Negotiate My Force Flow

Designing With Dynamic Concrete Formwork

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A composite system, made from layers of perforated plywood and latex film, together with ropes and rubber seals, performs as a flexible concrete formwork. In our research we investigated whether such a system could yield more than only one single repetitive concrete form. We sought to reduce the amount of material consumed by conventional formwork and we conceived formwork as part of the design process rather than a technical means during construction. We worked as a team of architects, structural engineers and artists and through the confluence of computational design, digital fabrication, material simulation and prototyping.

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INTRODUCTION
The way we design and build with concrete lacks innovation. Resources, energy and architectural potentials are wasted because concrete processing is stuck in the industrial logic of endless repetition and serial production. Concrete is treated as a passive material poured into rigid and massive containers that act as formwork (Forty 2012, 170).

In our research we challenge the notion of conventional concrete formwork as a massive and rigid systems that is only capable to producing repetitive elements. We seek for a formwork system that is not only flexible but rather dynamic, i.e. it enables casting of concrete objects with various shapes using one formwork. We want to overcome the formal limitations of flexible fabric formwork predefined by the tailored textile under tension and its boundary conditions (Manelius 2012, 30).

METHODOLOGY
Our investigation on novel concrete formwork is based on three major methods:

- Decomposing and carefully exploring the different functions of a formwork in order to find novel materials or material compositions for the various functions. (Veenendaal et al. 2014)
- Simulating and physically exploring the forces at work during the process of becoming.
- Linking designing and making through computation and digital fabrication, with the aim
to conceive both formwork and its outcome as a design challenge.

**Decomposing Formwork**
Instead of focusing on a particular form that we want to cast, we start with a functional analysis of formwork: What are the constituting elements and their functional dependencies? Which functional requirements - such as withstand the hydrostatic pressure of liquid concrete or the requirement of the formwork to be watertight - can we extract from this analysis? Can we find new materials for certain elements? Can we re-program the dependencies?

**Simulating and physically exploring formwork**
Our formwork is supposed to consume less material. Instead of being massive it should rather balance the forces at work during casting and curing. We explored and exceeded the limits of plywood thickness and pre-stressed the material with ropes to achieve strength through curvature. We furthermore simulated the process of bending with particle-spring models to quickly test the range of formal opportunities provided by the material system without actually entering the cumbersome process of physical prototyping.

**Designing with and through formwork**
We reversed the conventional design process when working with concrete: instead of designing a form and subsequently transcend its ideal geometry into concrete through whatever means, we reverse the process for the sake of research in formwork systems focusing on the question: What are the forms we can achieve through the use of our formwork prototype? What forms could be found when the concrete in its liquid state impacts its forces on the fragile formwork?
**DYNAMIC FORMWORK**

The dynamic formwork system is composed of two layers of perforated plywood, latex film, rope, and rubber seals as outlined above (Figure 2). Each of these elements deals with one particular function of a concrete formwork.

**Plywood**

Planar plywood has a low stiffness while being capable to bear high loads. Through carefully placed incisions the material gains even more elasticity so that bending and twisting can be combined (Figure 3). Slotted plywood strips gain almost textile-like properties but perform structurally not only in tension but also in bending. A wide range of forms can be achieved through bending, twisting and prestressing the strips. Consequently the concrete is formed into objects with multiple structural capacities.

Like folded paper their in-plane tensile loads are activated and create a high stiffness. The bending increases the effective depth of both the plywood formwork and the cast concrete object. When grabbing a piece of paper we intuitively twist and bend it and thereby exponentially increase the global moment of inertia, transforming a weak bending system into one that carries its loads as a membrane system (Eisenbach et al. 2013, 205).

Prestressing the plywood strips with ropes substitutes our hands and allows for differently shaped configurations of the formwork. Through varying the location and the tension strength of the ropes the re-

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Figure 2
Formwork components.
sulting forms change (Figure. 3, 7 showing different configurations), the formwork becomes dynamic.

**Latex film**
The porous nature of slotted plywood requires a second material layer to tighten the formwork. Latex film proved most capable to follow the changing shapes of the plywood strips without creating wrinkles in the cast object.

Under the hydrostatic pressure of the liquid concrete the latex bulges into the plywood slots but effortlessly withstands the forces. The material can be reused for multiple casts, however, silicon-coating wears off quickly through chemical reactions with the concrete. While the first concrete objects have a glossy surface later casts are rather matte. The sealing qualities of the latex are not affected.

