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EXTREMELY HEAVY AND INCREDIBLY LIGHT

Performative assemblies in dynamic environments

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Abstract. This research addresses the design and negotiation of two kinds of assemblies that are similar in topology but fundamentally different in performance. Firstly, Topological Interlocking Assemblies (TA) are made of solid elements. Their overall structural integrity relies on each element being kinematical constraint by its neighbours. Secondly, Bell Kites, similar in topology but fundamentally different in performance these kites are made of clusters of tetrahedrons. While TA are heavy, massive and exposed to gravity Bell Kites are super light and dominantly driven by wind forces. These two instances formulate the opposing ends of a spectrum in which a new system, one that is capable of covering the full range of performance, is developed and re-conceptualized in architectural context. The research seeks design-innovation by scrutinizing systems that are not yet part of the architectural ecosystem. Mapping out their performative characteristics and developing their spatial and programmatic potential through conscious design moves explore the potential for architectural applications. The work presented in this paper is the result of a design research studio of the Architecture and Performative Design Class at the Staedelschule in Frankfurt.

Keywords. Topology; interlocking; bell kite; modular; adjacency.

1. Introduction

With ‘Extremely Heavy and Incredibly Light’ we seek to merge two modular systems, which have similar geometrical properties but greatly differ in their performance: Topological interlocking originates from ancient timber construction and has only recently been rediscovered by material scientist. Bell Kites were a break-through in manned flight as they overcame the scaling laws usually limiting kites in size and potential payload. They also laid the ground for uniform space-frame structures later promoted by Konrad Wachsman and Buckmintser Fuller. In our design research we investigated the architectural potentials of a hybrid system.

In this paper we first describe the research on topological interlocking assemblies and their computational design and digital fabrication. This 'heavy' part of the research is followed by a presentation of parametric kites based on Bell's approach. After exploring the two extreme ends of the overall spectrum we present hybrid systems as integrated architectural design proposals.

2. Topological Interlocking Assemblies (TI)

Topological Interlocking Assemblies (TI) consist of many solid objects (Figure 1). Cubes or tetrahedrons are assembled in a way that they kinematically constrain each other. Every building block is locked by its neighbours and locks them.

This mutual affect dispossesses the system of any translational or rotational freedom. Only the specific geometry of the elements and the topology of the assembly create structural coherence. Adjacency replaces glues or mortar. The structural principle of TI resembles the reciprocal frame, a widely used construction techniques for ancient Asian timber structures but also known by medieval building master. In the 17th centaury Stereotomy, the art of cutting stone and creating the necessary drawing (traits) allowed the creation of geometrically complex building blocks and interlocking systems (Evans, 1995). The new technique made it possible to transfer the technique from linear timber elements to massive, solid stones. In 1699 Joseph Abeille patented his 'Flat Vault' a planar assembly of truncated tetrahedron shaped stones. The interlocking system was supposed to span without the curvature of a vault. Only the way the building blocks interlock refers to medieval vaults with keystones. The Flat Vault never became a successful construction system but material scientists rediscovered it very recently and revealed

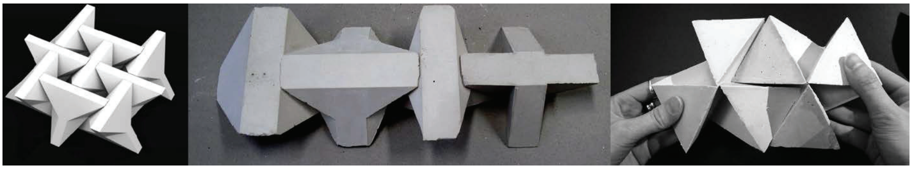

Figure 1. Examples of Topological Interlocking Assemblies.

its potential in a different scale (Estrin et al., 2011). Planar materials fail through propagating cracks. TI are fragmented already. Local cracks cannot propagate throughout the entire system.

3. Bell Kite Assemblies (BA)

Bell Kites are space-frame like structures based on tetrahedral cells. These cells can be cluster homogeneously or fractal-like into various forms including plates, bars, cubes, rings. Alexander Graham Bell invented these structures during his research into manned flight between 1895 and 1910. He challenged the notion of kites at the time which had the shortcoming of getting over-proportionally heavier when increasing the surface area thus putting an absolute limit on the size of kites. He discovered a concept of a cellular kite that overcame this problem and gave a way for carrying payload resulting in the first manned flight on a structure that was heavier than air.

4. Design Context and Methodology

In the context of this project we studied TI and BA as two extreme ends of a spectrum. TI as a massive solid system exposed to gravity and thrust suitable for retaining constructions massive walls and slabs. BK, in contrast, explore other aspects of performance and open up even more design opportunities. The methods to investigate and explore both systems are different and only partly overlap.

