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Formwork Performance –
On concrete/formwork interaction

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Abstract
The conventional interaction between concrete and its formwork is very passive. Concrete is poured into rigid and massive containers that keep the liquid material in the intended form until it is capable to embody this shape by itself. In our research we seek to make this material liaison a more dynamic one by investigating geometrical flexibility of formwork through material differentiation, kinetics and a delicate balance of hydrostatic pressure and its withstanding forces. By overcoming the paradigm of one mould/many similar copies we hope to find novel, material-efficient ways to make our built environment more versatile and differentiated.

Keywords: Dynamic formwork, flexible formwork, computational design,

1. Introduction
Mark Wigley conceives of concrete as "the single biggest form of evidence of our species's existence" on planet earth (Wigley, 2010 [1]). If the material is everywhere it is inevitable to enhance concrete performance i.e. respond to the socio-economic need for a diverse living environment that consumes less material and energy while adapting to various local contexts. Given the ubiquitous use of concrete, even minor improvements have a huge impact.

Concrete is one of the oldest construction materials in the world but likewise subject to intensive on-going research in material science. Concrete is an overarching term for a broad variety of different cement bound materials: Low-tech with coarse aggregates, cement and water but also high-tech with extremely fine-grained aggregates and chemical admixtures that accelerate or retard hydration and improve the workability through plasticizers. High-tech concrete is characterized by increased compression and tension strength. Thanks to the dense packing of aggregates modern concrete promises improved workability, slender structures, less weight, ceramic-like surface qualities and a long maintenance free lifespan; properties that contribute to sustainable constructions. Only few of those performance aspects are reflected during design and processing of the material. Architects admire concrete for its ability to take on almost any shape. This notion however dismisses the effort spent in constructing the formwork. Concrete is regarded as formless matter regulated by a superimposed geometry (Reiser, 2006 [2]). The material is neither an active design driver nor an element of a material system. Its self-organising capacities during processing are mostly neglected.

Only recently, however, computational design and digital fabrication renewed an interest of architects in the process from design to production. Digital technology became a means for representing, simulating and instrumentalising the complex relationship between form, material, structure and production process in material systems. Linking design and making in research proved to be necessary and successful in the work of various architects and engineers. Felix Candela who became architect, engineer and contractor in one person (Arup, 1963 [3]). The research of Renzo Piano's early office Studio Piano into lightweight structures and polymer matrix composites lead to full-scale prototypes in the 1960's which became the basis of later projects like the IBM pavilion in the 1980's The office did not only design buildings but also processes and machines to fabricate them (Bettum, 2009 [4]). Miguel Fisac became an entrepreneur to produce his concrete bone beams (Colomer, 2007 [5]). The examples show the need for the convergence of design and production. Today the digital craft offers new opportunities to bring the designing and the making closer together. Digital technologies allow us to simulate even more complex systems addressing material, structure, form, space, environment and fabrication.

Our research project aims at establishing a novel convergence of computational design, digital fabrication, concrete and innovative formwork. Linking these currently detached technologies has the potential to bear sustainable material systems which consume less material, allow differentiated and site specific constructions and reveal novel spatial and material qualities. We need to reach beyond the repetitive processes of industrial production that waste resources, energy and architectural potential through endless repetition and serial production. When investigating concrete-formwork it is necessary to understand material behaviour of both concrete and formwork materials and their interaction. Form emerges from an intricate interaction of concrete, formwork and environmental parameters. A refined balance between the forces at play enables formwork to consume less material and yields differentiated and specific results.

2. Three approaches to make formwork dynamic

We started our research by investigating different approaches of differentiating geometry of both formwork and concrete objects:

- **Displacing**: A formwork like a three-dimensional puzzle of elements that can be assembled in different ways
- **Hinging**: A formwork that translates hyperbolic paraboloids into a system of hinged triangles
- **Balancing**: A formwork that dynamically balances the forces at work during casting and curing

2.1. Displacing

The displacing strategy was developed within a design research project that migrated topological interlocking into an architectural context through the use parametric design and digital fabrication. Topological interlocking assemblies are dry stone structures that perform as load bearing and spanning systems exclusively through the geometry of its components and the topology if their assembly as described in an earlier paper by the author (Tessmann [6]). In our research we started with a chamfered tetrahedron as the basic interlocking element.

