Tavoosi Gazkoh *et al. Int J Concr Struct Mater* (2024) 18:91
https://doi.org/10.1186/s40069-024-00735-3

International Journal of Concrete Structures and Materials

REVIEW **Open Access**

Advancing Topological Interlocking Structures: Recent Developments, Applications, and Challenges in Civil Engineering

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Abstract

Topological interlocking structures have garnered significant attention for their distinctive properties, including robust resistance to crack propagation, outstanding energy absorption, adaptable flexibility, high resistance to missing elements and easy assembly and disassembly. Moreover, integrating various materials into a single structure enables versatile design possibilities. This paper comprehensively reviews recent research on topological interlocking elements and structures, encompassing element designs, manufacturing techniques and engineering applications. Furthermore, it explores the performance of topological interlocking structures, covering aspects such as fracture resistance, structural integrity, bending flexibility, ease of assembly and disassembly and energy absorption. While topological interlocking elements offer various benefits, challenges remain in their broader implementation, particularly as structural members in civil engineering structures. This paper engages in a critical discussion of existing research gaps and outlines directions for future research.

Keywords Topological interlocking, Bending flexibility, Fracture resistance, Structural integrity, Energy absorption

1 Introduction

Over the last few decades, there have been significant advancements in construction technologies (Dyskin et al., 2012; Xu et al., 2020). In the pursuit of a high-performance structure, optimising the geometries of both the structure and its components emerges as one of the most effective approaches (Autruffe et al., 2007). It facilitates the creation of structural elements with unconventional shapes, empowering structures to achieve superior performance and functionality (Xu et al., 2020). Topological interlocking is a powerful geometric design approach that involves arranging specially shaped elements to form structures held together by a global peripheral constraint. Topologically interlocked elements are typically derived by fragmenting materials and structures. In contrast to conventional interlocking techniques commonly used in the construction industry, the topological interlocking technique secures the elements locally through kinematic constraints imposed by their shape and arrangement (Dyskin et al., 2012). As a result, it eliminates the need for binders or connectors, which could otherwise weaken the structure by creating stress concentration points and require precise machining (Estrin et al., 2011). The concept of topological interlocking design has found potential applications across a wide spectrum of engineering domains. These include the construction of diverse structures such as wells, columns and corners (Dyskin et al., 2012), road pavement projects (Dyskin et al., 2012; Xu et al., 2020) and building floors (Piekarski, 2020; Weizmann et al., 2016, 2017, 2019). Furthermore, its potential has been demonstrated in the creation of vault structures (Fallacara et al., 2019; Lecci et al., 2021), as

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Journal information: ISSN 1976-0485 / eISSN 2234-1315.

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well as cylindrical structures like tunnels (Xu et al., 2020). Beyond that, topologically interlocked systems can be employed to safeguard coastal structures and buildings in seismic zones (Estrin et al., 2021). In addition, materials designed with topologically interlocking exhibit an exceptionally high sound absorption capability, making them applicable for sound insulation solutions in both industrial and residential contexts (Estrin et al., 2021).

In 1975, Robson (1978) introduced the concept of utilising shapes and relative positions of elements to ensure secure placement, involving the use of interlocking blocks with concavo-convex surfaces to achieve this objective. Later, Glickman (1984) developed a paving system using interlocking convex polyhedral elements, specifically tetrahedra. Plate-like assembly formed by the same interlocked tetrahedra elements was suggested by Dyskin et al. 2001a, (Estrin et al., 2011), and they demonstrated the feasibility of constructing monolayer assemblies by employing interlocking blocks shaped as any of the five Platonic solids, including tetrahedron, octahedron, cube, dodecahedron and icosahedron (Dyskin et al., 2003a, 2019). In 2003, Dyskin et al. (2003b) developed the so-called osteomorphic brick, which featured two curved side surfaces, leading to the first mortar-free structures built from specially engineered interlocking bricks. Recently, Rezaee Javan et al. (2017, 2018) proposed a different design of interlocking brick, in which all four side surfaces were interlocked. Xu et al. (2020) developed a new interlocking element with symmetrical geometry, including curved upper and lower surfaces and six curved side surfaces. This element was designed to assemble cylindrical structures, addressing challenges posed by non-planar surfaces in engineering applications (Ermolai et al., 2022). In addition, inspired by the 'scutoid' (Javan et al., 2018) that emerges in epithelial (animal skin) cells , Subramanian et al. (Subramanian et al., 2019) introduced a building block known as Delaunay Lofts, which can be mass-produced and lead to a space-filling packing. A space-filling shape is a form whose duplicates, when combined, can completely occupy space in a watertight manner, meaning there are no gaps between them. Consequently, a space-filling shape has the capability to create a tessellation of space (Estrin et al., 2021; Subramanian et al., 2019). More recently, inspired by Voronoi tessellation, Ebert et al. (2023) introduced a novel method employing symmetrically arranged Voronoi sites to generate corrugated blocks that fill space, resembling noodle-like structures.

The topological interlocking is a highly promising design approach that enables the development of innovative solutions that outperform traditional designs in terms of overall effectiveness and robustness. The topological interlocking design involves two key components: (1) the design of appropriate shapes for fragments and (2) the arrangement of fragments to achieve target configurations (Dyskin et al., 2001b). To date, the concept of topological interlocking design has demonstrated significant success in creating novel materials and structures (Chao et al., 2023; Djumas et al., 2016; Estrin et al., 2021; Feldfogel et al., 2024; Gao & Kiendl, 2019; Molotnikov et al., 2013; Wang et al., 2019; Weizmann et al., 2016, 2021) which exhibit exceptional attributes, including excellent resistance to impact, high capacity for energy absorption, resistance to local failure and crack prevention (Dyskin et al., 2012; Krause et al., 2012). Moreover, topological interlocking structures facilitate the seamless integration of diverse materials within a single interconnected framework, enabling the creation of multifunctional hybrid structures that leverage the unique advantages of each material (Ashby & Bréchet, 2003; Estrin et al., 2011). In addition, topological interlocking structures offer the benefit of easy assembly and disassembly, streamlining construction processes for greater efficiency (Dyskin et al., 2012; Estrin et al., 2021). Their self-adjusting ability and identical shape also provide efficient and cost-effective construction solutions (Weizmann et al., 2016).

The rapid evolution of topological interlocking design and its diverse applications underscore the need for a thorough examination of existing studies to consolidate knowledge, highlight advancements and identify gaps. Estrin et al. (Estrin et al., 2021) provided an overview of advancements in topological interlocking elements. However, the latest research findings and developments in the field were not incorporated. Furthermore, emerging challenges in topological interlocking structures require thorough analysis and discussion to understand their underlying causes and explore potential solutions. Existing research lacks the depth needed to effectively address these challenges, particularly in civil engineering applications. This paper aims to offer a comprehensive review of different types of topological interlocking elements, covering their distinctive characteristics, potential applications and the corresponding structural performance. In Sect. 2, various types of interlocking elements are discussed in detail, including their design and manufacturing methods, and engineering applications. Section 3 presents the characteristics and performance of interlocking assembly structures, emphasising their fracture resistance, structural integrity, bending flexibility, energy absorption capacity and streamlined fabrication and repair process. The advantages of topological interlocking design as well as the current research limitations are discussed in Sect. 4. Finally, Sect. 5 provides a summary of the discussed features and challenges associated with the utilisation of topological interlocking elements in structures.

2 Types of Topological Interlocking Elements

The topological interlocking elements can be broadly categorised into two main types: One involves the interlocking of regular polyhedral or platonic elements, while the other encompasses interlocking elements with curved surfaces (Estrin et al., 2011). This section begins by examining the interlocking of polyhedral elements, spanning from tetrahedra to truncated platonic bodies. The exploration is then extended to interlocking elements with curved interfaces, introducing concepts such as the osteomorphic brick, topological interlocking brick with four curved interfaces, space-filling blocks generated by the concept of Voronoi partitions and non-planar topological interlocking bricks. Furthermore, the optimisation, manufacturing techniques and potential applications of topological interlocking elements are discussed.

2.1 Interlocking Polyhedral Elements

Dyskin et al. (2001a) pioneered the use of tetrahedron-shaped elements to form an interlocking assembly monolayer, as shown in Fig. 1a. In this structure, interlocking occurred when each row of elements was divided into two sections perpendicular to the assembly plane. One section guaranteed kinematic constraint in one direction (normal to the assembly plane), while the other section imposed a constraint in the opposite direction on the same elements. For example, in Fig. 1a, each tetrahedron in this assembly has one of its second-order symmetry axes perpendicular to the layer and is in contact with four neighbouring elements. In the reference tetrahedron, labelled as R in Fig. 1a, the obstructive elements (neighbours 1 and 3) prevent upward movement, while impediment elements (neighbours 2 and 4) hinder downward shifts. Fig. 1b illustrates the middle section of this assembly, with arrows indicating the directions of movement for the sides of the reference tetrahedron and its adjacent neighbours when the section plane shifts upwards. The arrows denote the inclinations of the faces of neighbouring tetrahedra, with inward arrows blocking upward displacements and outward arrows blocking downward displacements, ensuring interlocking through alternating inclinations of the faces (Dyskin et al., 2003c).

To explore the geometric potential of such assemblies in designing innovative structures and materials, five different platonic solids, i.e. tetrahedron, cube, octahedron, dodecahedron and icosahedron, were investigated (Dyskin et al., 2003a) (Fig. 2a–e). In addition, interlocking assembly could also be achieved using truncated platonic bodies, such as buckyballs, truncated tetrahedra and truncated octahedra (Dyskin et al., 2003c; Mirkhalaf et al., 2018) (Fig. 2f and g). In all these cases, interlocking was realised using a reduced inclined contact area between the elements, leading to a decrease in the load-bearing capacity of the assemblies.

In 2D structures, the presence of discontinuities would result in the formation of key elements, which can be removed without kinematic constraints. To achieve the interlocking of platonic-shaped elements, the key elements were first identified in Dyskin et al.'s study (Dyskin et al., 2003a), inspired by the key block theory (Goodman & Shi, 1985) widely utilised in rock mechanics and mining engineering. Once the key elements were securely positioned, the remaining non-key elements became immobilised due to their kinematic constraints (Fig. 3a)

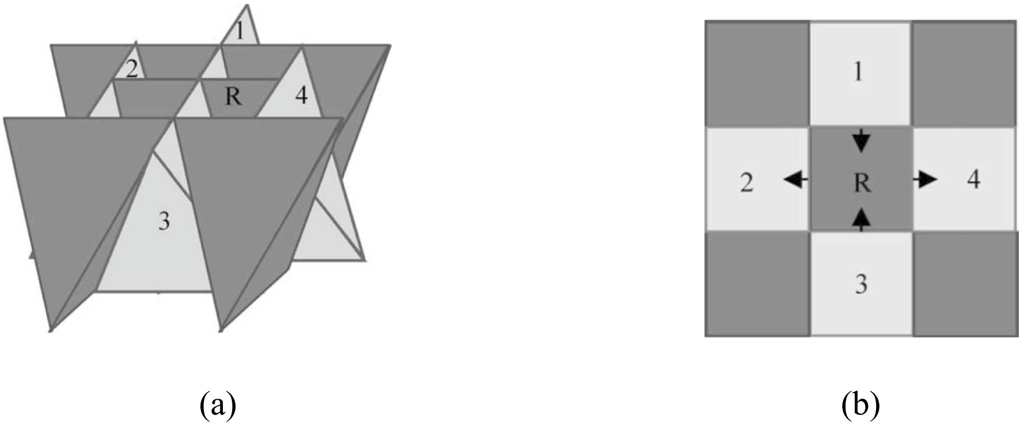
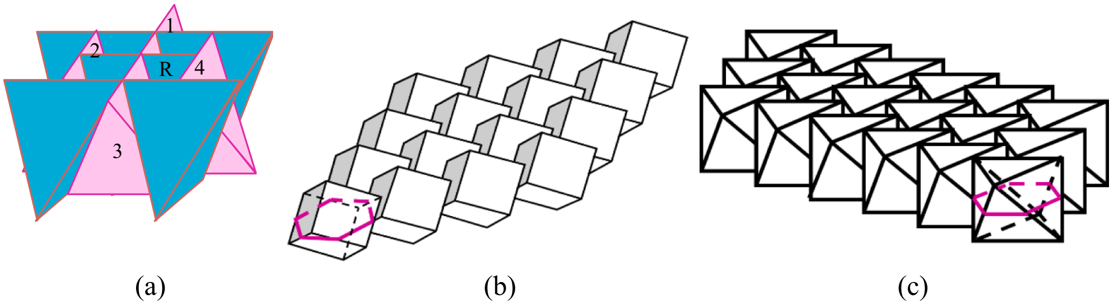


Fig. 1 The concept of interlocking tetrahedral elements (Dyskin et al., 2003c): **a** A segment of an interlocking assembly, and **b** the middle section of the segment



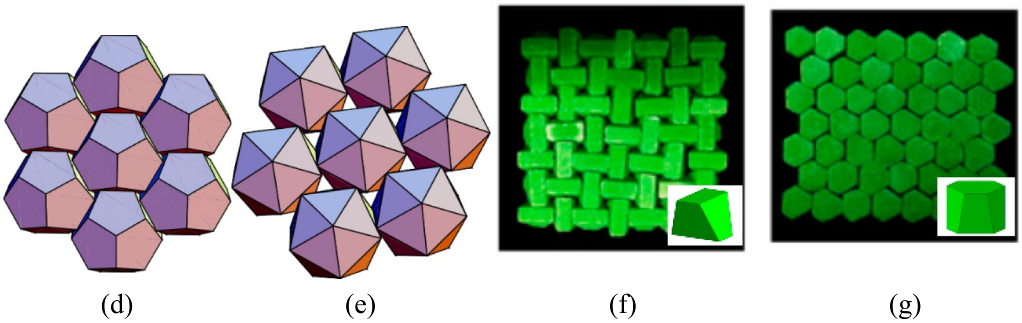


Fig. 2 Interlocking of polyhedral elements: **a** Tetrahedra (Dyskin et al., 2003a, 2019), **b** cube (Dyskin et al., 2003a, 2019), **c** octahedra (Dyskin et al., 2003a, 2019), **d** dodecahedra (Dyskin et al., 2003a, 2019), **e** icosahedra (Dyskin et al., 2003a, 2019), **f** truncated tetrahedra (Mirkhalaf et al., 2018) and **g** truncated octahedra (Mirkhalaf et al., 2018)

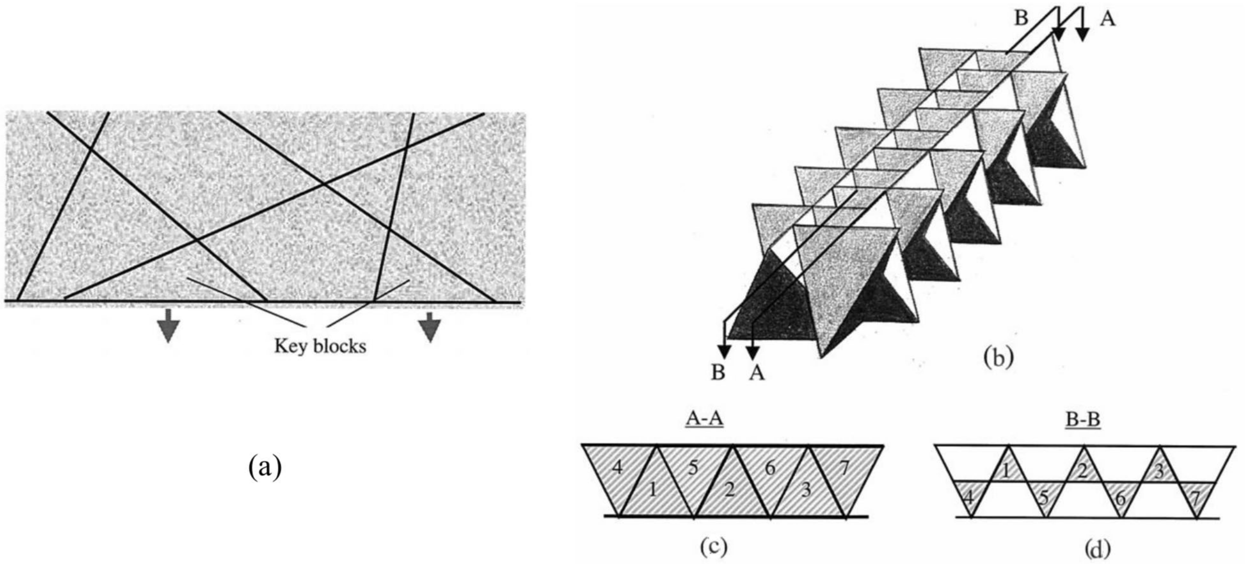


Fig. 3 Principle of interlocking elements in 2D and 3D structures (Dyskin et al., 2001a): **a** Schematic illustration of key block concept (2D)—only key blocks can move freely in the direction shown by the arrows, **b** general view of self-locking assembly of tetrahedrons (3D), **c** cross-section A-A (all numbered elements are key blocks) and **d** cross-section B-B (all numbered elements are non-key blocks)

(Dyskin et al., 2001a, 2001b). However, 3D structures might not necessarily have key elements due to specific element shapes and arrangements, enabling self-locking assemblies in 3D (Dyskin et al., 2001a). Fig. 3b–d show an example of self-locking assembly of identical tetrahedrons. A general design process for creating interlocked polyhedral elements was introduced by Estrin et al. 2011, (Weizmann et al., 2016), consisting of the following steps.

A base 2D grid plane (e.g. orthogonal and hexagonal) was initially populated, followed by the construction of a perpendicular plane at each edge of the grid's units. The planes were then inclined at a specific angle either towards or outwards from the centre of the shape. This arrangement would lead to the creation of 3D elements at the intersection of each set of planes. The neighbouring elements could also be created by following the same process, leading to the formation of a layer-like structure (Weizmann et al., 2016). Fig. 4 shows the construction of a layer-like interlocked tetrahedra on a square-based grid using this method. Kanel-Belov et al. (2008) presented a precise mathematical formulation for this method, outlining the principles that govern the rational design of topological interlocking elements. As outlined by Kanel-Belov et al. (2008), a hexagon-based tiling resulted in the formation of either a cube, an octahedron or a dodecahedron, while a decagon-based tiling created either a dodecahedron or an icosahedron.

