POLITECNICO DI TORINO

Corso di Laurea Magistrale
in Architettura per il Progetto Sostenibile

Tesi di Laurea Magistrale

Applications of Auxetic Models in Climatic Adaptive Building Shells

Relatori:
Fabrizio Barpi
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POLITO

Riconoscimenti

Questa ricerca sintetizza un lavoro sviluppato in un difficile periodo di pandemia globale, che non potrebbe essere stato sviluppato senza il fondamentale supporto di molti.

Ringrazio profondamente i professori Fabrizio Barpi e Pier Paolo Riviera, per i loro preziosi consigli ed aver direzionato verso la retta via nel percorso di ricerca.

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Contents

Abstract

The auxetic metamaterials' field of research is in constant expansion, and as engineering investigation keeps zooming with the magnifying glass on their microscopic properties, architects' points of view zoom out, leading their exploration to buildings scales.
From a research that ranges in several fields of architecture and observes their compatibility with auxetic models, this thesis work analyzes, in particular, the possibilities for new sustainable applications, crisscrossing from bio-mimicry, meta-materials, computational design to contemporary solutions for passive housing systems, opening prospects on large auxetic models applications. In conclusion, the current studies on Climatic Adapting Building Shells uncover this work's final objective, with a model proposal that synthesizes all the research work. A humble opening on auxetic materials for green futures.

Abstract

Il campo di ricerca sui metamateriali auxetici è in continua espansione, e mentre l'investigazione ingegneristica continua a enfatizzare con la lente d'ingrandimento le loro proprietà microscopiche, il punto di vista degli architetti svia la loro esplorazione verso la scala degli edifici.
Da una ricerca che si cala in molteplici settori dell'architettura ed osserva la loro compatibilità con i modelli auxetici, il progetto di tesi si incentra soprattutto su applicazioni sostenibili, incrociando materie di biomimetica, metamateriali, design computazionale fino a soluzioni contemporanee di edilizia passiva. In conclusione, gli attuali studi sui CABS (Climatic Adaptive Building Shells), scoprono l'obiettivo finale di questo lavoro, con una proposta di modello che sintetizza l'insieme del lavoro di ricerca, al fine di fornire una iniziale apertura sui materiali auxetici per un futuro verde.

Chapter 1

Introduction to Auxetic Materials

1.1 Auxetic Metamaterials Definition

The term *metamaterial* was coined in the year 2000, [1] defining any engineered material having physical properties not found in nature. [2] Examples include those designed to affect electromagnetic and acoustic waves or combining high-performance mechanical properties with significant mechanical or chemical resistance, often reducing the cost of the primitive bulk materials. [3]
Although the exploration of artificial materials began in the field of optics and electromagnetic field manipulation at the end of the 19th century, [4] over the past four decades, the aircraft, sport, automotive, and leisure sectors developed structurally efficient designs and technologies referring to metamaterials[3].
Among these innovations emerge *auxetic structures/materials*, defined as materials exhibiting a Negative Poisson's Ratio (NPR), v (nu). It is defined as the ratio between transverse strain e_t and longitudinal strain e_l under uniaxial stress [5]: $v = e_t/e_l$ or $v = -(\Delta D/D)/(\Delta L/L)$ (fig.1).
The vast majority of natural materials have a positive Poisson's ratio because when subject to a distorting pulling influence, they tend to extend the direction of the force and contract laterally, mathematically speaking, causing a positive and a negative variation (Δ) respectively, resulting in a positive v. For most solids such as metals, polymers, and ceramics, $0.25 < v < 0.5$. Glasses and minerals have $v \to 0$ and for gasses $v = 0$. Generally, classical elasticity theory places limits on v for isotropic materials of $-1 < v < 0.5$
Auxetic materials and structures are therefore designed to expand when stretched and contract when compressed.
The word 'auxetic' derives from the Greek *αυχητικοξ* (read auxetikos), meaning *tends to increase*; and the term 'auxetic materials' was first coined by Evans et al. in 1991. [6]

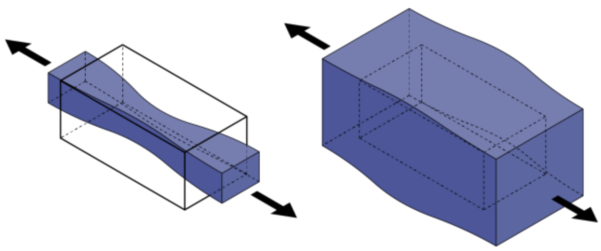

Fig. 1 : Reaction of a conventional material and an auxetic one

[1] **Sergei Tretyakov , Augustine Urbas and Nikolay Zheludev**. (2017). *The century of metamaterials*. Retrieved from: https://iopscience.iop.org/article/10.1088/2040-8986/aa77a8/pdf
[2] **Rakhesh Singh Kshetrimayu**. (2004). *A Brief Intro to Metamaterials*. Retrieved from: https://ieeexplore.ieee.org/document/1368916
[3] **A. Alderson and K. L. Alderson**. (2007). *Auxetic Materials*. Retrieved from: https://journals.sagepub.com/doi/pdf/10.1243/09544100JAERO185
[4] **John Ramsay**. (1958). *Microondas antena de guía de ondas y técnicas antes de 1900*. Retrieved from: https://ieeexplore.ieee.org/document/4065335
[5] **G. N. Greaves, A. L. Greer, R. S. Lakes and T. Rouxel**. (2011). *Poisson's ratio and modern materials*. Retrieved from: https://www.nature.com/articles/nmat3134
[6] **K. E. Evans, M. A. Nkansah, I. J. Hutchinson, S. C. Rogers**. (1991). *Molecular Network Design*. Retrieved from: https://www.nature.com/articles/353124a0

1.2 Auxetic Behaviour

Due to the NPR, auxetic materials behave in fascinating ways compared to conventional materials, giving them properties useful in different development areas of engineering physics, such as applied mechanics, thermodynamics, and acoustics, the principal branches in architecture studies.[7]

a. *Material's stiffness* and elastic behavior are described by four primary constants: Young's moduli (*E*: the tendency of a material to resist deformation along an axis a force is applied along that axis), shear moduli (*G*: tendency to resist shear subject upon by opposing forces), bulk moduli (*K*: tendency to resist compression) and the Poisson's ratio (*v)*. Most structural materials require a higher *G* than *K*. Since all these modules can be expressed in terms of *v*, it is possible to alter their values by keeping *E* constant and decreasing *v* to -1 by changing the materials' structure. [8]

$$G = \frac{E}{2(1+v)}$$

$$K = \frac{E}{3(1-2v)}$$

b. *Indentation resistance* (*H*) relates to the hardness of a material to deformation. When an auxetic structure is hit and compressed in one direction, the material also contracts laterally. The material "flows" towards the impact area, making it denser (fig. 2). *H* can again be expressed in relation to *v*, with higher indentation resistance by increasing negative *v* towards -1. [9]

$$H = \left(\frac{1-v^2}{E}\right)^{-1}$$

[7] **Yanping Liu and Hong Hu**. (2010). *A review on auxetic structures and polymeric materials*. Retrieved from: https://www.researchgate.net/publication/273889759_A_review_on_auxetic_structures_and_polymeric_materials

[8] **Wei Yang, Zhong-Ming Li, Wei Shi, Bang-Hu Xie and Ming-Bo Yang**. (2004). *Review On auxetic materials*. Retrieved from: https://link.springer.com/article/10.1023/B:JMSC.0000026928.93231.e0

[9] **Kenneth E. Evans and Andrew Alderson**. (2000*). Auxetic Materials: Functional Materials and Structures from Lateral Thinking!*. Retrieved from: https://onlinelibrary.wiley.com/doi/10.1002/%28SICI%291521-4095%28200005%2912%3A9%3C617%3A%3AAID-ADMA617%3E3.0.CO%3B2-3

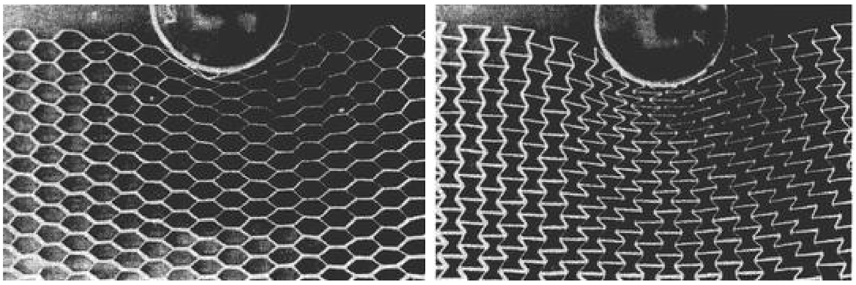

Fig. 2 Indentation resistance in a conventional material and in an auxetic one

c. *Fracture toughness* (K_c) under permanent volumetric compression ratio ($r_k = V_1/V_2$) had been seldom calculated due to the fact it was theoretically predicted from the previous studies mentioned above. It has been experimented on auxetic microstructures such as auxetic open-cell copper foams, obtaining enhancement by 80%, 48%, and 160% for a permanent volumetric compression ratio of 2, 2.5, and 3, respectively. [8] Additionally, auxetic materials respond better to existing cracks; the structure tends to expand in correspondence to the fracture, closing it up when being pulled apart. [7]

d. *Synclastic and anticlastic surfaces* (fig.3) present two curvatures along the surface and are, by definition, not-developable surfaces, meaning they cannot be flattened on a plane without stretching or shearing. When a generic material is forced in an out-of-plane bending moment, the edges curl upwards, giving a traditional anticlastic "saddle" shape. Auxetic materials tend to bend into synclastic curvatures, for example, a dome shape, without excessive force applied (fig. 4). [10] The same property can be applied to convert generic developable materials into synclastic and

Fig. 3 Anticlastic, synclastic and monoclastic surfaces

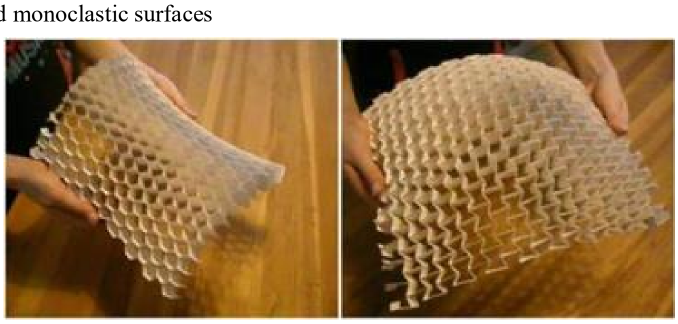

Fig. 4: Conventional material saddle shape and auxetic dome shape

[10] **Alderson and K. L. Alderson**. (2007). *Auxetic Materials*. Retrieved from: https://journals.sagepub.com/doi/pdf/10.1243/09544100JAERO185

anticlastic surfaces by inserting regular auxetic cutting patterns into the same material.

The new structure lets it expand locally and wrap around almost any double curvature surface (fig. 5). [11]

Fig. 5: Example of deployable auxetic pattern on complex surface

e. *Acoustic absorption* on auxetic foams was tested by F Scarpa, W. A. Bullough, and P. Lumley at the department of Mechanical Engineering at the University of Sheffield, UK. The experiment provided for use an auxetic open-cell polyurethane (PUR) flexible foam, with the addition of polarizable media to give an aspect of a flexible operation to the foam (electrical selection of the form of the sound absorption frequency spectrum). The results proved that auxetic open-cell foams have a higher acoustic absorption coefficient ($\alpha = E/E_0$) than their more-traditional counterparts at low frequencies, peaking at ~1.8kHz with a cut off frequency behavior ($\alpha \sim 1$). [12]

f. *Variable permeability* is the last of the previously studied peculiarity of auxetic materials. It refers to the possibility of the material to vary the fluid allowance through it. Auxetic materials usually present holes when stretched, and the pore sizes can differ depending on the force applied. This feature is useful in macro and nano-scale filtration applications, enhancing pore size and shape adjustments. Polymeric auxetic filter devices can also overcome the reduction of filtration efficiency and increased pressure across the filter due to clogged pores. [13]

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[11] **Mina Konaković Luković**. (2019). *Computational Design of Auxetic Shells*. Retrieved from: https://lgg.epfl.ch/publications/2019/Mina_Thesis/thesis.pdf

[12] **F. Scarpa, W. A. Bullough and P. Lumley**. (2004). *Trends in acoustic properties of iron particle seeded auxetic polyurethane foam*. Retrieved from: https://journals.sagepub.com/doi/pdf/10.1243/095440604322887099

[13] **A. Alderson, J. Rasburn, K. E. Evans and J. N. Grima**. (2001). *Auxetic polymeric filters display enhanced de-fouling and pressure compensation properties*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0958211801802998

1.3 Auxetic Behavior Scales

When talking about auxetics, it is crucial to understand that these phenomena can happen at various scales and analyzed in different semantic and physical fields. Different articles on the topic often do not avail themselves of compatible vocabulary between each other, using the same dictionary and lexicon with overlapped meanings. A correct classification of auxetics anticipates a basic understanding of the components *micro*, *meso,* and *macro,* referring to the case study scale. [14]

a. *Micro*-scale refers to the minimal unit of a material, usually concerning the single-molecule level ($\sim nm = 1 \times 10^{-9}\ m$) and its bonds between elements. Auxetic behavior at this level was observed in the smallest scale at molecular rods with a prismanic structure [15], and in larger scales in the form of crystals of arsenic and cadmium, α-cristobalite, iron pyrites, and many cubic elemental metals.[16] In this scale range, the auxetic properties are intrinsic of the material; therefore, the definition' auxetic material' is appropriate for this range.
b. *Meso* refers to a larger scale, where the microscopic structure and disposition of the compounds or cells behave in an auxetic manner, giving auxetic properties to the final product. Examples are special subsets of foams [17], long fibers composites [18], auxetic microporous polymers [19] , and certain forms of organic skins. [20] These materials are the ones nowadays, usually referred to as 'auxetic materials' in general literature.
c. *Macro*-scale auxetics reproduce auxetic models (Chapter 4) at a more extensive scale and auxetic properties depend merely on the elasticity of the core material they are made of and the conformation. Most 3D printed auxetic patterns fall under this category, as well as origami (folding models) and lattice structures; all these are generally defined as 'auxetic structures.'

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[14] **Lorenzo Mirante**. (2015). *Auxetic Structures: Towards Bending-Active Architectural Applications*. Retrieved from: https://www.politesi.polimi.it/bitstream/10589/116372/1/2015_12_Mirante.pdf
[15] **Nir Pour, Lior Itzhaki, Benaya Hoz, Eli Altus,Harold Basch, and Shmaryahu Hoz**. (2006). *Auxetics at the Molecular Level: A NegativePoisson's Ratio in Molecular Rods*. Retrieved from: https://onlinelibrary-wiley-com.ezproxy.biblio.polito.it/doi/epdf/10.1002/anie.200601764
[16] **Onur Gunel, Mostafa Ranjbar**. (2018). *Review on Auxetic Materials*. Retrieved from: https://www.researchgate.net/publication/331256823_REVIEW_ON_AUXETIC_MATERIALS
[17] **Rod Lakes**. (1987). *Foam structures with a negative Poisson's ratio*. Retrieved from: http://silver.neep.wisc.edu/~lakes/sci87.html
[18] **Carl T. Herakovich**. (1984). *Composite Laminates with Negative Through-the-Thickness Poisson's Ratios*. Retreived from: https://journals.sagepub.com/doi/pdf/10.1177/002199838401800504
[19] **K. L. Alderson, A. Alderson, K. E. Evans**. (1997). *The interpretation of strain dependent Poisson's ratio in auxetic polyethylene*. Retreived from: https://journals.sagepub.com/doi/10.1243/0309324971513346
[20] **D. R. Veronda**. (1970). *Mechanical characterization of skin—Finite deformations*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/0021929070900552

Another critical differentiation, especially in auxetic models, is between an auxetic cell and an auxetic pattern, structure, or material. A cell does not show all physical properties listed in chapter 2 and is usually limited to the expansion under stretch if pulled from the right nodes. Such units are, for example, the single re-entrant hexagon, four-points star, re-entrant triangle, or prisman molecular forms. The cells, however, if disposed correctly into a pattern or structure, create a material layer capable of behaving like a proper auxetic solid.

1.4 Auxetic Models

Most auxetic properties rely on the geometrical configuration of the material or structure; it is possible, therefore, to define 'auxetic models' as strictly related to mathematics. The primary objective of these models is to help researchers predict auxetic behavior, optimizing properties, achieving determined results. The models can theoretically perform at any scale but can be practically found only at a specific range. Although the next chapters cover what is probably an infinitesimal portion of countless auxetic geometries, these selected models were previously studied in numerous different papers, and therefore closer to an effective practical application.

a. 2D re-entrant structures

Usually referred to as auxetic macro-patterns or auxetic cellular structures, these models can be found in a wide variety of forms and often quickly clarify the auxetic effect concept. The most popular is the *re-entrant honeycombs*, first suggested by Gibson et al. in 1982 when studying honeycombs materials mechanics.[21] In the mathematical model, the auxetic effect is obtained through the alignment of the diagonal ribs along the horizontal direction of applied stretch, causing the ribs aligned along the vertical direction to move apart (fig. 6). However, in reality, with a ratio depending on the material, the auxetic behavior is a combination of the diagonal ribs flexure, hinging, and axial stretching of the ribs, all co-occurring.[22]

Re-entrant triangle 2D patterns, first studied in 1997 [23] (fig. 7a), not only present a Negative Poisson Ratio (NPR) but also a negative Coefficient of Thermal Expansion (CTE), creating a new horizon of applications. [24] Other 2D re-entrant structures are the *star-shaped honeycomb structure* [25] (3, 4, 6 points) and the *structurally hexagonal re-entrant honeycomb* [26] (improved planar isotropy due to symmetry along radical directions) (fig. 7b, c, d).

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[21] **L. J. Gibson, M. F. Ashby, G. S. Schajer and C. I. Robertson**. (1982). *The mechanics of two-dimensional cellular materials*. Retrieved from: https://royalsocietypublishing.org/doi/abs/10.1098/rspa.1982.0087

[22] **I. G. Masters and K. E. Evans**. (1996). *Models for the elastic deformation of honeycomb*. Retrieved from: https://www-sciencedirect-com.ezproxy.biblio.polito.it/science/article/pii/S0263822396000542

[23] **Ulrik Darling Larsen, Ole Sigmund and Siebe Bouwstra**. (1997). *Design and Fabrication of Compliant Micromechanisms and Structures with Negative Poisson's Ratio*. Retrieved from: https://ieeexplore.ieee.org/document/585787

[24] **Chun Kit Ng, Krishna Kumar Saxena, Raj Das and E. I. Saavedra Flores**. (2016). *On the anisotropic and negative thermal expansion from dual-material re-entrant-type cellular metamaterials*. Retrieved from: https://www.researchgate.net/publication/308750182_On_the_anisotropic_and_negative_thermal_expansion_from_dual-material_re-entrant-type_cellular_metamaterials

[25] **P. S. Theocaris, G. E. Stavroulakis and P. D. Panagiotopoulos**. (1997). *Negative Poisson's ratios in composites with star-shaped inclusions: A numerical homogenization approach*. Retrieved from: https://www.researchgate.net/publication/227279742_Negative_Poisson's_ratios_in_composites_with_star-shaped_inclusions_A_numerical_homogenization_approach

[26] **Rod Lakes**. (1991). *Deformation mechanisms in negative Poisson's ratio materials: structural aspects*. Retreived from: http://silver.neep.wisc.edu/~lakes/PoissonStruc.html

The *missing rib* model was initially introduced by C. W. Smith et al. in 2000. It can be conceptualized as a squared or rhomboid cell network with some sides removed, obtaining a swastika-shaped pattern (fig. 7e, f), [27] with a Poisson Ratio minimum at − 0.43 and − 0.6 for the lozenge grid and square grid, respectively. [28]

Another example, the *chiral quadratic lattice structure* is formed by sinusoidal ligaments, where the auxetic effect is given through the deformation of the curved re-entrant cells into almost rectangular cells (fig. 7g).

Single planar auxetic cells can also be considered in this category, simple examples are the re-entrant hexagon and the star shapes, but more complex geometries can be found. Ancient Islamic architecture shows auxetic geometric patterns in decorations and finishings. Nevertheless, it took centuries before the auxetic model was defined as the *Hoberman circle* (fig. 7h) after Chuck Hoberman.

[27] **N. Gaspar, X. J. Ren, C. W. Smith, J. N. Grima and K. E. Evans**. (2005). *Novel honeycombs with auxetic behavior*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S1359645405000820

[28] **C. W. Smith, J. N. Grima And K. E. Evans**. (2000). *A Novel Mechanism For Generating Auxetic Behaviour In Reticulated Foams: Missing Rib Foam Model*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S135964540000269X

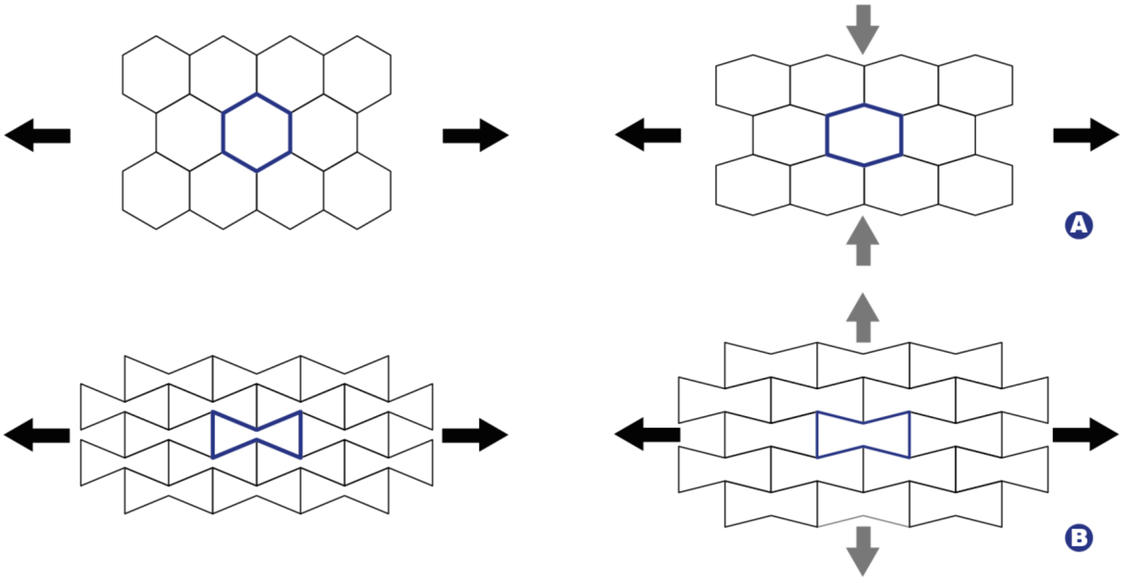

Fig. 6: Convential Honeycomb (a) and re-entrant honeycomb (b) response to axial deformation

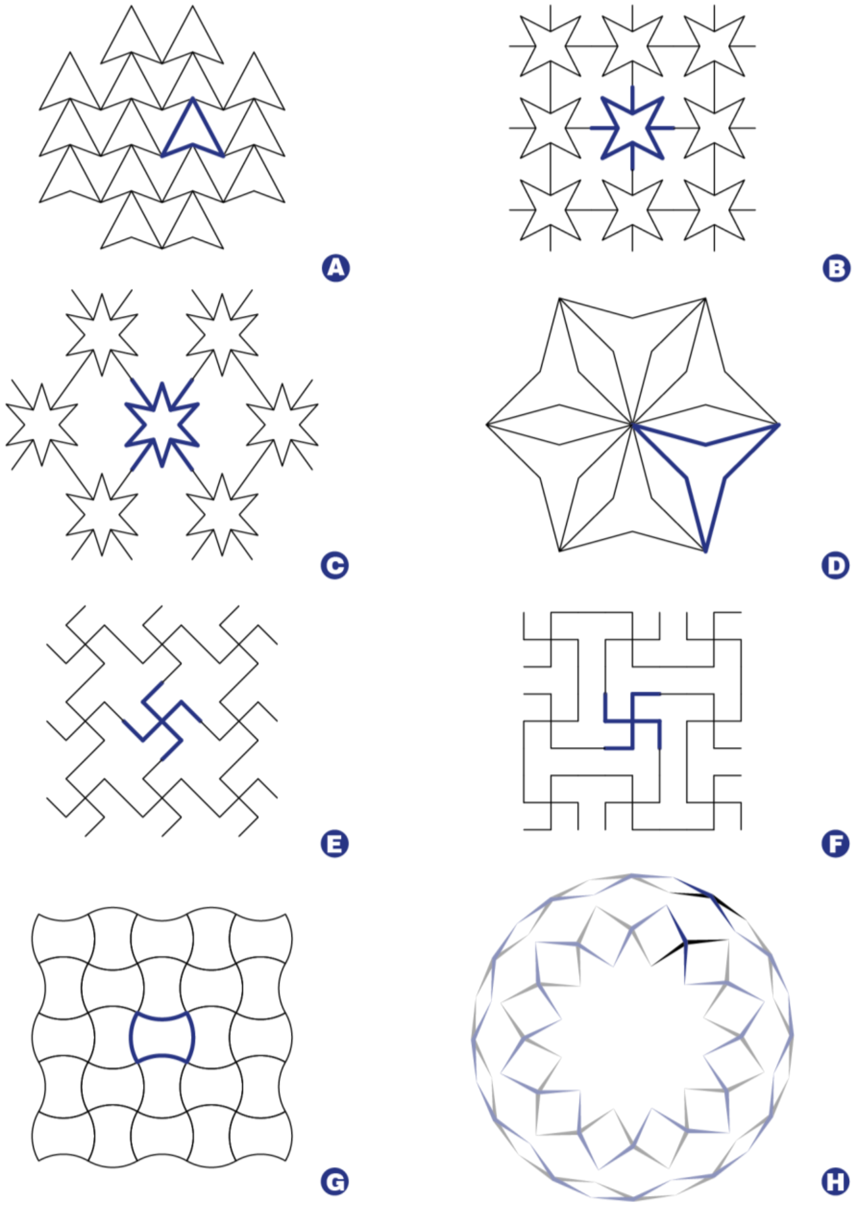

Fig. 7: 2D re-entrant tessellations: **a**: re-entrant triangle; **b**: 4-point star shape re-entrant honeycomb; **c**: 6-point star shape re-entrant honeycomb; **d**: structurally hexagonal re-entrant honeycomb; **e**: lozenge missing rib model; **f**: square missing rib model; **g**: chiral quadratic lattice structure; **h**: Hoberman circle

b. 3D re-entrant structures

3D geometries can also achieve auxetic effects and expand in volume when stretched. Most of the previously seen 2D patterns, if correctly intersected as perpendicular planes in the three dimensions, perform auxetically (fig. 8). There are, however, unique 3D re-entrant cells, such as the *re-entrant tetrakaidecahedron* model (fig. 9), used to explain the behavior of auxetic foams. [29] When the vertically protruding ribs are under tension, the ribs in the lateral directions will tend to move out, leading to lateral expansion. However, when compression is applied, the ribs will bend inward further, thus resulting in a lateral contraction in response to axial compression. [7] Another famous example is the *Hoberman sphere*, popularized as a toy, named after the homonymous creator precedently quoted (fig. 10). It typically consists of six circles corresponding to the edges of an *icosidodecahedron*. However, numerous variations and completely new auxetic mechanisms can be found in Hoberman's contemporary works, also named *transformable designs*. [30]

Certain models behave in an auxetic manner mostly under compression; a popular example is the *bucklicrystal* (fig.11) developed by Babaee et al. (2013) [31]. These soft metamaterials consist of an array of patterned elastomeric spherical shells, which, due to mechanical instability, undergo a significant isotropic volume reduction and uniform buckling under compression.