4.1. PARAMETRIC EXPLORATION

Parametric design techniques allowed us to differentiate the single elements within both assembly types to achieve more non-repetitive configurations. The geometric affinity between both was reason enough to explore the potential to merge the systems. Our research scrutinized the architectural potential of historic systems re-visited with contemporary design and analysis tools.

4.2. SIMULATION

Although both assembly types heavily rely on geometric properties, their performance cannot be revealed through mere geometric representation. Both systems are in some respect over-performing, leaving room for design innovation and including performative aspects that go beyond the primary function of the initial system. The TI can be altered in shape and reduced in volume as long as the contact faces between cells are maintained. BK generate an excess of lift thus leaving room for altering the effective area of each cell in favour for other criteria.

For TI we simulated the interaction of solid blocks under the influence of gravity with rigid bodies in animation software. The model served as a qualitative investigation rather than delivering exact numbers of forces and stresses. It nevertheless helped to understand the principal behaviour of parametric TI's. Conventional structural analysis tools used in the design of architectural structures are not capable to model the contact forces between adjacent building blocks. Brocato and Mondardini (2010) describe an approach of mechanical computation of Abeille's Flaut Vault transferred into a geodesic spherical assembly. Cast3M is used for a finite element model. The interfaces are modelled as joints that transfer compression forces and tangential forces limited by friction. The elements stay separate and glide on each other. The discrete element method (DEM), designed to simulate granular and discontinuous materials, is considered as another method to achieve precise numerical results. Nevertheless in our early design exploration we relied on available and quick-to-acquire qualitative simulations.

The kite dynamics of BK and their non-linear behaviour were simulated in animation software using a physics and cloth engine. The set-up aimed at establishing whether a given kite design would generate enough up-lift to get the kite airborne. These designs were then prototyped and flight tested. Only through physical testing the fine tuning of the bridle was set to the wind conditions of the day. The actual strength of joints and linear members could only be optimised by physical tests as the digital simulation was lacking the analysis of internal forces.

4.3. DIGITAL FABRICATION

The facetted polyhedra shapes are un-foldable, which allowed us to fabricate them from sheet material after unrolling in the modelling software (Figure 2). We established the technique for formwork production of TI elements and seamlessly transferred it to cut the canvas of the kites. In addition we 3d-printed only KI space

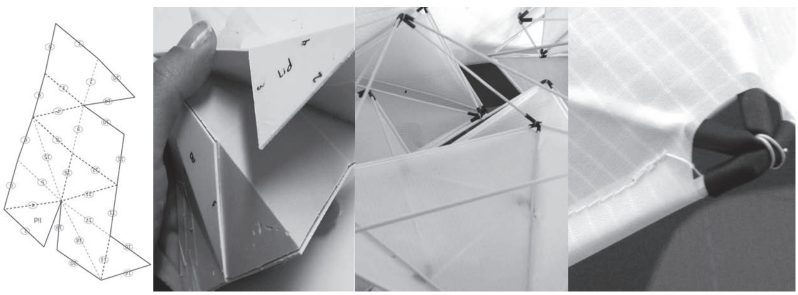

Figure 2. Unfolded cut pattern for TI mould (left). Laser-cut kite membrane and node.

frame nodes and TI elements that could not be unfolded or needed to be made from solid material.

5. Topological Interlocking Assemblies for Architectural Constructions

Within the above-described technological and methodological context we investigated TI as an architectural construction system. We differentiated the modules by manipulating the surface area of their adjacency, which yielded porosity in formerly sealed assemblies (Figure 3). Furthermore a parametric description of the element increased the geometric freedom beyond mere planar configurations. TI's could now become walls, ceilings, slabs, vaults or intrinsically interlocked sculptures with very ambiguous structural behaviour. Every avenue of exploration was not only investigated by computational modelling and simulation but also tested as physical prototypes. The actual making of the artefacts became a prototype of production workflows like mould making and casting. The research is extensively described in a previous paper (Tessmann, 2012).

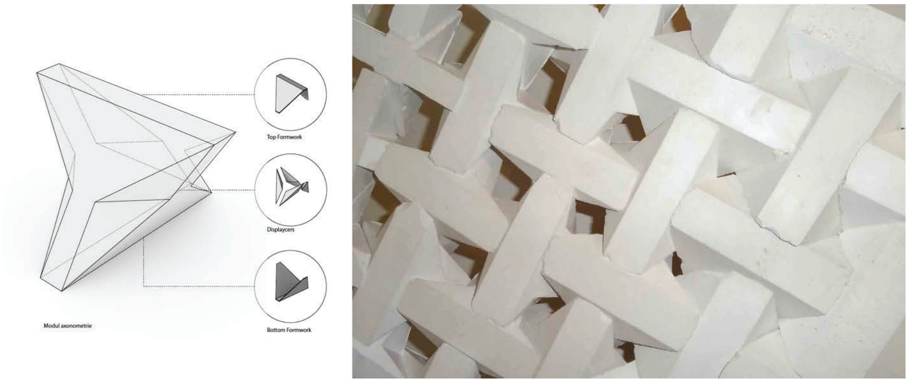

Figure 3. Truncated tetrahedra assembled as a porous wall/slab system (Design: P. Mecke).