**Rubber seal**
Rubber profiles with rectangular cross-section seal off the perimeter of the formwork. The latex film is either wrapped around the rubber or the different materials are clamped together. The rubber is able to follow the bent and twisted forms of the plywood. It furthermore defines the edge thickness of the concrete object.

All elements of the formwork are re-useable and can be re-configured in different shapes. The upper and the lower layer are either clamped or bolted together.

**DESIGNING FORMWORK**
Assembled from the above-described components we explored the formal capacities of the formwork. The cast objects are rather results of this exploration than a priori designed objects.

Perforated plywood with its almost textile-like behaviour allows for large rotational movement along the longitudinal axis of the strip. We tested the twisting shape with different rotational angles. A wooden frame locks the twisted strips in precise position.

Bolts between the two plywood layers clamp the rubber seal, the latex film and the wood together and form a precisely shaped edge of the concrete object. However, the freshly cast concrete induces horizontal bulging and reveals imbalance between the forces at work during the process of becoming. Thus we dismissed the wooden frame that reduces the formal flexibility of the plywood to twisting. In the next iteration pre-stressed ropes twist and bend the plywood. Since ropes can be used to pull their fixing-points together but not to push them apart they have to be placed on both sides of the formwork to create alter-
nating curvature. To bend a strip of plywood along the short axis, the rope has to be mounted parallel to the long side and to bend the plywood along the long axis, parallel to the short side respectively. To introduce twisting through ropes is a rather challenging task but can be achieved through diagonal ropes on both sides.

A computational particle-spring model supported the investigation of the formal possibilities through the simulation of the forces acting on the material system and complemented the physical testing. Proportions of the digital plywood sheets could be adjusted and ‘digital ropes’ were quickly re-configured. Thus a wide solution space of possible formwork formats and bent and twisted geometries could be examined. A crucial aspect is the calibration of the digital simulation with the physical prototype. Different thicknesses of the plywood as well as varying incision patterns produce various bending behaviours that need to be analysed and the simulation setup has to be adjusted accordingly. The impact of the hydrostatic pressure of liquid concrete onto the formwork was neglected in this stage of formal exploration.

Curvature analyses of the digitally generated shapes are a first indication of their structural capacities. The physical limitations of the actual perforated plywood sheets in regards to bending and twisting radii have to be kept in mind, since the ‘digital plywood’ does not break. Incorporating the sequence of
tensioning of multiple ropes increases the complexity exponentially. The order in which two or more ropes are pulled is however relevant for the resulting geometry. The effect the use of our hands - even unconsciously - has in the physical prototypes cannot be implement into a digital simulation.

The incision pattern changes the geometrical properties of the plywood strip: The elements can be bent into forms impossible to achieve with continuous material. Since the material properties are unchanged the novel forms cannot be called double-curved. The slots rather allow for various regions of different curvature and with it for a global form unachievable with non-perforated sheet material. The curvature changes are negotiated by the small-scale saddles (Figure 7) between the slots that twist under the external forces induced by the ropes. Bending led to additional curvature, which - together with a re-orientation of the formwork during casting - reduced the bulging significantly.

Bending the plywood requires a revision of the edge fixing detail. The strips are congruent as planar or twisted surfaces and allow for bolting through congruent holes. When bending, the offset between the wooden strips that forms the cavity for the concrete, leads to two different bending radii and previously congruent drill holes do not match anymore. A parametric model would obviously allow for fast reverse engineering of this geometrical problem and provide a precise alignment of holes. However, here we decided to have slotted holes to maintain the flexibility of the formwork system since every change of the bending radius required a new alignment of holes (Figure 9). In one formwork prototype clamps replace the bolts in a hanging formwork and simplified its reconfiguration. Moreover the clamps facilitate further minor shifting while the concrete is poured into the formwork, which was meant to deform during casting in this case.

CASTING
While casting, the uncured concrete acts upon the formwork system through hydrostatic pressure and quickly reveals every imbalance between the forces involved. Calibrating the pre-stressing forces to withstand the pressure proved to be a challenging task that could only be tested through prototyping. We used self-levelling screed to mimic free-flowing and self-compacting concrete. We needed a material that flows smoothly into narrow formwork and induces uniform dissipation of pressure.
Digital simulation as particle spring model and physical prototyping of the plywood strips under tension. Both approaches were used in parallel to inform each other.

Figure 7

Strength through curvature.
Exploration of the formal potential of the formwork systems.

