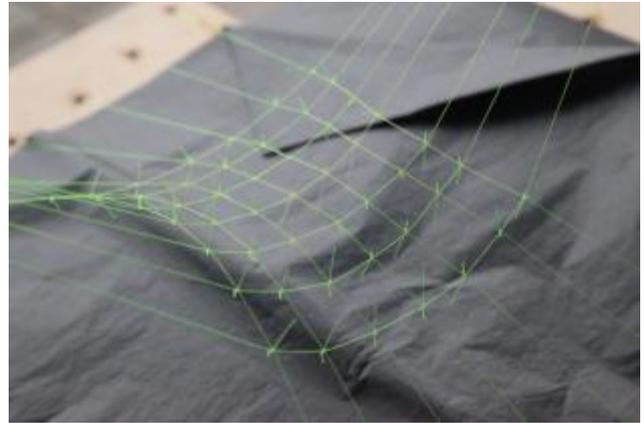

Figure 3: Initial wire model of the cable net

Figure 4: Final wire model of the cable net

3.2.2 Digital modeling

For the purpose of form finding, performing initial structural calculations and communicating the results, a parametric model of the proposed solution was made, using Grasshopper (Grasshopper, 2012) and a custom component written in Visual Basic. In this digital model the physical behavior of the cable net and fabric are being simulated with a particle spring system with a 4th order Runge-Kutta solver. The final shape of the crossing (Fig. 5) results from the interplay of the boundary conditions (local topography of the landscape, traffic requirements etc.) and from the physical properties (grid size, stiffness, static loading) etc.) of the proposed structure. The user does not directly define the form of the hypar shell, but controls it by picking the location in a 3D terrain and setting parameters like the required clearance, the width of the crossing and an initial geometry of the cable-net. All these parameters are being fed into the model, which

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then uses a physics simulation to come up with the resulting shape. It can thus be said that a specific design is an 'emergent property' of the input conditions.

Figure 5: Digital simulation of the hybrid formwork, showing the typical sagging behavior of the fabric

This design methodology has two possible advantages over a more traditional modelling method. It allows the designer, once the parametric model has been set up, to quickly investigate different design alternatives by changing the input parameters. Secondly, it implements a generic strategy that can easily be applied to different sites and conditions. This is an important quality because the design brief asked for a family of potentially 25 crossings.

3.3   Structural concept

The idealised hypar is a shape in which loads on the structure are transformed into forces parallel to the plane of the shell (membrane forces). Because of the near absence of bending moments it would be possible to use a very thin (<200mm) concrete shell as load-bearing structure. However, imperfections in material and asymmetries in the shape and loading lead to certain bending forces and instabilities. Therefore the shell was increased to a more substantial but still lightweight structure with an overall structural depth of 500mm, with the ability to carry uneven loading and reduce local bending stresses to an acceptable level.

The shell is composed of an outer layer of high strength concrete, reinforced with steel fibers and with a thickness of 200mm. On top of that polystyrene (EPS) blocks will be placed, spaced some distance apart. The gaps between the blocks, running over the length and width of the shell in a pattern dictated by flow of forces, will serve as channels to cast a network of reinforced concrete ribs. These ribs (300mm high) contribute in the shell action. After casting the EPS blocks remain in place. They fill the cavities between the ribs, resulting in a lower loading of the structure.

