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DOCTORAL (PHD) THESIS BOOKLET

LEVENTE SZÉLES

Impact analysis of geometric changes to improve the properties of auxetic lattice structures

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1 Research background

Traditional manufacturing technologies – based on material removal – significantly limit the shape of the parts that can be created. Among other things, ordered, specifically designed, internal space-filling structures, so-called lattice structures cannot be created via traditional manufacturing technologies. Lattice structures are periodic porous structures that can be classified as a regularly arranged group of metamaterials [1] (*metamaterials are materials whose properties do not depend on the constituent raw materials, but on the structure of the component [2]).* The continuously increasing and expanding requirements for technical creations can be met by the outstanding strength [3], energy absorption capacity [4,5], noise attenuation [6] and weight reduction capacity [7] of lattice structures. That is why lattice structures are widely used [8,9] [10].

There are numerous lattice structures; in my thesis I dealt with the property improvement of the very popular auxetic honeycomb (also known as the re-entrant honeycomb). Most materials expand under compression, but auxetic materials contract under compression, i.e., they have a negative Poisson's ratio [11]. Auxetic materials are gaining popularity due to their unique properties, such as increased energy absorption capacity [12,13], impact resistance [14], and high-velocity impact resistance [15]. The re-entrant honeycomb structure also has the above-mentioned advantages; however, the re-entrant deformation mechanism also has several disadvantages. The re-entrant deformation mechanism is prone to buckling [16], and its in-plane stiffness is low, making it unsuitable for applications requiring high load-bearing capacity [17].

To improve the properties of the re-entrant honeycomb structure, fellow researchers have created new, improved geometries based on two methods. One of the two possible methods is based on partial geometric modification, where some components of the unit cell are replaced, while the other method is the built-in (imbedded) geometric modification, where additional components are built into the unit cell.

Figure 1 (a) shows an example of a partial geometry modification, where the re-entrant edges were replaced with “zigzag” edges, increasing the stiffness of the structure. Figure 1 (b) shows an example of a built-in geometric modification, where researchers built in a rhombus element, thus also increasing the stability of the concave honeycomb.

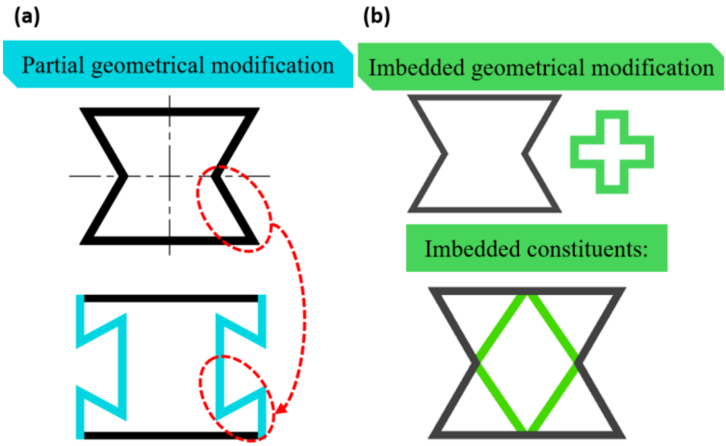


Figure 1. Illustration of possible ways to improve the re-entrant honeycomb structure. (a) Partial geometry modification, based on [18]; (b) integrated geometry modification, based on [19].

Naturally, in addition to geometric modification, material pairing-based methods [20], combination methods [21] and gradient design [22] can also lead to effective property improvements. The improvements investigated, although beneficial, have not always improved the deformation behavior or made the structure widely applicable.

2 Objectives

My objectives are to understand the effect of basic geometric parameters and to develop the auxetic honeycomb structure into a widely applicable structure, which in more detail:

- Developing a comprehensive test setup in which the effect of fundamental characteristics such as element number, stress state of the constituents and additional parameters can be investigated in a comparable manner.
- To assess the potential for improving the unfavorable properties of the re-entrant honeycomb structure.

- Increasing the deformation stability of the re-entrant honeycomb structure through geometric modifications in several steps.
- In all cases, geometric modifications must be parameter characterized, so that the effect of the modification can widely be investigated.
- Based on the performed modifications and parameter effect analysis, design and stability guidelines are formulated, along which I will continue the development.
- My aim is to achieve parameter independent deformation behavior for the re-entrant honeycomb.
- In addition to geometric modifications, the effect of segmented filling (material combination) is also investigated.