Moreover, Bejarano et al. (2019) developed an efficient algorithm, which eliminated the need for initial angle input, for creating topological interlocking configurations using tetrahedral elements. The algorithm started by creating a topological interlocking configuration through surface tessellation with convex tiles, initially represented as a mesh using a doubly connected edge list (DCEL). This DCEL categorised geometric components into vertices, faces and half-edges, allowing for efficient access to incidence references. The high-bisection method was then employed, utilising parameters such as height and face centre, along with rotation vectors to ensure alignment between top and bottom sections of the pieces. The resulting configurations preserved the alignment of the pieces, ensuring that their equatorial sections lay on the same plane as their corresponding faces in the mesh.

2.2 Interlocking Elements with Curved Interfaces

2.2.1 Osteomorphic Brick

One drawback of topological interlocking structures assembled with polyhedral elements is the reduced contact area, resulting in a reduction in the load-bearing capacity of the assemblies (Dyskin et al., 2001a). To address this issue, Dyskin et al. (2003b) introduced the 'osteomorphic brick', a different design aimed at enhancing element connections. This brick combined the advantages of topological interlocking with continuous, seamless contact surfaces between bricks. Unlike polyhedral elements with flat surfaces that only partially contact each other, osteomorphic bricks featured curved surfaces that interlocked more comprehensively, resulting in a stronger and more

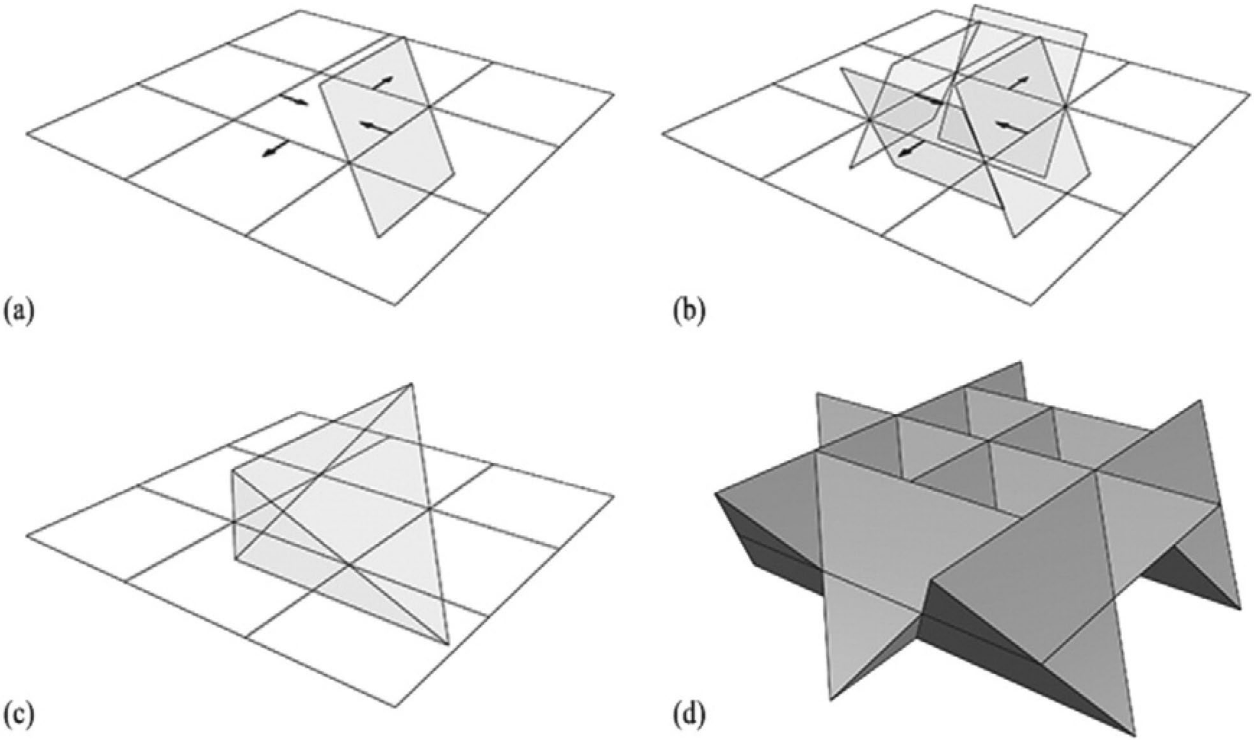


Fig. 4 A technique for creating an interlocking arrangement using square grid and tetrahedral units (Weizmann et al., 2016): **a** Perpendicular plane and tilting orientations, **b** four planes of the square cell, **c** tetrahedral cell formed by the intersection of planes and **d** a layer formed by tetrahedral cells

stable assembly. The osteomorphic brick was the first topologically interlocked brick featuring curved side surfaces. The brick was designed with a set of straightforward rules and mathematical functions to define its concavo-convex surface profile, resulting in two flat side surfaces and two curved side surfaces (Fig. 5a). This design enabled the osteomorphic bricks to be assembled into a variety of structures, such as plate-like, columnar and corner structures, as shown in Fig. 5b–e (Dyskin et al., 2012). Compared to polyhedral element, the osteomorphic brick ensures seamless and uninterrupted contact at the interfaces, enhancing the overall interlocking mechanism.

The osteomorphic brick design allows for matching and interlocking when one brick is shifted by a half-length relative to another. The two opposite non-planar surfaces of the osteomorphic brick (shown in Fig. 5a) are described by the following equations (Dyskin et al., 2003b):

$$Z_1(x,y) = \Delta h f(x) f(y) + h;$$

$$Z_2(x,y) = \Delta h f(x+a) f(y) - h; \qquad (1)$$

where $f(x)$ is an arbitrary function that meets the criteria of symmetry, periodicity and the specified boundary conditions as follows:

$$f(x) = f(-x);$$

$$f(x) = f(x+2a);$$

$$f(0) = 1;$$

$$f(a) = -1;$$

$$f\prime(0) = f\prime(a) = 0 \qquad (2)$$

The level of surface curvature is controlled by the parameter Δh, where $\Delta h < h$. The length scale of the brick ′a′ is arbitrary, and the coefficient of 2 is chosen for the length and width ($2a$ and $2h$) for corner structures.

Besides, alternative forms of osteomorphic-like brick have also been developed using Rhino (Djumas, 2018; Djumas et al., 2017; Estrin et al., 2021), as illustrated in Fig. 6. In these geometries, the osteomorphic brick was employed as a reference, and two contrasting surface geometries were created, showcasing a triangular curve and a square curve (Djumas et al., 2017).

2.2.2 Topological Interlocking Brick with Four Curved Side Interfaces

Inspired by the osteomorphic brick, Rezaee Javan et al. (2016) proposed a different design of topologically interlocked brick, as illustrated in Fig. 7. In contrast to the osteomorphic brick proposed by Dyskin et al. (2021,

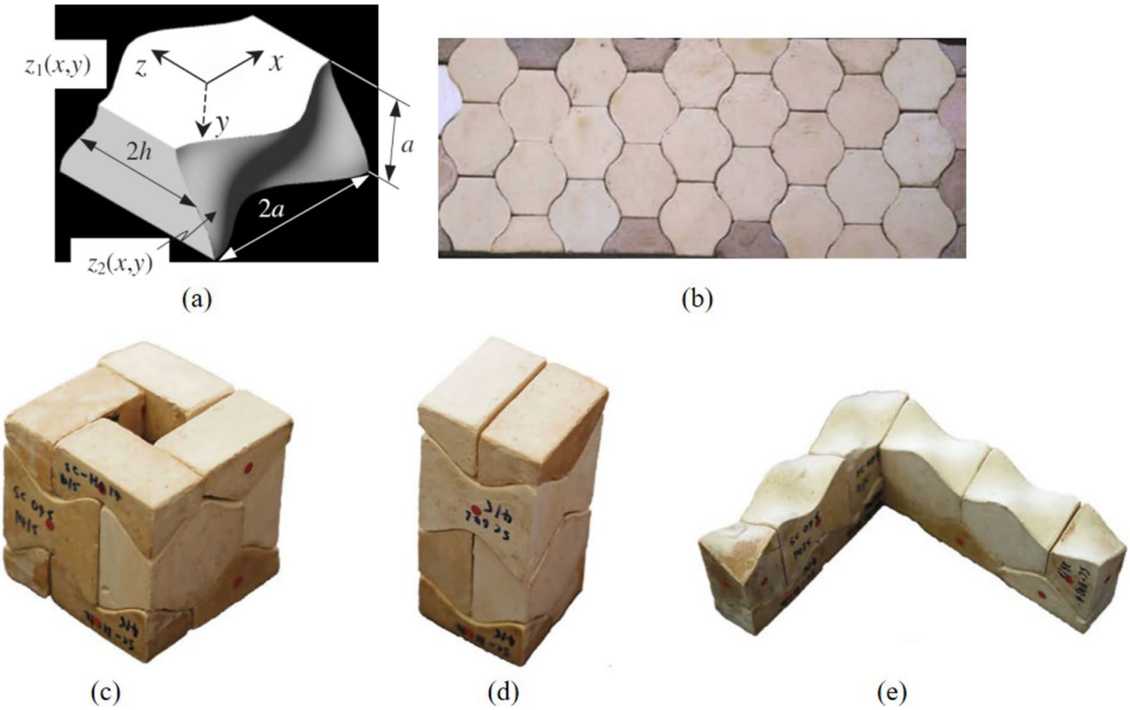


Fig. 5 Osteomorphic bricks (Dyskin et al., 2012): **a** Single brick, **b** plate-like assembly, **c** well assembly, **d** column assembly and **e** corner assembly

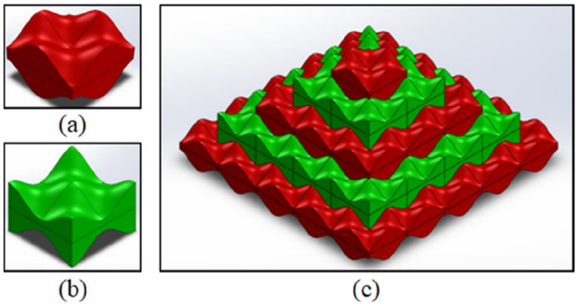


Fig. 6 Osteomorphic-like bricks and assembly (Djumas, 2018; Estrin et al., 2021): **a** and **b** Osteomorphic-like bricks of different shapes, and **c** a space-filling assembly

2001, 2018), which involved two interlocking curved interfaces and two flat interfaces, this design incorporated interlocking mechanisms on all four side surfaces. Consequently, the assembly plate exhibited symmetrical in-plane behaviour in two principal directions. This design enhancement enabled the efficient transfer and distribution of loads through the interlocking interfaces on each side, leading to improved friction and shear resistance. As a result, the structure exhibited enhanced resistance against out-of-plane movements. In addition, the patterns displayed on each face of the assembly plate showed remarkable similarity (Javan et al., 2018). The comparison between the osteomorphic brick and the interlocking brick developed by Rezaee Javan et al. (2016) is shown in Fig. 8.

The design depicted in Fig. 7a features a symmetrical geometry comprising four curved side surfaces as defined by Eqs. (3) to (6) (Javan et al., 2017).

$$f_1 : x = \frac{\sqrt{2}\cos\alpha - 1}{2} \times \cos\frac{\pi z}{h} \times L + \frac{L}{2}; y = \frac{\sqrt{2}}{2} \times L \times \sin\alpha \left(-\frac{\pi}{4} < \alpha < \frac{\pi}{4}\right); \tag{3}$$

$$\begin{aligned} f_2 : x &= \frac{\sqrt{2}}{2} \times L \times \cos\alpha; \\ y &= -\frac{\sqrt{2} \times \sin\alpha - 1}{2} \\ &\quad \times \cos\frac{\pi z}{h} \times L + \frac{L}{2}\left(\frac{\pi}{4} < \alpha < \frac{3\pi}{4}\right); \end{aligned} \tag{4}$$

$$\begin{aligned} f_3 : x &= -\frac{-\sqrt{2}\cos\alpha - 1}{2} \times \cos\frac{\pi z}{h} \times L - \frac{L}{2}; \\ y &= \frac{\sqrt{2}}{2} \times L \times \sin\alpha \left(\frac{3\pi}{4} < \alpha < \frac{5\pi}{4}\right); \end{aligned} \tag{5}$$

$$\begin{aligned} f_4 : x &= \frac{\sqrt{2}}{2} \times L \times \sin\alpha; \\ y &= \frac{-\sqrt{2}\sin\alpha - 1}{2} \times \cos\frac{\pi z}{h} \\ &\quad \times L - \frac{L}{2}\left(\frac{5\pi}{4} < \alpha < \frac{7\pi}{4}\right); \end{aligned} \tag{6}$$

In these equations, L and h represent the brick's length and height, which are equal to ‘$2a$′ and ′a′, respectively, and ′α′ is the anticlockwise angle within the x–y plane spanning from $-\pi/4$ to $7\pi/4$.

2.2.3 Space-Filling Blocks Generated by the Concept of Voronoi Partitions

2.2.3.1 Delaunay Lofts At present, architects have been exploring various types of space-filling modules. However, these studies are often unsystematic and tend to focus on a limited selection of known building blocks, highlighting the necessity for formal methodologies that facilitate the design and intuitive management of an extensive range of modular and tile-able building blocks. Subramanian

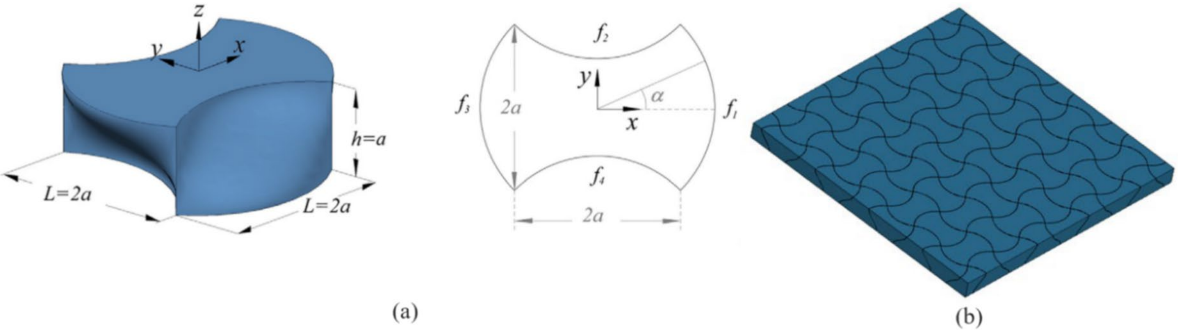


Fig. 7 Interlocking elements with four curved side interfaces (Javan et al., 2016, 2017): **a** Single block, and **b** a plate assembled by interlocking elements

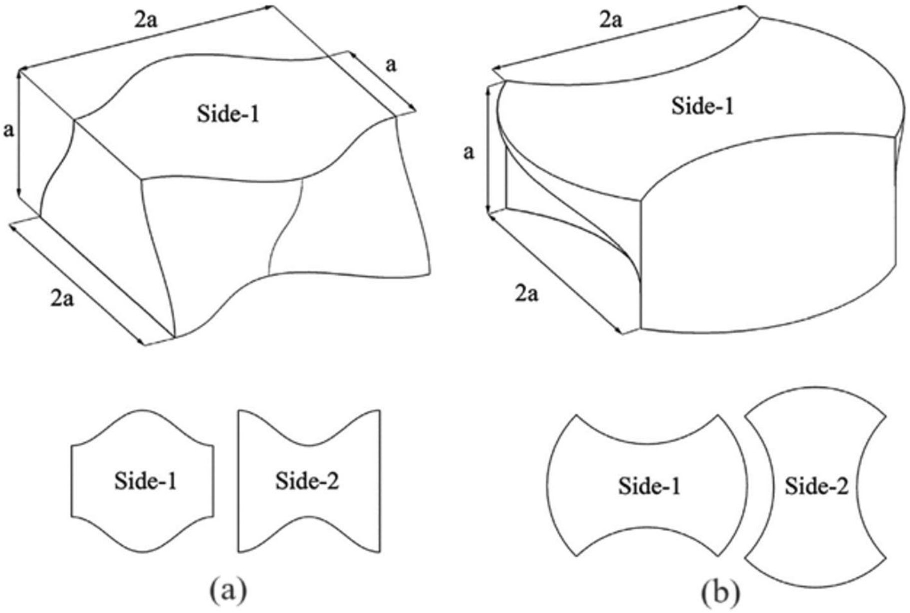
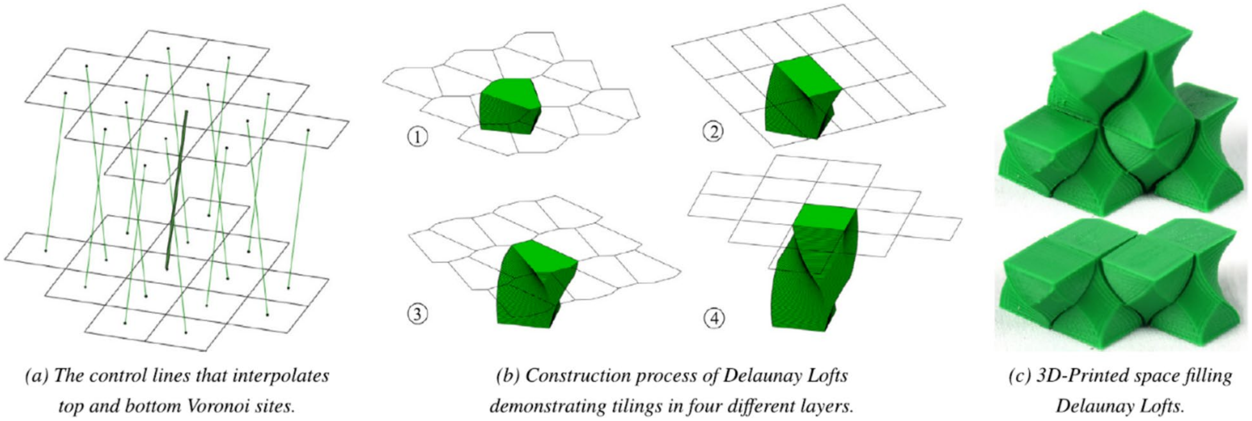


Fig. 8 Geometry comparison: **a** An osteomorphic brick (Dyskin et al., 2003b; Javan et al., 2018), and **b** an interlocking brick designed with four curved side interfaces (Javan et al., 2018)



(a) The control lines that interpolates top and bottom Voronoi sites.

(b) Construction process of Delaunay Lofts demonstrating tilings in four different layers.

(c) 3D-Printed space filling Delaunay Lofts.