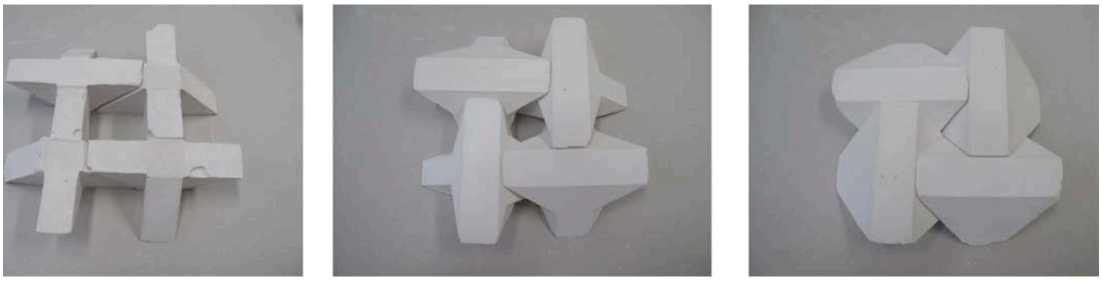

Figure 1: Interlocking tetrahedron made from plaster. Design: Philipp Mecke

In the initial configuration large parts of the tetrahedron surface area serve as the interlocking interface to the neighboring elements creating a closed planar configuration. These interfacing zones, however, can be reduced in size without compromising the logic of interlocking. Thus the structural capacity of interlocking systems can be combined with architectural requirements such as perforation, porosity and apertures.

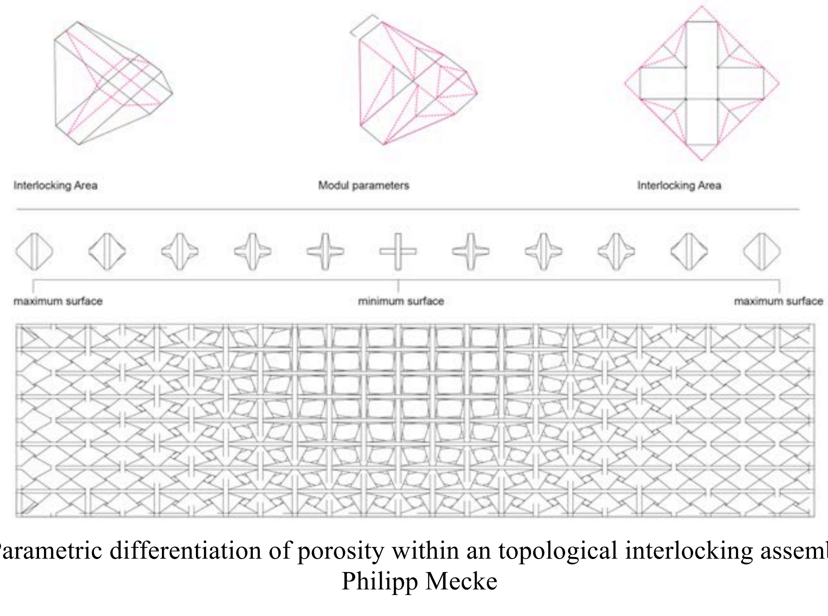

Figure 2: Parametric differentiation of porosity within an topological interlocking assembly. Design: Philipp Mecke

Within a parametric model we were able to control a gradual change of porosity in the interlocking system. Thus the structure could be locally differentiated: regions that are exposed to high loads would be made from elements with a large interfacing area, regions with the requirements for light penetration and vistas open up through less area of interlocking surfaces.