Figure 8

HYDROSTATIC PRESSURE AS DESIGN CRITERIA
A major criterion in designing any kind of formwork for concrete elements is the effect of the hydrostatic pressure. As described within the term, hydrostatic pressure describes a static load derived from liquids exerting pressure normal to its contacting surfaces dependent on the height of the column of liquid above. The magnitude of that pressure is linearly dependent from the self-weight of the poured liquid; thus the magnitude of the pressure of concrete is 2.5 times bigger than water pressure.

Complementary to the hydrostatic dead loads dynamic loads may occur from the casting process, depending on the pouring height. Since the concrete
is casted from the top of any formwork the concrete drops down a certain amount in a way that movements are happening from the clashing.

A second component of dynamic input may occur by compacting the concrete, which is dependant from the choice of concrete mixture and composition.

Obviously there is a natural contradiction when developing a flexible formwork: On the one hand a formwork surface is wanted to be as flexible as possible to be able to deform its shape; on the other hand a rigid surface is required to resist the forces originated from the casting process.

In our research approach we tried to take the advantage of the concrete pressure as a design criteria and to take it into account in the form finding process rather than to spend the effort in stringently working against the pressure (Figure 10).

CONCRETE OBJECTS
The cast prototypes are invaluable means to identify the potentials and the shortcomings of the formwork system. Their surface and overall form clearly incorporate and reveal its process of becoming. The incision pattern reappears as a relief in the concrete. Depending on the orientation of the formwork during casting the hydrostatic pressure reinforces or counteracts the curvature previously induces by tension ropes. In the hanging formwork (Figure 10) the concrete weight leads to increasing curvature, thus the initial form is exaggerated. The twisted concrete lamella in contrast suffered from horizontal bulging of the plywood (Figure 11).

COUNTER PRESSURE
One of the main challenges in the present research project is the handling of the hydrostatic pressure of the liquid concrete. It is a distinct effect that the results of the achieved form completely change when - for instance - changing the casting direction from standing to laying.

A promising approach is to work with counter pressure applied via a non-curing material surrounding the formwork. A simple way to resist the static load from the concrete in its liquid state is the build-up of a bed of sand below a laying formwork. In this manner a counter pressure can be achieved from both sides by placing the formwork in a box and, dur-
Concrete prototypes derived from dynamic formwork systems.

Such an approach was tested with a formwork for double curved surfaces, which has a setup similar to that of the dynamic formwork depicted above. Only the perforated plywood was substituted with a woven formwork from strips of plastic sheet material (PVC-foil with a material thickness of 0.5 mm). Layers of latex film and rubber seals were applied just as before. Before casting the formwork was placed in a box whereupon the gap between the formwork and the box was filled with sand. The woven formwork proved to be sound enough to withstand the pressure of the sand. The resulting cast - made from gypsum in this case - validated the conceived procedure.

Other than the perforated plywood, the woven formwork has only tiny openings between the individual strips. Therefore a further test was conducted using a formwork with no latex film. Here the sand not only provided the counter pressure necessary, but it absorbed the minor leakages of liquid gypsum as well, resulting in a perfect cast without deformation of the overall geometry and a high surface quality (Figure 12).

CONCLUSION AND OUTLOOK

The work presented in the paper is an on-going research project. The preliminary results are rather seen as the starting point for the subsequent research.

Further materials that act as counter pressure to the concrete in its liquid state will be tested. Reversible materials such as wax, soluble non-hardening mortar or even water are to be considered. For weaker formworks it will be necessary to study processes of casting concrete and fill-up material to counter its pressure simultaneously.

Furthermore the relation between the incision pattern and the deformation under pressure will be investigated. First tests have shown that a detailed understanding of this relationship allows exploiting the hydrostatic pressure as a design driver in the pattern generation. Such an approach will benefit from the integration of hydrostatic pressure as a force in our computational particle-spring model; another aspect that we will investigate further.
Significant enlargement of the geometrical spectrum, and thus a further research prospect, is the deformation ability of formwork faces not only in bending direction but also the extension and contraction in plane direction to allow fully three dimensional manipulations.

The experiments encourage the team to further investigate systems that overcome the notion of formwork as a massive and heavy means of construction and rather make it a part of the design process.

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Figure 12
Using sand to counter the pressure of the liquid concrete / gypsum. The genesis of casts on the right shows three differently deformed results in the top row and two non-deformed casts – with and without latex film – in the bottom row.