Fig. 9 Construction procedure for Delaunay Lofts (Subramanian et al., 2019): **a** Creating a set of control curves, **b** computing Voronoi decomposition in a set of layers and **c** constructing Delaunay Lofts by interpolating the Voronoi polygons

et al. (2019) introduced building blocks called Delaunay Lofts, inspired by 'Scutoids'—patterns commonly found in animal skin cells (Gómez-Gálvez et al., 2018). The study employed a formal methodology centred around a layer-by-layer interpolation of 2D tiles using Voronoi decomposition along the third dimension within a specified 3D domain. This conceptually simple approach is introduced to design unconventional building blocks capable of mass production and resulting in a space-filling packing. Fig. 9 shows the process of creating Delaunay Lofts. It starts with defining control curves (green lines in Fig. 9a) and Voronoi sites (black dots in Fig. 9a). By applying the Voronoi diagram to the Voronoi sites, the space is divided into regions based on the proximity to these sites, forming the polygons shown in Fig. 9b. These polygons are then extended into three dimensions, producing a space-filling packing suitable for mass production (Fig. 9c). This specific geometric form emerges in three-dimensional space through Voronoi partitioning of 3D space, which divides the space based on the distribution of seed lines. In general, any pair of non-coplanar lines in 3D space divides the space along a hyperbolic-paraboloidal surface, inherently possessing a concavo-convex shape, allowing for the potential of interlocking. In Fig. 9a, green lines represent control curves that interpolate Voronoi sites, while black dots indicate the Voronoi sites. The degree of topological interlocking in Delaunay Lofts varies based on the specific arrangement of these lines (Subramanian et al., 2019).

2.2.3.2 VoroNoodles In a recent study, Ebret et al. (2023) introduced an innovative technique for modelling topologically interlocked building blocks, which could be assembled to form watertight structures, thus enabling the creation of diverse structures. Drawing inspiration from methods that employ Voronoi tessellation in spatial domains with symmetrically arranged Voronoi sites (Krishnamurthy et al., 2022; Subramanian et al., 2019), their approach emphasised the creation of building blocks through the helical stacking of 2D honeycombs. The development of these honeycombs, illustrating tessellations of the plane with a single prototile, arose from an integration of wallpaper symmetries and Voronoi tessellation. This distinct combination resulted in structures that demonstrate both space-filling properties (attributed to Voronoi tessellation) and interlocking characteristics (due to helical trajectories). To create corrugated blocks that resemble noodle-like structures, helical ruled surfaces were used as Voronoi sites, and Bravais lattices were applied to populate the volume. The shapes were derived through a layer-by-layer Voronoi decomposition, a crucial step in ensuring the development of robust corrugation. This layer-by-layer Voronoi decomposition ensured the generation of surfaces with genus-0, and the resultant blocks could be consistently assembled (Ebert et al., 2023). Fig. 10 illustrates the process of generating VoroNoodles.

With this method, Ebert et al. (2023) presented two distinct types of VoroNoodles along with corresponding mathematical expressions: constant cross-sectional noodles, characterised by shapes sharing identical cross-sections resembling a swept volume, as shown in Fig. 11, and

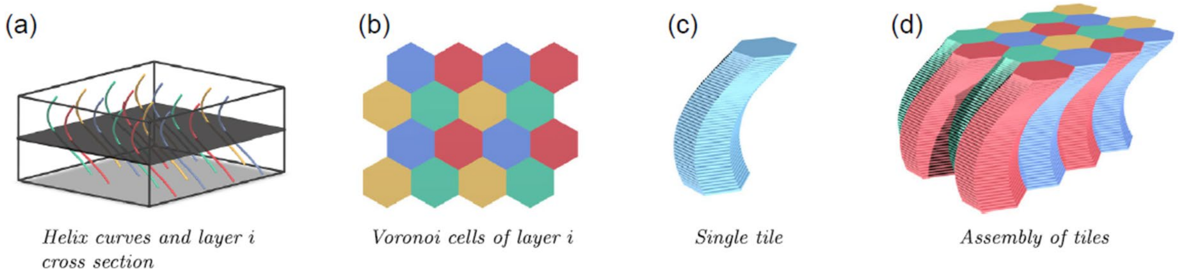


Fig. 10 The process of generating VoroNoodles (Ebert et al., 2023): **a** Positioning multiple helices within a structured slab, **b** calculating the Voronoi tessellation for each layer 'i', **c** generating a tile by extruding each layer 'i' and **d** constructing an assembly by utilising multiple tiles

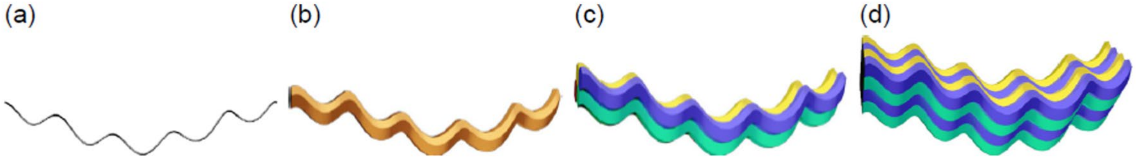


Fig. 11 VoroNoodles with constant cross-sections (Ebert et al., 2023): **a** A single curve, **b** a single constant cross-section noodle, **c** 2 * 2 assembly of a constant cross-section noodle and **d** 4 * 4 assembly of a constant cross-section noodle

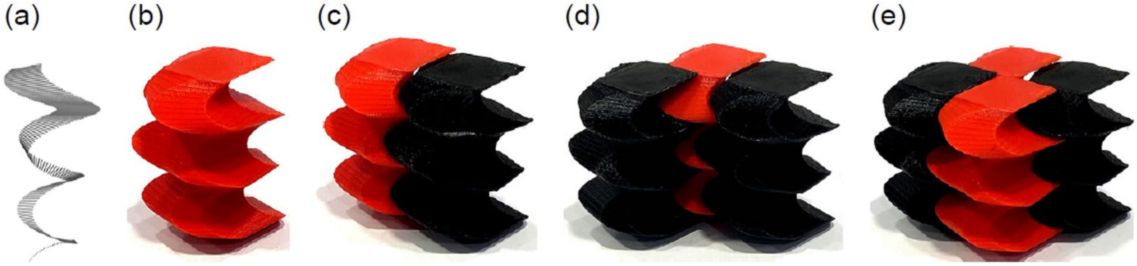


Fig. 12 VoroNoodles with variable cross-sections (Ebert et al., 2023): **a** A ruled surface, **b** a printed VoroNoodle, **c** two printed VoroNoodles, **d** an assembly of three printed VoroNoodles and **e** 2 * 2 assembly of VoroNoodles

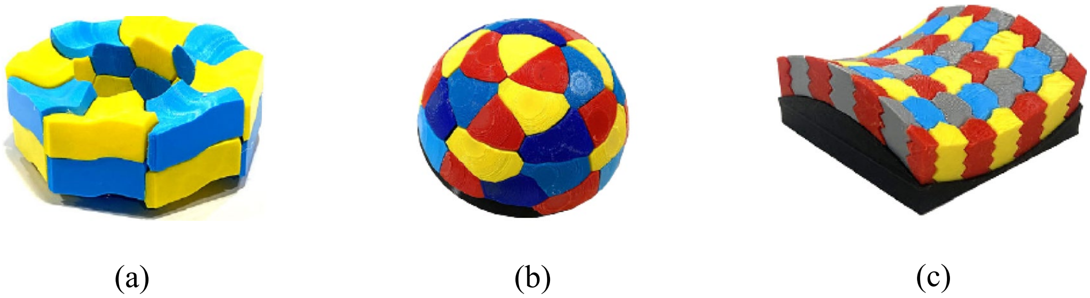


Fig. 13 Examples of VoroNoodles (Ebert et al., 2023): **a** Cylindrical assembly, **b** dome construction and **c** saddle shape

variable cross-sectional noodles, featuring shapes with diverse cross-sections akin to lofted volumes (Fig. 12).

This technique has also been extended beyond flat assemblies, allowing the construction of more intricate shapes through bijective transformations, as shown in Fig. 13. It should be noted that the congruence property of corrugated blocks can be maintained through certain bijective mappings, like scale, shear or cylindrical transformations, such as the cylindrical assembly shown in Fig. 13a. Nevertheless, with many bijective transformations, this congruence is not retained. In such cases, the corrugated block may appear similar but not identical, as illustrated in Fig. 13b and c, showcasing a dome and a saddle shape assembled from non-congruent corrugated blocks.

2.2.3.3 Other Designs It is noteworthy to mention that the concept of Voronoi sites has garnered significant attention among architectures for developing new types of space-filling modules. Krishnamurthy et al. (2020, 2021) introduced a novel framework for designing and fabricating interlocking space-filling shapes called 'woven tiles'. These woven tiles were derived from the symmetries of fabric weaves, such as plain, twill and satin. This framework combined Voronoi partitioning, using curve segments as sites, with weave patterns that were closed under symmetry operations. The study successfully demonstrated the creation of woven tiles on both flat and curved surfaces. Fig. 14 shows an example of creating a half-cylindrical shell using curved Voronoi sites and plain-woven tiles. Moreover, Akleman et al. (2020) introduced Generalised Abeille Tiles (GATs) as a novel design approach, extending Abeille vaults (Vella & Kotnik, 2016) by leveraging the symmetries of woven fabrics (Fig. 15a) and Voronoi decomposition with higher-dimensional Voronoi sites (Fig. 15b). Through comparative structural analysis of GATs in different fabric patterns, they demonstrated a correlation between fabric symmetries and stress distribution in tiled assemblies, revealing insights into optimising structural performance based on fabric choices.

2.2.4 Non-Planar Topological Interlocking Brick

Up to now, previous studies have primarily focused on the application of planar interlocking elements in structures, except for woven tiles (Krishnamurthy et al., 2021). Nevertheless, numerous practical engineering challenges necessitate solutions for non-planar surfaces. Fallacara et al. (2019) conducted one of the few studies exploring the use of non-planar interlocking elements. In their study, non-planar interlocking vault elements were achieved by transforming the Abeille and Truchet vault

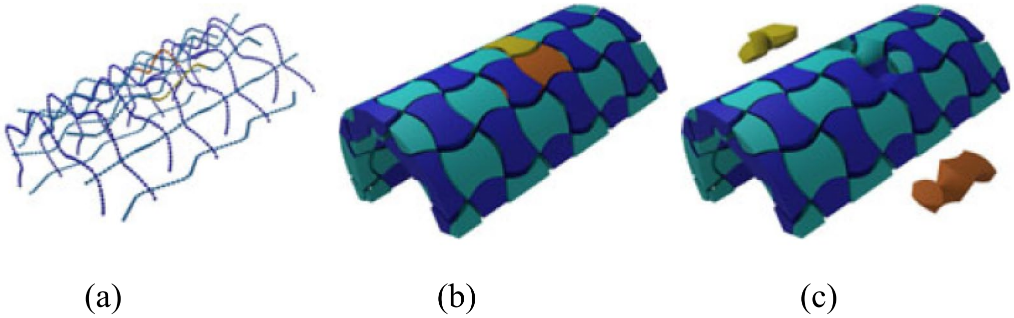


Fig. 14 Decomposing a half-cylindrical shell utilising curved Voronoi sites and plain woven tiles (Krishnamurthy et al., 2021): **a** Initial curve, **b** decomposition obtained by original curves and **c** exploded view showing two types of woven tiles

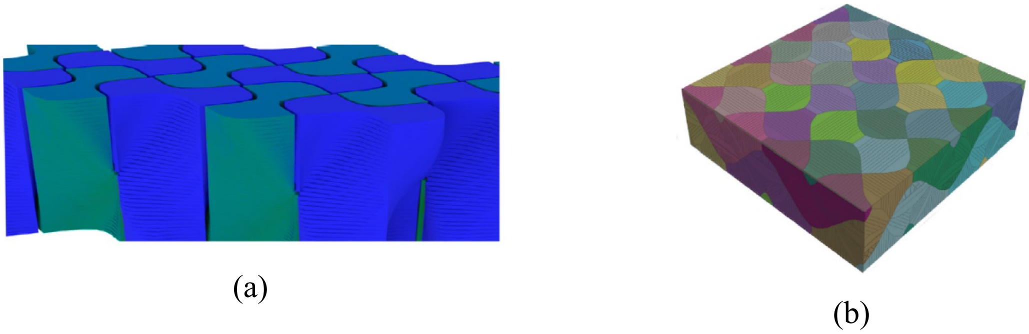


Fig. 15 Generalised Abeille Tiles (GATs) (Akleman et al., 2020): **a** An example of twill-woven Abeille tile designs, and **b** an example of a 3D Voronoi decomposition of a fundamental domain

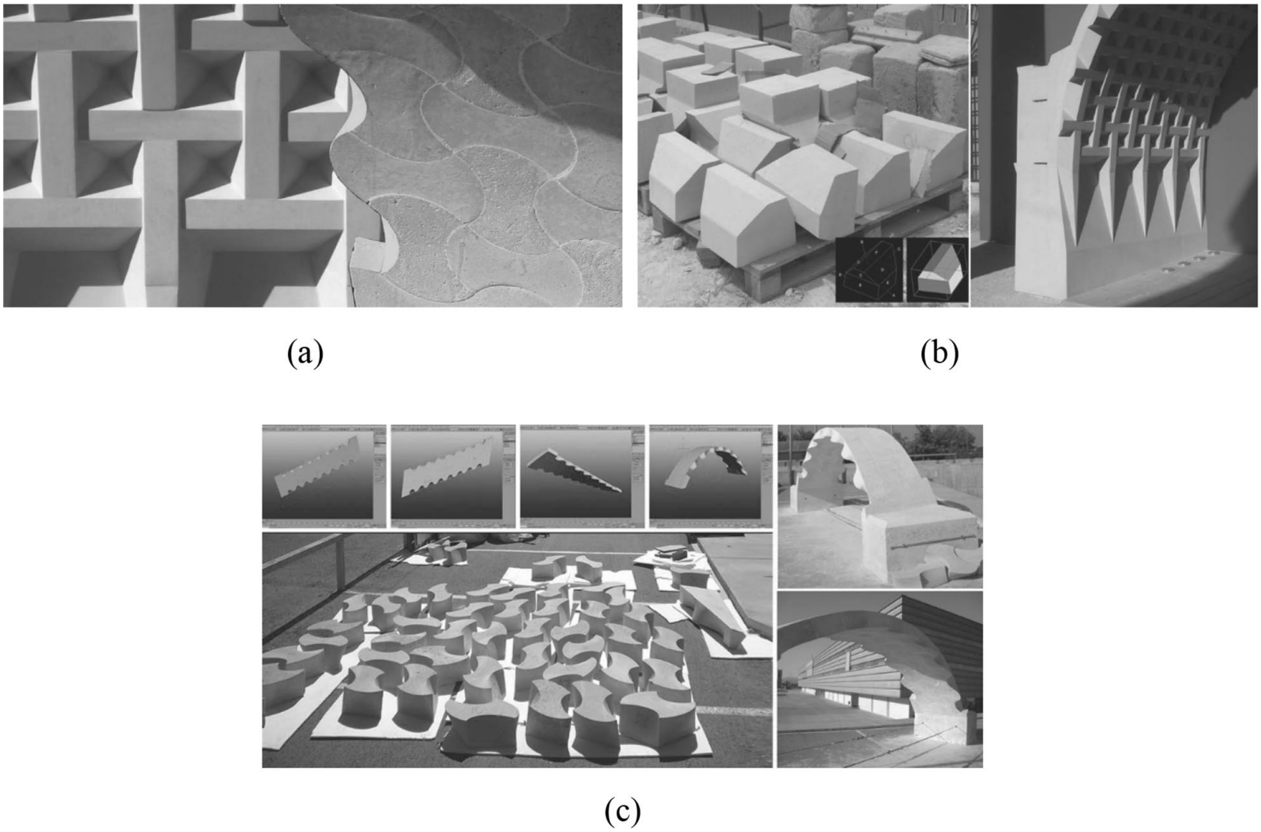


Fig. 16 Abeille and Truchet vaults (Fallacara, 2009; Fallacara et al., 2019): **a** Patterns, **b** Abeille construction and **c** Truchet vault construction

patterns through bending (Fig. 16). The study demonstrated the efficacy of transforming flat vaults with distinctive stone patterns into arches through the utilisation of a 3D modelling system (Fallacara, 2009). Furthermore, Estrin et al. (2003) proposed a non-planar osteomorphic block for tiling space shuttle surfaces. The suggested procedure for generating the shape involved mapping a planar arrangement onto the spacecraft's surface using a continuous function and extending this mapping into three dimensions to shape each tile in alignment with the spacecraft's profile. Fig. 17 illustrates the non-planar interlocking block introduced in this study.

More recently, a new non-planar topological interlocking element was proposed by Xu et al. (2020) for the construction of cylindrical structures. This novel element featured six curved side surfaces that interlocked with neighbouring elements, enabling the assembly of multiple identical non-planar elements to form a tubular

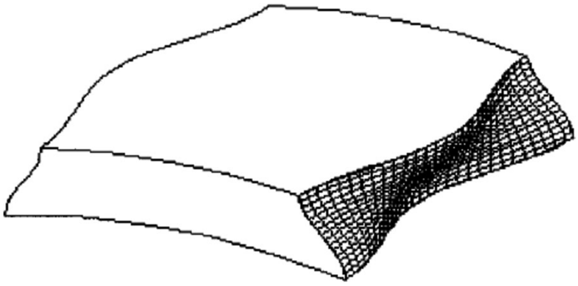


Fig. 17 A non-planar osteomorphic tile for Space Shuttle (Estrin et al., 2003)

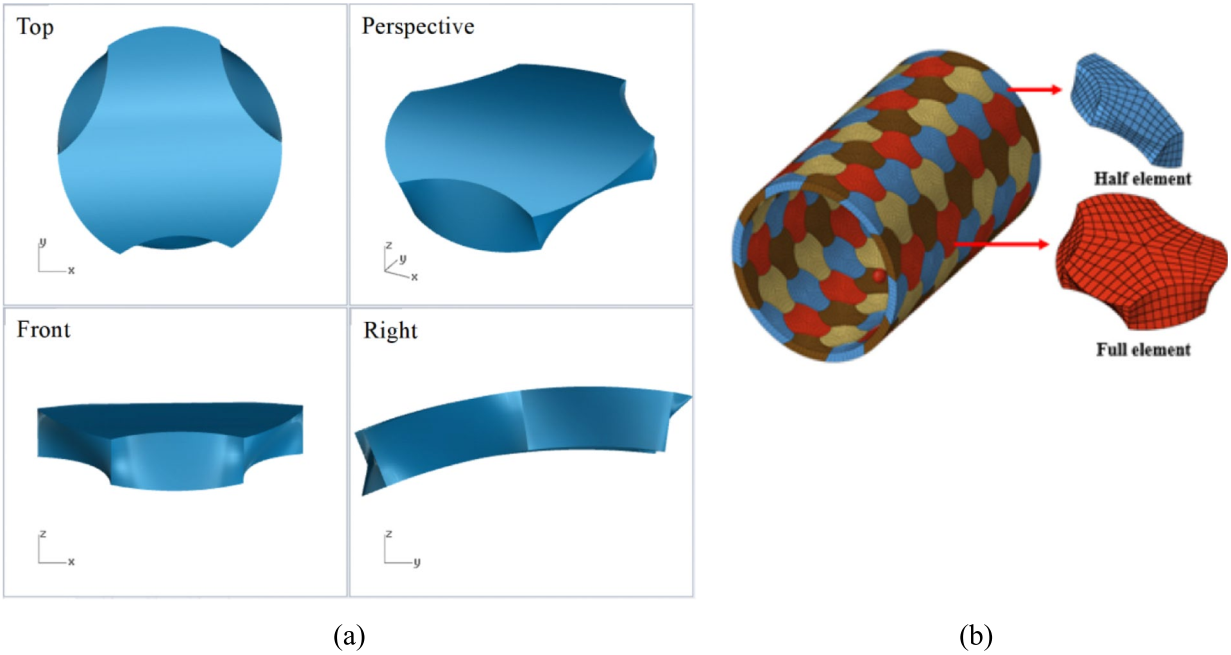
structure. The non-planar interlocking element and the assembled tubular structure are shown in Fig. 18.

