AUXETIC STRUCTURES:
TOWARDS BENDING-ACTIVE ARCHITECTURAL APPLICATIONS

MASTER THESIS

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ABSTRACT

This work suggests a possible direction towards the diffusion of on-site printed architectural systems with the use of a special category of structures that have an intrinsic capacity to be expanded and compressed due to their structure and perform specific curvatures when bent. This class of materials was discovered in late 1800 but only in 1991 they were named Auxetics by the scientist Ken Evans.

This work started by the will to design an architectural element with a bottom-up approach: the architectural proposals that will be given in the end are made possible only thanks to the definition of a technology which uniquely defines their shapes.

In the first part Auxetics are classified, analyzed from a mechanical point of view, and interesting nowadays applications are listed to clarify a possible architectural implementation.
In the second part a specific structure of auxetics - named hexagonal reentrant honeycomb - is chosen because of its capacity to perform a synclastic curvature when bent - therefore, a technology applicable both to the construction of lightweight pavilions and façade elements is proposed.

The possibility to use three dimensional printers and experiment with polymeric materials became an essential resource in the research part and a valid production tools for the project proposal. Three dimensional printers completely changed the conception of mass production giving a higher level of freedom in the production

of any-scale objects.
The possibility to print from a file means that a high level of customization can be reached even if operating in massive production processes. Each printing session can be varied in parametric way so that each created object can be differentiated from the previous without the need of changing molds or using specifically designed tools.
The possibility to create mass-customized elements can be finally achieved.

ESTRATTO

Con questo lavoro si vuole suggerire una direzione verso la diffusione di sistemi architetturali stampati on-site attraverso l'utilizzo e l'applicazione di una particolare classe di strutture che possiedono una capacità intrinseca di espandersi quando tirate e ritirarsi quando compresse e di riprodurre un curvatura anticonvenzionale quando sottoposte a flessione.
Questa classe di materiali e strutture è stata scoperta nel tardo 1800 ma solamente nel 1991 uno scienziato che risponde al nome di Ken Evans riuscì ad assegnarli un nome proprio ricavato dalla parola greca auxetikos "che tende ad espandersi", definendo al classe come degli Auxetici.

Questo lavoro nasce dal desiderio di progettare un elemento architettonico seguendo un processo bottom-up dove la proposta di design è direttamente data dalla tecnologia scelta, che ne condiziona unicamente la forma.

Il lavoro si divide in due parti: in una prima i modelli e materiali auxetici sono classificati, analizzati da un punto di vista meccanico e le più interessanti applicazioni che ne sono fatte al giorno d'oggi sono spiegate. Questa parte è definita "research".
E' stato scoperto che la caratteristica principale per cui questi materiali sono conosciuti non è solamente che una delle varie qualità possedute da essi. Il loro coefficiente di Poisson negativo, che sta ad indicare il loro anticonvenzionale diminuire di volume quando compressi, comporta tutta una serie di caratteristiche fisiche che li

rende idonei a molte sperimentazioni. Queste caratteristiche sono cinque e comprendono una generale resistenza alla compressione e una alta rigidità, la capacità di far fluire materiale verso l'area di impatto quando soggette a compressione, la capacità di assorbire alte quantità di energia e di dissiparla, la capacità di formare delle superfici a curvatura sinclastica quando flesse e la capacità di variare la loro porosità quando stirate/compresse.
Nella prima parte del lavoro sono stati elencati gli usi dei materiali auxetici all'interno di quelel classi del sapere umano dove queste qualità trovano più facilmente applicazione: nel settore ingegneristico e biomedico, nello sport, nel settore aerospaziale e automobilistico, nell'industria tessile e in quale sporadico caso di design del prodotto. La diffusione di questi materiali, per quando incalzante, fatica a diffondersi in quanto ha bisogno di essere supportata da una consistente attività di ricerca atta a definirne in maniera più conveniente gli usi e da una ricerca di processi di industrializzazione dettagliati che possano abbattere i costi e le difficoltà tecniche derivante dalle forme indentate che queste strutture assumono.

Nella seconda parte invece, una struttura auxetica tra tutte le conosciute , chiamata "ad esagoni rientranti", è scelta per la sua capacità di definire una curvatura sinclastica quando flessa. Successivamente una tecnologia costruttiva applicabile sia alla costruzione di padiglioni leggeri che elementi di facciata (e altro) è proposta. Per arrivare alla definizione di questa tecnologia è stato necessario passare attraverso più fasi. Inizialmente sono stati stampati dei pattern di strutture auxetiche con una stampante tridimensionale Kloner K320. Questo ci ha permesso di testare praticamente il loro comportamento e di scegliere quindi il più interessante.

Una volta scelto tra questi il pattern “ad esagoni rientranti”, è stato modellato in maniera parametrica attraverso l’utilizzo de software Grasshopper e gli sono state applicate delle forze per far avvenire la flessione tramite l’utilizzo del motore di calcolo Kangaroo Physics.
Numerosi test successivi ci hanno portato a capire come funziona questa struttura durante la flessione e quindi a suggerire delle strategie di design e un processo produttivo. Infine delle “visions” di applicazione sono state suggerite .

La possibilità di utilizzare stampanti tridimensionali e di sperimentare con materiali polimerici è diventata una risorsa essenziale nel lavoro di ricerca e un elemento di produzione vantaggioso anche per la proposta progettuale. Le stampanti 3D (nome molto generico che definisce in verità una vastissima scelta di prodotti) stanno effettivamente cambiando la concezione di produzione, rendendo possibile un più alto livello di liberà e variazione nella produzione di oggetti di diversa scala. La possibilità di creare un oggetto direttamente dal suo modello tridimensionale fa si che un altissimo livello di personalizzazione possa essere raggiungo anche nei processi produttivi di massa in quanto la forma di ogni oggetto può essere variata senza apportare un aumento dei tempi produttivi o del costo di produzione.
La possibilità di creare elementi mass-customized può essere finalmente raggiunta.

PART I

RES

EARCH

PART I

AUXETIC MODELS

CHAPTER I

1.0 ABSTRACT

This chapter is an introduction to the intricate world auxetic structures since it can be hard to understand this class of structure that are not characterized by a specific material composition or fixed shapes. Potentially every structure can be turn into auxetic. For a better clarification, auxetic structures are firstly defined in mathematical way - than is presented the historical evolution of the research on auxetics. A classification has been done following the existing literature.

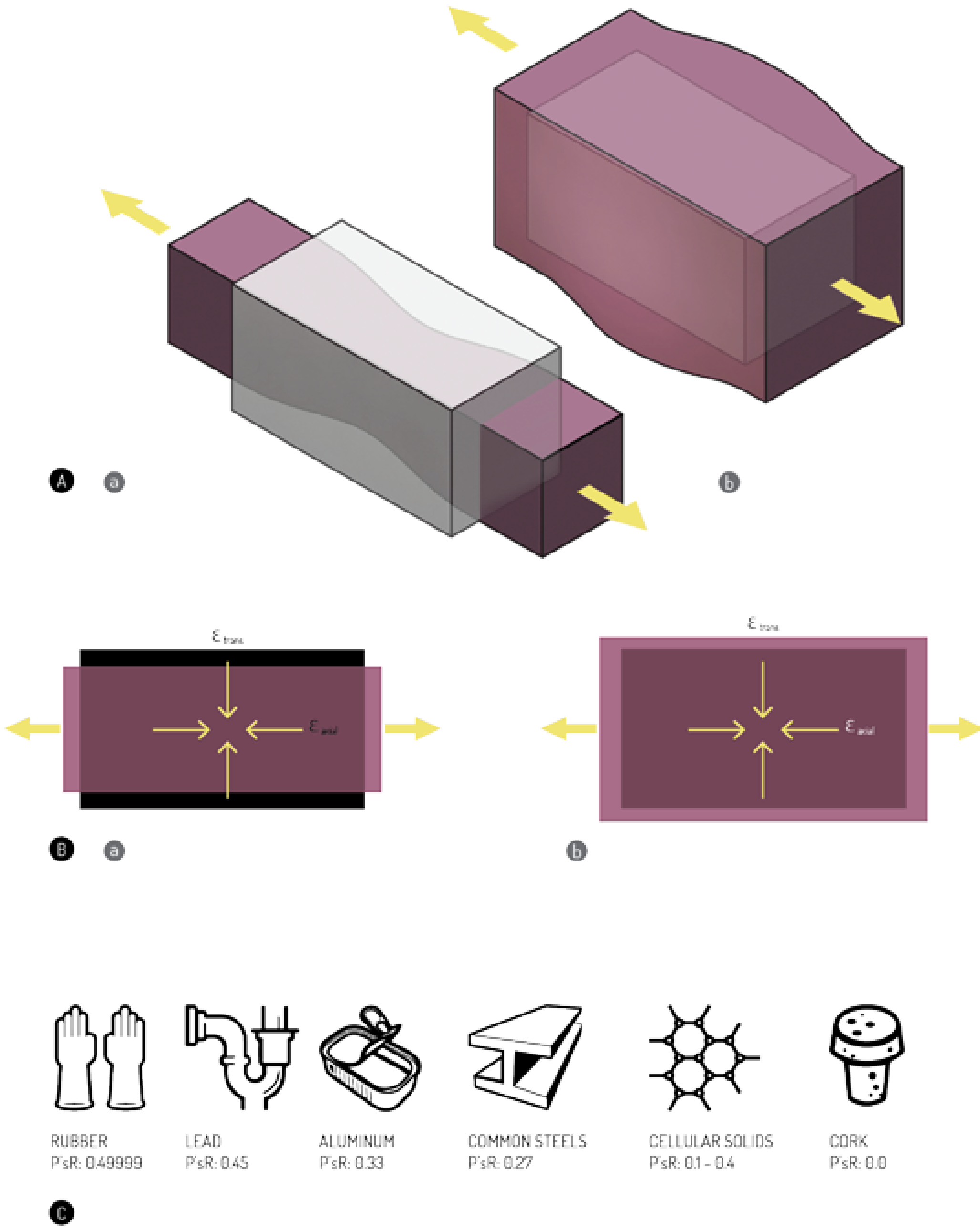

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Figure 1 **A**. Reaction of a conventional material **A.a** and an auxetic one **A.b**
B. Even if in conventional material **B.a** and in auxetics **B.b** the strains are equals, they behave differently
C. comparison among the Poisson's ratio of many different materials

1.1 ABOUT "AUXETIC"

1.1.1 Definition

Auxetics structures, by definition, are those structures that exhibit a Negative Poisson's Ratio (NPR), meaning that all the structures and materials whose Poisson's Ratio (ν) range from - ∞ to 0 can be named auxetics. For isotropic materials it may be shown that Poisson's ratio is between $-1 \leq \nu \leq 1/2$ in 3D and $-1 \leq \nu \leq 1$ in 2D, for anisotropic materials ν is not restricted by the above limits, ranging from -∞ to 0 (Cabras and Brun, 2014). In the Table 1.1 some positive Poisson's ratios are shown.

Here, the definition by R. Lakes (Greaves et al., 2011): Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio contains a minus sign so that normal materials have a positive ratio.

Practically, to be auxetic indicates that a structure/material expands when stretched and contracts laterally when compressed, in contraposition to a positive Poisson's ratio one, like rubber, who contracts when stretched and becomes in bulge when compressed (Figure 1).

A

B

C a b

Figure 2 Pei Cobb Free & Partners, Louvre Extension, Paris, 1989-1993
A. Macro scale: the architecture is percived in his general pyramid shape (Photography of the author)
B. Meso scale: it can be understood that the technology is formed by lozenge-shaped cells (Photography of the author)
C. Micro scale: the lozenge are contitued by Ca glass and Cb Inox Steel

Such materials are called also dilatational materials because they exhibit substantial volumetric changes when loaded (Małgorzata 2009). First auxetic cellular structures were created as 2D silicone rubber or aluminum honeycombs and were extensively investigated by Lakes in his many publications. Anti rubber material was also found to be used to refer to this kind of structures and materials.

1.1.2 Auxetic Model, Auxetic Material, Auxetic Organisms...?

Auxetics were discovered mostly thanks to empiric observations instead of analytical researches. For this reason in the existing literature on auxetics it is sometimes difficult to distinguish a clear limit of what is abstract and what is tangible - sometimes the reader hasn't a clear sight on the used words that refers to different semantic and physical fields. This happens because many models are studied for a specific application and usually are ameliorated for the production process, mixing what is theory with practice.

In this research, we felt the need to give a clear meaning to each of the words that gravitates around the word "auxetic". Hereafter, we will enter into this clarification process. The classification of a structure in Micro, Meso and Macro components will help us in this understanding (refer to Figure 2).

The word Micro refers to the material composition of a piece of structure. Imaging to extract a sliver of material and analyze it at the microscope, that results will give the Micro composition of the material - thus defining its materiality. Nowadays there are not material that behave auxetically at this scale - maybe in the future molecular auxetics will fill this void .

The word Meso refers to a bigger scale - for example, in a structural system composed by similar elements the Meso scale refers to a single cell, which has the same (or very similar) characteristics of the others. At this level, the cell is considered as an unicuum that doesn not commit interactions with other elements even though has reactions when subdued to forces. The response that a cell shows to specific stimula can give essential information when passing at the Macro scale.

Lastly, a structure can be considered at a Macro scale, where all the units composing the whole will interact among themselves. This will define a complex organism where is essential to consider the interactions among similar elements that, not always, behave in the same way since external factors can behave in an uneven way.

The words "auxetic material", even if nowadays it wouldn't be correct to use it since it refers to the Micro scale, will be used to refer to objects that behaving in an auxetic way that from a sight analysis seems a unicuum - a compact material. Nowadays in this class we can list foams, auxetic fibers and few others.

For these reasons, the words "auxetic model" will be used to refer to analytical and mathematical geometries that propose spatial configurations of elements ideally behaving in an auxetic way. The models consists into the abstraction of realizable organisms. Being abstract they don't need to have a link to any specific material or to a production process, dimensions or physical properties. But nothing implies that they can't be use to theorize functioning technologies and complex organisms. Often the models are studied at a Meso scale.

Finally, the word "auxetic organisms" or "auxetic structure" will refer to ensembles of Meso elements that behave in an auxetic way, thus giving auxetic behaviour to the whole structure. The reference scale is the Macro one.

1.1.3 Poisson's Ratio

In physics the Poisson's ratio is indicated with the greek letter , which is pronounced [n]. Auxetic models are of interest because of their counter-intuitive behavior under deformation and because of their enhanced properties, all related to the negative value of V that they posses. It has been found that auxeticity can be described in terms of particular geometry of the material system and deformation mechan axial tension (stretching) and positive for axial compression. Eaxial is the axial strain positive for axial tension and negative for axial compression (Figure 1).

V= - (variation of transversal strain/variation of axial strain)

V is the resulting Poisson's ratio, Etrans is the transverse strain (negative for axial tension - stretching - and positive for axial compression) and Eaxial is axial strain (positive for axial tension, negative for axial compression). Since the two strains are of the same physical quantity, the Poisson's Ratio is a pure number - it has no dimension.
Figure:

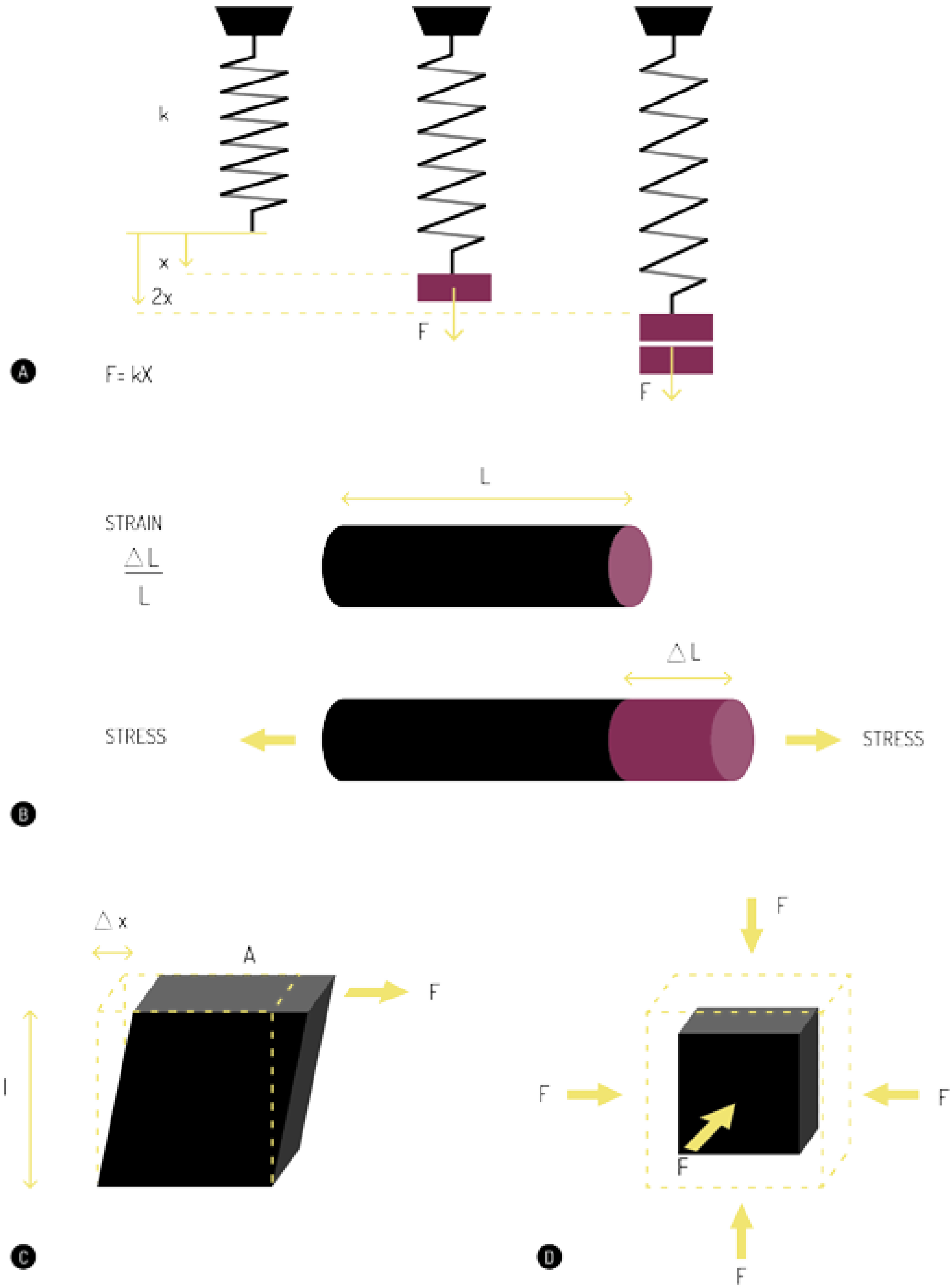


Figure 3 A. representation of Hooke's Law
B. representation of Young's Modulus
C. representation of the Shear Modulus
D. representation of the Bulk Modulus

1.1.4 Hooke's Law

In order to have a more precise mathematical description of the modification obtained by the auxetic body that undergoes a field of forces, many other physical quantities factors have to be taken into consideration. These are useful in measuring the stiffness of the materials. They all arise from the generalized Hooke's law, which is a principle that states that the force F needed to extend or compress a spring by some distance X is proportional to that distance (Figure 3) m which depends also on the k factor characterized by a constant, different for each material.
This law can be summed in: F=kX, meaning that the force equals the constant multiplied for the distance value.
This law is at the base of other laws - useful in analyzing materials with negative Poisson's ratio (Liu and Hu, 2010) :

$G = E/(2(1+V))$ and $K = E/(3(1-2V))$.

For isotropic materials, the four constants (V, E, G, K) are not independent. Thank to this relations it is possible to further understand the enhanced properties of auxetics. Since the discovery of the negative Poisson's Ratio it was possible to tailor new performances for many structures and materials. These constants, V-Poisson's Ratio, E-Young's Modulus, G-Shear Modulus and K-Bulk Modulus are explained as follow.

1.1.4.1 Young's Modulus (E)

Young modulus is also known as "tensile modulus" or "elastic modulus" and is a is a mechanical property of linear elastic solid materials. It is defined as the ratio of the stress along an axis (σ -

which has units of pressure) to the strain along that axis (ε - ratio of deformation over initial length - it is dimensionless) in the range of stress in which Hooke's law holds. Young modulus has units of pressure, its SI unit is therefore the pascal.

E= tensile stress/extensional strain

1.1.4.2 The Shear Modulus (G)

The sear modulus (G) is concerned with the deformation of a solid when it experiences a force parallel to one of its surfaces while its opposite face experiences an opposing force (such as friction). The shear modulus is the ratio between the force multiplied with the initial length to the area on which the force is applied for the transverse displacement. .

G= (Fl) / A(X2-X1)

1.1.4.3 The Bulk Modulus (K)

The bulk modulus of a substance measures the substance's resistance to uniform compression. It is defined as the ratio of the infinitesimal pressure P increase to the resulting relative decrease of the volume V. Its SI unit is the pascal.

K = -V [(P2-P1) / (V2-v1)]

1.2 HISTORY OF AUXETICS

The history of Auxetic structures dates back to the first decades of 1800, when the French mathematician, physician and astronomer Siméon-Denis Poisson (1781-1840) wrote the formula that defined the negative ratio of transverse to axial strain, which was then called the Poisson's Ratio. The first one to suggest that the Poisson Ratio could be also negative or greater than 0,5 was Saint Venant (Greaves 2013). Based on the mathematical theory of elasticity, the thermodynamic restrictions imposed on the constitutive law of elastic solids gave the limits of the limits of the poisson's ratio as - 1 <0<0.5 for isotropic solids (Fung, 1965). Negative poisson's Ratio materials have been known conceptually since 1944, and from that period some naturally occurring materials have been discovered to have auxetic effects for a long time, such as iron pyrites (Love, 1944), pyrolytic graphite (Garber, 1963), rock with micro-cracks (Nur and Simmons, 1969; Etienne and Houpert, 1989), arsenic (Gunton and Saunders, 1972), cadmium (Li, 1976), cancellous bone (Williams and Lewis, 1982), cow teat skin (Lees et al., 1991) and cat skin (Veronda and Westmann, 1970). Anyway the auxetic materials had not drawn more attention to people until 1987 when — in an article published for Science — R.S.Lakes (1987), from the University of Iowa, discovered that isotropic auxetic foams could be easily manufactured from conventional open-cell foam. Since then, extensive works have been done to gain insight into what makes materials auxetic and how these materials behave if compared with conventional non auxetic materials. Anyway in that years the knowledge on auxetics was a very at the beginning and they were called materials with

negative Poisson's Ratio — only in 1991 they were finally given the name Auxetics thanks to the British researcher Ken Evans, which wrote an article about these structures on Nature. The term auxetic derives from the Greek word αὐξητικός (auxetikos) which means "that which tends to increase" and has its root in the word αὔξησις, or auxesis, meaning "increase" (noun). Auxetic structures are also called dilatational materials because of their capacity to exhibit substantial volumetric changes when loaded. Many reviews have been written concerning auxetic materials in last decades. These includes, but not limited to, the work of Q. Liu (2006), Alderson and Alderson (2006-2007), Mir et al. (2014). The last one to which we refer is edited by Teik-cheng Lim in 2015.
The knowledge about these material was not so fast to widespread, and still in an article edited in 1995 by Prall and Lakes it was written that many textbooks were still stating that "materials with a negative Poisson's Ratio are unknown". Nowadays auxetics structures are well know by researchers and scientists, but anyway the knowledge about them is not so deep and it still needs further investigation.

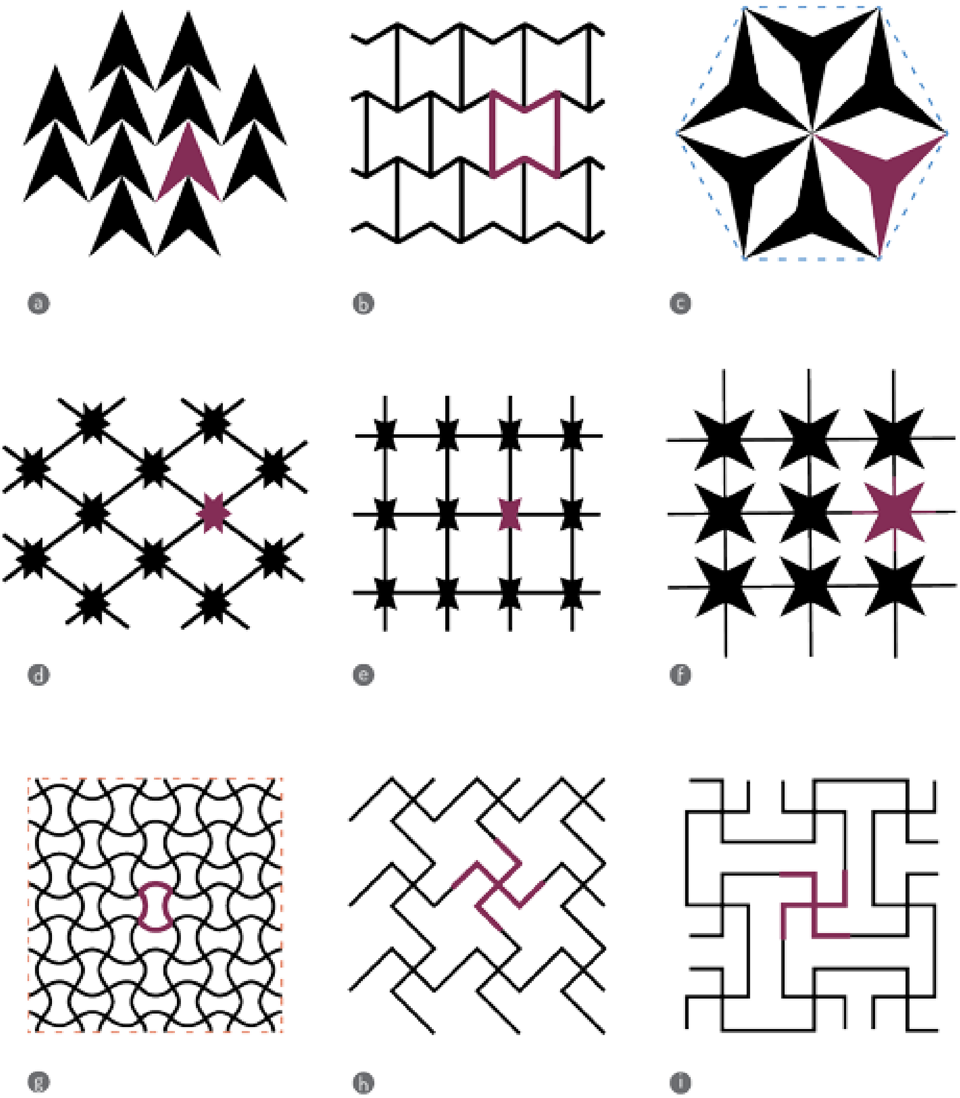


Figure 4 2D reentrant auxetic structures.
a. Arrow head structure - **b**. 2d reentrant honeycombs - **c**. Structurally hexagonal reentrant honeycomb - **d,e,f** Interconnected stars - **g**. Sinusoidal lattice - **h**. Lozenge - **i**. Square grids

1.3 CLASSIFICATION OF AUXETIC MODELS

1.3.1 About this Classification

Over the past decades, various geometrical structures and models that can result in auxetic effects have been proposed, studied and tested for their properties. Among the most important classes of such auxetic structures are 2 and 3 D re-entrant structures (Grima et al., 2005), chiral structures (Spadoni et al., 2005), rotating rigid/semi-rigid units, angle-ply laminates (Hine, 1997). This geometrical classification of auxetic structures is extremely useful, as it can help researchers to understand how auxetic effects can be achieved and how their properties can be optimized and predicted. These classes of auxetics are strictly related to mathematics and the way to utilize them in practical application is still a gap that has to be bridged. In this classification the structures has been grouped mostly following the work made by A.Alderson and K.L. Alderson in 2006-2007, by K.E. Evans and A.Alderson in 2000 and by Liu and Hu in 2010. Before to start the list of classes, a small digression about scale is done.

1.3.2 2D re-entrant structures

This class of auxetics is for sure the most known in terms of pattern and is the one that fastly clarify the auxetic effect. A broad research

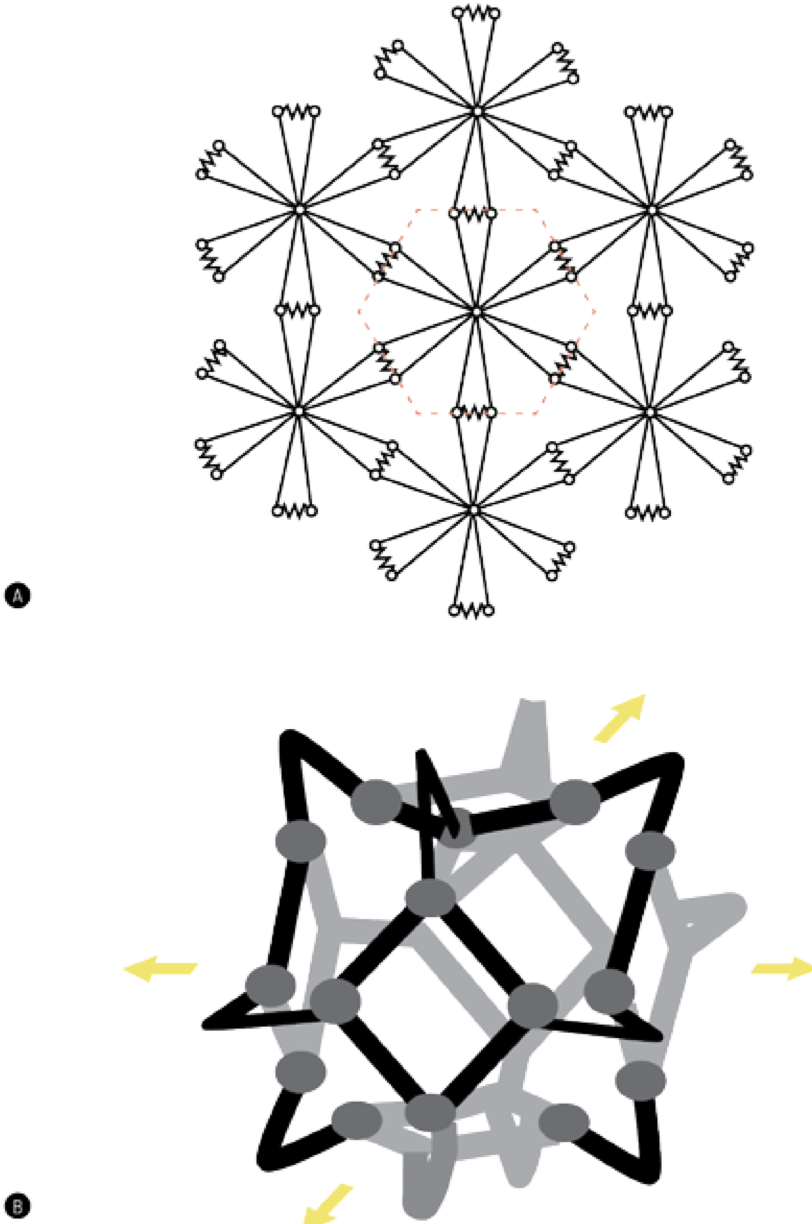


Figure 5 A. Auxetic model proposed by Cabras and Brun (2014)
B. 3D Reentrant structure

on this class lead to the creation and definition of a vast number of structures (see Figure 4).
The most known auxetic structure is for sure the one formed by honeycombs with concave angles (Figure 4b). Theoretically, the alignment of the diagonal ribs along the horizontal direction when stretched causes them to move apart along the vertical direction, thereby resulting in the auxetic effect. But in reality, most honeycombs of this type of structure deform predominantly by flexure of the diagonal ribs, with occurring of hinging and axial stretching of the ribs simultaneously. Flexure of the ribs equally leads to auxetic behavior in the re-entrant honeycomb system. Auxetic behaviour can also be obtained from other re-entrant structures: opening or closing of the arrowheads and stars respectively in double arrow-head structure (Larsen et al., 1997) and star (Theocaris et al., 1997; Grima et al., 2005) (Figure 4d, 4e, 4f) honeycomb structure due to rib flexure and/or hinging under uniaxial loading, will lead to auxetic behavior. A structurally hexagonal reentrant honeycomb (Lakes, 1991) (Figure 4c) has been suggested to get better planar isotropic property than 2D re-entrant structure shown in figure above, A due to structural symmetry along radial directions. However, the fabrication of auxetic materials with this structure has not been reported yet. Other two re-entrant structures respectively formed from lozenge and square grids by eliminating some side lines in each grid are shown in Figure 4h and Figure 4i, respectively. Their repeating units (unit-cells) are highlighted in bold. The auxetic effects are obtained due to rotation and extension of each side in the unit-cells. According to the analysis (Smith et al., 2000; Gaspar et al., 2005), the structure Square Grids (Figure 4i) exhibits higher auxetic effect than that of the structure Lozenge in Figure 4h under the same strain. Another structure is the structure formed with the sinusoidal ligaments (Figure 4g), whose auxetic effect comes from

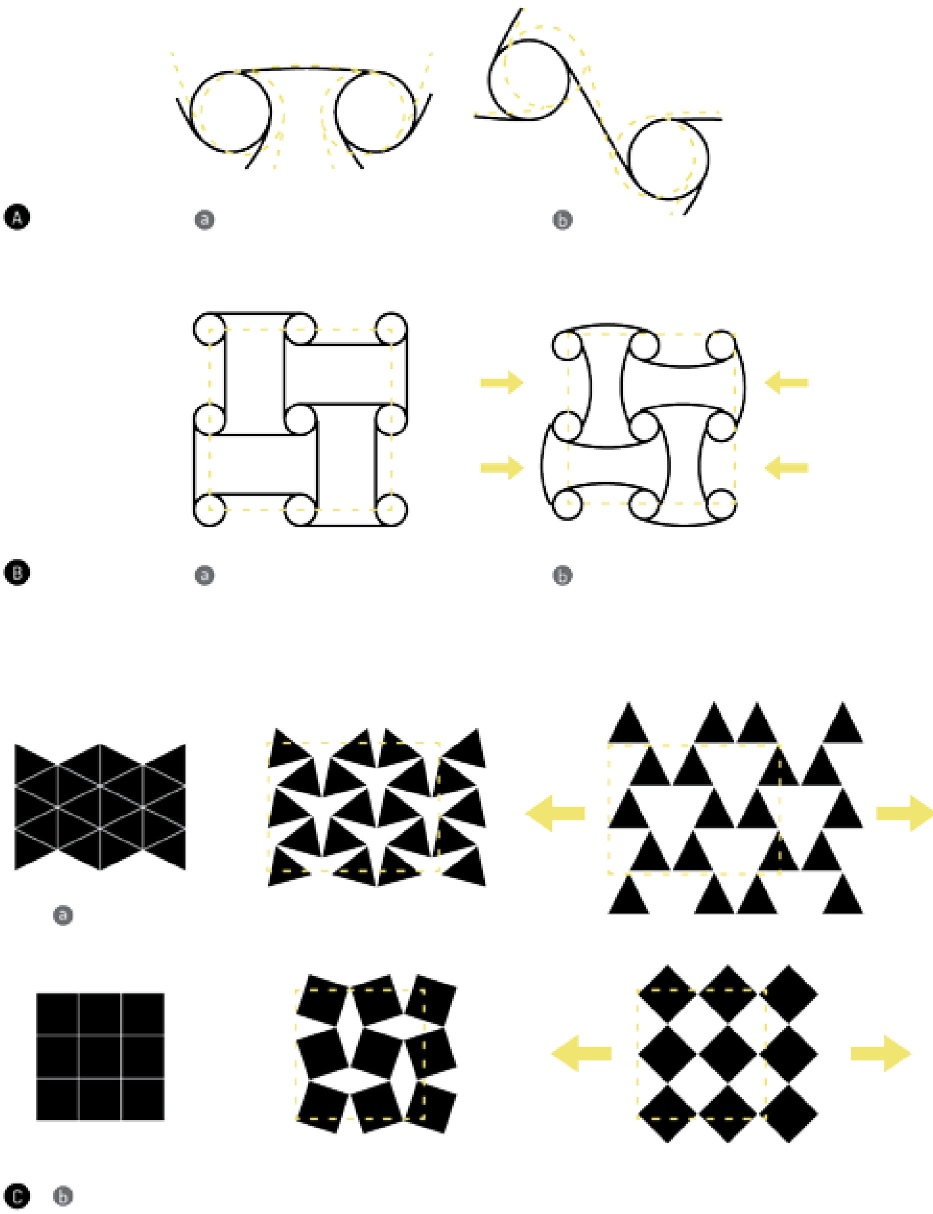
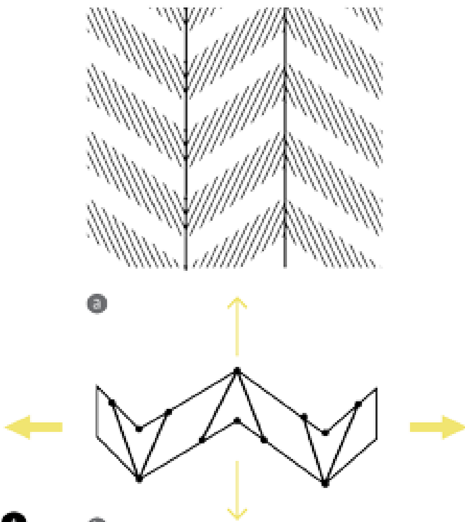


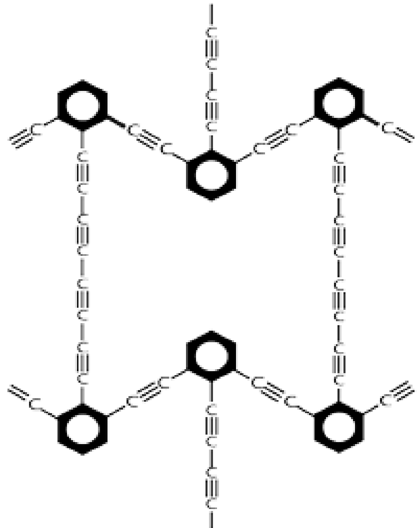
Figure 6 A. Chiral structures, relaxed and stressed (proposed by Prall and Lakes, 1997)
B. Chiral structure relaxed B.a, and stressed B.b
C. Semi rigid triangles C.a and squares C.b

opening up of re-entrant cells into almost rectangular cells. The rotational expansion auxetic lamina made with this structure was used for drug diffusion by Dolla et al. (2007). As an alternative, the sinusoidal ligaments can also be replaced by linear ligaments.
In 2014 Cabras and Brun proposed the model of a triangular lattice with a poisson's ratio gravitating around -1, depending on the proportions of the elements (Figure 5A).

