

# Review on Geometry Modifications and Material Combination Methods to Improve the Re-Entrant Honeycomb Structure

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*Abstract: Metamaterials can provide a unique answer to the ever-increasing and complex requirements from engineering products. Artificial metamaterials are mostly arranged lattices; a special subcategory are auxetic lattices. The most widely known and researched auxetic lattice is the re-entrant honeycomb structure. Besides its outstanding properties, the structure is characterized by low in-plane stiffness and buckling. These disadvantageous properties can effectively be compensated for by geometric modifications and with material combinations. In this review article, effective geometric modification approaches are categorized and introduced, followed by material combination methods.*

*Keywords: review; re-entrant honeycomb; auxetics; material combination; geometric modification*

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## 1 Key Concepts – the Need for Metamaterials

The ever-increasing requirements for unique creations can be considered the driving force of relevant research. Nowadays, in addition to outstanding structural performance, engineering products are also expected to have additional purpose-specific properties such as energy absorption or vibration damping [1]. Advances in metamaterial design, especially auxetic lattices, can be the answer to the increasing demands of the industry. Before proceeding further, we need to clarify several key concepts.

Metamaterials are materials whose properties do not primarily depend on their mechanical properties, but on their structural layout [2]. Lattices can be classified as a regularly arranged group of metamaterial cells. Fig. 1 illustrates the relationship of key concepts relevant to this review article.

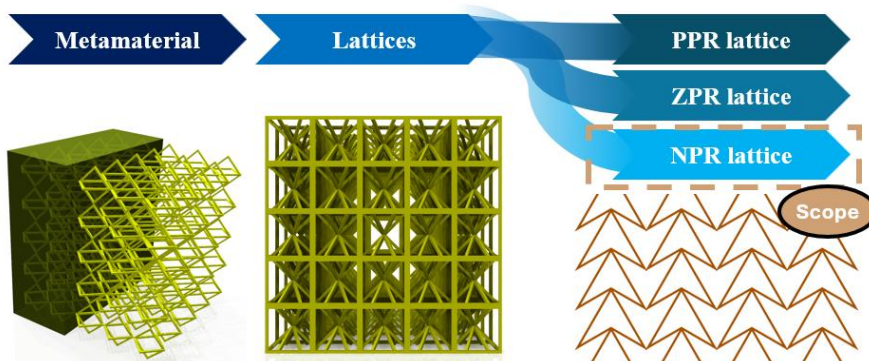


Figure 1

Visual representation of key concepts relevant to this review

Lattice structures are periodic, porous structures [3], and due to their outstanding energy absorption capacity [4,5], strength [6], and noise attenuation [7] capabilities, and due to the achievable weight reduction [8], these structures can be the answer to today's engineering demands. Lattice structures are, therefore, widely used in highly demanding industries such as the military [9], the automotive [10, 11], aerospace [12] and sport industry [13], just to name a few. Such lattices are man-made—artificially created purpose-designed structures. However, there are also stochastic, natural lattices, such as wood and bones [14].

Metamaterials can be classified and studied based on several vibrational [15-18], thermal [19, 20] and mechanical [21-24] parameters. Depending on the structure – especially if auxetics are the focus of the research area – classification can be based on sign of their Poisson's ratio [21].

Based on the sign of the Poisson's ratio, lattice structures can be classified into three groups: negative Poisson's ratio (NPR), positive Poisson's ratio (PPR) and zero Poisson's ratio (ZPR) materials [25] (Figure 1). Each group has specific advantageous properties and unique application areas. Positive Poisson's ratio structures are primarily used for weight reduction [26] due to their excellent strength-to-weight ratio [27] and specific, tailorable mechanical properties. The most iconic PPR lattice is the so-called honeycomb [28] structure. Materials with a zero Poisson's ratio (ZPR) are a less explored area, despite their many unique applications. ZPR materials have a promising future in the aerospace industry, especially in wing morphing [29]. Many natural tissues also have zero Poisson's ratio [30] therefore ZPR materials are also promising in tissue engineering [31].