To generate the desired geometry, Xu et al. (2020) proposed a design process for the brick that begins with the creation of a regular hexagon along with its corresponding circumcircle (Fig. 19a). The three non-adjacent arcs are then reflected. By connecting the arcs highlighted in red, the pattern for the top surface of a planar interlocking element is formed, and the bottom surface is achieved through a 60° rotation of the shape. The side surfaces of the element are created by lofting the edges of both the top and bottom surfaces (Fig. 19b). The planar elements are assembled to form a flat surface, as shown in Fig. 19c. To create a non-planar structure, the surfaces of the generated planar interlocking element are transformed to match the shape of a cylindrical surface using the technique known as 'flow along surface'. Through this process, the interlocking structure with non-planar characteristics is formed, as demonstrated in Fig. 19d.

In addition, the use of altered osteomorphic blocks as porous ceramic linings in combustion chambers, as shown in Fig. 20a, to enhance their sound-absorbing properties was reported (Ries et al., 2013). The findings indicated that these linings could improve the stability of lean premixed gas turbines by mitigating thermoacoustic instabilities (Ries et al., 2013). Besides, Fig. 20b shows another design that involves the segmentation of cylindrical structures using non-planar building blocks, which share similarities with osteomorphic elements (Gómez-Gálvez et al., 2018). These blocks were derived based on the geometric principles of scutoids, a shape found in natural epithelial systems, enabling efficient three-dimensional packing, particularly in curved structures like tubes or spheroids (Gómez-Gálvez et al., 2018).

2.3 Optimisation of Topological Interlocking Assemblies

Drawing from the interlocking elements and structures discussed in Sects. 2.1 and 2.2, it can be concluded that an interlocking structure consists of identical or nearly identical elements. These elements are strategically arranged and shaped to create constraints that prevent the removal of any element from the assembly. It is worth noting that only the peripheral elements of the structure require additional constraints, while no local



(a) (b)

Fig. 18 Non-planar interlocking element (Xu et al., 2020): **a** A single element and **b** the assembled tubular structure

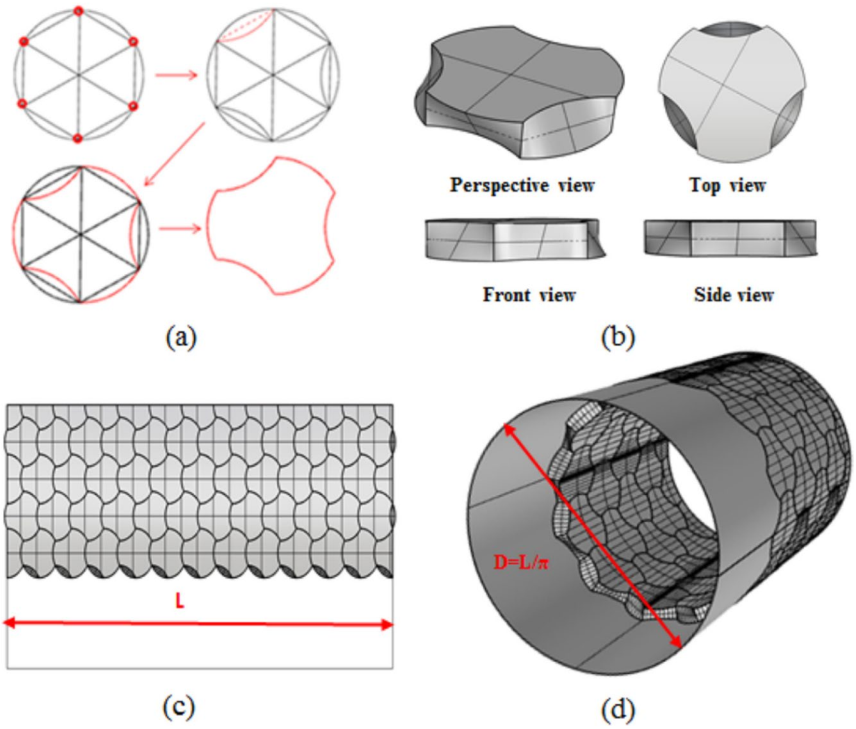


Fig. 19 Creation of a novel non-planar interlocking element and the assembly of a tubular structure (Xu et al., 2020): **a** Creation of the initial pattern for the top and bottom surfaces of a planar brick using a regular hexagon and its circumcircle, along with the reflection of non-adjacent arcs, **b** formation of side surfaces by lofting the edges of the top and bottom surfaces, **c** assembly of planar interlocking bricks into a flat plate and **d** transformation of the planar plate to create a non-planar structure using the 'flow along surface' technique.

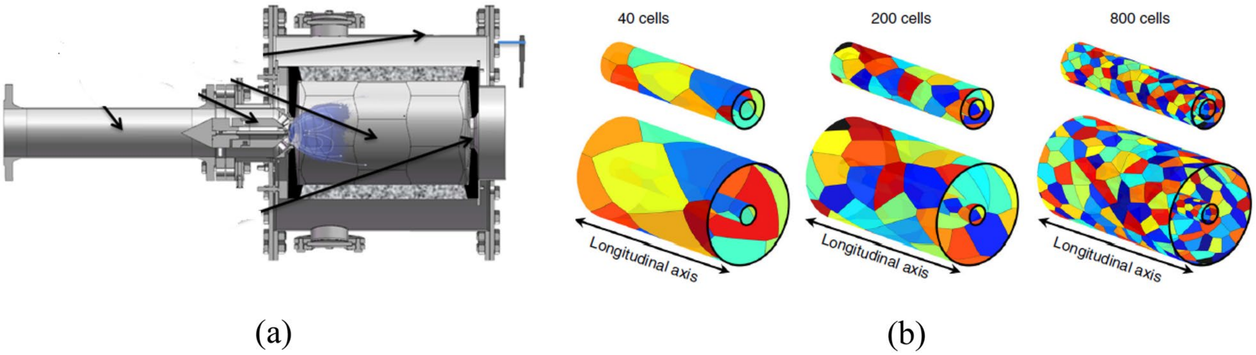
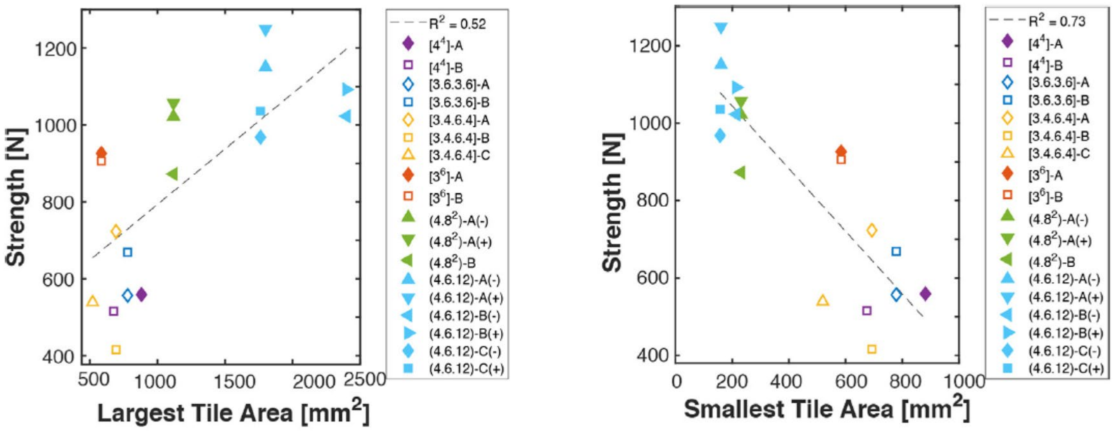


Fig. 20 Applications of non-planar topological interlocking elements: **a** Altered osteomorphic blocks for the tilling of cylindrical surfaces (Ries et al., 2013) and **b** non-planar blocks for the segmentation of cylindrical shell structures (Gómez-Gálvez et al., 2018)

connectors or binders are necessary. The meticulous design of the elements allows them to interlock securely within the structure. This interlocking is exclusively achieved through the geometry and positioning of the elements, without the need for any supplementary fastening materials. Furthermore, the interlocking geometry plays a pivotal role in determining the structural behaviour. This encompasses factors such as the configuration of profiles along the side surfaces, the number of interlocking interfaces, the element thickness and the quantity of elements. By fine-tuning these parameters, it is possible to create interlocking elements with distinct mechanical behaviours. In addition, optimising the performance of interlocking assemblies can involve considerations such as material properties, introducing asymmetry in element shapes and exploring modular variations to achieve a balance between structural integrity and adaptability.

Several studies have focused on the optimisation of these assemblies (Aharoni et al., 2021; Feldfogel et al., 2023). Williams and Siegmund (2021) used Archimedean and Laves tilings to study two-dimensional assemblies. They found that architectural configurations significantly affect force deflection responses under point loads, with stiffness, load capacity and toughness varying by at least threefold. The study showed a strong and linear correlation between stiffness, strength and toughness across all architectures. Importantly, the relationship between strength and tile size in tessellations was analysed to explore how system architecture affected mechanical behaviour. While larger tiles showed a moderate positive correlation with strength, the smallest tile area emerged as the most predictive measure of mechanical behaviour, highlighting its crucial role in optimising material system performance. The results for this can be observed in Fig. 21.

Moreover, in the parametric study reported by Koureas et al. (2022), it was found that the elastic modulus (*E*), friction coefficient (μ) and structural height (h) significantly influence interfacial failure mechanisms and response capacity in beam-like topological interlocking structures. This study specifically chose values for *E* (GPa) (including 1, 2, 3, 10, 20 and 30), to cover a broad spectrum of brittle materials. This selection facilitated the examination of how material elasticity affects the overall stiffness of topologically interlocked structures. In addition, a varied range of μ values (including 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2) were investigated to gain insight into the influence of interfacial friction among the blocks. Friction serves a crucial function in structures constructed using topological interlocking elements. Since the blocks are not bonded together, the integrity of topologically interlocked structures depends on the contact and frictional interactions between the blocks. In this study, as μ increased, the behaviour became increasingly influenced by stick-related factors, and the response parameters grew proportionally with h and linearly with *E*. In addition, Wang et al. (2019) introduced an optimisation algorithm in a study on assemblies of regularly arranged convex rigid blocks, aiming to approximate a specified freeform surface. It iteratively adjusted the geometry of convex rigid blocks to optimise stability based on a theoretical link between static equilibrium conditions and a geometric property indicating global interlocking. Fig. 22 provides a summary of the methodology used in this study.



(a) (b)

Fig. 21 Mechanical characteristics and maximum measures of fragmentation (Williams & Siegmund, 2021): **a** Strength versus largest tile area in the base tiling, and **b** strength versus smallest tile area in the base tiling

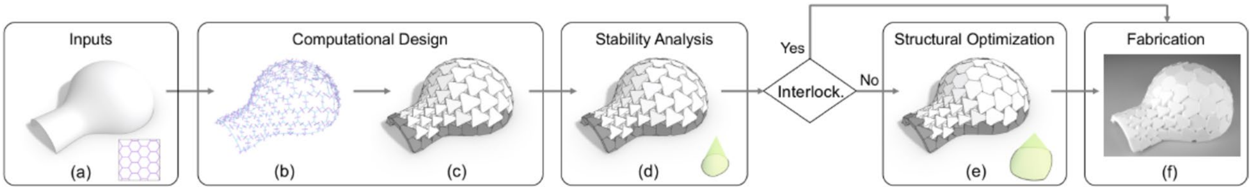


Fig. 22 Summary of Wang et al.'s optimisation algorithm (Wang et al., 2019)

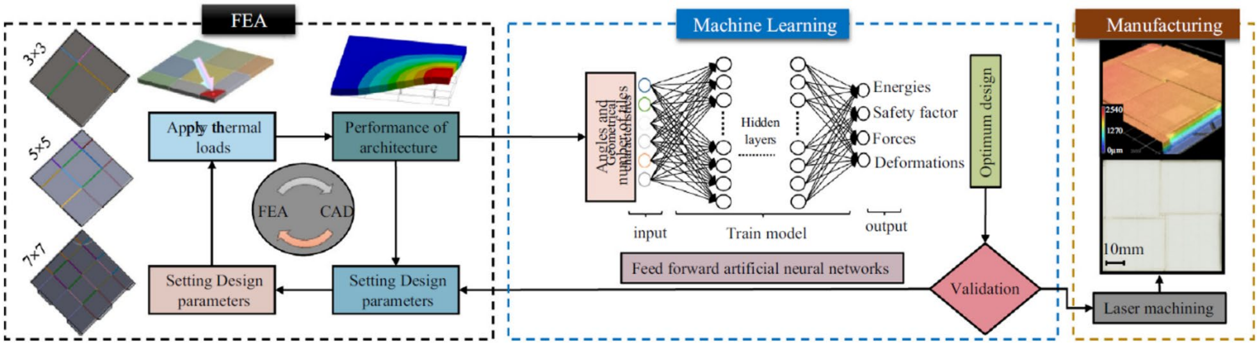


Fig. 23 Procedure for investigating the thermomechanical behaviour of architectured materials (Fatehi et al., 2021)

Fatehi et al. (2021) improved the mechanical performance, especially brittleness, of architectured ceramics by employing a non-regular truncated tetrahedron design for interlocking elements. A hybrid machine learning (ML)-finite element analysis (FEA) algorithm (Fig. 23) was used to optimise the angle of cuts between building blocks. A parametric study was conducted to explore the effects of various architectural parameters, such as interlocking angle, cutting angles between building blocks and number of blocks for assembling the structure on the multifunctional performance of these materials. The research findings demonstrated that by optimising the angles, architectured ceramic panels utilising ML-assisted engineered patterns showed significant improvements. These improvements encompassed a 30% increase in frictional energy dissipation, a 7% extension in sliding distance for the tiles and an impressive 80% reduction in strain energy, which enhanced the safety factor and postponed structural failure compared to conventional ceramics.

These studies demonstrate the intricate link between design optimisation and the mechanical behaviour of interlocking structures. The ability to fine-tune geometry, material properties and interaction mechanics offers significant potential for tailoring these structures for specific applications. However, these advancements also pose challenges for traditional manufacturing methods, which are discussed in the following section.

2.4 Manufacturing of Topological Interlocking Structures

The design and optimisation of topological interlocking assemblies require precise manufacturing to successfully realise these structures. The complex geometric configurations and the critical role of material properties necessitate advanced manufacturing techniques to preserve the mechanical characteristics such as strength and flexibility while minimising defects and ensuring structural integrity.

Topological interlocking systems can be formed through either assembling unit elements (bottom-up process) or segmenting existing monolithic solids (top-down process) (Siegmund et al., 2016). In both approaches, the elements interact through contact and friction, eliminating the need for adhesive bonding. This section describes manufacturing techniques such as assembly and 3D printing as bottom-up approaches, and segmentation as an approach for top-down process.

2.4.1 Assembly

To produce topological interlocking systems through assembly, the process begins with mass-producing individual unit elements. These elements can be manufactured using various methods, such as conventional computer numerical control (CNC) machining, casting (Dyskin et al., 2012; Javan et al., 2017; Krause et al., 2012) or additive manufacturing (Khandelwal et al., 2012). In traditional discrete structures like arches and domes, stability often heavily depends on the self-weight of the structure, with rigid scaffolding typically required during construction to support these forms. In contrast, topological interlocking systems derive stability from the geometric constraints between individual units. As a result, reliance on self-weight or traditional scaffolding is significantly reduced, as the interlocking mechanism can provide additional structural support (Siegmund et al., 2016).

Assembly structures can be formed using directional pick-and-place techniques as well as parallel assembly methods. In the directional pick-and-place method, machine tools are used to position individual parts at predetermined locations. While typical segmented structures allow parts to move orthogonally to the assembly plane without obstruction, topological interlocking systems pose challenges due to their specific geometry constraints (Siegmund et al., 2016). In such systems, it is essential not only to position the parts in specific locations but also to ensure directed motion within the assembly plane to achieve the desired interlocking geometry. The complexity of these motions makes this method less effective for highly intricate geometries, particularly when precision is required for a large number of elements, which can lead to increased time and cost. However, for simpler interlocking designs or scenarios where high precision is essential, this method offers enhanced accuracy and control.

In contrast, parallel assembly addresses the challenges of handling large numbers of unit elements and the directed motion required in pick-and-place methods by introducing a deformable scaffold. Initially, unit elements are placed onto a rectangular template, where unit elements are not yet interlocked. They are positioned on the scaffold according to the template pattern while the scaffold is in an open state, without needing exact placement. Interlocking is then achieved for all unit elements simultaneously by closing the scaffold (Siegmund et al., 2016). This method enhances precision by streamlining the positioning process and enabling interlocking in a single step. While it is particularly efficient for complex geometries, challenges may arise concerning scalability and material compatibility. The deformable scaffold might not be ideal for all element types, especially those made of rigid or brittle materials. Nevertheless, it offers a promising solution for the rapid assembly of intricate interlocking structures.