6. Bell Kite design and Flight Test

Based on the TI assemblies we developed the modular kites and replaced adjacent surfaces between elements by nodal connections. The massive TI dissolves into a lightweight skeleton/canvas system (Figure 4). The forces change from static (gravity) to dynamic (multi-directional wind).

After studying the properties of BK in their initial design and gaining expertise in their behaviour new designs were proposed. As with the TI system the aim

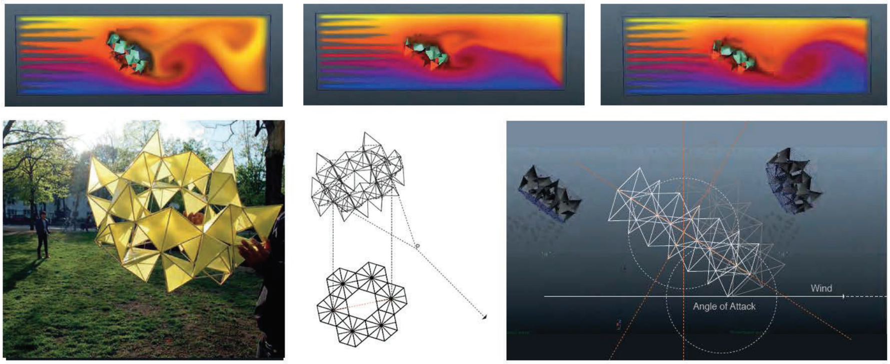

Figure 4. A kite based on hexagonal cells designed by Donlaporn Chanachai.

was to find architectural applications. Based on the findings this lead to the systems for large spanning roof structures and canopies where the potential uplift forces could overpower the dead-loads of the system. Also the self-stabilising properties of kites where higher wind forces lead to an overall more stable condition where developed into spatial and architectural features.

7. System Integration

Alexander Graham Bell's kites inspired not only the work of Max Mengeringhausen, Konrad Wachsmann, or R. Buckminster Fuller but also evolved in his own work into lightweight architectural structures. In 1907 he erected an 80-foot observation tower on his own premises. Four tetrahedral-celled trusses act as legs that intersect on the top to carry an observation platform (Wachsmann, 1959).

Bell paved the way for lightweight vector-active structures in architecture which where initially designed to fly. In our research we seek to further integrate the tetrahedral approach into a broader system: from flying, to lightweight, to extremely heavy interlocking assemblies; bound together by an overarching principle of geometrically related parametric building blocks. We developed two methods of integration in a series of architectural projects described below: A gradual one and a dialectic one. These building systems were tested in context of extreme sites such as the confluence of rivers, a coastal cliff and an abandoned amusement park. Making the leap from research on modular systems to an architectural design proposal is challenging and certainly not fully developed in the presented papers. Nevertheless the speculation on the architectural qualities of the integrated system was seen as an important part of linking design and research.

7.1. GRADUAL INTEGRATION

As both systems are based upon geometrically similar cells this approach called for defining a spectrum of cells that start of from the initial TI and span to the initial BK by inventing new cells along the way. This resulted in a system with around 6 - 10 Types of different weight, solidity, transparency, material and performance. By doing so this required also to assure valid interfaces between all possibly neighbouring cell types expanding the repertoire beyond the pure TI interface and the BK node connection.

"Performance Fields" started with a TI made from tetrahedra that gradually lost volume through subtractive techniques. The formerly sealed system gains porosity. With a similar gradual approach the development was carried on and transferred to the vector-active skeletal system of BK Figure 5 and 6).

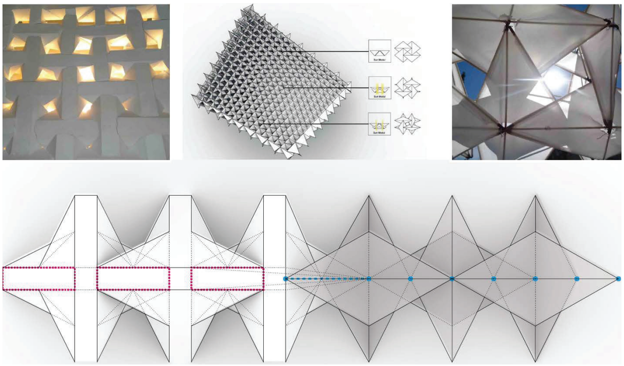

Figure 5. Performance fields by Philipp Mecke. The extreme ends of the modular spectrum are defined by cast plaster modules (top left) and skeletal kite tetrahedra (top right). Mass gradually decreases from left to right (bottom).