3.4   Structure and construction method

The construction method was designed to reduce the material usage and cost of construction, while at the same time keeping the inconvenience for the traffic on the highway to a minimum as the competition required the I-70 Interstate to remain open during construction. The proposed construction method is schematically shown in Figure 6 and discussed in the remainder of this section.
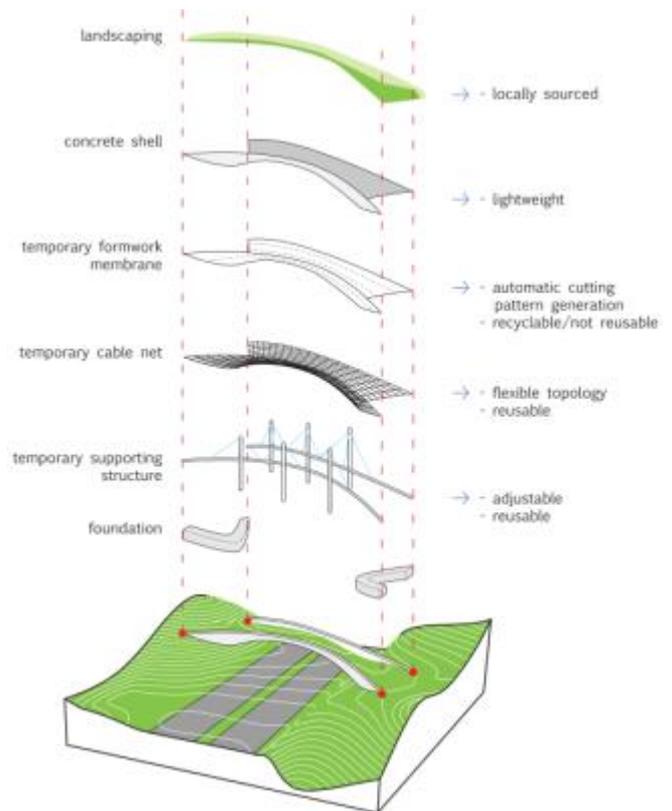

Figure 6: Exploded view of the construction elements

3.4.1   Temporary support structure

To support the fabric formwork a temporary support structure will be built. It consists of a grid of pre-tensioned steel cables spanning the length and the width of the shell. The longitudinal supporting cables are attached to the concrete basements on both ends of the structure, the crosswise cables are attached to temporary steel arches running along the two edges of the shell. At the points where the cables cross each other, they are fixed with specially designed and easily applicable clamps comparable to details in conventional in cable-net roofs. Together the cables form a pre-tensioned network in the desired shape.

The steel arches on either side of the bridge are kept in place by cables originating from the top of six temporary pylons. Those pylons in turn are supported by large concrete foundations and fixed with stayed cables on the other side. The cables are mounted on a steel frame and fixed to the underground with grout anchors.

3.4.2 Formwork

The formwork will be made of a geotextile, supported by the grid of pre-tensioned steel cables. It is cut and sown to the desired shape, specific for the particular crossing. This geo-fabric is covered with a non-adhesive coating to avoid bonding with the concrete surface while hardening. While applying the first 100mm layer of shotcrete the fabric will sag between the supporting cables, thus giving the surface its characteristic pillow-like look. Typical geotextile fabrics are produced in rolls up to 6m wide. For cable distances between 1 and 6m, fabric stiffness of 1000 kN/m, up to two layers of fabric and prestress up to 5% of 100 kN/m tensile strength, the sagging will range between ca. 30 to 300 mm, or about 1:33 to 1:20 of the span.

While applying the concrete, insulation measures might be necessary to prevent unacceptable variations in temperature during hardening, depending on the weather conditions at the time. Therefore the underside of the fabric formwork will be insulated, as well the top of the concrete while curing.

After applying and hardening of the first 100mm layer of the shell structure, the structure is able to carry the next layer of shotcrete. So the temporary support structure only needs to be able to carry the first layer of shotcrete while hardening and can now be loosened.

After curing of the second 100mm shotcrete layer the shell structure can be finished by applying the 300mm EPS blocks in the desired pattern, installing the reinforcement and pouring the concrete between the EPS blocks to form the girders.

After the concrete girders have set, the temporary support structures can be taken away and the superstructure is ready to be covered with soil and vegetation.

3.4.3 Reusable elements and cost estimation

To reduce the building costs of the superstructure and minimise material waste, the temporary supporting structures will be designed to be reused. This spreads the costs for these elements over more crossings. Therefore those temporary supporting elements need to have enough service life and must be designed to be adjustable.

The cost estimate for this design was based on the assumption that investments in the temporary structure, including the support cables, can be distributed over the first ten wildlife crossings.

A feasibility (class 4) cost estimate was made based on the American ASTM standard, It showed that the Landshape crossing would cost $1286 per m^2 (including shell, foundations, formwork and support structure). Assuming that the support structure and cable-net could be reused, the costs for one of ten bridges dropped to $970 per m^2, or $940/m^2 if the geotextile is to be reused as well. In this range the formwork system drops from 31% to 4% of the costs. For one bridge only, the costs consist of 12% for the geotextile, 34% for the cable-net and 54% for the supporting structure.