## 2 Auxetic Deformation Behavior and Unique Advantages

The relationship between transverse and longitudinal strain is described by the Poisson's ratio of the material, which typically ranges from 0 to +0.5, as most engineering materials expand in directions perpendicular to the direction of compression [32, 33]. However, some materials shrink under compression and expand transversely under tension—the Poisson's ratio of these materials is negative. This deformation behavior is illustrated and compared to standard, non-auxetic behavior in Fig. 2. Materials with a negative Poisson's ratio were named auxetic materials by Evans et al. [34] and this name is still used in scientific publications.

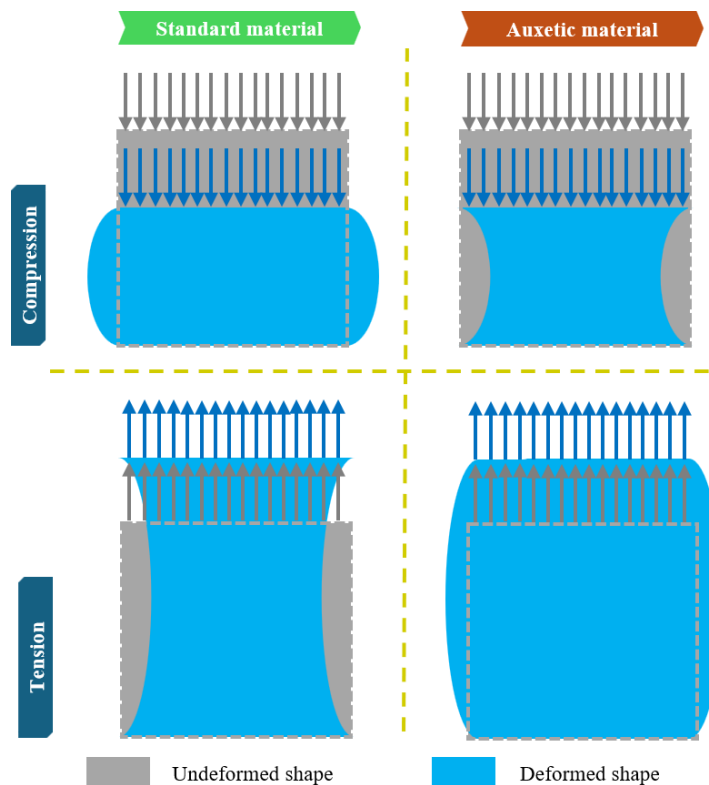


Figure 2

Illustration of the auxetic deformation behavior for compressive and tensile load compared with the behavior of standard materials

One might ask: why are these structures important to us? Auxetics has a plethora of unique, outstanding properties, such as increased resistance to fracture [35, 36], higher energy absorption [4,37], increased hardness [38], and resistance to indentation [39] and dynamic loads [40].

## 2.1 Brief Historical Overview

The history of auxetic materials dates back nearly 100 years, starting as early as 1927-28 [41]. There are two significant, noteworthy periods in the history of auxetic materials, the first being the second half of the 1980s, when researchers made auxetic behavior essentially designable by analyzing numerous geometric and topological effects [42-44]. In the 90-s auxetic materials gained more attention through real-world applications. Choi *et al.* [45] developed a novel auxetic rivet, which owing to its auxetic behavior expands when pulled, creating an even stronger connection when stressed. Based on the same principle, Evans *et al.* [34] claimed that auxetic seals are more reliable than conventional seals. The second, greatest period in the history of auxetics was brought about by the emergence of additive manufacturing, which enabled researchers to rapidly create and study, novel, intricate and complex lattice structures. Most of the novel auxetic unit cell designs introduced in this review article are produced by additive manufacturing.

Not all auxetic structures are man-made. In nature, we are surrounded by many materials that exhibit auxetic behavior; for example, the udder of a cow [46], the skin of a salamander [47] or a cat [48] are also auxetic. Minerals, elements such bismuth, cadmium, thallium and single-crystal arsenic are also auxetic [49-51] just to mention a few; several researcher projects have been inspired by nature [52].