Figure 6. Performance field by Philipp Mecke. Densities, materials and modules types gradually change and adapt to local requirements.

Figure 7. Adaptive Geometric Integration" by Donlaporn Chanachai. Left: The confluence of Rhône and Arve serves as a site for a pier where water, heavily saturated with mineral sediments, meets the clear fluids of the Lac Lemond.

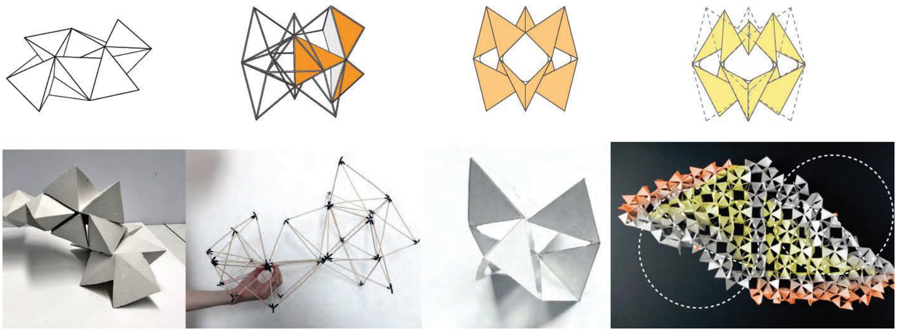

Figure 8. Adaptive Geometric Integration" by Donlaporn Chanachai. Hexagonal modules interlock with two adjacent faces (left). Vector-active and surface-active derivatives are developed for the kite and a lightweight pier structure.

The architectural implementation forms a leisure landscape that seamlessly configures the different module types based on local requirements like flatness for accessibility, cavities for soil hosting or low weight and transparency for large spanning roofs.

Located at the confluence of two rivers in Switzerland the project "Adaptive Geometric Integration" alters and relocates the Bell Kite system from air flow to the fluid flow management while the massive parts provide human access to a formerly inaccessible site (Figure 7). The TI challenges the limitation of interlocking cubes and tetrahedrons by inventing a hexagonal module with a more complex thrust-reducing interlocking behaviour (Figure 8).

Further on architectural functions and performances were mapped to different cells in the spectrum such as structural-foundation, counter weight, water container, buoyancy device, planter, structural column, sun-sail, water collector.

7.2. DIALECTIC INTEGRATION

This approach was aimed at maintaining the two systems as clearly as possible but finding ways of creating singular, linear, and spatial interfaces between them (Figure 9). This lead to solutions where a vertical structure of BK elements would join linearly into a vertical spanning structure of TI. In other instances undulating layer of BK was resting in parts on a pile of TI.

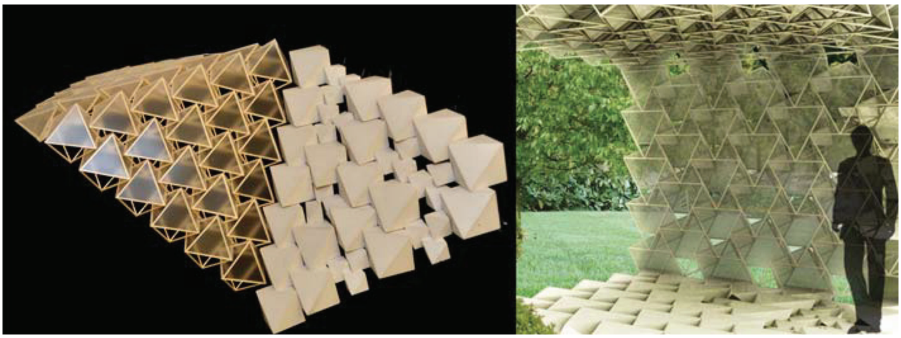

Figure 9. A recursive cube system controls porosity by differentiating element dimension. The lightweight system is clearly distinguished from the TI.

8. Conclusion

This research aimed at synthesising two very different design systems, both coming with their particular dependencies. The TI always requiring a fixed boundary condition, the BK being depended on some anchoring or counter weight. Where the boundary requirement of the TI poses a design problem on how that situation is articulated (Tessmann, 2012), the anchoring of the BK finds a perfect match in the gravity-ruled TI. In that respect the dependency of one system could be solved by the characteristics of the other, integrating them into a single system that performs beyond geometric similarities.

As the architectural community becomes more familiar in designing in systems, this research demonstrates the possibilities and potential of merging systems and thus overcoming inherent limitations while maintaining their internal dependencies.

There is also an interesting subset of further questions on different levels such as tectonics, education, and analysis, which could from the basis of further research in more detailed aspects.

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