INTRODUCTION

The concept of topological interlocking as a means of designing new materials was developed by the Institute of Material Science, Technical University Clausthal, Germany. The research led to planar assemblies of solid and repetitive polyhedrons and osteomorphic blocks. Cubes and tetrahedrons are assembled in mutually kinematically constraining planar configurations (Figure 1). These assemblies are capable of resisting external loads impacting perpendicular to the main load bearing direction due to force-locked interfaces between their elements. Given fixed boundary conditions the assemblies are able to resist high bending forces and even tension without any additional binding material like mortar. Structural coherence is achieved by the interlocking interfaces. This property distinguishes them from compression-active vernacular arcs, vaults, shells, brickwork structures and masonry. Planar materials fail when cracks are able to propagate through the entire dimension of an element. Topological Interlocking Assemblies are broken down into small-scale elements already. Thus the approach increases material strength by fragmenting the material. Cracks cease to propagate at the interface between to modules (Dyskin et al. 2001).

The concept of interlocking has a long legacy in architecture. The closely fitted stones in the masonry of Inca architecture are an early but highly sophisticated example. Recently it has been scrutinized in architectural research by Gramazio & Kohler with projects like the Programmed Wall and Explicit Brick (Bonwetsch et al. 2007). Greg Lynn’s Blob Wall is another example of linking interlocking to contemporary fabrication techniques (Lynn 2009). The Block research group at ETH Zurich developed differentiated voussoir elements to create compression-active structures (Rippmann et al. 2011). Zaha Hadid explores he formal potential of interlocking with her

Topological Interlocking Assemblies

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Abstract. Topological interlocking is a concept developed in material science. Solid modules form a structural system without the use of glue or mortar. Given fixed boundaries the elements constrain each other kinematically. This project seeks to re-conceptualize the system within an architectural framework by embracing computational design, analysis and fabrication tools and procedures. The goal is to develop geometrical differentiated, reversible, force-locked systems and the processes and methods to design and manufacture them. Students of the Architecture and Performative Design Studio (APD) at the Staedelschule Architecture Class (SAC) and the author developed the presented projects. The paper discusses the pedagogical approach of starting a design research studio from a very narrow material system. The research is continued at the School of Architecture of the Royal Institute of Technology (KTH) in Stockholm.

Keywords. Digital Fabrication; Parametric Design; Topology, Structure; Modular.
TOPOLOGICAL INTERLOCKING ASSEMBLIES AS ARCHITECTURAL MATERIAL SYSTEMS

This project adopts the research from the realm of material science and tests its potential as an architectural material system. Contemporary digital design, analysis and manufacturing tools and procedures are used to investigate the following topics:

- How can we increase the geometrical repertoire of topological interlocking assemblies beyond mere repetition?
- How can we integrate generative as well as analytical capacities into one single parametric design systems?
- When casting modules, how do we solve the conflict of reusing formwork while pursuing the aim of module differentiation?

WORKFLOW AND TOOLS

The research was started within a design studio. Computational design and analysis tools were introduced to test and simulate the performance of interlocking systems. Despite a departure point, highly constrained by geometry, mere geometrical representation would be insufficient to explore the potential of topological interlocking.

Rigid body dynamics, simulated in animation software, served as a simple analysis tool for structural coherence and for gathering a qualitative understanding about mechanisms of failure within the system. TopoStruct became an explorative tool for material distribution. The software developed by Sawako Kaijima and Panagiotis Michalatos at AKT in London is based on Topology Optimisation (Kaijima and Michalatos 2011). The research team was less interested in the aspect of minimising material use as suggested by Topology Optimisation but rather in the differentiation of modules and their material properties from load bearing to moistening or light transmitting driven by a generative digital model in TopoStruct. Here, structural capacity is achieved through continuous material distribution. Zones, free from material allocation in TopoStruct, can be used for requirements beyond load bearing.

A parametric model finally gathers and processes all information, adjusts and augments the module geometry accordingly. Furthermore all data needed for mould making and other fabrication techniques is generated here.

INCREASE GEOMETRICAL REPertoire OF TOPOLOGICAL INTERLOCKING ASSEMBLIES

When used in an architectural context, topological interlocking assemblies need to provide a larger geometrical repertoire beyond mere planar homogeneous systems. Architectural constructions
require differentiation in orientation, dimension, porosity and directionality. Despite these additional degrees of freedom the interlocking principle has to be maintained. Philipp Mecke achieves differentiation by a parametric setup that controls the local porosity within the system while maintaining a certain repetition. The initial assembly of tetrahedrons, repetitive in size and geometry, forms a closed plane.