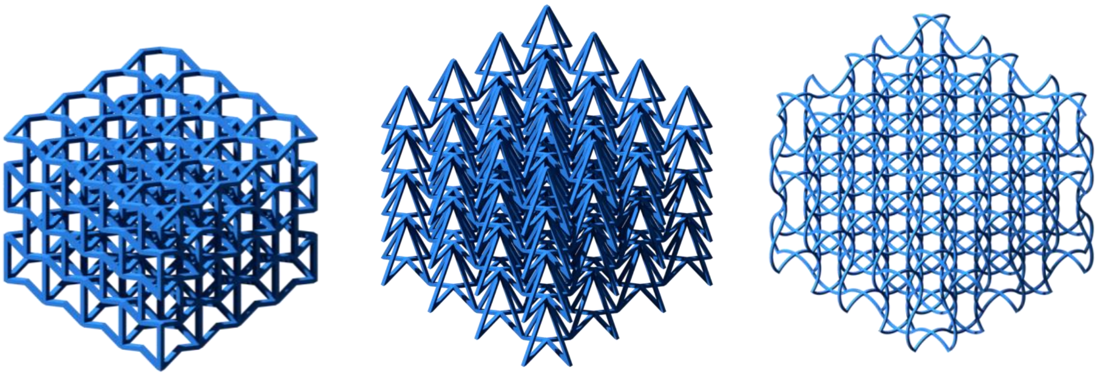

Fig. 8: 3D tessellations: re-entrant hexagons, re-entrant triangles, sinusoid ligaments

[29] **R. S. Lakes and R. Witt**. (2002). *Making and characterizing negative Poisson's ratio materials*. Retrieved from: http://homepages.cae.wisc.edu/~lakes/PoissonEduc.pdf

[30] *Welcome To Hoberman*. Retrieved from: https://www.hoberman.com/

[31] **Sahab Babaee, Jongmin Shim, James C. Weaver, Elizabeth R. Chen, Nikita Patel and Katia Bertoldi**. (2013). *3D Soft Metamaterials with Negative Poisson's Ratio*. Retrieved from: https://bertoldi.seas.harvard.edu/files/bertoldi/files/advmat_3013_3d_0.pdf

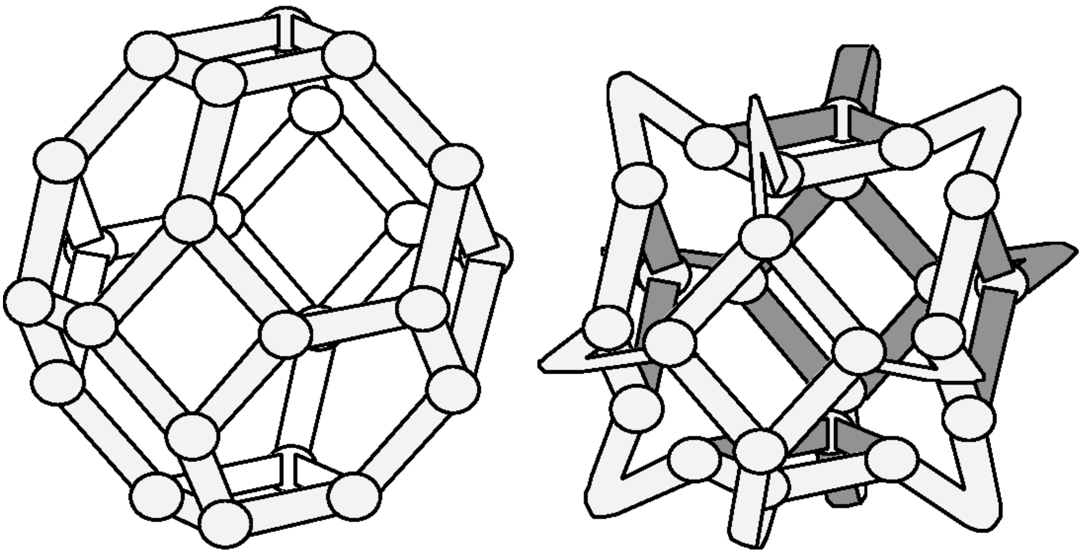

Fig. 9: Classic and re-entrant tetrakaidecahedron

Fig. 10: Chuck Hoberman with Hoberman sphere toy

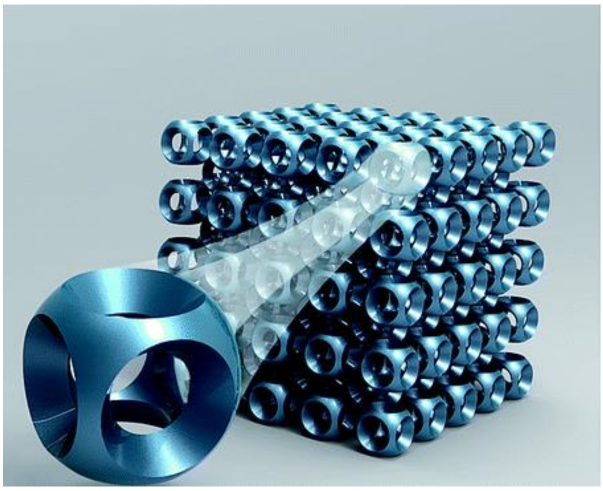

Fig. 11: Bucklicrystal

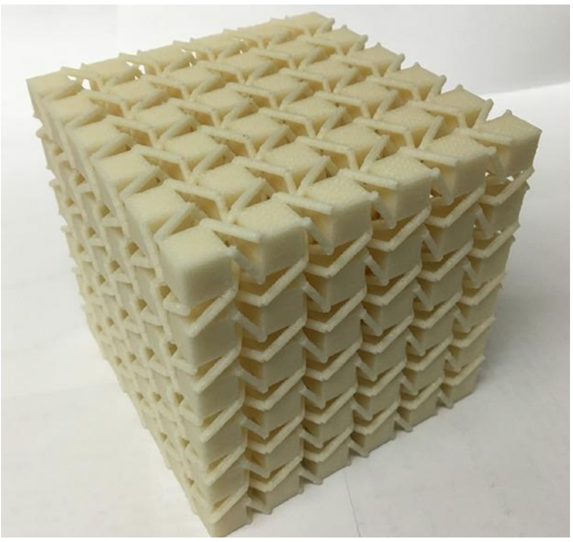

Fig. 14: Chan Soo Ha et al. 3D chiral lattice structure

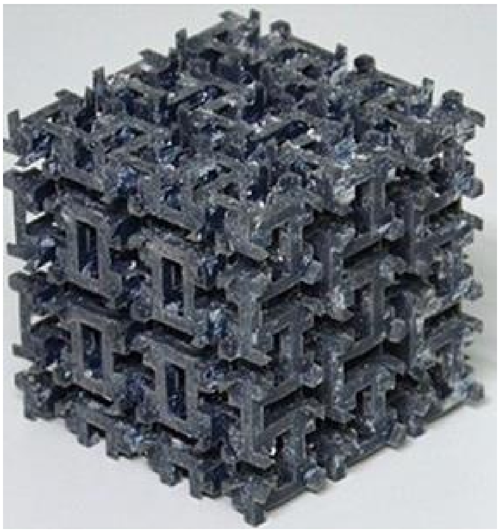

Fig. 15: Hsin-Haou Huang et al.3D meta-chiral lattice structure

c.   Chirals

The Chiral (Noncentrosymmetric) honeycomb structure is composed of circular or rectangular elements/nodes joined by straight ligaments (fig. 12). The ligaments are constrained to be tangential to circular nodes and connecting all the chiral units to obtain the general pattern. The auxetic effect is achieved through the clockwise, or anticlockwise, unwrapping of the ligaments around the nodes in response to the applied stretching force. According to the theoretical and experimental studies performed by Prall and Lakes (1997), Poisson's ratio of the chiral structure under in-plane deformations is around -1.[32] Several variations can be found depending on: the number of ligaments per unit, from 6 (*hexa-chiral*) to 3 (*tri-chiral*) (fig. 13a, b, c)[33], the clockwise and anticlockwise reciprocal node connection (*anti-chiral*) or the mixture of the two in the structure (*meta-chiral*) (fig. 19), and the rectangular nodes [34] (fig. 13 d, e). In reality, the chiral structures deform predominantly by a combination of unit rotation and ligament bending. An applied compressing or stretching force generates a torque on the nodes such that they undergo in-plane rotation, which induces a moment on the ligaments connected to each node, causing them to bend. [35]

Chan Soo Ha et al. (2016) analyzed several chiral 3D lattice structures, made out of cubes and deformable ribs connecting the different corners of the cubes (fig. 14). The Poisson's Ratio varies depending on the number of cubes and thickness of the ribs, reaching a minimum of −0.1393.[36] A different *3D meta-chiral* model (fig. 15) studied by Hsin-Haou Huang et al. (2016) reached a Poisson's ratio down to -0.92 ± 0.03, showing isotropy when being compressed in the z-direction. In contrast, anisotropy was observed for compressive loading in the x- and y-directions. [37]

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[32] **D. Prall and R. S. Lakes**. (1997). *Properties of a chiral honeycomb with a Poisson's ratio -1*. Retrieved from: http://silver.neep.wisc.edu/~lakes/PoissonChiral.pdf

[33] **Davood Mousanezhad, Babak Haghpanah, Ranajay Ghosh, Abdel Magid Hamouda, Hamid Nayeb-Hashemi and Ashkan Vaziri**. (2016). *Elastic properties of chiral, anti-chiral, and hierarchical honeycombs: A simple energy-based approach*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2095034916000210

[34] **J. N. Grima, R. Gatt, P. S. Farrugia**. (2008). *On the properties of auxetic meta-tetrachiral structures*. Retrieved from: https://onlinelibrary.wiley.com/doi/abs/10.1002/pssb.200777704

[35] **Andrew Alderson, K. L. Alderson, D. Attard, K. E.Evans, R. Gatt, J. N. Grima, W. Miller, N. Ravirala, C. W. Smith and K. Zied**. (2010). *Elastic constants of 3-, 4- and 6-connected chiral and antichiral honeycombs subject to uniaxial in-plane loading*. Retreived from: https://shura.shu.ac.uk/7200/1/In-plane_chirals_revised_clean.pdf

[36] **Chan Soo Ha, Michael E. Plesha, and Roderic S. Lakes**. (2016). *Chiral three-dimensional isotropiclattices with negative Poisson's ratio*. Retrieved from: https://onlinelibrary. wiley.com/doi/abs/10.1002/pssb.201600055

[37] **Hsin-Haou Huang, Bao-Leng Wong, and Yen-Chang Chou**. (2016). *Design and properties of 3D-printedchiral auxetic metamaterials byreconfigurable connections*. Retrieved from: https://onlinelibrary.wiley.com/doi/abs/10.1002/pssb.201600027

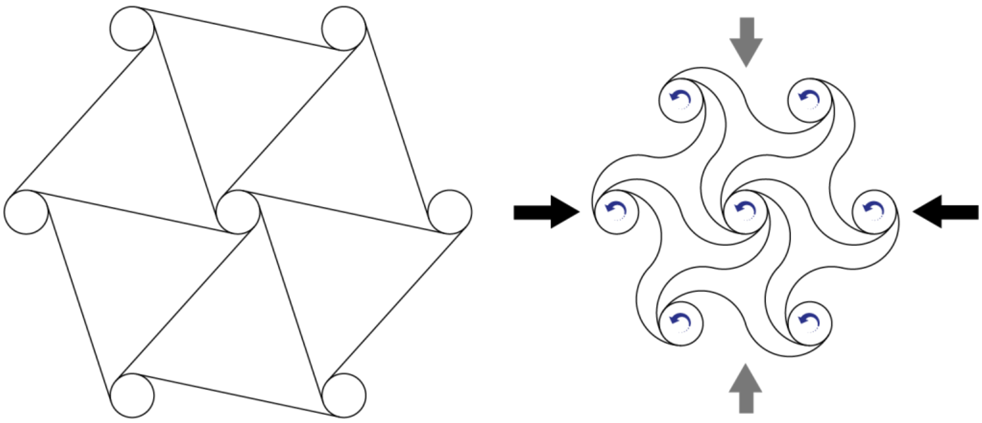

Fig. 12: Deformation of a chiral honeycomb structure under compression

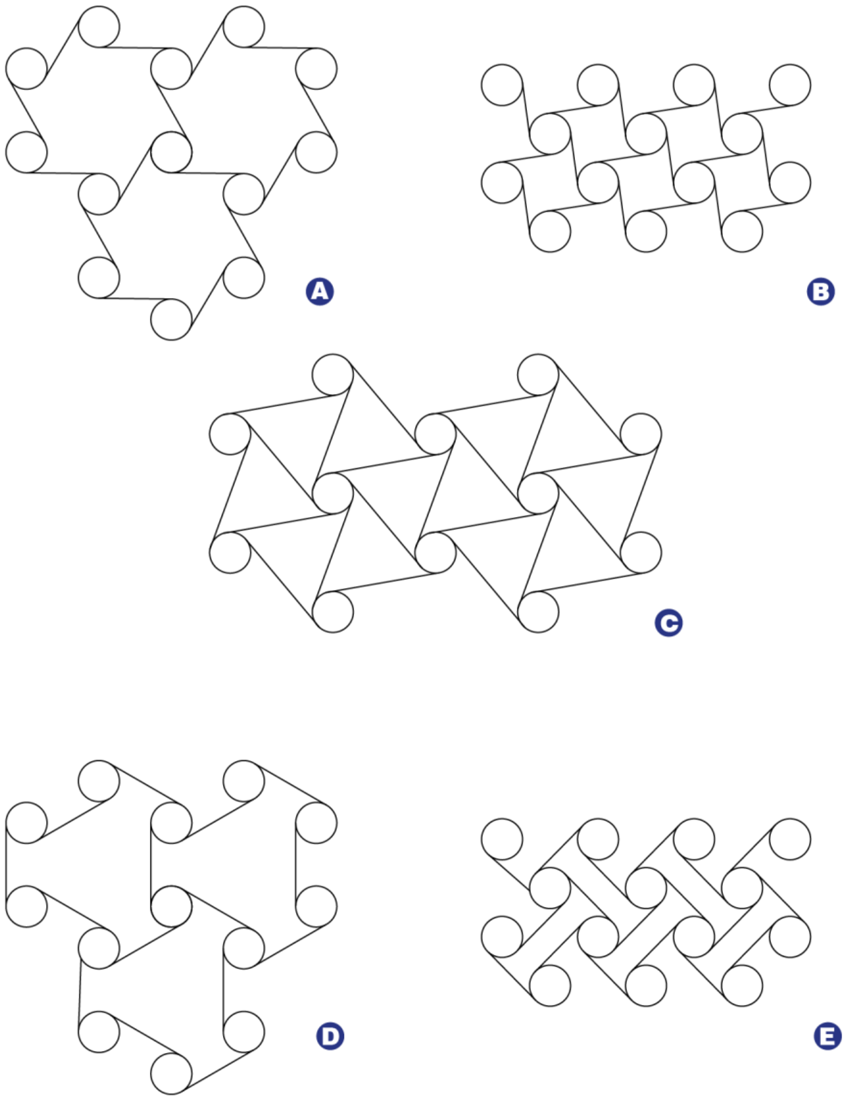

Fig. 10: 2D chiral tessellations: **a**: tri-chiral; **b**: tetra-anti-chiral; **c**: hexa-anti-chiral; **d**: tri-meta-chiral; **e**: tetra-meta-chiral

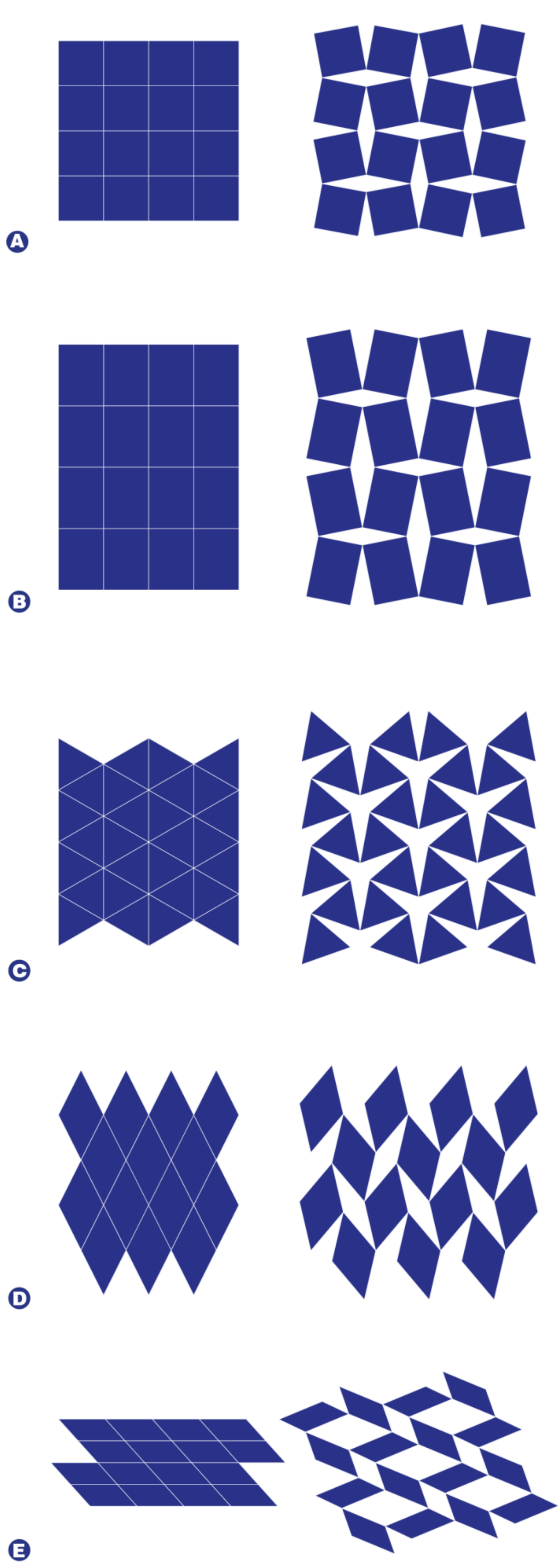

Fig. 16: Rotating rigid units models: **a**: squares; **b**: rectangles; **c**: rectangle triangles; **d**: rhombi; **e**: parallelograms

d. Rotating rigid units

A simple model that exhibits negative Poisson's ratio can be abstracted using squares

connected through a simple hinge at the vertices. When loaded, the squares will rotate (hinge), either expanding or contracting depending on the loading type.[38] The concept presents a wide range of variations by using squares, rectangles, triangles, rhombi, and parallelograms, all in their rigid or semi-rigid conformations (fig. 16). The same model can be expressed, especially for manufacturing purposes, as an insertion of a regular cut pattern into a plane, enabling it to behave in an auxetic manner (see *kirigami*, chapter 4.e.).

The auxetic potential of rotating squares was the first to be analyzed by Grima et al. (2000)[38] while searching for a new mechanism capable of achieving an NPR. The arrangement of rigid squares showed a Poisson's Ratio of -1, meaning the model would maintain its aspect ratio under deformation (fig. 16. a). This was proved through to principle of Conservation of Energy, with only the constants l (square sides length) and θ (angle between the squares). However, if the rotating units were assumed to be semi-rigid, the Poisson's Ratio would become dependent on the relative rigidity of these units concerning the stiffness of the hinges, as well as the direction of loading. [39]

Rotating rectangles are a more general model than squares and behave very differently from the previous ones. They exhibit both positive and negative Poisson's Ratios depending on θ and higher or lower values depending on the *a/b* ratio (fig. 17). [40] Furthermore, for rectangles, two distinct connectivity schemes were studied. These configurations are referred to as Type I and Type II networks, in which Type I networks show rhombi-shaped empty spaces, and the Type II networks show parallelograms (Fig. 18). As Type I behaves as mentioned before, Type II was found to mimic the behavior of the rotating rigid squares structure with an isotropic Poisson's ratio of -1. [41]

Rotating rigid triangles behave very similarly to squares, maintaining its aspect ratio under deformation but subject to higher angle θ between each other (fig. 16 c). [42] Auxetic models can be obtained with configurations of

[38] **J. N. Grima and K. E. Evans**. (2000). *Auxetic behavior from rotating squares*. Retrieved from: https://link.springer.com/article/10.1023/A:1006781224002

[39] **Joseph N. Grima. Pierre S. Farrugia, Christian Caruana, Ruben Gatt and Daphne Attard**. (2008). *Auxetic behaviour from stretching connected squares*. Retrieved from: https://link.springer.com/article/10.1007/s10853-008-2765-0

[40] **Joseph N. Grima, Andrew Alderson and Kenneth E. Evans**. (2004). *Negative Poisson's Ratios From Rotating Rectangles*. Retrieved from: https://www.researchgate.net/publication/270745112_Negative_Poisson's_ratio_from_rotating_rectangles

[41] **Joseph N. Grima, Ruben Gatt, Andrew Alderson, Kenneth E. Evans**. (2005). *On the Auxetic Properties of `Rotating Rectangles' with Different Connectivity*. Retrieved from: https://www.researchgate.net/publication/241389678_On_the_Auxetic_Properties_of_Rotating_Rectangles'_with_Different_Connectivity

[42] **Joseph N. Grima and Kenneth E. Evans**. (2006). *Auxetic behavior from rotating triangles*. Retrieved from: https://link.springer.com/article/10.1007/s10853-006-6339-8

rotating scalene and mixed triangles as well, but depending on a more significant number of parameters. [43]

Many other patterns of rotating units can show an NPR, such as different configurations of rhombi [44], parallelograms [45] (fig. 16 d, e), and several tessellations inspired by Islamic art [46] (fig. 19).