## 2.2 Introduction and Shortcomings of the Auxetic Honeycomb

One of the most widely known and perhaps most widely studied and improved lattice structure is the 2.5-dimensional auxetic honeycomb—the topic of our recent review article (also known as the re-entrant honeycomb). This structure has most of the favorable properties of auxetic structures presented in the previous chapters. The mechanical behavior of the honeycomb structure—characterized by parameters such as the Poisson's ratio and Young's modulus—has been extensively investigated by numerous researchers [53-55], resulting in a comprehensive understanding of the influence of geometry on its properties [56].

Another, very prominent grouping principle in the case of lattice structures is the deformation mechanism. The auxetic honeycomb, or re-entrant honeycomb as its name suggests has a re-entrant deformation mechanism [57]. Under a tensile load, the re-entrant edges open outwards, thus expanding the unit cell laterally, while under a compression load; the behavior is reversed. The theoretical deformation mechanism is illustrated in Fig. 3a. The deformation mechanism can only be fully exploited if there is a significant amount of porosity, thus auxetic structures have limited in-plane stiffness, and are, therefore, not recommended for applications requiring high load capacity [58].

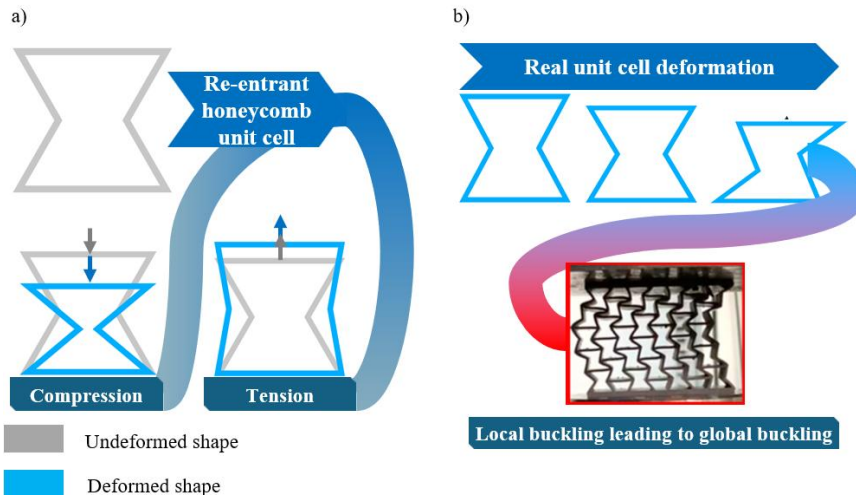


Figure 3

The theoretical and real deformation behavior of the re-entrant honeycomb structure; a) the theoretical deformation response of the structure to compression and tension; b) the real deformation behavior for compression—initial auxeticity is followed by buckling, based on [59]

Fig. 3a illustrates the theoretical deformation of a re-entrant structure. However, in reality (Fig. 3b), initial (theoretical) auxeticity is followed by lateral buckling. Lateral buckling is the greatest disadvantage of the re-entrant honeycomb and all other re-entrant structures as well [57]. The tendency to buckle increases with decreasing relative density (i.e., increased porosity), thus limiting the achievable weight reduction [14]. Local (limited to a single unit cell) and global (affecting the entire specimen) buckling modes are both characteristic of the re-entrant honeycomb, but global buckling occurs more typically [60]. Researchers have investigated whether minute modifications, not affecting the unit cell design, can delay buckling—geometrical modifications such as changing the aspect ratios have minimal effect, while increasing thickness can lead to a small increase in buckling load [61].

Therefore, buckling cannot be avoided even by changing certain geometrical parameters, so in order to make the re-entrant honeycomb a truly high-performance, predictable structure, more advanced geometrical modifications are required.

### 3 The Basic Concept of Metamaterial Design and Improvement

The basic concept of metamaterial design is the artificial creation of structures that have certain desired properties. Another option is to create an improved or fundamentally novel structure based on an existing lattice structure. If the objective is to improve an existing structure (as the scope of this review article), there are two basic concepts: either replace certain unit cell constituents and perform a partial geometric modification (Fig. 4a) or add additional constituents to the structure (Fig. 4b) [62]. The latter is referred to as embedded or nested geometric modification.

Improved metamaterial design can be achieved by combining two existing structures, even with different deformation behaviors (Fig. 4c). Material combination (Fig. 4d) is another method that can greatly improve mechanical properties, just as much as gradient design.