Figure 2
Left: The tetrahedron is cropped to eliminate sharp edges which are difficult to cast and vulnerable in construction. Right: Study on the variation of contact zones between the modules. Areas marked in black establish an interlocking zone with the neighbouring module. Altering size and location of these zones changes the porosity of the system the topological interlocking is unaffected (Image: Philipp Mecke).

Figure 3
Top: Envelope as outline, displacers in blue, cast volume in grey. Middle: Planar assembly of module with different degree of porosity. Bottom: Module differentiation and interlocking with changing contact zones (Image: Philipp Mecke).
Here various displacers in a mould allow for a repetitive use of the formwork and a differentiation of modules. Nevertheless only planar configurations are possible. The approach suits the need for repetition when working with cast elements but as its clear geometrical limits.

To broaden the formal repertoire of topological interlocking assemblies beyond planar configurations, modules and their assembly need to be described in a parametric fashion. Fixed dimensions are replaced by relative coordinates driven not only by the module size and geometry but also by its location within the overall assembly and adjacent contact faces. Like the keystone at the apex of an arc needs a specific wedge-shape to lock all other stones in position, topological interlocking assemblies with individually shaped modules lock each other while achieving spatial and geometrical complex configurations beyond mere planar or compression-active structures. The overall shape of an assembly emerges from the orientation of modules and their contact faces.

Mecke subsequently enriches his parametric model. The modules now follow a reference geometry consisting of curves, surfaces or volumes. The interface planes between the modules are defined according to the local orientation of the overall reference system. First the interface planes of one module need to lock all rotational and transitional degrees of freedom. Then the geometrical elements between the interface planes are generated to form a solid module.

Nasim Delkash develops a design system that integrates generative and analytical aspects within one single parametric set-up. The generative system orchestrates the assembly and differentiation of modules and ensures that the interlocking capacities are provided at every location of the structure. Thus generation and analysis coalesce in one single model that constrains and drives the assembly process.

Based on the tetrahedron with four faces Nasim Delkash develops a module with 16 faces, which enable curved assemblies while maintaining the initial topological principle (Figure 5). A single tetrahedron face is subdivided into three to four faces. The modules are classified in four different organizational hierarchies, which are generated subsequently. Specific contact points – displayed as red dots in the upper left diagram of Figure 5 - of the first hierarchy level drive the module generation of subordinated levels. This master-and-slave-principle guarantees sound interfaces for interlocking between the modules. Large-scale reference geometry defines the overall form the module configuration follows parametrically.

Figure 4: Curved interlocking system through the use of differentiated multi-faceted modules. Repetition appears only in planar zones of the object (Image: Nasim Delkash).
Likewise the following tube-like interlocking assembly relies on sequential generation of its modules. The elements are based on distorted cylinders with a circular cross section in the middle and ellipse-shaped cross sections at both ends (Figure 6). Tangential interfacing zones create the interlocking effect (Dyskin 2001). The parametric assembly is differentiated in cross section and its orientation, material thickness and module size. The generation process is twofold: The first module generation is based on circles and ellipses as exemplified by the blue and green modules in Figure 7. Then, NURBS curves adjust to the circles and ellipses of the first generation geometry. A loft surface creates tangentially interlocking modules shown grey in Figure 7.

The 3D printed shell-like prototype with fixed boundaries exemplifies the challenges of interlocking systems during assembly. First of all a very precise jig is necessary since structural capacity unfolds only after the very last element is placed in its particular position. The colour becomes a code for the position and orientation of each module. Comparing digital and physical model reveals the challenge of assembling modules with tangential interlocking. The rotational freedom during assembly quickly propagates throughout the entire system.

*Increase the degree of interlocking*

All systems presented so far use one interfacing zone between two modules to constrain movement...
in one direction. The non-constrained degrees of freedom create thrust that needs to be transferred into fixed boundaries. Donlaporn Chanachai challenges this limitation of the tetrahedron and cube assemblies by inventing a module with a different interlocking behaviour. The hexagonal modules interlock at two interfacing planes with different orientations (Figure 8).

The windmill-like modules, assembled in planar configurations, resemble closest packing pattern of circles. Beyond planes, interlocking even works when one of two modules is rotated by 90° to form three-dimensional configurations. Both planar and three-dimensional configurations do not require fixed border conditions because the complex interlocking prevents thrust in the system as soon as three modules interact.

The prototypes are cast from plaster and soap to create load bearing and translucent modules. Acrylic moulds provided smooth surfaces and, more important, allowed for controlling a proper material distribution in the mould without air locked voids. Donlaporn Chanachai subsequently tested a multitude of possible configurations emerging from the modules and their unique assembly logic. Additional modules in smaller scales were built to quickly test these various configurations (Figure 9).