To achieve this variation in the cast elements we needed to develop a formwork system that allows for a geometric differentiation without building one formwork for each element. To guarantee constant interlocking throughout the entire system we needed to maintain the chamfered tetrahedron envelope while change the geometry of the elements. The concepts could be transferred to the mould making as well: Within a chamfered tetrahedron volume we needed to control the geometric variation. This was achieved through subdividing the volume into the interlocking element and displacers that together form a three-dimensional puzzle in the formwork. Displacers are commonly used within concrete to reduce the weight of structures and avoid concrete in regions where it is not needed for load bearing. The bubbledeck® technology for example uses plastic balls in slaps to reduce concrete consumptions where is has no carrying effect and create hollow decks. Our displacers became form-defining elements placed in the formwork. In a small-scale prototype we tested the formwork, the fabrication process and its outcome.

The formwork consists of a top and a bottom element. Together they create the chamfered tetrahedron envelope and become the repetitively used formwork. Within the envelope four displacers along the edges of the form allow the cast element to deviate from the basic shape and open up the interlocking system. We designed and fabricated a family of differentiated displacers derived from the parametric model that controlled the regional porosity of the interlocking system.

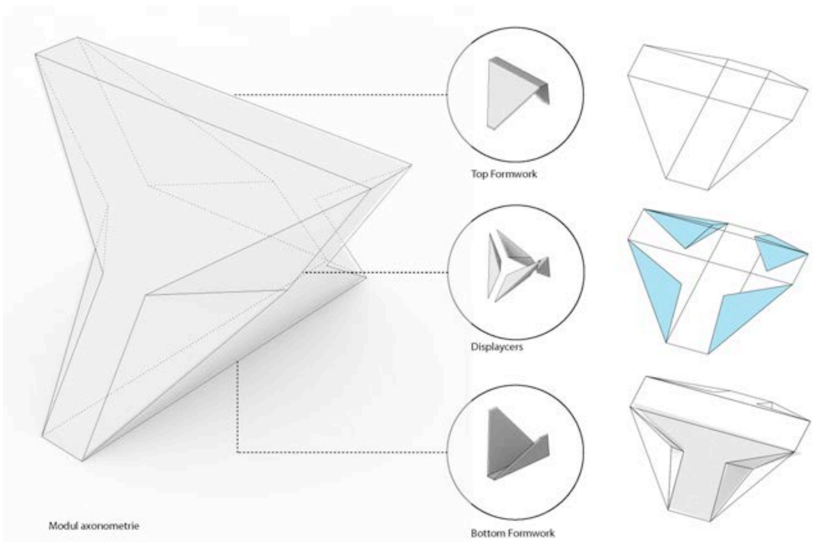

Figure 3: Formwork made from a envelope and displacers. Design: Philipp Mecke

A first prototype shows the interlocking assembly as a horizontally spanning system with locally differentiated apertures. The formwork in combination with the displacers allowed for variation of cast elements while reusing large parts of the formwork and only customizing a minimum amount of displacing elements.