All the above-mentioned methods are widely researched, with the aim of improving the re-entrant honeycomb. Fig. 4 summarizes and illustrates the methods which are reviewed in this article.

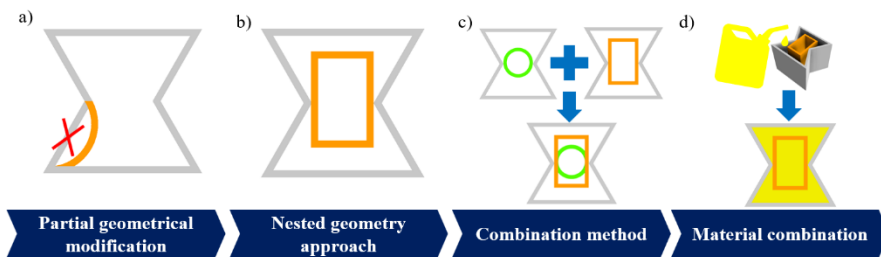


Figure 4

The four main paths of improving the re-entrant honeycomb structure; a) partial geometrical modification; b) nested geometry approach; c) combination method; d) material combinations

#### 3.1 Methods Based on Partial Geometrical Modifications

First, methods based on significant geometric modifications to the initial unit cell are presented. Developments in this concept category include geometry modifications where one or more edges (hereinafter referred to as constituents) of the original unit cell are replaced with a new constituent (Fig. 4a).

Yilin *et al.* [63] replaced the re-entrant edges of the re-entrant honeycomb with zig-zag-shaped elements (Fig. 5a). The authors concluded that many novel geometries sacrifice auxetic behavior for increased stiffness. They also stated that many novel structures cannot be manufactured with traditional cost-effective techniques.

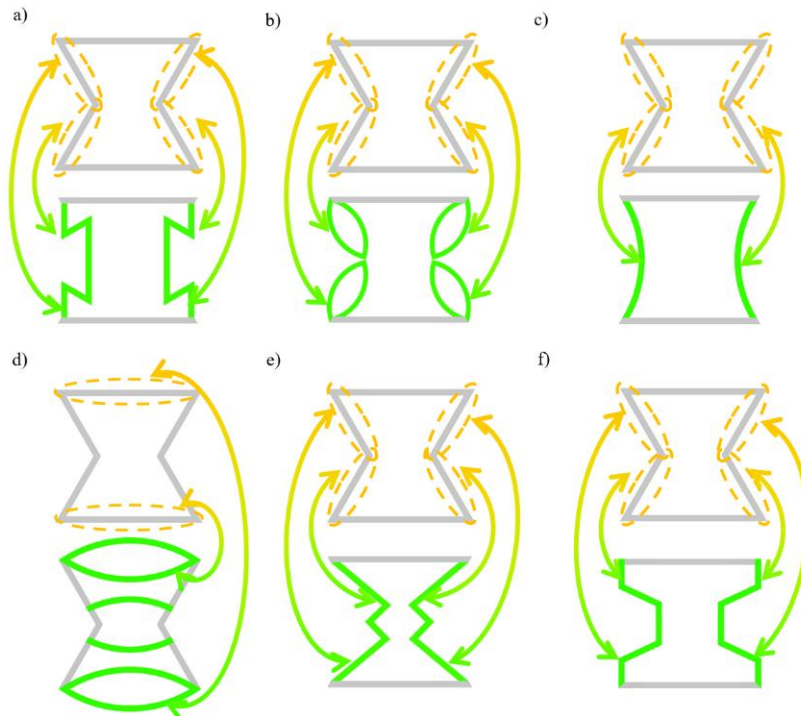


Figure 5

Effective structures based on the partial geometric modification method; a) Re-entrant edges replaced with “zig-zag” constituents [63]; b) Re-entrant edges replaced with circular constituents [64]; c) Re-entrant edges replaced with a single arc [65]; d) Horizontal edges replaced with an arc segment [66]; e)

Re-entrant edges modified to be doubly re-entrant [59]; f) Re-entrant edges with added straight sections [67]

Based on the above, they created their zig-zag-shaped modification, in a way that provides the structure with increased stiffness and can be fabricated with traditional manufacturing technologies (the mortis and tenon method), and the structure retained its auxetic properties.