One disadvantage of the re-entrant honeycomb system is the difficulty in manufacturing the honeycomb on a commercial scale. The usual method of gluing strips of material together at regular intervals and then pulling to produce the conventional hexagonal honeycomb geometry cannot be employed for the re-entrant honeycomb geometry. Other methods are possible (such as rapid prototyping and moulding techniques), but clearly these will require justification through a full cost-benefit analysis before current methods of honeycombs manufacture for commercial aerospace use are abandoned (Lakes, 1987).

In last years, a methodology was proposed by (Grima et al, 2005) which is called "Empirical Modelling Using Dummy Atoms" (EMUDA), which is particularly suitable for studying the properties of two-dimensional hexagonal honeycombs deforming through stretching or hinging of the rib elements, and it correctly predicts the magnitudes of Poisson's ratios (Figure 5d, 5e, 5f). They presented the potential for auxetic behaviour of a structure that can be described as "connected stars" since they contain star-shaped units which are connected together to form two-dimensional periodic structures. A macrostructure which has been studied for its auxetic properties is the hexagonal reentrant honeycomb constructed from arrow-shaped building blocks. However, the re-entrant hexagonal





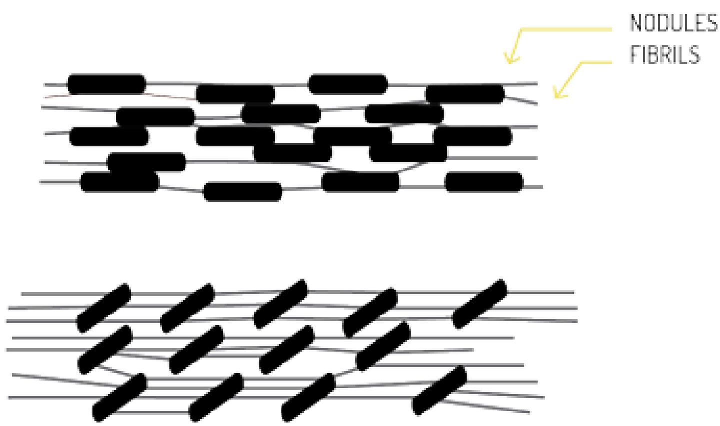


Figure 7 **A**. Biphasic composite material proposed by Milton (992). **A.a** shows the model, **A.b** the structure
B. Molecular Auxetic by Wojciechowski and Braika (1989)
C. Polymeric structure, closed and stretched

honeycomb is not the only tessellate which can be constructed from arrows. Star-shaped building blocks which have rotational symmetry of orders = 3, 4, and 6 may be built by connecting = 3, 4, and 6 arrows in such a way that the arms of the arrows form stars. This study is based on an analysis through the "force field molecular modeling simulations" (EMUDA). Several conclusions have been drawn based on this technique. It has been shown that star shape containing systems with the rotational symmetry of orders 4 and 6 show auxetic behavior to a greater degree when compared with systems that have a rotational symmetry of order 3. Also, the stiffness of the hinges connecting different rod structures affects the overall Poisson's ratio. An alteration in the hinge stiffness also has a different effect on different systems.

1.3.3 3D re-entrant structures

Besides 2D reentrant structures, 3D reentrant structures are also possible to get auxetic effects. As shown in (Figure 5B), a 3D reentrant cell has been used to explain the auxetic behavior of auxetic foams (Lakes and Witt, 2002). This cell was produced by transformation of the conventional cell structure into a re-entrant cell structure in which the ribs protrude inwardly. 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 lateral contraction in response to axial compression. Based on this model, auxetic polymeric foams could be easily understood. The next paragraph is a digression on this class of important auxetic materials that find a wide range of application in many fields.

1.3.3.1 Foams

A lots of different kind of magnetic foams exists, each of them characterized by the production process and the materials (Alderson and Alderson, 2006-2007). A method of converting fully reticulated open-cell thermoplastic (polyurethane) foam displaying positive Poisson's ratio behaviour into auxetic form was reported in 1987 (Lakes), and subsequently methods for the production of thermoplastic (silicone rubber) and metallic (copper) auxetic foams have been developed: foam slabs having dimensions of the order of a few 10s of centimetres and foams displaying isotropic and anisotropic mechanical properties can be produced. Microcellular foam and closed-cell foam have also both been converted into auxetic form.

If comparing the structure of a polyurethane foam before and after the conversion to auxetic form, the second one will show contorted three-dimensional reentrant topology if compared to the regular convex cell structure of the conventional starting foam material. Auxetic foam displays synclastic curvature, improved resilience, indentation resistance, shear resistance, fracture toughness, and vibration control. Multi-functional auxetic foams have been developed through soaking the foams in electrorheological and magnetorheological (MR) fluids, and their mechanical, electromagnetic, and acoustic properties are investigated. Application of magnetic or electric fields leads to changes in the stiffness of the foams, and significant magnetostrictive effects have been observed. Compared to conventional foams the MR-coated auxetic foams demonstrate increases in the loss factor and refractive index.

1.3.4 Chiral structures.

Chiral structures are another kind of structures which have been developed for auxetic honeycombs. As shown in Figure 4A and 4B, in this kind of structures basic chiral units are firstly formed by connecting straight ligaments (ribs) to central nodes which may be circles or rectangles or other geometrical forms. The whole chiral structures are then formed by joining together the chiral units. Usually these structure are referred to as chiral if all the nodes rotate in the same direction, anti-chiral if the nodes are oriented both clockwise and anticlockwise. The auxetic effects are achieved through wrapping or unwrapping of the ligaments around the nodes in response to an applied force. According to the theoretical and experimental investigations performed by Prall and Lakes (1997), Poisson's ratio of the chiral structure in Figure 4A under in-plane deformations is around -1. In contrast to most of other auxetic structures, this structure can maintain a high auxetic effect over a significant range of strains. Based on this structure, a novel class of structure referred as 'meta-chiral' (Figure 5B) has been recently developed by Grima et al. (2008). In this kind of structure, either the same chiral units (also called chiral building blocks) or symmetric units can be connected together to form different chiral structures. The over mentioned structure is formed by connecting the symmetric blocks where the node in each chiral building block is a rectangle. Though there is an infinite amount of ligaments attached to each node to form a building block, only the building blocks attached with 3, 4, or 6 ligaments may be used to construct space filling periodic structures. It is evident that the auxetic effects depend on the shape of node and the length of attached ligaments.

The chiral and anti-chiral honeycombs deform predominantly by a combination of cylinder rotation and ligament bending (Q. Liu, 2006). For example, Figure 6Aa shows the local cylinder-ligament structure of an anti-trichiral honeycomb lattice where a compressive load is applied, generating a torque on the cylinders such that they undergo in-plane rotation. This rotation induces a moment on the ligaments connected to each cylinder causing them to bend. In the case of the anti-trichiral honeycomb the bending of the ligaments forms a half-wave ligament shape. The ligaments of the anti-tetrachiral honeycomb were also found to form a half-wave shape under in-plane uniaxial loading.
On the other hand, the 'off-axis' ligaments in the trichiral system undergo flexure into a full-wave shape (Figure 56Ab), rather than the half-wave shape observed in the anti-trichiral system. The flexure of Figure 56Ab is again a consequence of the cylinder rotation effect due to the generation of a torque on the cylinders by an applied load. However, it is noticeable that the cylinder rotation is significantly lower than that observed in the anti-trichiral system, and that ligament flexure also occurs due to orientation of the off-axis ligament itself. Full-wave ligament shape was also found for the hexachiral and tetrachiral systems under in-plane uniaxial loading - As a structural concept, the hexachiral structure was proposed by Prall and Lakes in 1995 and by Lakes in 2001, although the chiral topology and its NPR behaviour has been identified for the first time by Wojciechowski and Branka (1989).

1.3.5 Rotating Rigid Units

This kind of structure has been developed to produce the auxetic

behavior in foams and hypothetical nanostructure networked polymers by jointing the rigid or semi-rigid triangles (Figure 6Ca) squares (Figure 6Cb), and tetrahedron at selected vertices. The vertices can be hinged or connected by springs. The auxetic effects come from the rotation of the triangles, squares, rectangles and tetrahedron when loaded.
It has been found that the V is a scale independent property; that is, the deformation mechanism can operate at any scale ranging from the nanolevel (molecular level) to the macroscale. In some cases, the presence of auxetic behaviour in very different systems has been explained by using the same deformation mechanism, and a valid example is the use of the rotation rigid units model to account for the auxetic behaviour in materials ranging from silicates and zeolites (where the auxetic effect is due to nanostructure of the materials) to polymeric foams (where the auxetic effect is due to features at the micro-millimeter scale) and macrostructures (Grima et al., 2005).

1.3.6 Angle-ply Laminates.

Laminated angle-ply composites have been designed and fabricated to have auxetic properties (Liu and Hu, 2010). A 1 incorporating stiff inclusions and a compliant matrix as shown in Figure 7Aa has been proposed by Milton (1992). Hatched regions represent a compliant phase simulated by compliant tensile but flexurally rigid rods. The periodicity cell is shown by a dashed line. This can be easily attained by placing a sliding element in the middle of each rod. Besides, each rod is replaced by a pair of parallel rigid rods fastened by two triangular links in order to retain parallelism for preventing the surfaces sliding relative to each other. The voids formed by the displacing rods to be filled by an elastic medium can obtain an auxetic composite structure with characteristic angular parameters. A rod model describing the deformation behavior of such laminates is presented in Figure 7Ab in which the thicker arrows show the direction of forces and the thinner arrows that of shear. Under an infinitely small deformation, expansion of width AB is directly proportional to the increase of length CD. A sandwich like stack of such structures could achieve auxetic effect.

1.3.7 Molecular Auxetics

Naturally occurring auxetic biomaterials are also known, although there are obvious difficulties in determining the exact elastic properties of biomaterials in the natural state. Examples of naturally occurring auxetic biomaterials (Evans and Alderson, 2000) include cow teat skin and cat skin where the auxetic effect is believed to occur because of fibrillar structures at the microstructural level. In a joint experimental and theoretical study, load-bearing cancellous bone with a cellular microstructure also showed some evidence of being auxetic.There are a growing number of natural materials that have been discovered to possess one or more negative Poisson's ratios (Evans and Alderson, 2000). In fact the existence of a negative Poisson's ratio in iron pyrites was first observed in the early part of this century (Love, 1944) although this was considered to be something of a little known anomaly at the time. Subsequently, auxetic behavior has been observed in other naturally occurring single-crystal materials such as arsenic and cadmium. Baughman et al. at AlliedSignal Inc. have extended earlier studies to reveal that

69 % of the cubic elemental metals and some face-centered cubic (fcc) rare gas solids are auxetic when stretched along the specific off-axis direction.

Starting from the studio of natural auxetic materials, models of auxetic molecular structures had been proposed. The first attempts at designing auxetic materials at the molecular level were performed for a 2D system of hard cyclic hexamers (Evans and Alderson, 2000) with auxetic behavior being predicted for high densities such that the tangential forces exceeded the normal contact forces between hexamers. These predictions were followed by others for molecular networks based on the re-entrant honeycomb geometry known to lead to auxetic functionality at larger length scales. Baughman et al. (1998) showed that the auxetic effect is correlated with the metal's work function and proposed that auxetic metals could be used as electrodes sandwiching a piezoelectric polymer to give a two-fold increase in piezoelectric device sensitivity. Models based on rigid "free" molecules proposed by Wojciechowski (1989 and others) are concerned with choosing the intermolecular interaction in such a way as to obtain a thermodynamically stable, elastically isotropic, auxetic phase in a system of particles interacting. A 'molecular' model of cyclic hexamers (that is, molecules composed of six 'atoms' placed on the vertices of a perfect hexagon, (Figure 7B) was constructed and solved exactly at zero temperature according to the references (Wojciechowski and Braika, 1989). The negative Poisson's ratio of the hexamer system results only from the intermolecular interaction potential. This is in contrast to most of other works in which the Poisson's ratio is a product of both an artificial structure of the material used and its intermolecular interaction (Evans and Alderson, 2000).

1.3.8 Microporous and Liquid Crystalline Polymer Models

For auxetic microporous polymer (Caddock and Evans, 1989; Evans and Caddock, 1989), the characteristics of the microstructure can be interpreted by a simple 2D model, as shown in Figure 9. This basically consists of an interconnected network of nodules and fibrils. If a tensile load is applied, the fibrils cause lateral nodule translation, leading to a strain-dependent negative Poisson's ratio.

Liquid crystalline polymer needs a brief introduction: in general, molecular models have used the macroscopic re-entrant honeycomb structure as a template. In addition, auxetic behavior of these models have been predicted (Evans et al., 1995), but these structures are not realized in practice because of too heavily cross-linked (Alderson and Alderson, 2006-2007). Recently, Griffin's group (He et al., 1998, 2005) has proposed a route to a successful molecular level polymer in the form of a liquid crystalline polymer (LCP) (He et al., 1998) due to site-connectivity-driven rod orientation in a main-chain LCP as shown in Liquid crystalline polymer. The LCP is composed of chains of rigid rod molecules transversely or longitudinally connected to flexible spacer groups. The laterally attached rigid rods in the quiescent or un-stretched state orient parallel to the terminally attached rigid rods. However, when the system is stretched, the laterally attached rigid rods change their position (Figure 7C). This site-connectivity driven rigid rod reorientation causes an increase in the inter-chain distance, which re- sembles the nodule-fibril mechanism. Progress has been made on the synthesis of these systems and molecular modelling has been used to predict auxetic behaviour, however thus far such materials with negative Poisson's ratio have not been created (Yao, Uzun and Patel, 2011).

1.3.9 Folding Models

The Japanese word "Origami" itself is a compound of two smaller Japanese words: "oru", meaning to fold, and "kami", meaning paper. Until recently, all forms of paper folding were not grouped under the word origami. Exactly why "origami" became the common name is not known; it has been suggested that the word was adopted in the kindergartens because the written characters were easier for young children to write.
Japanese origami began sometime after Buddhist monks carried paper to Japan during the 6th century. The first Japanese origami is dated from this period and was used for religious ceremonial purposes only, due to the high price of paper.
In the last few decades, with the massive increment of the computational capacities of computers and the development of specific softwares, the art of origami started to influence architecture. Three are the softwares that are mostly used to design and test this kind of structures, and they are: Origamizer (Demaine and Tachi 2010), Freeform Origami and Rigid Origami.
In the research on auxetic structures, origami are often studied as a possible structure even though they are not present in the most traditional reviews on the theme. In this research origami are included in the classification since it is possible to design origami patterns that behave auxetic. They can infact perform synclastic curvature and their Poisson's ratio can be negative. In Chapter III

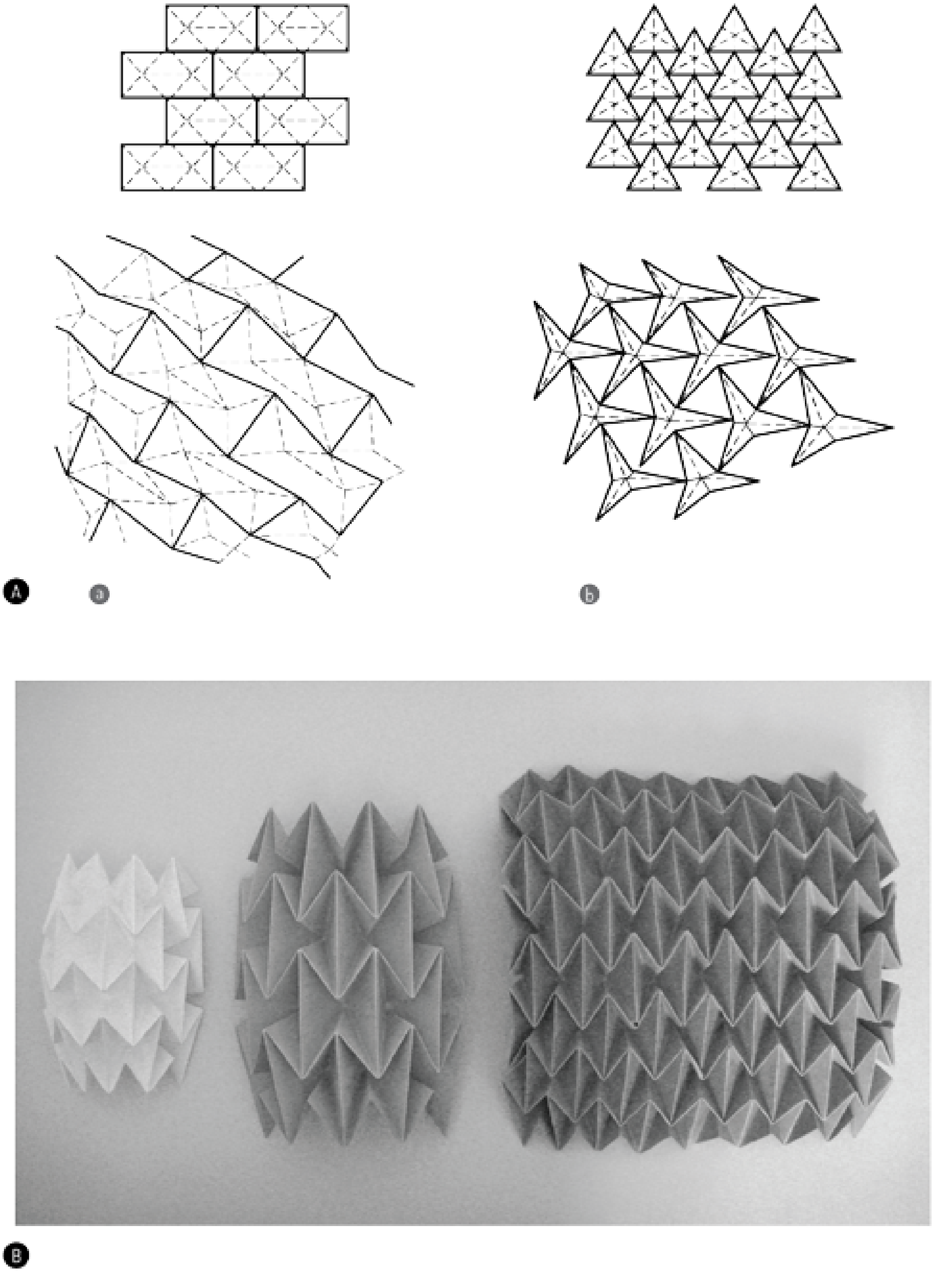


Figure 8 **A**. Auxetic origami patterns. **A.a** reentrant hexagons and **A.b** stars. Redrawn from the blog by Daniel Piker.
B. Origami auxetic shells

is presented a design application of auxetic rubber origami called OriMetric designed by Mads Hansen.

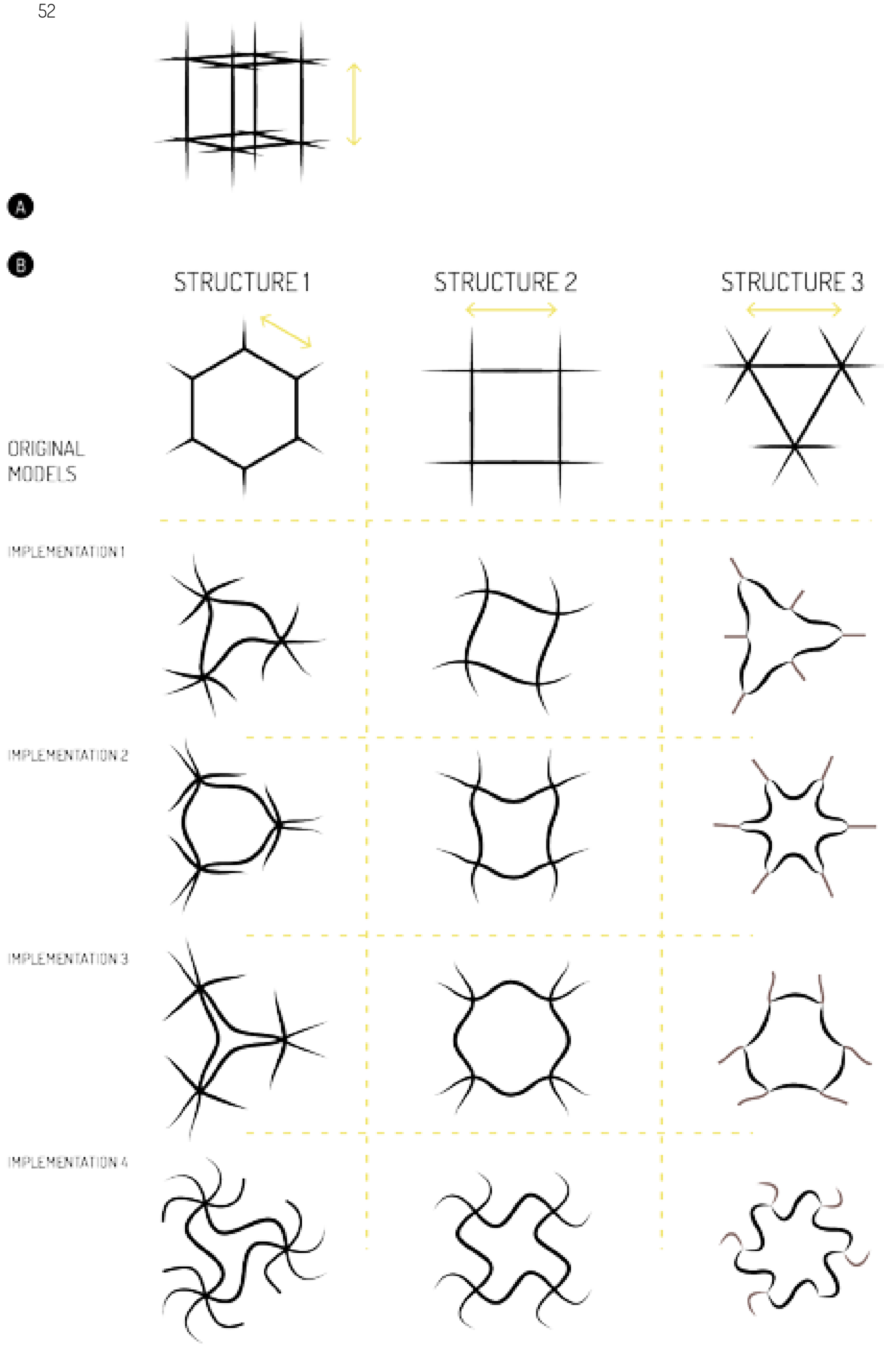


Figure 9 A. Cube auxetic cells
B. Triangle, square, hexagonal auxetic cells and their implementations

1.4 FORM FINDING OF AUXETIC GEOMETRICAL MODELS

With this paragraph, that is mainly readapted from the articles "A systematic approach to identify cellular auxetic materials" (by Körner and Liebold-Ribeiro, 2014) and "Auxetic two-dimensional lattice with Poisson's Ratio arbitrarily close to -1" (Bruna and Cabras, 2014), the intent is to introduce the reader into the understanding of the complexity and the uncertainties that there are behind the research on auxetics. In addition we hope that it can give hints towards new ways of researching auxetic patterns. In the scientific literature on the argument, it was not possible to find a systematic approach to identify auxetic structures before this, which is a first interesting attempt. Generally, a new auxetic structure is conceived after an intuition that subsequently is tested so to demonstrate its auxetic behavior. In two dimensions this approach can be successful and a consequent introduction into some class can be done (consult Chapter I). When moving into the research of new volumetric auxetic structures, the identification can be very complex and is still far from any systematic approach. Many of the three dimensional structures are realized by stacking two dimensional auxetic planes or three dimensional reentrant cells, resulting in highly anisotropic or complex structures.
The starting point of the first article is the observation that the two dimensional quadratic chiral lattice structure, which shows full auxetic behavior, is an EME (Eigen Mode Expansion - a computational electrodynamics modelling technique) of the quadratic lattice.

The article begin with the definition of four basilar auxetic cells: triangle, square, hexagonal (Figure 9B) and cube for three-dimensional evolutions (see Figure 9A). At a later stage are found the Eigen Mode implementations (EME) of each of them with periodic boundary conditions: the nodes are (usually) fixed and the ribs starting from them can freely rotate. The shaped reached are sometimes regular and symmetric, sometimes not (Figure 9B).
Subsequently, the eigenmodes are assembled to form periodic lattices and they numerically tested to determine the Poisson's ratio. This research showed that a systematic analysis of the structures showing negative Poisson's ratios reveals the underlying mechanism leading to auxetic behavior. An interesting note is that nearly all auxetic structures known from the literature emerge by this simple approach.
In 2014 Brun and Cabras presented their research on a new typology of auxetic 2D structure (Figure 5A) proposing a model that leads to a Poisson's ratio arbitrarily close to the thermodynamic limit corresponding to = −1. The effect is achieved by the superposition of clockwise and anticlockwise internal rotations, that bring to a macroscopic non-chiral effect (this means that the auxetic effect is not reached by the bending of the rods but by the pivot of them on the hinges). The elements of the structure have been produced with a three dimensional printer in thermoplastic polymer ABS with two different colors, blue and white. This structure is reaching the auxetic effect only when working in plane and it has not auxetic characteristics when forces act out of plane (like in the occasion of a bending).

1.5 CONCLUSIONS

This first chapter showed how Auxetics models are a multitude and can be very differentiated among themselves - looked from afar, there doesn't seem to be any relationship among themselves. Though, their qualities starts to pop up at the reader's eyes and it was shown how it is possible to look for new designs that have all the characteristics proper of the models that have negative Poisson's Ratio.
The possibility of tuning and modifying this structures, while still maintaining their characteristics, is a remarkable observation to start this work because it means that they can be versatile.

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PART I

AUXETIC MATERIALS

CHAPTER II

2.0 ABSTRACT

In this chapter we will focus on the description of the most diffused auxetic materials and on their production processes. Afterwards the characteristics for whom auxetics are mostly appreciated will be described.
The productions process of an auxetic material is of interest because it usually starts by adapting the steps used for crafting similar materials but in their positive poisson's ratio configuration. Nowadays, there are few production processes that permits to fabricate high quantities of auxetic materials and components. For this reasons tools like three dimensional printers - that are not thought used in industrial processes - play an important role in the production of prototypes.

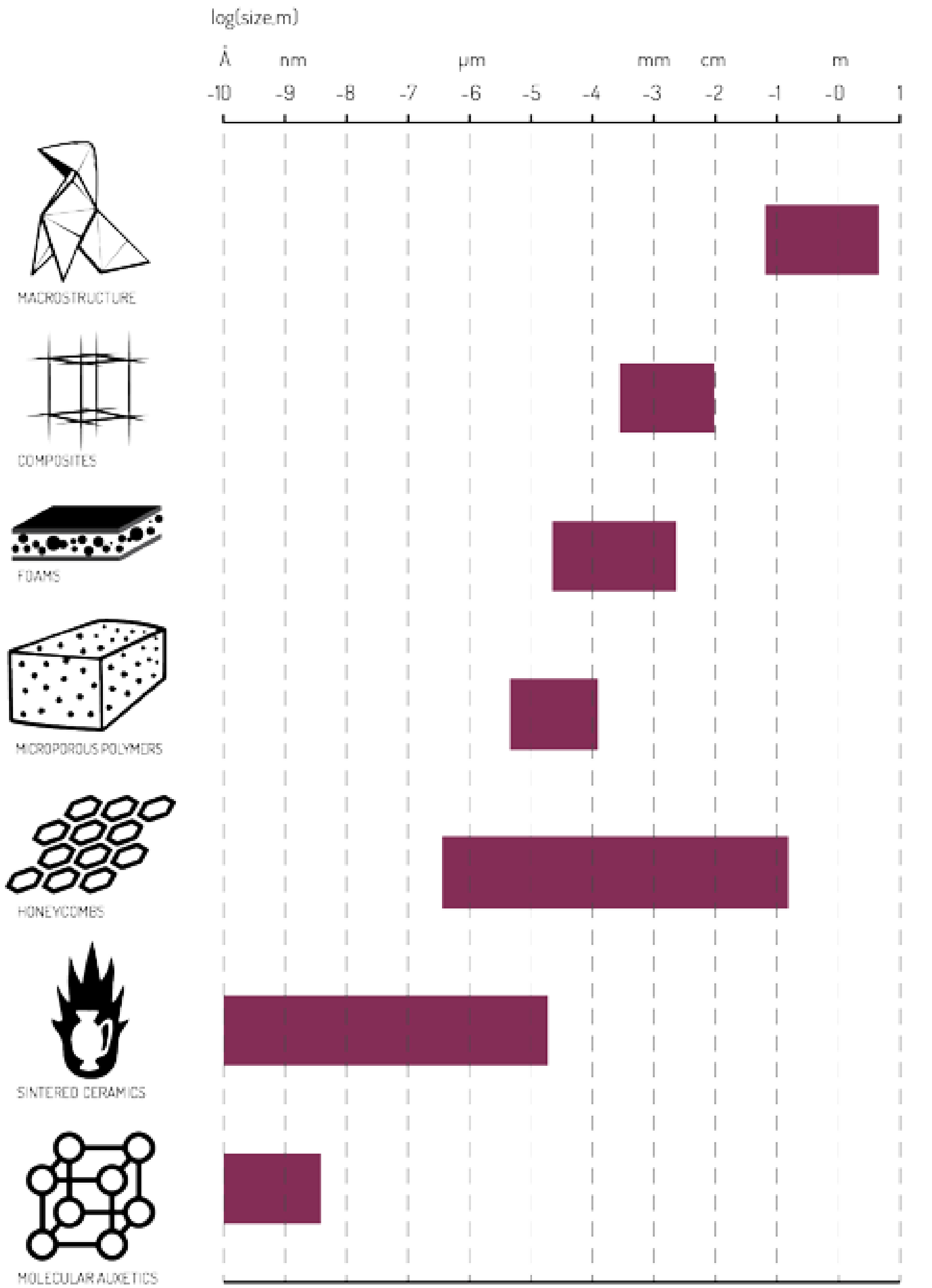
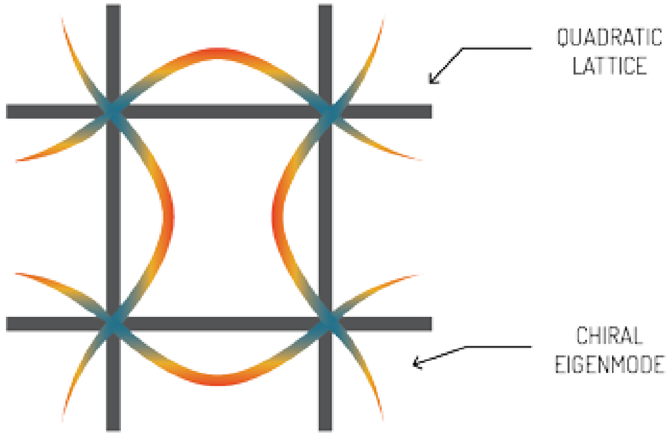


Figure 1 Auxetic structures can be found at any scale

2.1 SCALE

Materials with auxetic characteristics can be theoretically found at any scale. In Figure 1 it is shown the dimensional range of eight auxetic materials and structures.
Starting from molecular auxetics on the bottom - the smallest known scale where auxeticity can be found - the diagram shows materials with auxetic characteristics that arrive at a human scale. The class of "molecular auxetic" is not a real material but is still a model that haven't found any way of realization yet (quote). Anyway this class it is interesting since shows how auxeticity can be found at any scale.



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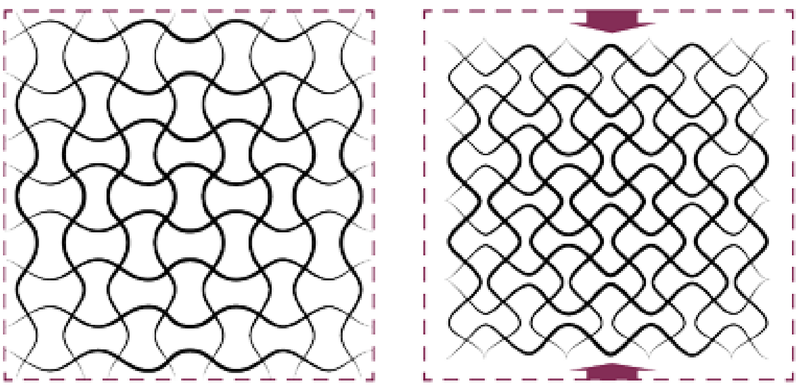

B

Figure 2 A. Stress analysis on sinusoidal auxetic lattice, by Korner and Liebold-Ribeiro (2014)
B. Deformation of the same structure as above

2.2 DEFORMATION MECHANISM

Movement is a peculiar characteristic of auxetics - by definition they change shape when stretched or compressed. In auxetics the movement can be performed mainly by:

- flexion of the ribs,
- by the hinging under uniaxial loading,
- by peculiar characteristic of the used material,
- by torsion,

Usually, structures with curved elements are thought to work under the bending of the ribs and they present fixed joints. Watching the stress analysis made by Körner and Liebold-Ribeiro (2014) it's observable that the main stresses are presents in ribs while the joints are often unstressed (Figure 2.A). It is possible to point out that, in a network of a positive Poisson's ratio structure with cells having the conventional hexagonal geometry, the cells elongate along the axis Y and close up along the axis X in response to stretching the network in the Y direction, giving a positive V. By maintaining the same deformation mechanism (rib hinging) but modifying the honeycomb cell geometry to adopt the reentrant structure, the cells of the network now undergo elongation both along and transverse to the direction of applied load (in Figure 2.B). Hence the re-entrant honeycomb deformed by rib hinging is an auxetic structure, which is generally anisotropic. This means that the value of V when loaded along the ⊠-direction (V) differs from that when loaded along the -direction (V).

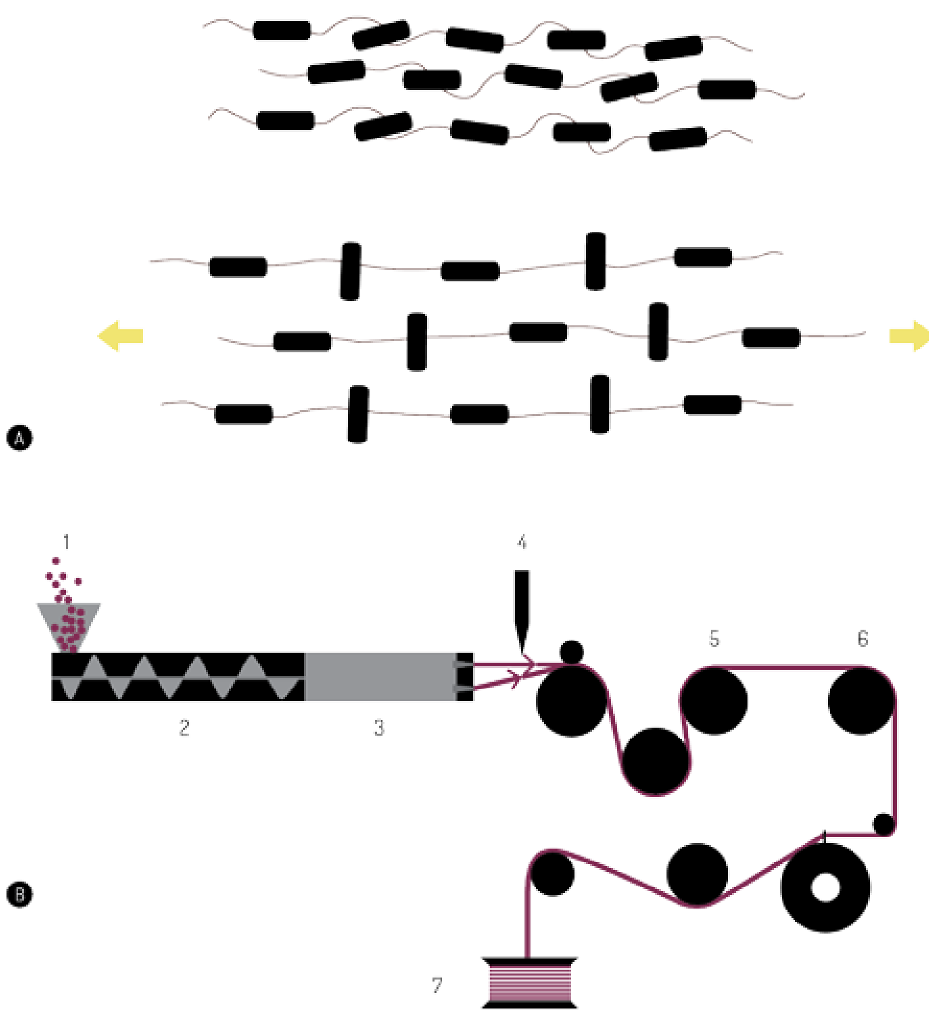

Figure 3 A. Microstructure characterizing auxetic microporous polymers, by Evans and Caddock (1989)
B Production of auxetic polymeric filament, patented by Alderson and Simkins.