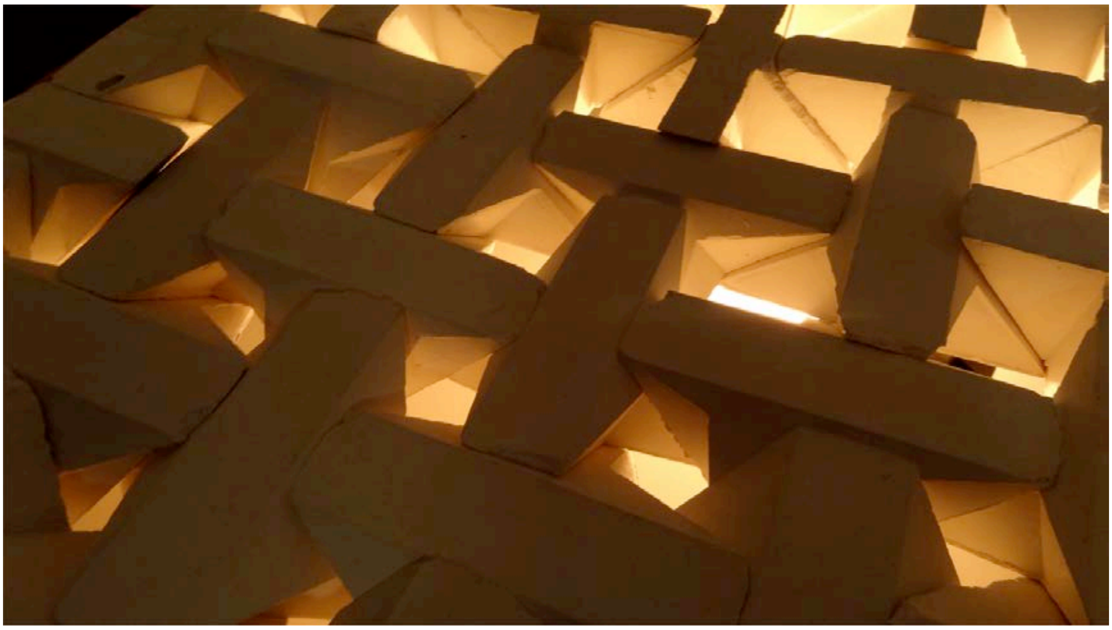

Figure 4: Prototype of topological interlocking assembly with locally differentiated porosity. Design: Philipp Mecke

2.2. Hinging

The hinging approach started with an exploration of the hyperbolic paraboloid as a digital parametric model and its transformation into a foldable formwork that allows for casting concrete elements with various shapes from one single formwork. The well-known anticlastic saddle surface is double curved and can be build from a stretched textile with two high points and two low points. It is also a doubly-ruled surface which is why it can be materialized through an array of linear elements that gradually rotate in space.

We tested a third approach which seeks to approximate the double curvature with a folded shape made from sheet material. The exploration started with folded paper models – an approach borrowed from Josef Albers (Horowitz and Danilowitz 2006 [6]) - which fold easily and embody the desired dynamic qualities we were after.

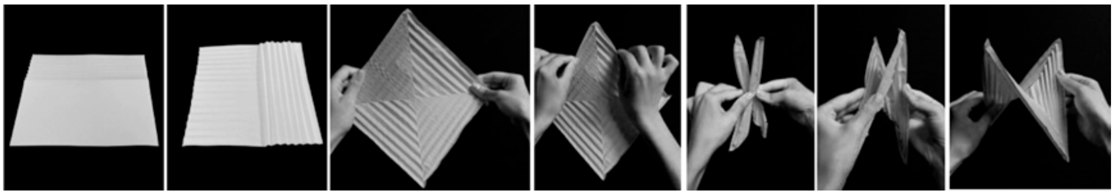

Figure 5: Recipe to fold a hyperbolic paraboloid from a planar sheet of paper

Once we understood the process we folded plastic sheets with engraved fold pattern that served as moulds for plaster casting and simulated the process of folding in a digital parametric model. While the plastic material was able to balance the conflicting requirements of flexibility during form creation (folding) versus the rigidity during plaster casting, it proved to be too weak for the increased hydrostatic pressure of concrete.