Another approach to constructing structures is through self-assembly. In general, self-assembly creates an organised structure from a disorderly system of pre-existing components through localised interactions among the components themselves, without any external direction. Golosovsky et al. (1999) and Grzybowski et al. (2000) showcased various forms of self-assembly among millimetre-sized particles, though not specifically in the context of topological interlocking structures. While self-assembly offers a compelling way to create ordered structures from disordered components, its application to topological interlocking systems presents both opportunities and challenges. At smaller scales, self-assembly is effective due to the dominant influence of surface tension forces and the precise control over component interactions. This method is beneficial in scenarios where manual assembly is impractical or where scalability poses a challenge. However, at larger scales, surface tension alone often fails to overcome inertia, which can hinder the self-assembly process. Incorporating magnetic forces offers a viable solution for large-scale self-assembly, providing the necessary force to manage larger or heavier components. The mobility of unit elements is critical, as it directly affects the efficiency and effectiveness of the self-assembly process. Utilising a liquid scaffold facilitates the self-assembly process effectively. Siegmund et al. (2016) reported a method where tetrahedral elements were packed at the liquid–air interface to form a dense planar structure. This assembly was achieved by positioning four small magnets at the centroid of each tetrahedron facet, requiring the tetrahedra to float and align with one edge parallel to the fluid container's bottom. Although the liquid scaffold method is promising, it is not without challenges. The success of this approach relies on precise control of fluid dynamics and magnetic forces, which can complicate the process and restrict its applicability to certain materials and environments. In addition, scalability remains a concern for larger or more complex structures, as it requires careful management of both magnetic and fluidic interactions to ensure effective assembly. Overall, self-assembly provides a flexible and innovative approach to constructing topological interlocking systems, but its practical application is constrained by scale and material limitations. The method is most suitable for lightweight components and in environments where precise external control is feasible.

2.4.2 Fabrication of Topological Interlocking Concrete Elements

Concrete is one of the most widely used materials in civil engineering (Haddadian et al., 2023). The use of topological interlocking concrete structures offers the potential to create robust, scalable solutions for modern construction (Al-Fakih et al., 2018). To manufacture topological interlocking concrete elements, precision is of utmost importance. The intricate geometry of topological interlocking elements demands advanced fabrication techniques to ensure that each piece fits perfectly with others, maintaining the structural integrity and performance of the assembly. Traditional methods may fall short in achieving the required accuracy, making modern manufacturing technologies, such as high-precision casting (Li et al., 2023), 3D printing (Wang et al., 2023) and automated moulding (Xu et al., 2022), essential. These technologies enable the production of complex shapes with minimal tolerances, ensuring consistent quality. Furthermore, innovations in material science, such as fibre reinforcement (Xu et al., 2023), help enhance the durability and reduce the brittleness of these elements, contributing to the overall structural efficiency and longevity of interlocking systems. Therefore, continued advancements in both manufacturing processes and material technology are crucial to fully unlock the potential of topological interlocking concrete designs.

2.4.3 Three-Dimensional Printing

Additive manufacturing techniques, such as 3D printing (Shahrubudin et al., 2019; Song et al., 2015), are commonly used to create complex geometries, including topologically interlocked materials. With 3D printing, layers of material are deposited on top of each other based on a digital model. Various materials, including plastics, metals and ceramics, can be used in 3D printing. This approach facilitates the integrated manufacturing of unit cells directly at their final positions. Computer-aided design (CAD) software and scripting tools are essential for creating geometric models of topological interlocking material assemblies and generating input files for 3D printing (Siegmund et al., 2016). 3D printing offers unprecedented versatility in engineering, particularly for concrete structures (Wang et al., 2023), enabling rapid prototyping and customisation while potentially reducing material waste and construction time. This technology allows for the creation of complex concrete geometries with greater precision and fewer defects. These advancements are crucial for fully harnessing the potential of topological interlocking designs in concrete structures.

However, 3D printing may not always be efficient for large-scale production, especially when high-resolution settings are needed for complex interlocking designs. In addition, material constraints, such as the limited availability of high-strength or heat-resistant materials in certain 3D printing technologies, could limit its application in high-performance or load-bearing structures. Nonetheless, the ability of 3D printing to streamline manufacturing and assembly makes it an attractive option for low- to medium-scale production of complex designs.

2.4.4 Segmentation

Unlike the bottom-up method, topological interlocking panels can be produced using a top-down approach known as the segmentation method. In this technique, the boundaries of the elements are precisely carved within a solid block of material (Mirkhalaf et al., 2016). This method offers several advantages, as the elements are formed in their final positions, and it can be applied to existing products or structures. It relies on advanced technologies, such as 3D laser engraving (Diaci et al., 2011), to precisely separate materials along designated surfaces (Siegmund et al., 2016). This method is particularly useful for retrofitting existing structures or producing panels where maintaining the exact geometry of each element is crucial. However, segmentation comes with its own limitations. While it excels in precision, it is highly dependent on advanced technologies which can be costly and time-consuming for large structures. Moreover, material selection is constrained to those that can be precisely segmented without fracturing or deforming under laser or machining forces, especially when creating complex geometries like curved interfaces. Thus, segmentation is best suited for applications where precision is paramount and cost considerations are secondary.

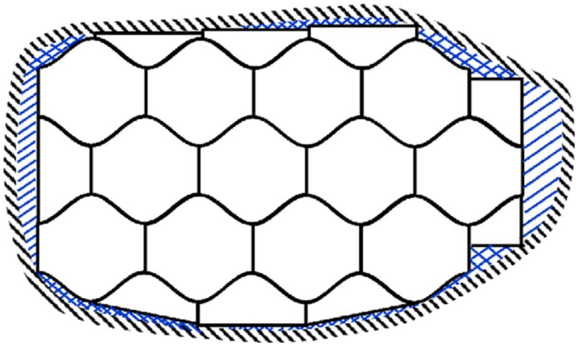


Fig. 24 Interlocking foundation built in a pit (Dyskin et al., 2005)

2.5 Application of Topological Interlocking Elements in Engineering Structures

Topological interlocking design has begun to find applications in a variety of engineering structures, presenting significant advantages for construction. One remarkable application is the use of plate-like assemblies composed of topological interlocking bricks to construct flexible foundations. This application showcases exceptional resilience as it remains insensitive to local reductions in the load-bearing capacity of the ground (Dyskin et al., 2012). Fig. 24 depicts an example of a foundation made of interlocking elements constructed in a pit. The grey hatched area represents the pit wall. Expanding grout was used to fill the top and bottom gaps between the walls and the structure (double-hatched), while the other gaps were left without filling (Dyskin et al., 2005).

Furthermore, several notable constructions, such as the Escorial monastery (Mozo, 2003), the Cathedral of Lugo (Rabasa Díaz & La bóveda plana de Abeille en Lugo, 1998) and Casa Mina de Limpia (Nichilo, 2003) in Spain, have successfully employed flat vaults using topological interlocking techniques. These examples demonstrate the practical viability of flat vault concepts.

Interlocking bricks also prove to be an excellent option for pavement construction, particularly in addressing local settlement issues. Their successful application in road pavement construction has been demonstrated in various countries, including Japan, America and Iran (Xu et al., 2020). In contrast to tetrahedral, cubic and octahedral bricks that require truncation to create a flat working surface, the osteomorphic brick is more efficient due to its inherently flat surfaces (Dyskin et al., 2012). Moreover, topological interlocking offers a versatile option for tiling applications, serving both protective and decorative purposes. Their longevity stands out, as the interlocked tiles can only be removed when completely demolished, ensuring extended serviceability (Dyskin et al., 2012). Floor construction is another promising field where topological interlocking has been explored, leading to the development of a new method for floor design (Weizmann et al., 2016, 2017). Furthermore, construction without the use of formwork can pose a significant challenge in enhancing productivity and minimising waste at a construction site. Topological interlocking systems offer possibilities for construction without relying on formwork, representing a significant innovation in the realm of civil engineering construction (Loing et al., 2020). This approach aligns closely with global sustainability goals by reducing material waste and energy consumption. By eliminating the need for traditional formwork, which often leads to substantial material waste, these systems promote more sustainable building practices and significantly reduce the carbon footprint of construction projects.

Another promising application of topological interlocking is in freeform roof construction, as shown in Fig. 25. In addition, the latest non-planar interlocking element design, specifically tailored for tube-shaped structures (Xu et al., 2020), represents a significant advancement in the potential applications of topological interlocking design, particularly in the construction of tunnel structures. These innovations offer not only technical benefits but also socio-economic advantages. The topological interlocking design plays a crucial role in enhancing structural performance by ensuring improved load distribution and overall stability. Although the fabrication of such structures may initially incur higher costs due to the advanced manufacturing technologies required, the resulting structures exhibit superior durability, reduced maintenance demands and enhanced safety. Thus, the long-term benefits outweigh the initial investment.

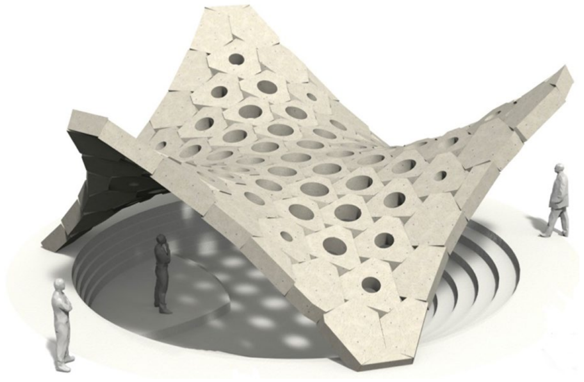


Fig. 25 Application of topological interlocking elements in roof design (Wang et al., 2019)

Besides, the principle of topological interlocking has also been explored for extra-terrestrial construction (Dyskin et al., 2005), particularly for structures that utilise self-adjusting osteomorphic bricks as modular bases or for spaceships with interlocking assemblies designed for easy construction on uneven surfaces. This adaptability is particularly advantageous in environments with limited resources and precision tools, underscoring the practicality of these systems under extreme conditions.

Beyond engineering structures, the concept of topological interlocking has gained popularity among architects who appreciate the aesthetic appeal of assemblies (Brocato & Mondardini, 2012; Ebert et al., 2023; Estrin et al., 2021; Fallacara et al., 2019; Gómez-Gálvez et al., 2018; Subramanian et al., 2019; Tessmann & Rossi, 2019; Weizmann & Amir, 2015). Examples of the application of topological interlocking elements in architectural designs include the Alexandros Obelisk, Bin Jassim Dome and Truchet and Abeille vault (Fallacara et al., 2019), as shown in Fig. 26.

Overall, the application of topological interlocking structures in civil engineering holds socio-economic potential by reducing construction time and costs. Despite requiring advanced precision in manufacturing and assembly, the topological interlocking systems offer benefits in structural performance and sustainability. The modular design facilitates easier maintenance, enabling targeted repairs or replacements of individual elements with minimal disruption and waste while supporting circular economy principles. As the construction industry moves towards more sustainable practices, topological interlocking systems present a valuable opportunity to align with global sustainability goals and promote economic growth through innovative and resource-efficient techniques.

3 Characteristics and Performance of Interlocking Assembly Structures

Interlocking assembly structures exhibit a variety of intriguing characteristics, such as increased bending flexibility, strong fracture resistance, remarkable tolerance to missing blocks and excellent energy absorption capacity (Ali et al., 2013; Autruffe et al., 2007; Dalaq & Barthelat, 2020; Dyskin et al., 2001a, 2001b, 2003b, 2012, 2019; Estrin et al., 2009, 2021; Feldfogel et al., 2024; Feng et al., 2015; Javan et al., 2017, 2018; Khor et al., 2002; Krause et al., 2012; Mirkhalaf et al., 2016; San Ha & Lu, 2020). In the past, studies have

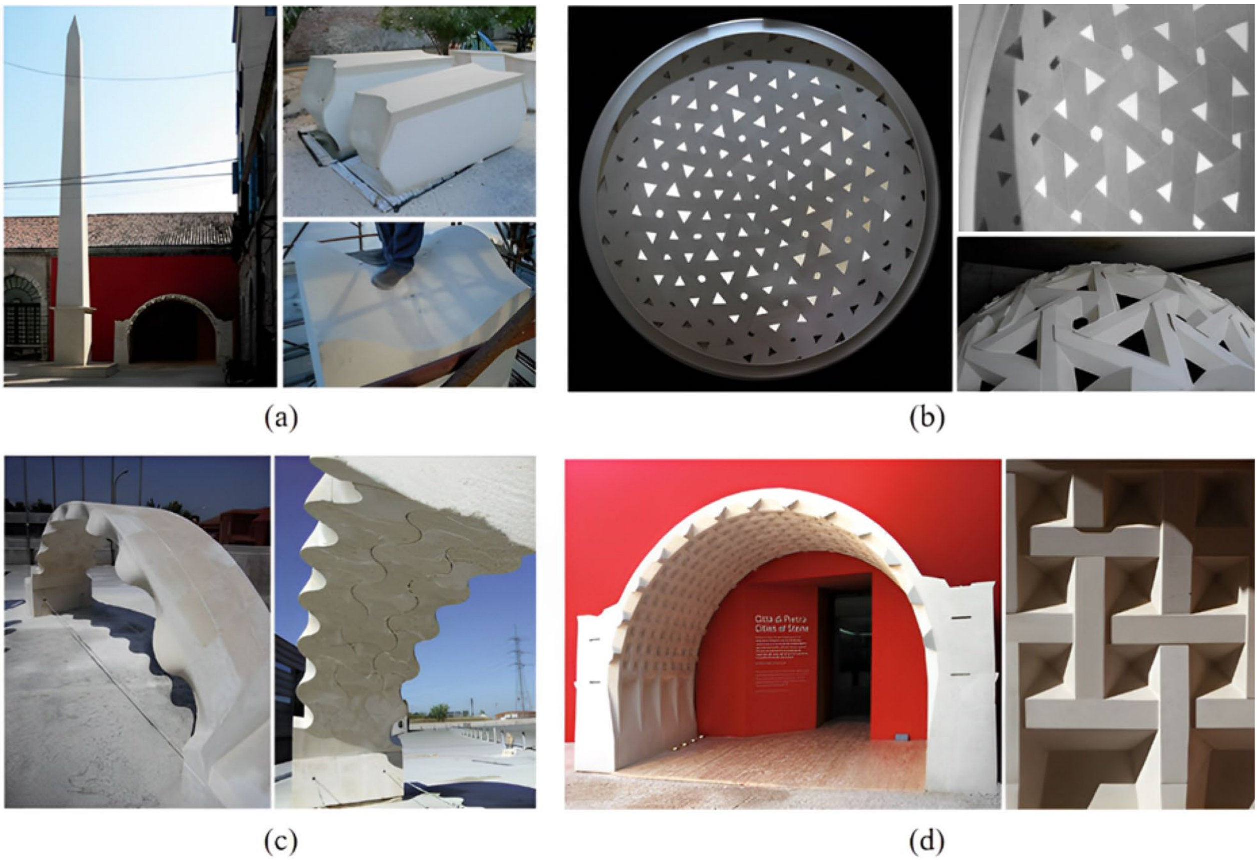


Fig. 26 Applications of interlocking elements in architectural designs (Fallacara et al., 2019): **a** Alexandros Obelisk, **b** Bin Jassim Dome, **c** Ponte Truchet and **d** Portale Abeille

been performed to analyse the behaviours of assemblies incorporating various topological interlocking elements. For instance, through indentation test, unusual negative stiffness was observed in the topological interlocking assemblies formed by cube-shaped elements (Estrin et al., 2004, 2009; Schaare et al., 2008). Schaare et al. (2009) examined the mechanical behaviour of cube assemblies, identifying a two-stage deformation process and highlighting the unusually high damping capacity (0.2–0.9) in these structures, primarily due to mechanical vibrations and friction at the contact surfaces of the cubes. An indentation test was conducted on a plate-like assembly that utilised interlocked tetrahedral elements, and the results demonstrated that the plate exhibited effective energy absorption capacity and appropriate stiffness in the specified direction (Khandelwal et al., 2015). Moreover, Mahoney and Siegmund (2022) utilised rolled monolayers of convex polyhedral units to generate topologically interlocked tubes. The behaviour of the tubes was investigated under diametrical loading, a significant enhancement in both strength and toughness was obtained, compared to non-interlocking ones. In 2012, Carlesso et al. (2012) studied sound absorption in structures segmented with osteomorphic bricks. They found enhanced sound absorption by assembling topological interlocking osteomorphic bricks made from dental stone GC Fujirock material. Moreover, Carlesso et al. (2013) demonstrated that the geometry and arrangement of osteomorphic bricks offer an additional level of flexibility that can be adjusted to improve acoustic characteristics (Carlesso et al., 2012, 2013). In 2013, Molotnikov et al. (2013) found that segmenting a monolithic sandwich core into interlocked osteomorphic blocks significantly improved deflection at failure and energy absorption in three-point bending tests. Despite a simultaneous decrease in flexural modulus, this compromise was considered acceptable for achieving a balanced set of properties in the sandwich panels (Molotnikov et al., 2013). Furthermore, Molotnikov et al. (2015) demonstrated that the stiffness of the topological interlocking materials could be controlled through active management of internal constraints. Koureas et al. (2023) examined the behaviour of topologically interlocked structures, specifically slab-like assemblies with curved and wave-like interfaces. Simulations revealed that the blocks maintained structural integrity despite realistic friction, overcoming challenges with high friction values. The study underscored that utilising such blocks markedly improved work-to-failure and ultimate deflection, offering novel insights into the strength and energy absorption of these structures. In 2016, Djumas et al. (2016) explored the influence of different altered osteomorphic blocks on the mechanical properties in nacre-inspired materials. The hybrid structures in their research included rigid blocks with intricate soft interfaces, constituting around 13.5% by volume. Their study revealed improved mechanical performance, preventing brittle failure in composite structures. In addition, Rezaee Javan et al. (2020) conducted a set of quasi-static experiments and utilised a 3D numerical model to investigate the mechanical responses of an assembly plate composed of topological interlocking concrete bricks with rubber serving as soft interfaces.

In addition to exploring the quasi-static behaviour of topological interlocking structures, researchers have recently turned their attention to their dynamic response (Ali et al., 2013; Feng et al., 2015; Javan et al., 2016). Rezaee Javan et al. (2017, 2018) conducted comprehensive experimental and numerical studies on the impact response of assembly plates constructed from the concrete interlocking bricks with four curved side surfaces, particularly focusing on structures subjected to drop-weight impact. It was found that, compared to the concrete monolithic plate and the plate assembled with concrete osteomorphic bricks, the assembly plate constructed with the interlocking bricks with four curved side surfaces exhibited significantly better flexural performance (the capacity of the assembly to resist bending or flexing without experiencing permanent deformation or failure), impact energy absorption, deflection, crack resistance and structural integrity (Javan et al., 2017, 2018).

It should be noted that brittleness of concrete presents challenges in interlocking structures, potentially compromising their integrity and performance. However, this can be mitigated through fibre reinforcement or other strengthening techniques (Słowik, 2019).

