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Topological interlocking as a material design concept

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ABSTRACT

We review the concept of topological interlocking of identical elements in single-layer structures on which we have been working over the last decade and outline its advantages over monolithic structures. Multi-layers involving topological interlocking are also introduced and their unusual properties are discussed. In a broader sense interlocking also occurs in living organisms, and a connection of our artificial, geometry-inspired design to some recent observations of interlocking in nature is made.

1. Introduction

Structures occurring in living organisms are never monolithic. Segmentation into constituents of various shapes and morphologies provides them with a high degree of flexibility and responsiveness, as well as amazing multifuctionality. By contrast, engineering structures are usually monolithic and are designed to fulfil a particular function, often just load bearing. It is only recently that the benefits of segmentation, or fragmentation, as an engineering design principle started gaining popularity with the material engineering community [1]. A potent tool for developing fragmented materials and structures in which the elements are held together without any binder or connectors is topological interlocking — a design concept we have been proposing over the last decade. In this article we present the salient aspects of this concept and outline some new possibilities it offers.

Topological interlocking [4,6–14,17,21] is a design principle by which elements (blocks) of special shape are arranged in such a way that the whole structure can be held together by a global peripheral constraint, while locally the elements are kept in place by kinematic constrains imposed through the shape and mutual arrangement of the elements. What distinguishes *topological* interlocking from the conventional interlocking used for instance in the construction industry is the avoidance of keys or connectors, which would require high-precision machining and which can act as stress concentrators reducing the overall strength of the structure. In essence, the topological interlocking is a way to combine the flexibility and tolerance to local failures offered by fragmentation of a material with its overall structural integrity.

The fragmented nature of the topological interlocking structures and materials has a number of advantages. Firstly, it is the possibility to combine elements made from different materials, including dissimilar ones, which is important in creating hybrid materials. (A hybrid material is 'a combination of two or more materials in a predetermined geometry and scale, optimally serving a specific engineering purpose', [1].) Secondly, fragmentation may offer some advantages in terms of strength and structural stability. This can be accomplished by capitalising on the negative scale effect. Indeed, normally strength drops with increasing size of a structural member made from a brittle material due to a higher probability that it contains a critical defect giving rise to failure. The interlocking principle makes it possible to assemble a structure from small blocks, thus providing it with a higher strength. Furthermore, arresting of a crack emerging within a block at its interfaces with the adjacent blocks tends to confine failure [5]. Enhanced structural stability stems from the ability of some interlocking structures to hold when a certain percentage of its elements fail at random or are missing by design, [20]). This percentage can be as high as about 25% [24], as long as the blocks fail at or are removed from random locations. Enhanced stability also derives from the ability of fragments to undergo small movements within the structure (within the limitations of the kinematic constraint imposed by interlocking) thus avoiding failure under high amplitude vibrations and dissipating vibrational energy in

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the process. This effect is well known in civil engineering providing evidence of stability of mortarless structures in seismically active regions, most remarkable being the segmented load-bearing columns, such as e.g. those in the Temple of Zeus erected circa 330 BC (e.g. [22]).

The ability of the elements of interlocking structures to undergo limited displacements and even rotations can produce some unusual mechanical response, such as negative stiffness in indentation loading of interlocking structures of cubes [15,26]. This is a structural property of the assembly of interlocked blocks rather than the property of the material the blocks are made from. Neither is the negative stiffness associated with damage nor is it a result of failure (opposite to mechanisms of post-peak softening in brittle materials as rock or concrete, e.g. [3]), nor does it stem from buckling. This paper overviews the types of interlocking structures discovered so far and considers a possible use of the structural negative stiffness.

2. Topological interlocking structures

2.1. Interlocking of polyhedral elements

Historically, the first interlocking assembly of convex polyhedral elements *viz.* tetrahedra, was proposed by Glickman [18] in a quest for developing a new paving system. Without the knowledge of Glickman's work, the same plate-like assembly of interlocked tetrahedra was proposed by Dyskin et al. [4] based on a simple idea: 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, Fig. 1. This design principle was later used to develop the so-called osteomorphic interlocking blocks.

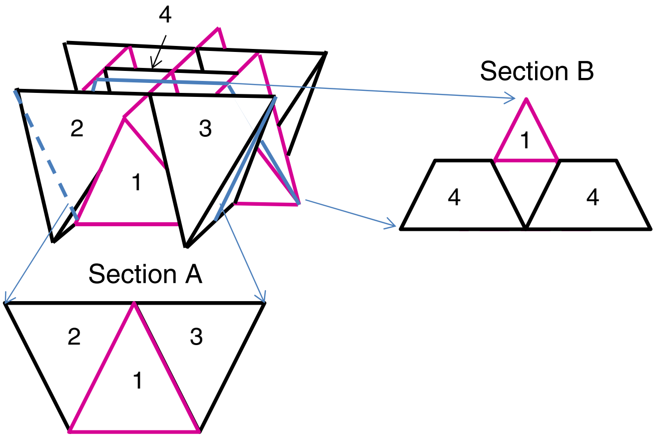

Fig. 1. Topological interlocking: design based on vertical sections through an assembly of tetrahedra. In section A, the upward movement of block 1 is prevented by blocks 2 and 3, while in section B the downward movement of block 1 is prevented by blocks 4.

