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Topological interlocking in buildings: A case for the design and construction of floors

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ABSTRACT

The paper presents the results of a study that examines the potential of using the concept of topological interlocking as a structural and organizational mechanism for buildings. 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 buildings. This is followed by the results of an examination on the potential to use topological interlocking for the construction of building floors.

1. Introduction

The paper 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. 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 [3].

The presented research derives from the understanding that recent technological developments in digital design and fabrication seem to dissolve the limits in designing and fabricating complex architectural forms [9]. It thus facilitates design that goes beyond the traditional repetitive forms. Therefore, it seems that it is now possible to examine new approaches to the design and fabrication of building elements, such as TI, that rely primarily on geometry rather than only on material properties, while aiming to achieve better performance in various criteria such as seismic resistant and fabrication time.

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 on the potential to use TI for the construction of various building elements. The next section presents a two scale (entire floor and individual tile) structural optimization process of a floor that is based on TI. The large scale concentrate on structural analysis of an entire floor and the small scale focus on topological optimization process of a single tile.

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

2. Topological interlocking in research and practise

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. 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 reciprocal frame structures in various culture in the east and west [12]. In masonry structures it can be traced back to the 2nd century BC with the development of the arch. However, reciprocal frames and arches only create a primary structure that has to be filled with another system in order to create a roofed area.

Early renaissance has brought the idea of reciprocal structural systems, which was studied by several scientists, including Leonardo da Vinci [12]. 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

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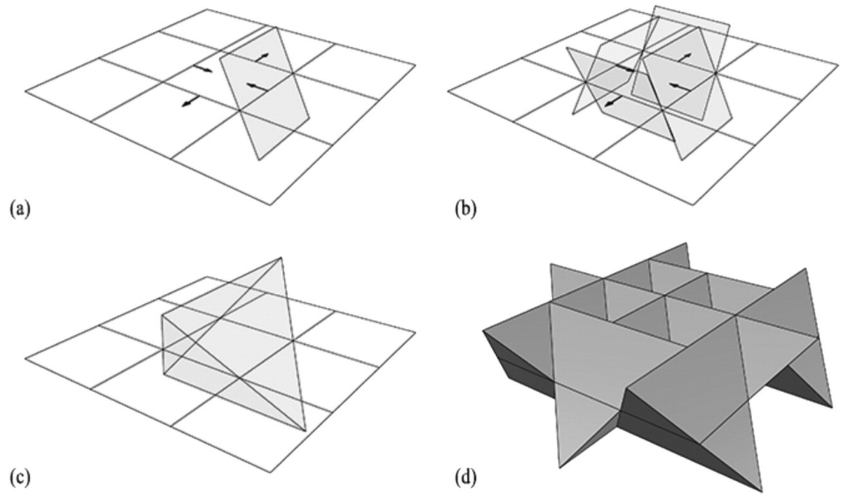

Fig. 1. A method of constructing an interlocked assembly on a square grid and tetrahedral units: a) vertical plane and tilting directions; b) four planes of the square cell; c) tetrahedral cell from planes' intersection; d) continuous layer of tetrahedral assembly.

perpendicular to the structure's plane. The absence of additional joints allowed the elements to displace freely along the beam's direction.

A more complex implementation of a similar principle, which was based on volumetric elements, was invented by French architect Joseph Abeille in the 17th century [2]. The invention suggested a solution for a stone building structure that could cover space with a flat ceiling.

One of the main advantages of Abeille's structure 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. Abeille's structural idea, which was named stereotomy, has been followed by numerous architects and was part of the teaching programme in art schools such as Ecole du Génie du Mézières (18th century) and the Ecole des Beaux-Arts (19th century) [6].

Topological interlocking and stereotomy are similar terms. The main difference between the terms seems to be that the idea of stereotomy focuses on the exploration of stone walls and curved or dome like structures, while topological interlocking refers to a more general geometrical and structural concept of structure, which is made with interlocking elements without defining the material or the potential use. A more recent development by Kanel-Belov et al. [11] proposed the following theoretical definition of "topological interlocking"; It 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." [11]

An interesting review on stereotomic design, which focuses on the design and fabrication of wall and domed/curved ceilings can be found in a recent book by Fallacara and Minenna [4]. Another research, which was not included in the book and aims to create a commercial wall based on stereotomic design, can be found in Brocato et al. [1]. It suggests a new type of prefabricated stone wall in wooden frame, which is inspired by Aberille's 17th century assembly.

Contemporary research based on interlocking tetrahedral packing can be traced to Glickman [7], who suggested using it as an efficient paving system. Feng et al. examined the impact mechanics of topologically interlocked material assemblies [5].

Estrin et al. [3] 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 (Fig. 1).

Although there is a considerable amount of research on TI/stereotomic based elements for building walls and domes, the literature review did not find research that focused on the implementation of the idea of TI for building floors. This can perhaps be explained by the difficulty to design and simulate the behaviour of these complex tile arrangements. This research will, therefore, focus on bridging this gap examining the potential of developing TI based systems for building floors.

3. The potential and limitations of employing topological interlocking in architectural design

Employing topological interlocking based structures has potentially several advantages in comparison to traditional construction (Fig. 2):

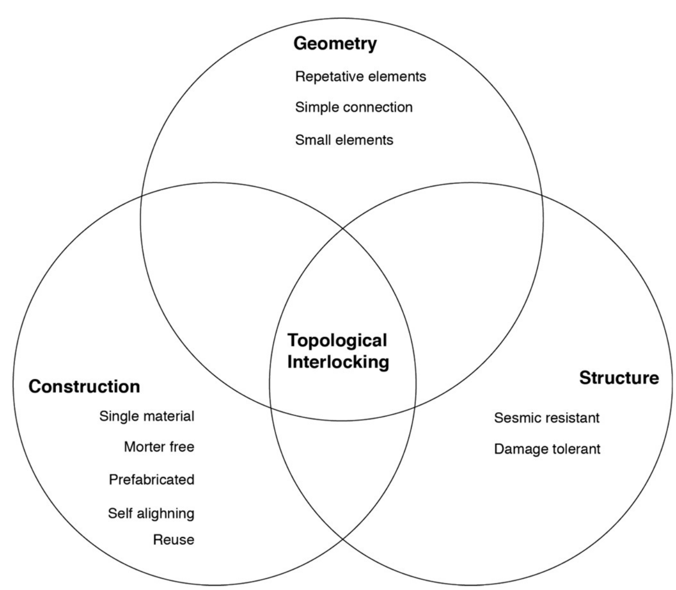

Fig. 2. possible advantages of employing topological interlocking in building construction.