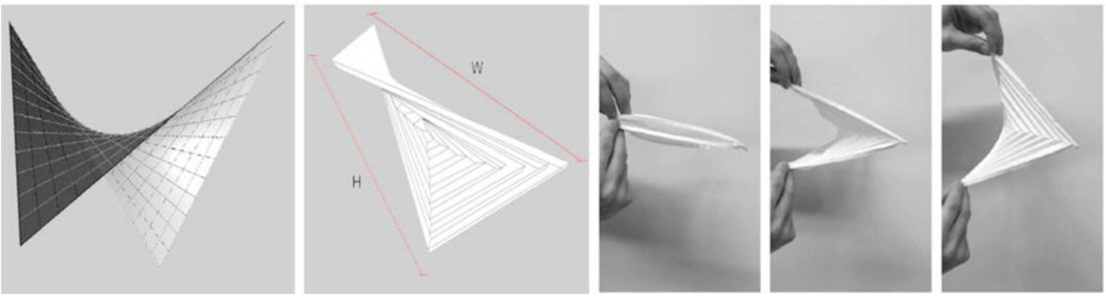

Figure 6: Range of geometric differentiation of a folded model

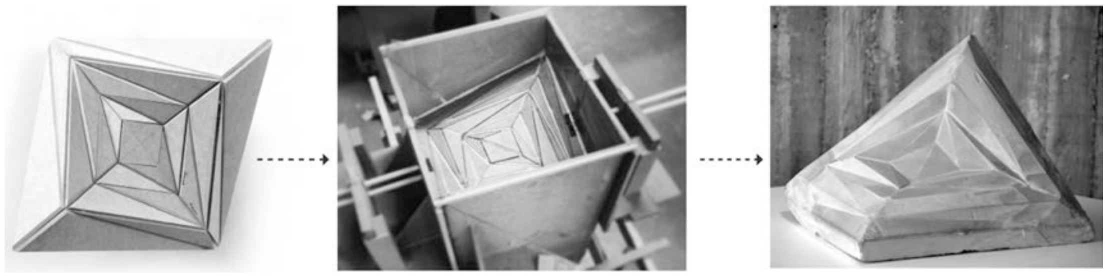

Figure 7: Folded MDF, Formwork setup, cast object. Design: Gusten Eriksson Hemström, Robin Lee, Maxime Boileau, Björn Liljeqvist

Thus we produced the concrete formwork from CNC-cut 3mm MDF sheets with fabrication dada derived from the parametric model. The folds now transformed into hinged made from textile reinforced tape between two CNC-cut triangular sheets. Two of these folded hyperbolic paraboloids in a distance of 20mm in a wooden box now formed the formwork system. Diagonal cuts in two sides of the box allowed for changing its shape: The formwork was now able to change its shape for the production of differently shaped folded hyperbolic paraboloid concrete objects. The folding pattern – a strong trace from the production process – became a kind of ornament that structured the surface.

Figure 8: Concrete demonstrator object made with our hinging dynamic formwork system. Design: Gusten Eriksson Hemström, Robin Lee, Maxime Boileau, Björn Liljeqvist

2.3. Balancing

The balancing approach challenges the notion of formwork as massive rigid containers that define the form of a concrete object. Instead we tested a formwork which is composed of layers of perforated plywood covered with latex film with sealed rubber edges. The flexible system can change shape through pre-stressing ropes. Through the resulting curvature the formwork withstands the hydrostatic pressure of the liquid concrete and therefore replaces the massiveness of conventional formwork. To fully understand what formwork does and to find inspirations for novel formwork materials we started with decomposing it into its various functions: A formwork needs to define shape, withstand the pressure of liquid concrete and must be tight. Subsequently we distributed these requirements to different elements of a composite formwork

Figure 9: Formwork components: plywood, latex film, rubber profiles, rope, and screws. Design: Ulf Edgren, Felipe Franco, Zijian Han, Svenja Krieg

To overcome our preconceptions of concrete formwork we inverted the conventional design process. Not the final form made from concrete was our starting points. Instead we departed from an experimental formwork system, made from materials usually not used for moulds and tested the formal repertoire of such a system. Concrete form was found through its formwork. The physical exploration was accompanied by a digital simulation within a parametric design software. We used a particle spring model to digitally explore the dynamic qualities of the formwork with the aim to mimic and simulate its physical behaviour in the digital realm. Being able to migrate the system and its behaviour into the a parametric would allow architects and engineers to conceive of formwork as part of the design process rather than a mere technical problem in the late construction phase of a project.

We increased the low stiffness of thin plywood through laser-cut incisions which leads to a textile-like behaviour of the wood. With bending and twisting a wide range a forms could now be achieved with the manipulated material through pre-stressing it with ropes. The resulting curvature increases the structural depth of the plywood as well as of the final concrete element, the flexibility of the material allows for the generation of many different shapes with one formwork system.

