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## TOPOLOGICAL INTERLOCKING IN ARCHITECTURAL DESIGN

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**Abstract.** The paper presents the initial results of a study that examines the potential of using the concept of topological interlocking as a structural and organizational mechanism for architecture in general, and for building façades in particular. The paper opens with a review of existing research on the notion of topological interlocking. It then presents a catalogue that characterizes the various types of topological interlocking systems and compares the potential of these types to be employed in architectural design. This is followed by a discussion regarding the results of fabrication experiments that examine the specific types, which appear to have the best potential for architectural design.

**Keywords.** Structural fragmentation, building facade, parametric design, surface tessellation, complex geometry.

### 1. Introduction

Throughout the entire history of construction, the basic structure of the building envelope has hardly changed: it has been essentially a laminated entity made of different layers that are used as a barrier. As opposed to the complex cellular structure of natural skins, traditional building envelopes are typically based on flat orthogonal geometry, repetition, limited functions and structural homogeneity. Recent trends in digital design and fabrication imply

that in the near future, the possibilities of designing and fabricating complex architectural forms will be practically unlimited, thus facilitating design that goes beyond repetitive forms. Therefore, it seems both necessary and desirable to examine new approaches to design and fabrication of building elements. These new approaches are expected to rely primarily on geometry rather than only on material properties, while aiming to achieve better building performance in various fields. The current contribution presents the results of a research that examines the potential of using the concept of topological interlocking (TI) as a structural and organizational mechanism in architecture in general and specifically in building façades. Topological interlocking is a design concept in which simple elements are arranged in a way that an entire structure is held together by kinematic constraints inflicted through the form and through the mutual arrangement of the elements (Estrin et al., 2011).

The paper opens with a review of existing research on the notion of TI. It then presents a catalogue that characterizes the various types of TI systems and compares the potential of these types to be employed in architectural design. This is followed by a discussion regarding the results of a fabrication experiments that examine the specific types, which appear to have the best potential for architectural design. The experiments focus on a special type of TI – using only convex polyhedrons. These geometry types are advantageous because they do not require any additional joints. Furthermore, they do not have any protruding parts that can be considered as joints and thus cause stress concentration.

The paper concludes with a discussion on the advantages and limitations of the suggested direction in general and of the selected types in particular, leading to a definition of research directions worth perusing in this realm.

## **2. Background**

The idea of using interlocking blocks is not new. An example of an implementation of the idea in building construction can be traced back to the ancient Inca structures. It allowed assembling stable, self-aligning structures, without any use of mortar or additional joints. Moreover, fragmented structures such as the Inca structures showed higher seismic resistance by diffusing the loads through the structure. In fact, some of them are still in good condition as of today.

A basic, rather linear use of the interlocking idea can be traced back to the 2<sup>nd</sup> century BC with the development of the arch. However, arches only create a primary structure that has to be filled with another system in order to create a real covered area.

Early renaissance has brought the idea of reciprocal structural systems, which was studied by several scientists, including Leonardo da Vinci (Figure 1). The main purpose of this type of structures was to cover large areas with structural elements that were shorter than the target span. The structures were made of wooden beams, each one leaning on two beams and supporting two other units. One of the disadvantages of these structures was the inability to sustain loads that were not acting perpendicular to the structure's plane. This is because in the absence of additional joints, the elements could displace freely along the beam's direction.

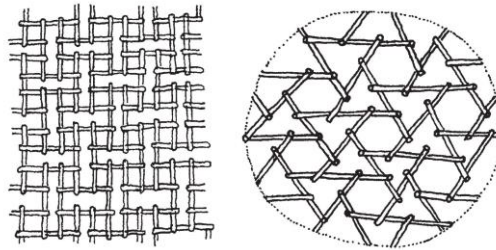


Figure 1: Reciprocal frame structures by Leonardo da Vinci (Source: Larsen, 2008)

A more complex implementation of a similar principle, which was based on volumetric elements, was invented by French architect Joseph Abeille in 1735 (Figure 2), and improved later by Sebastian Truchet (Brocato and Mondardini, 2012). The invention suggested a solution for a stone building structure that could cover space with a flat ceiling.