The testing of each development involves setting up a highly accurate finite element testing environment, thus eliminating the need to create specimens using additive technologies, thus accelerating development.

3 Materials and methods

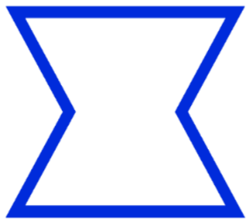
The presented developments were all made using additive manufacturing technologies. The samples prepared to investigate the effect of fundamental parameters were made using powder bed SLA technology, while the samples prepared for the testing of new unit cell designs were made using photopolymerization, more precisely masked stereolithography (mSLA). Printing was followed by technology-specific post-treatment in each case. Specimens were subjected to compression tests, and the measured and calculated results formed the basis for the evaluation. For each development an individually composed material mixture was created, which were subjected to tensile tests to determine the material properties (according to EN ISO 527-2 standard [142]).
In addition to the real compression tests, I also subjected the samples to finite element compression tests. The aim of setting up the finite element environment was to accurately represent real conditions.

3.1 Introduction

The deformation behavior and mechanical properties of lattice structures (compression resistance, energy absorption capacity) are influenced by many properties. In my research work, I created and examined a self-repeating geometry built from fractal-inspired square unit cells, and in addition to examining the effect of fundamental properties, I also set a goal to improve the deformation behavior of the re-entrant honeycomb structure (see the attached figure).

Since the re-entrant honeycomb structure is prone to buckling due to its significant porosity and re-entrant deformation behavior, in addition to improving the deformation properties, I also aimed to improve other mechanical properties, primarily increasing the compression resistance and increasing the energy absorption capacity. I aimed to achieve the desired goals with geometric modifications and by filling porosities.

The deformation behavior and other mechanical properties of the re-entrant honeycomb structure can effectively be improved if the central structural zone is more prominently designed.
Regarding the impact analysis of the basic characteristics and the improvement of the deformation and other mechanical properties of the re-entrant honeycomb, I formulate the following new scientific results:



Homorú méhsejt elemi cella

I. Thesis:

I created a new, fractal-inspired geometric arrangement of square unit cells, in which the specimens have the same volume and mass regardless of the increase in the number of elements (with the same enclosing dimensions) (Figure I). I found that increasing the number of elements – which results in a decrease in the size of the unit cells – results in improved compression resistance and energy absorption capacity. A slenderness ration, which can be interpreted as the ratio of the height to thickness of the vertical components, can be defined for the specimens created *(40x40x12.5 mm, created with SLA technology on ProX PA substrate; tests at 50% relative humidity)*. I have established that there is a limit to the increase in the number of elements, and thus the defined slenderness ratio, above which the tested mechanical properties – the compression resistance and the energy absorption capacity – do not change significantly (in the current square-based, fractal-inspired testing environment). I have proven this finding for the range of n=4…100 elements. Knowing the limit of the slenderness ratio, additive manufacturing technology accuracy required to produce a specimen with a given geometry can be determined, and a more economical technology can be selected.

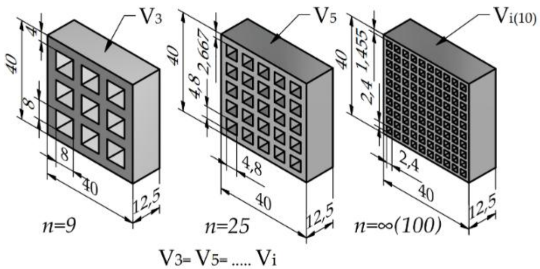


Figure I. Fractal-inspired samples built from square unit cells with different element numbers, indicating the main dimensions and properties.

Thesis I. is based on the following publications [S1] [S5].

II. Thesis:

To improve the deformation and other mechanical properties of the re-entrant honeycomb, which is prone to buckling, I created a modified, doubly re-entrant honeycomb structure. The new structure is based on the re-entrant honeycomb, and the geometric modification is characterized by the offset and deg parameters (Fig. II). The new break points introduced by the doubly re-entrant design give the structure greater deformation freedom, thus encouraging continuous auxetic behavior under compressive loading. Furthermore, increasing the values of the *offset* and *deg* parameters used to describe the doubly re-entrant honeycomb shifts the deformation behavior of the structure towards continuous auxetic behavior as opposed to buckling.

a) Increasing the offset and deg parameter values in the investigated range (offset = 0.6…1.4 mm; deg = 30…40°) results in gradually improving mechanical properties that surpass the properties of the original structure for all investigated parameter combinations.
The maximum increase in the specific energy absorption capacity of the new doubly re-entrant honeycomb structure (enclosing dimensions: 50.6x60x30mm) created by masked stereolithography technology from a material mixture of 37% Photocentric U DLP and 63% Resione F69 can reach 514%, while the maximum increase in the compression resistance can reach 1750% depending on the offset-deg parameter used.

b) Buckling of the new doubly re-entrant honeycomb structure can be avoided with the following five offset-deg parameter combinations: 1mm-35°,1mm-40°,1.4mm-30°,1.4mm-35°,1.4mm-40°.