Configurations of rotating solids have been hypothesized to explain the auxetic mechanism of α-cristobalite [47] and other cubic elemental metals, in the shape of tetrahedron and cube, respectively (fig. 20). These structures often tend to a Poisson's Ration of ~ 0^- behaving more specifically as anepirretic materials. [48]

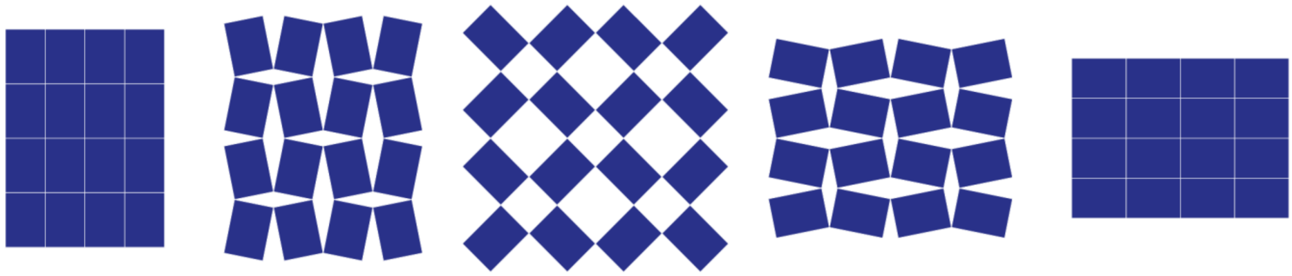

Fig. 17: Rotating rigid rectangles exhibiting both positive and negative Poisson’s ratio

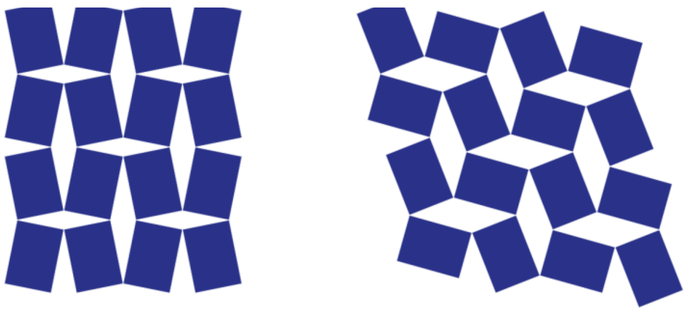

Fig. 18: Type I and type II rectangular tesselations

Fig. 19: Rotating rigidi units inspired by Islamic tesselations

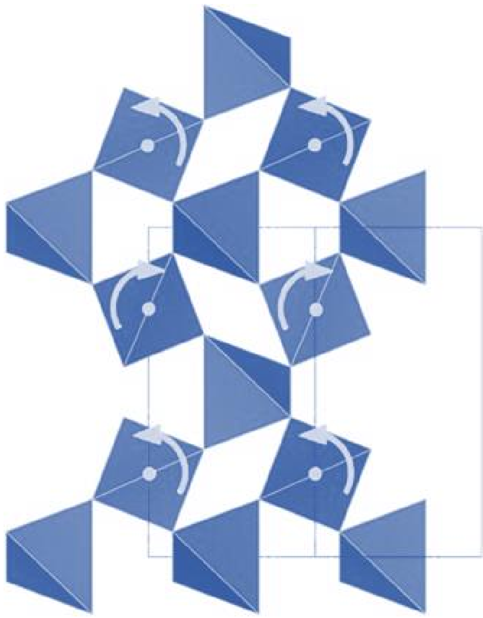

Fig.20: α-cristobalite rotating rigid tetrahedron model

[43] **Joseph N. Grima, Elaine Chetcuti, Elaine Manicaro, Daphne Attard, Matthew Camilleri, Ruben Gatt and Kenneth E. Evans.** (2011). *On the auxetic properties of generic rotating rigid triangles*. Retrieved from: https://royalsocietypublishing.org/doi/10.1098/rspa.2011.0273

[44] **Joseph N. Grima and Daphne Attard**. (2008). *Auxetic behaviour from rotating rhombi*. Retrieved from: https://www.researchgate.net/publication/227960073_Auxetic_behaviour_from_rotating_rhombi

[45] **Joseph N. Grima, Daphne Attard and Elaine Manicaro**. (2009). *On rotating rigid parallelograms and their potential for exhibiting auxetic behavior*. Retrieved from: https://www.researchgate.net/publication/227964426_On_rotating_rigid_parallelograms_and_their_potential_for_exhibiting_auxetic_behaviour

[46] **Ahmad Rafsanjani, Damiano Pasini**. (2016). *Bistable auxetic mechanical metamaterials inspired by ancient geometric motifs*. Retrived from: https://www.sciencedirect.com/science/article/abs/pii/S2352431616301298

[47] **Andrew Alderson and Kenneth E. Evans**. (2008). *Deformation mechanisms leading to auxetic behaviour in the α-cristobalite and α-quartz structures of both silica and Germania*. Retrieved from: https://iopscience.iop.org/article/10.1088/0953-8984/21/2/025401

[48] **John Dagdelen, Joseph Montoya, Maarten de Jong and Kristin Persson**. (2017). *Computational prediction of new auxetic materials*. Retrieved from: https://www.nature.com/articles/s41467-017-00399-6

e. Folding and cutting models

The Japanese word 'Origami' is a compound of two smaller Japanese words: 'ori,' meaning to fold, and 'kami,' meaning paper. Origami was a historical hobby not only in Orient but in Occident as well. There are pieces of evidence already in 1492, in an edition of the XII century's *De sphaera Mundi* by John of Holywood, as the most popular paper-boat. The first Japanese's proof was in a verse from Ohara Saikaku from 1680, when origami was still called by their with an elder name: *Rosei-ga yume-no cho-wa ori-sue*, "The butterflies in Rosei's dream would be origami," referring to a particular model where two butterflies, a male, and a female, were folded one upon the other during Shinto ceremonies for weddings, to wrap bottles of Sake. [49]

In the last few decades, with the massive increment of the computational capacities of computers and the development of parametric design software, the art of origami started to influence engineering and structural thinking.

Origami structures indeed are eligible as mechanical metamaterials, described as systems whose mechanical behavior is primarily driven by the folding sequences, crease patterns, , and other parameters describing the geometry of a typical origami structure. In addition, the mechanical behavior of folded sheets could be entirely different from those of the paper from which they are realized. Indeed, some of the mechanical properties of specific origami structures may be entirely independent from those of the paper and only dependent on the geometry of the origami structure itself. [50]

The most widely studied origami tessellation is the herringbone pattern known as *Miura-ori,* and it can be configured to show both positive and negative Poisson's Ratio depending on the design parameters (fig. 21), [51] as well as its three-dimensional version: the Tachi-Miura polyhedron (TMP) (fig. 22). [52]

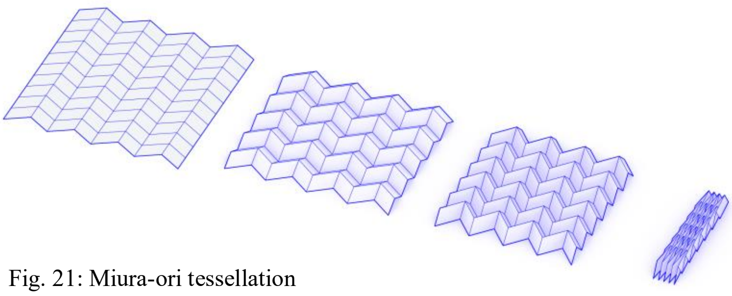

Fig. 21: Miura-ori tessellation

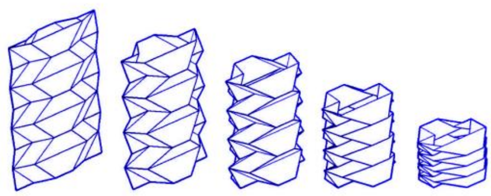

Fig. 22: Tachi-Miura polyhedron

[49] **Piergiorgio Odifreddi**. (2011). *Una via di fuga, il Grande Racconto della Geometria Moderna*. Mondadori.

[50] **Z. Y. Wei, Z. V. Guo, L. Dudte, H. Y. Liang, and L. Mahadevan**. (2013). *Geometric Mechanics of Periodic Pleated Origami*. Retrieved from: https://arxiv.org/abs/1211.6396

[51] **Sebastien J. P. Callens, Amir A. Zadpoor**. (2017). *From flat sheets to curved geometries: Origami and kirigami approaches*. Retrieved from: https://www.researchgate.net/publication/321165318_From_flat_sheets_to_curved_geometries_Origami_and_kirigami_approaches

[52] **H. Yasuda and J. Yang**. (2015). *Reentrant Origami-Based Metamaterials with Negative Poisson's Ratio and Bistability*. Retrived from: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.185502

Kirigami is a less explored variation of origami that includes cutting, rather than folding the paper. The term was coined by the American writer Florence Temko merging Japanese 'kiri' cut, 'kami' paper, in her book, *Kirigami, the Creative Art of Papercutting* (1962). Fractal cut kirigami result in an auxetic model (fig. 23), mimicking the rotating rigid units model (see 1.4.d.). Just as this last example, most folding and cutting models usually reproduce previously seen structures: for instance, TMP can be considered as a re-entrant 3D structure, and Ron Resch tessellations (fig. 24) can work as chirals or rotating rigid units depending on the folding.

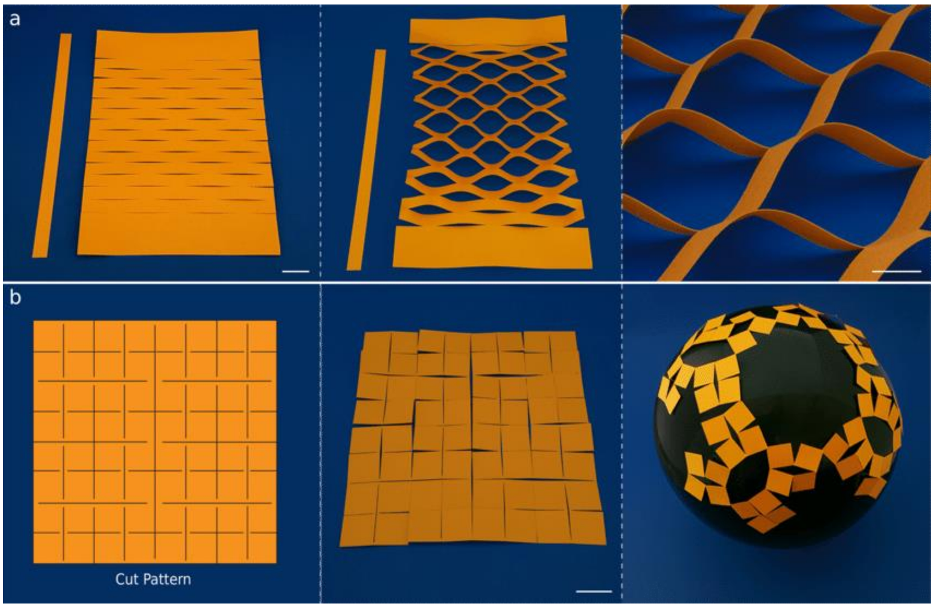

Fig. 23: **a**: generic kirigami **b**: fractal cut kirigami, reproducing an auxetic rotating rigid square model

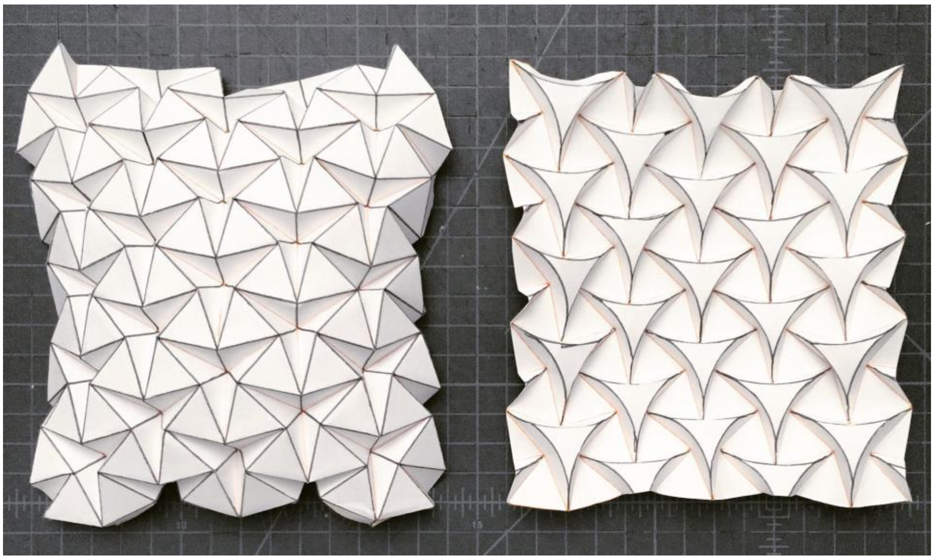

Fig. 24: Ron Resch tesselations

f. Microporous polymers models

The studies on the large NPR ($v = -12$) of polytetrafluoroethylene (PTFE) led to a new model where the interconnection of nodules and fibrils give the auxetic behavior [53]. This model has later been used to describe liquid crystalline polymers (LCP), and fiber-reinforced composites [10], generally *micro* and *meso* structures.

The auxetic mechanism functions in the following way: if a tensile load is applied, the fibrils cause lateral nodule translation, plus, in the relaxed state, all the nodules are oriented along with the fibril directions[54]. Auxetic behavior occurs due to the rotation of the laterally attached rods upon stretching of the material (fig. 25).

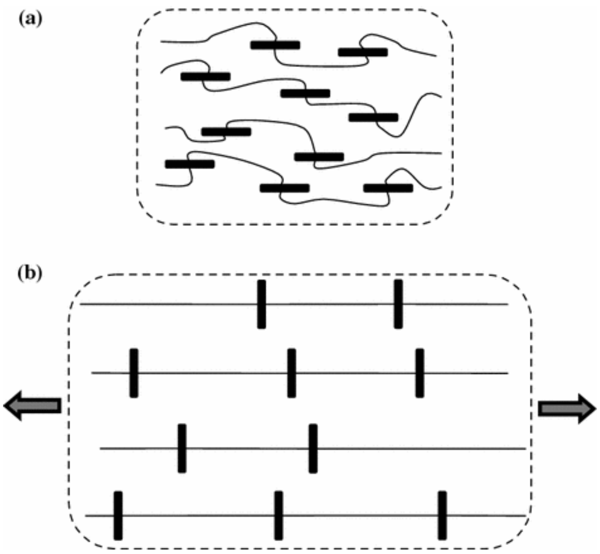

Fig. 25: Auxetic behavior of generic microporous polymer models, before (**a**) and after load (**b**)

g. Molecular models

Some models exist only at the molecular level, and the auxetic behavior depends merely on intermolecular bonds interaction and energy levels. Therefore, they can hardly be reproduced as a macro-structure. Dense solid structures of pentamers and heptamers [55], molecular rods with a prismanic structure [15] both have been proved to exhibit a negative Poisson's Ratio and represent the most primal definition of an auxetic material (see chapter 3. a.).

[53] **B. D. Caddock and K. E. Evans**. (1989). *Microporous materials with negative Poisson's ratios. I. microstructure and mechanical properties*. Retrieved from: https://iopscience.iop.org/article/10.1088/0022-3727/22/12/012

[54] **B. D. Caddock and K. E. Evans**. (1989). *Microporous materials with negative Poisson's ratios. II. mechanisms and interpretation*. Retrieved from: https://iopscience.iop.org/article/10.1088/0022-3727/22/12/013

[55] **K. W. Wojciechowski, K. V. Tretiakov and M. Kowalik**. (2003). *Elastic properties of dense solid phases of hard cyclic pentamers and heptamers in two dimensions*. Retrieved from: https://www.researchgate.net/publication/10810670_Elastic_properties_of_dense_solid_phases_of_hard_cyclic_pentamers_and_heptamers_in_two_dimensions

h. *Form-finding of cellular auxetic models*

In the article "A systematic approach to identify cellular auxetic materials" (by Carolin Körner and Yvonne Liebold-Ribeiro) [56], a method is presented to identify and predict cellular auxetic materials based on static *eigenmode* analysis (a normal mode in an oscillating system, being one in which all parts of the system are oscillating with the same frequency [57], from the software Abaqus 6.13). The starting point was the observation that the well-known 2D quadratic chiral lattice structure, which shows full auxetic behavior, is an eigenmode of the quadratic lattice. Consequently, the eigenmodes of basic cellular structures (triangle, square, hexagon, cube) with periodic boundary conditions were determined (fig. 26). Subsequently, the eigenmodes were assembled to form periodic lattices (fig. 27) and numerically tested to determine the Poisson's ratio. The research proved nearly all auxetic structures known from the literature and various combinations emerge by this simple approach. [57]

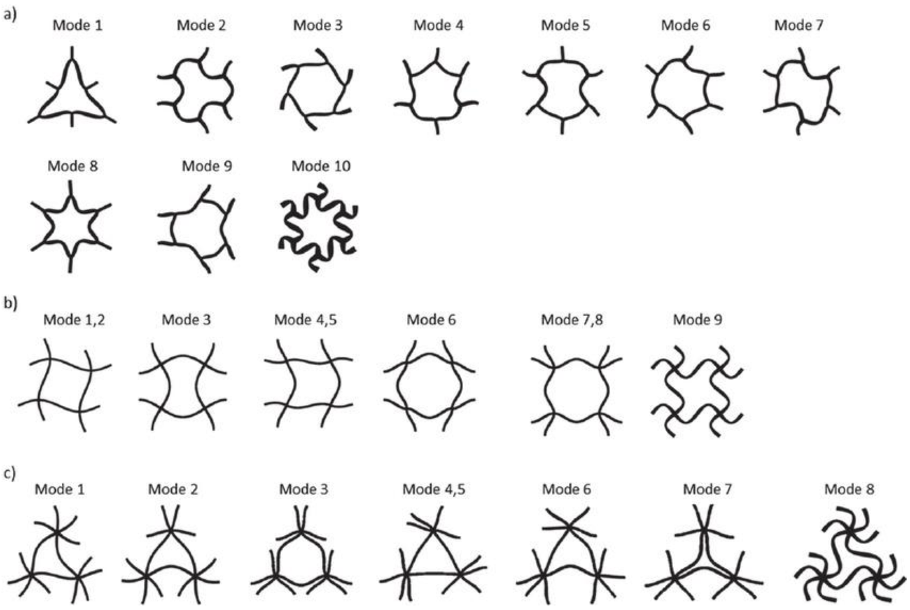

Fig. 26: First eigenmodes of the basic 2D structures with periodic boundary conditions. (**a**) hexagon, (**b**) square, (**c**) triangle.

[56] **Carolin Körner and Yvonne Liebold-Ribeiro**. (2014). *A systematic approach to identify cellular auxetic materials*. Retrieved from: https://iopscience.iop.org/article/10.1088/0964-1726/24/2/025013

[57] **Collins Dictionary:** https://www.collinsdictionary.com/dictionary/english/eigenmode

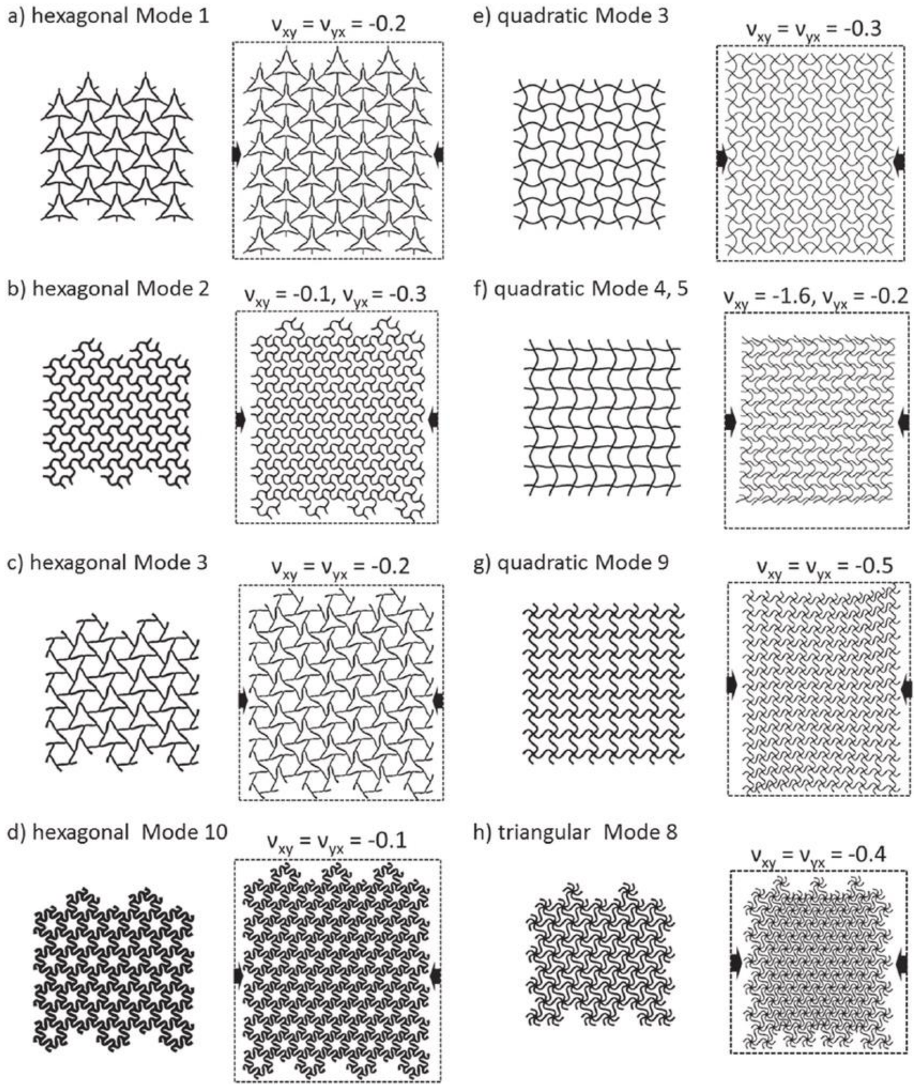

Fig. 27: Periodic lattices from the eigenmodes of figure 26 that show auxetic behavior.

g. *Mixed and unclassified models*

The most popular models were reviewed in the earlier chapters; however, a few other essential models have been studied by most of the before mentioned researchers.