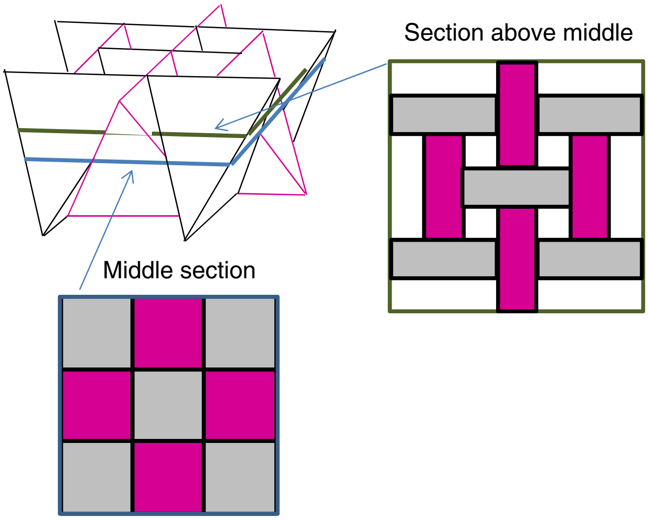

Fig. 2. Topological interlocking: geometrical construction based on displacement of the middle section. The upward constraint is provided by the section above the middle one, which leaves insufficient room for moving blocks upwards. If the section moves further up the corresponding rectangles will eventually degenerate to straight segments. Due to symmetry, similar considerations prove the existence of interlocking with respect to downward displacements.

A more general design principle is based on considering the evolution of a cross-section through a layer-like array of interlocked tetrahedra as it moves away from the middle section through the layer. In simple terms this principle of building up an interlocked structure upwards and downwards starting-off from the middle plane can be illustrated by Fig. 2, which shows the transformation of the tiling in the middle section of an assembly of interlocked elements when the section is moved parallel to the middle one. The figure demonstrates that for the case when interlocking exists, the middle section of an element cannot fit into the 'window' formed by the sections of its neighbours in a plane parallel to the middle one. A criterion for interlocking of convex polyhedra was given in Dyskin et al. [9] by considering the polygons formed by the intersections of the extensions of an element faces constrained by the element's neighbours with a section plane parallel to the layer. The condition for interlocking can be worded as follows: An element is locked within the layer if, and only if, by continuously shifting the section plane in either direction with respect to the middle plane the polygon representing its cross-section in the plane of the cut eventually degenerates to a straight segment or a point. It is assumed that the contacts between the solids are maintained in sections above or below the middle one (at least in a small vicinity of the middle section). This excludes for instance assemblies of periodically arranged spheres, which are not interlocking.

We illustrate the implementation of this principle by showing how the interlocking assemblies of cubes or octahedra can be constructed, Fig. 3. We cover the plane with hexagons, add walls to turn them into hexagonal prisms and then incline the walls in an alternating manner, as indicated by arrows in Fig. 3. This by itself will ensure interlocking. Furthermore, being extended to meet each other these inclined walls will form, depending on the inclination angles, either cubes or octahedra.

Using this principle, interlocking arrangements were constructed for the remaining platonic bodies (dodecahedra and icosahedra, Dyskin et al. [9]) and for buckyballs [7]. A rigorous mathematical formulation of the principles guiding rational design of topologically interlockable elements was presented in Kanel-Belov et al. [19].

Strictly speaking, one does not need to engage the whole faces of the blocks to ensure interlocking; therefore new shapes can easily be generated through transformation of structures based on blocks shaped as platonic bodies, Dyskin et al. [6]. Fig. 4 shows the octagonal middle sections as well as a result of ultimate transformation of tetrahedra by transforming the 2D shape of their middle sections by doubling their side/apex number. Ultimately, as a limit case, the squares in the middle section turn into circles. Fig. 5 shows the result of this transformation for a specific embodiment of the transformed tetrahedra as hollow tubular interlocking elements [16].

2.2. Interlocking elements with curved surfaces

The principle of generating topologically interlocking structures based on considering sections normal to the assembly plane, Dyskin et al. [4], can be extended using a continuous transformation of a section as it moves through the assembly, as exemplified by Fig. 6.