Re-entrant edges can be replaced with curved edges as Qi et al. [64] did (Fig. 5b). They replaced re-entrant edges with facing arc segments. In their comprehensive study, they also investigated the effect of the distance between these supplemented arc segments. Mechanical properties were not compared to the original re-entrant structure but deformation behavior became more stable and Poisson’s ratio became tailorable in the investigated parameter range. Partial geometric modifications can also be inspired by nature; Fig. 5c shows a novel unit cell design inspired by turtle shells. This shell inspired continuous arc segment replaces the two re-entrant edges with one single continuous curve segment: which as expected, results in homogeneous shrinkage deformation and smaller stress fluctuation during compaction [65].

Not only the re-entrant edges but the upper and lower horizontal edges can be replaced as well. Fundamentally, the re-entrant edges form the basis for the re-entrant behavior of the structure, therefore understandably, researchers have mainly focused on modifying these edges. However, Zied *et al.* [66] replaced the horizontal edges with curved segments resulting in increased in-plane stiffness. Developing their concept further, they also incorporated additional intermediate arc segments parallel to the lower and upper arcs (Fig. 5d). The additional arc segments resulted in increased in-plane stiffness with a moderate deterioration of the auxetic behavior.

Széles *et al.* [59] used a different approach compared to the ones presented above. Instead of completely replacing the re-entrant edges of structure, they made these edges doubly re-entrant by adding additional breakpoints (Fig. 5e), thus preserving the original structural intent. They achieved continuous auxeticity throughout a large deformation range and eliminated buckling.

Fig. 6f shows another novel re-entrant unit cell design created via the partial geometry modification method. Researchers aimed to improve the auxeticity of the structure via added straight sections, stabilizing, breaking up the sharp corners of the original design [67]. The novel design significantly increased the negative Poisson's ratio of the structure.

### 3.2 Nested Geometry Approach

The nested geometry approach is the most widely researched and most frequently used approach to improve the properties of a given lattice structure. Fig. 6 shows significant nested geometry approach modifications. In 2016, Lu *et al.* [68] increased the elastic modulus of the re-entrant honeycomb by installing a horizontal bar connecting the intersection point of re-entrant edges (Fig. 6a).

This is the simplest form of the nested geometry approach, which, in addition to its unquestionable improvement, significantly and unstably limits in-cell auxetic behavior. In contrast, to the simple straight, horizontal line arrangement, the inner four corners of the re-entrant unit cell can diagonally be connected, resulting in two additional constituents [69] (Fig. 6b). The added diagonal lines resulted in increased in-plane stiffness and Young's modulus. Authors also considered a similar diagonal approach (Fig. 6c), in the form of a rhombus stiffener, which proved to be effective as well [70].

Széles *et al.* diagonally connected the newly formed breakpoints of the doubly re-entrant edges (Fig. 6d) to further improve the doubly re-entrant structure, which is based on the re-entrant honeycomb (Fig. 5e). This resulted in stable deformation without buckling, regardless of geometric parameters [71]. Chen *et al.* combined two existing embedded designs, namely the ones in Fig. 6a and Fig 6c, and created their own novel structure (Fig. 6e) [72]. This geometry has given the structure a more flexible and stable deformation behavior in contrast to the design limiting deformation (Fig. 6a), and specific stiffness also increased. Considering the above,

we can state that even a design that is not completely innovative in terms of geometric structure can provide outstanding properties.