Note that a conventional structure with two 45m spans costs between $1600 and $3000 per m2 (from cast on site with standard formworks to prefabricated beams and slabs), while a 90m span bridge would cost between $3000 to $4000 per m^2 (from cantilevered formwork to steel arched bridge).

3.5 Results

The Landshape structural concept works out to be a cost effective solution for the wild life crossing. The biggest part of the construction costs of the wildlife crossings is due to the material costs of the load bearing structure and the execution of the project. Therefore a method was investigated to further reduce the costs for these two aspects especially. The architectural design is based on a double curved hypar shape, making it is possible to create a lightweight structure with low stress surfaces and a thus minimal amount of material. In addition a construction method has been developed that enables a great deal of the flexible formwork to be made of prefabricated customized elements. This reduces the execution time and thereby the costs. Also, prefabricating elements serves to minimize the impact on the flow of traffic during the build.

The structure can be further optimized in several ways in the next stage. For instance through advanced form finding (form follows forces) and the possible reuse of the fabric formwork.

4   Extended Waal Bridge

The following project is an invited design for an extension of the Waalbrug in Nijmegen (Fig. 7). Along the existing run of the Waal River, a secondary, shallow channel will be dug to carry excess water in case of extreme water levels. To cross this secondary fairway an extension to the existing bridge is needed, the 'Verlengde Waalbrug', or Extended Waal Bridge. Designing the extension to the Waalbrug is part of a much bigger project initiated by the municipality of Nijmegen and the Dutch government. The overall project aims to improve the water management of the Waal River and develop the city and infrastructure surrounding it.

4.1   Project description

The original Waal Bridge, a steel arch, was built in the 1930's and was considered a high point of engineering art in its day.

The aim was to come up with a design that would not compete with the scale of the arch of the existing bridge, but that would nonetheless inherit the curved forms of the original. This was achieved by designing the bridge as a series of supporting ca. 80m arches. The monolithic arches will mirror the construction of the main bridge, while at the same time having its own distinct construction and material.

It was clear from the outset that, like in the original Waal Bridge, the design should be based on modern engineering principles. And the appearance of the bridge should be a reflection of the construction method that was used.

The experience of the Landshape Wildlife Crossing suggested that a similar visual language of smooth surfaces, created by stretching fabric, might be used for this project. And possibly also a similar construction method could be employed.

The initial design of the bridge was based on the bending moment diagram along the span (Fig. 8).
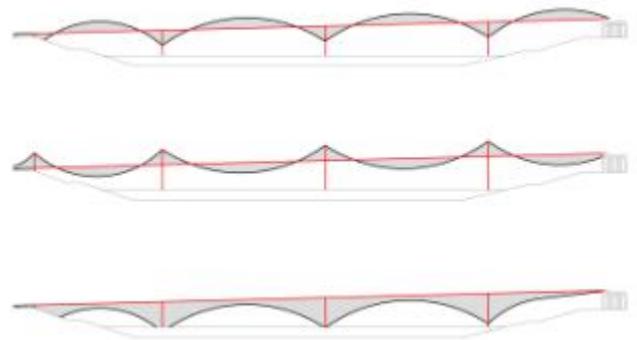
Figure 8: The overall shape of the bridge is derived by rotation and translation of the bending moment diagram

4.2   The design process

Designing the bridge has been a process of switching back and forth between physical and digital models.

A physical model was the first step in the design process, but to optimise the design and communicate with other parties involved a digital, parametric model,

Figure 7: The design for the Extended Waal Bridge.

key in further developing the design.

Still, in all stages of the design small physical models have been made (and will be made in the ongoing process). Those models, made from plaster, nylon fishing wire, or CNC milled from foam and wood, are miniature versions of a future reality. They provide an important spatial and tactile experience that a computer screen cannot deliver.

4.2.1 Physical modeling

The first sketch of the design was again a physical model. A piece of latex, tightly stretched over a wooden framework was pulled down in three places (Fig. 9).