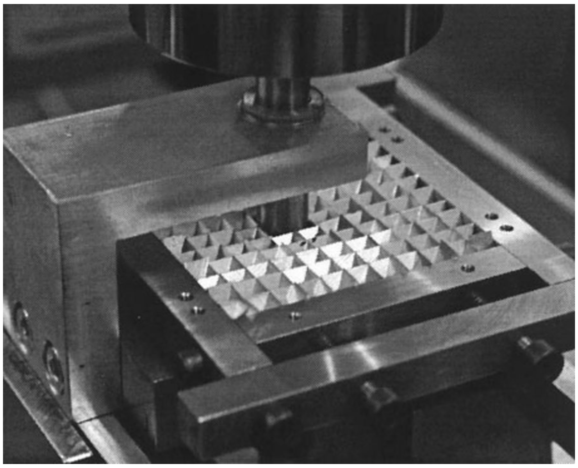


Fig. 27 Indentation test conducted on a self-locking assembly of tetrahedrons (Dyskin et al., 2001a)

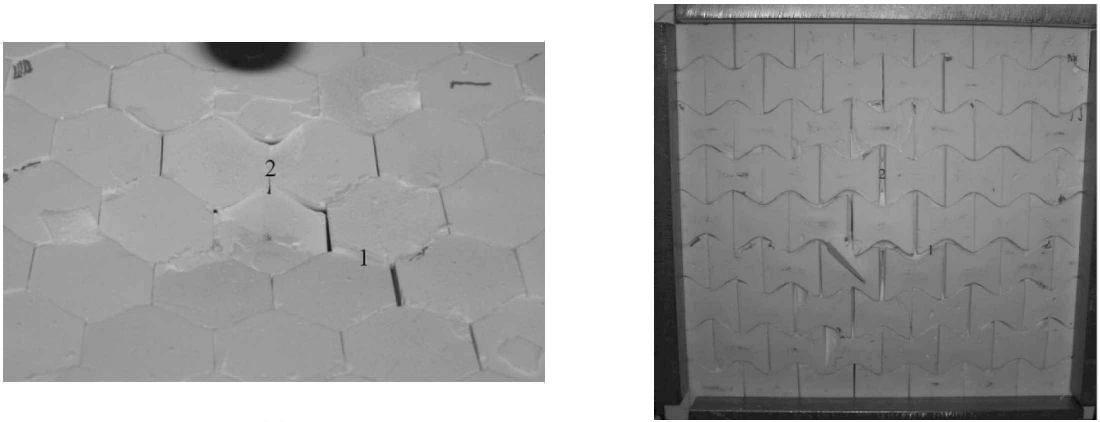
Xu et al. (2023) conducted drop-weight tests on a tubular structure with non-planar topological interlocking steel fibre-reinforced concrete (SFRC) elements. This study revealed that the interlocking interface could limit crack formation and propagation, enabling the remaining bricks to continue operating and preventing a complete failure of the structure. Recently, Schapira et al. (2024) studied blast dynamics in prestressed segmented columns with osteomorphic interlocking blocks. They found that block detachments significantly affected energy absorption. Key parameters influencing blast response included block number, axial prestress and interlocking level, with interlocking identified as a crucial factor for passive blast load mitigation.

In the subsequent sections, a more detailed review is provided on the fracture resistance, structural integrity, bending flexibility, energy absorption and movability and reparability of topological interlocking structures.

3.1 Fracture Resistance

One significant characteristic of topological interlocking structures is their exceptional ability to withstand fracture. Using the indentation test shown in Fig. 27, Dyskin et al. (2001a, 2001b) demonstrated that the utilisation of topological interlocking tetrahedral elements could effectively prevent crack propagation, leading to substantial improvement in fracture toughness.

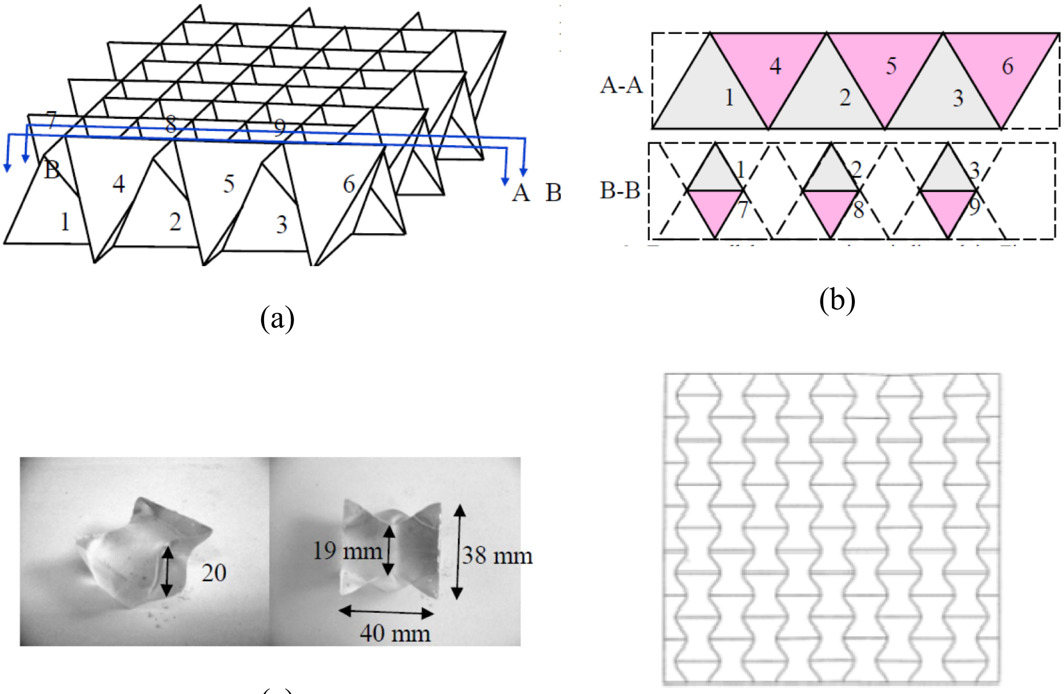
In the studies carried out by Autruffe et al. (2007) and Krause et al. (2012), indentation tests were conducted on plate-like assemblies made of osteomorphic blocks under quasi-static load. In both studies, it was demonstrated that cracks, when initiated within an individual block, proved incapable of propagating across interfaces into adjacent blocks. Fig. 28 shows the result of the damage distribution in the study carried out by Krause et al. (2012). Furthermore, Khor et al. (2002) examined the fracture resistance of two plate-like structures with interlocking elements through indentation tests. One structure consisted of tetrahedra arranged in a specific configuration (Fig. 29a and b), while the other was assembled with osteomorphic blocks (Fig. 29c and d). The results showed that when cracks initiated in an individual block, they could not propagate across



(a)

(b)

Fig. 28 Damage distribution in the plate assembled with osteomorphic ceramic bricks after an indentation test (Krause et al., 2012): **a** Top surface and **b** bottom surface



(a)

(b)

(c)

(d)

Fig. 29 Plate-like structures made of topological interlocking elements (Khor et al., 2002): **a** The assembly of topologically interlocked tetrahedra, **b** two parallel cross-sections, i.e. A-A and B-B, **c** a single osteomorphic brick and **d** top view representation of the assembly comprising osteomorphic bricks

interfaces into adjacent blocks. The fracturing of the assemblies was confined to the blocks directly exposed to the load, with all other blocks remaining intact.

Rezaee Javan et al. (2017, 2018) conducted drop-weight impact tests on a monolithic concrete panel and a concrete panel assembled with topological interlocking bricks featuring four curved side surfaces. The

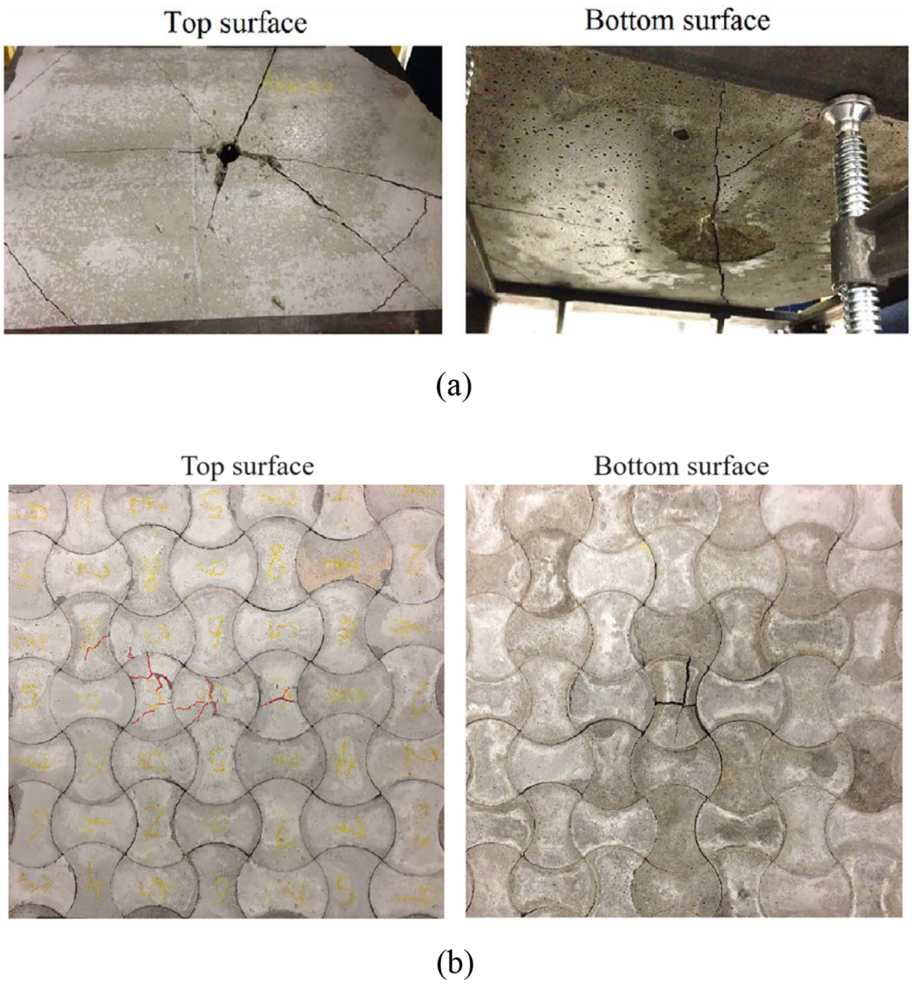
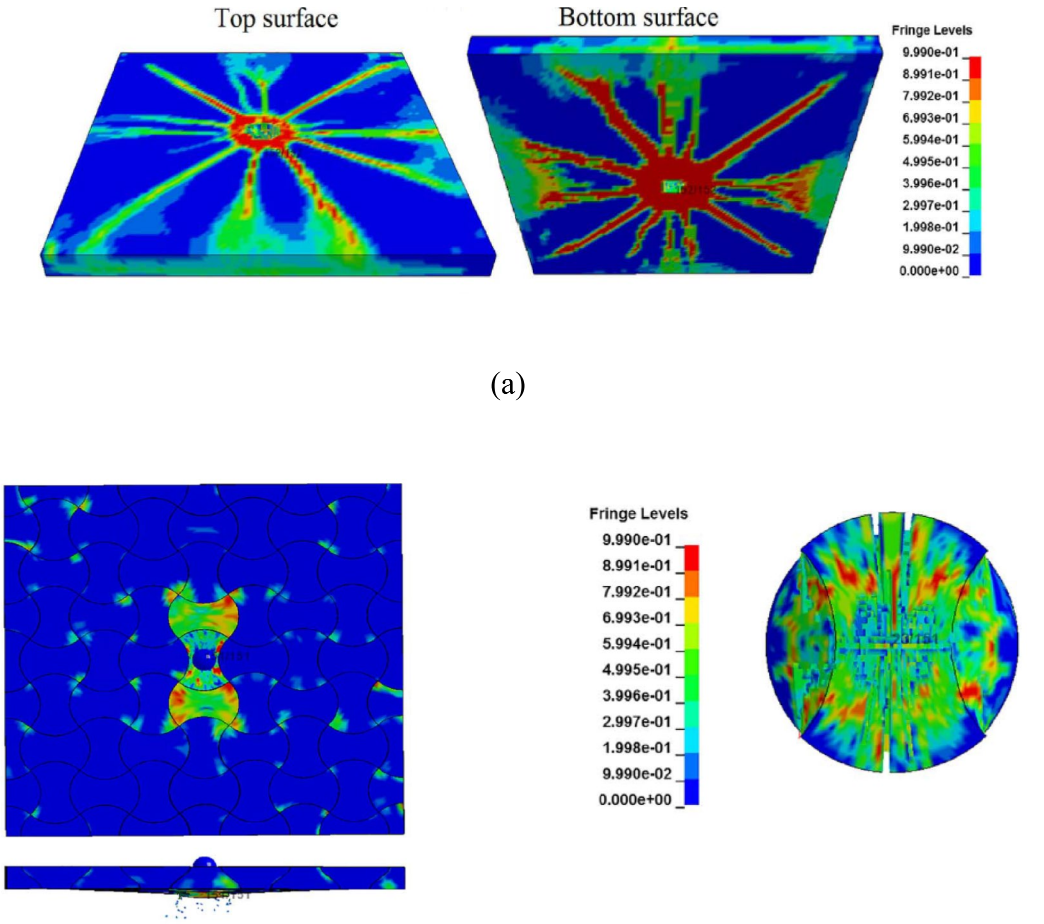


Fig. 30 Damage distribution under impact load (drop-weight tests) (Javan et al., 2017, 2018): **a** A monolithic plate and **b** an assembled plate using topologically interlocked bricks with four curved side surfaces

authors additionally developed 3D finite element models to replicate the dynamic reactions of the assembly plate formed by their suggested interlocking bricks when subjected to impact loads (Javan et al., 2018). As shown in Figs. 30a and 31a, cracks propagated throughout the monolithic plate, encompassing its entirety up to the edges. In contrast, the propagation and spread of cracks were effectively impeded in the interlocking assembly plate. Only limited bricks experienced failure, allowing the remainder of the assembly to maintain its structural integrity (Figs. 30b and 31b) (Javan et al., 2017, 2018). A similar phenomenon was also observed in Xu et al.'s study (Xu et al., 2020) involving a non-planar interlocking tubular structure subjected to impact.

Fig. 32 shows the predicted damage distributions for tunnels subjected to impact, comparing monolithic, normal assembly and interlocking assembly types as studied by Xu et al. (2020). The interlocking assembly tunnel experienced localised damage at the impact location with less overall damage. In contrast, the monolithic and normal assembly tunnels suffered extensive damage. The interlocking structure demonstrated superior damage control and maintained its integrity even when individual elements were missing.

Since interlocking bricks are not bonded to each another, when cracks form in a brick, the interfaces between the bricks act as barriers to prevent the cracks from propagating further. Furthermore, cracks tend to follow complex paths within interlocking assemblies, generating secondary cracks at the contact points between the bricks, as shown in Fig. 33. This would lead to enhanced energy dissipation and an overall increase in the resistance to fractures at macroscopic level (Autruffe et al., 2007; Krause et al., 2012).



(a)

Effective plastic strain contour (top surface)

Effective plastic strain contour of the centre brick (bottom surface)

(b)

Fig. 31 Damage distribution under impact load (FEA models) (Javan et al., 2018): **a** A monolithic plate and **b** an assembled plate using topologically interlocked bricks with four curved side surfaces

3.2 Structural Integrity

In the past, experimental studies have been conducted on plates constructed with different types of topological interlocking bricks, demonstrating a remarkable capability to maintain structural integrity, even when elements were damaged or removed (Krause et al., 2012). In the study reported by Khor et al. (2002), indentation tests were performed on plate-like assemblies formed by topological interlocking tetrahedra and osteomorphic bricks, as well as an assembly of rectangular bricks with the same thickness. The number of removed blocks varied from 1 to 8 before applying the load. Fig. 34 shows the positions of missing block in assemblies made up of tetrahedra bricks, osteomorphic bricks and rectangular blocks. It was found that the topological interlocking assemblies could withstand local failures without compromising their integrity and exhibited higher flexibility and tolerance towards missing bricks in comparison with the assembly of rectangular blocks.

A similar property was also observed in the experiment performed by Rezaee Javan et al. (2017) on a concrete panel assembled by interlocking bricks with four curved side surfaces. Dyskin et al. (2005) explored this aspect in the context of extra-terrestrial construction, revealing varying tolerance to missing blocks in different structural assemblies. Osteomorphic blocks and square-based tilling, such as a layer-like structure of topologically

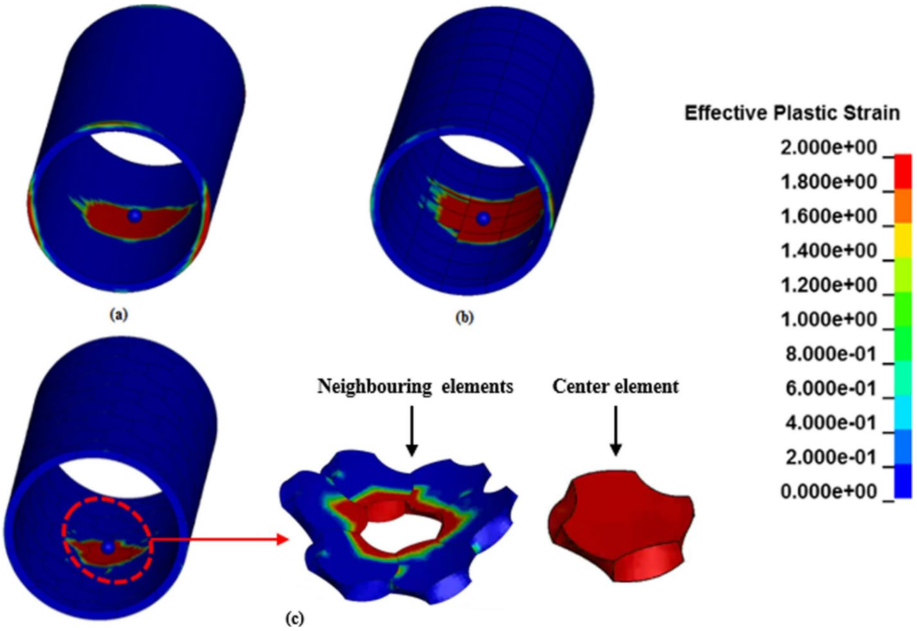


Fig. 32 Damage distributions in concrete tunnel models (Xu et al., 2020): **a** Monolithic, **b** normal assembly and **c** interlocking assembly

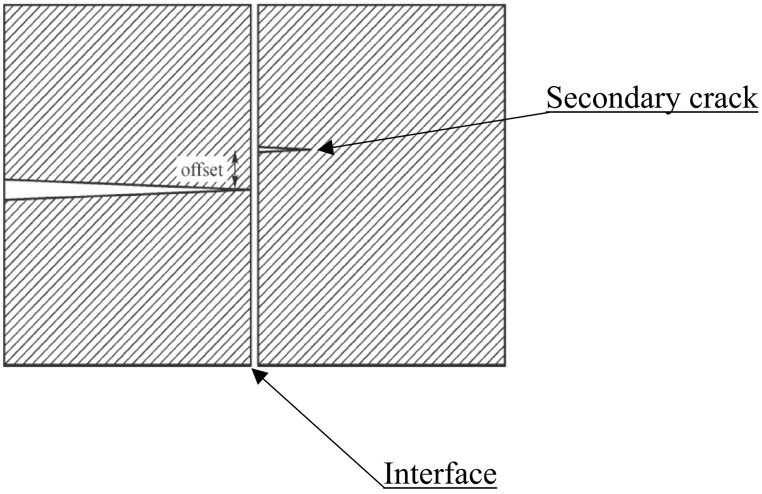


Fig. 33 Deviation in the propagation of fractures at the interface between topological interlocking blocks. (Dyskin et al., 2012)

interlocked tetrahedra, maintained integrity even with the removal of individual blocks. On the contrary, hexagon-based tilling structures disintegrated under similar circumstances. They suggested that for structures prioritising overall integrity with some acceptable element loss, square tiling or osteomorphic blocks were suitable. If easy element replacement was a priority, hexagon tiling-based structures were recommended. In this case, each element can be accessed by removing elements one by one via the shortest path, as illustrated in Fig. 35 (Dyskin et al., 2005).