2.3 PRODUCTION OF AUXETIC STRUCTURES

Even though auxetic materials can be found in nature, they mainly exist because synthesized in form of ropes, fabrics or foams, and they can be found modeled into structures that for some interest reproduce auxetic models. Examples are the works of Bettini et al. (2009) Yang et al. (2013) Scarpa et al. (2015) and Choie and Lakes (1991). In the research "Composite chiral structures for morphing airfoils: numerical analyses and development of a manufacturing process" (2009) Bettini investigates complex composite cellular chiral structures manufactured using CC90/ET443 SEAL plain weave carbon fabric plies with the ability to undergo large overall displacements with limited straining of its components. Even though they indagate on an auxetic structure the material in which this structure is composed is not an auxetic material.
In this chapter only auxetic materials will be discussed.

In the industrial processes there is a wide predominance of polymers. The possibility to synthesize polymeric materials with precisely tailored characteristics permits to use them as a cheaper replacements to more expensive and less versatile materials. Moreover, polymers come in such a vast number of families to widen the possibilities even more (like biopolymer, inorganic polymer, organic polymer, conductive polymer, fluoropolymer, poly terpene, phenolic resin, polyanhydrides, polyester, polyolefin, rubber, silicone, silicone rubber, superabsorbent polymer, synthetic rubber, vinyl polymer). By their capacity to blend easily to other materials, polymeric composites are numerous. Metals and ceramics can be also found in auxetic version, usually in foams and piezoelectric materials.

2.3.1 Polymers

Auxetic polymeric materials are those designed and manufactured to have a macromolecule framework or macroscopic structures that cause auxetic behavior. So far, a series of auxetic polymeric materials have been produced in the form of foam, fibers and composites. Some molecular-level auxetic polymers have been designed, but they have not been synthesized yet.
The microstructure characterizing auxetic microporous polymers is a simple 2D model (Evans and Caddock, 1989) that basically consists of an interconnected network of nodules and fibrils (Figure 3.A). If a tensile load is applied, the fibrils cause lateral nodule translation, leading to a strain-dependent negative Poisson's ratio.
A field in fast development concerns the production of auxetic polymeric fibers which are elongate bodies having a length at least hundred times its diameter. Many production processes are patented and already underway.

Here I will report the patent EP1165865B1 named "Auxetic Materials" (by Alderson K.L. and Simkins V.R.) that describes a how to produce auxetic polymeric filaments with nowadays technologies (figure 3.B). The described procedure may be applied to process polypropylene. Other polymeric materials, such as nylon or polyolefin or polyamide materials, may be used. The polymeric material may

be mixed with or incorporate to any other suitable material such as fillers or other polymers. The process can be applied to the production of continuous monofilaments, or short filaments, and these may be twisted or otherwise combined to give multifilament or fibrous yarns. These filamentary or fibrous materials may be formed into textile structures such as woven, knitted or felted fabrics alone or in combination with any other suitable materials. Filaments or fibre made in accordance with the invention may be used as reinforcements in composite materials to impart enhanced energy absorption properties and fibre pullout resistance like in the production of protective clothing where enhanced indentation properties and low velocity impact resistance are advantageous.
The production apparatus has three zones, a barrel zone, an adapter zone and a die zone which are capable of independent temperature control. Temperature is essential in the production of auxetic polymers since it is believed that for a fibre to be auxetic its maximum melting temperature should be as close as possible to those of the powder from which it has been derived (figx).

2.3.1.1 Microporous polymer cylinders

The auxetic effect was first observed in microporous polymeric foam in 1989 (Caddock and Evans, 1989 when an expanded form of polytetrafluoroethylene (PTFE) was found to exhibit a highly anisotropic negative Poisson's ratio as low as = −12. This is due to its complex microstructure which consists of nodules interconnected by fibrils. In essence, the reentrant structure of the foams and honeycombs has been reproduced by the nodule-fibril structure and the dominant deformation mechanism for auxetic behaviour is nodule translation through hinging of the fibrils. The observation of the auxetic effect in PTFE revealed that there are no underlying reasons why other polymers should not be processed in such a manner as to produce this particular microstructure. A batch process consisting of three distinct stages of compaction, sintering, and extrusion has been developed and used to produce auxetic microporous samples of ultra high molecular weight polyethylene, polypropylene (PP) and nylon. If the compaction stage is omitted, the extrudate produced is highly fibrillar and very auxetic but has low mechanical properties and low density. Equally, the extrusion stage may also be replaced by compaction followed by multiple sintering, resulting in a material which retains some of its auxeticity, but has excellent structural integrity. Two other interesting features have been examined for these materials: the indentation resistance and the absorption of ultrasound. Enhancements of up to four times over conventional materials have been found in indentation resistance for the more structurally sound auxetic polymers whereas for ultrasound absorption, the very highly fibrillar forms of the polymers are so good at absorbing the signal that it was undetectable. Thus, the possibility of tailoring the mechanical properties through processing is apparent for the microporous polymers.

2.3.1.2 Microporous polymer fibres

There is a disadvantage in using the processing route developed for auxetic polymers and this is that it is geared towards the production of cylinders. Although useful for assessing processing parameters and measuring some simple mechanical properties, this shape is difficult to machine and to use in applications-based work. Alderson et al (2002) were the first to successfully produce auxetic fibers. They developed a kind of auxetic polypropylene (PP) fiber by employing a novel thermal processing technique, based on modified conventional melt spinning technique. This enabled a continuous fabrication process of auxetic polypropylene (PP) fibers. They used a laboratory scale melt extruder in place of a benchtop extruder and a flat profile of 159 °C across all zones of the extruder. Even though aligning the molecules, as a consequence of drawing, gives fibers their high modulus, drawing the auxetic fibers causes a loss of the auxetic property. Ravirala et al. (2005) reported that the main approach for the production of auxetic fibers lies in maintaining the minimum draw ratio. The developed fabrication process of polypropylene fibers is flexible enough to be used for the production of other polymeric fibers with the ability to achieve auxetic behaviour.

Consequently, in 2001, auxetic fibres were fabricated using a partial melt spinning technique. PP, polyester and nylon fibres have been produced with this technique. This development has opened up areas such as reinforcements in auxetic composites, and technical textile applications. The processing route can also be adapted to produce auxetic PP films, which have inplane Poisson's ratios approaching −1. Auxetic films are potentially important as membrane materials and preliminary experiments have been performed showing their potential as self-healing films due to the closing up of a tear when the film is placed under tension along the direction of the tear.

2.3.1.3 Molecular-level polymers

In order to develop polymeric fibres having high strength and stiffness properties it is necessary to produce polymers in which the auxetic effect is derived from microstructures operating at the molecular and nano scales. As already noted, a number of inorganic and metallic materials exist where the auxetic effect occurs at the molecular scale. Despite this, and the presence of a significant literature on modelling studies of auxetic molecular-level materials, no molecular-level auxetic polymers have so far been synthesized. Early molecular models have used the macroscopic re-entrant honeycomb structure as a template for polymeric molecular honeycombs. Auxetic behaviour has been predicted but these structures are too heavily cross-linked to be realized in practice.

2.3.2 Metals, Ceramics and Composites

It is possible to find auxetic materials composed by metals, ceramics and composites. Copper is often used to produce auxetic foams (Lakes 1987) while ceramics are used in the creation of sensor and actuators (Topolov and Bowen 2008) which are usually composed by a base in polymer added with metals and/or ceramic piezoelectric materials to give the "active" behaviour.
In the work by Topolov and Bowen (2008) wants to demonstrate and understand how the piezoelectric performance and the potential benefits of a piezoelectric composite depend on changes of the non polymeric components, so on the characteristics of the ceramic and metal elements. They found out that if the polymeric matrix of this material is composed by and auxetic polymer (more specifically they refer to the isotropic auxetic polymer defined by Lakes in 1987), the overall characteristics of the composite encrease. Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins (Holler et al 2007) in response to applied mechanical stress. The word piezoelectricity

means electricity resulting from pressure. It is derived from the Greek piezo or piezein (π), which means to squeeze or press, and electric or electron ( ), which means amber. Piezoelectricity was discovered in 1880 by French physicists Jacques and Pierre Curie.

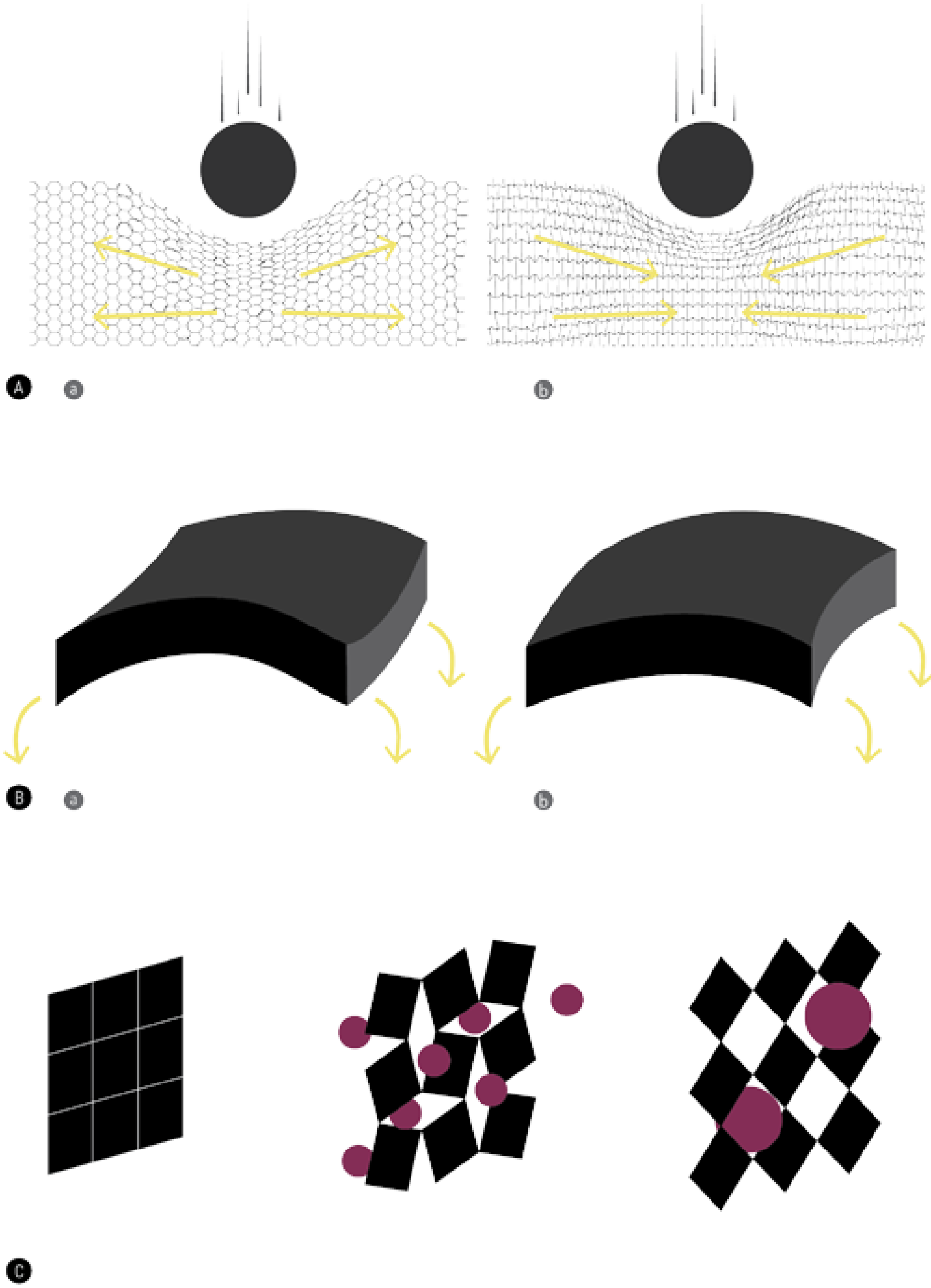

Figure 4 **A**. Indentation resistance on PP'sR structure **A.a** and NP'sR structure **A.b**
B.a Anticlatic curvature - **B.b** Synclastic curvature
C. Variable permeability

2.4 BEHAVIOURAL PROPERTIES OF AUXETIC STRUCTURES

Because of the negative Poisson's ratio auxetic materials and structures exhibit a series of fascinating properties compared with the conventional materials. These behaviours are a direct consequence of the NPR's and can be found at different levels in each material or structure.

2.4.1 Compressive Strength and Shear Stiffness

Auxetic effect can play an important role in tailoring the mechanical properties of a structure to give enhanced performance. In elastic theory, the material's elastic behavior is expressed by four constants (refer to paragraph 2.2.4 Hook's Law for more informations): the Young's modulus (E), the shear modulus (G), the bulk modulus (K) and the Poisson's ratio (v). For isotropic materials, the four constants are not independent. They are related by the following equations:

$G = E/(2(1+v))$ $K = E/(3(1-2v))$

Most structural materials are required to have a higher G than K. If we can change the microstructure of a material in a way that E remains constant but v changes, we can alter the values of K and

G. For example, when decreasing v to -1, a very high shear modulus relative to the bulk modulus can be obtained. Potentially, when $\to$ −1 the shear modulus tends to infinite. In other words, the material becomes difficult to shear but easy to deform volumetrically (Yang et al. 2004). Materials with negative Poisson's ratio are more resilient than non-auxetic materials, and the linear strain-stress relationship can reach up to 0.40 compressive ultimate strain compared to 0.05 strain for conventional cellular materials (Małgorzata 2009).

The particular conformation of auxetic structure lead to a limitation. The special microstructural features for auxetic materials need space to allow the "hinges" to flex, or the "nodules" to spread out leading to a substantial porosity. Therefore, materials with negative Poisson's ratio are substantially less stiff than the solids from which they are made and this causes limitations on the structural applications of the materials with negative Poisson's ratio (Yang et al. 2004). For example, they are normally not stiff enough or not dense enough for high load-bearing applications. Metallic auxetic foams are an example.

2.4.2 Indentation Resistance

Hardness can be increased in auxetic material due to the hinged structure. When an object hits an auxetic material and compresses it in one direction, the material also contracts laterally, that is, material 'flows' into the vicinity of the impact (Evans and Alderson 2000). This creates an area of denser material which is resistant to indentation. See image above where A represent the behaviour of a positive Poisson's ratio material and B represents a negative one (auxetic). This phenomenon can be explained theoretically: the indentation resistance or hardness of an isotropic material is proportional to E/(1-2v) when an indenter with a uniform pressure distribution is assumed. As stated above, the variation scopes of v for 3D isotropic materials are from -1 to 0.5. Thus, the (1-v2) will approach to 0 when v approaches to -1. In this way, for an isotropic material with a given value of E, the indentation resistance increases (towards infinity) with increasingly negative v. As an example. Smith et al. (2000) (ci sono delle belle immagini in questo paper) found that the auxetic foams demonstrated enhanced indentation resistance independent of bulk density and modulus. Their results showed that auxetic foams densify under indentation and the strain field under the indenter is much larger, probably due to enhanced shear stiffness.

2.4.3 Synclastic Curvature

When a conventional material is subjected to an out-of-plane bending moment its surface is inevitably slightly stretched and leading into shrink the perpendicular direction displaying anticlastic curvature due to the edges curl upwards and showing a saddle shape (Alderson and Alderson 2006-2007). However, an auxetic material will display synclastic or double curvature, producing a dome shape without the need for excessive machining or forcing the material to take up the desired shape which could result in possible damage (Evans 1990). All auxetic materials have a common deformation characteristic to an ellipsoidal shape, referred to as the synclastic curvature. Consequently, a plate made of auxetic material will take up a dome-shaped configuration when bent, with no crimps induced by in-plane buckling. A normal material responds to this by attempting to shrink in the perpendicular direction, so the edges tend to curl upwards, producing a saddle-shaped surface. But in auxetic materials the response is to cause the edges to curve downwards, the same direction as the bending force. This double curvature characteristic of auxetic materials can be used to design and build domes of other structures with complex curvature and shapes, to moulding and shaping panels for cars or aircraft components such as nose cones.

2.4.4 Energy Absorption and Dissipation

In a NPR's material the energy dissipation levels can be up to fifteen times higher than in conventional foams and five to six times higher than in conventional foams with high density (Scarpa 2008). It is observed that auxetic materials possess attractive acoustic properties, and it is found that at frequencies up to 1600 Hz auxetic forms of polymeric and metallic foams possess enhanced acoustic absorption when compared with conventional materials. Acoustic absorption at low frequencies (between 400 and 800 Hz) is higher in auxetic materials than in conventional foams by an average factor of two (Scarpa 2008). Caddock and Evans (1989) examined two interesting features of microporous polymers cylinders: the indentation resistance and the absorption of ultrasound.

Enhancements of up to four times over conventional materials have been found in indentation resistance for the more structurally sound auxetic polymers whereas for ultrasound absorption.

2.4.5 Variable permeability

Auxetic materials are able to open pores when stretching and close them when compressing. This feature can be useful in various types of filtration applications. Evans and Alderson (2000) first hypothesized how auxetic materials could offered improved filter performance from the macro-scale to the nano-scale because of their unique pore-opening properties and characteristics. Polymeric auxetic materials and structures can enhance pore size and shape adjustment when pressure is increased or when they are subjected to uniaxial stretching. These characteristics can overcome the reduction in filtration efficiency and increased pressure across the filter due to the pores blocked. In addition, the pore size is a function of applied strain which is smart release mechanism (Alderson and Alderson 2006-2007).

2.5 CONCLUSIONS

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PART I

CURRENT APPLICATIONS

CHAPTER III

3.0 ABSTRACT

In this chapter we will focus on the description of the most diffused auxetic materials, on their production processes and afterward examples of applications will be described. We will present processes to product auxetic materials and their properties
In this chapter it is clarified how auxetic structures, materials and models can be applied in the development of high-performance products by giving some example. Thanks to their enhanced properties auxetics are gaining attention from industries and researchers - the standardization and amelioration of their production processes turns auxetics into reality. Six recently realized projects will be analyzed to better understand the technology and its production process. The examples are chosen among realized and theoretical projects.

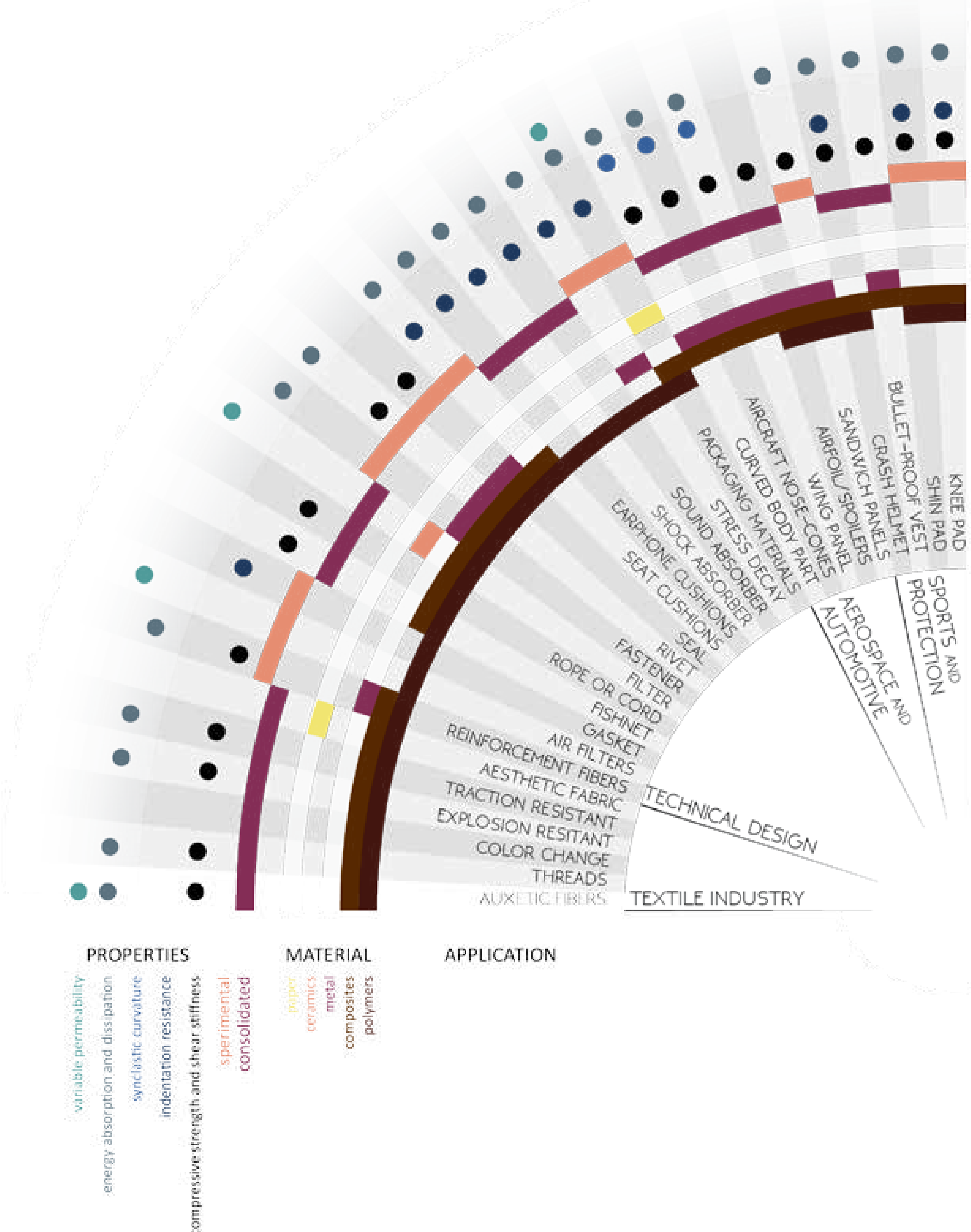
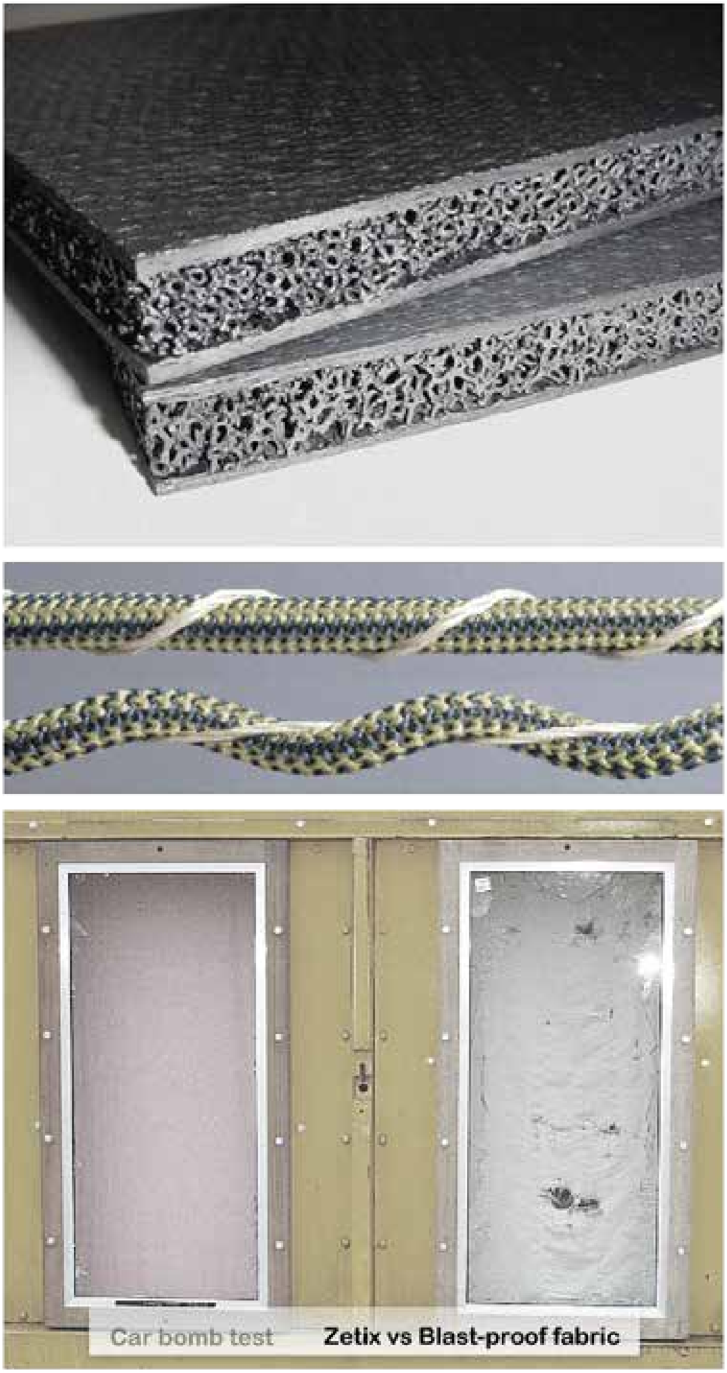

KNEE PAD
SHIN PAD
BULLET-PROOF VEST
CRASH HELMET
SANDWICH PANELS
AIRFOIL/SPOILERS
WING PANEL
AIRCRAFT NOSE-CONES
CURVED BODY PART
PACKAGING MATERIALS
STRESS DECAY
SOUND ABSORBER
SHOCK ABSORBER
EARPHONE CUSHIONS
SEAT CUSHIONS
SEAL
RIVET
FASTENER
FILTER
ROPE OR CORD
FISHNET
GASKET
AIR FILTERS
REINFORCEMENT FIBERS
AESTHETIC FABRIC
TRACTION RESISTANT
EXPLOSION RESITANT
COLOR CHANGE
THREADS
AUXETIC FIBERS
SPORTS AND PROTECTION
AEROSPACE AND AUTOMOTIVE
TECHNICAL DESIGN
TEXTILE INDUSTRY
PROPERTIES
variable permeability
energy absorption and dissipation
synclastic curvature
indentation resistance
compressive strength and shear stiffness
sperimental
consolidated
MATERIAL
paper
ceramics
metal
composites
polymers
APPLICATION

Figure 1 Applications of auxetics depending on areas of interest

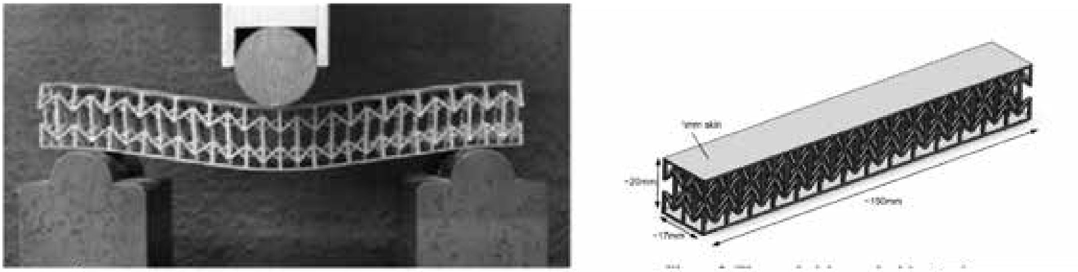


A

B

C

Figure 2 **A.** Isolating panel filled with auxetic metal foams
B. Auxetic Double Helix Yarn
C. Test comparison between auxetic fabric (by Zetix) and non auxetic fabric during a car bomb explosion



D

E

F

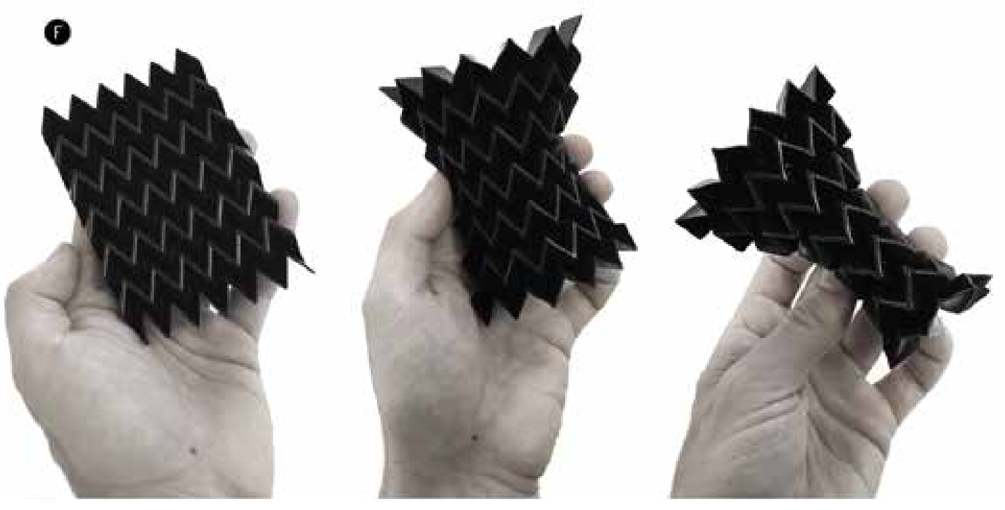


Figure 3 **D.** Auxetic sandwich panel, by Li Yang et al (2013)
E. Sportswear Underarmour Firm patented a material used in training shoes sole called Micro G®. The model shown contains this technology. An auxetic graphic pattern was choosen also per the outer shell drawing. Image via www.underarmour.com
F. OriMetric rubber origami, by Mads Jeppe Hansen. Image via www.trex-lab.com)

3.1 INTRODUCTION

To the development of new auxetic materials and processing routes in recent years followed the creations of patents and publications from organisations including Toyota, Yamaha, Mitsubishi, AlliedSignal Inc, BNFL and the U.S. Office of Naval Research - all related to the emerging potential of these materials. These patents touch many field of interest. In the architectural field there are few examples which are not so compelling..
Even if there is a lot of research going on it is difficult to find commercial products based on auxetic technologies.
In Figure 1 are shown possible applications of auxetics depending on seven areas of research. The aim of this chart is not to enclose all the applications into only one area of interest, but it wants to help in the comprehension of how an auxetic material che be applied and which are its potentialities. It happens often that the auxetic structures are used in one field in a similar way in which they are used in another one thus interconnecting all the fields among themselves and eliminating the straight boundary of the chart.
Observing the chart it can bee seen that auxetic filaments are the most available auxetic material in commerce because of many characteristics: they are easily deliverable and easiest to be produced, gaining a lot of interest in many fields (textile industry, industry, biomedical, sports).

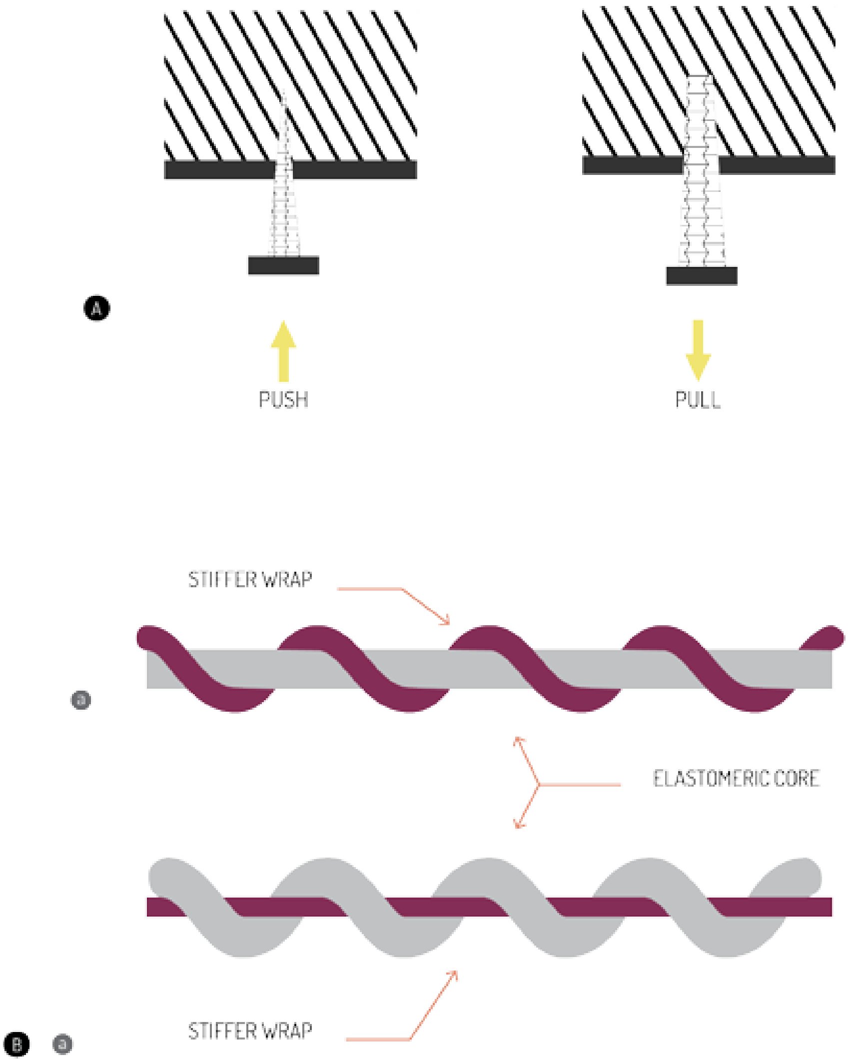


Figure 4 A. Auxetic fastener, gets shorter and thinner whilst "going in" - gets longer and fatter whilst "going out"
B. Auxetic double-helix yarn (DHY)

3.2 GENERAL ENGINEERING APPLICATIONS

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). The large number of applications is related to the peculiar deformation mechanisms of auxetic configurations. The possible use of auxetic materials for viscoelastic damping applications has been examined 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 a modified route from the classical production layout.

In the field of vibration absorber pads, testing of anti vibration glove cushioning materials has been the subject of several research studies which have lead to the establishment ISO standard 13753:1999, which defines a method for measuring the mechanical transmissibility of glove cushioning materials.

The cyclic stress-strain behaviour of polymer foams and elastomers has attracted recent attention, particularly when damping ability is considered, since both types of material have good vibration absorption qualities. When samples are loaded under strain control and then unloaded, subsequent extension to the same strain requires a lower force. Further cycling results in continued softening at a progressively slower rate and a steady state may be reached. This softening phenomenon is an important indication of the amount of energy that the material can continue to absorb. A polyurethane foam open cell subjected to compressive cyclic until 100 cycles has been investigated by Shen et al. (2001) proposed a model which could be applied to express the cyclic stress-strain relationship for conventional polyurethane foam at any given cycle. Polymeric foams are viscoelastic materials, and the rate of loading, or frequency of the load cycles, become important factors to consider. In sandwich structures with polymeric foam core, it is expected that the viscoelastic behavior of the foam play an important role in absorbing and dissipating energy especially during dynamic loading. Such dynamic 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 important issues on selecting foam materials for applications where both vibro-acoustics and structural-integrity targets have to be met. While for positive Poisson's ratio materials the analysis of viscoelastic core properties (in particular for sandwich pads and structures applications) has been considered in few studies there is even more scarcity of available results for auxetic open cell PU-PE foams.

In a publication by Scarpa et al (2006) is presented a combined series of experimental results on negative Poisson's ratio open cell foams, both from a vibration and cyclic fatigue point of view These foams offer multiple advantages in terms of transmissibility

reduction above 100 Hz – 150 Hz, indentation resistance, stability of stiffness under compressive cyclic loading, and damping capacity for energy absorption under repeated compressive forces. In figure 2.A is shown a metallic foam panel.
Auxetic foams have also been used to demonstrate applications which exploit the auxetic effect directly. The use of auxetic materials as fastening devices has been shown in the form of 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 process of insertion of the fastener (Figure 4.A). When the copper foam is pulled (stretched) to try to extract it from the hole, the foam expands radially and locks into the walls of the surrounding hole, leading to increased pull-out resistance for the fastener. The auxetic fibre specimens withstood more than twice the maximum load and required up to three times more energy to extract the fibre than the equivalent positive Poisson's ratio fibre specimens. This behaviour can also be applied in biomedical sutures and ligament/muscle anchors (Scarpa, Giacomin et al. 2015).