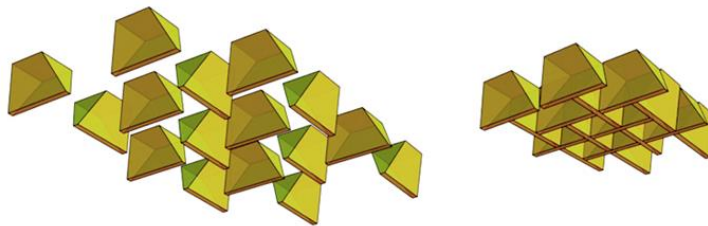


Figure 2: Abeille's flat vault based on truncated tetrahedral assembly (Source: Brocato and Mondardini, 2012)

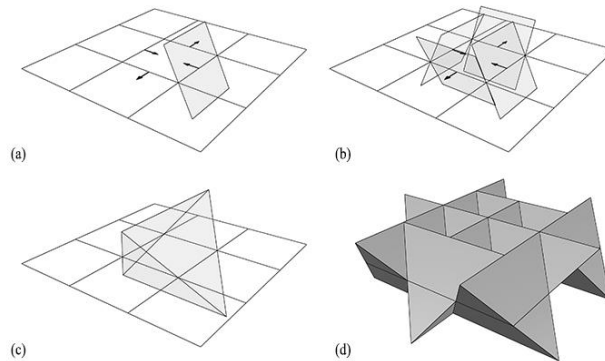
One of the main advantages of Abeille's dome was the fact that the elements' movement was locked not only in positive and negative z axis relatively to the structure's plane, but also in any direction parallel to the plane.

### 3. Parametric design of topological interlocking

Contemporary research based on interlocking tetrahedral packing can be traced to Glickman (1984), who suggested using it as an efficient paving system. A more recent development by Kanel-Belov et al (2008) proposed the following theoretical definition of "topological interlocking", which is described a set of geometric rules occurring in TI and discovered several additional types of interlocking solids:

"Interlocking is achieved if in every row of elements one can identify two sections normal to the assembly plane such that while one section ensures kinematic constraint in one direction (normal to the assembly plane), the other section provides the same elements with constraint in the opposite direction." (Kanel-Belov et al., 2008)

Estrin et al (2011) developed a method for creating TI. It consists of the following steps: Step 1 – the base plane is populated with a two-dimensional grid (orthogonal, hexagonal, etc.); Step 2 – a plane, perpendicular to the base surface, is constructed on every edge of the grid's units; Step 3 – the planes are tilted by a certain angle towards or outwards from the shape's center, alternating the direction; Step 4 – Finally, three-dimensional elements are constructed from the intersection of every set of planes (Figure 3).



*Figure 3: A Method of constructing an interlocked assembly on a square grid and tetrahedral units. a) Vertical plane and tilting directions; b) Four planes of the square cell; c) Tetrahedral cell from planes' intersection; d) Continuous layer of tetrahedral assembly*

#### 3.1. THE ADVANTAGES OF EMPLOYING TOPOLOGICAL INTERLOCKING IN ARCHITECTURAL DESIGN

While maintaining a relative formal simplicity, topological interlocking systems have several potential advantages in comparison to other structural systems. Fragmented systems can easily facilitate the combination of elements that are made from different materials, while adjusting the performance of

the structure to different engineering and architectural needs. Another important attribute of TI systems is their inherent vibration attenuation mechanism that can be advantageous in the design of seismic-resistant structures (Yong, 2011). Certain types of interlocking assemblies showed the ability to tolerate the removal of blocks (Estrin et al., 2011), thus allowing to replace destructed elements without deconstructing the whole structure.

From the perspective of efficient construction, the possibility to maximize the amount of prefabricated elements can offer a decrease in construction time. Moreover, straightforward disassembly of TI systems makes them attractive for temporary buildings.

### 3.2. DEVELOPING A TOPOLOGICAL INTERLOCKING CATALOGUE

The initial stage of the research concentrates on developing a catalogue of TI convex shapes, based on the two-dimensional grid. A parametric geometric algorithm was developed based on the design steps described previously. The algorithm allows generating a TI system from any set of closed curves. As opposed to an earlier approach suggested by Tessmann (2013) that focused on the transformation of known polyhedral assemblies, the suggested approach uses two-dimensional tessellations as a platform for discovering new interlocking blocks.

The results are classified according to the mid-plane grid's geometry and divided into three main groups which consist of regular tessellations, semi-regular tessellations and non-regular tessellations (Pearce, 1980). Triangular tessellations were not examined because it was understood that only shapes with four edges or more could be used for constructing an interlocking assembly. The second regular tessellation, rectangular grid, has a potential to support TI. It can be populated only with tetrahedral units for assembling interlocking structure. The second possible regular grid, which is based on hexagons, allows using several convex polyhedral for achieving TI system (See example in Figure 4).