The *Dual Helix Yarn* systems (DHY) consists of a wrap yarn wound helically around the relatively thicker elastic core. The mechanism of auxetic nature of the DHY system relies on the fact that the spatial positions of constituents wrap and core are interchangeable during the application of tensile load. This means that a helically wound wrap tends to straighten by displacing a larger diameter core laterally from its original position such that the negative Poisson's ratio is attained in the DHY (fig. 28).[58] It has been demonstrated that

[58] **W. Miller, Z. Ren, C. W. Smith and K. E. Evans**. (2011). *A negative Poisson's ratio carbon fibre composite using a negative Poisson's ratio yarn reinforcement*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0266353812000462

the lower helix angles and smaller diameter of wrap yarns tend to give larger NPR.[59]

The horizontal plane of the structure of a Magnox reactor radially keyed graphite moderator core (fig. 29) is a perfect example of a structurally efficient auxetic model generally known as *Keyed Brick Structure*. [9] The structure was required to have a high resistance to shear deformation in the horizontal plane and low resistance to volume change. The model expands in all radial directions when subjected to a tensile load in the horizontal plane and retains the square lattice during deformation; hence this structure is auxetic with $\nu = -1$ in the horizontal plane. [9]

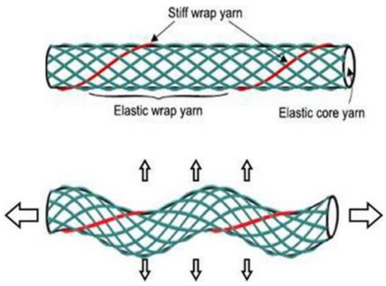

Fig. 28: Auxetic Yarn Made with Circular Braiding Technology

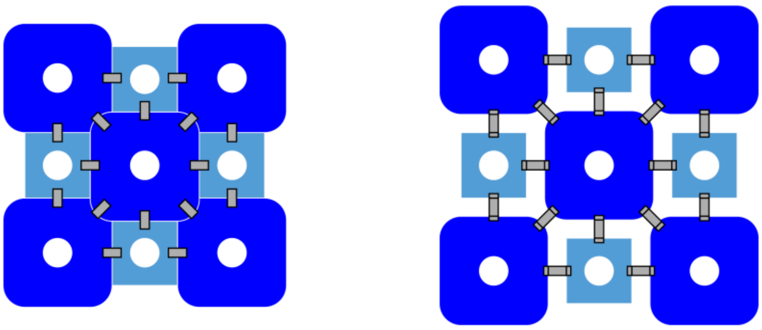

Fig. 29: keyed brick structure model

[59] **Apurv Sibal and Amit Rawal**. (2015). *Design strategy for auxetic dual helix yarn systems*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0167577X15305747

Chapter 2

From Contemporary to Architecture Applications

2.1 Current Auxetic Materials Applications

The following chapter will review most of the auxetic materials currently used or experimented in different industries and application fields, taking into consideration the scale of the auxetic model, the core material, and which properties of auxetics they make use of for improved or new performance. These classifications will also help a better understanding of how auxetic models can be applied and its potentialities.

a. Textile industry

The revolutionary development of a continuous process to produce auxetic materials in fibrous form has created the opening to apply the unique characteristics of negative Poisson's ratio structures in a wide range of applications. Commonly there are two approaches to producing auxetic textiles: the first one comprises the use of auxetic fibers to create an auxetic textile structure; the second one entails the use of conventional fibers to produce a complex textile structure with auxetic properties.[60] Advanced auxetic fibers include multi-filament yarns in which an auxetic filament is wrapped with one or more other threads, perhaps high strength /stiffness, dyeable or conductive filaments so that the advantages of the auxetic material are combined with other beneficial properties for smart technical textiles applications. This leads to the possibility of hierarchical composites displaying auxetic behavior at more than one length scale. Several research pieces on auxetic composites are concentrated on the use of nonauxetic constituents, so the benefits owed to the auxetic effect occur at a macrostructural level. Employing auxetic fibers as the reinforcement enables some interest, such as acoustic energy absorption and impact energy, to be achieved at the microstructural level, useful for interior design textiles.

The DHY construction by Miller et al. (2009) (see chapter 4.g.) consists of a high-stiffness filament helically wrapped around a thicker, low-stiffness thread, with neither of these two constituents required to be auxetic. Upon longitudinal stretching, the high stiffness filament straightens and causes the lower stiffness filament to wrap around it helically. Such multi-filament construction exhibits auxetic behavior and can be fabricated on existing textile machinery, such as warp spinning. Helical auxetic yarns that provide a net

[60] **Rant Darja, Rijavec Tatjana and Pavko-Cuden Alenka**. (2013). *Auxetic Textiles*. Retrieved from: https://www.researchgate.net/publication/259449548_Auxetic_Textiles

increase in the effective diameter of the composite thread under strain, thereby exhibiting pore-opening effect, when incorporated into fabrics, are suitable for different applications. One such case is fabrics that change color and can be used for indicative or aesthetic purposes. These fabrics comprise an underlying tissue of different colors than the overlaid porous material made from auxetic fibers. Such an arrangement enables color change under an application of strain, with potential in fashion and other fields where an accurate indication of the suitable tension is required.[61] Pore-opening is also applicable in textile filtration devices, where intentional scaling of tensile or compressive load application serves as a tool to vary the pore size in order to control the filtration process.[62] A third possible area of use includes release capabilities, such as garments containing antiperspirant in the pores of the material, which is released upon stretching the garment due to swelling. Other possible substances stored in the porous material include antibacterial, antifungal, antiviral, anti-yeast or antiamoebic agents, different additives for use in dental floss; applications also include drug delivery and exudate removal, for instance (fig. 30).[63]

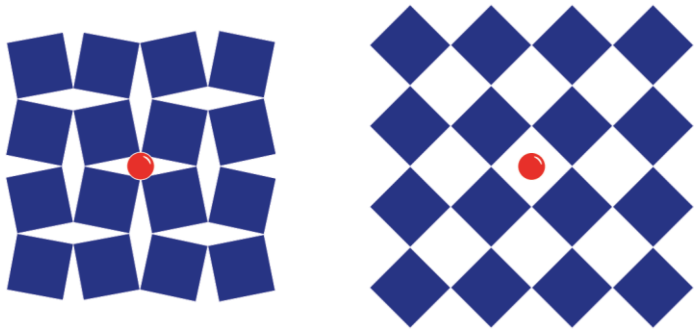

Fig. 30: Example of variable permeability in a rotating rigid units model, used for drug delivery

b. Aerospace and automotive

In this field of applications, much research has been done, and many uses can be found. Auxetics are mostly appreciated because of their capacity to resist shocks and to absorb vibrations and energy. Bettini et al., in 2009, presented a work that tried to apply chiral geometries into the design of an airfoil with morphing characteristics. From experimental tests, the chiral geometries were found to be an effective way to enhance the performances of the wings and rotor blades, improving flow conditions, minimizing the drag, eliminating the need for flap mechanisms, improving handling and control of aircraft. The

[61] **P. Hook**. (2011). *Uses of auxetic fibres*, US Patent Number 8002879 B2
[62] **A. Alderson, J. Rasburn, S. Ameer-Beg, P. G. Mullarkey, W. Perrie and K. E. Evans**. (2000). *An Auxetic Filter: A Tuneable Filter Displaying Enhanced Size Selectivity or Defouling Properties*. Retrieved from: https://pubs.acs.org/doi/abs/10.1021/ie990572w
[63] **Mariam Mir, Umar Ansari and Murtaza Najabat Ali**. (2017). *Macro-scale model study of a tunable drug dispensation mechanism for controlled drug delivery in potential wound-healing applications*. Retrieved from: https://journals.sagepub.com/doi/pdf/10.5301/jabfm.5000280

chiral model used inside provides compliance and allows continuous deformation of the airfoil that can be modified to adapt to wind force. The chiral structures become useful because of its negative *v*, estimated to be -0.9, increase the shear modulus, and allows large deformations while materials remain in the elastic range. The airfoil hosts a macroscopic chiral structure, which takes shapes from a chiral structure inscribed into a rectangle, which is mapped into the willowy shape of the airfoil. During the research, it was found that large node radius facilitates the bending deformation of the ligaments (which are the main contributors of overall auxetic deformation effect), and the core can be designed to achieve different compliance through a change in a limited number of geometric parameters characterizing the chiral inner structure. To manufacture the core, it is used Selective Laser Sintering (SLS) technique, which permits to create complex shapes in a short time and with high precision results. The core was customized, joining only nodes onto the skin and following the curvature of the airfoil (fig. 31).[64]

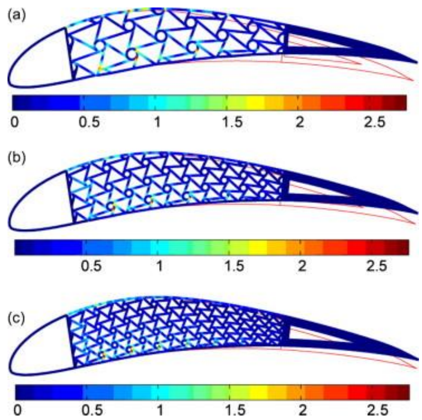

Fig. 31: Axial stress distribution (100 MPa) at the limit of the elastic regime of the material for aluminum alloy airfoil: (a) 2-cell configuration, (b) 3 cells, and (c) 4 cells.

c. *Sports and protection*

Another field in which auxetics gains more and more achievements is in the design of human protection devices. Auxetic polymers have been used to make protective helmets or vests more resilient to knocks and shrapnel. The most used materials in these fields are auxetic foams because of their high indentation coefficients, which were considered of importance in the creation of auxetic helmets by Sanami et al. (2014).[65] Due to the indentation behavior when there is an impact from one direction, material flows in from other

[64] **Paolo Bettini, Alessandro Airoldi, Giuseppe Sala, Luca Di Landro, Massimo Ruzzene and Alessandro Spadoni**. (2009). *Composite chiral structures for morphing airfoils: Numerical analyses and development of a manufacturing process*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S1359836809001899

[65] **Mohammad Sanamia, Naveen Ravirala, Kim Alderson, Andrew Alderson**. (2014). *Auxetic materials for sports applications*. Retrieved from: https://www.researchgate.net/publication/275536178_Auxetic_Materials_for_Sports_Applications

courses to compensate for the effect. Therefore, head injuries may be prevented or be less severe.

Another application of auxetics is made by the sports outfit industry Underarmour, Nike, and others patented severals in trainers' sole and shoe designs that have optimized characteristics in weighing absorption and deformation through auxetic models and foams (fig. 32).

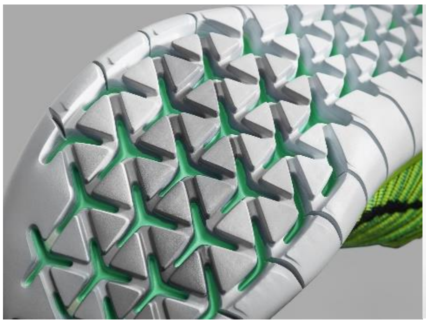

Fig. 32: Nike auxetic sole and UnderArmour Auxetic shoe

Currently, the use of a three-point seat belt is the most diffused system to protect the occupant's car. The existing seat belts webbing use mainly nylon or polyester woven material: smooth surface, high strength, ductility, and proper energy absorption are the essential characteristics. However, this universal belt webbing has a substantial impact on the thorax when car crashes happen because it cannot absorb the forces of the collision properly. The web contracts due to its positive Poisson's ratio becoming more rigid, consequently the human thorax and abdomen area are compressed, causing severe damages. Due to the positive Poisson's ratio characteristic of the conventional belt webbing material, it is impossible to overcome these shortcomings. In the patent "Vehicle safety belt braid - CN 102729948" is the implementation of the traditional seat belt with the use of negative Poisson's ratio bands. The new belt consists in a vehicle safety belt braid which is formed by auxetic fibers jointed one another and shown as a continuous belt structure. "When a vehicle has a crash, the braid is impacted by the upper trunk of the human body having acceleration and thereby being stretched longitudinally: the braid is expanded and deformed transversely due to negative Poisson's ratio pull expansion characteristic, so that the contact area of the braid with the human body is increased. Under the same impact force, the area of force bearing is increased so that pressure on the chest and the stomach of the human body is accordingly reduced. Squeezing to the trunk of a passenger is reduced and damage on the ribs and the viscera is avoided." (fig. 33).[66]

[66]**Yuang Chang, Yang Shu, An Wenzi and Wang Dong**. (2012). *Vehicle safety belt braid*, China Patent Number CN102729948A

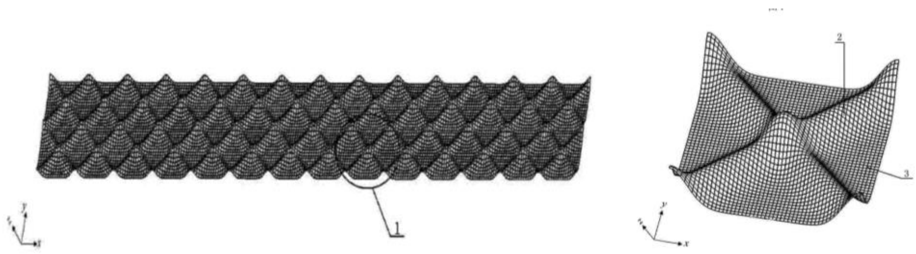

Fig. 33: Vehicle safety belt braid - CN 102729948

d. Biomedical

The research on auxetics done in the biomedical field is the most predominant. The primary utilization is the production of prosthetics, where three primary auxetic bioprostheses can be identified. *Artificial blood vessels* are a typical example of the medical application. If blood vessels are made of conventional material, they tend to undergo a decrease in wall thickness as the vessels open up in response to a stream of blood flowing through it. This could lead to the rupture of the vessel with potentially catastrophic results. However, if an auxetic blood vessel is used, the wall thickness increases when a pulse of blood flows through it (fig.34).[9]

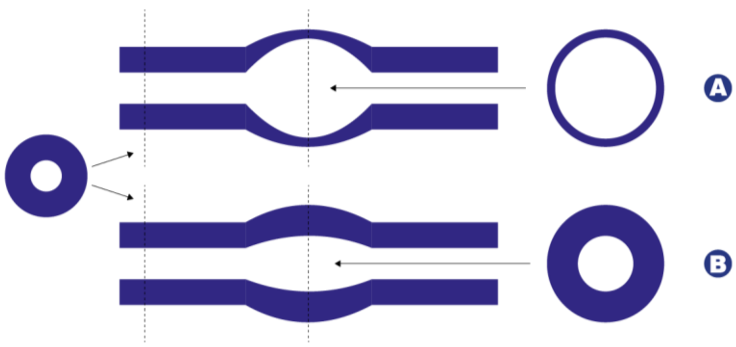

Fig. 34: Coventional (**a**) blood vessel and auxetic (**b**) deformation differences

Artificial intervertebral discs were proposed by Erik O. Martz et al. (2005),[67] a cost-effective design to prevent excessive bulging in compression of the disc to a greater extent than usual of an injured or diseased spinal disc. The implant was tested with a core made of extruded re-entrant honeycomb model, and the final and optimized result was a mesh reproducing a bucklicrystal model. *Annuloplasty prostheses* invented by G. Burriesci and G. Bergamasco (2005)[68] consist of high-performance surgical implantation of an auxetic support prosthesis on the dilated or deformed annulus of cardiac valves, in order to return it to its physiological shape or dimensions so that it can function correctly (fig. 35). The functionality is similar to auxetic artificial blood vessels. Other auxetic biomedical instruments and devices can be found. A

[67] **Erik O. Martz, Roderic S. Lakes, Vijay K. Goel and Joon B. Park**. (2005). *Design of an Artifi cial Intervertebral Disc Exhibiting a Negative Poisson's Ratio*. Retrieved from: https://journals.sagepub.com/doi/10.1177/026248930502400302

[68] **G. Burriesci and G. Bergamasco**. (2005). *Annuloplasty prosthesis with an auxetic structure*. EU Patent No. EP1803420B1

famous experimented auxetic biomedical tool is a dilator for opening the cavity of an artery or similar vessel for use in heart surgery (angioplasty) and related procedures. The coronary artery is enlarged by the lateral expansion of

a flexible auxetic PTFE hollow rod or sheath under tension.[69]

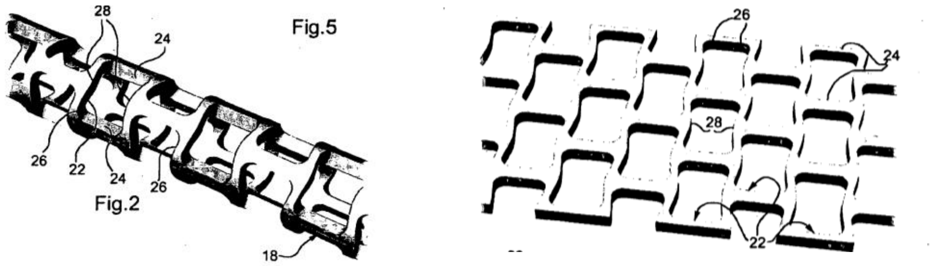

Fig. 35: Annuloplasty prostheses - EP 1 803 420 B1

e. Sensor and actuators

Energy harvesting is concerned with utilizing small amounts of energy available within the local environment to power small electronic devices. This technology's popular potential applications include self-powered sensor nodes in a distributed wireless network, typically used for structural health monitoring. In some cases, ambient vibration energy in buildings, vehicles, or machinery may be sufficient to provide power to such a device via a harvesting mechanism such as piezoelectricity. Most innately, auxetic materials have infolding internal structures, meaning they would lack the authority to stretch a stiffer material bonded to them (such as most piezoelectric materials). The research by William J.G.Ferguson et al. (2018) proved that using an auxetic structure increases the power output of a strain vibration energy harvester, relative to a plain equivalent structure.[70]

f. General engineering[71]

Since their introduction in 1987 (Lakes R.), there has been a recent surge of interest in auxetic materials for a wide range of engineering applications, from damage-tolerant laminates (Alderson, Simkins et al. 2005), microwave absorbers (Smith, Scarpa and Chambers 2000) and medical prosthesis (Martz, Lakes, Goel and Park 2005). A large number of applications is related to the peculiar deformation mechanisms of auxetic configurations. The promising use of auxetic materials for viscoelastic damping applications has been

[69] **R. E. Moyers**. (1992). US Patent No. 5 108 413

[70] **W. J. Ferguson, Y. Kuang, K. E. Evans, C. W Smith and M. Zhu**. (2018). *Auxetic structure for increased power output of strain vibration energy harvester*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0924424718311105

[71] **F. Scarpa, J. A. Giacomin, A. Bezazi and W. A. Bullough**. (2006). *Dynamic behavior and damping capacity of auxetic foam pads*. Retrieved from: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/6169/1/Dynamic-behavior-and-damping-capacity-of-auxetic-foam-pads/10.1117/12.658453.short?SSO=1

surveyed in a studio by Chen and Lakes (1996), where biphasic auxetic composite showed loss tangent exceeding lower Voigt limit, and close to Hashin upper bound. In more recent papers (Scarpa, Ciffo, and Yates 2004), increases in loss factor and storage moduli have been shown for auxetic PU foams manufactured using an adapted route from the standard manufacture layout. In the field of vibration absorber pads, testing of anti-vibration glove cushioning materials have been the subject of several research studies that have lead to the establishment of ISO standard 13753:1999, which states a method for measuring the mechanical transmissibility of glove cushioning materials. The cyclic stress-strain behavior of polymer foams and elastomers has attracted recent attention, mainly when damping ability is concerned since both material types have good vibration absorption potentials. When trials are loaded under strain control and then unloaded, the subsequent extension to the same strain requires a lower force. Further cycling outcomes in continued softening at a progressively slower rate, and a steady-state may be reached. This softening phenomenon is an essential indication of the amount of energy that the material can absorb. A polyurethane foam open cell subjected to compressive cyclic until 100 cycles have been investigated by Shen et al. (2001) proposed a model that could be applied to express the cyclic stress-strain relationship for traditional polyurethane foam at any given cycle. Polymeric foams are viscoelastic materials, and the rate of loading, or frequency of the load cycles, become significant factors to consider. In sandwich structures with a polymeric foam core, it is expected that the viscoelastic behavior of the foam plays an important role in absorbing and dissipating energy, especially during dynamic loading. Such active loading could be in terms of cyclic or high strain rate loading during impact. Both vibration transmissibility and damping capacity under repeated cyclic loading are vital issues on selecting foam materials for applications where both vibro-acoustics and structural-integrity targets have to co-occur. For positive Poisson's ratio materials, the analysis of viscoelastic core properties (particularly for sandwich pads and structures applications) has been considered in very few studies. There is even more lack of available results for auxetic open cell PU-PE foams. A publication by Scarpa et al. (2006) presented a combined series of experimental results on negative Poisson's ratio open-cell foams, both from vibration and cyclic fatigue. These foams offer multiple advantages in terms of transmissibility reduction above 100 Hz – 150 Hz, stability of stiffness, indentation resistance under compressive cyclic loading, and damping aptitude for energy absorption under repeated compressive forces. Auxetic foams have also been used to demonstrate applications that exploit the auxetic effect directly. The use of auxetic materials as fastening devices has been shown in an auxetic copper foam press-fit fastener (Choi, J. B. and Lakes, R. S., 1991). In this device, the copper foam contracts radially as it is pushed (compressed) into a hole, thereby easing the fastener's insertion. When the copper foam is pulled (stretched) to extract it from the spot, the foam expands radially and locks into the surrounding hole walls, leading to increased pull-out resistance for the fastener. The auxetic fiber specimens withstood more than twice the maximum load and required up to three times more energy to extract the fiber than the equivalent positive Poisson's ratio fiber specimens. This behavior can also be applied in biomedical sutures and ligament/muscle anchors (Scarpa, Giacomin et al. 2015).

Finally, cords or ropes with high resistance, anchors, fastener, rivets, shock, sound absorber (Scarpa et al. 2015), etc. are also possible. The use of auxetics is potentially so extensive that it is impossible to give a precise classification: all the characteristics of negative Poisson's ratio structures can find applications to help engineers in finding new solutions.

2.2 Architectural Applications

Architectural applications relying on auxetic geometries solutions is a field yet to be explored, several studies had been conducted, but very little, if none, actually made it into realization. The following chapter will analyze some original solutions as well as the ones already proposed by other researchers concerning different semantic fields of architecture, scales, and materialities.

a. Transformable interior design/furniture

The experimentation of auxetic models for interior design or furniture usually relies on the *objects' transformability* or its capacity to create synclastic and anticlastic shapes rather than its engineering properties. Tom Cecil's Coffee Table reproduces a rotating rigid square pattern capable of opening and closing by either pushing, pulling, or rotating a single part due to hinges' mechanism between the birch plywood units (fig. 36). [72] Martina Panico conceptualized an ergonomic Auxetic Chair [73] where a chiral model composes the seat, this time relying on synclastic curvature and indentation resistance properties (fig. 37). Fundamental Berlin's PUSH brass bowl lets the user define the item's concavity out of a flat disc composed by auxetic rotating rigid triangles (fig. 38).[74] Lampshades mimicking auxetic folding models are also quite common. Based usually on miura-ori, waterbomb, Ron Resh, and square waterbomb tessellations (fig. 39),[75] the propositions are countless, and appreciated thanks to the easily transformable and suggesting lighting designs. Another auxetic lampshade example is briefly introduced in the work of Konaković Mina et al. (fig. 40),[76] showing a rotating rigid triangular model, or, more precisely, a triangular fractal cut kirigami, taking advantage of variable permeability properties for variable light-blocking. This particular technology is more common in shading systems (see chapter 2.2.b.).

The interior space planning is generally conceptualized as a static environment; since Rem Koolhaas's Maison Bordeaux, not many examples of dynamic room units have been brought to life. The idea of shape-shifting and expanding interior spaces through auxetic models remains unexplored.