Auxetics can also be employed as filters using their capacity which has been defined as Variable Permeability offering enhanced potential for cleaning fouled filters, for tuning the filter effective pore size and shape, and for compensating for the effects of pressure build-up due to fouling. These benefits rely on the pores opening up both along and transverse to the direction of a tensile load applied to an auxetic filter. The pores of a non-auxetic filter open up in the stretching direction but close up in the lateral direction, leading to poorer filter performance. Combinations of some of these properties point to significant potential as sandwich panel component core material and as seat cushioning material with improved comfort characteristics in aerospace, automotive applications, energy absorption.

At last, cords or ropes with high resistance, anchors, fastener, rivets, shock and sound absorber (Scarpa et al 2015), etc etc. are also possible. The use of auxetics is potentially so wide that 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.

3.3 CASES

"It is clear, then, that auxetic materials have the potential to make a key contribution to the development of new and improved structural and functional materials. They are an example of how lateral thinking, in more ways than one, can lead to new materials and applications"

(K.Evans and A.ALderson, 2000)

As follow many examples about the use of auxetic structures and materials will be presented.

3.3.2 Textile industry

The breakthrough development of a continuous process to produce auxetic materials in fibrous form has created the opportunity to apply the unique characteristics of negative Poisson's ratio structures in a wide range of applications. Generally there are two approaches to producing auxetic textiles: the first one includes the use of auxetic fibers to produce an auxetic textile structure; the second one entail the use of conventional fibres to produce a complex textile structure with auxetic properties (Rant et al., 2013). Advanced auxetic fibres include multi-filament yarns in which an auxetic filament is wrapped with one or more other yarns, perhaps high stiffness/strength, dyeable or conductive filaments, so that the benefits of the auxetic material are combined with other beneficial properties for smart technical textiles applications (Figure 2.B). This leads to the possibility of hierarchical composites displaying auxetic behaviour at more than one length scale. Current research on auxetic composites is concentrated on the use of non-auxetic constituents and so the benefits owed to the auxetic effect occur at a macrostructural level. Employing auxetic fibres as the reinforcement enable some benefit, such as impact energy and acoustic energy absorption, to be achieved at the microstructural level. In paragraph 2.3.1 it is discussed the possibility to create auxetic fibers, and a short description of the industrial processes was reported (Rant et al. 2013). In opposition to that, an entirely different way to overcome the disadvantages of producing auxetic materials, which includes a post-processing stage or processing by non-traditional methods, with each step providing additional costs, is to produce auxetic textiles with conventional yarns, as defined by Alderson (K. Alderson, 2007).

Miller et al. (2009) presented an auxetic multifilament construction consisting of a high-stiffness filament helically wrapped around a thicker, low-stiffness filament, 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 helically wrap around it. Such multifilament construction exhibits auxetic behaviour and can be fabricated on existing textile machinery, such as warp spinning. The starting wrap angle of the Helical Auxetic Yarn (HAY) has the greatest effect on auxetic behavior as regards both the magnitude and the strain range over which it appears. Other parameters which influence auxetic performance are the diameter ratio of wrap to core fibers and the fibers' inherent Poisson's ratio. Hook (2011) patented the woven porous fabric in warp arrangement comprising an array of pairs of adjacent helical auxetic yarns with mirror placement of helices. The weft fibers, interconnecting warp yarns may be auxetic or non- auxetic. Helical auxetic yarns that provide a net increase in the effective diameter of the composite yarn under strain, thereby exhibiting pore-opening effect, when incorporated into fabrics are suitable for different applications. One such case are fabrics that change colour and can be used for indicative or aesthetic purposes. These fabrics comprise a basic fabric of different colour than the overlaid porous material made from auxetic fibers. Such an arrangement enables colour change under an application of strain. This has potential in fashion and other fields where an accurate indication of the suitable tension is required. Pore-opening is also applicable in filtration, 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. Hook also presented a sample of these fibers made into a porous material that was then used to disperse blast energies from an explosion. The porous material, comprising a plurality of layers, enabled energy from the explosion to be efficiently dispersed through layers and voids between them to mitigate the blast effect. The third possible area of application includes release capabilities, such as garments containing anti-perspirant in the pores of the material, which is released upon stretching the garment and pore-opening. 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.

3.3.2.1 Report: Production of Auxetic Polymeric Monofilament

The creation of auxetic filaments is a department in research that is developing very fast, there is enough research and knowledge to produce auxetic filaments but the problem is about the production techniques (Adapted from "Auxetic material" EP 1 165 865 by K.L. Alderson and V.R.Simkins). Auxetic filaments are usually processed at a temperature in the vicinity of the melting temperature of the starting powder, requiring relatively slow throughput speeds. The process has been successfully scaled up to commercial scale extruders, but production volume currently remains significantly lower than commodity conventional monofilaments and films.

Equally, the production of auxetic 'double helix' yarns, comprising wrap and core components, and auxetic fabrics made from them, require very careful positioning and/or fixation of the wrap component, and close control over alignment of adjacent yarns, respectively, thus complicating the manufacturing processes compared to conventional wrapped yarns and fabrics. In the study made by Miller et al (2009), a new simple composite is proposed, using a novel helically wound yarn to achieve large negative Poisson's ratios, both by itself, in a textile, and in a fibrous composite (see Figure 4.B). The yarn is based on a double-helix geometry where a relatively stiffer fibre, referred to as a 'wrap', is helically wound around a more compliant and initially straight elastomeric cylinder, referred to as a 'core'. When this double-helix yarn (DHY) is stretched longitudinally, both the thin wrap and thick core are elongated. However, the much stiffer wrap laterally displaces the more compliant, and importantly, thicker core, causing an overall lateral expansion of the yarn's maximal width. At zero strain the compliant core is a helix with zero pitch, and the stiff wrap is a helix with an internal helical diameter equal to that of the outer diameter of the core. Under a large tensile strain the situation becomes fully reversed, i.e. the wrap has become a helix with zero pitch, and the core has become a helix with the internal diameter

equal to the external diameter of the wrap. In such DHYs, the core performs two functions: to cause large lateral deformation when strain is applied, and to act as a 'return spring' to recover its former position and reform the original helix in the wrap when the load is removed. DHY samples were manufactured using a modified yarn-wrapper in which a 'wrap' fibre is helically wound around a central 'core' commercial fibre, allowing control over the geometrical parameters. The filament posses a Poisson's ratio of -2.1. This work is of significant importance as it is the first time reported in the research literature that an auxetic composite has been produced from inherently auxetic fibres, and this has been achieved using standard manufacturing processes and commonly available materials.
This technology find different application and many industries are producing these auxetic fabrics, each one enhancing some characteristic. Xtegra™ team created an auxetic fabric who transmits longitudinal stress through the whole yarn, allowing greater energy to be absorbed than comparable fabrics [D]. Another interesting fabric, named Zetix ™, is studied and produced by Auxetix [E], and find a useful application in the protection from explosions and crashes (Figure 2.C).

3.3.3 Aerospace and automotive

In this field of applications a lot of research has been done and many applications can be found. Auxetics are applied because of their capacity to resist shocks and to absorb vibrations and energy.

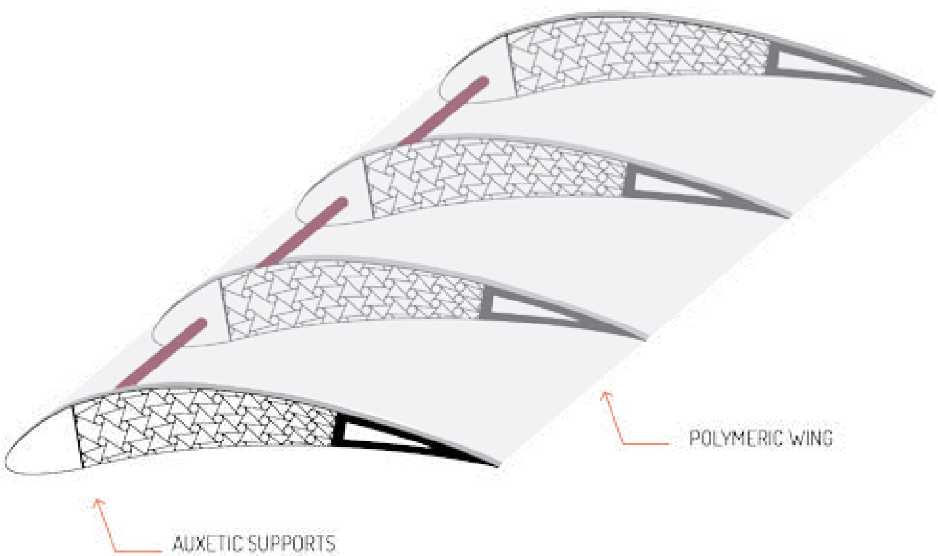
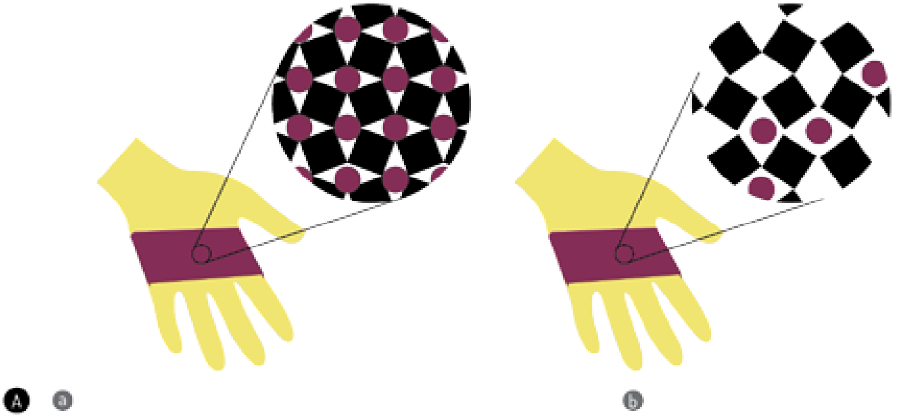


Figure 5 Auxetic wing for a race car [Bettini et al, 2009]



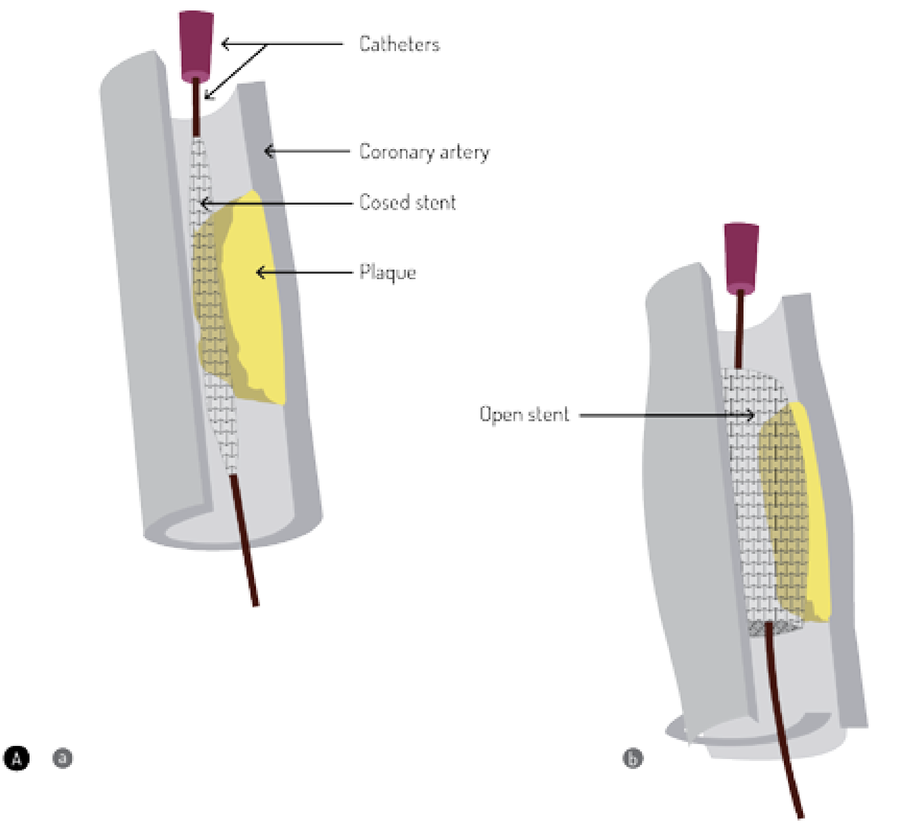


Figure 6 **A**. Smart dressing. **Aa** the units are closed and doesn't permits the drug to pass - **Ab** the drug can pass
B. Auxetic stent. **Ba** the stent is closed - **Bb** the stent is dilated

3.3.3.1 Report: Wing for Race Car

Bettini et al. in 2009 presented a work that tried to apply chiral geometries into the design of an airfoil with morphing characteristics since, 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 chiral model used inside provides compliance and allows continuous deformation of airfoil that can be modified to adapt to wind force. The chiral structures becomes useful because of its negative v: the negative Poisson's ration, estimated to be -0.9, increase the shear modulus and allows large deformations while materials remains in 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 deformation) and it is interesting that 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 short time and with high precision results. The core was customized joining only nodes onto the skin and following the curvature of the airfoil (see Figure 3.A).

3.3.3.2 Report: Sandwich Panel

In many applications, the sandwich structures are often subject to conflicting requirements such as the need for minimal weight versus the need for high stiffness. In 2013 Li Yang et al presented a structural application of auxetics (Figure 3.A). Starting from the consideration that two-dimensional cellular structures and stochastic foams - predominantly used for sandwich cores - often lack the level of properties that satisfy all requirements they propose to use three-dimensional cellular structures that possess many advantages in such applications. However, their practical use is largely hindered by the restrictions of manufacturing processes and the resulting limitation in the development of design theories. One such three-dimensional structure that shows potential was identified in structures that exhibits negative Poisson's ratio in one or more directions. The combination of high shear modulus and strength, high toughness, large bending compliance as well as tailorable elastic modulus and yield strength makes auxetic structures especially suitable for sandwich structure applications. In the research the hexagonal three dimensional re-entrant auxetic structure is investigated finding an appropriate design of the structure for sandwich panel applications. The focus of bending compliance and energy absorption abilities is carried out to compare two re-entrant auxetic sandwich structures to conventional sandwich structures with non-stochastic cellular cores, and the results demonstrate the feasibility of using auxetic structure for such applications. Based on an analytical modeling analysis the sandwich structure implemented with the three dimensional re-entrant auxetic core is designed. Auxetic samples are produced by electron beam melting (EBM) and selective laser sintering (SLS), and compared to other regular cellular sandwich structures through various experiments. It is show that sandwich structures with pre-designed auxetic cores can exhibit significantly improved mechanical properties such as bending compliance and energy absorption, which are critical to many structural applications. This work demonstrate an alternative of effectively designing 3D cellular structures, and also showed the potential of this type of auxetic structure in applications via careful design.

3.3.4 Protection and sports

Another field in which auxetics gain 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 material in this fields are auxetic foams because of their high indentation coefficients which were considered of an interest in the creation of auxetic helmets by Sanami et al. (2014). Thank to these indentation behaviour when there is an impact from one direction material flows in from other directions to compensate for the impact. Therefore, head injuries may be prevented or be less severe. Another interesting application of auxetics is made by the sport outfit industry Underarmour which patented a material used in training shoes sole called Micro G® that has optimized characteristics in weigh absorption (Figure 3.B). The material consist into a polymeric auxetic foams that have a strong indentation behaviour.

3.3.4.1 Report: Safety belt

Currently the use of 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 good energy absorption are the most important characteristics. However, this universal belt webbing has strong impact on the thorax when car crashes happens because it has not capacities of absorbing the forces of the impact. The web contract 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 implementation 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.

3.3.5 Biomedical

Prosthetic materials, surgical implants, suture ligaments, muscle ligaments, anchors and a dilator to open up blood vessels during heart surgery are all possible in auxetic configuration (Fabrizio S. et al, 2008). The research on auxetics done in biomedical field is the most predominant. The utilization of auxetic structures to produce prosthetics is increasing - three major auxetic bio prostheses are:

artificial intervertebral disks: sandwich elliptical plates with an auxetic core have been recently proposed as artificial intervertebral disks. The core, made of re-entrant prismatic honeycomb cells, allows an auxetic effect through the thickness of the plates, providing the lateral compression of the artificial disk under compressive loading ;
annuloplasty prostheses (heart surgery): auxetic effects can be also achieved in tubular truss-like structures having a cellular topology similar the ones of honeycombs and chiral assemblies. Recently, European patents (G. Burriesci and G. Bergamasco, 2005) have proposed auxetic solutions for annuloplasty prostheses, i.e., prostheses that provide plastic repair of a cardiac valve. The motivation behind these designs is the lack or crimping in an auxetic tube, leading to the development of high-flexibility stems for cardiac applications ;
cushion pads and knee prosthetics: open-cell polyurethane foams are commonly used to manufacture cushion pads for seats. However, a positive Poisson's ratio open cell foam features performs an uneven distribution of normal stresses when indented, with a localization of the peak stresses around the contact area. By contrast, an auxetic (NPR) foam wraps around the indenter, providing a more uniform

stress distribution with peak stresses lowered by an average factor of three. These characteristics have made NPR foams a good choice as cushion pads for people with disabilities or medical conditions. In addition, the same equipartition of mechanical stresses and mechanical resilience have recommended them for use in knee prosthetics.

3.3.5.1 Report 5: Auxetic Stent

In 2013 Bhullar et al. presented a work about auxetic stent which investigated how auxetic structures can be useful in medical environment and how to resolve artery blockages with the aid of auxetic stents. It is proposed a tool made up with biocompatible polymers shaped into an auxetic tube which can be shrinked once introduced into the obstructed veins and dilate once arrived at the needed position so that the vain increase its range. Even though the technique to introduce stents into the obstructed veins is consolidates, in this research the proposal for the design of an auxetic stent have multiple improving factors:
the auxetic tube has reduced diameter when inserted into the veins
its has enhanced capacity to extend and inflate
it can be easily expanded once inside the blood vessel
the auxetic tube is more resistant to pressure and and twisting moment
it can be produced with nanofibers for drug delivery.
Auxetic stents are not already produced but they are recognized to be positively useful materials and techniques to develop their production are being tested.

3.3.5.2 Report 6: Compression bandage

Compression bandages are used to facilitate healing. For example, a compression bandage rolled around a patient's leg gives a pressure gradient that can facilitate the healing of venous ulcers. Knitted and woven stretchable fabrics are used for this purpose in addition to wounds healing. However, with known fabrics the pressure applied in use can cause discomfort to the patient at pressure points, e.g. around bony prominences, and may give rise to chafing or injury. To avoid this it may be necessary to introduce padding beneath the bandage. Softer bandage fabrics are known such as non-woven or felted fabrics, but these do not have sufficient strength in themselves to permit application of satisfactory levels of compression. Current bandaging methods used in the treatment of venous leg ulcers use two or more, possibly up to four, individual bandages applied in layers to build up to the correct sub-layer pressures. Usually, the outermost applied layer is a cohesive bandage which secures the sublayers and helps to mould the dressing to the shape of the limb. In the research by Leeming and Woosey (2012) the creation of a bandage with an auxetic layer inside is shown to resolve this problems. By using an auxetic spacer fabric it was possible to attain high levels of compression with a soft, comfortable padding structure. The present invention provides a multi-layered bandage comprising:

an inner wound facing layer made in viscose or cotton;

an intermediate layer including a spacer auxetic fabric having opposite face structures united and held in spaced disposition by threads.

The inner wound facing layer preferably incorporates absorbent viscose fibres, and may incorporate bacteriostatic yarns including silver-based bactericide, and/or polysaccharide fibres, and/

or a proportion of elastic yarns or fibres to provide a degree of compression. The intermediate layer incorporates auxetic materials to permit maintenance of a steady consistent pressure. The inner, intermediate, and outer layers may be made by a knitting operation, particularly warp knitting; or alternatively it can be weft knitted to form a tubular spacer fabric, or produced on weaving machinery to produce a woven spacer fabric.

An implementation of the over proposed bandage can be done following the suggestions given by Alderson and Alderson (2006-2007):
"A potential technical textile application is the 'smart bandage' concept which releases wound healing agent in a controlled manner in response to swelling of an infected wound. The concept describes a bandage fabric consisting of auxetic fibres containing a wound healing drug within the fibre micropores. Wound swelling due to infection stretches the fibres in the bandage and therefore causes the micropores to open up (due to the auxetic effect) to release the wound healing agent onto the wound. Once the wound healing agent has taken effect, the wound swelling decreases, causing the fibres and fibre micropores to recover their original dimensions and thus stop the controlled release of the active agent."

3.3.6 Sensors and actuators

Another interesting area of application is found in the creation of piezoelectric sensors and actuators. Auxetic metals could be used as electrodes sandwiching a piezoelectric polymer, or piezoelectric ceramic rods could be embedded within an auxetic polymer matrix.

These are expected to increase piezoelectric device sensitivity by at least a factor of two, and possibly by ten or a hundred times. The development of auxetic materials for micro and nano-mechanical and electromechanical devices is also being investigated.

3.3.7 Computational design and origamis

Auxetic structures find application also in architecture and design. One of the most diffused way to experience the spatial capacities of auxetic structures consist in the creation of origamis: as most people envision origami as folding swans and cranes, it's only by the last decades that architects, designer and engineers started to explore their technological potential, define performative origami patterns. Interesting is the fact that many three dimensional origami pattern have negative Poisson's ratio behaviours, leading to its application in a wider range of occasion.

The possibility to study this kind of auxetic structures became easier in last years thanks to the development of parametric design softwares that permit to define mathematically a wide range of origami structures. This softwares demonstrated to be of a strong importance in approaching origami to the design world since they can output complex three dimensional origami structure avoiding complex calculation. A wide variety of auxetic folding structures (origami-like) can be found in the video blog of Daniel Piker (https://vimeo.com/user798992) an architectural student based in London which digatally speculates on the thematic.

Practical is instead the work by Amir Shahrokhi (retrieved from http://amirshahrokhi.christopherconnock.com/2011/12/11/auxetic-origami-surface/), who developed a building responsive surface inspired by the behaviors of the Oxalis plant. Through a series of physical and digital models, an auxetic-origami form was developed. A servo-driven mechanism was designed to control the 'opening' and 'closing' of these modules in clusters of four. A set of Arduino controllers connects to the servos and a series of photo-sensors. The light readings from the sensors are processed by a Firefly/Grasshopper interface which interprets the data and sends corresponding instructions to the servos. The result is a dynamic modular surface that is responsive to local and global changes in the environment that utilize a simple idea put into practice thank to a series of cutting edge technologies.

Another application of a folding auxetic surfaces is OriMetric, designed by Mads Jeppe Hansen (retrieved from http://www.trex-lab.com/who/) (Figure 3.C). It consist into a rubber based material that follows an intelligent pattern which allows itself to inherit multiple functional qualities as shock absorption and expand and collapse while always remembering its original shape. Moreover it has some characteristic of sound-absorbing. OriMetric is made in different patterns, some of them are more "intelligent" (ability to shock absorb, expand or pack large amounts of material into a small package), others have pure decorative purposes.

3.4 TOWARDS ARCHITECTURAL APPLICATIONS

This chapter was a practical gaze in the auxetic words. But what does the future hold for auxetics? Despite the very significant developments only the surface of this field has been scratched. The successful synthesis and development of molecular and multi-functional auxetics represent key opportunities for the future. In addition to leading to materials with extreme properties such as high modulus and strength, these advanced structures will have potential in sensor, drug-release, interactive walls and performative fabrics. Even if as far as now the application of auxetics is related to small-scale materials in high-tech fields, it is interesting to study bigger scale applications for structural usages. Liu and Hu wrote (2010) that for future work it is necessary the collaboration among researchers coming from different areas such as textile, mechanics, engineer, architecture, chemistry and biological.

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PART II

PR

OJECT

INTRODUCTION TO PART II

The objective of Part II-Project is to understand how auxetics can perform in architecture as bending-active structures towards the generation of lightweight synclastic shells. The generation of the form in this case might be directly driven and informed by the application of an out-of-plane bending moment and the physical behaviour of the auxetic material to which it responds. Synclastic surfaces in architecture are difficult to be achieved using traditional construction methods since the reach of the synclastic curvature is nowadays limited to air-supported structures.

Considering the necessity to preview the dynamic behaviour of bending-active structures, the research implements a computational design methodology to simulate the form-finding of synclastic auxetic gridshells. Additive Manufacturing is used in different phases to prototype test models as well as to empirically investigate different material configurations, to tune and enhance the response of an auxetic pattern. Sub-goals of the research are:

- implementing a convenient computational methodology to design and simulate auxetic bending behaviour in a controlled way;
- determining optimal auxetic patterns for their structural implementation in architecture;
- understanding the main parameters which affect the configuration of auxetic structures and their spatial articulation;
- define a technological ;
- give applicational visions of the defined technology.

PART II

ARCHITECTURAL SHELLS

CHAPTER IV

4.0 ABSTRACT

This chapter is an introduction to the Part II, which is the project part. It will be first clarified the architectural context in which we are going to operate by first explaining what is an architectural shell (many different typologies will be listed depending on the curvature and the thickness will be given) and secondly by looking for ways to create using the potentialities of auxetic structures.

A

Figure 1

A. *Multihalle By Frei Otto. Photography @ Atelier Frei Otto Warmbronn*
B. *Roofing for main sports facilities in the Munich Olympic Park for the 1972 Summer Olympics, Munich, Germany. Both images @ Atelier Frei Otto Warmbronn.*

8

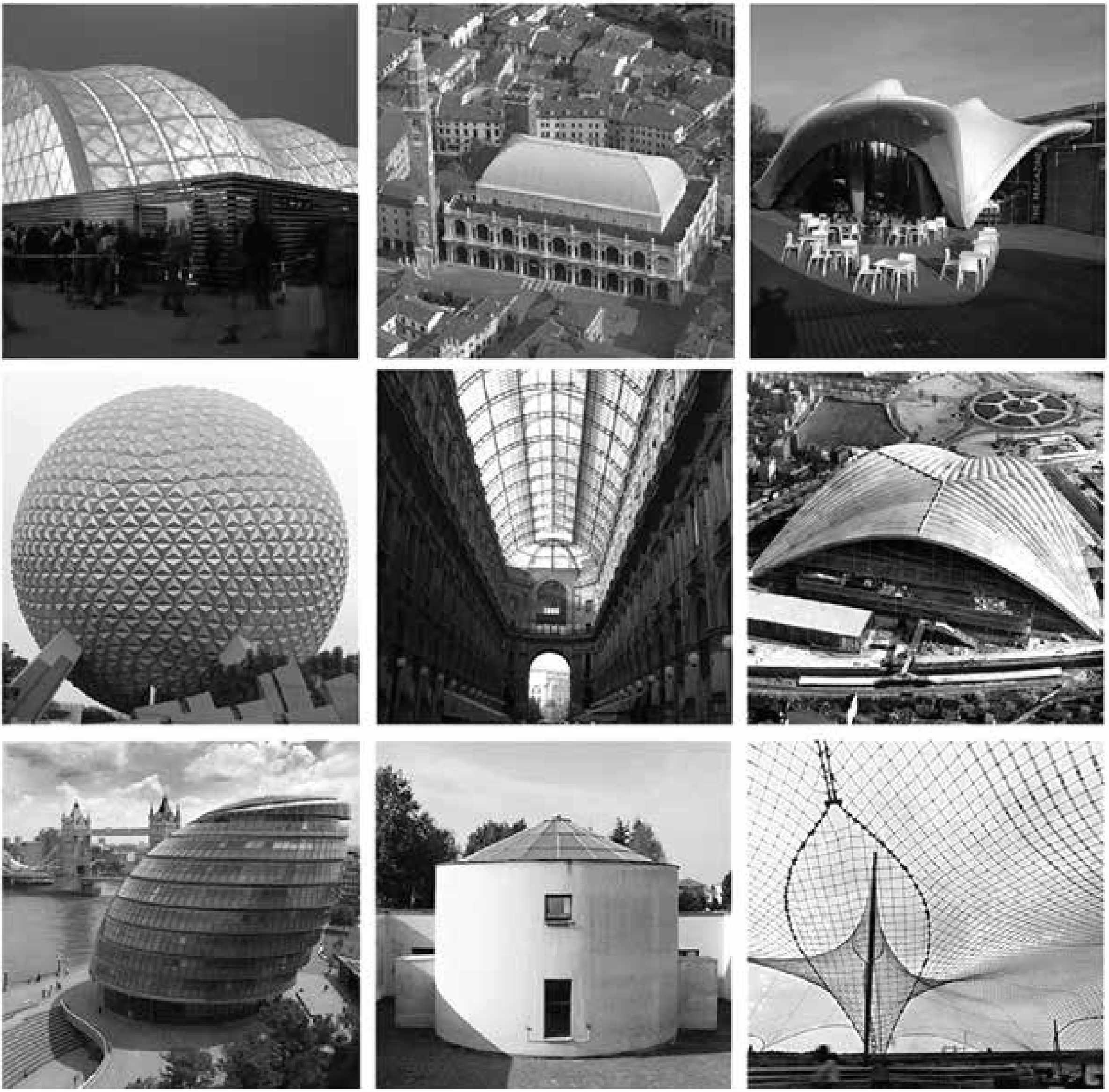
B

A

C

Figure 2

A. Music Pavilion at the Federal Garden Exibition, 1955, Kassel, Germany. Pic by Atelier Frei Otto Warmbronn
B. Multihalle By Frei Otto. Photography @ Atelier Frei Otto Warmbronn. Pic by Atelier Frei Otto Warmbronn.
C. Serpentine Gallery Extension, Zaha Hadid, London, 2013. Image of the author.



A B C

Figure 3

A. Synclastic curved buildings. From above: Shigeru Bahn, Japan Pavilion, Hannover, 2000 - Epcot Dome, DIsney World - Fosters and Partners, City Hall, London, 2002.
B. Developable curved buildings. From above: Andrea Palladio, Basilica, Vicenza, 1614 - Giuseppe Mengoni, Galleria Vittorio EManuele II, Milano, 1877 - Aldo Rossi, Scuola, Fagnana Olona, 1976.
C. Anticlastic curved buildings. From Above: Zaha Hadid, Expansion of the Serpentine Gallery, London, 2013 - Emmanuel Pouvreau, CNIT, Paris, 1958 - Frei Otto, Expo Pavilion, Montreal, 1967.

4.1 ARCHITECTURAL SHELLS

"*Over the past years shell structures have been taking up a more prominent role in modern architecture. The range of use of shells is broad and it does not limit itself to civil engineering. Mechanical engineering, aerospace engineering are all fields of application. Even though man made shell structures have been in existence for many years, one can think of the many domes built during the Renaissance or even during the 'Roman era', we can see a revival of interest in shell structures. One could wonder what it is that makes shell structures appealing. Cost factors, materials availability and labour supply all play a part. The generally high strength-to-weight ratio of the shell form, combined with its inherent stiffness, has formed the basis of modern applications of shell structures.*"

(Ramos 2013)

Principally, building envelopes as facades or roofs are the separating and filtering layers between outside and inside, between wild and adapted spaces occupied by people (Cremers 2011). In historical terms, the primary reason for creating this effective barrier between interior and exterior was the desire for protection against a hostile outside world and adverse weather conditions. Various other requirements and aspects have been added to these protective functions: light transmission, an adequate air exchange rate, a visual relationship with the surroundings, aesthetic and meaningful appearance etc. Accurate knowledge of all these targets is crucial to the success of the design as they have a direct influence on the construction. New materials and technologies play an essential role in creating compelling structures capable to amaze the sight while fulfilling the basilar needs of protection and separation from the world. In this context, the possibility to bring the structure to the essence - leaving huge quantity of vacuums - change the vision that humans have of the shells. The process of structural simplification started with the structural gothic research has never stopped and still emerge in the interest that we have in light essential structures. Shells became nowadays an interactive layers that not anymore has the mere function to separate two spaces but, on the contrary, that look for new relationship among humans and matter.

One could wonder what it is that makes shell structures appealing. Cost factors, materials availability and labour supply all play a part (Melaragno 1991). The generally high strength-to-weight ratio of the shell form, combined with its inherent stiffness, has formed the basis of modern applications of shell structures (Melaragno 1991).

In the last few decades rapid developments in material production types and surface refinement of membrane materials have been constant stimuli for innovation (Ramos 2013). The development of high performance membrane and foil materials on the basis of fluoropolymers, e.g. translucent membrane material such as PTFE- (poly tetrafluoroethylene) coated glass fibres or transparent foils made of a copolymer of ethylene and tetrafluoroethylene (ETFE) were milestones in the search for appropriate materials for the building envelope (Cremers 2010).

"Shells play a special role for engineers. Their shape directly derives from their flow of forces, and defines their load-bearing behaviour and lightness, saving material by creating local employment, their social aspect. This is especially true for thin concrete shells with

their characteristic curvatures: single curvature (cylindrical and conical), synclastic (dome-like), anticlastic (saddle-like) or free (experimental). If well formed, there are no bending but membrane forces only (axial compression and tension) in a shell, permitting its thickness to be around 80mm for reinforced or prestressed concrete, even down to 12mm for fibre reinforced concrete. Though these concrete shells initially do not leave much space for an architect (or even for the fantasy of an engineer), it is fortunately not unusual that the two collaborate fruitfully or that an engineer himself has the courage and imagination to go beyond strict logic.".

(Adriaenssens et al. 2014)

The main difference between shells compared to plates and beams is that shells possess surface and curvature providing both strength and stiffness. The beam resists any applied transverse loading by bending, unlike the arch which resists such a loading primarily by internal thrust action. The plate, which can be idealized as a flat surface, has to bend to carry applied transverse loading. Shells, which can be idealized as curved surfaces, are able to resist transverse loading through the action of internal forces in the tangential plane of the shell's mid-surface, i.e. in-plane actions. From this, it is evident that the property that makes both shells and arches capable of resisting external transverse loading by extensional action is curvature (Zingoni 1997). Thin shells are designed with the purpose to resist loads through in-plane forces, i.e. tensile and compressive ones. Usually a mixture of both membrane forces and flexural action (i.e. bending and shear forces) occurs - good design consists of minimizing the flexural actions.

4.1.1 Classification of Architectural Shells

Architectural shell structures can be classified following different criteria.

A first classification can be done distinguishing among the construction materials - reinforced concrete, steel, wood, tensiles fabrics are only few of them.

A second classification can be done measuring the thickness of the shell. Most concrete shells have thickness from 4 cm to 15 cm. Many factors are involved in establishing their thickness. Building codes, which vary from one country to another, have major influence on minimum legal ones. In mexico, for instance, Felix Candela was able to cast concrete thin shells that were less than one inch thick, because of the more permissive code of that country (Melaragno 1991). When the thickness of a shell is so thin that is negligible compared to the radius of curvature we can speak of membranes (Zingoni 1997) which are usually erected using tensile structures and fabrics. When there is the need to create a light shell so to assemble and disassemble it in short times, applications of textile materials serve the purpose to keep off the sun, wind, rain and snow while offering the advantage of enormous span widths and a great variety of shapes. Besides glass, a variety of other translucent and transparent materials are just as highly attractive to architects: plastics, perforated metal plate and meshing, but maybe most of all membrane materials which can also withstand structural loads. The variety of projects that offer vastly different type and scale shows the enormous potential of these high-tech, high performance building materials which in its primordial form are among the oldest of mankind. The predecessor of modern polymer membranes, i.e. animal skins, were used to construct the very first type of building

envelopes, namely tents.
Lastly, the Gaussian curvature can be used to classify the shape of the shell surface. Gaussian curvature is explained in the following paragraph.

4.2.2 Gaussian Curvature

In differential geometry, the Gaussian curvature (or Gauss curvature) of a surface at a point is the product of the principal curvatures, 1 and 2, at the given point. It is an intrinsic measure of curvature, depending only on distances that are measured on the surface, not on the way it is isometrically embedded in any space. It is named after Carl Friedrich Gauss, and is the content of his Theorema egregium (Kühnel 2006). Depending on the value of the Gaussian curvature, surfaces can be divided into three categories: synclastic surfaces (concave or convex curves) have positive Gaussian curvature, anticlastic surfaces have negative Gaussian curvature and developable surfaces are characterized by zero Gaussian curvature. A developable surface is a surface that can be flattened onto a plane without distortion - two examples of such surfaces are cone and the cylinder.