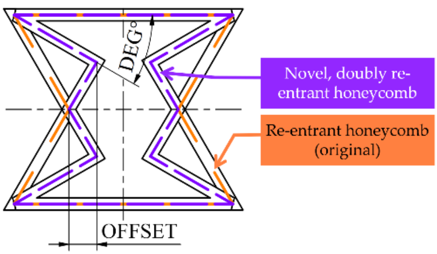


Figure II. Derivation of the new doubly re-entrant honeycomb structure, and presentation of the parameters used for characterization

Thesis II. is based on the following publication: [S2].

III. Thesis

The partial conversion of the doubly re-entrant honeycomb structure, created by masked stereolithography technology from 75% Litliq FX60 and 25% Litliq TH50 3D printing resin blend, into partial absorber elements by filling has an effect on the energy absorption capacity of the structure under compressive loading. The formation of the absorber elements can be achieved by filling the rectangular segments enclosed by the neighboring elements with a flexible (Soudal polysiloxane-based industrial silicone) material (Figure III). As a result of the absorber elements, the energy absorption characteristic of the structure becomes bimodal, the first stage of which is characterized by high deformation and low energy absorption, after which a so-called damping stage appears, indicating a gradually increasing energy absorption capacity, when the filled regions gradually engage in load absorption. By installing absorber segments, a purposefully designed energy absorption characteristic can be created, in the initial stage of which the impact velocity is reduced and then the impact energy is effectively absorbed.

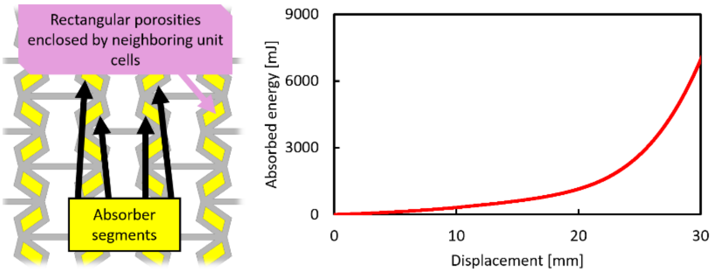


Figure III. Presentation of the segmented filling of the doubly re-entrant honeycomb, the birth of the absorber segments; the two-segmented energy absorption characteristic achieved by the incorporation of the absorber segments.

Thesis III. is based on the following publication: [S3].

IV. Thesis

As a further development of the new, doubly re-entrant honeycomb described in Thesis II, I created a new lattice structure by incorporating central stiffening segments, which I named x-reinforced doubly re-entrant honeycomb. I used compression tests and the *offset* and *deg* parameters for its characterization and impact analysis (Figure IV).

a) The x-reinforced doubly re-entrant honeycomb structure (enclosing dimensions: 50.6x61x30mm) created from a mixture of 80% Litliq FX60 and 20% Litliq TH50 3D printer resin using masked stereolithography technology results in a self-contained, completely buckling-free deformation behavior, providing a small and stable Poisson's ratio. Poisson's ratio value ranges from 0.1-0.22 depending on the geometric parameters. In the case of a sample characterized by a given combination of parameters, the value of Poisson's ratio changes by a maximum of 30% even when 40% deformation is reached.

b) I have proven, that for the tested parameter range geometric parameters only affect the tested mechanical properties. Deformation is independent of the values of the offset and deg parameters in the tested parameter range (test range: offset = 0.6…1.4 mm; deg = 30…40°).

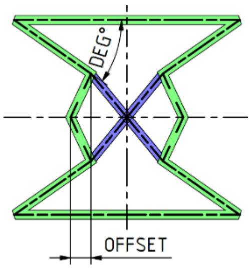


Figure IV. Presentation of the x-reinforced doubly re-entrant honeycomb structure

Thesis IV. is based on the following publication: [S4].