[72] **Tom Cecil**. *#146 Auxetic* table. Retrieved from: http://tomcecil.co.uk/work/146-auxetic-table/
[73] **Martina Panico, Carla Langella, Carlo Santulli**. *Auxetic structures*. http://www.hybriddesignlab.org/auxetic-structures/
[74] *PUSH - SOLO BOWL BRASS*. Retrived from: https://fundamental.berlin/products/push-solo?variant=18077221511
[75] **Arthur Lebée**. (2015). *From Folds to Structures, a Review*. Retrieved from: https://www.researchgate.net/publication/282461993_From_Folds_to_Structures_a_Review
[76] **Konaković Mina, Crane Keenan, Deng Bailin, Bouaziz Sofien, Piker Daniel and Pauly Mark**. (2016). *Beyond developable: Computational design and fabrication with auxetic materials*. Retrieved from: https://dl.acm.org/doi/10.1145/2897824.2925944

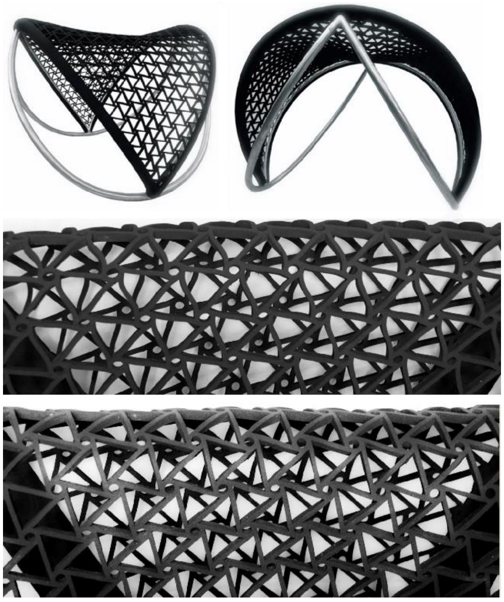

Fig. 36: Tom Cecil's Coffee Table

Fig. 37: Martina Panico’s ergonomic Auxetic Chair

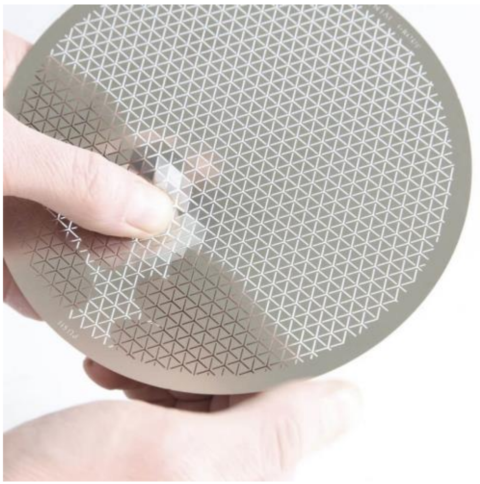

Fig. 38: PUSH brass bowl

Fig. 39: Miura ori tessellation lampashades

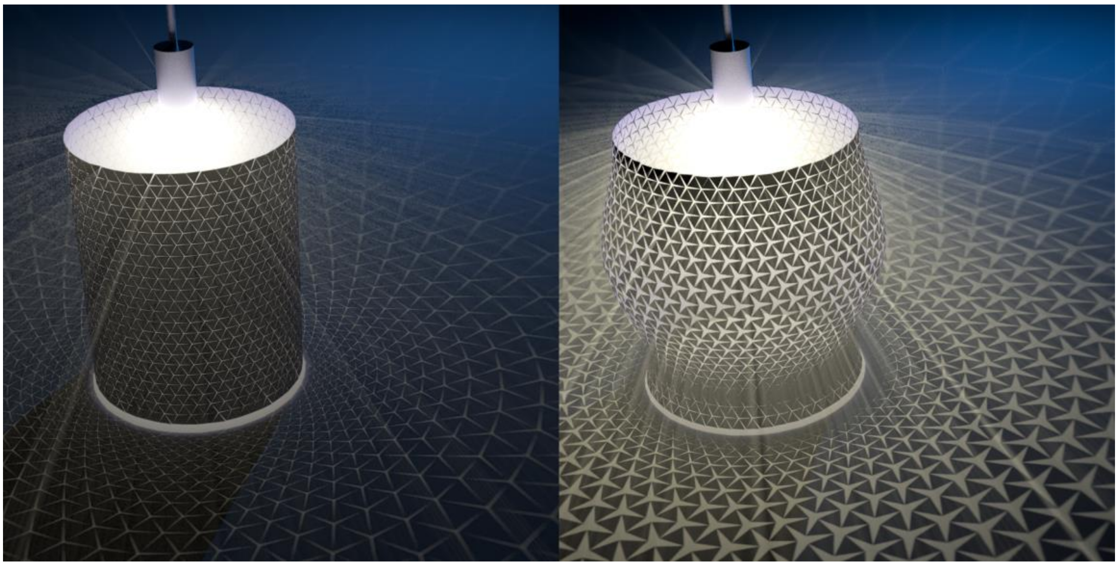

Fig. 40: Konaković Mina’s Auxetic lampshade

b. *Auxetic kinetic shading systems*

According to the U.S. Energy Information Administration in 2018, the residential and commercial sectors accounted for about 40% of energy consumption, of which 17% due to air conditioning, 15% by space heating, and 10% by lighting.[77] A contemporary response in contemporary architecture to this problem has been responsive façades. Kinetic shading systems proved to be energy efficient and sustainable technologies to reduce CO_2 emissions by buildings. A particular case study is Al Bahr Towers's shading system design by Abdulmajid Karanouh and Aedas Arquitectos, located in Abu Dhabi (fig. 41). It is based on the concept of flower adaptation and the 'mashrabiya' - a wooden lattice shading screen, traditionally used to achieve privacy while reducing glare and solar gain. The shading screen's geometry folds and unfolds in response to the sun path, reducing solar gain by up to 50% while simultaneously improving the transmission of natural diffused light into the towers, improving visibility.[78] The hexagon's planar shape composed of six open shading systems reproduces an auxetic model named structurally hexagonal re-entrant honeycomb (see chapter 1.4.a.), and the system consisting of six panels behaves as a triangular folded model also considered as an anisotropic auxetic cell. However, the shading system mechanism is located in a rigid lattice structure on the facade, neglecting auxetic behavior in the entirety of the structure tesselation. In fact, the word 'auxetic' has never been used by the designers and engineers describing this building technology in the literature. However, several researchers amplified the field of auxetic kinetic shading systems, some by using auxetic cells, often in the form of folding models,[79] others by taking full advantage of auxetic models and variable porosity properties.

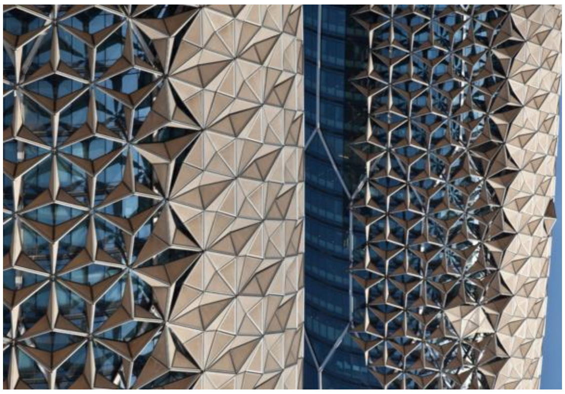

Fig. 41: Al Bahr towers shading system

[77] *How much energy is consumed in U.S. residential and commercial buildings?*. Retrived from: https://www.eia.gov/tools/faqs/faq.php?id=86&t=1
[78] *AL BAHR TOWERS.* Retrieved from: https://www.ahr.co.uk/Al-Bahr-Towers
[79] **Filipa Osório, Alexandra Paio and Sancho Oliveira**. (2014). *Kinetic Origami Surfaces, From Simulation to Fabrication*. Retrieved from: http://papers.cumincad.org/data/works/att/cf2017_229.pdf

Yun Kyu Yi, Ryan Sharston, and Dua Barakat developed a simple but effective adaptation, designing auxetic structures inspired by Hoberman circles pattern for window shading (fig. 42). The geometry, and opening or closing of the cells, was created through grasshopper, DIVA, and Rhino software. The results suggested that the auxetic shading structure can effectively block the sunlight from entering the room by adjusting its geometry in response to varying outdoor and sky conditions.[80]

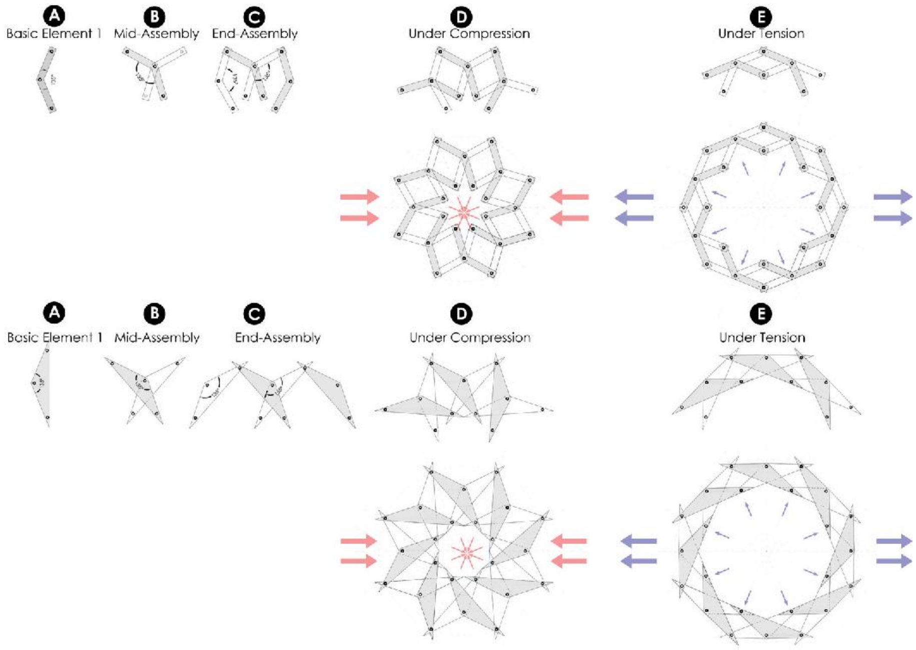

Fig. 42: Shading system developed by Yun Kyu Yi et al.

The works of Amira Abdel-Rahman and Elnaz Tafrihi proved the possibility of converging auxetic structures with shape memory alloys (SMA) and polymers (SMP) [81]. The discovery of shape memory effect by Chang and Read in 1932 [82] is a revolutionary step in the field of active meta-materials research. These materials can recover the original permanent shape after a temporarily fixed deformation by exposure of external stimuli such as heat, light, etc. Thermally-induced shape memory effect is common when the recovery takes place with a specific critical temperature. SMP can be designed by taking a polymer material, in which the polymer chains can fix a given deformation by cooling below one particular transition temperature (T_s). The transition temperature (T_s) can be the glass transition or the melting point of the polymer. Upon reheating to above T_s, the oriented, or crystalline chains in the network,

[80] **Yun Kyu Yi, Ryan Sharston and Dua Barakat**. (2018). *Auxetic Structures and Advanced Daylight Control Systems*. Retrieved from: https://www.researchgate.net/publication/331497056_Auxetic_structures_and_advanced_daylight_control_systems
[81] **Amira Abdel-Rahman and Elnaz Tafrihi**. (2018). *Heat-Actuated Auxetic Facades*. Retrieved from: *https*://www.researchgate.net/publication/326633575_Heat-Actuated_Auxetic_Facades
[82] **L. C. Chang and T. A. Read**. (1951) Trans AIME 189:47

restore the random coil conformation resulting in a macroscopic recovery of the original shape (fig.). [83] The research designed an auxetic shading system prototype combining SMPs resins and SMAs capable of passive actuation tested via 3D printed in the form of an auxetic buckling rotating rigid units model (fig. 43).

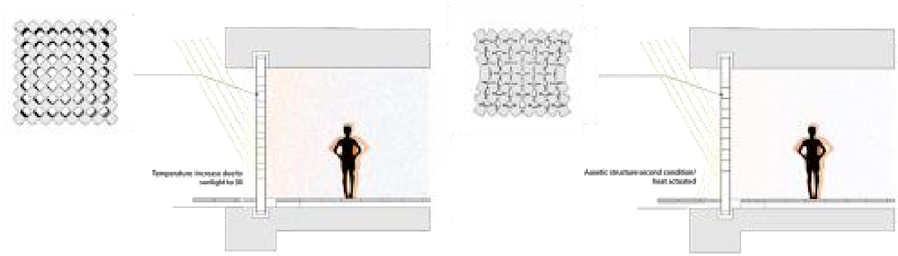

Fig. 43: Shading system developed by Amira Abdel-Rahman et al.

Achim Menges, Steffen Reichert, and colleagues at the University of Stuttgart's Institute for Computational Design coined the term *meteorosensitive architecture* as morphologies that can respond directly to changes in the atmosphere through biomimetics (see chapter 2.3). Their design is based on composite veneers that would either lie flat or roll up according to humidity levels (fig. 44).[84] They affirm that: "complex electromechanical systems have the disadvantage that they are complex to build and difficult to maintain and tend to frequently malfunction. Material embedded actuation provides a new perspective to these challenges as it intrinsically engages weather conditions." [85] Such technology holds great potential in architectural skins in combination with auxetic structures due to its "activation mechanism" Through bending and folding, typical of multiple auxetic models.

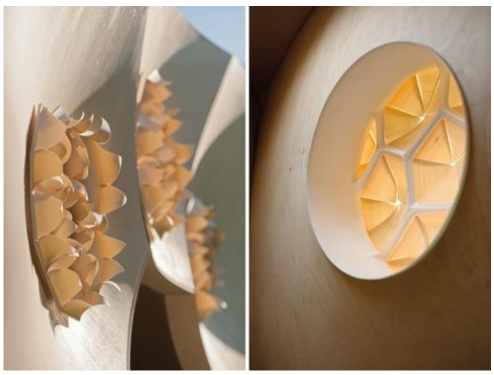

Fig. 44: Achim Menges's Hygroskin, in humid and dry atmosphere

[83] **Debdatta Ratna and J. Karger-Kocsis**. (2007). *Recent advances in shape memory polymers and composites: a review*. Retrieved from: https://link.springer.com/article/10.1007/s10853-007-2176-7

[84] **Achim Menges, Oliver David Krieg and Steffen Reichert**. (2013). *HygroSkin – Meteorosensitive Pavilion*. Retrieved from: http://www.achimmenges.net/?p=5612

[85] **Steffen Reichert, Achim Menges and David Correa**. (2015). *Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0010448514000438?via%3Dihub

c. Auxetic reinforcement systems and composites in concrete

Auxetic materials have been thoroughly analyzed for their engineering properties, and among construction materials, concrete auxetic composites and reinforcement systems can improve performance for a low cost. Having already a low embodied energy, obtaining more satisfying mechanical results in concrete constructions can reduce building maintenance and elongate its life cycle, aiming towards more sustainable design.

Christopher Zmuda's research explored the strength of an auxetic reinforcement system for use in concrete, in particular using a 2D thin metallic re-entrant honeycomb and a modified tube and sheet pattern, with unit cells' size from ~ 2.5 to 0.65 cm, embedded in the concrete mixture. The results of the simulation test in compression of the concrete bar proved mainly an increased resistance to impact loading. [86]

Tarık Baran (2019) directed a similar approach by using an auxetic structure as reinforcement in a reinforced concrete beam. A 3D hexagonal re-entrant honeycomb grid substituted the classic concrete reinforcement and resulted slightly positively effective in the concrete's stress distribution, shear strength, and indentation resistance (fig. 45). [87]

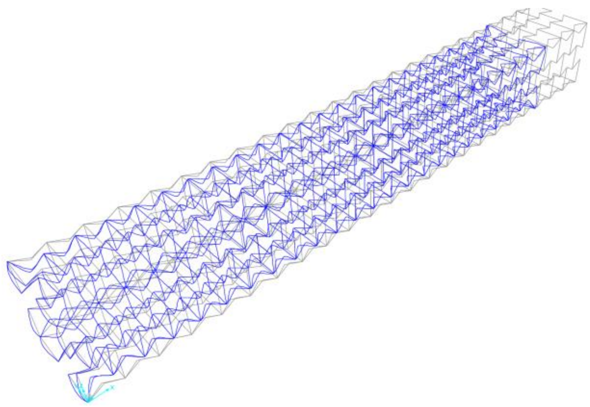

Fig. 45: 3D hexagonal re-entrant honeycomb grid for reinforced concrete beam

Other researches on this topic include the mixture of cementitious mortar with auxetic materials, like auxetic foams [88] and auxetic fabrics [89] (fig. 46). Both were found to be more useful on the extremity or surface of the mortar sample, beneficial respectively for the alteration of the brittle behavior of the mortar

[86] **Christopher Joseph Zmuda**. (2017). *Design of Structural Composite with Auxetic Behavior*. Retrieved from: https://digitalcommons.wpi.edu/cgi/viewcontent.cgi?article=1295&context=mqp-all

[87] **Tarık Baran**. (2019). *Using of an Auxetic Structure as Reinforcement of a Bending Reinforced Concrete Beam*. Retreived from: http://davidpublisher.org/index.php/Home/Article/index?id=39378.html

[88] **Tatheer Zahraa and Manicka Dhanasekar**. (2017). *Characterisation of cementitious polymer mortar – Auxetic foam Composites*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0950061817307912

[89] **Mohammad Asad, Manicka Dhanasekar, Tatheer Zahra and David Thambiratnam**. (2019). *Characterisation of polymer cement mortar composites containing carbon fibre or auxetic fabric overlays and inserts under flexure*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0950061819317933

render and energy dissipation in the polymer-cement matrix. These last two material compounds, however, are still hard to imagine for an actual

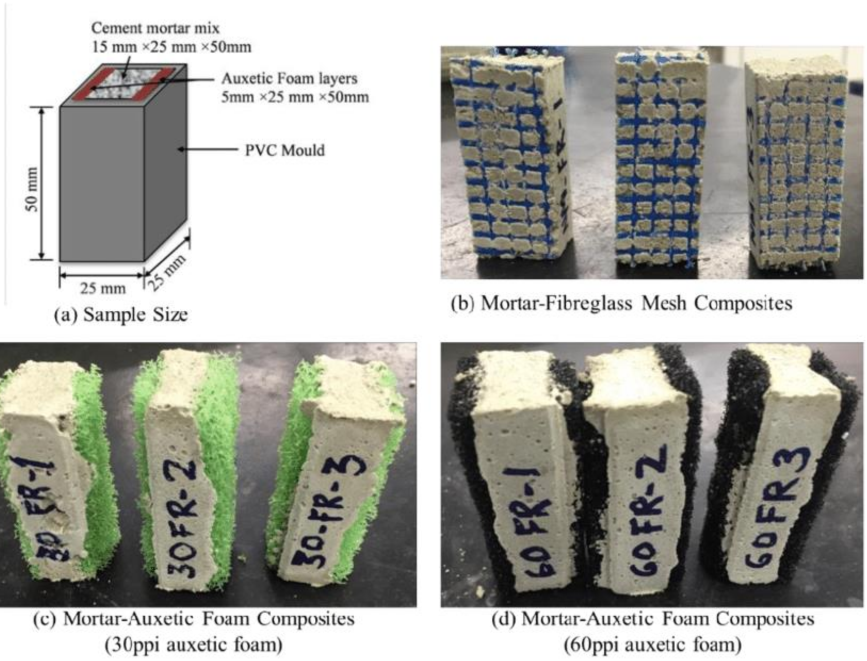

Fig. 46: Mortar-Auxetic Foam Composite Samples

application in architecture.

d. Auxetic bending-active structures

Bending-active structures are defined as structural systems, including curved beam or shell elements that base their geometry on the elastic deformation from an initially straight or planar configuration. Existing structures can differ in the way bending is induced and maintained in the system: *pre-bent components*, pre-assembled in the workshop, *self-restraining systems*, bent through the component interaction, or *post-restrained structures*, assembled on the ground. The stiffness of the structure is given by the manipulation of the elastic behavior of the components. The core material should have a high elasticity to strength ratios to allow the bending, as well as the cross-section and geometry of the elements. The stiffness of the structure is defined by the initial displacement of the deformed geometry and the geometric stiffness, result of the stress-stiffening effect, represented by the flow of forces.[90] However, it is important noting that it is not possible to approach bending-active structures with a single or a general theoretical concept, [91] giving space to experimentation through auxetic structures.

[90] **Stijn Brancart**. (2017). *Bending-active structures: a review of design principles*. Retrived from: http://www.novelstructuralskins.eu/wp-content/uploads/documents/Other/Educational/COSTActionTU1303_Intro_Bending-active.pdf
[91] **Julian Lienhard**. (2014). *Bending-Active Structures*. Retrieved from: https://elib.uni-stuttgart.de/bitstream/11682/124/1/Diss_Bending_Active_Structures_Julian_Lienhard.pdf

The research by Lorenzo Mirante and Roberto Naboni [92] proved the possibility of applying a 2D auxetic pattern to a bending-active structure. The synclastic curvature property of auxetic tessellations makes possible the creation of curved surfaces through 3D printed re-entrant honeycombs. Several planar models were simulated on the kangaroo software, varying the rods' stiffness and height, influencing the different curvatures of the actively-bent structure (fig. 47). Architectural scale 3D printed pavilions were also suggested in the research constructed via additive manufacturing (AM).Such technologies can erect architecture fast, with lower energy consumption and workforce. The architectural solutions in which they can be applied are countless, such as pavilions, refuge camps tents, or concrete shells formworks.

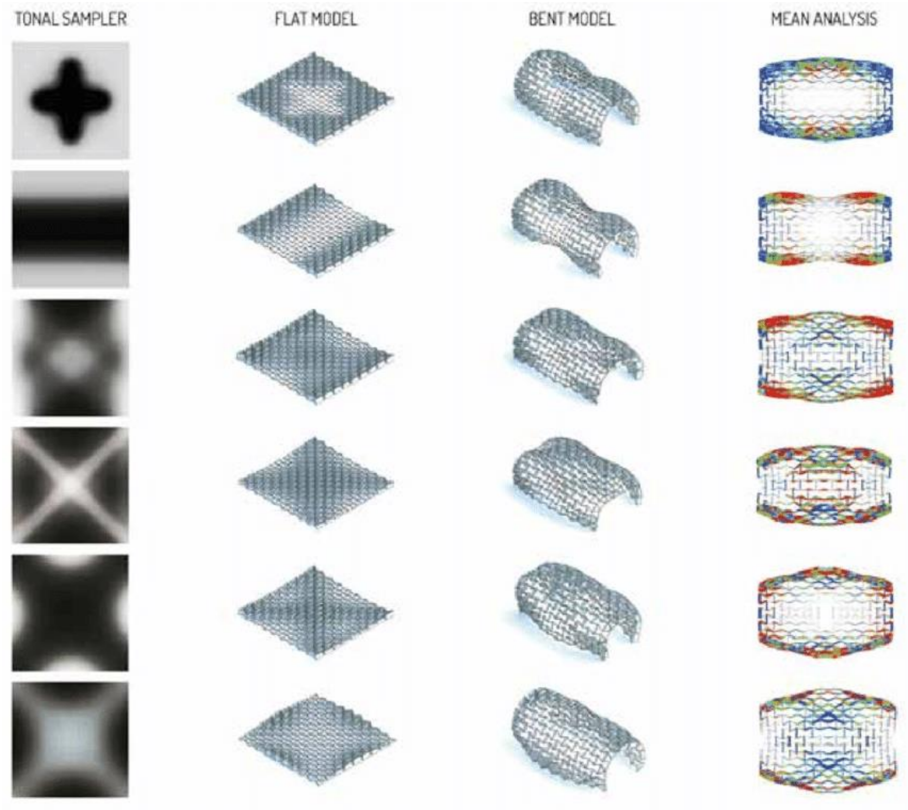

Fig. 47: Differentiation of the pattern extrusion depending on the set of gradients. For each example is shown: flat configuration, bent configuration and curvature analysis of the structure.

e. *Acoustic and thermal isolation auxetic sandwich panels*

Sandwich panels in engineering are usually applied when a combination of high structural rigidity and low weight is required. [93] In architecture, they are commonly used for their thermal resistance and acoustic insulation characteristics. The damping properties of auxetics have been studied in

[92] **Lorenzo Mirante and Roberto Naboni**. (2016). *Computational Design and Simulation of Bending-Active Auxetic Structures*. Retrieved from: https://www.researchgate.net/publication/322776708_Computational_Design_and_Simulation_of_Bending-Active_Auxetic_Structures

[93] **H.G. Allen**. (1969). *Analysis and design of structural sandwich panels*. Retrieved from: https://www.sciencedirect.com/book/9780080128702/analysis-and-design-of-structural-sandwich-panels

sandwich panels by several researchers, mostly in the field of aerospace engineering and structural applications.

Li Yang et al. (2013)[94] analyzed the properties of 3D re-entrant auxetic structures in sandwich panels in particular bending performance and low energy impact performance, and D. Qing-Tian et al. (2010)[95] proved their great potential in aerospace engineering, in particular, dispersive properties of wave propagation in the sandwich panel.