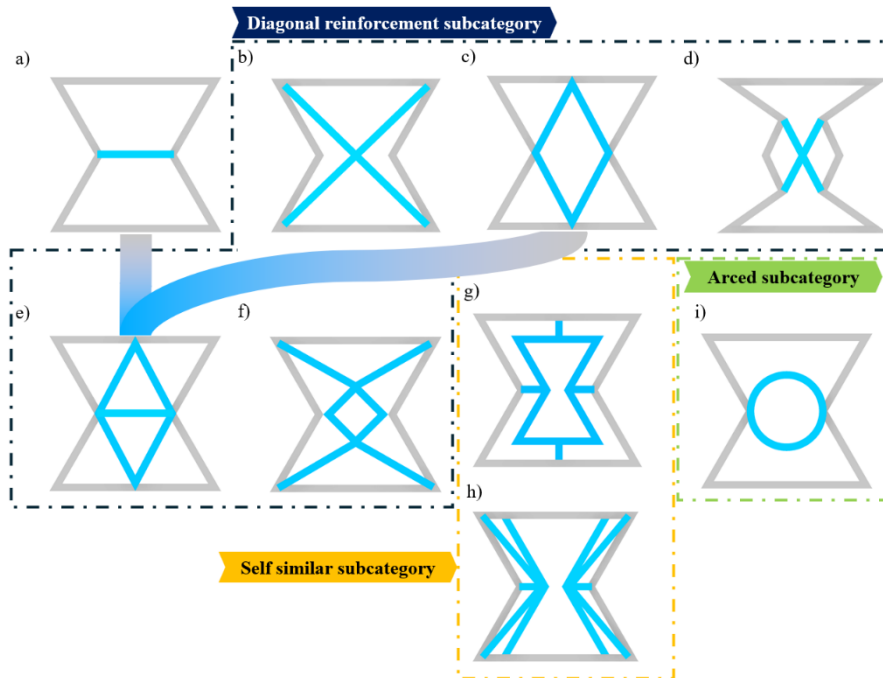


Figure 6

Significant examples and categories based on the nested geometry approach. a) added horizontal constituent [68]; b) diagonally connected corners [69]; c) embedded diagonal rhombus; d) diagonal reinforcement in the doubly re-entrant honeycomb structure [71]; e) a combination of structures in figures a and c [72]; f) multiple added diagonal constituents [73]; g) and h) examples for self-similar nested geometry modifications [74-76]; i) added circular segment [77]

Nedoushan et al. [73] created a uniformly complex unit cell design (still based on diagonal–rhombus reinforcement), in which each segment has its own, unique addition. In the middle, a rhombus reinforcing member is connected to the four corners of the unit cell with diagonal edges, resulting in a fairly complex structure (Fig. 6f). This novel structure with many added constituents resulted in increased strength and controllable Poisson's ratio. Another widely researched subset of the nested geometry methods is the self-similar unit cell design. Fig. 6g and Fig. 6h present self-similar unit cells based on the nested geometry approach. Self-similarity can significantly improve the stability of the re-entrant honeycomb [74-76].

Similarly to the partial replacement method, the beneficial effect of curve segments has also been proven in the nested geometry approach category as well [77] (Fig. 6i). Partially curved or fully curved segments result in a greater overlap between

segments, thus increasing the stiffness, energy absorption capacity [78] and auxeticity [79] of the structure, while simultaneously eliminating high-stress regions forming at sharp corners [80]. Curved elements also favorably affect the properties of the re-entrant honeycomb structure [81-83]. Fig. 6i shows an example of an arc-based nested geometry approach unit cell design. The added ring-shaped element provides a connection between the horizontal and re-entrant members, thus increasing the stability of the sutures without significantly affecting the Poisson's ratio of the structure.

### 3.3 Combination Methods

Unit cell designs in the previous two chapters showed novel ideas. However, we concluded that desired properties can also be achieved by combining two existing ideas, as was the case with the structure in Fig. 6e. Combination methods, as their name suggests, combine existing elements, thus creating a novel structure. The field of combination methods is diverse; combination can include two effective scientific results combined in hope of further property advancement. Another group of combinations, relevant to auxetic honeycombs, is the combination of deformation mechanisms. Reza *et al.* [84] combined the re-entrant and the significantly different chiral constructs, thereby overcoming the low compression resistance and anisotropy of re-entrant structures.

### 3.4 Combination of Materials

The mechanical properties of metamaterials can be further improved by material combinations. The most common and widely known material combination method is mixing additional material into the base materials. The best-known method is fiber reinforcement, which is well suited for extrusion-based technologies such as FDM (Fused Deposition Modelling) [85, 86]. The main advantage of mixing additional materials into the base materials is that the unit cell geometry can remain unchanged, and therefore unaffected. The effect of continuous fiber reinforcement on the re-entrant honeycomb was investigated by Quan *et al.* (Fig. 7a) [87]. They achieved a dramatic increase in compressive stiffness. One might assume that if fiber reinforcement is used, leaving the unit cell geometry unaffected, deformation behavior would remain unaffected as well. This assumption is correct, as fiber-reinforced re-entrant honeycombs still buckled laterally, although their Poisson's ratio decreased.