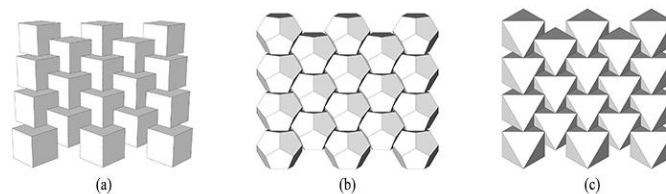


Figure 4: Interlocking assemblies based on a hexagonal grid. a) cubes; b) dodecahedra; c) octahedral (Source: Kanel-Belov et al., 2008)

Out of seven known semi-regular tessellations we found three types that were appropriate for constructing interlocking assemblies. Unlike TI assemblies introduced previously that were built using a single repetitive cell, we examined TI assemblies that employ two or three different tetrahedra (Figure 5).

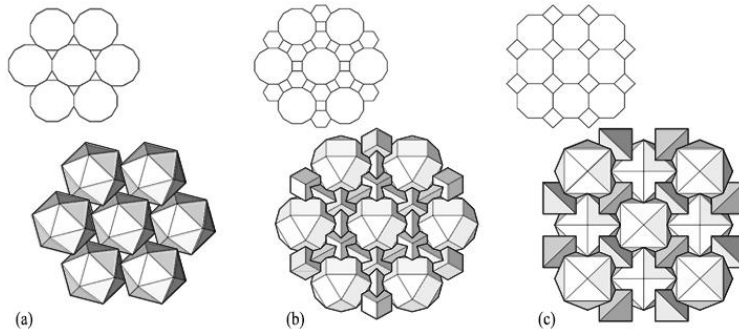


Figure 5: Semi-regular tessellations and corresponding topological interlocking structures – a)  $3.12^2$ ; b)  $4.6.12$ ; c)  $4.8^2$ .

Another examined direction employed non-regular surface tessellations, which were mostly built with distorted simple geometries, such as tetrahedra or cubes. The distortion was necessary in order to match the mid-plane grid. The distortion grants different structural properties to the same topologies – increased amount of neighbor units at a vertex, larger overlapping area between two units, etc. (see Figure 6).

Since there are an infinite number of non-regular tessellations it is clear that there are numerous additional TI assemblies based on non-regular tessellations yet to be discovered.

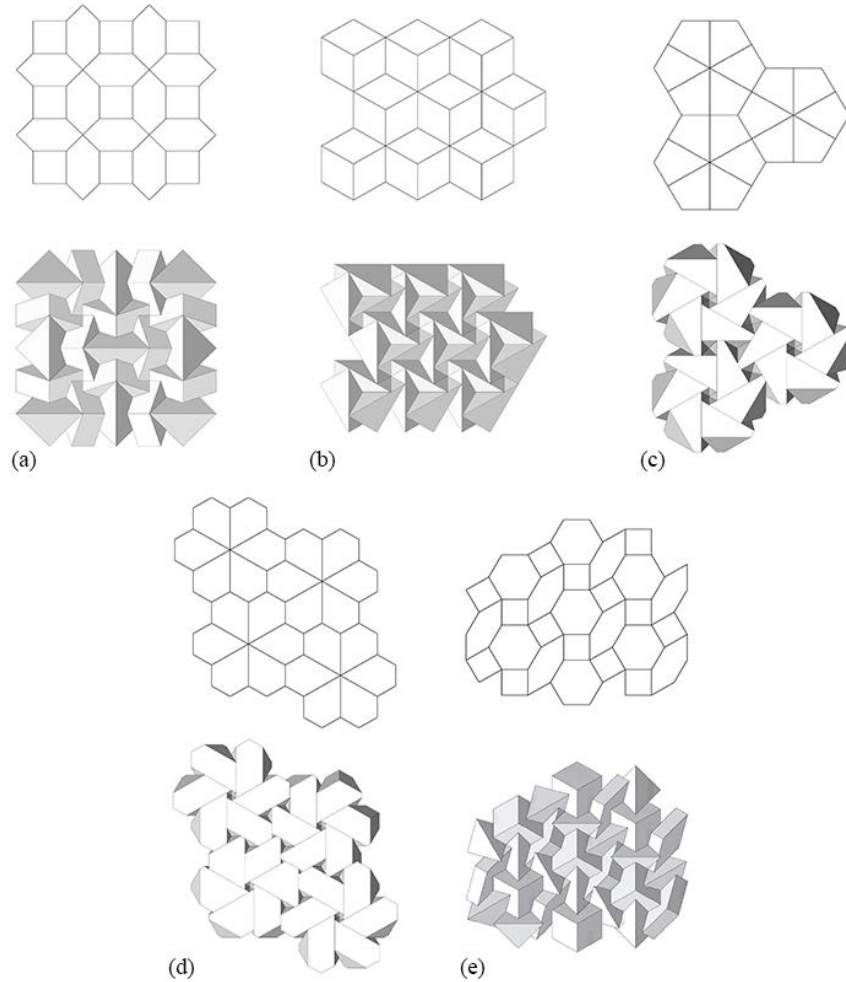


Figure 6: Non-regular tessellations (Grunbaum and Shephard, 1986) and corresponding discovered topological interlocking structures – a)  $4.6^2, 6^4$ ; b)  $3.6.3.6$ ; c)  $3.4.6.4$ ; d)  $3^4.6$ ; e)  $4.6.4.6, 4.6^2$