To this day, there is no record of auxetic core sandwich panels for architectural applications.

f. Deployable auxetic structures

Deployable structures can move, expand, and contract by changing their geometric, material, or mechanical properties. In architecture, deployable structures can adapt their form and behavior in response to changing conditions, from sun radiation (shading systems) to weather conditions, as well as for load-bearing and storage. Examples of this can be found already in satellite solar arrays modeled on a simple unfolding pattern based on the principle of chiral auxetic models (fig 48).[96]

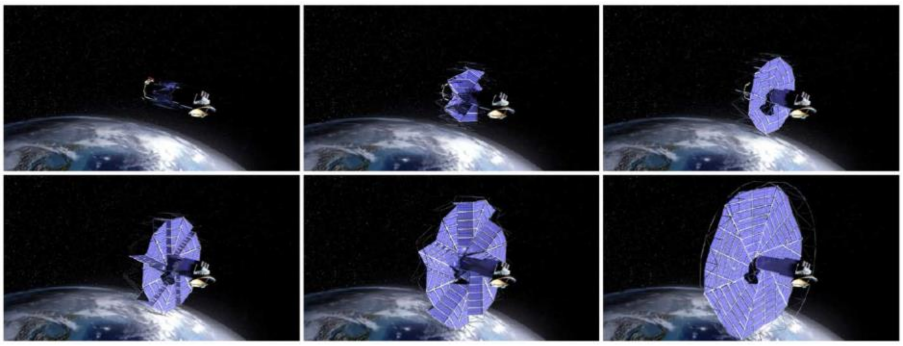

Fig. 48: A theoretical model of self-deployable solar panels using the principles of the Miura-Ori fold

Designer and Pioneer of deployable structures, Chuck Hoberman, merged art, architecture, and engineering under singular projects, usually relying on the Hoberman sphere mechanisms' auxetic properties. From the Olympic Arch (2002) to the Iris Pavilion at MOMA (2000) and several interior designed

[94] **Li Yang, Ola Harrysson, Denis Cormier, Harvey West, Chun Park, Kara Peters**. (2013). *Design Of Auxetic Sandwich Panels For Structural Applications*. Retrieved from: https://www.researchgate.net/publication/287435788_Design_of_auxetic_sandwich_panels_for_structural_applications

[95] **D. Qing-Tian and Y. Zhi-Chun**. (2010). *Wave Propagation in Sandwich Panel with Auxetic Core*. Retrieved from: https://www.researchgate.net/publication/267690036_Wave_Propagation_in_Sandwich_Panel_with_Auxetic_Core

[96] **Elizabeth Landau**. (2014). *Solar Power, Origami-Style*. Retrieved from: https://www.nasa.gov/jpl/news/origami-style-solar-power-20140814

spheres (fig. 49), his projects rely on their transformability to astonish and entertain the viewer.

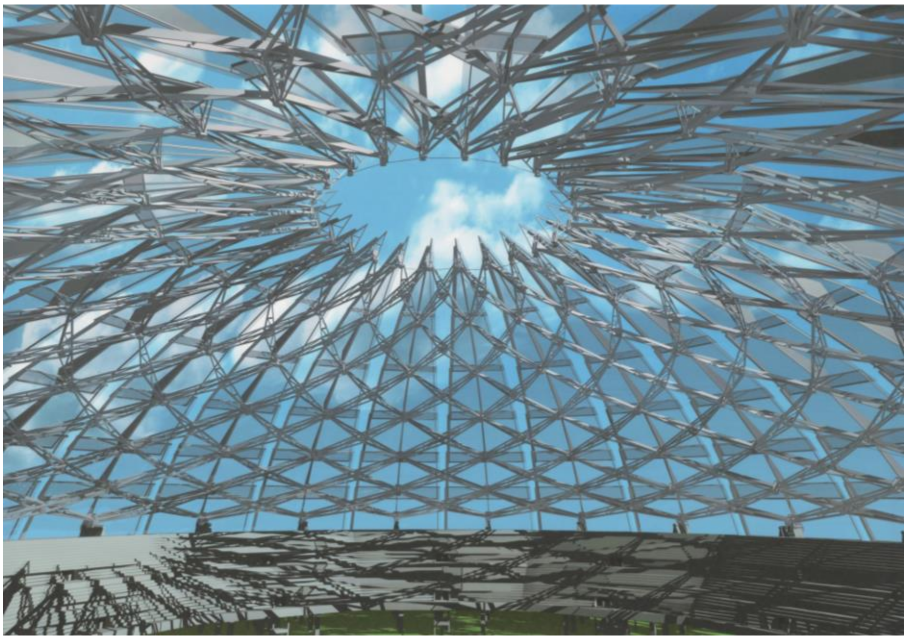

Fig. 49: Chuck Hoberman - Iris Dome Project

Deployable structures can be advantageous if compacted for transportation and set in place in the desired destinations, useful as emergency and temporary architecture. In particular, auxetic structures could be implemented in this field thanks to their property of expanding in the three dimensions under a single axial force. Several foldable container units have been prototyped and produced. Most reproduce a re-entrant hexagon model, transported with the paralleled stacked floor, sidewalls, and ceiling, and when pulled orthogonally by a crane opens in the typical container rectangular parallelepiped form, in which the front and back panels are inserted (fig. 50).

Damian Granosik, Jakub Kulisa, and Piotr Pańczyk's design achieved first place in 2018 eVolo's Skyscraper Competition[97], and it's a perfect example of a large scale deployable architecture for disaster zones.

Fig. 50: Foldable container prototype

[97] **Damian Granosik, Jakub Kulisa, Piotr Pańczyk**. (2018). *Skyshelter.zip: Foldable Skyscraper for Disaster Zones*. Retrieved from: http://www.evolo.us/skyshelter-zip-foldable-skyscraper-for-disaster-zones/

g. Application of auxetic models to large static structures

The auxetic models applications seen in all previous examples take advantage of the dynamics and deformations of the auxetic products. However, the models could hold beneficial properties in static environments useful in architectural scale structures, where high resistance to axial loading as well as flexibility is required. Diagrid and exoskeleton both serve the purpose of shifting the support structure to the outside or extremity of the building, creating interiors that aren't interrupted by vertical supports and using less steel than a standard structural steel frame. Despite high indentation resistance and fracture toughness are necessary for such structures to cope with wind and seismic action in tall buildings, it is yet to prove that auxetic structures at building-scales can perform amply. The main issue of the application of auxetic technologies in lattice structures it's that single auxetic cells are, by definition, deformable and statically indeterminate, while for building structures, it is necessary relying on non-deformable shapes such as triangles. Although it does not refer to a specific auxetic model, a generic origami folding, it gives a perfect sense of the scale, mainly vertical, in which these technologies could be implemented.

2.3 Auxetics and Biomimetics

In nature, materials are expensive and shape is cheap.

PROFESSOR JULIAN VINCENT [98]

Biomimetics is defined as a design inspired by the way practical challenges have been solved in biology.[99] Most of this discipline's activity has been in the fields of robotics and material science, but the opportunity now exists for architects to embrace this source of innovation. Nature generally makes exceptionally economical use of materials, often achieved through evolved ingenuity of form. Using folding, vaulting, ribs, inflation, and other means, natural organisms have created effective structures that demonstrate astonishing efficiency, most of which we reviewed related to auxetics in chapter 2.2.

Eons of evolutionary refinement adapted nature into using the least amount of resources for the most optimal effect; human inventions for sustainable

[98] **J. F. V. Vincent**. (1997). *Stealing ideas from nature*. RSA Journal, Aug/Sept.

[99] **Michael Pawlyn**. (2016). *Biomimicry in architecture*. RIBA Publishing, London.

structures tend to obtain the same thing. Biomimetics can, therefore, be defined as the synthesis of the human potential for innovation coupled that the best that biology can offer.

Despite the definition of auxetic metamaterials (artificial materials with properties that do not exist in nature), nature found its way in these efficient structures over fifty million years before human inventions. Aquatic salamander connective tissue sheaths were proved to have NPR,[100] as well as cow teat skin and cat skin, obtaining elastic, yet tough skins. Convulus flowers (fig. 51), on the other hand, rely on a folded chiral auxetic model cell to open its petals with the minimum energy: merely the morning sun heat, increasing the pressure of the liquid inside cells at the base of the petals, making them rigid and causing the flower to unfold over a relatively large area.[101]

Fig. 51: Opening blossom of Ground Morning Glory

Biomimetics in architecture has gained vast popularity among researchers in the last decade, from Neri Oxman's 'Mediated Matter' at MIT, to the Wyss Institute for Bio-inspired Engineering, of which the previously quoted Chuck Hoberman is part of.[102] However, auxetic geometries are still to be combined with this discipline on the architectural scale, holding great potential for highly sustainable structures.

Nano-scale self-assembly is crucial to how nature operates. Intramolecular self-assembly in nature is the process by which molecules arrange themselves in order without external guidance or management, and also by which they fold into macromolecular assemblies.[103] A significant opportunity lies in the prospect of growing materials for buildings by accretion or self-assembly that mimics natural processes. Additive Manufacturing (AM), generally referred

[100] **L. M. Frolice, M. La Barbera And W. P. Stevens**. (1992). *Poisson's ratio of a crossed fibre sheath: the skin of aquatic salamanders*. Retrieved from: https://www.researchgate.net/publication/229984633_Poisson's_ratio_of_a_crossed_fibre_sheath_The_skin_of_aquatic_salamanders

[101] **Angela Carson**. (2015). *Motion without Muscles: How Flower Petals Move*. Retrieved from: https://davesgarden.com/guides/articles/motion-without-muscles-how-flower-petals-move

[102] **Wyss institute**. *Chuck Hoberman, M.S.* Retrieved from: https://wyss.harvard.edu/team/associate-faculty/chuck-hoberman/

[103] **Shashi Jasty**. (2006). *Introduction to molecular self-assembly*. Material Matter, 2006 *1.2, 3.* Sigma-Aldrich Materials Science.

to as '3D-printing', was a momentous breakthrough for designers in the digital revolution because it allows a three-dimensional computer model to be turned directly into a physical model with a high degree of accuracy. AM also allows approximating the bottom-up manufacturing that goes in nature, in the way materials can be positioned precisely where they need to be. Consequently, it offers the ability to achieve the efficiency of materials through complexity of form, such as auxetic morphologies, at no added cost.[90]

Recent discoveries by 'Mediated Matter' managed to print with chitosan, a chitin derivative, and functionally graded materials with spectacular results (fig. 52).[104] The robotic fabrication of water-based biological raw materials allows continuing the natural resource cycles that enabled their synthesis.[105]

Fig. 52: Water-Based Digital Fabrication

[104] **The Mediated Matter Group**. (2018). *Water-Based Digital Fabrication*. Retrieved from: https://mediatedmattergroup.com/waterbased-digital-fabrication

[105] **The Mediated Matter Group**. (2018). *Aguahoja*. Retrieved from: https://mediatedmattergroup.com/aguahoja

Chapter 3

Design proposition: Auxetic Climatic Adaptive Building Shell

3.1 Biomimetic Building Skins

Building facades can be interpreted as biomimetic technologies due to the several similarities they share with protective layers developed by nature (skins, membranes, shells, cuticles). The skin is usually the largest organ protecting the body from external invaders, as well as regulate, control, absorb, maintain, sense, and camouflage for the health and the well-being of the organism. Similarly, building facades provide UV, moisture, and thermal defense, as well as protection from dirt, micro-organisms, and radiation. Façades communicate by transferring information; they can exchange and store energy, heat, and water. Façades have always been separating external and internal environments. To maintain constant internal climatic conditions, façades have to counteract the influence of several different external environments depending on the climate zone. In hot and humid zones, they mainly protect against the sun radiation and allow the airflow of cooling night breezes. In temperate climates, façades have to adapt to seasonal changes. In northern environments, façades are designed to protect against the winter cold. This has always affected the construction material used and the shape and configuration of windows, building orientation, and the heating strategy. In order to idealize a new sustainable facade system based on auxetic morphologies without copying contemporary influences, a biomimetic approach based on plants and other organisms will lead the design. The following chapter summarizes the concept exposed in Bio-based Building Skin by Anna Sandak, Jakub Sandak, Marcin Brzezicki, and Andreja Kutnar (2019) (fig. 53).

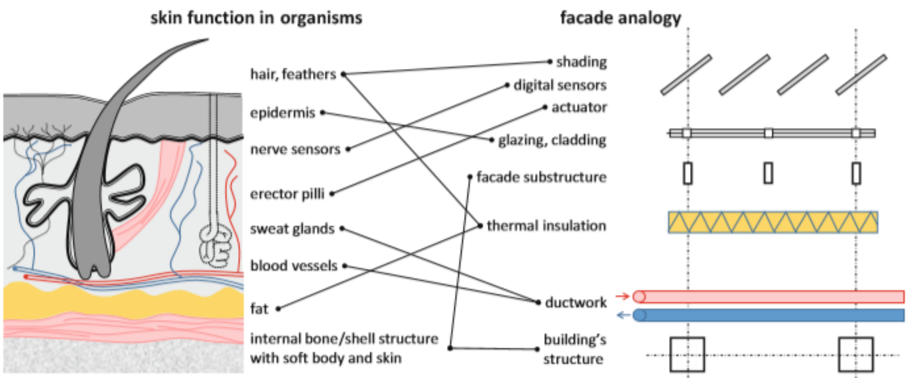

Fig. 53: Analogy between organisms' skin and architectural facades

a. Plant inspired skins design

Florae have been evolving for approximately 460 million years. As a result of constant environmental challenges, they have become exceptionally well adapted to different climatic conditions. Living organisms use smart, elegant, and optimized solutions to survive, thanks to continuous evolutionary processes. Consequently, plants have developed specific tissues with barrier properties after facing several survival pressures (extreme temperatures, water loss, UV and solar radiations, and parasites) (fig. 54). These are often identified as straightforward inspirations for the responsive skins solutions.

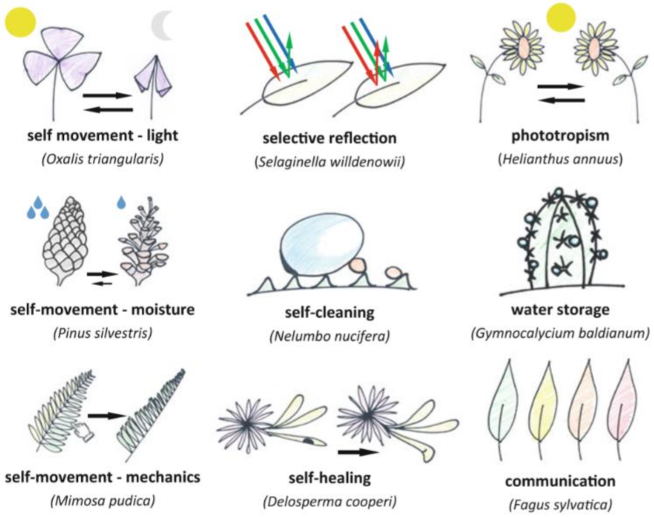

Fig. 54: Adaptations of plants and their possible implementation in façade systems

Different plants present mechanisms where plants' chemical composition, anatomy, morphology, and behavior respond to external environment protection against excessive wind, drought, water, cold, heat, and light (tab. 1). The difference between engineering and nature becomes clear when one looks at which elements of the periodic table are used in the two approaches. Roughly 96 percent of all living matter is made from four elements: carbon, oxygen, hydrogen, and nitrogen. So nature uses a minimal subset of the periodic table, whereas we use virtually every element in existence for engineering, most of which cannot be recycled through biodegradation. In plants, heterogeneity, anisotropy, and hygroscopicity are utilized as response tools with strategies adapted to various climatic constraints and structural solutions. The hierarchical structure of natural materials and multiple properties at different length scales allowed plants to meet adaptation requirements better.

Consequently, humble material elements simultaneously act as sensors, regulators, and actuators. Full analysis and evaluation of plant adaptation strategies (both static tactics and dynamic mechanisms) to their environment

Climate description	Biological adaptation	Façade biomimetic
Desert—Arid (BW)		
Dry Hot Direct sun Strong wind Extreme temperatures Water loss Drought	Thick, small leaf H_2O storing Reduced transpiration Hair and spines Collecting H_2O Thick layer of wax Low H_2O loss Light reflection Long root system H_2O capturing	Reducing evaporation UV protection Shading system Reflective system Filtering system
Prairie—Arid (BS)		
Hot summers Cold winters Strong wind Uncertain rainfall Common drought	Narrow leaves plant shape H_2O storing Low transpiration Protection against animals Thick bark Fire resistance, high regeneration Seed dispersing system Reproduction	Dynamic Opening–closing system Self-healing materials External protection
Rainforest—Tropical (A)		
Hot Wet Uneven solar radiation Heavy rains	Drip tips High water runoff Wax Protection and hydrophobicity Aerial roots High H_2O, CO_2 uptake Low decay Plant morphology H_2O storing	Self-cleaning Filtering Phytoremediation Self-cleaning surfaces External protection
Tundra—Polar (E)		
Short cool summers Long/severe winters Low rainfall Permafrost Solar light variation	Colour of plant Modulated light reflection Plant movement High absorbance of solar radiation Wax and hairs Protection against freeze	Anti-freezing Energy storage Dynamic shading system Modulation of light Transmission Shading system
Temperate Forest—Temperate (C)		
Hot summers Winter bellow 0 °C No problem with H_2O availability Four seasons	Lightweight leaves High photosynthesis Reaction wood High mechanical resistance Nyctinasty, thigmonasty Different response to light and mechanical stress Thick bark High thermal isolation	Reaction to stress Shading and signalling Dynamic energy storage Insulation, shading Self-healing materials Communication
Water—Everywhere ()		
Continuous wet Stable temperature No direct sun Constant H_2O availability Water current, flood	Flexible stem Floating Hydrophobic surface H_2O protection Thin cuticle High CO_2 uptake Floating seeds Reproduction	H_2O storage Stiffness change Hydrophobic surfaces Self-cleaning surfaces Flexibility

Tab. 1: Biological adaptations of plants and its possible implementation for façade systems

in diverse climate zones are crucial for shifting concepts from nature to architecture. As a result, unique adaptation solutions can be implemented in new materials that will be used in building envelopes erected in specific climate zones. Mixing of length scales together with biological, physical, and chemical concepts for adapting properties of materials during their preparation should lead to improved design of future smart materials. This optimization development should promote the progress of active biomaterials performing as interfaces between internal comfort and outdoor conditions that are able to regulate humidity, temperature, CO2, and light and also capture and filter pollutants, self-clean, self-assemble, and self-heal. Such materials could be used as responsive facade elements and contribute to an improved performance and energy efficiency of building skins. [106]

i. Design procedure

Plants respond to external stimuli through movement, called tropisms or nasties, according to whether the motion or response is dependent on the position or direction of the stimulus. Auxetic structure can efficiently be designed as responsive, exhibiting rapid and reactive movements, in a timescale that we can perceive. In this way, we can adapt auxetic morphologies to how plants react to light, temperature, or water changes through responsive mechanisms in the macroscopic and microscopic scales.[107] Seeds of many Mesembryanthemums (fig. 55), dispersed thanks to a valve mechanism that uses rainwater as a trigger,[108] and leaves of Rhododendron (fig. 56) that roll in response to temperature,[109] are two examples of dynamic mechanisms at the macro-scale. On the other hand, stomatal movements (fig. 57) in response to water, light, temperature, and carbon dioxide are examples of dynamic micro-scale mechanisms.

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[106] **Anna Sandak, Jakub Sandak, Marcin Brzezicki and Andreja Kutnar**. (2019). *Bio-based Building Skin*. Retrieved from: https://link.springer.com/book/10.1007%2F978-981-13-3747-5

[107] **Marlén López, Ramón Rubio, Santiago Martín and Ben Croxford**. (2016). *How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S136403211630510X

[108] **Matthew J. Harrington, Khashayar Razghandi, Friedrich Ditsch, Lorenzo Guiducci, Markus Rueggeberg, John W.C. Dunlop, Peter Fratzl, Christoph Neinhuis and Ingo Burgert**. (2011). *Origami-like unfolding of hydro-actuated ice plant seed capsules*. Retrieved from: https://www.nature.com/articles/ncomms1336

[109] **Erik Tallak Nilsen**. (2017). *Causes and Significance of Winter Leaf Movements in Rhododendrons*. Retrieved from: https://scholar.lib.vt.edu/ejournals/JARS/v40n1/v40n1-nilsen.htm

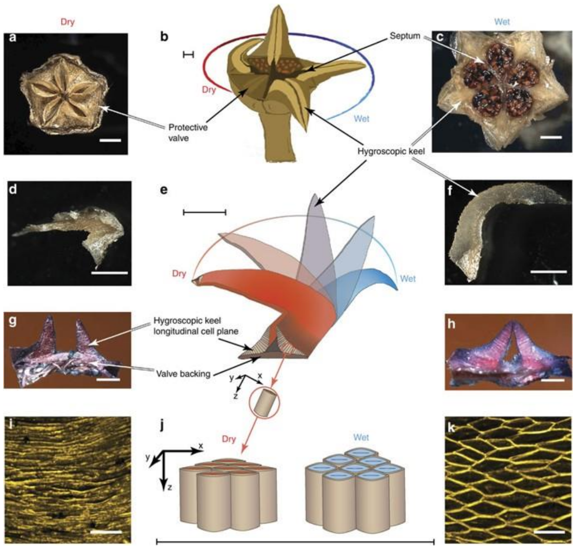


Fig. 55: Seeds of Mesembryanthemums dispersion mechanism

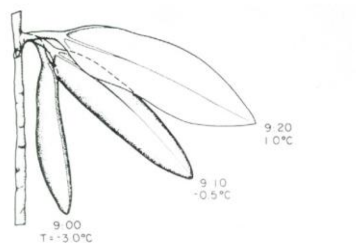


Fig. 56: Rhododendron leaves

Fig. 57: Stomata of Lavendula Dentata

This methodology was presented by Marlén Lopex et al. (2016) to lead the concept designs for adaptive architectural envelopes proposed to facilitate the transfer between biological information and architectural application (fig. 58).

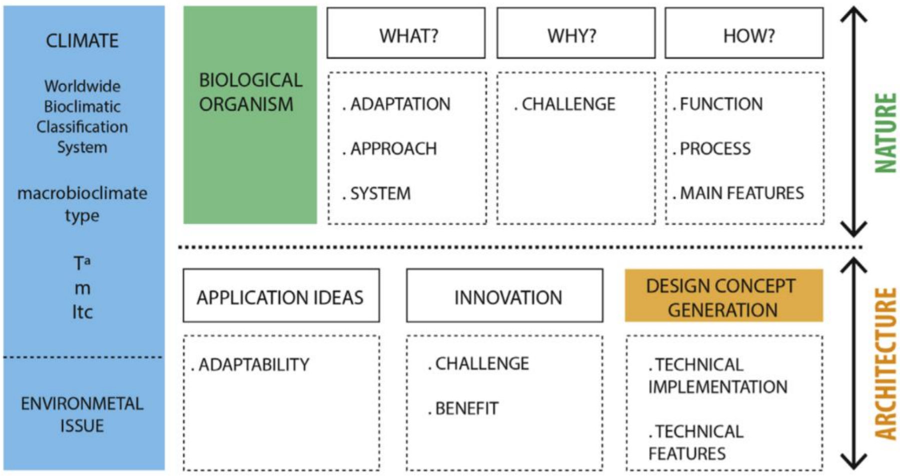


Fig. 58: Diagram showing design concept generation proposed by Marlén Lopex et al.

"There are four different stages during a biomimetic process from biology to engineering: analysis, synthesis, evaluation, and implementation. With this mapping, the first three stages may be carried out as a basis for possible technical implementation in the future. In order to understand how plant principles can be utilized to create adaptive architectural envelopes, the proposed methodology is divided into two major stages: the first one is referred to 'Nature,' and how to identify adaptive strategies and mechanisms in plants in different climates. The second one is referred to 'Architecture' and how to abstract and transform the selected ideas into innovative solutions for buildings. The Stage of Nature is related to more analytic and scientific concepts, and it combines with the stage of Architecture that is more deductive and creative. Climate data concern both stages, nature, and architecture directly because we try to achieve the adaptability in each type of environment." .[98]

This research, however, needs to take a different path as it starts by the thesis of the application of auxetic structures, not thoroughly present in nature, as building envelopes or other applications seen in chapter 2.2, and later to use biomimetics to activate the auxetic kinetic mechanism, for a combination of artificial metamaterial structures with biological and sustainable means.