Figure 9: Initial plaster model.

It was assumed that tension forces in the fabric would correspond to compression forces if the resulting shape was built as a thin shell structure.

This process created a mold, from which a plaster model was cast, the first in a long series of physical models that would be made throughout the various stages of the design process. They serve to check the physical qualities of different designs, as well as to inspire solutions. The final physical model, constructed after digital modeling (Fig. 11),

4.2.2 Digital modeling

The plaster model was the starting point for the design but it showed that an important problem would have to be solved. Stretching a single sheet of material with constant stiffness results in supports that are too massive, both esthetically and functionally. To accommodate the flow of water under the bridge, the supports can have only a certain, limited dimension. As a consequence the transition from support to the deck would need to have a smaller radius.

To test designs, a parametric model was set up in Grasshopper, and used the more user-friendly and flexible Kangaroo for form-finding instead of the earlier custom component. It takes boundary conditions, such

as the alignment, the width of the road and number of supports and physical parameters such as grid size, stiffness of the material and vertical loading as input parameters. Given these conditions a mesh is stretch between the fixed edges (Fig. 10).
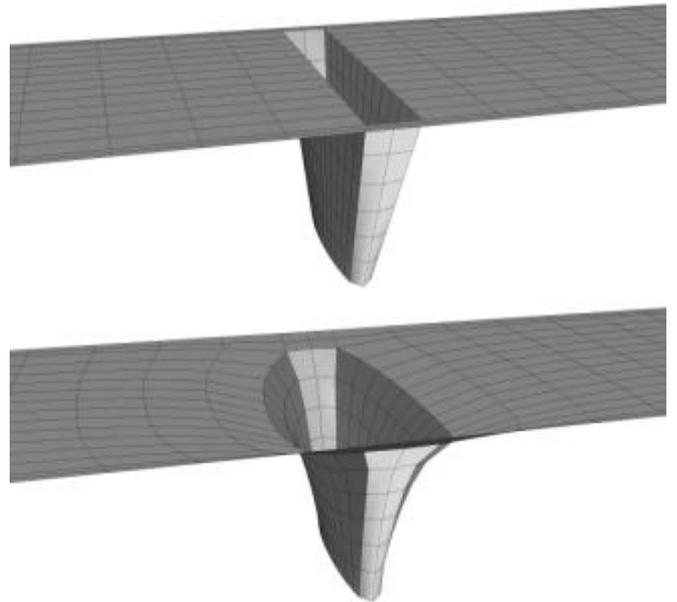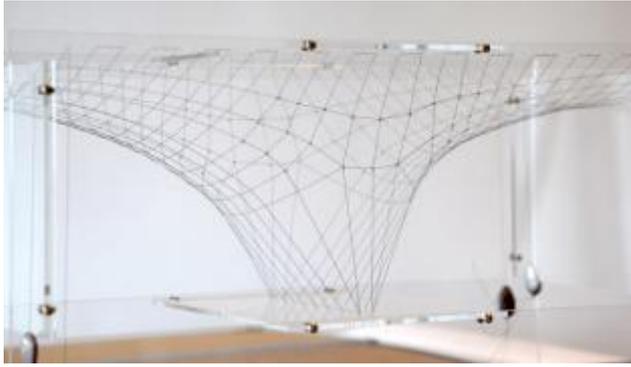

Figure 10: The modified / tailored mesh before and after relaxation.

The important difference however is that instead of using one single rectangular mesh, meshes were considered that consist of multiple panels, 'sewn' together. The topology of such a mesh is, in its unstressed initial state already a coarse approximation of the intended final shape and would hopefully overcome the limitations of the initial model.

This change in topology is also reflected in the physical model that was subsequently derived from the digital one. As can be seen in Figure 11, most of the vertices have four edges coming together, but some have five. These are the points where multiple panels of the composite mesh meet.

Figure 11: Final wire model of the modified, 'tailored' mesh.

Although pre-assembling an initial mesh this way brought the model closer to the desired shape, it did not completely solve the problem. Additional forces were introduced in the digital model to arrive at the required profile of the supports and the associated sharper corners.