In addition to base material combinations, the porosity (voids) of lattice structures can be filled with a secondary, bulk material mostly to improve energy absorbing and damping properties [90-92]. A wide range of lightweight materials can be used to fill lattice structures such as polyurethane foam [92-94], metal foams [95, 96] and agar gels [88] (Fig. 7b).

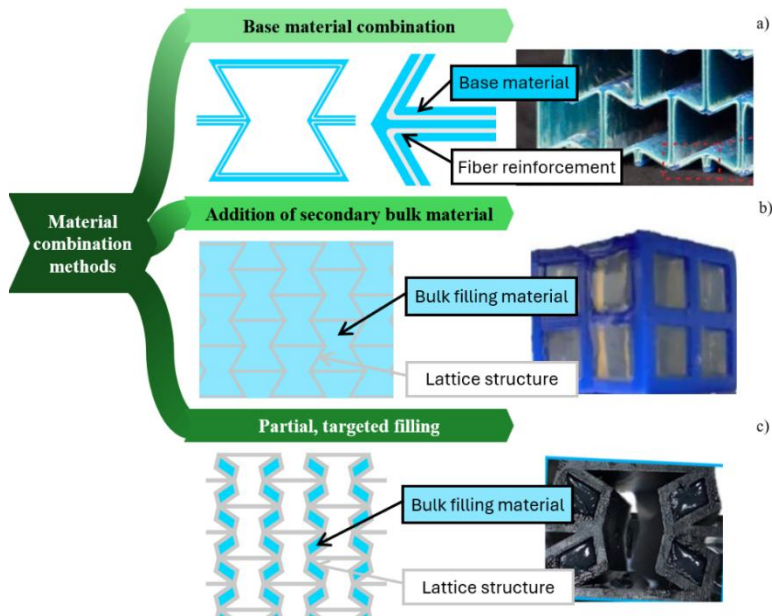


Figure 7

Material combination methods: a) base material combination – based on [87]; b) addition of a secondary bulk material – based on [88]; c) partial, targeted filling – partially based on [89]

In the paragraph above and in Fig. 7b, all voids of the lattices were filled with the secondary bulk material. However, no matter how compressible the bulk material is, it still limits deformational freedom. Széles et al. [89] investigated the effect of the partial filling of the doubly re-entrant honeycomb (Fig. 7c). Partial filling increased the energy absorption capability of the structures 2.5 times. Even more noteworthy, however, is the effect of partial filling on energy absorption characteristics. Researchers with this partial filling achieved bimodal energy absorption characteristics; first, impact speed is slowed down by large deformation and low resistance, followed by a sudden significant energy absorption zone. This bimodal characteristic is ideal for passenger protection in vehicles.

Finally, the disadvantages of material combination should also be mentioned. For successfully combined properties, the appropriate bonding of materials is essential. In the case of most of the presented methods, failure occurred along the interfaces (delamination, etc.), therefore, the bond must be at least as strong as the weaker material, otherwise the pairing is disadvantageous [97, 98].

## Conclusions

Auxetic lattices owing to their vast range of extraordinary properties can and are applied in a series of industries. The re-entrant honeycomb, is the most well-known such structure. However, besides its outstanding properties, it has its considerable disadvantages, which make it unsuitable for demanding purposes. This underscores

the importance of geometry improvement, as demonstrated by numerous examples in this review article. The presented categorized and subcategorized methods and techniques present fellow researchers with a state-of-the-art review on the tried and tested approaches which might inspire the creation of novel re-entrant honeycomb-based structures or other auxetic structures.

### Acknowledgements

Project no. 2025-2.1.1-EKÖP-2025-00019-FK-143 has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the 2025-2.1.1-EKÖP University Research Scholarship Programme (EKÖP) funding scheme.

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