3.2 Auxetic Climatic Adaptive Building Shell design

a. Rotating rigid units CABS

Among the several auxetic models studied in chapter 4, rotating rigid units offer the closest to reality shading systems due to the fact they merely rely on hinges connections of simple two-dimensional geometric shapes for the auxetic effect. The opening and closing mechanisms of such geometrical tesselations hold great potential for being implemented as building envelopes due to their application as shading panels. The main complication derives from the area expansion of the model from an open to closed-form, which applied on a building façade can result in not optimal shading of the interior: mainly overshading on a reduced façade area in the

closed-form, with a constant occlusion factor, given by a regular number of units and their size (fig. 59).

A similar rotating unit model can be implemented to keep the covered area constant during the opening and closing mechanism by rescaling the units as the rotation happens (fig. 60).

The following experimentations were conducted using Rhino 6 + grasshopper software by compiling a script based on an array of triangles as the origin.

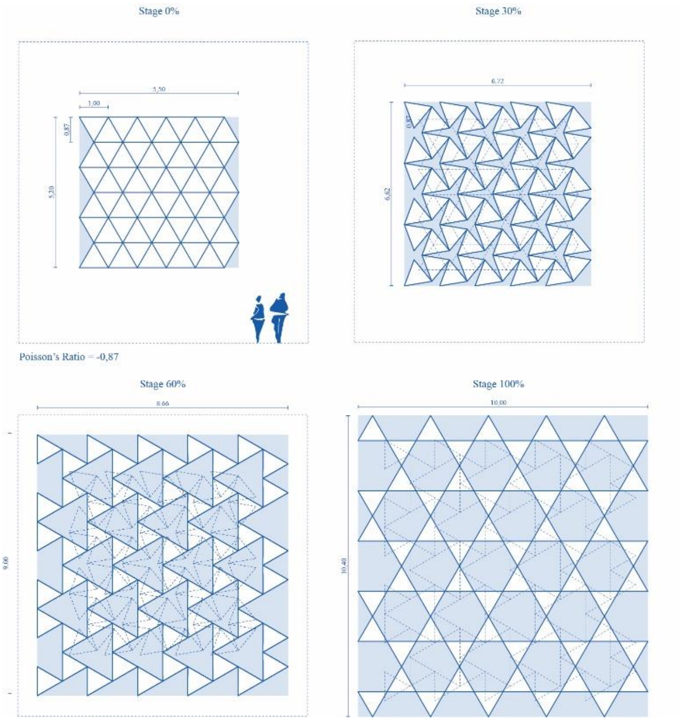


Fig. 59: Opening mechanism of rotating rigid triangles

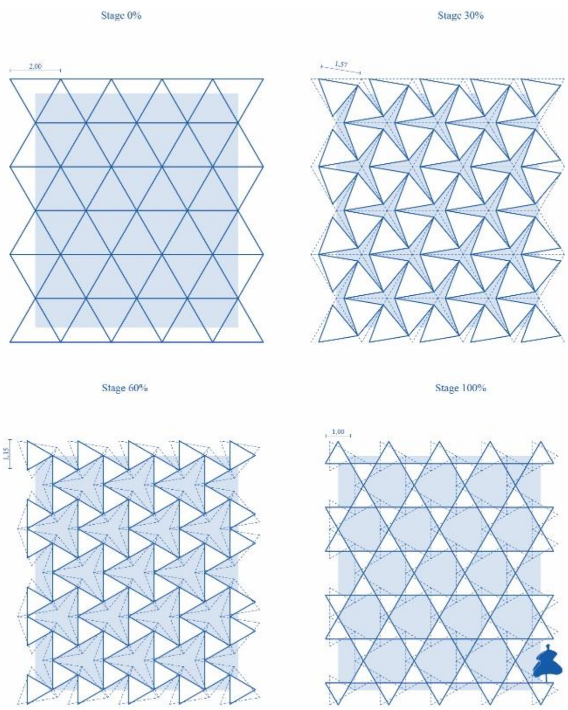


Fig. 60: Opening mechanism of proposed rotating scaling triangles

With this conformation, the opening and closing present a valid set of properties for architectural implementation:

i. *Asimmetric tessellation scaling*

Assuming a slight flexibility and elasticity in the panels itself and/or the hinges, the rotating units' scaling can happen through attractor points, where a smaller scaling factor reduces the unit's size in proximity to a selected area. This is a useful feature in architecture considering the presence of surrounding elements that might already provide shading on the façade, such as trees or surrounding buildings.

The same property can be implemented when the shell is developed on a curved surface: depending on the façade location and orientation, the tilted surface might need additional or less shading (fig. 61).

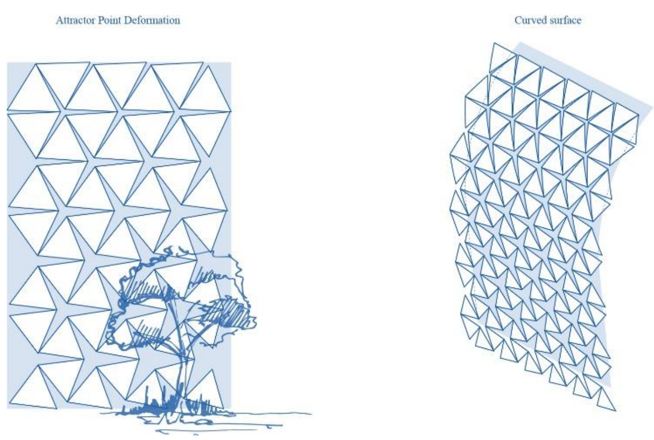


Fig. 61: Possible applications of proposed rotating scaling triangles tessellation

ii. Fixed support grid

During the rotation and scaling of the triangles in the tessellation, the centroids do not change their position, allowing a fixed retrofitting support structure connecting to the units' barycenters. Depending on the panels' load and rigidity, some layout lines might get discarded without compromising the network's solidity (fig.62).

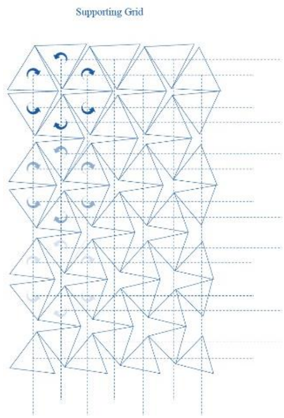


Fig. 62: Fixed support grid and rotation of proposed tessellation

iii. Unit scaling prospects

Until this point, the triangles have been considered simple 2D geometries; however, to change the units' scale, in reality, more complex geometries must be implemented. Choosing the correct unit scaling system is fundamental to perfecting the shell's functioning and its climatic adaptive features. As previously stated in chapter 8, the ideal sustainable biomimetic skin elements simultaneously act as sensors, regulators, and actuators. A few viable options of passive actuation were reviewed in the previous chapters: hygroscopic materials offer the possibility of altering the unit's shapes by responding to ambient humidity changes. The research by Yin-Yu Fong et al. (2018), Self-Forming Hygrosensitive Tectonics[110], exhaustively analyzed the potentials of hygroscopic bilaminates in architecture (fig. 63), testing six different hardwood species, sizing, and grain orientation to determine the expansion and bending behavior of the

[110] **Yin-Yu Fong, Kirk Gordon, Nicholas Grimes and Mengzhe Ye**. (2018). *Self-Forming Hygrosensitive Tectonics*. Retrieved from: https://issuu.com/yin-yu/docs/self-forming_hygrosensitive_tectoni

planks. Triad aggregation patterns, in particular, resemble the shape of triangles decreasing in planar size due to the out of plane curvature of the surface, which, if connected with the correct hinge they become ideal for the rotating rigid units CABS (fig. 64), creating a completely passive skin actuated by ambient humidity.

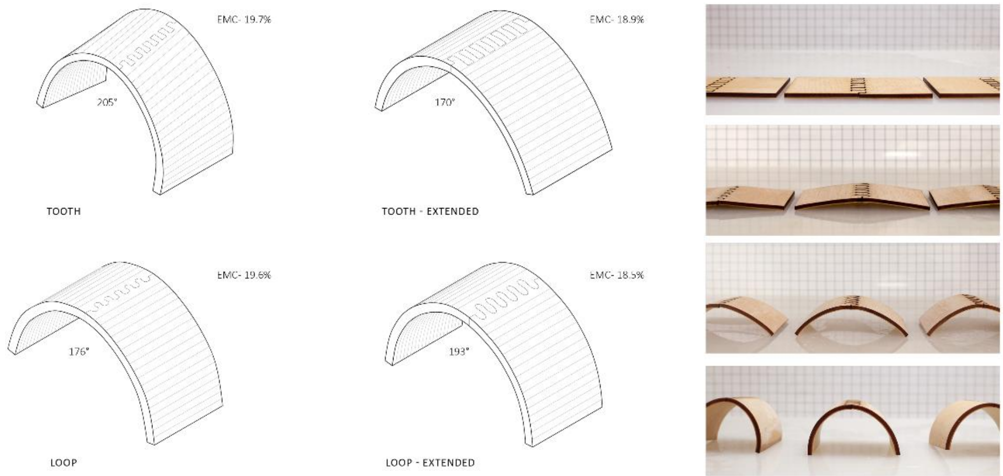


Fig. 63: Self-Forming Hygrosensitive Tectonics

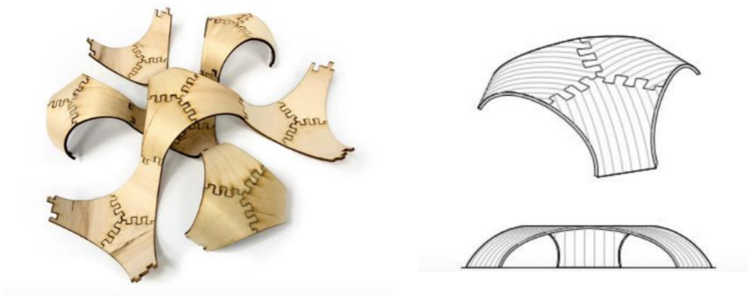


Fig. 64: Triad aggregation patterns

A secondary solution relies on umbrella origami triangles, similar to those used in the precedently quoted Al Bahr towers (fig. 65). These particular models are auxetic cells, an extracted portion from the auxetic Ron Resch patterns (fig.66).

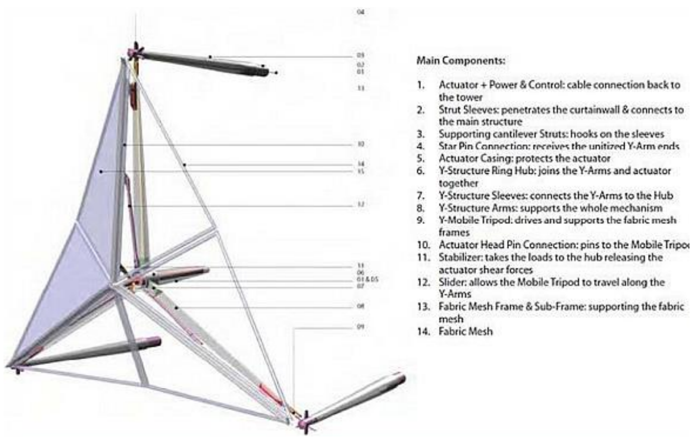


Fig. 65: Al Bahr shading system

Their auxetic behavior will allow their buckling (opening and closing mechanism) in the proposed skin. For this panel technology, it's hard to design a realistic, entirely passive actuation. However, since the rotation and scaling of the units will be proportional, and it can be hypothesized, and eventually tested, that the forced rotation and scaling starting from the centroid of a single unit in the tessellation will cause the connected elements to perform the same motion, obtaining an attractor effect around the original deformed unit. Such property could significantly reduce the number of engines required to adapt the skin to external environmental factors. A main constrain from this geometry regards the scaling factor of the units (triangular bounding box), limited to 0,75 determined by the folding model; however, at the same time, the shading factor in planar view is ideally reduced to 0, as all the faces composing the model are rotated normally to the original plane, not compromising the functionality of the skin.
The final solution could be a union of the two precedent positions: as the folding happens proportionally on a linear axis, the joints could be realized as humidity respondents (fig. 67).

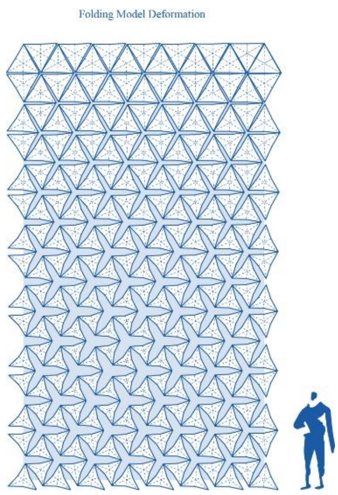


Fig. 66: Proposed tessellation with auxetic triangular umbrella origami

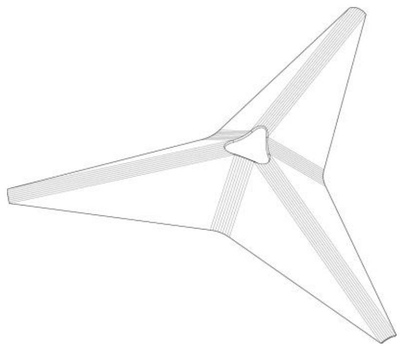


Fig. 67: Auxetic triangular umbrella origami as hygrosensitive tectonic composition

iv. Parametric Definition of the Model

The tessellation has been created through parametric modeling on Grasshopper plugin on McNeel's Rhinoceros 6 (fig. 68). Starting from a triangular array, the data tree of cells is divided and reversed depending on the units' rotation in the auxetic tessellation. The rotation and scaling happen through the same component group by sliding the triangles' vertices on the edges until their midpoint (fig. 69), creating a gear-like rotation system. Such computational design could allow other technological solutions to the actuation system of the components other than the forced centroid rotation.

The second component group determines the scaling factor, from 1 to 0.75, depending on the pull force located on the attractor point. Once the flat triangle tessellation is complete, the units are substituted with the origami model, proportioning its folding opening and closing mechanism with the scaling factor.

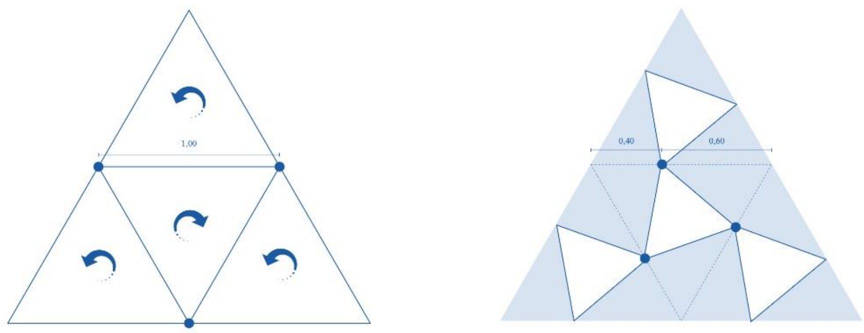


Fig. 69: Scaling model in the Grasshopper script

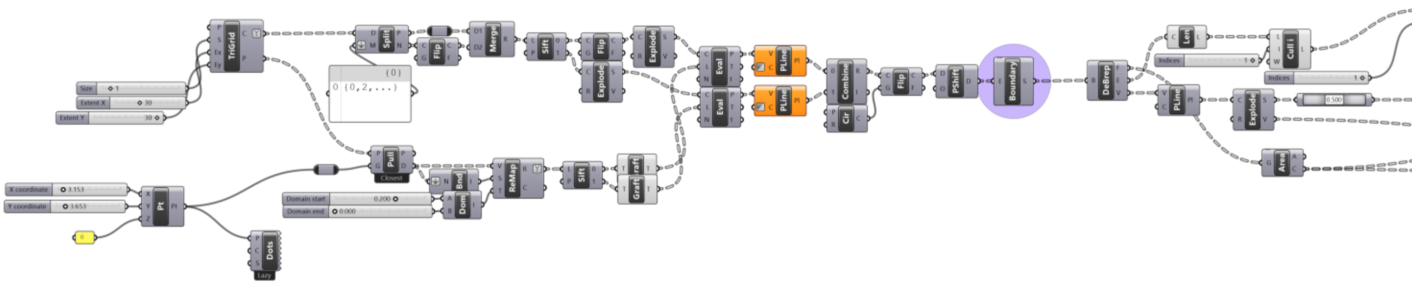


Fig. 68: Grasshopper script

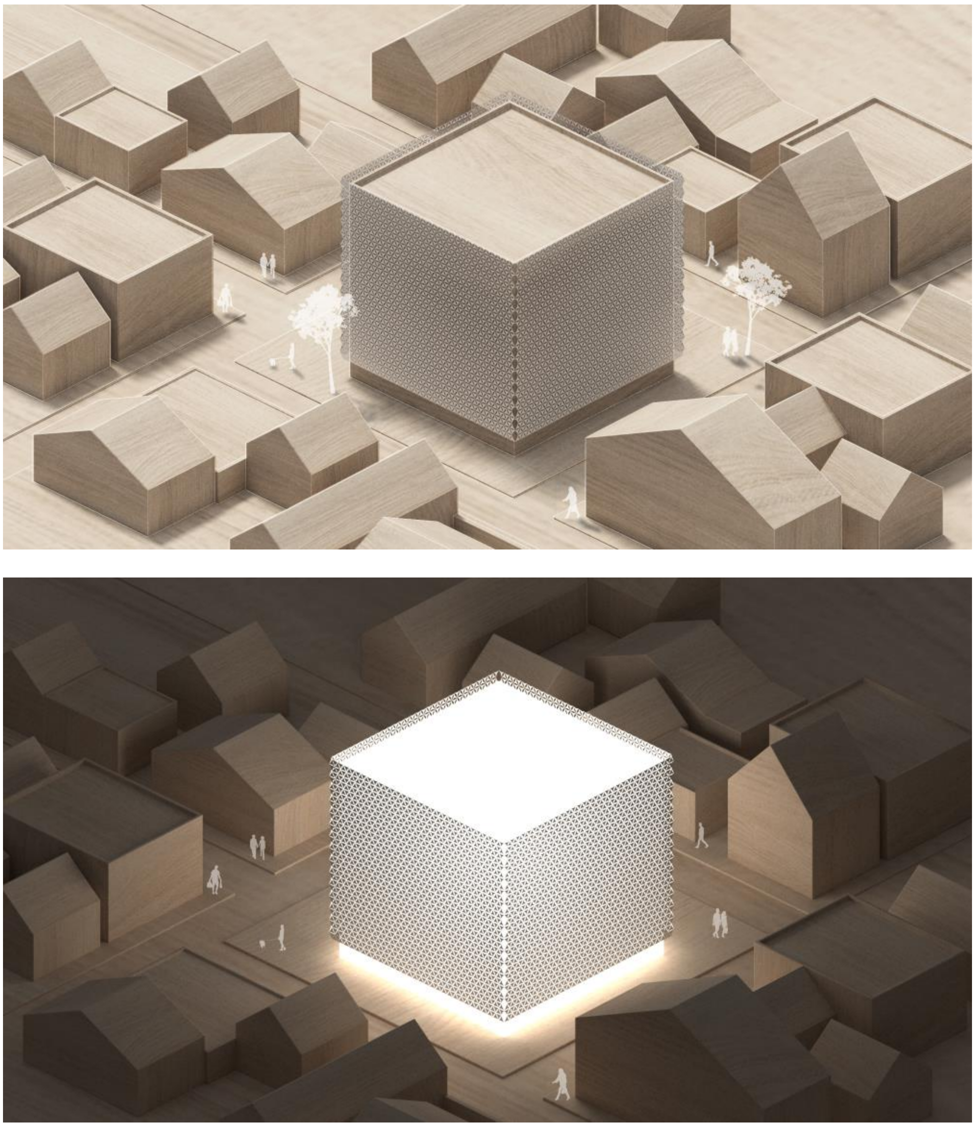
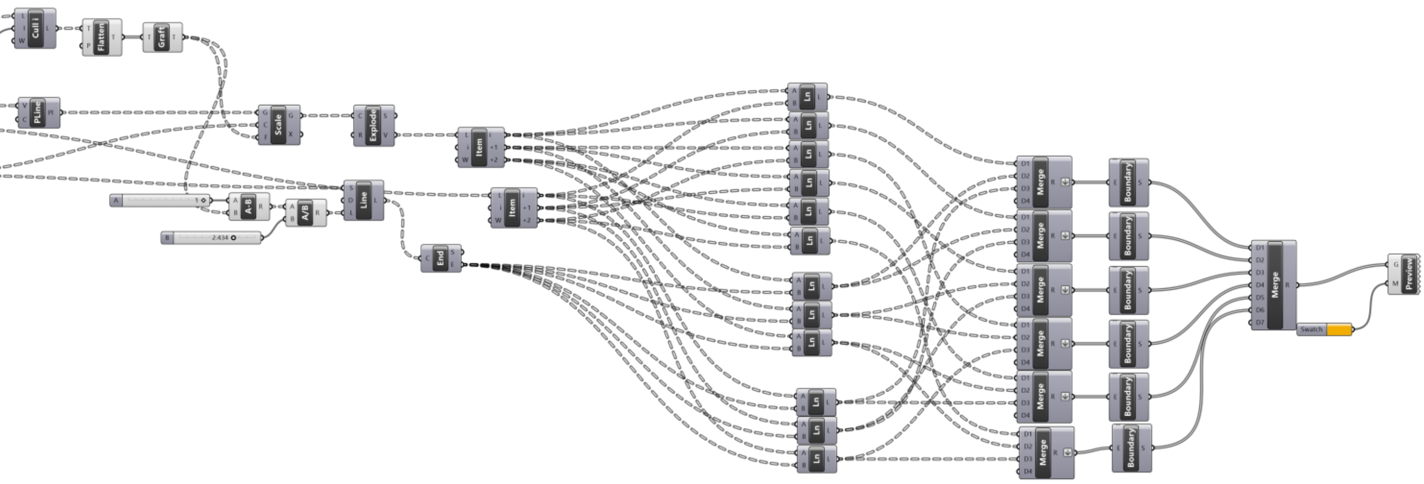


Fig. 70: Model view in urban context



v. Radiation analysis

Solar radiation is the most significant contribution to the surface and volumetric energy balance during the daytime. Significantly, solar radiation is the main contributor to heat gains in buildings, especially in residential buildings, where internal gains are meager. The utilization of daylight in buildings may result in significant savings in electricity consumption for lighting while creating a higher quality indoor environment.[111]

We analyzed the skin radiation shading through the grasshopper plugin *ladybug* on the summer and winter solstices in the preferred system stage. The test ran on a Turin located .epw file (https://energyplus.net/weather-location/europe_wmo_region_6/ITA//ITA_Torino.160590_IWEC) on a 9.5x8 m façade facing south, with the flat origami panel measuring *l=1 m*.

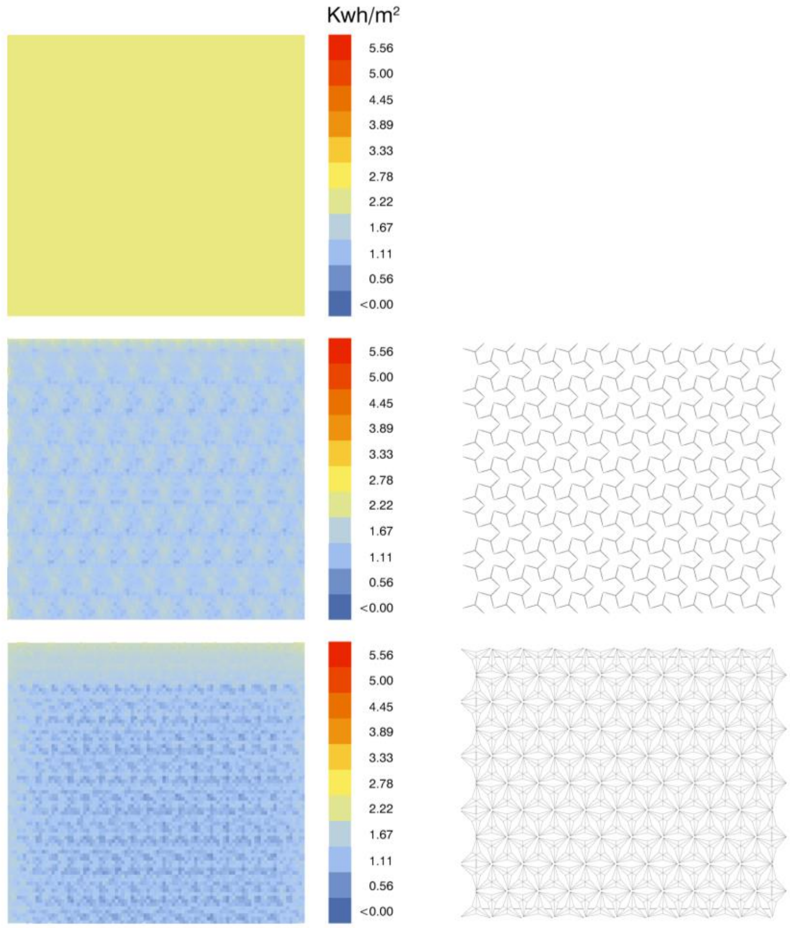


Fig. 71: Solar radiation analysis. 21/06, Turin. Fully exposed façade, open structure, and semi-closed.