In architecture this kind of curvatures are considered differently depending on historical period and consequent technological possibilities. Developable surfaces are the easiest to be realized and in history of architecture are common since old empires. Arches and barrel vaults are an example. Anticlastic curvatures (saddle-shaped) are a mere modern discovery and the most prominent figure that brought these curvatures into the architectural debate

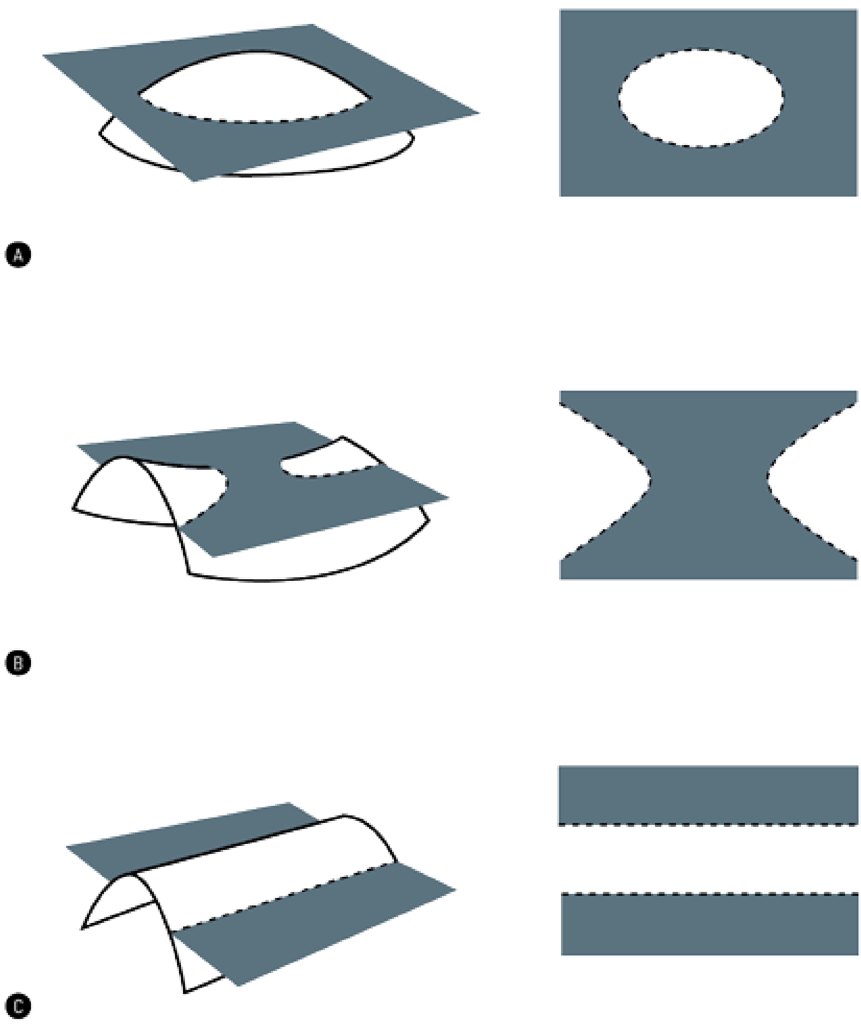


Figure 4

Curvature typologies
A Synclastic surface and section
B Anticlastic surface and section
C Developable surface and section

is for sure Frei Otto (1925-2015). His research was mainly based on form active structures which are structures like domes, cable nets, tensioned fabrics, etc that are sometimes flexible, and either shaped or of material such that under load no bending stress exists, only compression and tension stresses (Figure 1, 2). Rigid domes and arches will have compressive stresses, while fabrics and cable nets will have only tensile forces (flexible cables and fabrics have no ability to resist compressive loading). Synclastic curvatures, usually utilized in spherical vaults like pantheon in rome, are mostly identifiable in the sphere and are impossible to be performed with form-active lightweight structures (i.e. gridshells, tensile structures, etc).

The capacity of auxetic structures to generate synclastic curvatures suggests a development perspective as a bending-active structure which defines complex curved geometries from the erection processes of planar elements that are elastically deformed. This creates advantages in the transportation and assembly processes. The curved structures are influenced by residual stresses in their load bearing behaviour and structural capacities (Lienhard 2014). Moreover, working with sufficiently elastic structures, it is therefore possible to envision a dynamic process of shape adaptation through the implementation of kinetic structures

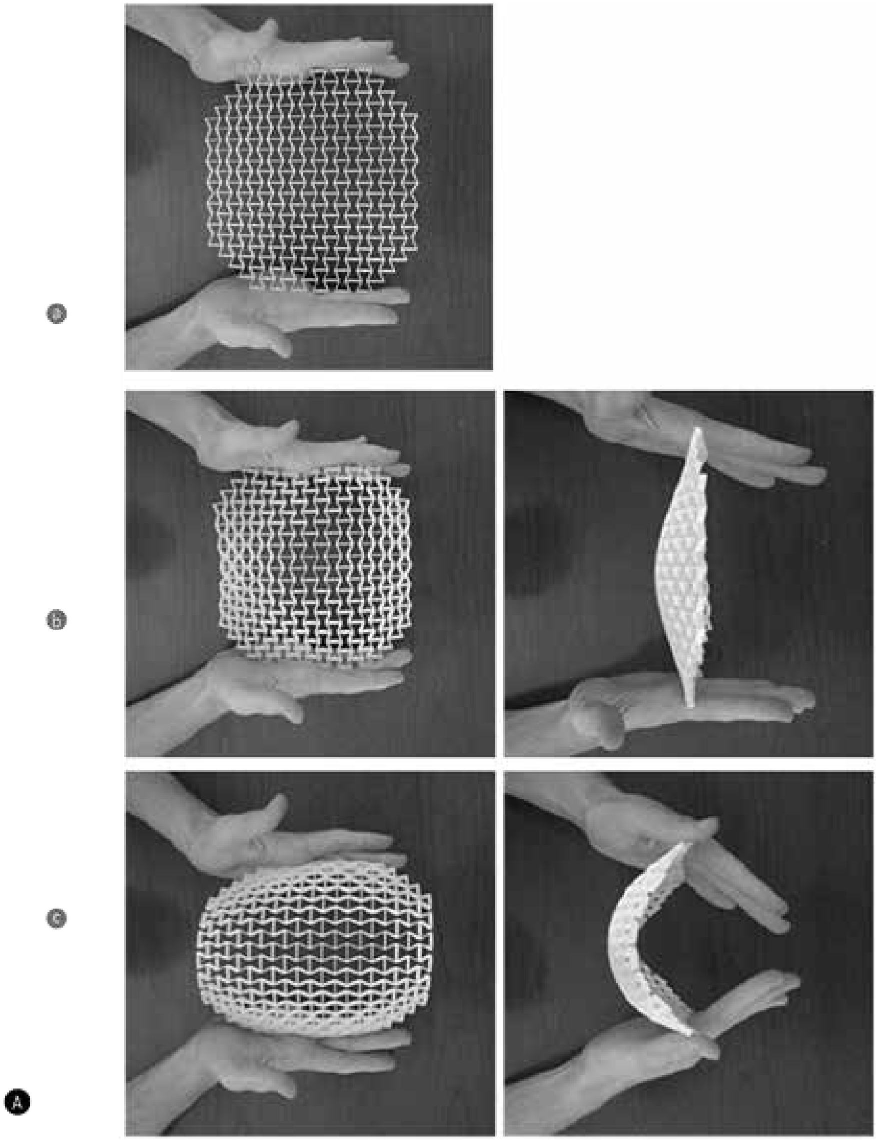


Figure 5

A. Bending tests on PLA 3D printed models of reentrant hexagonal honeycombs to show its anisotropic behaviour. A.a Unstressed model - A.b Stressed model on one axis - A.c Stressed model on the other axis
Next pages. Bending tests on different auxetic patterns to show their curvature outcome. For each column, the upper figure shows the relaxed state, whereas the others show compressed states from different point of views. All the samples perform auxetic behaviour in the in-plane stretching, while only the Re-entrant honeycombs and mesostructured patterns show auxetic response also in the out-of-plane bending. - B Mesostructured Metamaterial by Andres Bastian - C Hexagonal Stars - D Triangular Based Chiral Structure - E Lozenge Based Chiral Structure - F Sinusoidal Lattice.

5.1.3. Out-of-plane bending behaviour

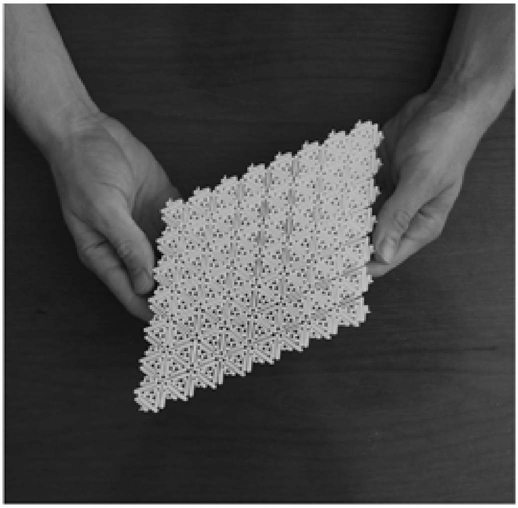
We can now state that a shell is a curved surface which has embedded in itself, depending on the curvature and technology, the capacity to resist to forces of pressure and bending.

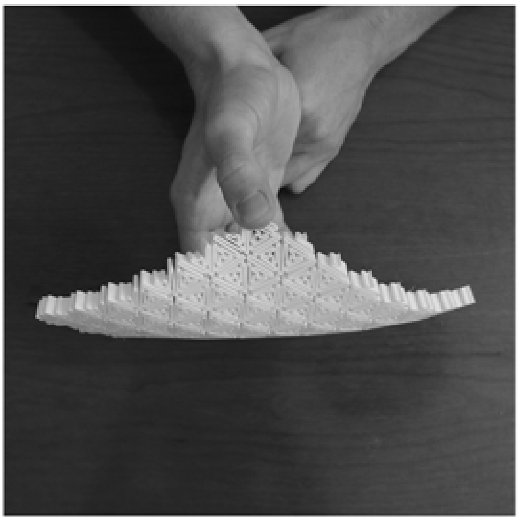
"One of the goals of the designer is to avoid wrinkles in the structure, because wrinkles can't guarantee an effective behavior of the system as a whole and they can generate unpredictable deformation under loading".

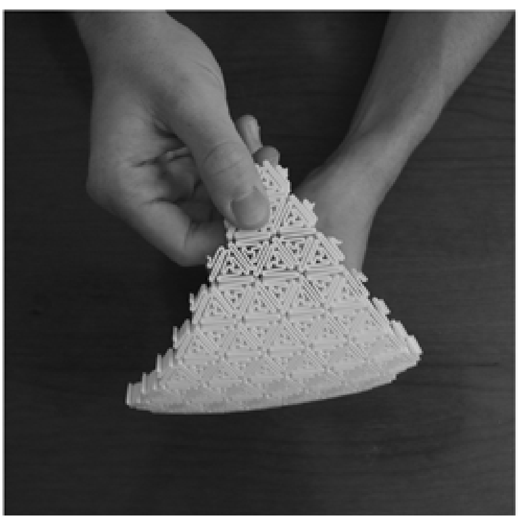
(Maffei, Luchsinger, Zanelli 2011)

This statement stress the importance to have smooth surfaces when the bending/inflating of a structure happens - requirement that can be satisfied by the capacity of auxetic structure to deform following a synclastic curvature. If the structure is flexible enough it can bent without creating the "wrinkles" that would create the weaknesses. In this therms, auxetic foldable structure are suitable for creating a dome architectural shell.

It was observed that many papers indagated on the out-of-plane bending capacities of auxetics to create shell structures (Steffen 2012, Tachi 2013, Tara 2013). From these it was possible to notice that not all the structures exhibiting negative Poisson's ratio in in-plane actions worked as well in the out-of-plane bending: sometimes, apparently auxetic structures, created anticlastic curvatures (Tara 2013). This pattern are non-auxetic if referencing to all the three dimensions (x,y,z). From Tara (2013): "[...]pattern could be observed to have a negative Poisson's ratio in two different ways: extension and bending" (Tara 2013). As far as now, we didn't found any







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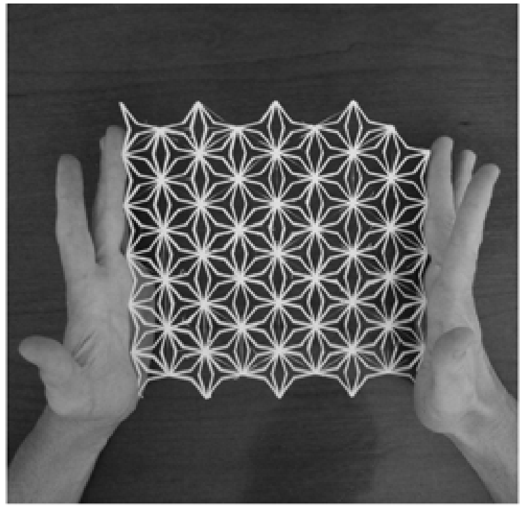
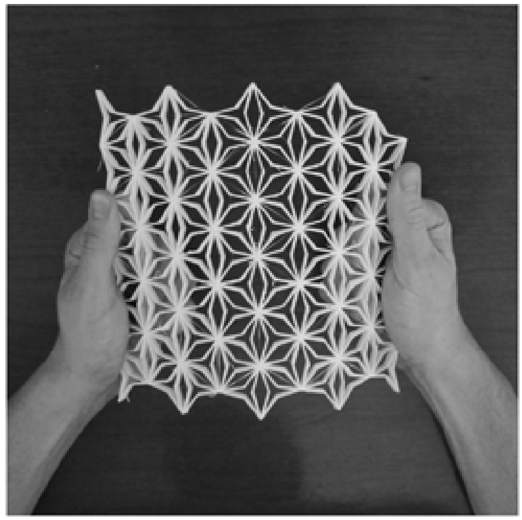
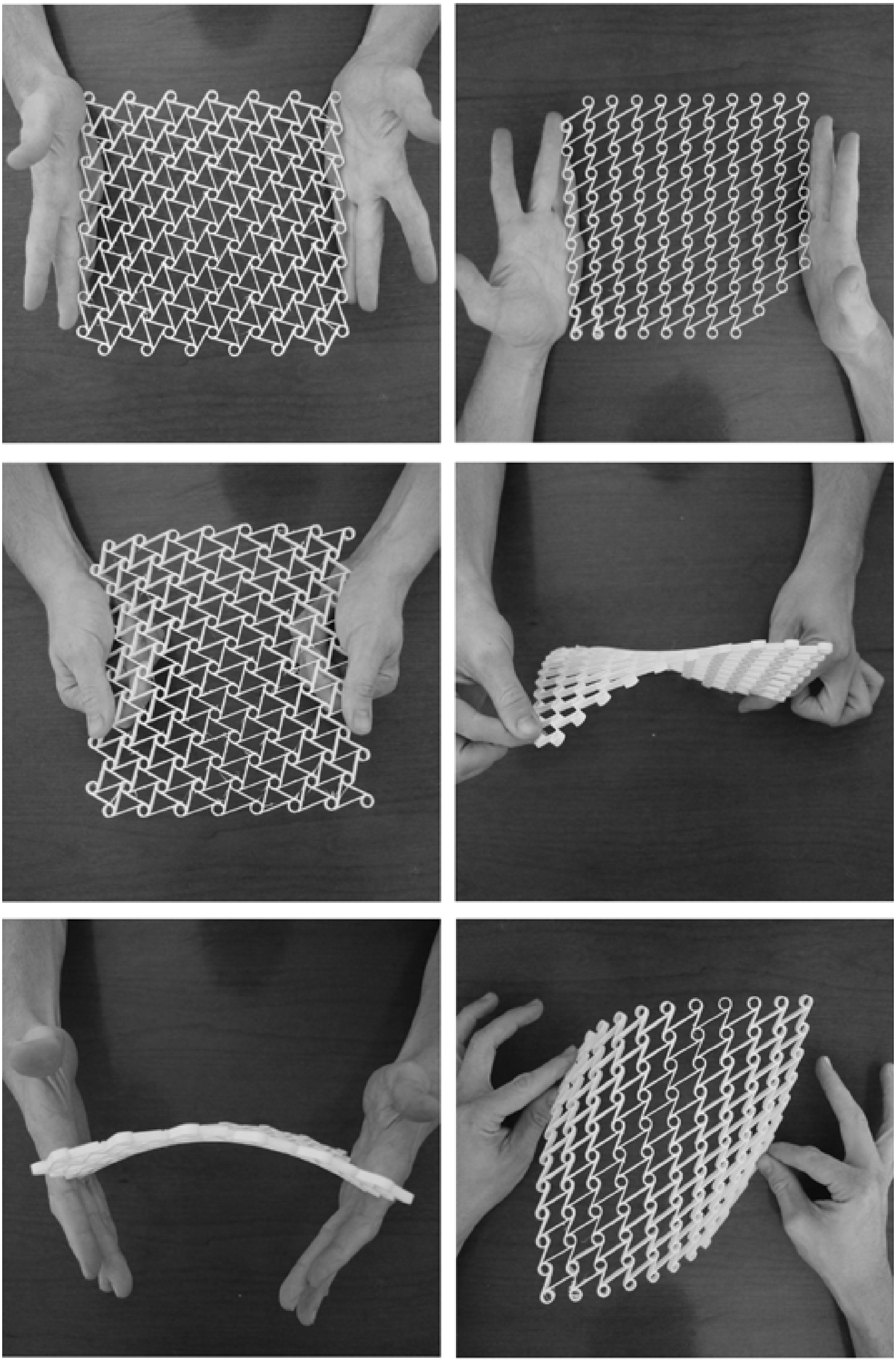


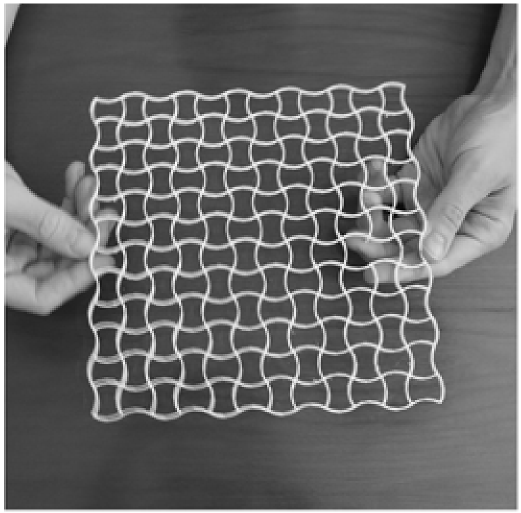


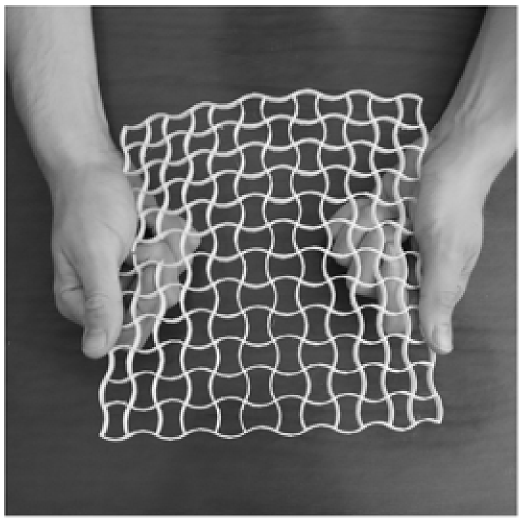
C



B

F





D

mathematical rules to define if a pattern works auxetic in the out of plane bending.

4.2 PARAMETRIC DESIGN OF AUXETIC PATTERNS

A variety of auxetic patterns exist and each of them is characterized by a set of parameters that influence their behaviour. In literature, auxetic structures are classified into several macro groups: re-entrant structures, chiral structures, rotating rigid units, angle-ply laminates, molecular auxetic structures, polymer models, origami-like structures and others (Mir, 2014). Scientific literature already tackled the topic of 3D origami-like auxetics and their potential applications in lightweight architectural structures (Schenk, 2010). Our research, on the other hand, focuses on three-dimensional auxetics whose architectural potentialities have not been yet fully explored. In contrast to origami-like auxetics, these types of auxetic patterns achieve synclastic curvature through the bending of structural elements rather than through the rotation of faces along edges.

In the initial phase of research, different basic patterns have been explored and developed parametrically with the use of Grasshopper for Rhinoceros as lattice samples divided into a defined grid of 20 by 20 cells. After the digital models were designed, prototypes were materialized with a double extruder FDM printer using a standard PLA filament allowing for an intuitive understanding of the bending properties of the different patterns (Figure 5B).

The comparative tests highlighted the 2D re-entrant honeycombs as a compelling design option for further research and development given the enhanced synclastic curvature they are able to generate, their simple geometric configuration (Malgorzata, 2009) and ease of customization. This pattern is composed of indented elastic rods which are called Inclined Rods and inelastic rods which are called Parallel Rods (Figure 6A).

This bi-directional pattern reaches a different configuration according to the axial direction of bending forces (Fig. 6). Research and experiments on the creation of isotropic auxetic lattices can be found in literature (Lorato, 2010). In our research differential responses according to the bending direction is considered as an exploitable feature to generate less predictable architectural results. Empirical tests proved that forces applied on the indented sides produced synclastic curvatures in opposition with forces applied in the parallel direction.

4.3 AUXETIC BEHAVIOUR IN TWO DIMENSIONAL STRUCTURES

The simulation of the bending behaviour of an auxetic pattern is fundamental in order to develop its architectural application and to preview configurations under certain loading conditions. Considering the advantage of working within a common modelling environment, simulations were performed with the Particle Springs Engine (PS) Kangaroo for Grasshopper. This workflow guarantees the easy and effective testing of different pattern solutions by defining anchor points and forces applied to the structure, without the need of exporting geometries, a factor of great importance in evaluating many different patterns.

An initial test was performed on a default 2D re-entrant honeycomb structure with no extrusion on the z axis (Figure 6C) in order to understand the auxetic expansion/compression in relation to the variation of the parameter t (Figure 6B), which defines the angles characterizing the hexagons. Through the variation of this parameter within a range from 0 to 1, it is possible to generate different kinds of hexagons: values from 0 to 0.5 define convex hexagons, while values ranging from >0.5 to 1 produce reentrant hexagons. The simulation shows how the variation of this parameter influences the Poisson ratio and consequently the auxetic properties of the structure. In figure 6.C are shown the results of this test, with Figure 6Ca presenting the layout of the structure in a relaxed condition,

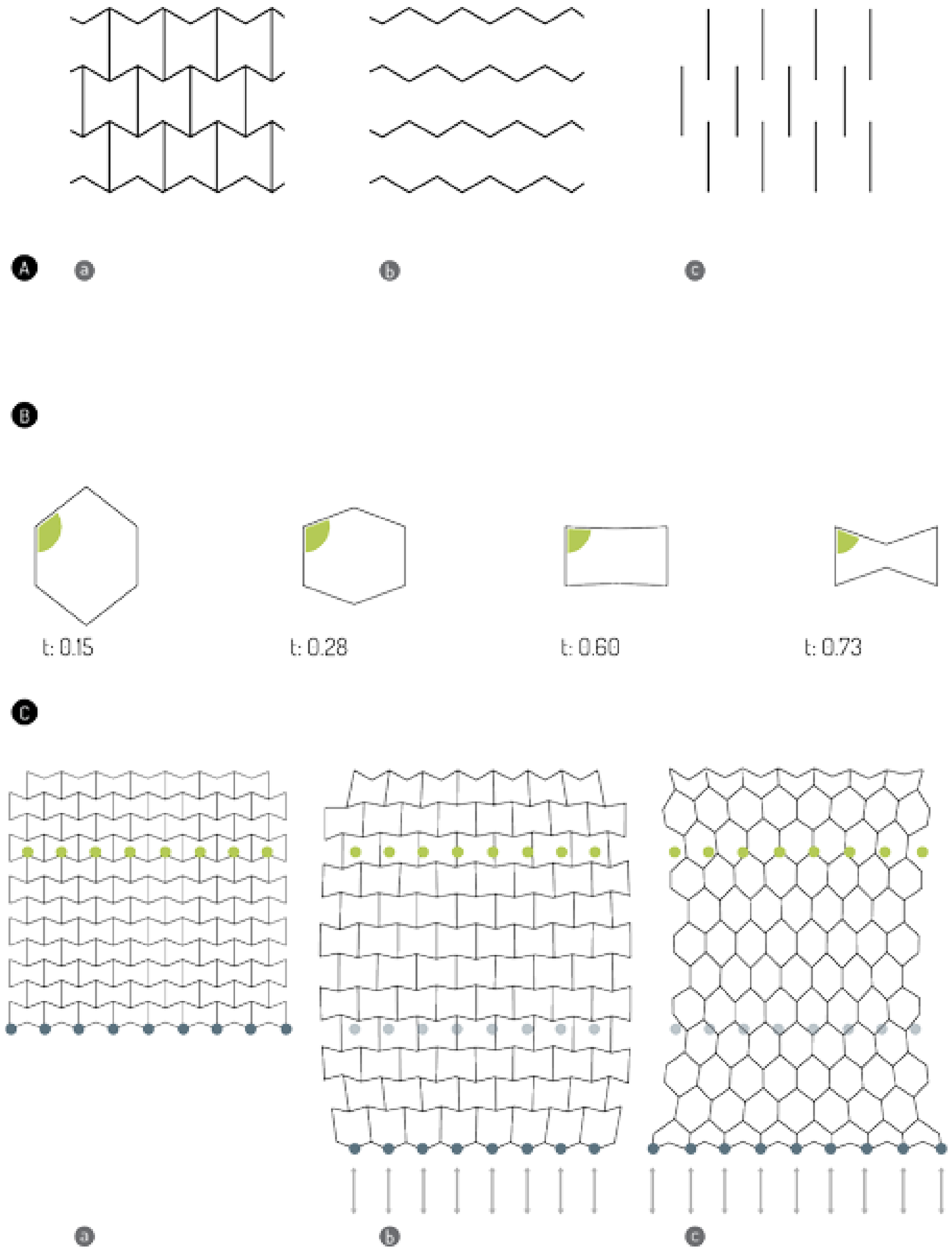


Figure 6

A. Differentiation of the rods - Aa complete pattern - Ab inclined rods - AC parallel rods.
B. Variation of the hexagon depending on the parameter t
C. Ca relaxed state - Cb stretched state with negative parameter t - Cc stretched state with positive parameter t.

Figure 6Cb shows the expanding behaviour of the structure in an auxetic configuration (t = 0.73), whereas Figure 6Cc reveals how the structure is stretched when turned into its non-auxetic version (t = 0.28) and the overall area decreases.

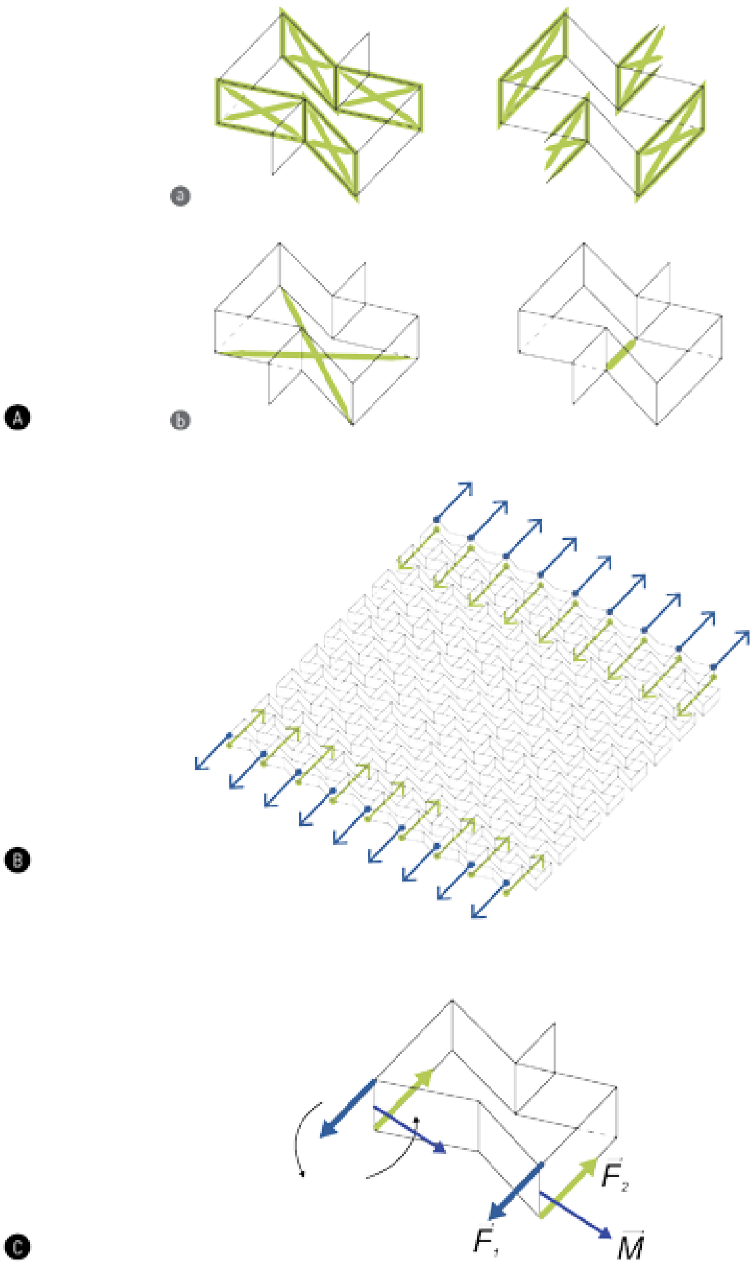


Figure 7

A. Forces set to stiff the model. Aa forces on parallel and inclined rods - Ab forces acting on the base of the model
B. Application of the forces to the edges of the model to create the bending moment
C. Explanation of the forces to create the bending moment in detail

4.4 AUXETIC BEHAVIOUR IN THREE DIMENSIONAL STRUCTURES

With this second phase of tests it will be experimented how the extrusion in Z axis can change the behaviour of the structure in the out-of-plane bending.

Firstly, Figure 7 helps in understanding how the simulations were set in the three dimensional model. The hexagonal honeycomb pattern - extruded in the z-direction - is tested with Kangaroo Physics Engine, where physical forces are assigned to simulate the actual physical response of the pattern. A first set of forces named as springs is used to keep both inclined and parallel rods stiff (Figure 7Aa), a second set (Figure 7Ab) of the same topology of forces is applied to guarantee the overall structure in tension. A third set of forces (Figure 7B) is applied on two external edges of the structure to induce a moment of forces by the combination of linear vectors with opposite direction acting with equal distance from a pivot point (Figure 7C).

4.4.1 Stiffness Bending Tests

This first part of the paragrapfh refers to analysis shown in pages 162-163
STIFFNES BENDING TESTS - INNER SPRINGS VARIATIONS

Within internal and external loading configurations, a realistic bending behaviour is obtained by assigning the maximum stiffness parameters to all of the internal springs, thus accurately reproducing the behaviour recorded in the physical prototypes. In "BENDING ANALYSIS - INNER SPRINGS VARIATIONS" are shown the results of the simulation at the variation of the stiffness parameters of the rods. It can be seen that only in tests 5 and 6 the curvature could happen, since in the previous ones the structure had not enough firmness to bear its own self weight.

This second part of the paragrapfh refers to analysis shown in pages 164, 165 and 167
STIFFNES BENDING TESTS - CONSTANT EXTRUSION VARIATIONS

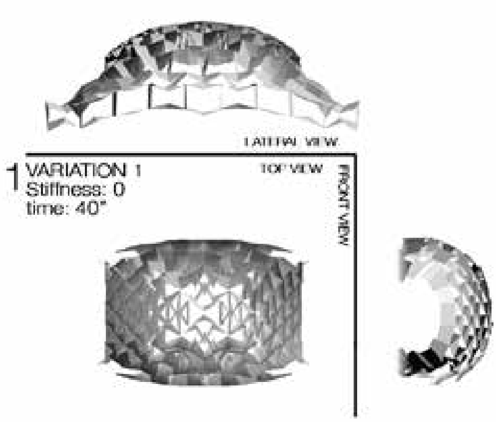
Another series of tests is carried out in order to understand how the extrusion factor could influence the bending output, and the general stiffness of the structure. With an extrusion of 1 unit the structure is not able to define a stable shell: the inclined rods are not rigid enough to support its self weight.
Increasing the extrusion values up to 30 units, equivalent to 15% of the span, confers higher rigidity. Values ranging from 2,5% to 10% of the span of the shell are considered suitable for a bending-active structure. Variation of the parameter t in structures with constant extrusion values determine the creation of synclastic and anticlastic shells, with values t = 0.76 and t = 0.40, respectively.

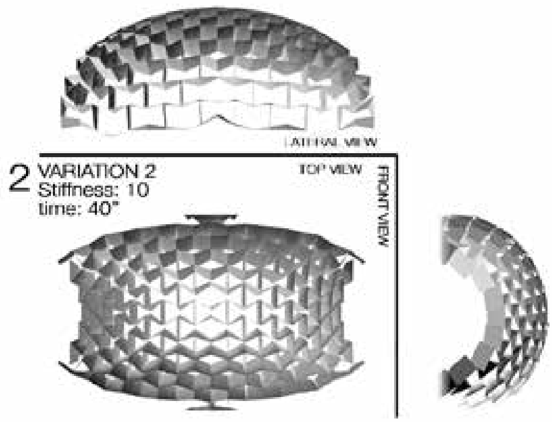
4.4.2 Tonal Sampler Bending Tests

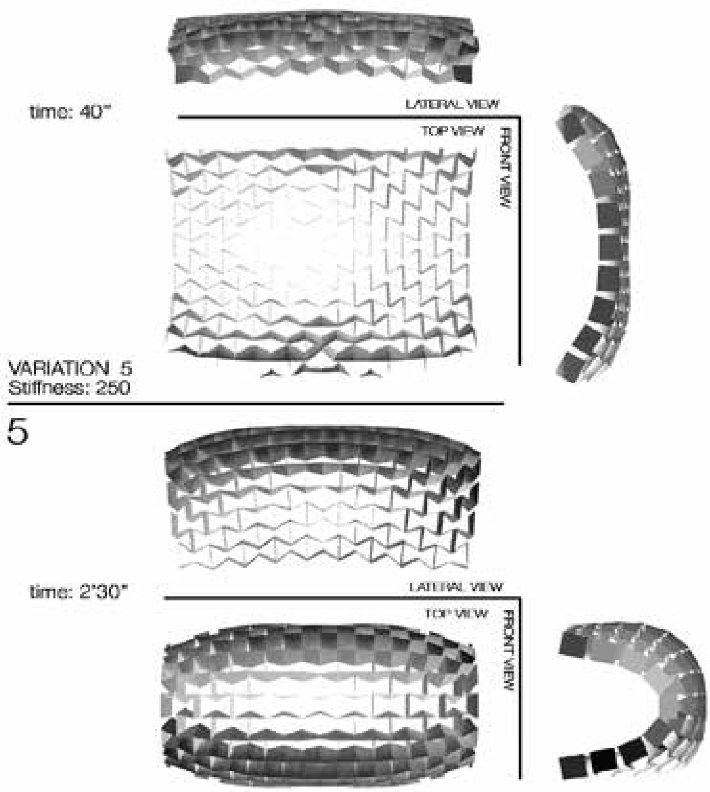
This paragrapfh refers to analysis shown in pages 168 to 173.

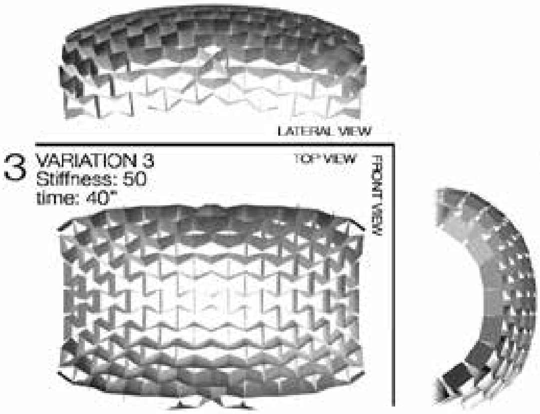
Finally various patterns with variable extrusions were generated by a tonal image sampler to understand the influence of complex height arrangements in the form-finding process. Firstly, six examples of tonal patterns (black and white) where created - some referring to stress analysis tryouts (patterns 1, 2, 3, 4) others intuitively (5, 6). The "flat models" show the initial configuration on a relaxed state. Confronting this with the tonal samplers it can be seen how the tonal sampler varies the extrusion factor for each of them and how the curvature is also affected by the different extrusions. On the bottom of each page, are presented, separately, the mean curvature analysis on parallel and inclined rods. Mean analysis is used to verify if a surface is minimal. In this case, mean analysis is useful since it shows if the surface is not planar - thus, if it is deformed by the bending process. For this reason, the more a surface is colored, the more that area is stressed.