Interestingly, in one of our examinations we studied a mid-plane grid TI type that was suggested by Kanel-Belov et al (2008). It is based on rotated decagons, with partial edges' overlapping (Figure 7a). We noticed that there are only three consecutive faces tilted in one direction and three other faces tilted in the opposite direction. Therefore, the assembly seems to be unstable as a structural system. A 3-D printed model of a single unit with its borders confirmed our concern that the unit can be easily removed from the structure by tilting it around the center, which makes it unstable as a TI system (Figure 7b).

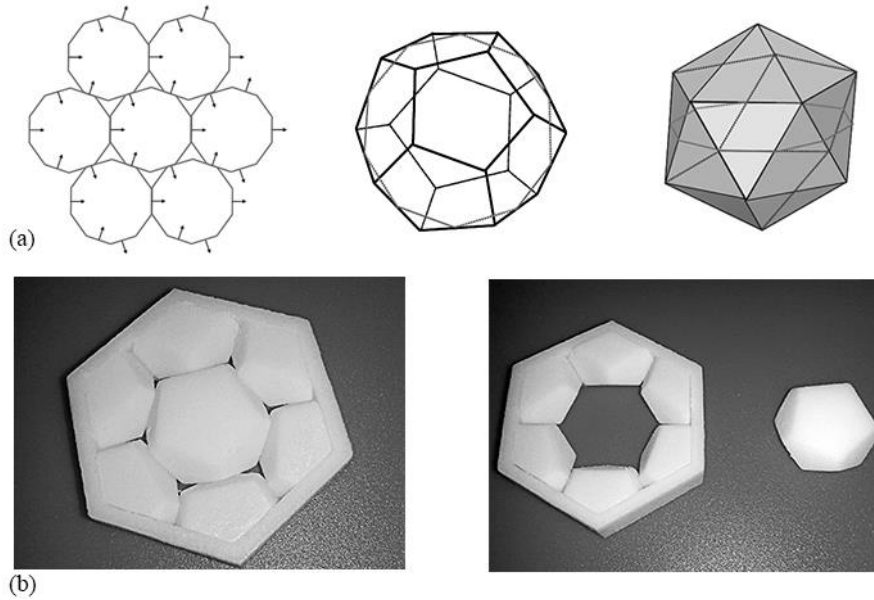


Figure 7: a) decagonal tiling, dodecahedron and icosahedron as structural units, b) 3d-printed prototype of dodecahedron block.

### 3.3. COMPLEX GEOMETRY AND TOPOLOGICAL INTERLOCKING

There has been a significant increase in the amount of complex, curvilinear shapes used in architectural design since the end of the 1990's. This increase is clearly explained by the recent development of computer design and fabrication software tools and machines that can handle complex geometry. However, contemporary complex geometry-based design still often needs to be simplified and rationalized before the geometry can actually be built. The cellular nature of TI seems to have a potential to be used as a mechanism for simplifying and rationalizing complex geometries.

Therefore, the following part of the research focused on testing the ability of the previously discussed TI systems to be assembled as curvilinear shapes. In order to populate complex surfaces, a new step was introduced into the generation algorithm that included projection of an initial planar tessellation on to the selected curved surface before building the structure's blocks. Thus in the next steps each unit's geometry was built according to the curvature of the base surface (Figure 8).



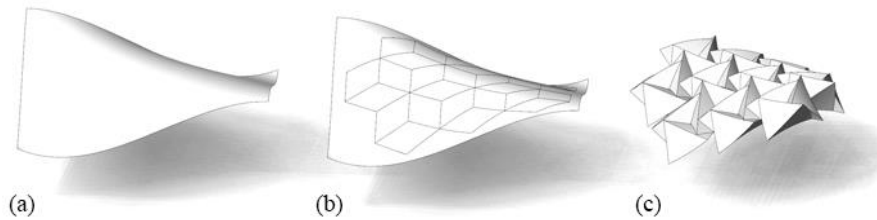


Figure 8. Curvilinear surface modelling with interlocking blocks: a) base surface; b) topological interlocking base tessellation on the surface; c) assembly units based on the tessellation.