[111] **Francisco José Sánchez de la Flor, Rafael Ortiz Cebolla, José Luis Molina Félix and Servando Álvarez Domínguez**. (2015). *Solar radiation calculation methodology for building exterior surfaces*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0038092X05000253

Although the shading system is purposely made to block hot months' solar radiation, it was necessary testing if the skin reduces solar radiation heat gains in winter, fundamental for reducing energy consumption for the interior heating.

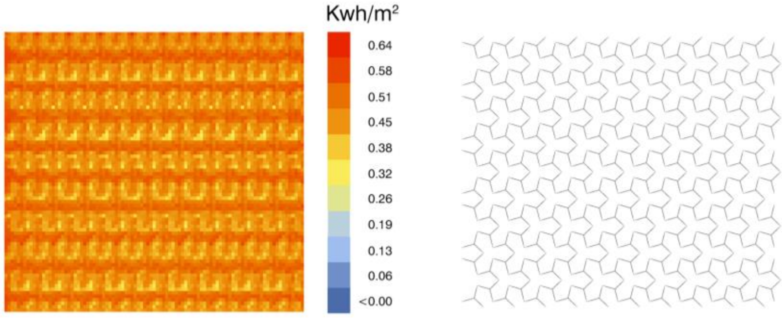


Fig. 72: Solar radiation analysis. 21/12, Turin. Open structure.

From the obtained data, it is possible to declare that the prototyped skin functions efficiently in both seasons. During summer months, the solar radiation on the façade drops from ~2.78 Kwh/m^2 to an average of ~1.67 Kwh/m^2 for open and 0.56 Kwh/m^2 for semi-closed conformation. In winter months, the skin does not block most of the solar gains, making the prototype suitable for temperate climates as well as for warmer climate zones. However, the software's extracted data have a purely indicative value and usually indicate the maximum possible shading of the façade. The vast majority of shading panels are not entirely opaque, allowing more sunlight and radiation to pass through. Al Bahr tower's identified PTFE-coated glass fiber mesh, a fabric material, as the most durable and best-performing option. PTFE (Polytetrafluoroethylene) fiberglass coating is capable of withstanding high temperatures and it is a ‘self-cleaning’ fabric, which helps reducing cleaning and maintenance time. The final fabric presents an open area of 15% and a light transmission of 25%.[112]

[112] *The Al Bahar Towers: Shading, The Real Envelope*. Retrieved from: https://igsmag.com/market-trends/super-tall-buildings/the-al-bahar-towers-shading-the-real-envelope/

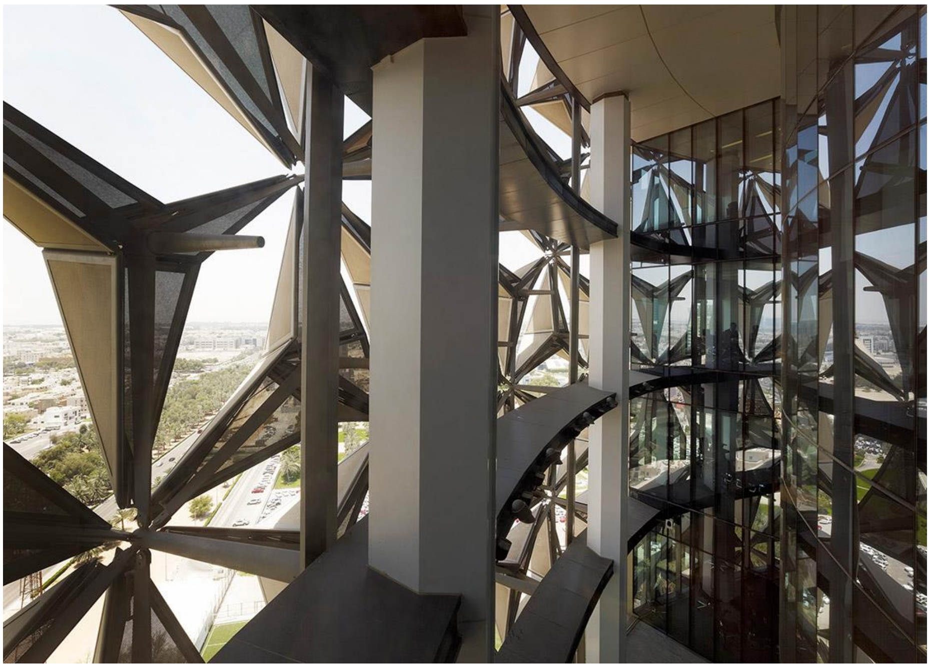


Fig. 73: Al Bahr Towers, interior.

vi. Skin geometric alternatives

The proposed skin can be reinterpreted in any rotating units tessellations seen in chapter 1.2.d, as long as the unit geometry can be expressed as the planar projection of an auxetic origami umbrella. Triangles, squares and hexagons can easily be transformed in auxetic cells by applying the umbrella folding on the planar shapes (fig. 74), and they all have their respective rotating units tessellations. Allowing the skin to function with the same principles, but different aestetic presentation and shading properties (fig. 75).

Fig. 74: Primitive shapes origami umbrellas

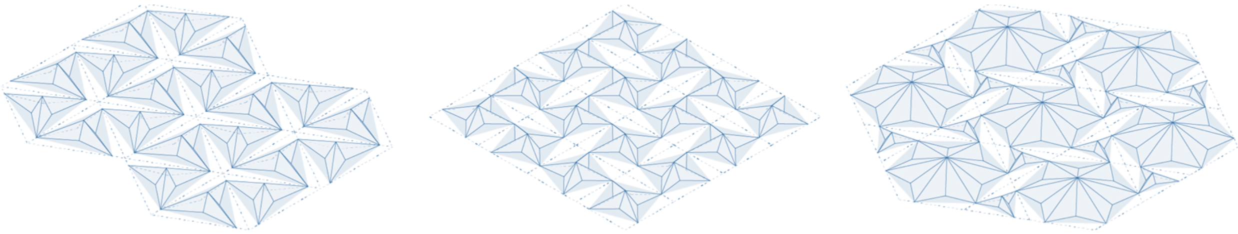


Fig. 75: Scaling rotating units tessellations of primitive origami umbrellas

It is however safe to assume that any auxetic cell maintaining its aspect ratio under deformation will behave similarly in such skin conformation (fig. 76): primitive umbrella origami can ideally be substituted with more complex auxetic origami, such as miura ori or Ron Resch tessellations.

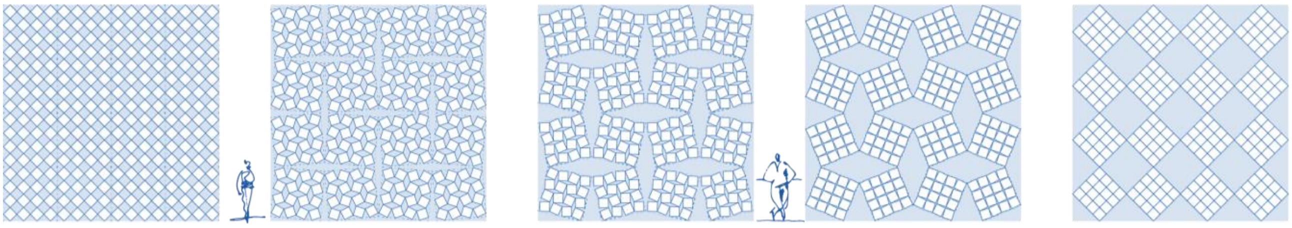


Fig. 76: Fractal pattern: proposed skin with auxetic rotating rigid units as auxetic cells

3.3 The Physical Model

To verify the previously theories exposed, we constructed a physical model. The first concept was to realize a PLA 3D printed model; however, the printed plastic rigidity and scale made it impossible to test the folding mechanism. The printed entire origami wouldn't allow the folding on the edges without breaking, and a hinge mechanism to connect the individual faces did not perform correctly. The failure happened because it is a scaled flat model, almost two-dimensional, 3D printing technology in PLA did not provide satisfactory results in such physical geometry, producing whether a fragile element or hinges not sufficiently defined for a smooth folding motion.

Therefore we realized a secondary paper model (220 g/m^2) (fig.75). This material is, in fact, made for origami bending and eased the possibility for testing from which we extracted the following considerations:

a. The model behaves auxetically under tension if not constrained at the barycenters; the origami umbrellas tend to remain flat.

b. By constraining the barycenters, the rotation of the units corresponds to their planar scaling

However, the main goal is to verify that a single unit's rotation and scaling mechanism will affect the attached units and force their same motion in both opening and closing. By performing this test, new observations can be determined:

c. A single paper actuator unit influences the motion only in near proximity to the connection. The paper origami is not rigid enough so that the folding on a single edge obliges the entire model to fold. It is theoretically possible to overcome this limitation by using a more stiff material.

d. The folding motion proved to be easier if the origami umbrella is reversed (Type II); this is probably because the origami is overturned so that the greater folding angle lies on the shorter edge, opposing less bending resistance. The Type II umbrella origami is still an auxetic cell and the planar triangle vertices can be scaled to a factor equal ideally to 0, unlike the Type I cell, limited to a scaling factor of 0,75 (fig. 73).

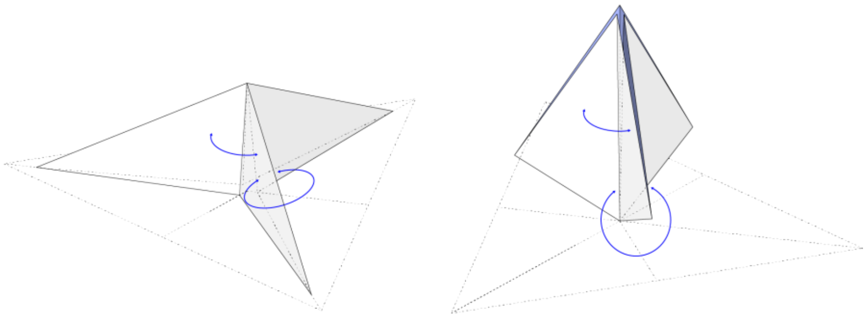


Fig. 76: Type I and Type II auxetic origami triangular umbrella

e. By forcing the closing of three units connected to a single one, the unit located in the center is scaled and rotated automatically (fig. 74). In the entire tessellation, the alternation of an actuator and a passive unit will activate the whole system: this means that only half of the units need to be actuators, and the others will move without force applied to them directly.

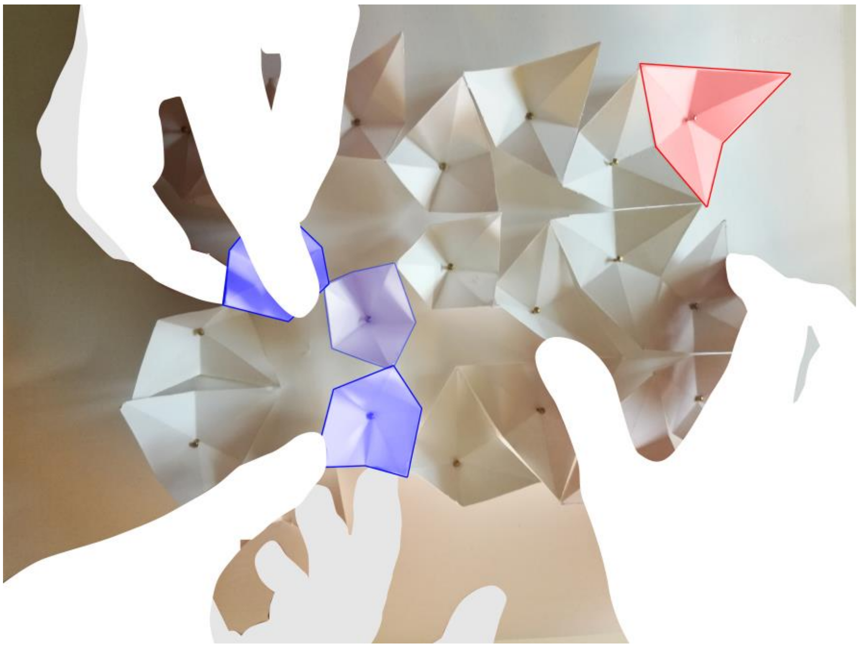


Fig. 77: Paper model, actuation by hand (blue) transmitting to the connected unit. (Relaxed state in red)

Although the paper model has its limitations, it proved that the initial theory is possible: **in a model of fixed auxetic rotating units, the deformation, by rotation and uniform scaling, of a single unit, transmits a mechanical motion to the connected auxetic elements, inducing the same scaling and opposite rotation**.

In architectural terms, it proves the possibility of implementing auxetic morphologies as adaptive building shells, removing a sensible number of actuators to activate the skin's kinetic motion. This leads to contemporary sustainable design strategies set out in chapter 3.1., with the design of a system with embedded self-actuation. The following step would be realizing the same morphologies, proven functional, with climate-responsive materials to further push passive CABS technologies.

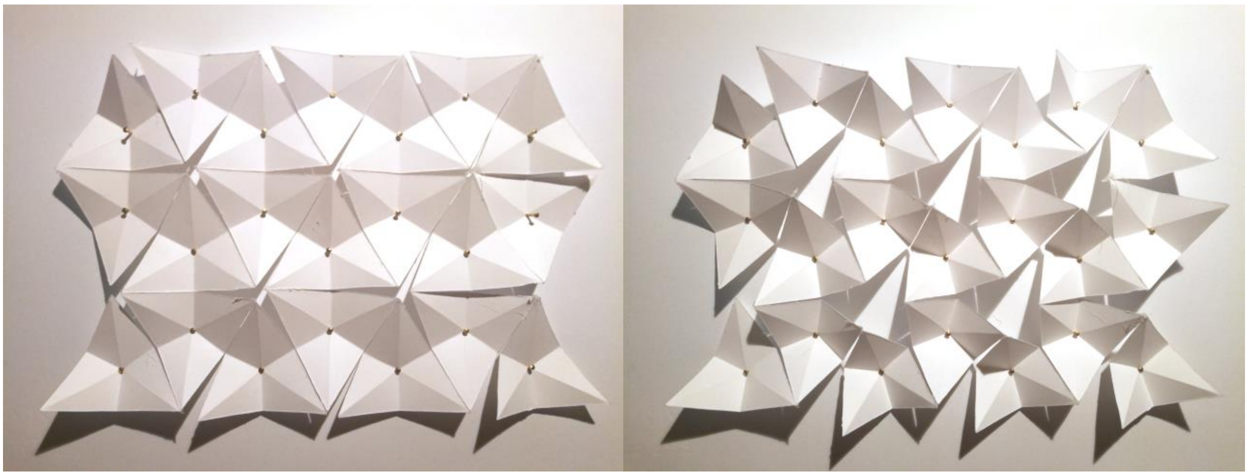
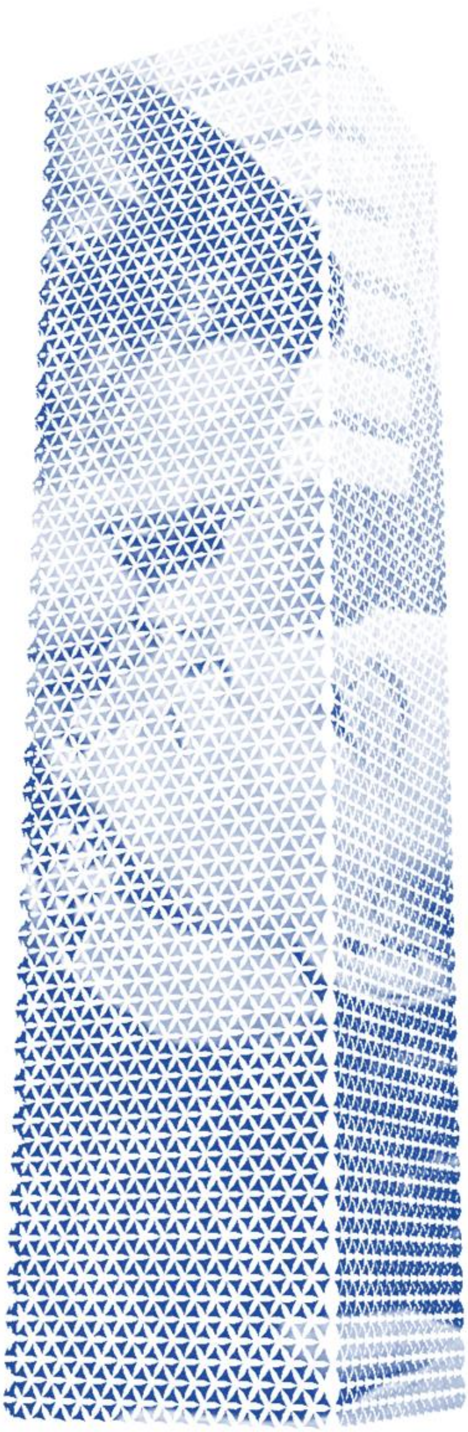
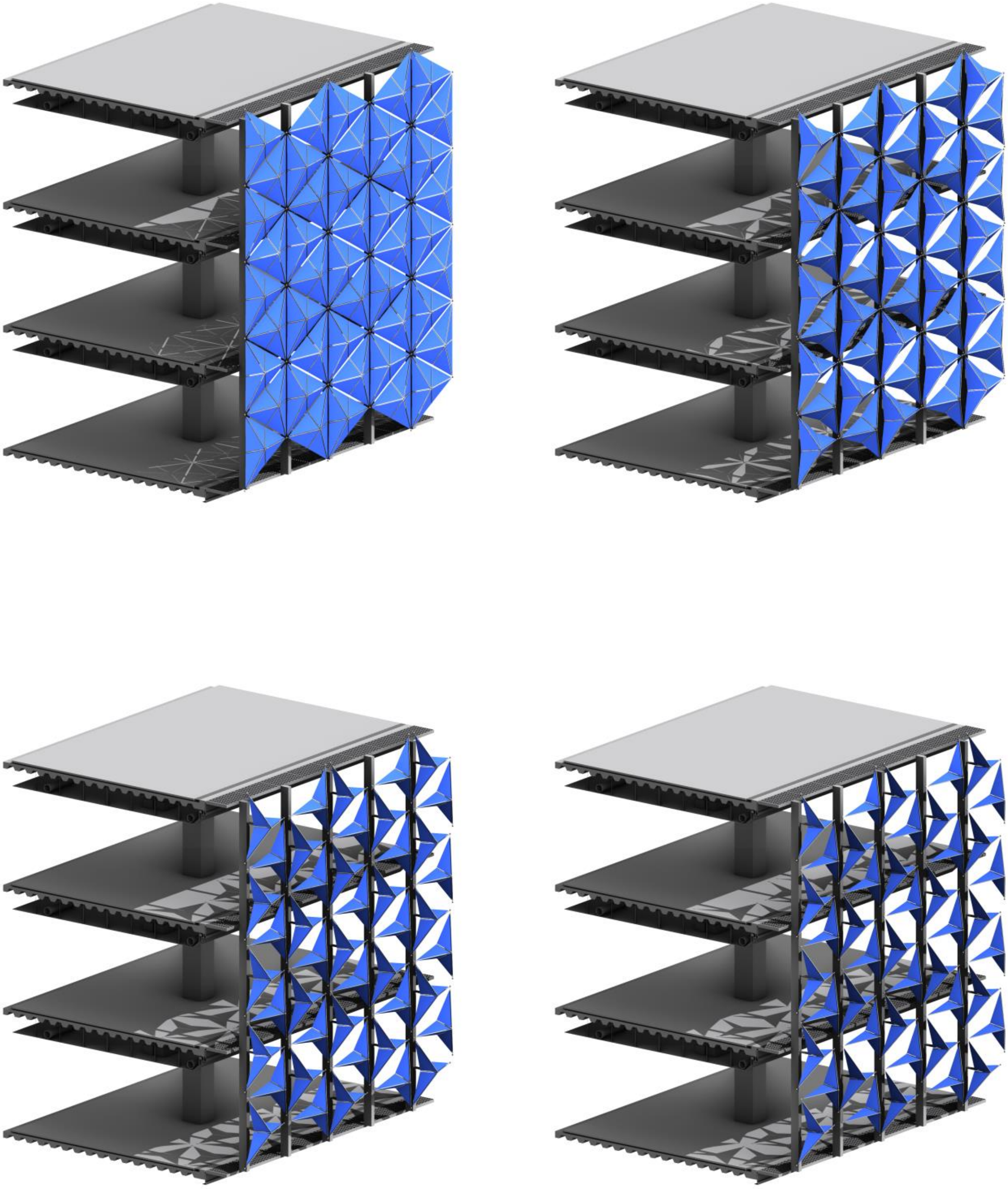


Fig. 78: Paper model, in closed and semi-open conformation

Chapter 4

Visions





Conclusions

A Look Into The Expanding Future

From the extensive analysis of their current applications and research progress, we've studied the most substantial properties of auxetic models at all scales. From an initial definition of auxetic materials as expanding under tension, we recognized countless different applications, taking advantage of several combinations of properties of the auxetic in a wide variety of production fields.

Very few applications were found in architecture, proving that auxetics are yet to be exploited to their full potential at the macro scale in this sector. The ones already proposed often do not recognize the auxetic component in their designs, not giving credit to their negative Poisson's ratio in their functioning, proving that auxetic technologies are still to find their way in general knowledge transformable design.

The study on the most popular auxetic geometries set the ground for merging canonical tessellations into a more complex design, as it was in our case, standard two-dimensional tessellations and three-dimensional origamis created a visually exciting and functional Climatic Adaptive Building Shells in line with the contemporary rule of the art, improving existing designs with outstanding versatility.

As the sustainable component was fundamental to us as a final objective, the prototype design was virtually tested and adapted to obtain satisfactory solar radiation control results without compromising daylight entry.

From a sustainability point of view, as climate change progresses, the auxetic CABS is both a solution and a cure to it. The prototype is, in fact, capable of reducing emissions from HVAC (Heating, Ventilation, and Air Conditioning) occupation, providing thermal comfort in especially in warmer seasons, with minimal actuation cost. The auxetic transformability phenomenon makes the proposed CABS unique in its activation; as traditional shading skins require complex actuators to deploy or retract the shading panels, the auxetic tessellations open and close by self-interacting, behaving as a biological entity would, plants in particular. The parcel study of biomimicry inspired us to design a sophisticated yet straightforward functioning skin. By studying plants' response to climate variations, we refined the adaptive auxetic shell to a similar responsive mechanism, still far from a complete self-actuation, but significantly reducing the engine input count. As the investigation in this field progresses, and research papers on related topics are published daily, further development of the proposed design might transform it from an abstract solution to a real application.

Although we focused on a more traditional sustainable technology, it is fundamental to consider valuable all of the different architectural and engineering applications we have described along with the research. Several have probably not made their way in the chapters we proposed, which is why the thesis work aims to encourage opening new prospects on auxetic models designs rather than finding a singular solution.

A further reflection focuses on the current, as this thesis is being written, Covid-19 worldwide pandemic. Transportable and quick-developable architecture found in these times its importance on a larger scale than natural disasters. The necessity of plug-in intensive care units brought several architectural firms in designing quick-to-deploy solutions to ease the pressure on healthcare systems by *expanding* emergency facilities treating patients infected by coronavirus. Unfortunately, auxetic solutions did not make an appearance in such a needing time, being far from practical applications in architectural design, but as we've seen in the research, ideal for such requirements.

With this research, we proved that auxeticity is not limited to a microscopic world, and what is generally considered a material embedded property can, through architecture, find new sustainable technological solutions. We achieved to transform a natural geometric-mathematical principle into a large-scale architectural element.

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