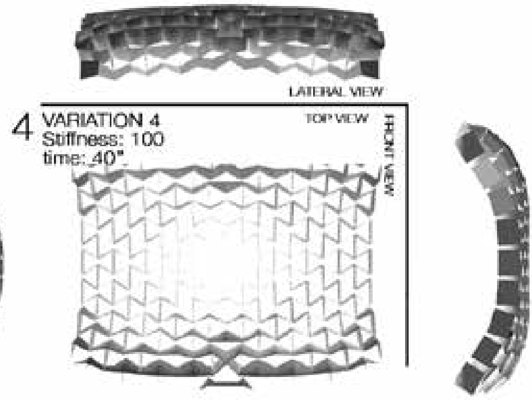
STIFFNESS BENDING TESTS - INNER SPRINGS VARIATIONS

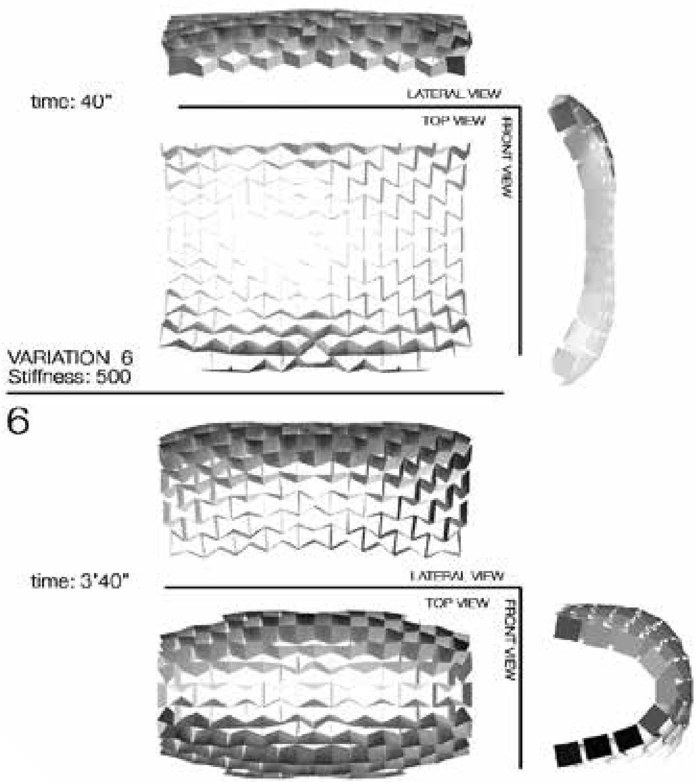






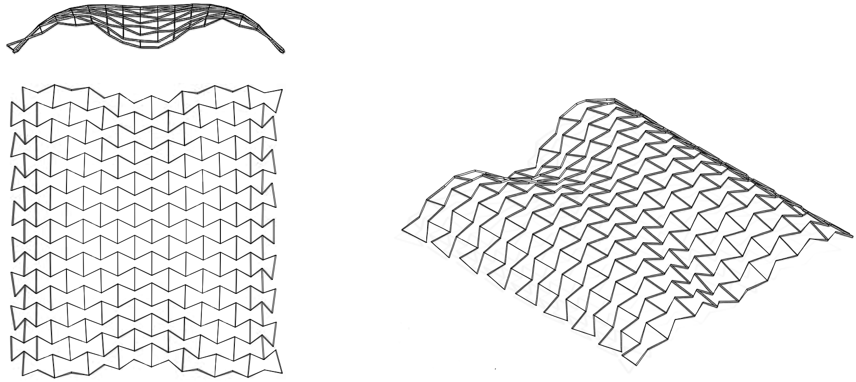

LATERAL VIEW
3 VARIATION 3
Stiffness: 50
time: 40"
TOP VIEW
FRONT VIEW


LATERAL VIEW
4 VARIATION 4
Stiffness: 100
time: 40"
TOP VIEW
FRONT VIEW

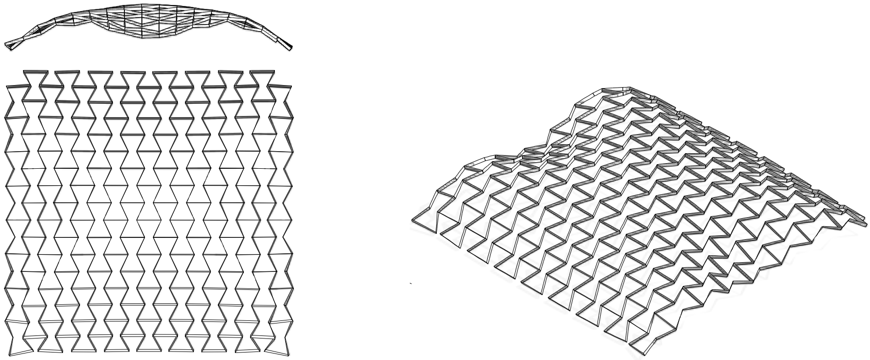

time: 40"
LATERAL VIEW
TOP VIEW
FRONT VIEW
VARIATION 6
Stiffness: 500
6
time: 3'40"
LATERAL VIEW
TOP VIEW
FRONT VIEW

STIFFNESS BENDING TESTS - CONSTANT EXTRUSION VARIATIONS

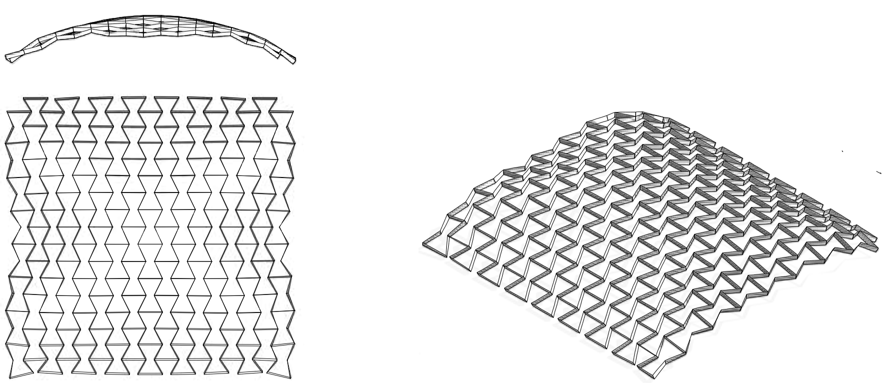
EXTRUSION FACTOR
1 UNIT



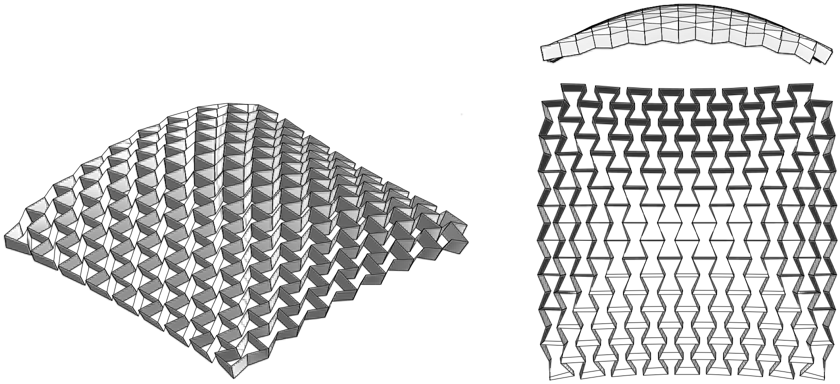
EXTRUSION FACTOR
2 UNITS



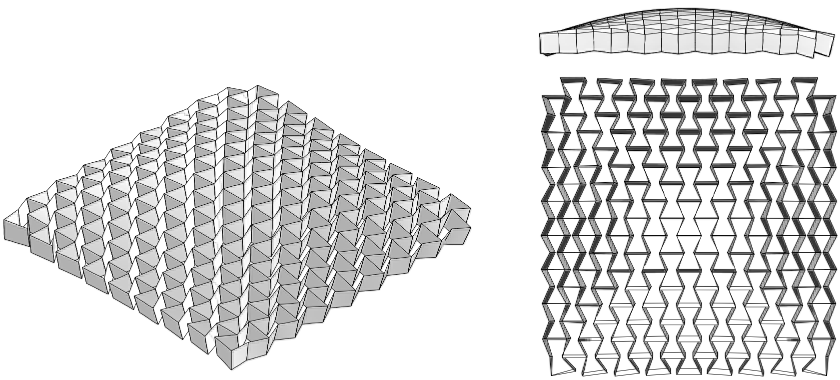
EXTRUSION FACTOR
3 UNITS



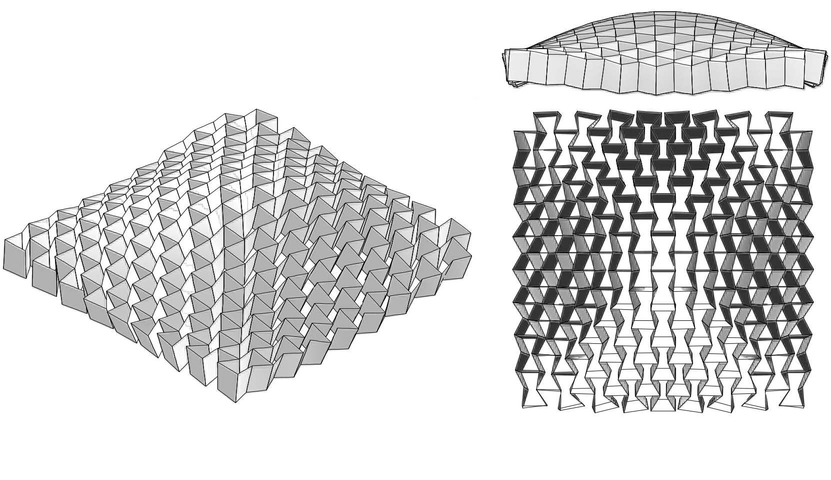
EXTRUSION FACTOR
10 UNITS



EXTRUSION FACTOR
15 UNITS



EXTRUSION FACTOR
20 UNITS



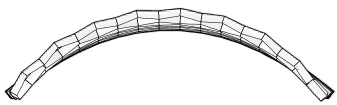
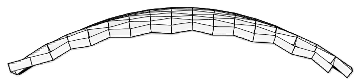
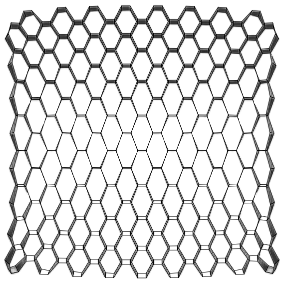
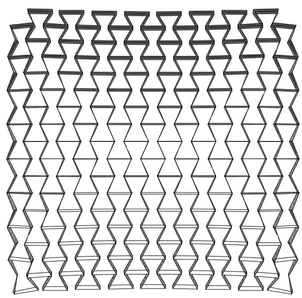
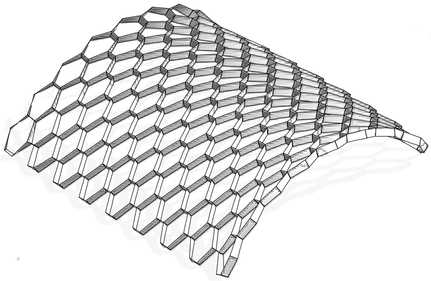
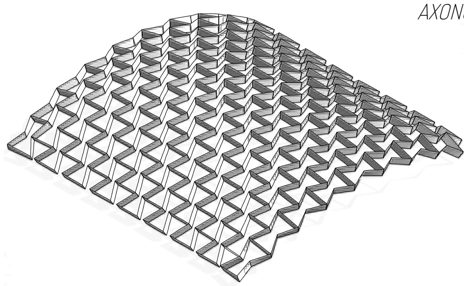
ANALYSIS RECAP:

Pag. 162-163
Bending Analysis - Constant Extrusion Variations
this analysis tests the stiffness of the structure at the variation of the extrusion factor

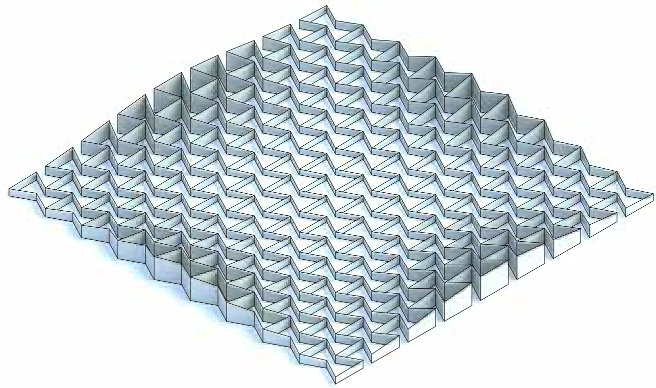
Pag. 164, 165, adn 167
Bending Analysis - Inner Springs Variations
this analysis tests the stiffness at the variation of the rigidity of the springs (shown in figure 7Aa and 7Ab)

STIFFNESS BENDING TESTS - CONSTANT EXTRUSION VARIATIONS

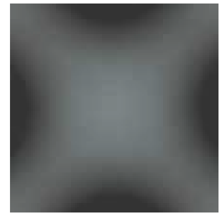
EXTRUSION FACTOR
15 UNITS

REGULAR HEXAGONAL PATTERN	*RE ENTRANT HEXAGONAL PATTERN*	
		*LATERAL VIEW*
		*TOP VIEW*
		*AXONOMETRY*

TONAL SAMPLER - PATTERN 1

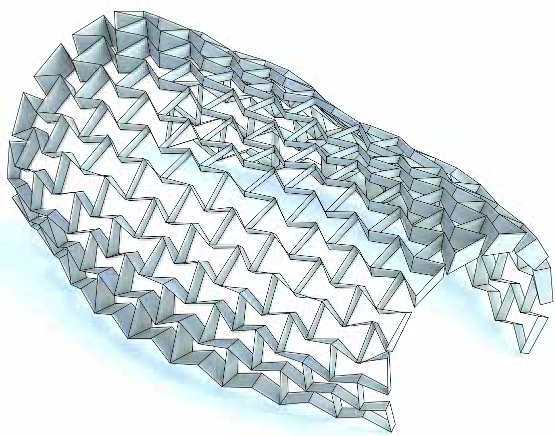


FLAT MODEL

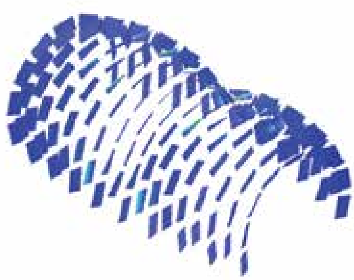


TONAL SAMPLERS

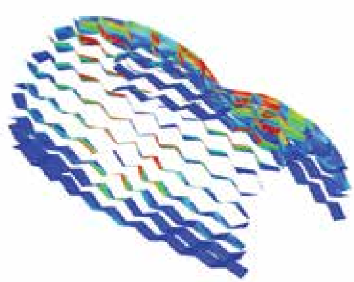
BENT MODEL



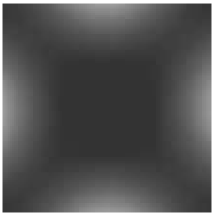
MEAN ANALYSIS
ON PARALLEL RODS

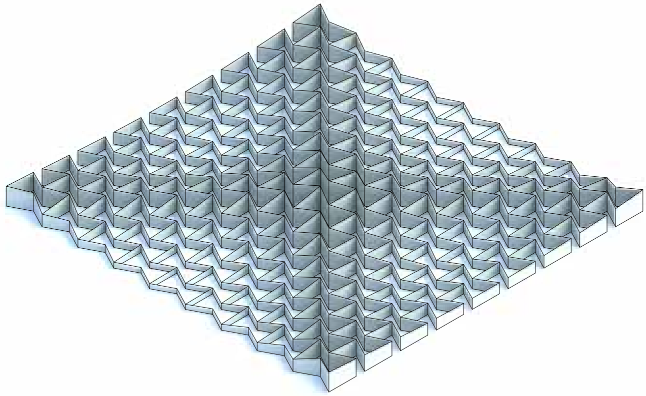


MEAN ANALYSIS
ON INCLINED RODS



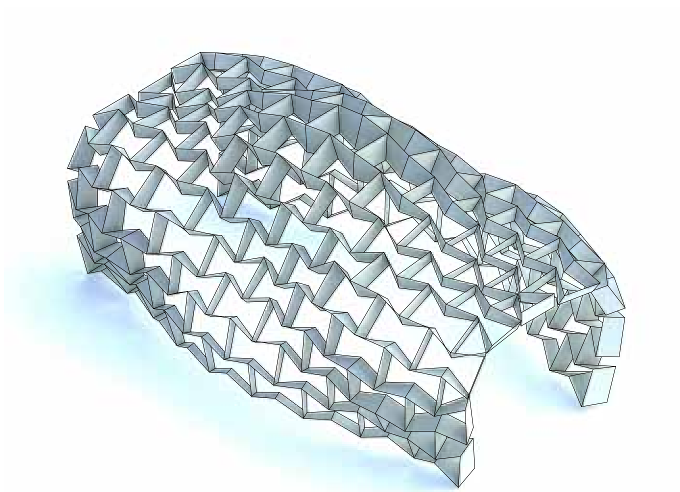
TONAL SAMPLER - PATTERN 2



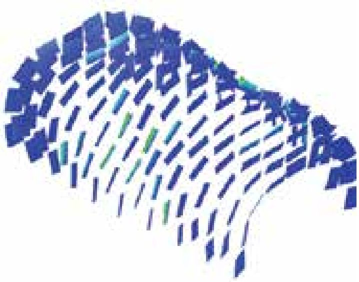


FLAT MODEL

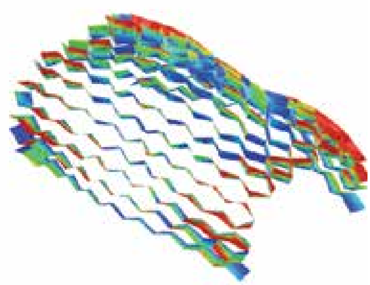
BENT MODEL



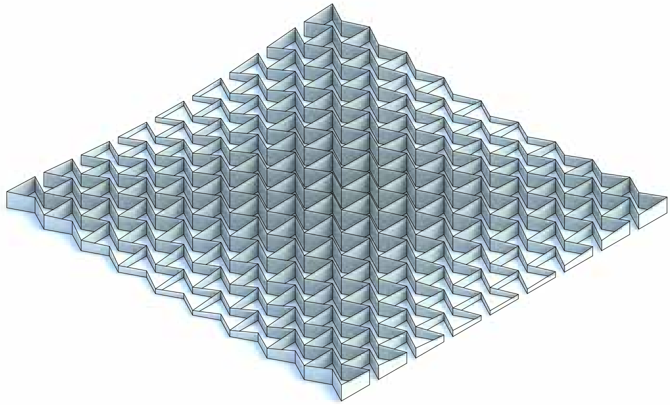
MEAN ANALYSIS
ON PARALLEL RODS

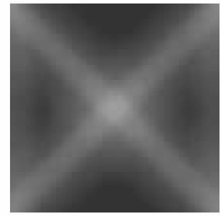


MEAN ANALYSIS
ON INCLINED RODS



TONAL SAMPLER - PATTERN 3

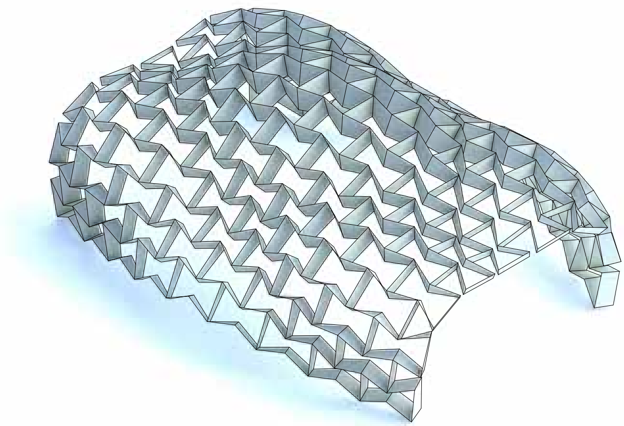




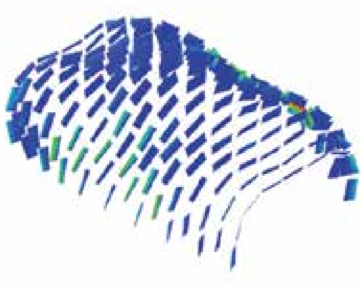
TONAL SAMPLERS

FLAT MODEL

BENT MODEL

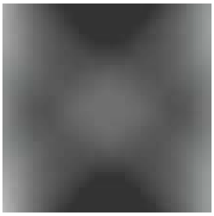


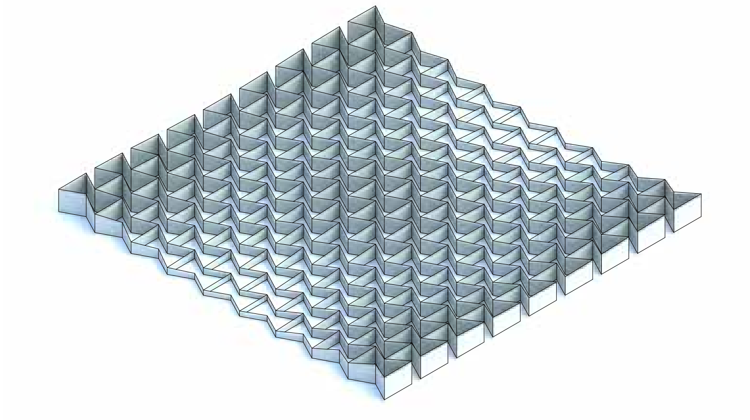
MEAN ANALYSIS
ON PARALLEL RODS



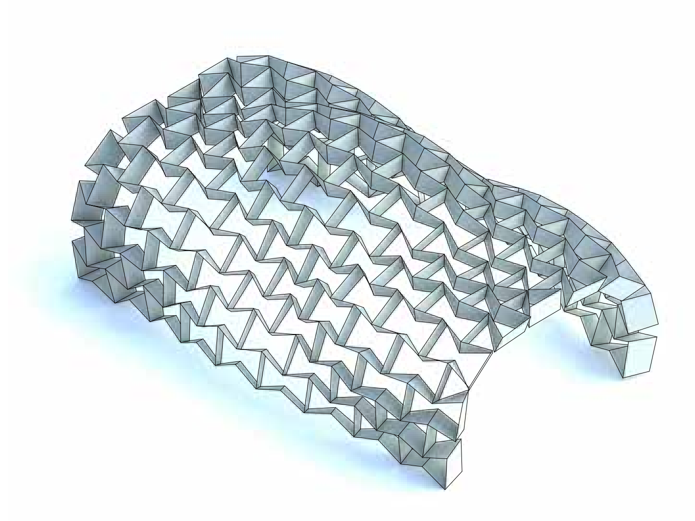
MEAN ANALYSIS
ON INCLINED RODS

TONAL SAMPLER - PATTERN 4





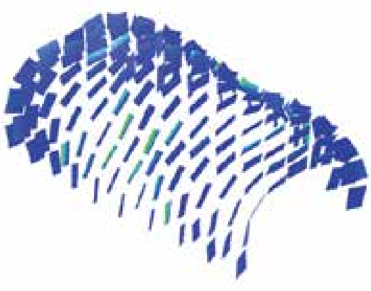
FLAT MODEL

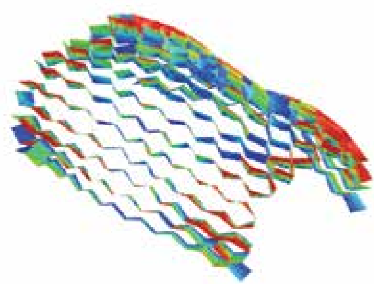


BENT MODEL

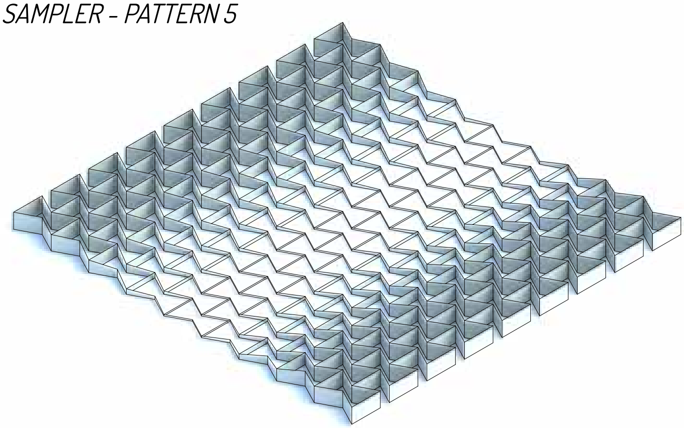
MEAN ANALYSIS ON PARALLEL RODS

MEAN ANALYSIS ON INCLINED RODS

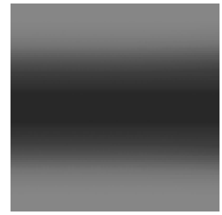




TONAL SAMPLER - PATTERN 5

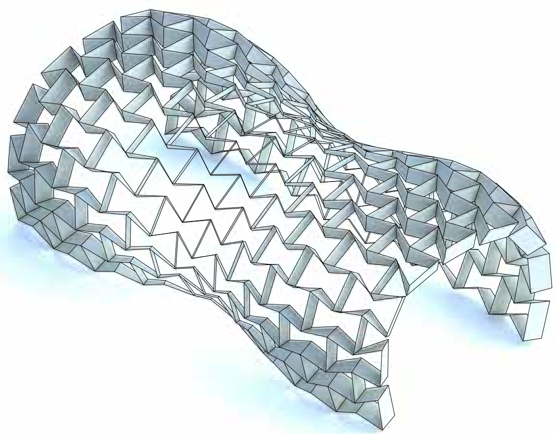


FLAT MODEL

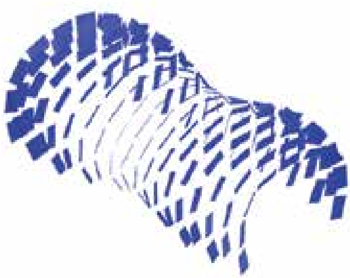


TONAL SAMPLERS

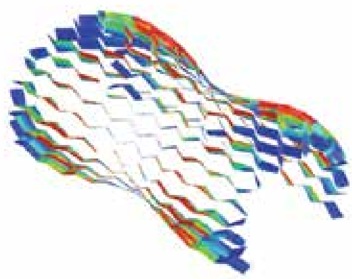
BENT MODEL



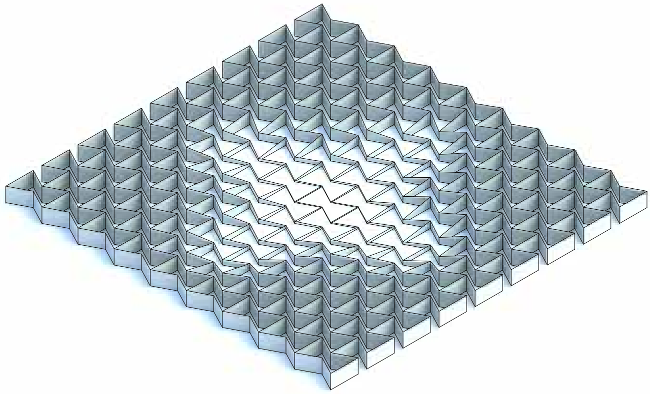
MEAN ANALYSIS
ON PARALLEL RODS



MEAN ANALYSIS
ON INCLINED RODS

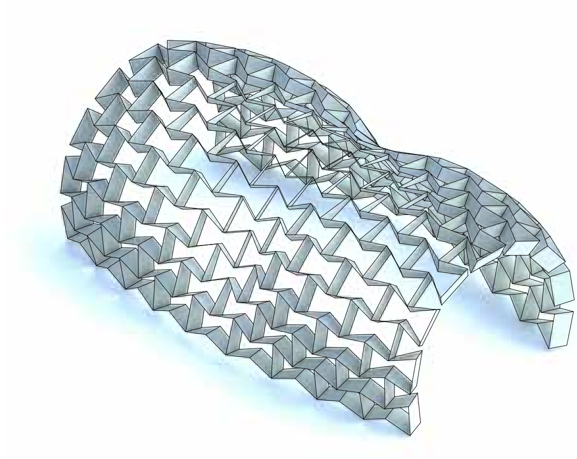


TONAL SAMPLER - PATTERN 6

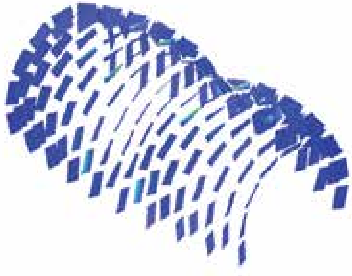


FLAT MODEL

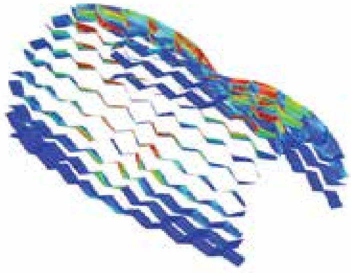
BENT MODEL



MEAN ANALYSIS
ON PARALLEL RODS



MEAN ANALYSIS
ON INCLINED RODS



4.5 CONCLUSIONS

Among various tested pattern, hexagonal reentrant pattern proved to be a valid choice for the creation of synclastic shells since they perform a defined synclastic surface once bent. From many test it resulted that the curvature can be modulated thanks to the tuning of defined parameters like the extrusion factor. The use of computational models managed with parametric softwares proved to be of an essential importance.

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PART I

TECHNOLOGY DESIGN

CHAPTER V

5.0 ABSTRACT

In this chapter is analyzed the synclastic shell performed by the reentrant hexagonal pattern so to define a technology that will be referred to as Auxetic Bending-active Structure (AB-aS).
It will be explained the behaviour of the singles elements that characterized this structure - inclined beams, parallel beams and joints - and specifications about the materials and techniques of production, foundations and management process will be proposed.

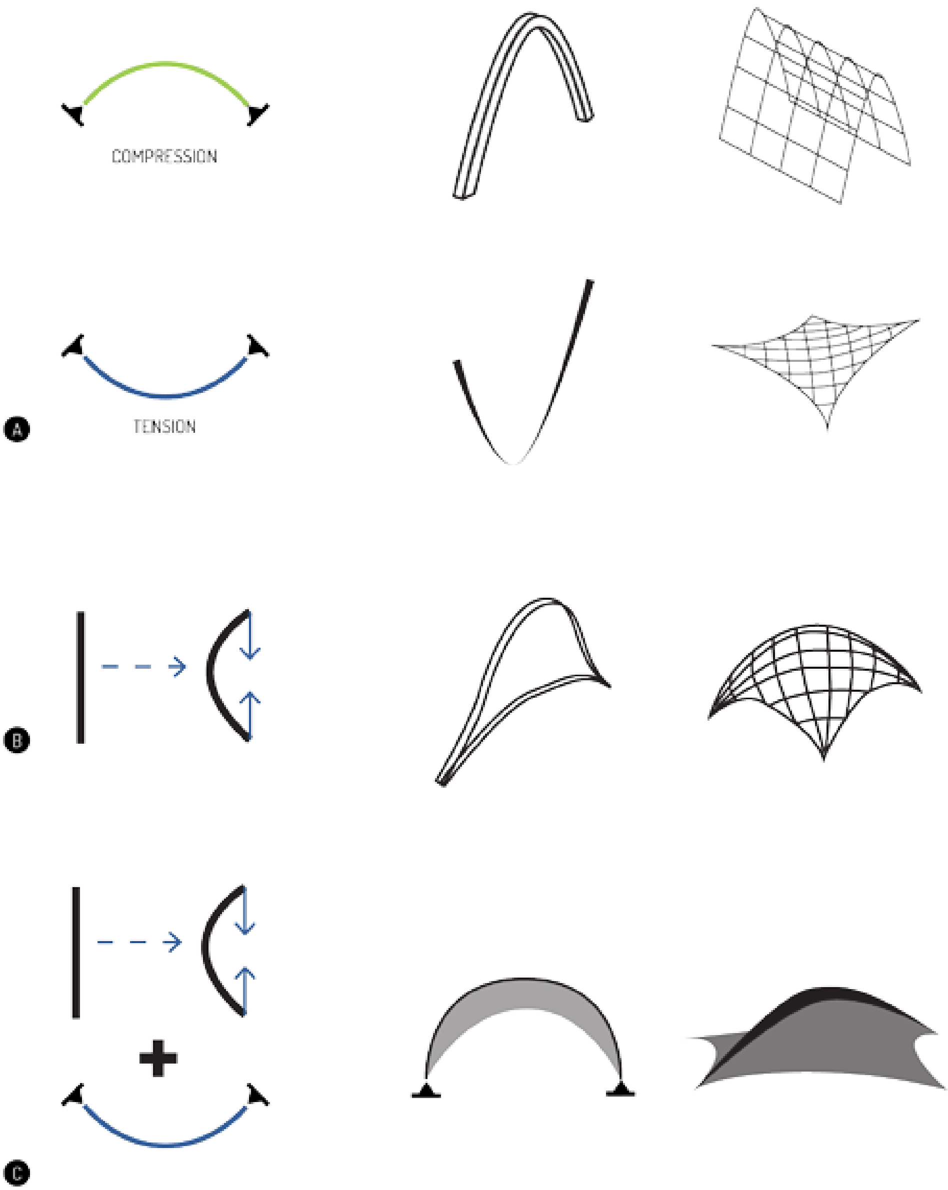


Figure 1

Different types of load bearing structures categorised according to structural action. Based on Knippers et al (2011: 135)
A. Form-active structures
B. Bending-active structures
C. Hybrid structures

5.1 BENDING-ACTIVE STRUCTURES

The term "bending-active" describes curved beams and surface structures that base their geometry on the elastic deformation of initially straight or planar elements (Knippers et al 2011: 134). Active bending in this context is understood to be a form defining strategy based on systemized elastic deformation, i.e. bending. In general, bending- active structures are understood to be an approach rather than a distinct structural type. The path of forces, as a yardstick for the efficiency of a structure, cannot be generalised in terms of an all inherent mechanism for bending-active structures. Their common denominator is therefore not a circumscribed load bearing behaviour or geometrical definition, but a formation process during which they are elastically bent. Bending-active in structural terms: constrained statically indeterminate structures with residual bending stress. A key feature of bending-active structures is their potential for structural integration and heterogeneity, leaving the limits of strictly categorised building structures by accumulating different load bearing strategies in hybrid systems (Lienhard, 2014). This leads to the following definition of bending-active structures:

Bending-active structures are structural systems that include curved beam or shell elements which base their geometry on the elastic deformation from an initially straight or planar configuration.

The pre-stressing of bending-active structures is generated through

Figure 2

*Inside the ICD/ITKE Pavilion of 2010.
This pavilion is working as an active bending structure. Is composed by plywood bent planks.
Photography by Frank Kaltenbach.*

large nodal displacements in statically indeterminate structures. As a result, individual building elements are largely deformed and therefore exposed to a constant bending stress, i.e. pre-stress. The element stiffness is chosen so that the induced bending stress never reaches the elastic limit of the used materials (Lienhard, 2014). Therefore, a linear material law (Hooke's Law) is always used for the subsequent investigations. As a consequence to the large deformations of bending-active structures, the calculations generally must be performed geometrically non-linear

The main motivation for active-bending lies in the simplicity of producing complexly curved elements, leading to the overall understanding: Bending-active structures are understood to be an approach rather than a distinct structural type!
(Lienhard, 2014)

Another typology of structure classified by Lienhard (2014) is the class of Hybrid structures, where the principal mechanisms of load transfer introduced above in praxis often appear in combined form, acting simultaneously in a structural system and even within one structural element. The intentional combination of load transfer mechanisms is referred to as a hybrid structure. In general, hybrid structure systems result from the linkage of two parental systems of dissimilar internal load transmission into a coupled system. If the parental systems are equipotent in terms of their structural capacity, their coupling to a hybrid system may be in favour of the two when reciprocal stress compensation and/or additional rigidity through opposite system deflection are actively enabled.