In order to validate the process several physical models of TI types were 3D printed (Figure 9). Due to schedule constraints the structures were printed already assembled, having all the blocks in their final arrangement. In order to maintain the properties of TI systems the prototypes still had to be made of separate blocks. Leaving a 0.2 mm gap between all the elements allowed printing the whole model at once as a fragmented entity and not one solid body. Printed models showed structural stability and proved that the designed CAD model could be successfully transferred to a physical model.

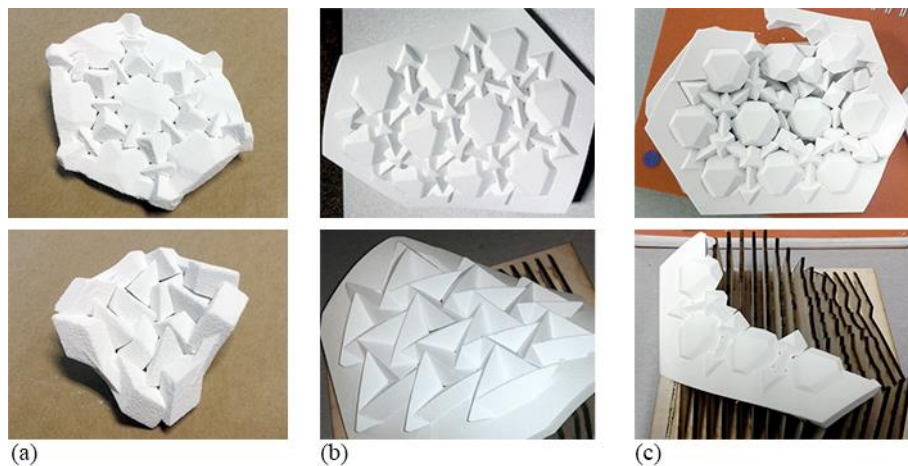


Figure 9. 3d printed plaster models: a) 70\*70 mm models with a slight curvature; b) 135\*190 mm models with a stronger surface bending; c) Frame failure and further reassembling of the structure.

In case that the blocks are fabricated as separate pieces, structure's assembling has to be done in a certain order. Figure 10 shows the logic of TI assembling - starting from the structural frame the blocks are added in one direction layer by layer. In the end all the elements are locked together by adding the second fragment of the frame.

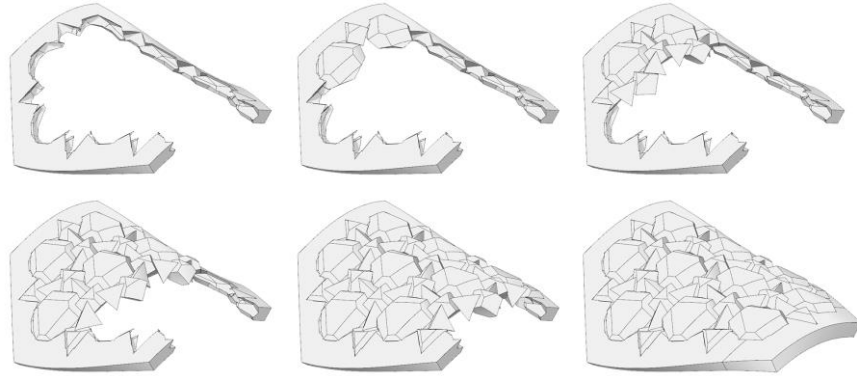


Figure 10. Topological interlocking structure's assembling sequence (left to right).

#### 4. Conclusions

The paper presents a methodology for exploring geometries that can be used for assembling topological interlocking systems on 2D planar surfaces and complex curved surfaces. Some of the presented examples were examined in physical models in order to test their affordance of being implemented in architectural structures. It also displays and discusses the potential of implementing TI systems for non-repetitive parametric structures and presents a variety of possible assemblies. The paper shows that in the case of topological interlocking systems, there is a direct connection between the geometry and the structural performance of the system. This fact calls for implementing parametric design tools not only for form-based design, but also for geometry optimisation in terms of performance. Although this requires a detailed study of the relation between the blocks' geometry and the structural properties, the design of interlocking systems could rely on additional data – for example, areas of stress concentration as observed in computer simulation of the structural response of the desired surface.

Further research steps will focus on testing the structural properties of physical models and on developing finite element models for structural simulation of complex TI assemblies. It will allow optimizing the formal and material properties of the various blocks that creates the systems and will allow to study the potential of employing TI systems for horizontal surfaces in architecture.

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