4 Potential utilization of the results

In this dissertation, I have presented methodologies and specific developments, my results can be utilized in specific practical applications or as a basis for further research work.

The fractal-inspired experimental setup is a great example for my fellow researchers on how to create a connection between different fundamental characteristics and study their effects in a parallel, comparable way. The fractal-inspired test space can be used in many other scientific fields, or my current study can be extended to other lattice structures.

As presented in the literature review, the re-entrant honeycomb structure, in addition to its many advantageous properties, is prone to buckling, thus its practical application requires significant simulation and computational preparatory work. The doubly re-entrant honeycomb structure presented in my dissertation retained the advantageous auxetic deformation behavior of the structure under significant (more than 50%) deformation load, so this new structure can be used in all areas where auxetic behavior and significant energy absorption capacity are important.

The structure with absorber segments created as a result of segmented filling can be utilized from both a methodological and a practical point of view. With segmented filling, I proved that although filling-based property improvement is an actively researched area, novel results can be achieved by deviating from trends (in this case, with partial filling). My goal with segmented filling was to achieve a programmable characteristic, the absorber elements are positioned in such a way that they only become involved in the load absorption later as the load progresses. The resulting bimodal energy absorption characteristic can be effectively used, for example, to protect vulnerable road users, where the first step is to significantly reduce the impact speed and then the to absorb impact energy. The created structure can also be imagined as a shock absorber for smaller experimental vehicles in the future, since it can be manufactured using additive manufacturing technology, thus it can be manufactured together with the vehicle (i.e. print in place), without requiring subsequent assembly.

From the beginning of my research work, my goal was to achieve the widespread practical application of individual lattice structures. To do this, I had to achieve parameter-independent deformation behavior and mechanical properties that could clearly be adjusted depending on the parameters. I achieved the set goal with the x-reinforced, doubly re-entrant honeycomb structure. The deformation of the created structure is

self-contained, so during its installation and planning, the design engineer is not required to perform complex simulations; furthermore, the lattice structure is set to the specified load values using geometry parameters.
Due to the high porosity of the auxetic structure, their load capacity is limited, and with my results I pointed out that the load capacity and deformation stability of the structures can be increased with centrally emphasized unit cell structures. My findings, which I called the stabilization guideline, can improve the properties of many other auxetic lattice structures.
Finite element tests were also a cardinal part of my studies. The established finite element models accurately followed the real test results in terms of both simulation and material models. The presented problems, and the solutions and methodologies offered for the problems, can be used for educational purposes in the field of nonlinear finite element tests.

5 Scientific publications related to theses

[S1] Széles Levente; Horváth Richárd; Rádics János Péter: Design and Study of Fractal-Inspired Metamaterials with Equal Density Made from a Strong and Tough Thermoplastic
POLYMERS 15 12 p. 2650. (2023); https://doi.org/10.3390/polym15122650
Lektorált külföldi folyóirat IF:5.0 (Q1 – Chemistry, Polymers and Plastics)

[S2] Széles Levente; Horváth Richárd; Cveticanin Livija: Analysis of Mechanical Properties and Parameter Dependency of Novel, Doubly Re-Entrant Auxetic Honeycomb Structures
POLYMERS 16 12 p. 2650. (2024); https://doi.org/10.3390/polym16172524
Lektorált külföldi folyóirat IF:4.7 (Q1 – Chemistry, Polymers and Plastics)

[S3] Széles Levente; Horváth Richárd; Cveticanin Livija: Research on Auxetic Lattice Structure for Impact Absorption in Machines and Mechanisms
MATHEMATICS (2227-7390): 12 13 p. 1983. (2024); https://doi.org/10.3390/math12131983
Lektorált külföldi folyóirat IF:2.3 (Q2 - Computer Science, Engineering, Mathematics)

[S4] Széles Levente; Horváth Richárd; Réger Mihály: Parameter-Independent Deformation Behaviour of Diagonally Reinforced Doubly Re-Entrant Honeycomb
POLYMERS 16 : 21 p. 3082 (2024); *https://doi.org/10.3390/polym16213082*
Lektorált külföldi folyóirat IF:4.7 (Q1 – Chemistry, Polymers and Plastics)

[S5] Széles Levente; Horváth Richárd: Eltérő elemszám mellett is azonos térfogattal rendelkező fraktál inspirált metaanyagok tervezése és zömítéssel szembeni mechanikai tulajdonságai
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