Using this method it proved possible to interactively shape the bridge by fine-tuning the input parameters. The resulting, relaxed mesh was then subdivided and smoothed to arrive at the final shape (Fig. 12).

It should be mentioned that in order to arrive at the desired shape some parameters (e.g. static loading, stiffness) had to be set to values that were no longer physically meaningful. Although the parametric model was not intended to completely and realistically model an actual cable-net and its static behavior, this liberal use of variable settings has implications for the role of such a tool in the design process. Instead of approximating the behavior of an actual physical structure, it is now used to help arrive at a more or less predetermined visual appearance.
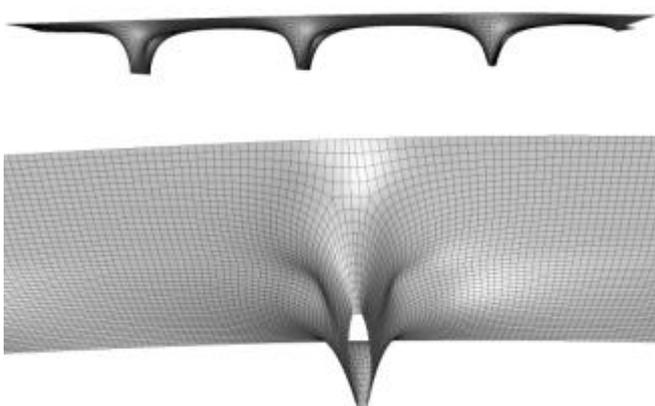
Figure 12: The final mesh

The parametric model has changed in character from being a simulation tool into being a drawing tool. That is not a problem per se, but means that additional analysis or extension of the tool is required to obtain meaningful structural quantities. That a realistic cable-net with the same shape can be obtained is certain because the form finding problem is material-independant and the process guarantees a tensioned structure in static equilibrium. However, having altered the shape to fit certain projects constraints, does mean that cable forces and therefore shell forces will vary significantly, which influences both the structural response (susceptibility to bending and ultimately shell buckling) and structural design (local dimensioning and stiffness of cables, shell thickness and reinforcement). These issues are the focus of further research.

4.3   Construction method

The project tender will be awarded as a Design and Build contract. The consequence of this is that the contractor, in collaboration with the architects, will eventually decide on a building method and further specify the design. The architects cannot prescribe a specific method beforehand. So, at various stages during the design, apart from a cable-net and fabric formwork, alternative methods for constructing a formwork had to be investigated.

Because of the smooth, doubly curved surfaces it seems appropriate to investigate the use of fabric formwork supported by a cable grid. After applying a first layer of fibre reinforced shotcrete, the skin of the structure, including partitions for stiffening if needed, could be cast. Finally the deck of the bridge could serve to stiffen the structure.

The building site is unique in the sense that the bridge will replace an existing road that sits on top of a dike. This suggests an alternative strategy that makes use of this special circumstance, by shaping the mold from the existing earth body, i.e. excavating the formwork from the existing ground body. This method has been used for the Teshima Art Museum in Japan by architect Ryue Nishizawa and engineer Mutsuro Sasaki.

Other alternatives that are being considered at this point include CNC milling of the formwork from polystyrene (e.g. the Spencer Dock Bridge in Dublin, Ireland), or subdividing the design in panels with single curvature which would allow the use of bent plywood to create the mold (e.g. the Mercedes-Benz Museum in Stuttgart, Germany).

Because of the aforementioned contract limitations, the possibility of using any of these techniques has to be kept open. Each construction method will have its own implications for the final appearance of the bridge. A cable-net and membrane formwork will sag between the supporting cables and might show wrinkles at the corners, depending on the cable grid size, fabric stiffness and possible prestress, as well as the casting strategy. Subdividing the surface in singly curved panels will produce specific patterning of the skin (Fig. 13). Likewise, in a milled mold the toolpaths of the milling machine will be visible as well as the seams between the blocks of polystyrene (Fig. 14). This explicit visibility of the chosen building method is considered a feature and will guide further elaboration of the design.