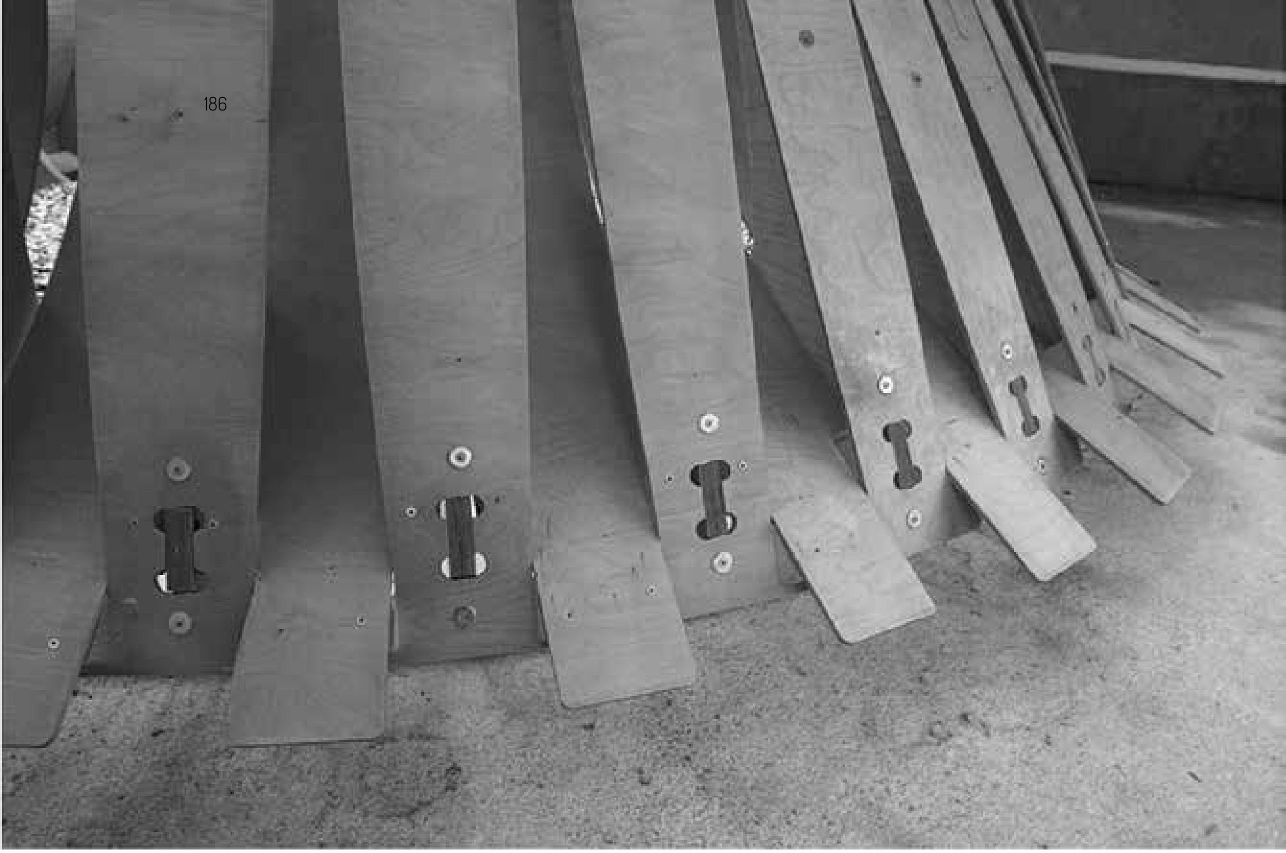


Figure 3

Image above: detail of teh wooden joints, on the right it can be seen the computational model showing the passages from planar to bent. In green are shown the most stressed areas. Photography by Frank Kaltenbach and graphics by ICD/ITKE

5.1.1 ICD/ITKE Pavilion 2010

The work that is going to be presented had a major importance in influencing our proposal for the pavilion. It is working in the same structural way of the AA-bS and also is proposed for similar scopes, displaying the structure and creating and entertaining space.
The starting point for the pavilion built in 2010 by the master students of the Institute for Computational Design (ICD/ITKE) was the unexploited structural potential of plywood (Figure 2 and 3). The geometry is based on linked pairs of segmental arches, 40 of which (i.e. 80 radial strips) were needed to close a torus with an external diameter of 10 m. With a span of 3.5 m, this filigree structure is both efficient and stable. The faculty's own industrial robot, configured as a CNC milling machine, was used to give each of the more than 500 timber elements its own geometry. The 10-metre plywood strips also had to be cut into segments for transport. The individual segments are subject to either tensile or bending stresses, whereby each tensile segment elastically maintains the form of the adjoining bending segment. The entire pavilion was constructed from birch-plywood strips only 6.5 mm thick. The digital information model was based on the bending behaviour and a script with roughly 6,500 lines of code. This forms the basis of all further steps: the structural calculations in a process of "coiling up" the flat strips by finite element analysis (FEA); and the robotic production of the elements and their positioning on site. The relaxation behaviour of the finished pavilion as a result of ageing can be measured and the results used as data input for future virtual 3D models

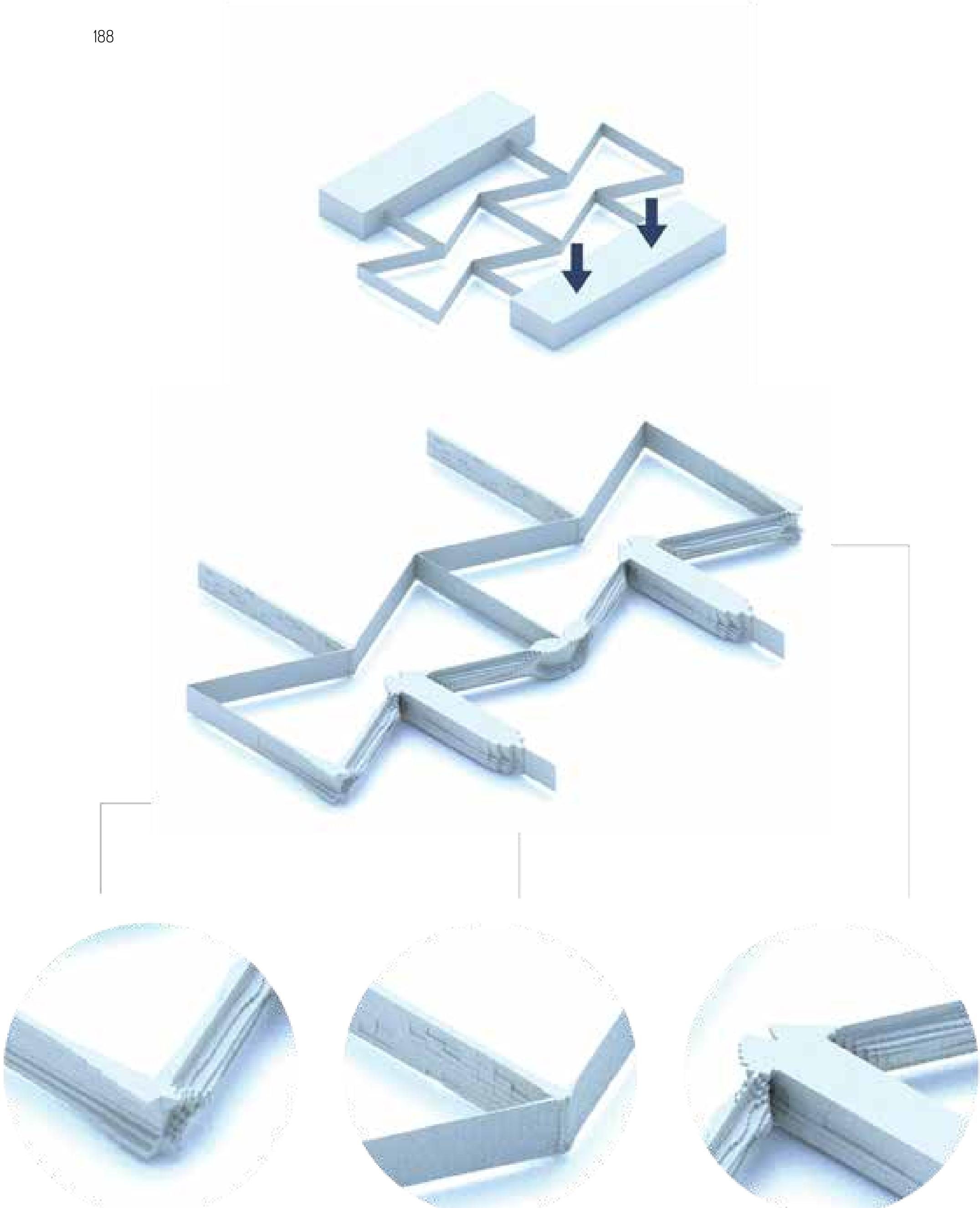


Figure 4

Optimization analysis done with software Millipede for Grasshopper. On the top it is showed the analysis layouts.; the arrows indicate the direction of the inserted forces. Below, it is shown the output and some details. This results are used to better understand the flows of forces inside the structure.

5.2 STRUCTURAL LAYOUT

The conversion from a geometrical model to a realizable structure are made possible after that the forces acting in the model were understood. The functioning of the structure had to be supported by analysis since only an empirical and practical understanding was completed up to now. In this paragraph the analysis done on the structure will be explained.

Inclined Rods

These beams play an essential role in tuning the elasticity of the structure. From the previous analysis it is possible to notice how the inclined beams are the most affected by the twisting made by the fluxus of the forces. It was understood that the twist doesn't have to be avoided but it has to be controlled: is in fact this particular deformation that makes possible the erection of a synclastic shell. If these beams would be too rigid, the movement wouldn't succeed.

Moreover confronting the physical model with the analysis it was discovered that each rods have a different degree of twisting: the more the extrusion factor of the rod is high, the more the rigidity of the rods increase. Considering this behaviour, a relation between shape and twisting capacity we can affirm that the synclastic curvature is made possible by the changing of the rigidity of the inclined rods. For this reason, to be able to control the rigidity of each rods means that it is possible to control the curvature.

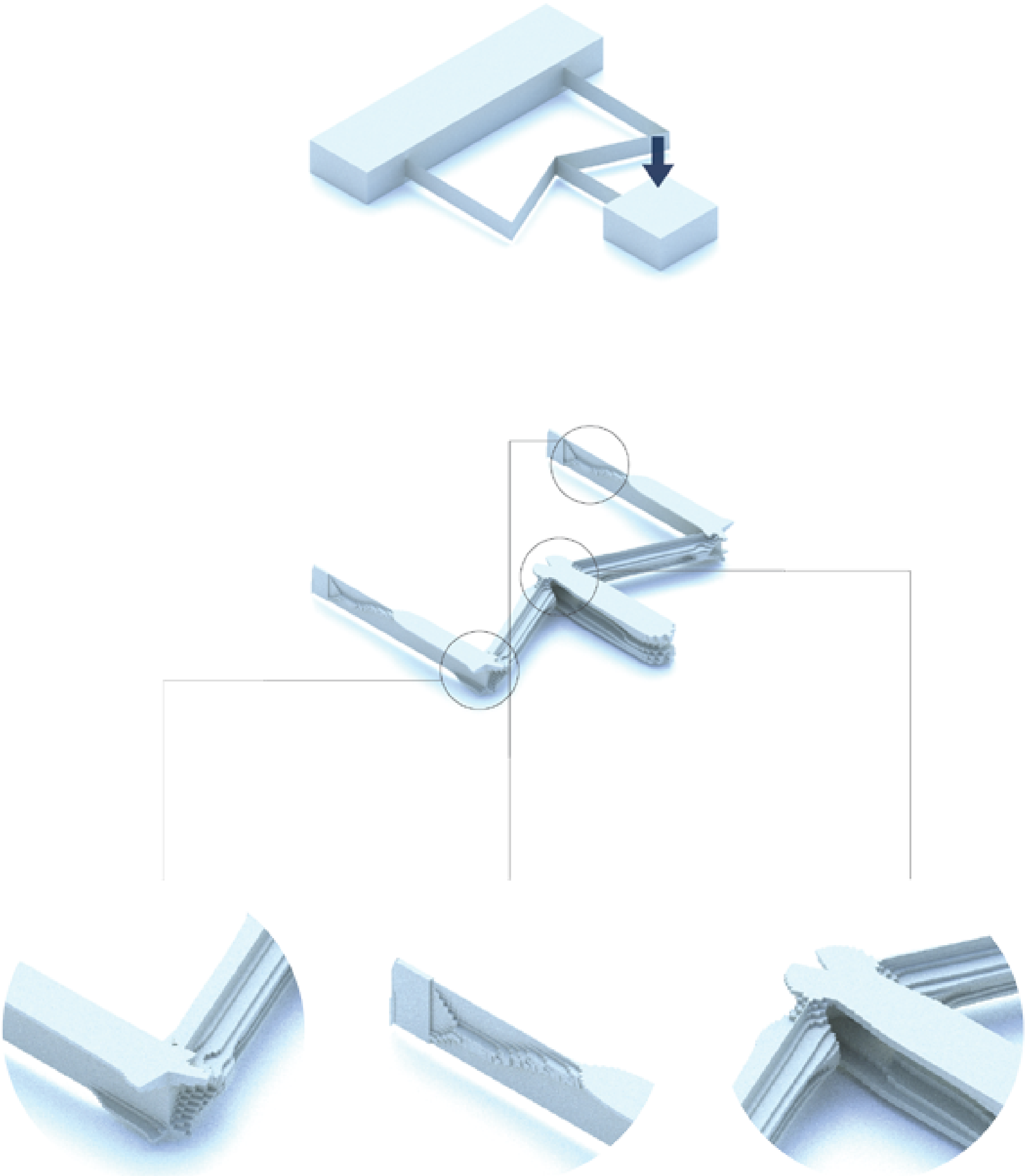
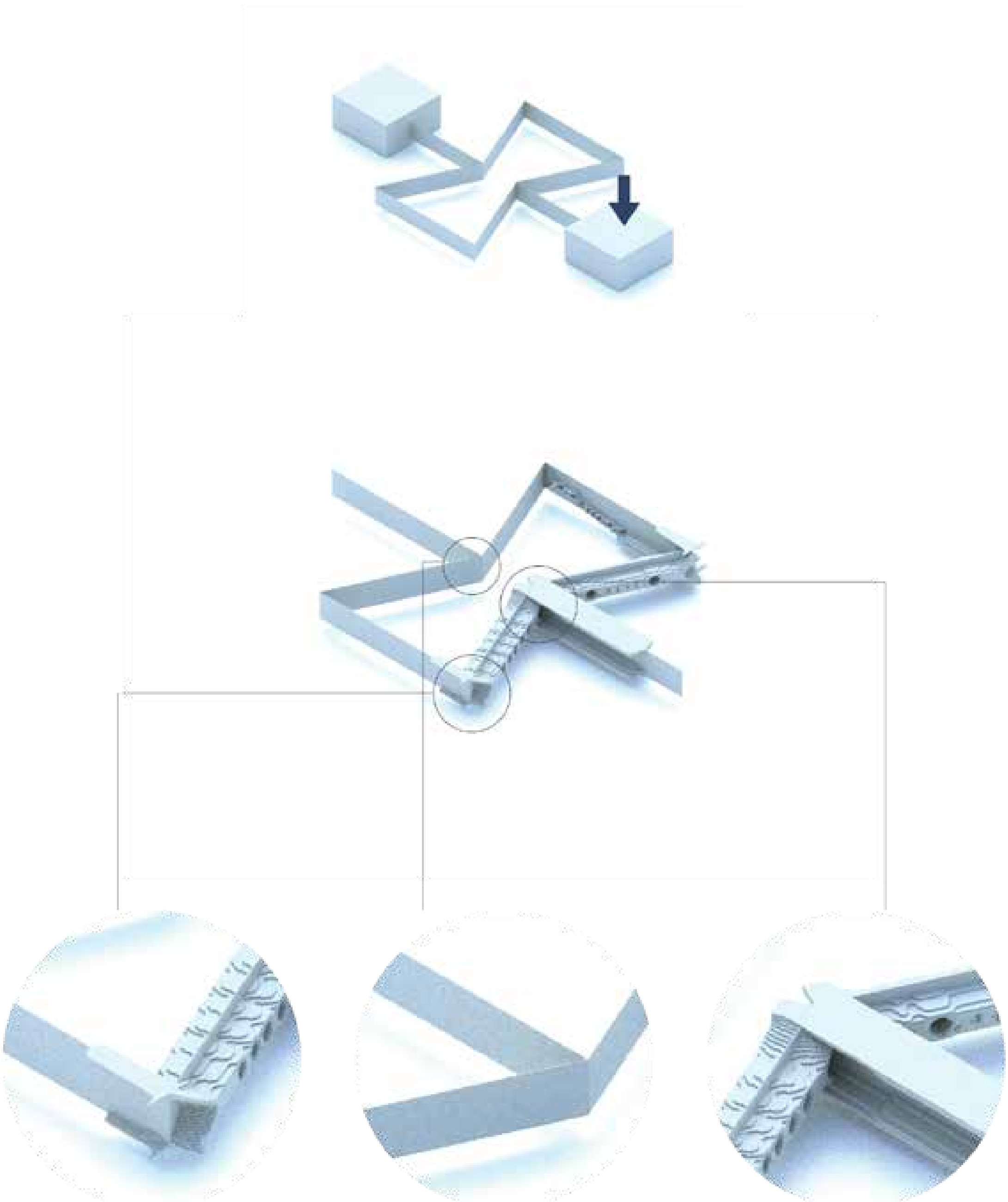


Figure 5

Optimization analysis done with software Millipede for Grasshopper. On the top it is showed the analysis layouts.; the arrows indicate the direction of the inserted forces. Below, it is shown the output and some details. This results are used to better understand the flows of forces inside the structure.



Parallel Rods

ùFrom previous analysis it was noticed that the parallel beams were not deformed during the bending and that they remained almost parallel among themselves. Thanks to the software Millipede it was possible to test this typology of rods (Figure 4 and 5). The process starts by defining a flat area on which the forces can act and than by assigning clouds of points that work as pivot for the forces and supports. Starting the computation, an offset where the stress are mainly influencing the mesh is created. In parallel rods the output was similar to a IPE beam, confirming the hypothesis that the parallel rods are staying rigid while bending.

Joints

Since this structure works on active-bending, a big amount of stresses is flowing inside the structure. It was not possible to perform tests on the joining part since the mesh is reades as unitarian. Anyway, from Figure 4 and 5, it can be observed that on the joining parts the meshes are thickened and tends to conjoin, avidentiating the stresses on that area.

5.2.4 Study Model, 1

After the process of optimization of the structure a prototype was fabricated.
The notions got from the optimization processes were applied in the model exhibited in Figure 7. The AB-aS was designed with three different materials, each of them chosen to fulfill specific needs.

- *joints*: they are printed in White PLA, it is very resistant and it is possible to have precise printing results. The joints are the elements that interconnect the two kinds of beams and they have to bear the stress collected from the rods and avoid the separation of the elements.
- *parallel beams*: wood bars are used. Each of them measure 7 centimeters.
- *inclined beams*: this are the beams that have to flex in order to permit the bending. For their materialization it was chosen a flexible filament produced by TreeD Filaments called Kyoto-Flex. This polymeric filament prove to be more resistant than others and in order to obtain even more stiff beams, a process of shape optimization (using Millipede) was executed showing how to make them stiffer by thickening them along specific lines.

This model was built thinking that having separate elements could be helpful in the transportation of a large-scale technology usage. Problematics are found in the assembly process since caused by the joining system.
The elements were sometimes difficult to be inserted one into the other and when the forces were not compressing towards the

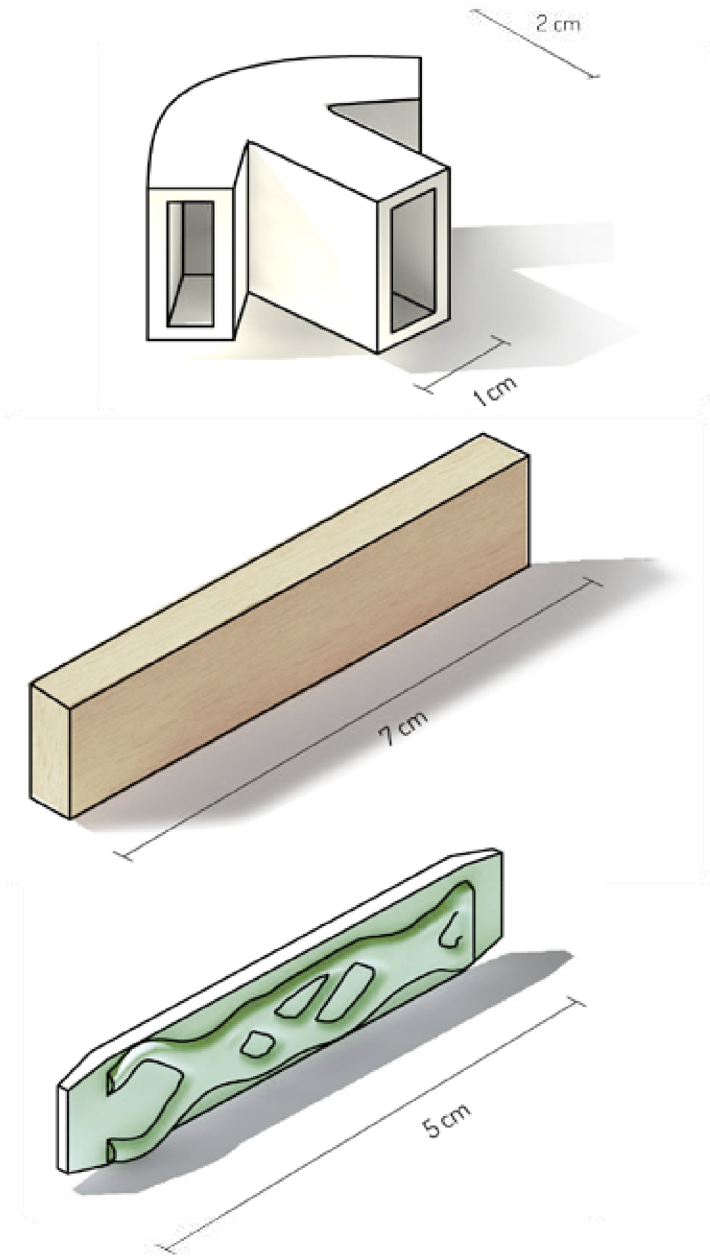


Figure 6

Element composing the model showed in the next pages.
From top: Inclined rods are printed in Kyoto-flex, experimental PLA-based flexible material, parallel rods are cutted from wooden bars, joints are printed in white PLA.

center of the structure but outwards, the join failed and the structure opened. However, the model displayed a synclastic curvature and could guarantee a nice level of stiffness when bent.

Figure 7

The two images show the Study Model 1, prototyped after the structural layout analysis. It was chosen a rigid polymer (PLA) for the joints, a flexible experimental polymer (tokyoFlex) for the inclined rods, and wooden bars for the parallel rods. In the next page is possible to see the model performing a synclastic shell while bent.

5.3 TUNABILITY

The Auxetic Bendig-active Structure (AB-aS) is based on the geometry of an irregular hexagon which behave as the meso-component characterizing all the final geometry. By tuning few parameters characterizing this meso element, the whole macro structure can be managed.
During the tests, both computer and printed prototypes, it was understood how these few parameters could influence the structure in terms of and resistance and curvature output.
They are:

- Referenced Surface
- t Parameter
- Extrusion Parameter
- Width Parameter

The Referenced Surface consists into the planar shape onto whom the pattern will adapts, following the parameter assigned in the creation of the script.

The t Parameter was already introduced in the previous chapter. This parameter can vary the angles persisting among the rods, thus varying the shape from reentrant to open. This parameter is mainly tuning the curvature of the final surface. Open cells will cause a saddle shaped whereas close shell will display a synclastic shape. When the factor is close to 0.5 (figure 7Ab) the cells will be rectangles and their rods will work as rectilinear beams, thus

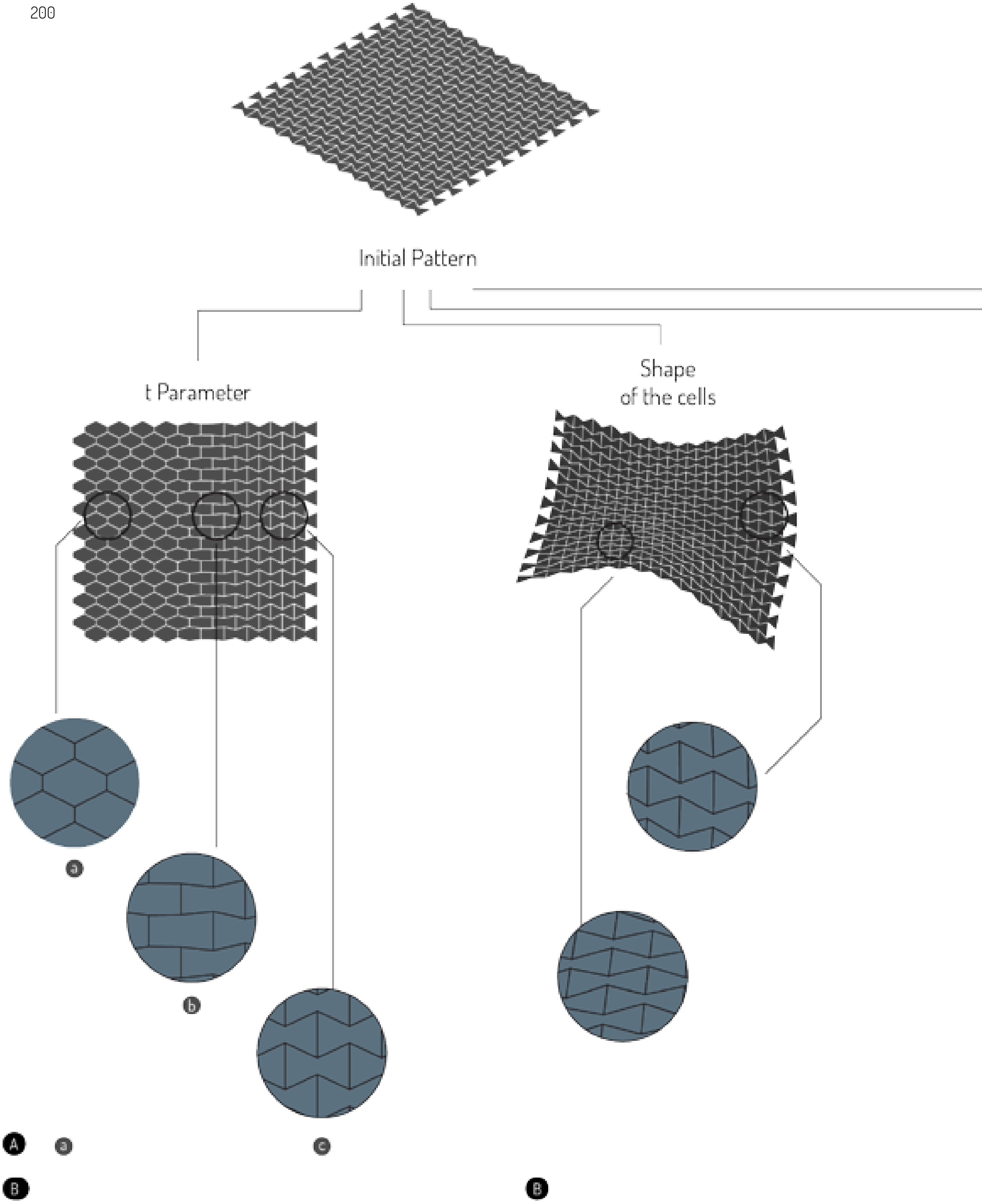
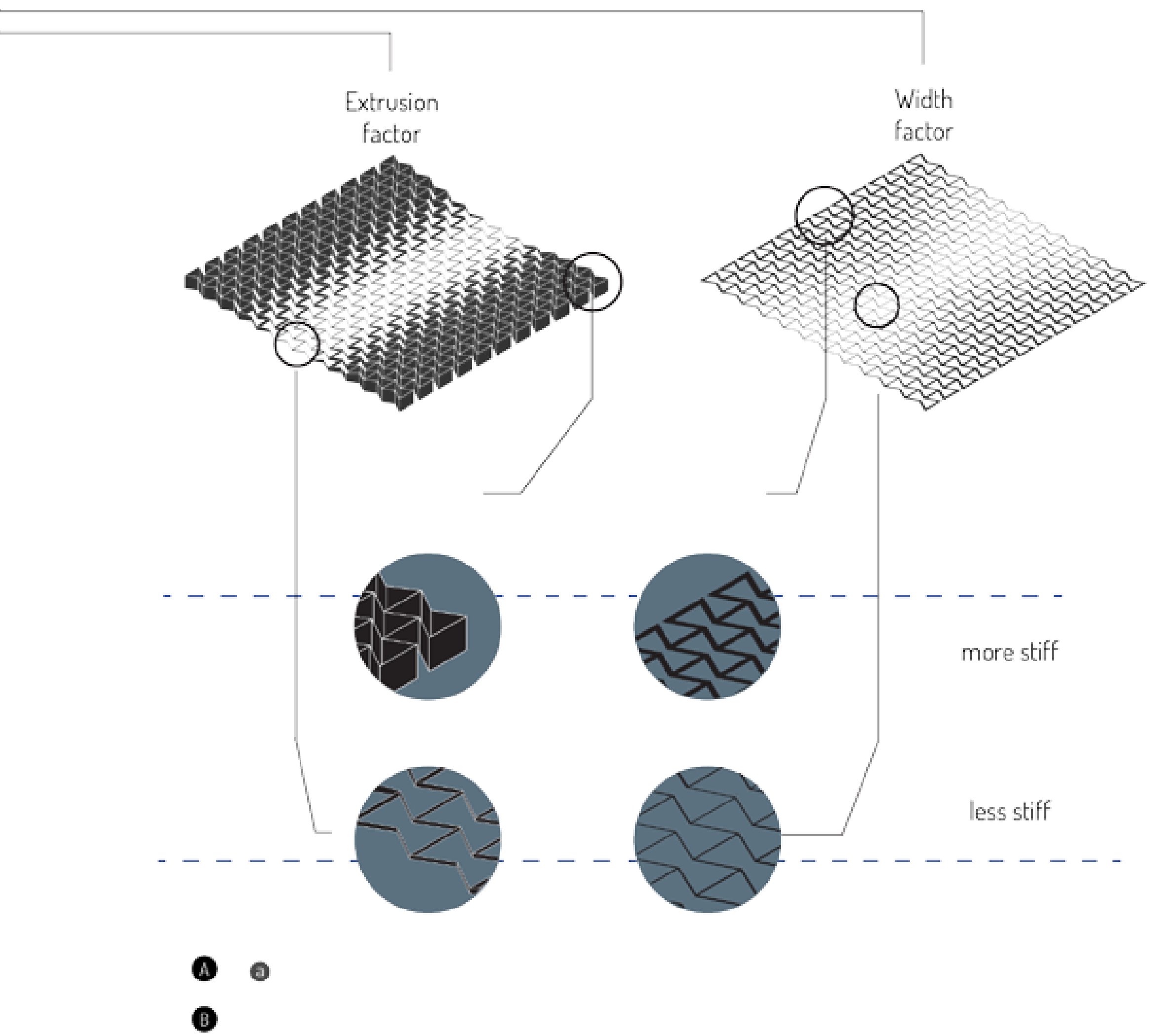


Figure 8

Tunability of the parameters.


Extrusion factor
Width factor
more stiff
less stiff
A
a
B

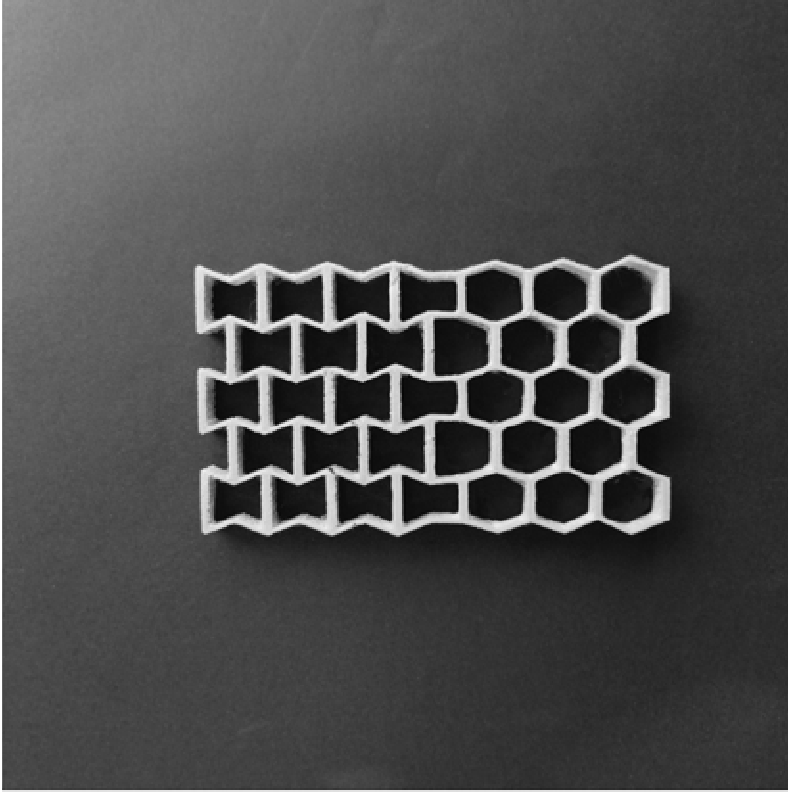
creating planar surfaces.

The Extrusion Parameter and the Width Parameter influences the curvature in a similar way. It was understood that the rigidity of the rods is an essential parameter in creating the willed curvature. Therefore, the more the extrusion and the width will be increased, the more the cells will display the curvature defined in the t parameter. If the extrusion parameter and Width Parameters are too low (the real measure has to be related to the dimension of the final model) the rigid rods will bend together will the parallel ones and the synclastic curvature won't be reached.

All of these parameters contribute to define a shape, and the same result can be reached in different ways. The designer will have a wide range of possibilities to resolve both structural and aesthetic problems.

5.3.1 Study Models, Series 2

All the acquired knowledges were empirically tested thanks to models.
From Figure 9 to 13 are presented different models that were made in order to understand the bending resistance of the structures, in relation to materials and geometry, and to confront different printing materials. In the images themselves, explanations are carried out model by model.



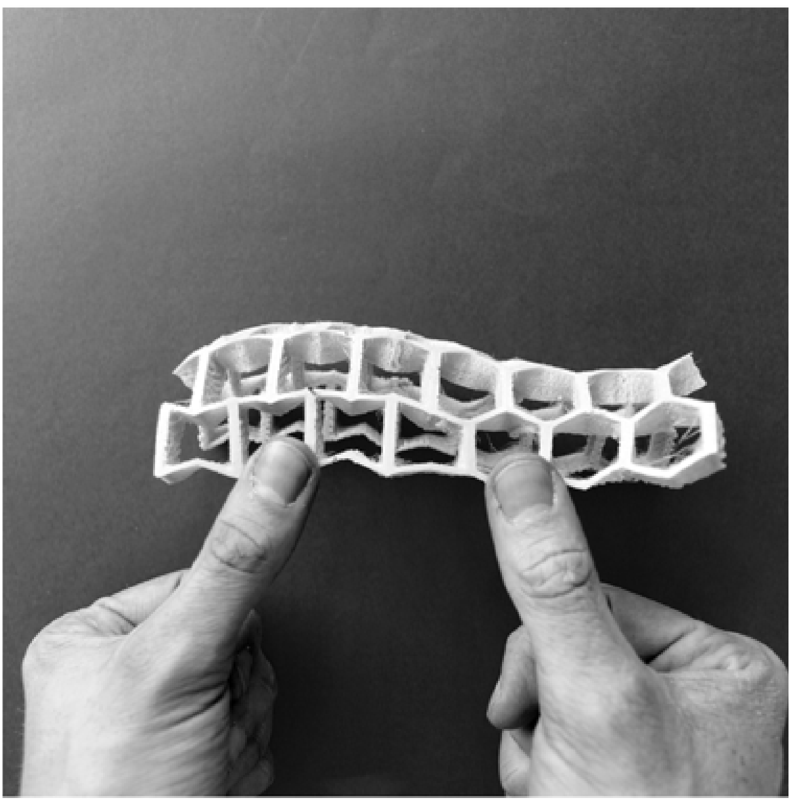
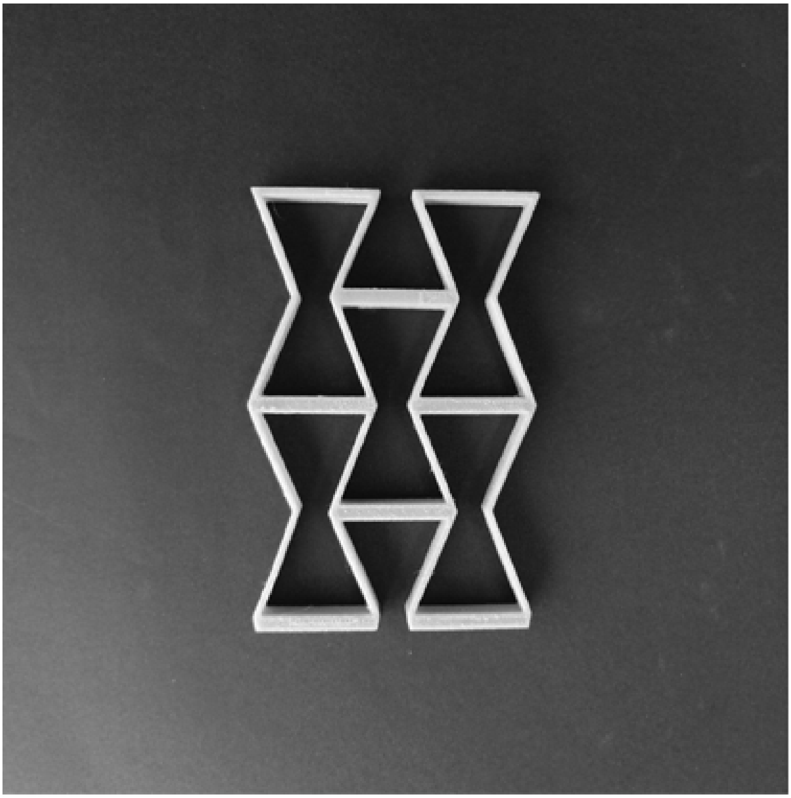


Figure 9

Hexagonal reentrant honeycomb structure printed in flexible material (Filaflex 3D by Recreus). In this model the transition from closed cells to open cells is implemented along another axis compared to previous experiments.