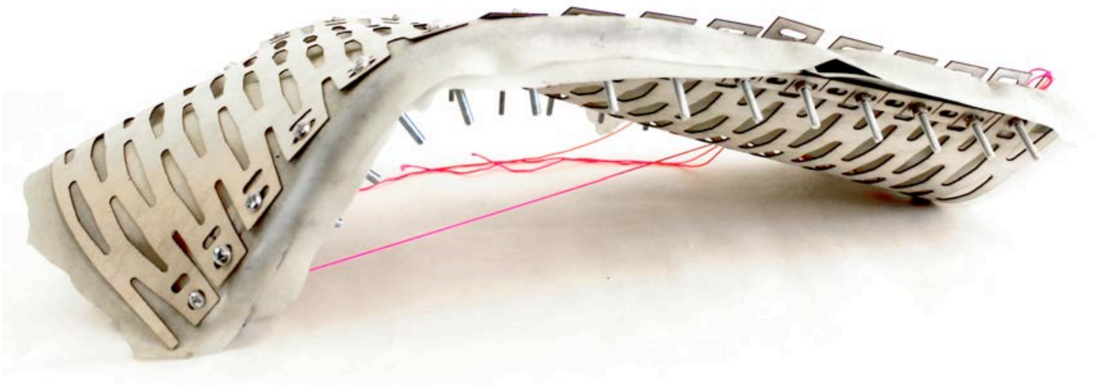

Figure 10: Formwork composite in a pre-stressed state. Design: Carlotta Brucker, Mimmi Gustafsson, Michelle Vallomy, Cynthia Ward

To provide a watertight system we covered the plywood with a latex film. The material easily follows the shape changes of the plywood without wrinkles and folds. During casting the concrete pushes the latex through the incisions of the plywood and an ornament-like pattern that emerges and reveals the differentiated hydrostatic pressure of the casting process in the final object. The two-layered assembly is sealed with rubber profiles that run along the edges and follow the curved shape. Casting self-levelling screed into the formwork reveals the challenge to balance the various forces at work during the fabrication of concrete elements.

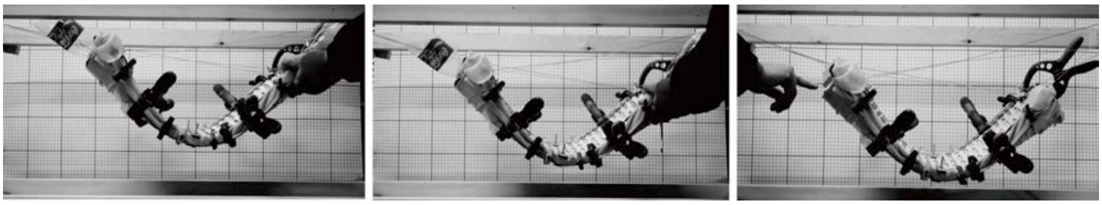

Figure 11: Hanging formwork sagging under the load of liquid concrete. Design: Ulf Edgren, Felipe Franco, Zijian Han, Svenja Krieg

Our experiments revealed the contradiction of a dynamic formwork: It needs flexibility during setup and form finding but it need to be strong during casting and curing. However hydrostatic pressure here served as a design driver that forms the formwork in a more or less controlled way. Mastering such a delicate balance requires further research in calibrating these different forces. Physical prototyping becomes an invaluable means that could only partly be supported by digital simulation.

Figure 12: Concrete prototypes derived from dynamic formwork systems.

3. Conclusion

All three approaches of dynamic formwork presented in the paper are subject to further development and show on-going research. The current state of the work reveals certain shortcomings in the ambition of making formwork a part the architectural design process because technical aspects of the novel systems overrule other design intends. The displacing elements only provide a limited range of differentiation constrained by the envelope. The hinging approach limits the degree of rotational freedom and the balancing system gains strength from curvature thus planar elements are not easy to produce with it. Thus none of them will serve as generic concrete formwork system that allow for the production of any shape.

The hinging and the balancing approaches have limited possibilities to be scaled up since the concrete mass will increase at the cube of the scale factor. Both approaches are rather promising for prefabricated concrete elements with limited scale. A promising approach to counter-act hydrostatic pressure is the use of 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, during the casting process of the concrete element, the box outside of the formwork is filled up as well.

However the ambition here is to make formwork a part of the architectural design process and let it have an influence on the final form. The process of becoming leaves a trace in the final object. In that sense our formworks runs alongside many famous ancestors of concrete constructions.

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