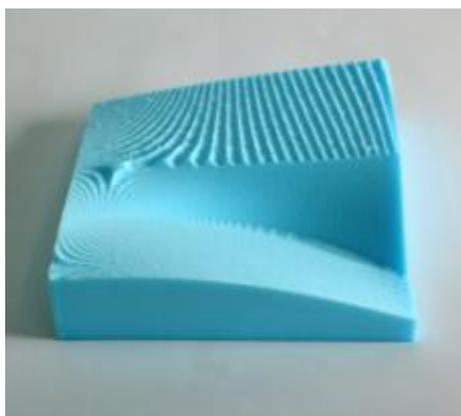*Figure 13: Explorations into subdividing the mold in flat or singly curved panels.*

Figure 14: Traces of toolpaths when milling a mold from EPS foam.

4.4 Results

It is not clear yet which building technique will be chosen for the Extended Waal Bridge. Using a cable supported fabric formwork, although always considered as an option, does not seem to be the preferred building method at this point. It has proven to be difficult to arrive at a satisfying geometry by using just the tension in a cable network as driving force to generate the final shape. This suggests that in a real world application similar problems might arise. The contractor that eventually wins the Design and Build contract will most likely try to minimise the associated risks. This favours better understood, more traditional building methods with proven results.

5 Discussion

Thin shell concrete hypars have rarely been constructed after the 1960s, with the cost of the formwork due to increasing labor costs often cited as the main reason for their decline. For large scale structures the proposed approach of using a hybrid cable supported fabric formwork seems to have potential as new economically feasible construction method. Especially in the case of the Landshape Wildlife Crossing it provided a vocabulary of shapes that was both functional and esthetically pleasing. It also proved to be cost effective when compared to conventional type bridge structures using traditional building methods. This was in large part due to the possibility to reuse parts of the temporary support structure for up to 25 crossings in similar site conditions. The potential of a prestressed cable network as a new construction method for hypar shells is underlined by the many recent examples of prestressed membranes used in academia for small-scale concrete prototypes and digital models (Pronk et al., 2007, Tysmans et al., 2009, Van Mele & Block, 2011, Pedreschi, 2012). In the case of the Extended Waal Bridge the use of this method is not self evident. Possible reuse of parts is limited in this project, increasing the costs. Also, the conditions imposed on the shape of the bridge by the required water flow may have pushed the design beyond what is still natural to build using this method.

The technical and financial feasibility of cable-net formworks compared to the actual construction method used for the Extended Waal Bridge will be the subject of further investigation, supervised by Prof. Philippe Block and the fourth author, at the Institute of Technology in Architecture, ETH Zurich, Switzerland.

Beyond this, additional research is needed on detailing of the formwork, in particular adaptable joints for reuse and connections between fabric and cable-net. Furthermore, methods to translate data from the digital design model to the workshop or site need to be developed.

6   Conclusion

The use of cable-network supported fabric, as a flexible and adaptable formwork, is promising as an economically viable method for construction of large-scale, large-span concrete structures. The concept consists of a cable-net and supporting structure at the same scale as those of built tensioned cable-net roofs, combined with a geotextile formwork at the scale of the cable grid size, the same scale as those of existing fabric formworks. It is therefore a combination of technically proven construction techniques. It is also economically feasible, especially so when concerning series of structures with similar geometries. Cost estimation of the Landshape Wildlife Crossing demonstrated it to be competitive with traditional methods for conventional type bridge structures. For a single, unique design such as the Waalbridge, economic feasibility remains unclear and cannot be confirmed until a comparison with the other possible methods is made. It is noted that the Wildlife Crossing project required continuous use of the freeway during construction. None of the other three methods would allow this as they each require substantial falsework, whereas the cable-net and fabric formwork has a clear span with lightweight material with an entirely external support structure.

The design of these formworks is possible by constructing physical models and facilitated by recent advances in digital modeling and fabrication, respectively allowing for integration in traditional software in the building industry and offering an economically viable method of manufacturing the doubly curved geometry.

Using these methods has the potential to reduce waste of materials and energy both for construction and the resulting structure. It provides a vocabulary of shapes that would otherwise be hard to build under current economic conditions. This form language has the flexibility to adapt to a wide range of sites and circumstances.

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