**BORDER CONDITION**

The topological interlocking systems require rigid peripheral constraints to unfold load-bearing behaviour. The assemblies developed in Clausthal achieve rigidity through massive solid edges, which is not always practicable when scale and therefore weight increases. In larger scales the border condition has to be reconsidered and requires different solutions. Pre-stressing and jointing techniques need to be developed and integrated into the system.
Philipp Mecke develops a border system, which consists of special modules with an increased number of interlocking directions (Figure 10). Similar to Donlaporn Chanachai windmill-shapes modules two elements meet and constrain each other in more than one direction. The special corner and edge modules allows for constructions with modular boundary condition. Further testing of load paths and local stresses is needed to size the interlocking faces. Different from Chanachai’s assemblies thrust forces will always occur in Mecke’s system.

Apertures increase the complexity of border conditions. Whenever modules are missing in the assembly kinetic freedom is provided to the neighbouring elements. Thus border conditions do not only appear at the edges of the system but with every opening.

Eladio Dieste is known for a completely different approach. He is one of the first to combine discontinuous brick structures with steel cables. The technology also used in large spanning concrete structures benefits from the compression strength of bricks or concrete and even increases compression by adding tension cables to a compression-active system. The entire system is pre-stressed; meaning stress is introduced into the system prior to exter-

Figure 9
Cardboard models. All assemblies are based on one repetitive module. Interlocking and friction exclusively bind the elements together (Image: Donlaporn Chanachai).

Figure 10
Multiple interlocking within between two modules constraint the edges of the assembly (Image: Philipp Mecke).
nal forces act upon it. These tension forces create compression forces in the system that supersede the force impacting from outside.

Nasim Delkash transfers this approach to her shell-like shelter structure. Cables that run inside and outside the modules tie the lower concentric layers of the structure together. The approach requires additional research since tests have been made with small-scale models and very light modules.

**MATERIAL DIFFERENTIATION**
The principle of topological interlocking is not limited to the tetrahedron and its derivatives. Fenny Laurin assembles cubes and investigates potential for material differentiation. While limited in achieving curved assemblies, cubes allow for three-dimensional stacking and change of orientation. Given fixed boundaries, horizontal and vertical planes can be linked and volumetric assemblies with voids create interior space. The porosity of Laurin's plaster cube modules is differentiated through displacers made from soap. The material may stay within the modules to create translucency or is removed to create porous effects.

**CONCLUSION**
The project proved to be successful in integrating teaching and design research. All participants developed a deep understanding of their systems and created novelty upon this knowledge. The close link

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**Figure 11**
Shelter structure for a desert in central Iran. The border is consolidated by tension cables that counteract the horizontal thrust in the system (Image: Nasim Delkash).

**Figure 12**
Cast plaster cubes. Porosity is achieved through soap displacers within the mould (Image: Fenny Laurin).

**Figure 13**
Light transmission through translucency and porosity (Images left to right: D. Chana-chai, N. Delkash, P. Mecke.)
between analytical and generative models became a key technique that calls for further integration of system specific aspects.

Chanachai’s windmill-like modules exemplify how systems may unfold from the design of one of its elements. Without any preconceived tectonic system the research in modules and their configuration bears interlocking performative sculptures that developed further into a proposal for retaining facilities against mud floods in the Thailand’s Khao Phanom region.

Delkash’s faceted tetrahedrons and the tubular configuration designed by the author exemplify the need to inform module geometry by aspects of assembly. The cumbersome, fragile and time-consuming aggregation process calls for better sequencing and self-organisation of elements within the system. Topological Interlocking Assemblies offer a broad range of possible applications. They tolerate deformations and seismic loads while maintaining structural capacity. This property could be beneficial in various contexts. Topological Interlocking Assemblies are load bearing and at the same time easy to disassemble. These properties can be used for temporary constructions and makes recycling of building material easier. The principle of interlocking works in various scales: from micro particles to large scale coastal barrier modules.

ACKNOWLEDGEMENTS
This research project would not have been possible without the students participating. Donlaporn Chanachai, Nasim Delkash, Fenny Laurin and Philipp Mecke spend a lot of enthusiasm, time and energy into their design research.

The Staedelschule Architecture Class (SAC) and Johan Bettum as its program director did not only provide a research platform by establishing the master specialisation APD but the school also proved to be a place for vivid international exchange, discussions and exciting design explorations.

I would like to thank Ben van Berkel, Mirco Becker and Anton Savov from SAC, Karola Dierichs from ICD Stuttgart and Mark Fahlbusch from Bollinger + Grohmann. Their invaluable inputs during desk-crits, juries and presentations had a major impact on the successful development of the projects.

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