Furthermore, based on the investigations into the deformation of monolithic plate and plate-like assemblies of osteomorphic blocks under three-point bending and point loading, Piirainen and Estrin (Piirainen & Estrin, 2017) demonstrated that the structural integrity characteristics of topological interlocking could offer a significant and innovative approach to road construction. In addition, in the numerical simulation carried

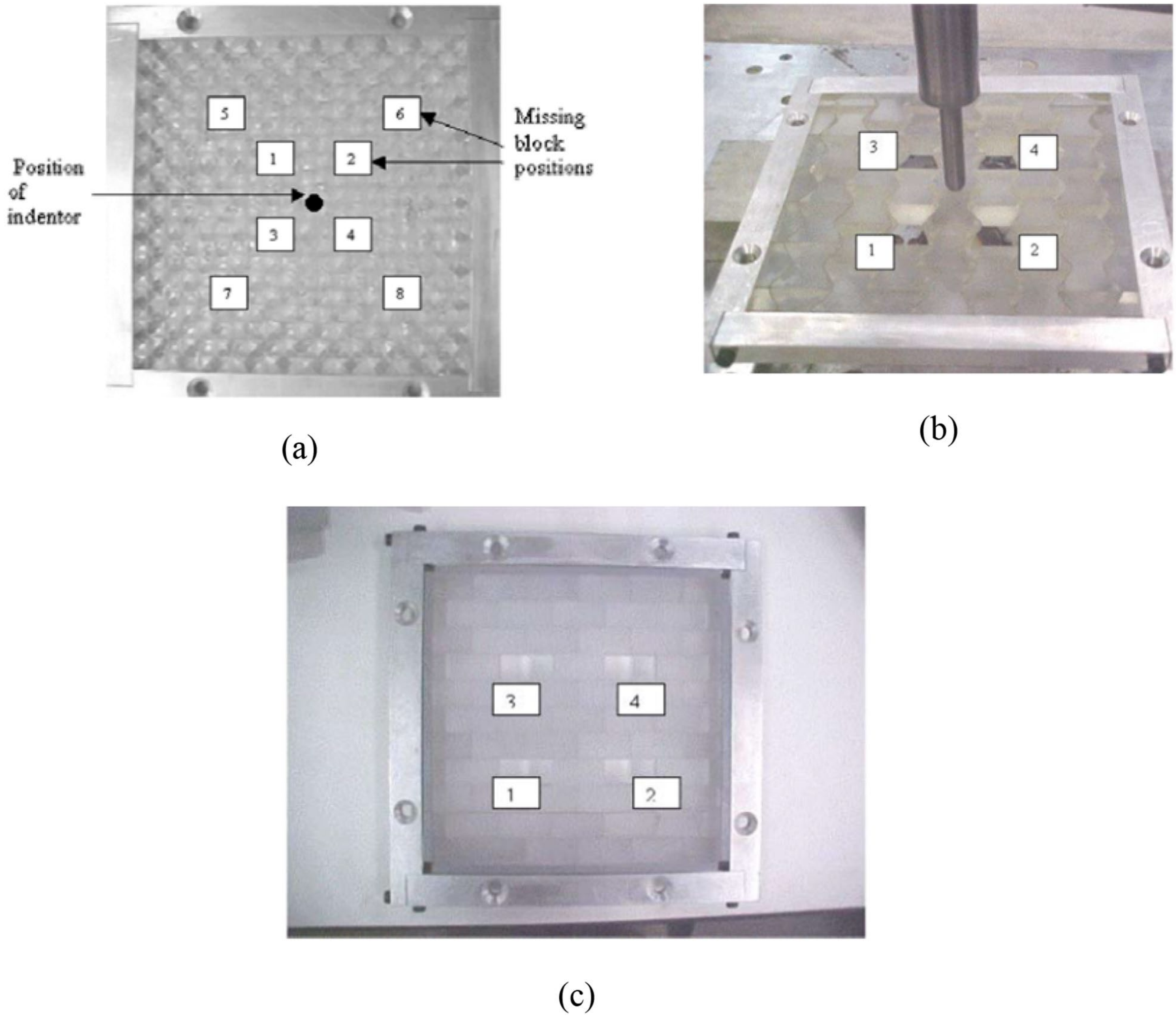


Fig. 34 Positions of missing blocks (Khor et al., 2002): **a** Assembly of tetrahedron-shaped blocks, **b** assembly of osteomorphic blocks and **c** assembly of rectangular blocks connected through friction

out by Molotnikov et al. (2007), the damage tolerance of osteomorphic brick assembly was investigated. The study simulated scenarios involving random failure of individual bricks, similar to situations with projectiles or random impacts on a protective structure. The results indicated that the plate assembled with osteomorphic bricks exhibited the capacity to withstand a loss of up to 25% of its bricks without compromising its structural integrity. This characteristic found versatile applications in engineering structures, including but not limited to protective shields, anti-blast walls, bulletproof vests and other similar applications (Estrin et al., 2021; Molotnikov et al., 2007).

3.3 Bending Flexibility

The absence of binder phase in topological interlocking structures results in a significant increase in bending flexibility. Through segmentation of a solid plate into an interlocking assembly, a remarkable transformation occurs, effectively converting a stiff and brittle structure into a more flexible one with reduced bending stiffness. The bending flexibility of topological interlocking structures was showcased in a comparative study conducted by Dyskin et al. (2003b), where they examined a plate assembled with osteomorphic bricks made of Al–Mg–Si alloy (as shown in Fig. 36a) and compared it to a monolithic plate made from the same material using indentation tests. Despite having

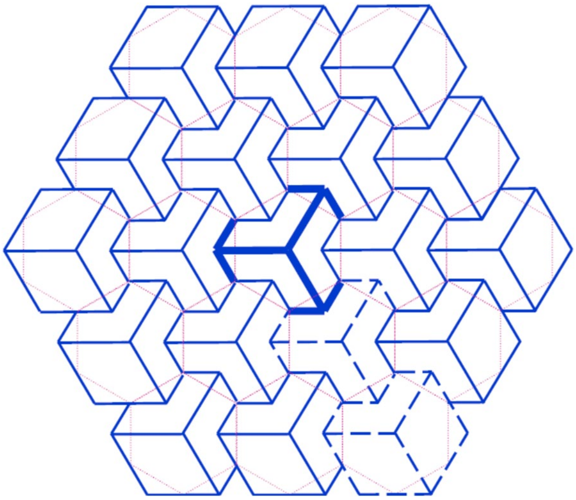


Fig. 35 A route for addressing a defective element (highlighted): Dashed lines display the elements that need removal to reach the faulty element (Dyskin et al., 2005)

a lower load-bearing capacity compared to the reference monolithic plate, the interlocking assembly plate exhibited remarkable resilience in terms of withstanding significant deflections (Fig. 36b). This was achieved through the relative movement of bricks, rather than relying solely on structural bending. Furthermore, Khor et al. (2002) demonstrated that interlocking plates provide greater flexibility compared to solid plates or plate-like structures constructed from conventional rectangular bricks and mortar. Krouse et al. (2012) also observed the same results in their study on topologically interlocked assemblies with osteomorphic bricks fabricated from ceramic. In addition, plates constructed using tetrahedral and cubic elements also exhibited similar characteristics (Dyskin et al., 2001a; Estrin et al., 2004; Schaare et al., 2008). Fig. 37 shows the indenter displacement results obtained from drop-weight impact tests on both monolithic and topological interlocking assembly concrete plates, each confined with initial torques of 5 Nm and 10 Nm, at a drop height of 200 mm, as reported by Rezaee Javan et al. (2017). The test results revealed that the deflection of the interlocking assembly plate was approximately 30% greater than that of the monolithic plate, indicating superior flexural tolerance of the topological interlocking assembly concrete plate.

Two factors may contribute to the increased bending compliance in topological interlocking structures: The presence of interfaces leads to a reduction in the elastic moduli within the plate, and bending resistance is decreased as partial contact loss occurs at the interface during bending (Dyskin et al., 2012).

3.4 Energy Absorption

Another major feature of topological interlocking structures is their high energy absorption capacity. In Mirkhalaf et al.'s study (Mirkhalaf et al., 2018), 15 interlocking ceramic panels with different designs incorporating truncated forms of the Platonic solids (as illustrated in Fig. 38), along with a monolithic panel, were tested under quasi-static and dynamic loads through applying a localised force to the top face of the central blocks. Fig. 39 shows the test results. It can be seen that, among the various assemblies, the interlocking octahedral panel exhibited superior energy absorption and load-bearing capabilities. In addition, the energy absorption in

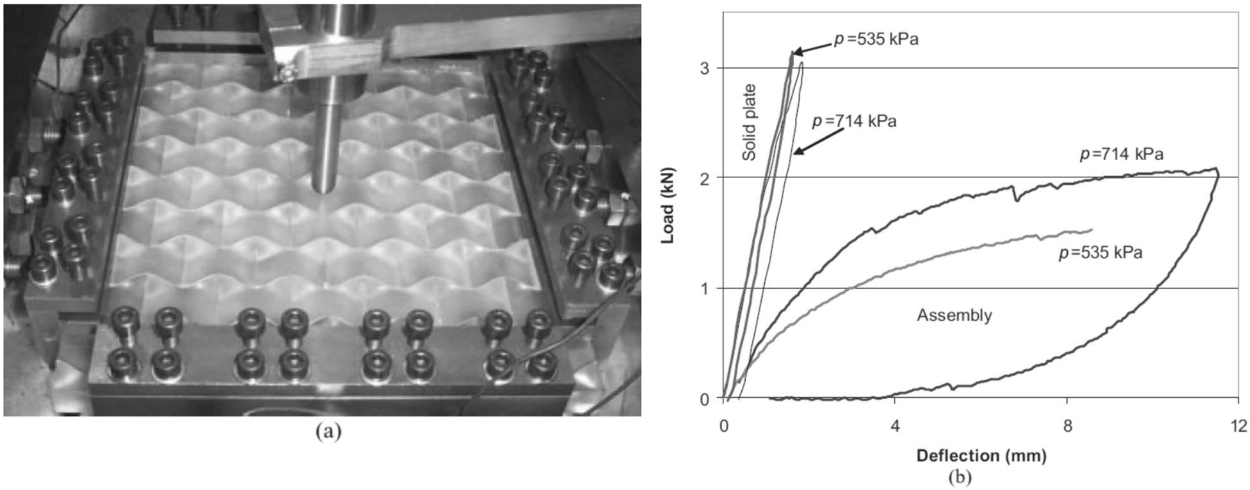


Fig. 36 Indentation test on interlocking assembly plate (Dyskin et al., 2003b): **a** Experimental setup, and **b** load versus deflection curves

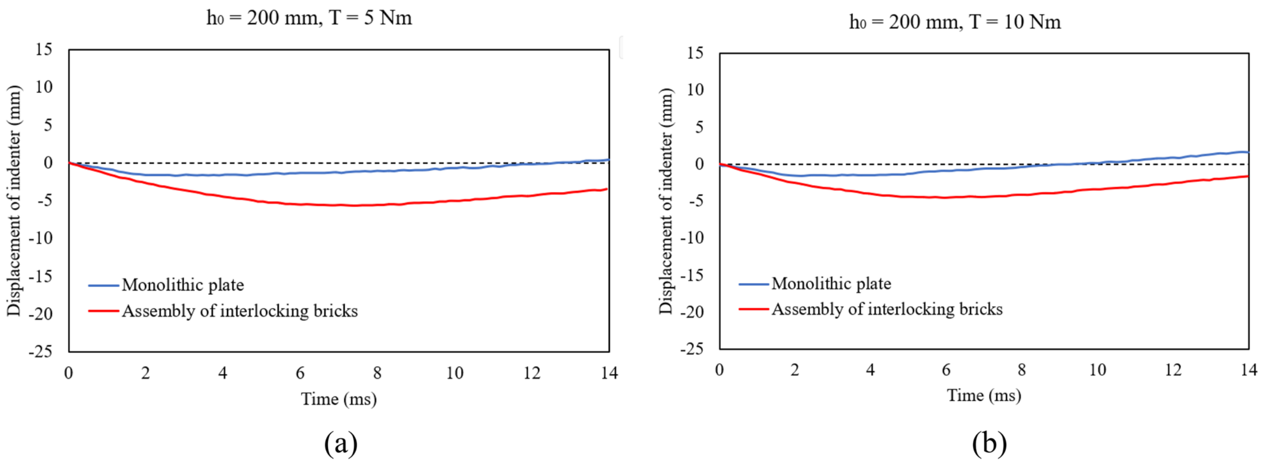


Fig. 37 Indenter displacement in topological interlocking assembly and monolithic plates confined with initial torques of **a** 5 Nm and **b** 10 Nm at a drop height of 200 mm (Javan et al., 2017)

interlocking panels was significantly greater than that in the monolithic panel.

Dramatically enhanced energy absorption ability was also achieved in the quasi-static studies reported in Refs. (Dyskin et al., 2001a, 2003b; Estrin et al., 2004; Schaare et al., 2008) on interlocking panels assembled with tetrahedron-shaped elements, cube-shaped elements and osteomorphic blocks. Moreover, Rezaee Javan et al. (2017, 2018) explored the impact response of interlocking assembly plates through drop-weight impact tests and finite element analysis. They discovered that these plates exhibited greater impact energy absorption capacity compared to monolithic plates. The impact loading configuration and the plate specimen in Rezaee Javan et al.'s study (Javan et al., 2017) are presented in Fig. 40. In addition, through a 3D numerical study, Xu et al. (2020) showed that tunnel lining structure assembled with non-planar topological interlocking elements could absorb significantly more energy than both the monolithic structure and the one made of regular pieces when subjected to impact loads. As shown in Fig. 41, a rise in impact velocity unveiled a more evident contrast in energy absorption, underscoring the superior effectiveness of tunnels constructed using interlocking elements.

3.5 Streamlined Fabrication and Repair Process

The mutual support among elements in topological interlocking assemblies is facilitated by local kinematic constraints, which result from the shapes and relative positioning of the elements. Also, the elements can be assembled and disassembled as a rigid body through translation and rotation, without any deformation (Estrin et al., 2021). Utilising topological interlocking allows for the construction of structures that offer the unique advantage of effortless disassembly and relocation. By removing constraints, the entire structure can be dismantled, transported to a different location and reassembled. This facilitates the convenient replacement or repair of damaged components once the structure is disassembled (Piirainen & Estrin, 2017; Ross et al., 2020).

In the study reported by Ross et al. (2020), a three-point bending test was conducted on a beam made of interlocking tessellated acrylic tiles (Fig. 42a). The result revealed that localised damage could occur within individual tiles, as shown in Fig. 42b. Such damage can be addressed through substitution to restore the load-bearing capability. When the beam collapsed, the damage was primarily localised in two tiles, leaving the rest of the tiles undamaged throughout the test. The impaired tiles were then replaced, and the beam underwent another round of testing. The mended beam exhibited strength and rigidity that were essentially indistinguishable from those of the beam in its initial condition.

In addition, Mather et al. (2012) studied the effects of damage, repair and reassembly on small-scale tetrahedral plate-like structures made of ABS (Acrylonitrile Butadiene Styrene). Three remanufacturing strategies were applied to the topologically interlocked materials (TIMs). After initial loading, a new TIM was disassembled, and the tetrahedra positions were randomised before reassembly and a second loading, resulting in TIM-R1. This process was repeated to produce TIM-R2. Mather et al. (2012) then investigated partial replacement of failed tetrahedra, creating TIM-R3R. For TIM-R3R, six of thirteen failed tetrahedra from TIM-R2 were replaced with new ones, reducing the damage level to that of TIM-R1. Fig. 43 compares the force–displacement behaviour of a new TIM, fully remanufactured TIMs with randomly

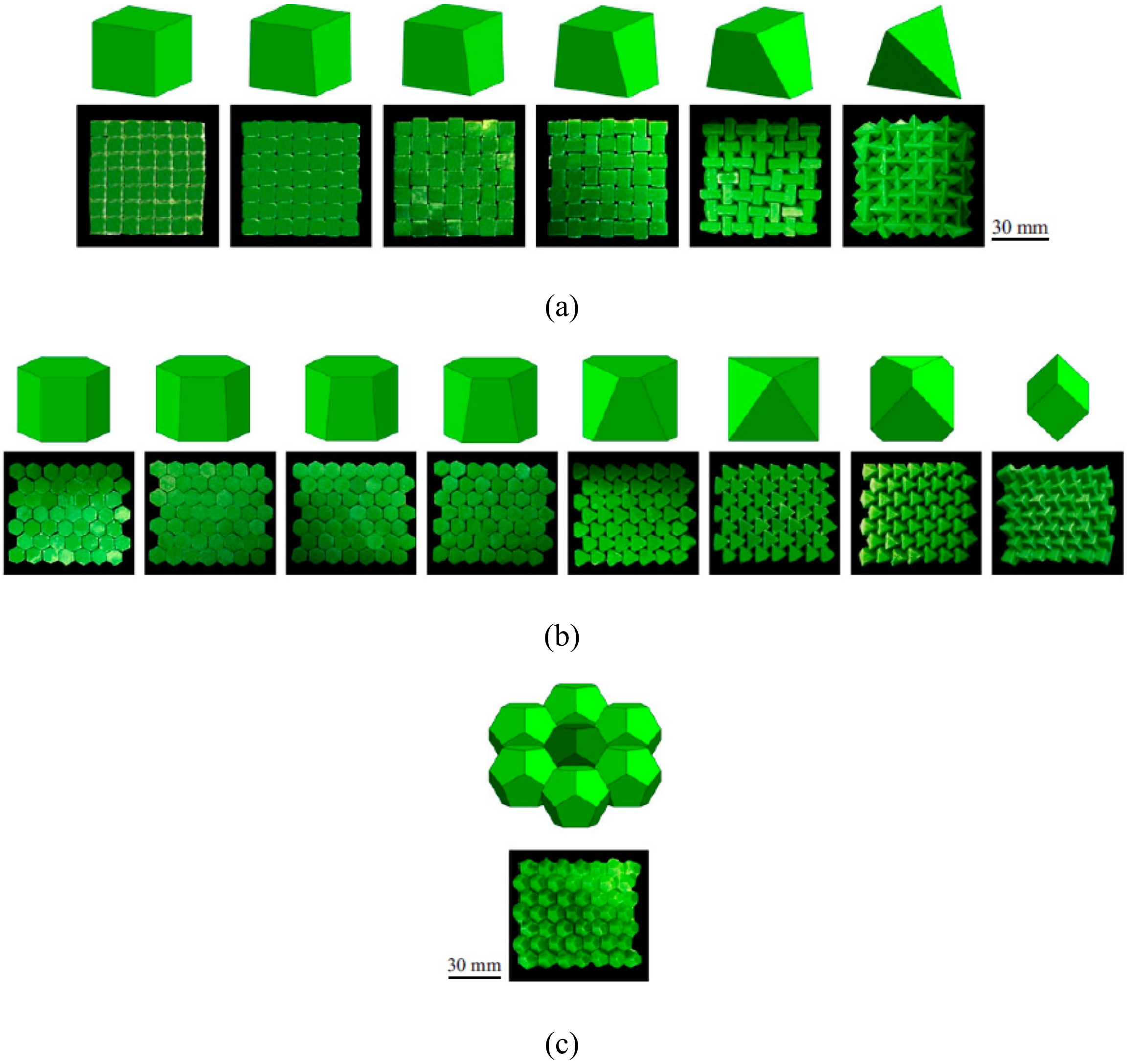
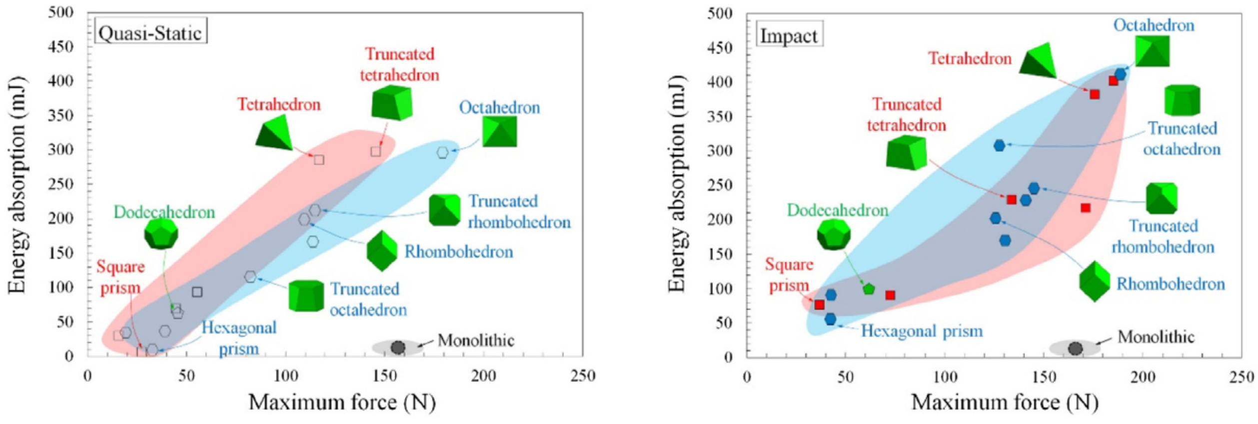


Fig. 38 Interlocking ceramic panels (Mirkhalaf et al., 2018): **a** Truncated tetrahedra, **b** truncated octahedra and **c** dodecahedron

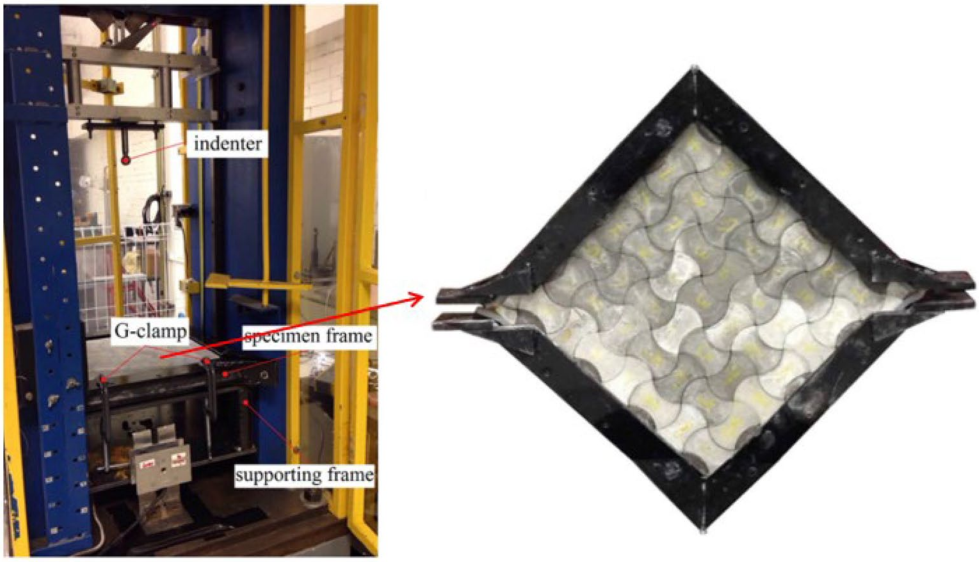
placed damaged and intact elements (TIM-R1, TIM-R2) and a TIM with replaced damaged elements (TIM-R3R). Although stiffness and ultimate load decreased with repeated remanufacturing, the TIMs retained considerable structural integrity and energy absorption capacity. Replacing damaged elements (TIM-R3R) improved both stiffness and load-bearing capacity compared to TIM-R2 but did not achieve the performance levels of TIM-R1. The results suggest that strategic remanufacturing could effectively mitigate performance degradation during reuse. Their findings demonstrated that remanufacturing TIMs was feasible, highlighting their potential for sustainable and reusable applications.

Despite these advantages, the repair process faces several challenges. A major issue is ensuring precise matching of replacement parts. Variations in material quality and manufacturing tolerance can make it difficult to achieve a perfect fit, which is crucial for maintaining the assembly's structural integrity. In addition, the assembly's integrity may be compromised with multiple repairs, as repeated disassembly and reassembly can cause wear or misalignment. Overcoming these challenges requires precise attention to both the design and manufacturing processes. This includes ensuring that replacement parts are manufactured with tight tolerance and that the assembly process accounts



(a) (b)

Fig. 39 Mechanical behaviour of ceramic panels composed of topological interlocking bricks derived from both full and truncated Platonic bodies, subjected to **a** quasi-static and **b** dynamic loads (Mirkhalaf et al., 2018)



(a) (b)

Fig. 40 Impact test on interlocking assembly plate (Javan et al., 2017): **a** Experimental setup, and **b** interlocking assembly plate specimen

for potential wear and misalignment. By focusing on these details, the structure can remain robust and fully functional throughout its lifecycle, even after multiple repairs.

4 Discussion

Topological interlocking structures are assembled with a number of elements without binders or connectors. The elements rely on their unique shapes and arrangement, as well as a global external constraint, to keep them in place. In addition, the constraints imposed by the surrounding elements restrict the movement of the local elements, ensuring their precise alignment. The review of topological interlocking systems in this paper highlights their potential as innovative solutions for materials and structures. The distinctive mechanical properties and versatility of interlocking materials designate them as promising candidates for a wide array of applications. Through a comprehensive examination of existing research and experimental findings, the characteristics of the topological interlocking structures can be summarised as follows:

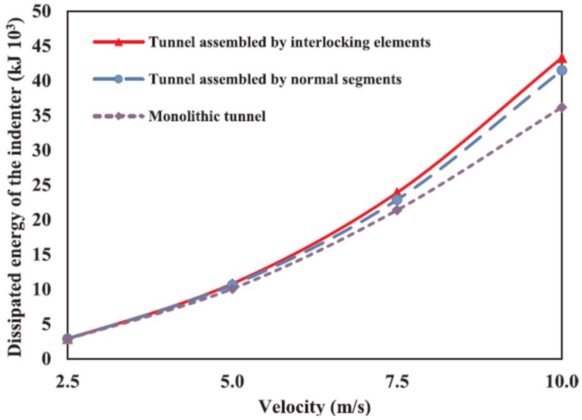


Fig. 41 Energy absorption capacity of three underground concrete tunnels subjected to a confining load of 0.3 MPa (Xu et al., 2020)

- These structures exhibit remarkable resistance and tolerance to crack propagation and local failures.
- In comparison to solid structures, topological interlocking structures offer increased flexibility and compliance.
- These structures possess high energy and sound absorption capabilities.
- They feature ease of assembly and disassembly, making them well suited for robotic manufacturing, and the bricks are completely recyclable.
- The structures showcase the potential to integrate diverse materials within a single interconnected framework, thereby providing multifunctionality to the overall structure.

Despite the promising aspects of topological interlocking systems, there remain research gaps and challenges that need to be addressed. For example, the reported high sound absorption capabilities are based on a limited number of studies (Carlesso et al., 2012, 2013), with varying degrees of detail. Further research is needed to confirm the consistency of this property across different interlocking structures and engineering applications. While these properties have shown promise, more comprehensive investigations are required to assess whether they can be reliably replicated in diverse contexts.

Most existing applications of interlocking elements centre around assembling planar elements. Nevertheless, there is a requirement to explore non-planar surfaces to tackle diverse practical engineering challenges, including those found in tunnels, bridge barriers, pipelines and other areas, which have not been thoroughly explored to date. The sufficiency of work related to non-planar

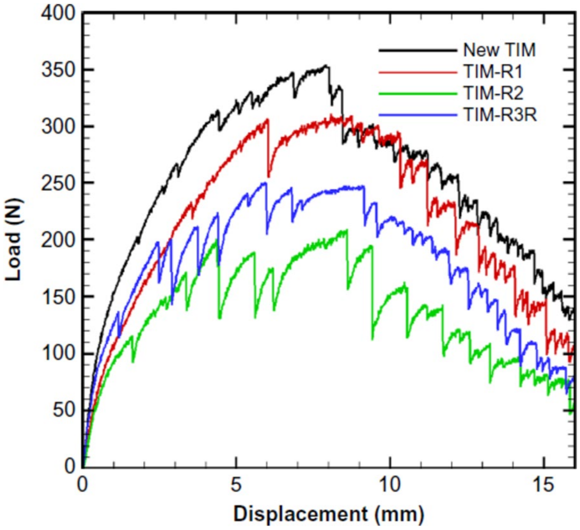


Fig. 43 Force–displacement behaviour of different TIMs (Mather et al., 2012)

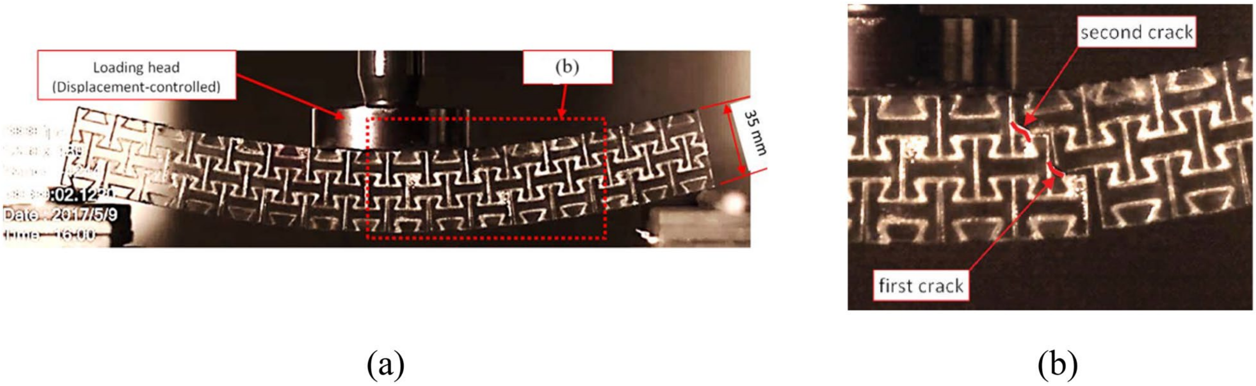


Fig. 42 Three-point bending test (Ross et al., 2020): **a** A beam comprising topological interlocking tessellated tiles, and **b** localised damage within individual tiles

elements may be limited due to historical emphasis on planar structures, coupled with challenges, such as complex design requirements, advanced manufacturing needs and the lack of standardised approaches. While initial progress has been made in creating non-planar elements, there is a lack of a mathematical method to explicitly describe the interlocking features of such elements, hindering further development for achieving optimum design. Utilising computational tools and optimisation algorithms can help in designing both planar and non-planar interlocking elements for specific applications.

Moreover, most of the current research appears to focus on relatively small-scale laboratory tests. Size effect has the potential to impact the structural behaviour of a system, including energy absorption, impact resistance, damage tolerance, load-bearing capacities and overall stability (Djumas et al., 2017; Mirkhalaf et al., 2019; Short & Siegmund, 2019; Zakeri et al., 2023a, 2023b). To ascertain the scalability and practicality of interlocking structures in real-world scenarios, a comprehensive examination of the potential size effect is essential to better understand and optimise their structural behaviour. Exploring advanced testing methods and computational simulations may contribute to addressing these challenges effectively.

Although interlocking structures have demonstrated promising attributes under static conditions in many existing studies (Autruffe et al., 2007; Dyskin et al., 2001a, 2001b, 2003b; Estrin et al., 2004, 2009; Khor et al., 2002; Krause et al., 2012; Molotnikov et al., 2007, 2015; Schaare et al., 2008), their response under various loading conditions, which is essential for engineering applications, remains inadequately investigated. Factors to consider encompass dynamic loads, such as cyclic loading, seismic events and impact scenarios, as well as high-temperature or fire exposures, and extreme environments affecting long-term structural integrity and performance, such as corrosion induced by chloride iron penetration. A more comprehensive investigation into these aspects will contribute to a more robust analysis of the performance and reliability of interlocking structures in diverse real-world scenarios. Researchers can develop algorithms that take into account various loading types, material properties and desired structural performance to create optimal interlocking designs and assess performance beyond static conditions.

Furthermore, investigating the integration of multiple materials within interlocking structures holds the potential for novel applications. The combination of materials with distinctly different properties in a single structure may result in enhanced performance and functionality. Although some limited studies have been conducted in this area (Ashby & Bréchet, 2003; Estrin et al., 2011; Javan et al., 2020; Xu et al., 2023), more investigation is needed to ensure the use of these kinds of materials in engineering projects. This avenue of research further harnesses the advantages of interlocking structures, particularly when exploring hybrid structures.

Also, future research should explore the use of advanced materials, such as high-performance composites and engineered ceramics, to improve the performance of topological interlocking structures. It is important to investigate how these materials influence structural behaviours, such as fracture resistance, flexibility, crack propagation, local failures and overall structural compliance. This research will pave the way for developing more effective interlocking systems.

In addition, it is crucial to assess the economic feasibility of implementing interlocking structures in real-world projects. This includes evaluating material costs, manufacturing processes and construction techniques, particularly in relation to mass production, assembly and maintenance. Methods like additive manufacturing and advanced modular construction can play a key role in improving production efficiency and precision, making these evaluations even more relevant.

Interdisciplinary collaboration between material scientists and structural engineers is essential for addressing the complex challenges of interlocking structures. By jointly exploring material properties and structural behaviour, researchers can develop new design methodologies and optimisation strategies. Integrating insights from structural engineering, materials science and computational modelling will promote holistic and effective interlocking systems.

5 Conclusions

In this paper, a comprehensive review of various types of topological interlocking elements is conducted, elucidating their distinctive characteristics, potential applications and structural performance. Utilising topological interlocking elements in construction facilitates the design of structures with improved mechanical properties, achieved by arranging specially shaped elements without binders. This approach shows positive results in fracture resistance, bending flexibility, energy absorption as well as efficient assembly and disassembly. It also allows for the integration of diverse materials, enabling the creation of multifunctional structures.

Despite these promising results, research on topological interlocking structures is still in its early stages, with significant gaps remaining. Key areas requiring further investigation include understanding the behaviour, stability and long-term durability of interlocking structures under various loading scenarios and environmental conditions; exploring non-planar applications; addressing size effects and integrating sustainable materials and advanced manufacturing techniques. Addressing these research gaps is crucial to fully realise the potential of topological interlocking structures. Overcoming these challenges will not only advance the field but also has the potential to revolutionise the construction industry by introducing more efficient, sustainable and innovative infrastructure solutions.

It is recommended to develop a holistic design approach that integrates the geometric design of topological interlocking elements with their arrangements, taking into account material performance. Ongoing research should also prioritise exploring the behaviour, stability and durability of interlocking structures under various loading scenarios, including extreme conditions like dynamic loads and high temperatures, to enhance its applicability. Furthermore, integrating sustainable materials and exploring advanced manufacturing and construction techniques will improve the environmental performance and efficiency of interlocking systems. Addressing these research areas has the potential to unlock the full capabilities of topological interlocking, shaping the future of construction and infrastructure development.

Acknowledgements
Not applicable.

Author contributions
MTG carried out the conceptualisation and investigation and participated in writing, reviewing and editing the article. XL supervised the student and contributed to the conceptualisation, methodology, writing, reviewing and editing of the article. AZ supervised the student and contributed to writing, reviewing and editing the article. All authors read and approved the final manuscript.

Funding
This work was supported by the Australian Research Council [DP200100631, FT240100301].

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 26 July 2024 Accepted: 29 September 2024

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