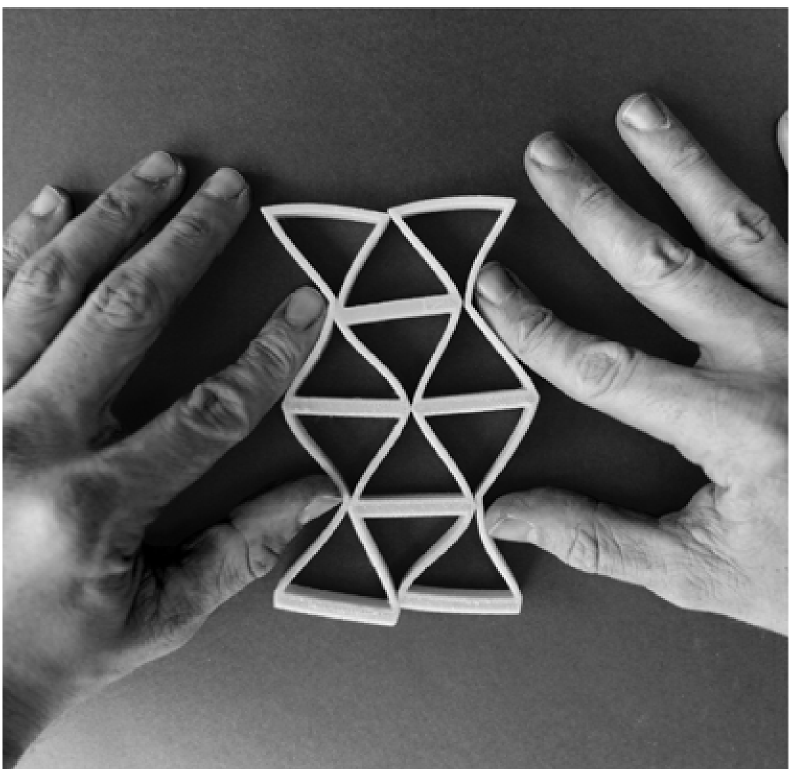


Figure 10

Hexagonal reentrant honeycomb structure printed in flexible material (Filaflex 3D by Recreus). This structure proved to be too flexible.

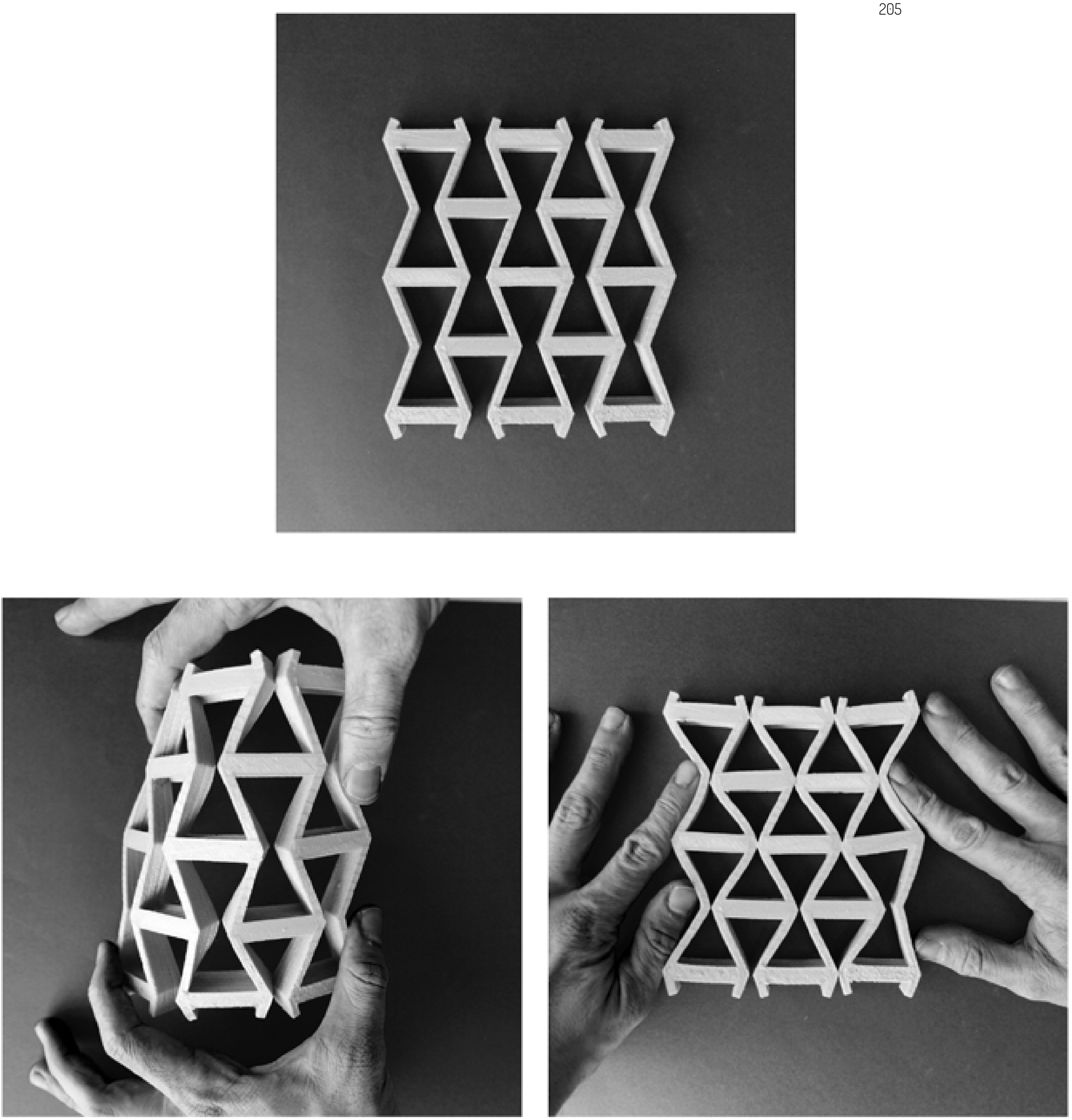
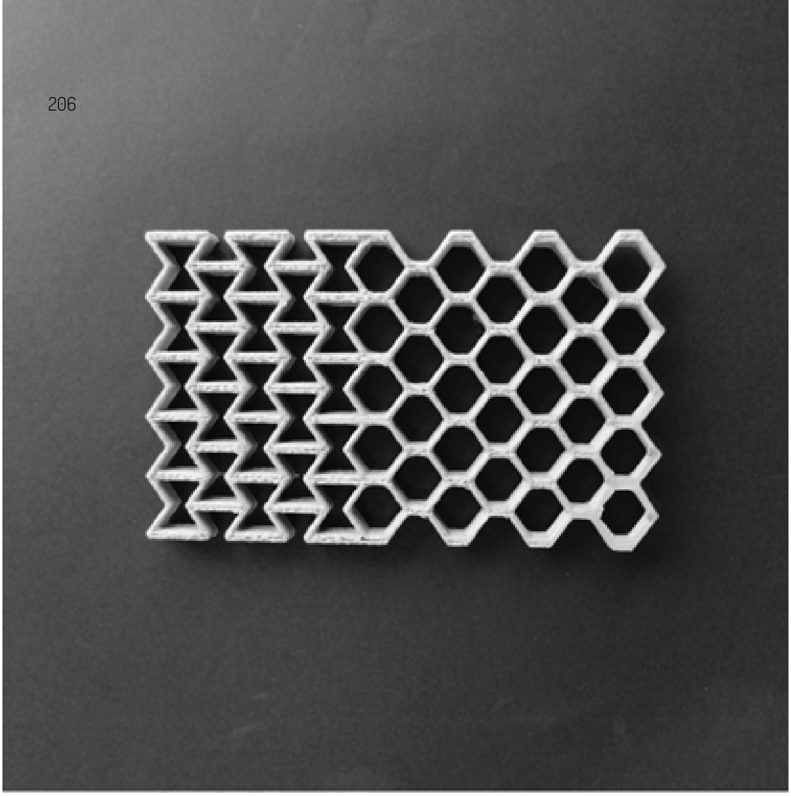


Figure 11

Hexagonal reentrant honeycomb structure printed in flexible material (Flex Mark 9 by TreeD Filaments). This structure proved to have a higher degree of resistance if compared to the one in Figure 5. In this model the inclined rods are thicker (4mm) and the section of the parallel rods is stretched a little outward in order to resist to bending (as in a double T beam).



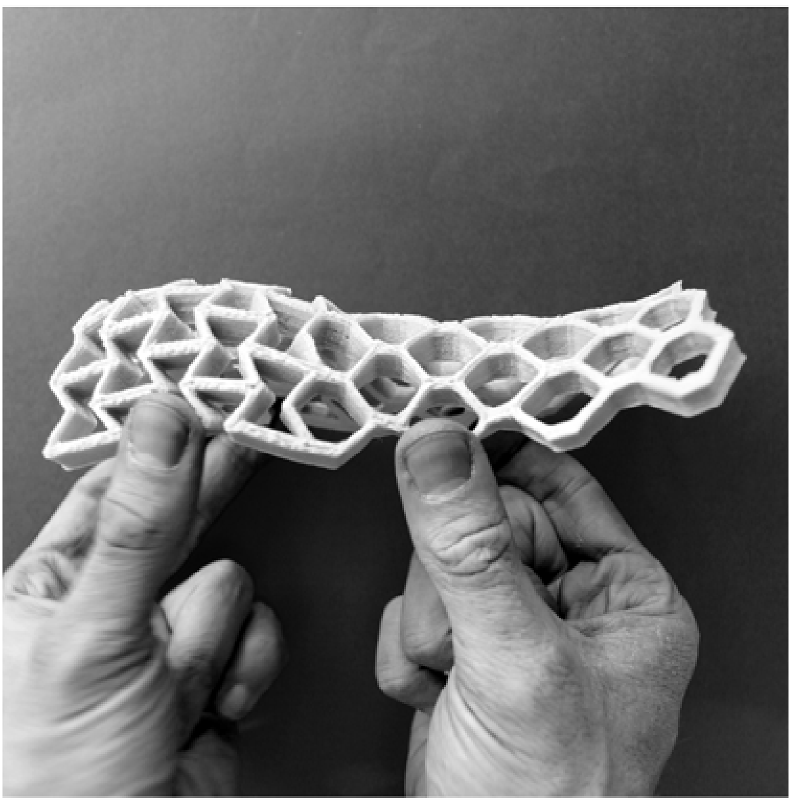
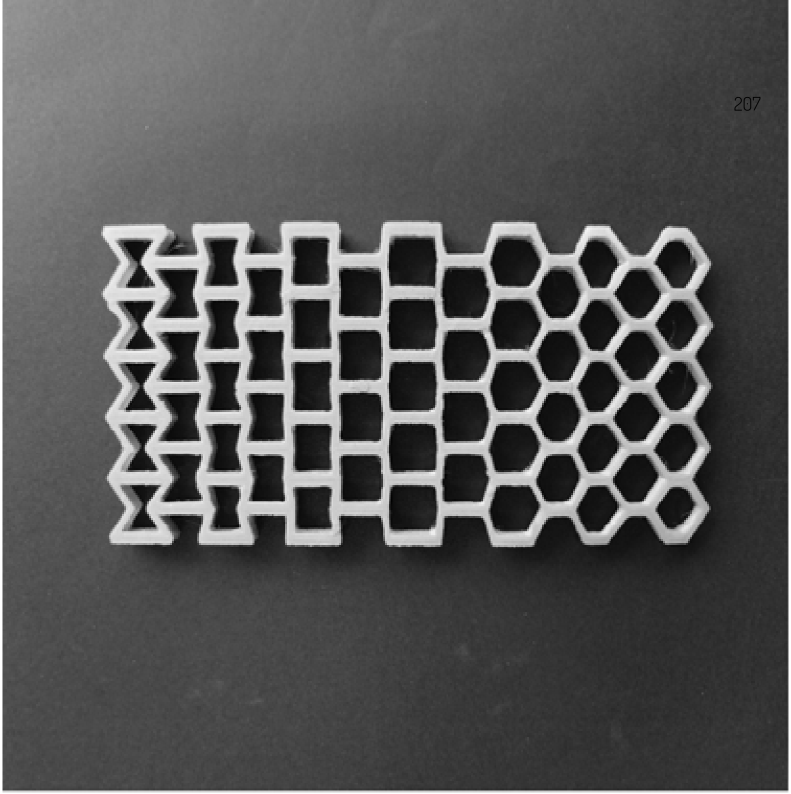


Figure 12

Hexagonal reentrant honeycomb structure printed in flexible material (Filaflex 3D by Recreus). This model is a first attempt to evaluate the "opening parameter".
In figure below is shown how the structure assumes a different curvature in the different areas.



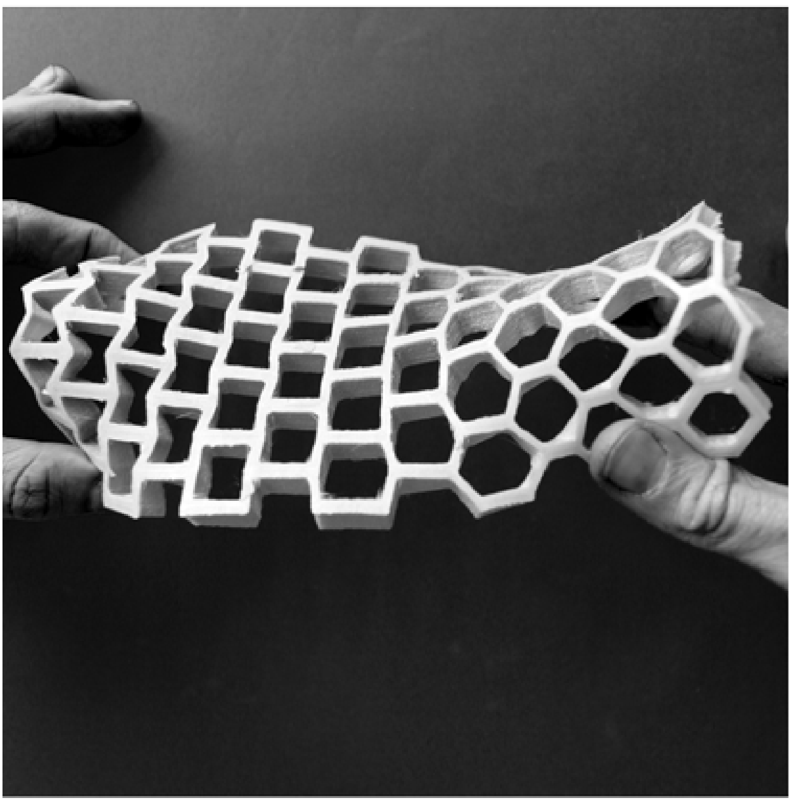


Figure 13

Hexagonal reentrant honeycomb structure printed in flexible material (Filaflex 3D by Recreus). This model is a second attempt to evaluate the "opening parameter".
In figure below it can be observed how the curvature changes. In the median portion (t parameter: 0.5) the structure shows high resistance to bending.

	ECOGENIUS PLA	FLEX MARK 9	ULTRAFLEXX+
Printable Properties: Nozzle temperature	195°C	225°C	220°C
Build Plate	60°C	45°C	45°C
Print Speed	70mm/s	30mm/s	35mm/s
Mechanical Properties Nozzle Charpy Impact at +23°C	Ø	No Break	No Break
Charpy Impact at -30°C	Ø	No Break	No Break
Tensile strength (MPa)	53	55	Ø
elongation break	105 %	600 %	200 %
Physical Properties Density (g/cm3)	Ø	1,15	1,24

Figure 14

Comparison among the materials utilized in past prototypes. Materials similar to these could be used in the printing of the AB-aS.

5.4 MATERIALS

In the building industry - even though widely presents - polymers are used mainly for minor components: tubes, insulation, membranes, foams, eaves, etc.etc. They are used for their affordability, availability, lightness, facility of movimentation, long duration, but the innovative potentialities of them are usually not considered since associated to the idea of being a “poor” and perishable material and, for this reason, they are usually camouflaged into the structure (Cecchini, 2003). In the presented technology, polymers are used as principal material, also in the load bearing proposal of the pavilion.

- The materials used to print the most of the prototypes were:
- polylactic acid (PLA)
- TPU polymers
- Nylon based polymers

Polylactic acid or polylactide (PLA) is a biodegradable thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, tapioca roots or sugarcane. In 2010, PLA had the second highest consumption volume of any bioplastic of the world. PLA is a polyester and, when used in 3d printing, is usually exploited for its rigidity and because it is easy to be printed.

Thermoplastic polyurethane (TPU) part of a class of polyurethane plastics with many properties, among whom elasticity. Technically, they are thermoplastic elastomers.
The crystalline areas the the polymeric chain, are located in a soft

and flexible matrix which account for the high elasticity level of TPU, whereas the flexible chains will impart the elongation characteristics to the polymer. Usually the flexible filaments that can be found for three dimensional printers are based on this polymer.

An interesting exception is made by the filaments Ultraflexx+, which is an elastomer based on nylon which guarantee a stronger tenacity while maintaining a certain flexibility.
NYLON is a generic designation for a family of synthetic polymers, more specifically aliphatic or semi-aromatic polyamides. They can be melt-processed into fibers, films or shapes. Because the nylon molecular chain is so regular and symmetrical, nylons often have high crystallinity and make excellent fibers. When extruded into fibers the individual polymer chains tend to align and if subjected to cold drawing afterwards, the fibers align further, increasing their crystallinity, and the material acquires additional tensile strength.

In order to continue on the structural analysis, it would be necessary a strong collaboration with the polymer producer so to arrive to define a material that have a constitutive law with the right proportion between stress and deformation.

5.5 FOUNDATIONS

Since the characteristic of the AB-aS is to be printed with flexible elements, it does not have to work as an hyperstatic structure, reacting to all the forces as a rigid body, but it has to go after the forces flowing into it by working as an isostatic structural element - that permits little deflections and oscillations in order to maintain its asset intact.
In order to give the necessary degree of freedom to the structure, a spatial joint has to be applied. Joints are spatial if they impede both linear movements and rotations. In the volumetric spaces the degree of freedom (DoF) possessed by an elements are six and depending on the number of the DoF that the joints will impede, they will be called simple, double, triple, quadruple, quintuple and sextuple.

Figure 15

Large scale printer produced by WinSun (China). Images via australiandesignreview.com

5.6 ON-SITE PRODUCTION OF THE STRUCTURE

During this work, the proposed structure was prototyped with 3d printers, i.e. Kloner3D K240 and K320. This fast prototyping method proved to be of an essential help - other processes would have had high costs and request longer periods of production. It was understood how this tool could be useful also in a scaled-up version, so to produce the final product directly on site and with similar materials to the one that were used. For this reason a research on the already existing large-scale printers is presented. Similar machinery would be used in the fabrication of an AB-aS.

5.7.1 Large-Scale Printers

As previously mentioned, the structure is supposed to be fabricated on-site employing a 3d-printer. Nowadays there are examples of large-scale printers, here are reported three of main interest. In the creation of a AB-aS there would be the need of a printer extruding polymeric materials in large scale, which is something that nowadays is still not happening.

WinSun - China

After constructing ten houses in under twenty-four hours, Chinese

Figure 16

Large scale printer produced by Wasp (Italy). Images by WASProject

company WinSun Decoration Design Engineering Co has expanded the capabilities of 3D printing with both the world's tallest 3D printed building - a five-story apartment block - and a 1,100 square meter mansion with internal and external decoration to boot.
On display in Suzhou Industrial Park in Jiangsu province, the two buildings represent new frontiers for 3D printed construction, finally demonstrating its potential for creating more traditional building typologies and therefore its suitability for use by mainstream developers
The buildings were created using the same 6.6 by 10 meter tall printer which builds up layers of a mixture of glass fibre, steel, cement, hardening agents and recycled construction waste. With this technology, WinSun is able to print out large sections of a building, which are then assembled together much like prefabricated concrete designs to create the final building.

Wasp - Italy

Italian 3D printer producer wasp built a machine capable to p
Another option to 3D print a house is the Big Delta 12m 3D Printer by WASP.
Ever since it started making 3D printers, WASP's founder Massimo Moretti has dreamed of creating a 3D printer that can build homes on location, using soil and minimum energy. The goal is to help solve the world's housing problems in the most sustainable way possible. To achieve this, the company has built progressively larger delta 3D printers with special extruders.
After the 6 meter and 8 meter model, the final Big Delta has been built to be 12 meters tall and able to 3D print cylindrical habitable structures as tall as 6 meters.

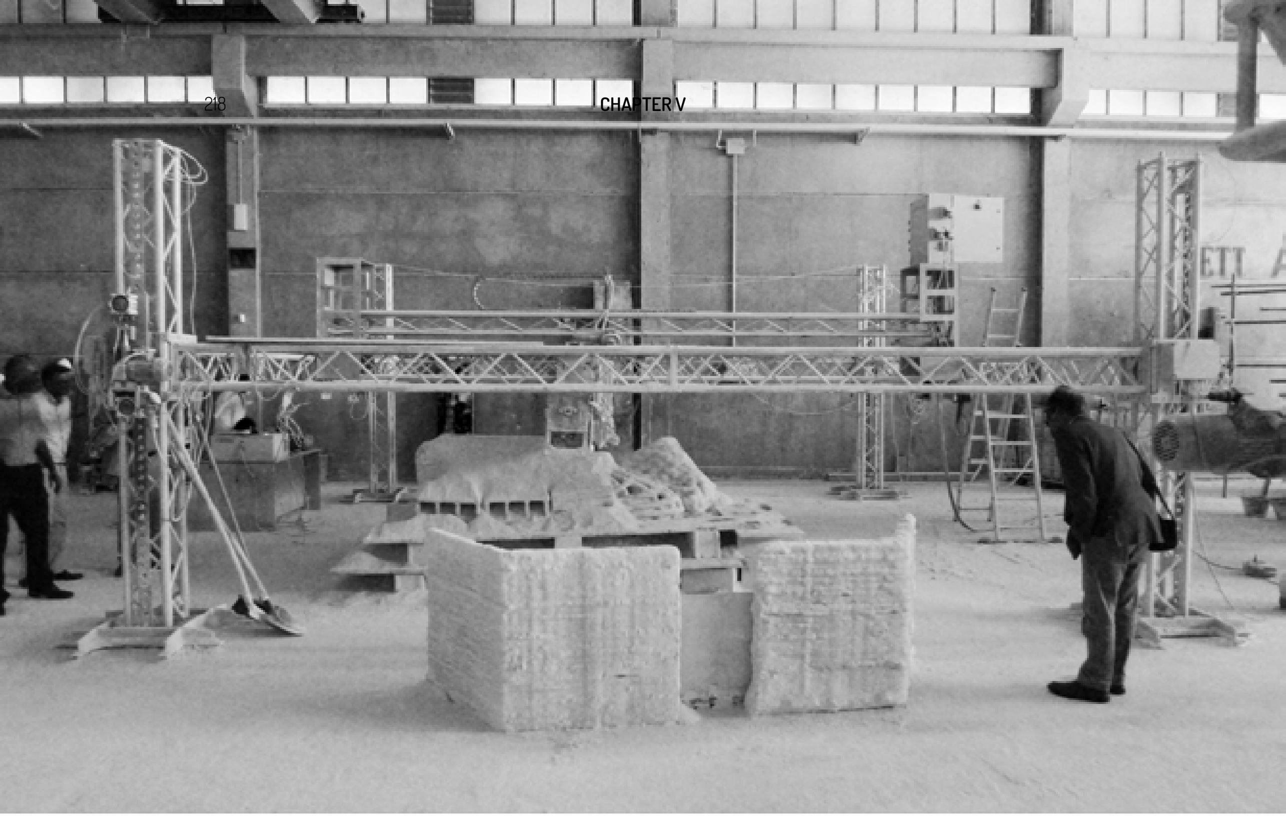


Figure 17

Large scale printer produced by D-Shape (Italy). Images via d-shape.com

D-Shape - Italy

Enrico Dini has been the forefather of house 3D printing ever since he invented the D-Shape concept. His technology is being used for a study by the European Space Agency (ESA) on the construction of Lunar colonies using lunar regolith. This 3D printer does not work on extrusion like the other construction 3D printers. Instead, it uses a binder jetting process, which means it deposits layers of a particular artificial sandstone. Then it creates the construction layer by applying a binder. This offers more geometrical freedom for construction than other technologies. His creations are currently picked up by ESA, as All3DP reported.
The D-Shape building process is similar to the "printing" process because the system operates by straining a binder on a sand layer (more on materials in the next section). This is similar to what an ink-jet printer does on a sheet of paper. This principle allows the architect to design fantastically complex architectural structures and despite its large size, the structure is a very light and it can be easily transported, assembled and dismantled in a few hours by two workmen.

The process begins with the architect designing his project using CAD 3D Computer technology. The Computer design obtained is downloaded into a STL file and is imported into the Computer program that controls D-Shape's printer head. The process takes place in a non-stop work session, starting from the foundation level and ending on the top of the roof, including stairs, external and internal partition walls, concave and convex surfaces, bas-reliefs, columns, statues, wiring, cabling and piping cavities. During the printing of each section a 'structural ink' is deposited by the printer's nozzles on the sand. The solidification process takes 24 hours to

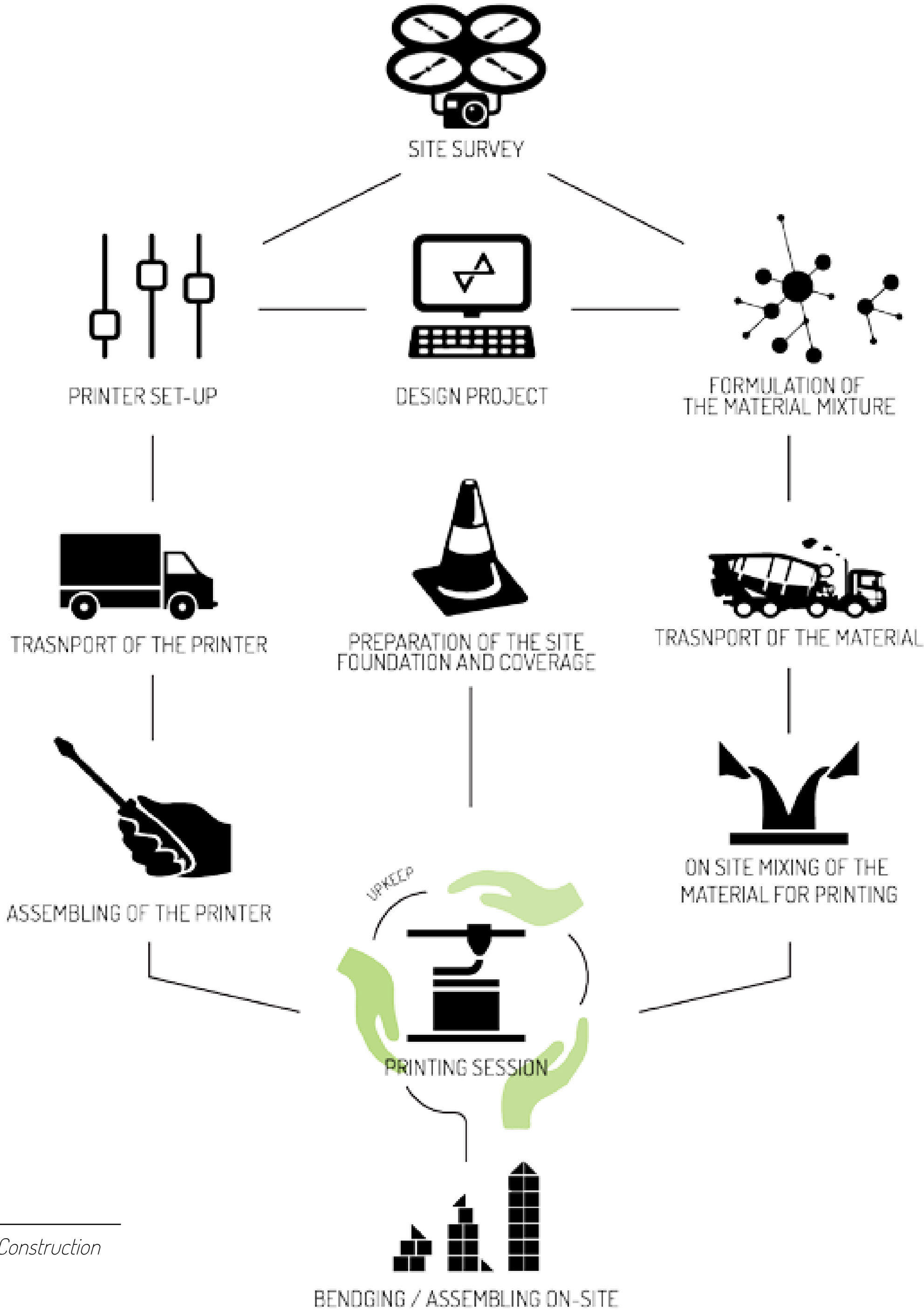


Figure 18

Building Construction Process

complete. The printing starts from the bottom of the construction and rises up in sections of 5-10mm. Upon contact the solidification process starts and a new layer is added.
Surplus sand that has not been embedded within the structure acts as a buttressing support while the solidification process takes place. This surplus sand then can be reused on future buildings.

5.6.2 Logistic and Management of the Construction Site

The Auxetic Bending-active Structure (AB-aS) is intended to be a versatile technology useful for the production of shells, façade elements, interior design etc.etc.
Previous a comprehension of the technology, the architect can survey the site and prepare the computer models. Each elements that is going to be printed will be saved as a separate file and it will be printed directly on site. This will avoid the problematics related to the transportation of big elements. The architect will directly communicate to the company producing the printer which are the dimensions needed and the company itself will deliver the printer on the site, previously prepared for the printing session. Depending on the structure that has to be erected, the printer will occupy the whole site - in the case of the construction of a pavilion or similars - otherwise - in the case of façade elements - a smaller area will be assigent to it.
In parallel, the designer will collaborate with the industry producing the printing materials to find a perfect mixture that fully satisfy the structural needs.

Once that everything is prepared on site, the printing session can start and workers will upkeep the process, collaborating with softwares experts and printer technicians.
Finally, the element can be moved to their place or bent directly on site, after that the printer has been removed and the the joining elements are arrived.

5.7 STRUCTURAL CONSIDERATIONS AND CRITICS

As follows, elements of interest and critiques are considered.

Freedom from Joints :

Thanks to 3d printing, the structure will be a solidal element that can guarantee that the flux of inner forces and tensions has no interruptions - as it would be in a non-homogeneous structure where joining elements are present. 3D printing was understood to be a uniquely versatile process.

Embedded Systems:

The production with 3D-printing can offer a high level of versatility in the introduction into the structure of different implants needed to guarantee climatic comforts, electrical supplies and fulfill specific aesthetic choices.
In the case that there would be the need to bring light inside the space delimited by an auxetix bending-active technology, a specific design strategy would answer to the needs.
If in traditional cases small tubular elements would be applied onto the structure to host the passage of electrical filaments - with 3D printing the same need would be fulfilled by layering filaments of conductive-polymers inside the structure - which itself would work as insulating parament (see imageX). Applying the same criteria, water tubes could be printed or inserted into the structures or an

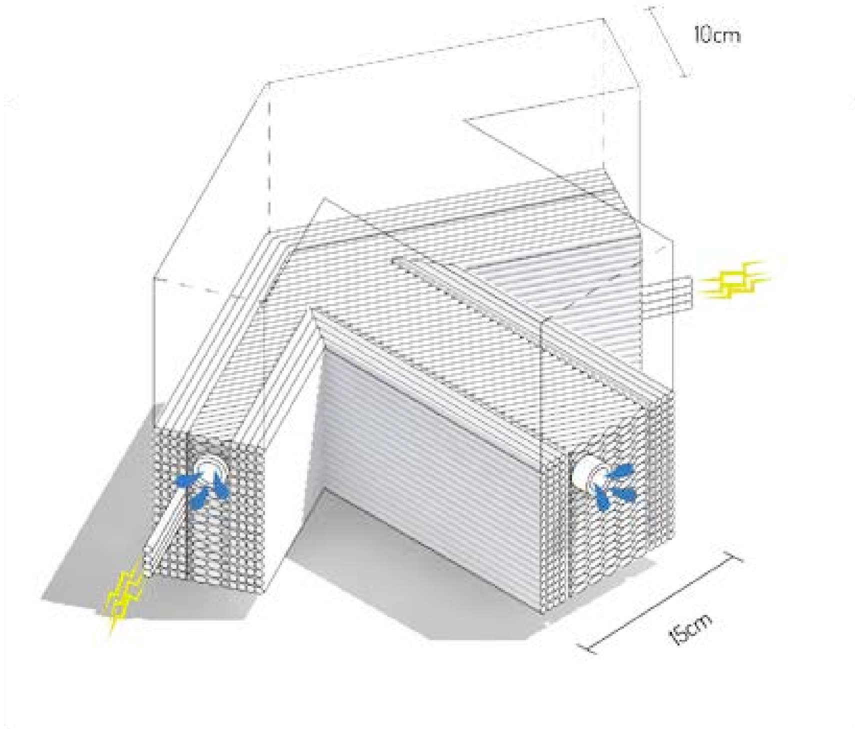


Figure 19

Changing the materials and inserting elements while printing can help in embed other systems into the structure. In this example, electricity is brought through the use of a polymer mixed with carbonium (high-conductive material) and water is supplied thanks to the insertion of a small tubular element.

infinite amount of aesthetic finishes could be studied. The limits for this application are only imposed by the study of materials that have similar characteristics in terms of resistance and structural-cooperation while still carrying out the needed embedded-sytems specimens.

Scale Effect:

When using this technology to build up an architectural element, it will be essential to pay attention to the scale effect: polymeric materials are not working in the same way when the scale varied. Increasing the transversal section of the elements over certain limits will lead to problematics related to self weight coefficients. Anyway - considering that these flexible polymers have a self weight that is around 1'200 kg/m3 - this should not be a problem if the dimensional range will to go over the small-pavilion size.
A comparison can help: the self weight of the proposed polymers is much lower than steel, which is 7'800kg/m3 but higher than spruce wood, whose value is around 700 kg/m3 thus positioning the material near to the values obtained by structural materials.

On-site bending:

The proposed technology derives interest also by the possibilities of the on-site bending.
Nowadays curved façades are reclaiming more and more interest, but still the production processes of curved elements are expensive and difficult in the execution. An example is given by the production of curved glass sheets that nowadays are bent directly on site instead that coming curved from the fabric. The project of specific laminated glass in fact, permits to bring the laminates to

the building site in planar configuration and to bend them into the structural frame once arrived, thus saving space and avoiding the costs of the heat-bending process.
processing of heat-curved sheets of glass, that thanks to modern developments areInteresting considerations can learnt by the new technologies discovered in the cold bending of glass sheets.

Bearing/Supported Structure:

Another important consideration as to be done regarding the usage of the structure.
In italy, as well as in the other countries, materials are controlled by legislations that classify them as material that have structural characteristic and other that are not structural.
With the term structural we refer to materials used for applications where the mechanical characteristics are relevant. Moreover, a good structural material have to adapt to the environmental conditions, like temperature and thermal shocks, and the chemical interaction with it. The most common structural materials are glass, metals, concrete and wood.
For italian legislations, polymers are not included into this list and they cannot perform the structural function. For this reason, longer intervals of time would be needed to start a construction, slowing down the realization process.
But in the case that the technology is applied as a supported structure, the process of acceptance would be much easier. In the case of facade elements, partitions walls, interior design,etc.etc. laws are less restrictive. In this last cases, the elements bearing the auxetic bendig-active structure would be built in conventional structural materials like wood or metals.

5.8 CONCLUSIONS

With this chapter it was proposed a technology based on auxetic re-entrant honeycombs-cells pattern working as bending-active structure which is defined Auxetic Bending-active Structure (AB-aS). The structure is thought to be applied both as bearing structure as well as supported structure. In both cases, diverse characteristics enhance the structural performances and gives the possibility to vary aesthetichs and geometry. In a possible construction definition, it will have to be considered that polymeric materials are not feasible for structural purposes.

After analytical procedures, it was understood how the different rods works inside the structure: some of them work as rigid beams whereas other, in order to permit the synclastic curvature to happen, has to undergo to a certain flexion. The prototyping of models confirmed the computational analysis and showed that the structure has four parameters of tunability: in collaboration to the chosen polymeric materials these parameters will vary the output. The suggested materials are polymeric-based because of their specifically designable characteristics. Another point of interest are the simplification of the production and movimentation process given by printing the elements directly on the construction site, whether this would be for structural purposes or not, avoiding the repetitive transportation of the finished elements from the production factory to the site.

To conclude,
this studio provides a consistent analytical base for further development of the technology towards a detailed research on real-scale applications, which are already suggested and discussed. In the next chapters two visions of the technology will be presented. These visions has to be considered as such and they don't have to be intended as definitive solutions.

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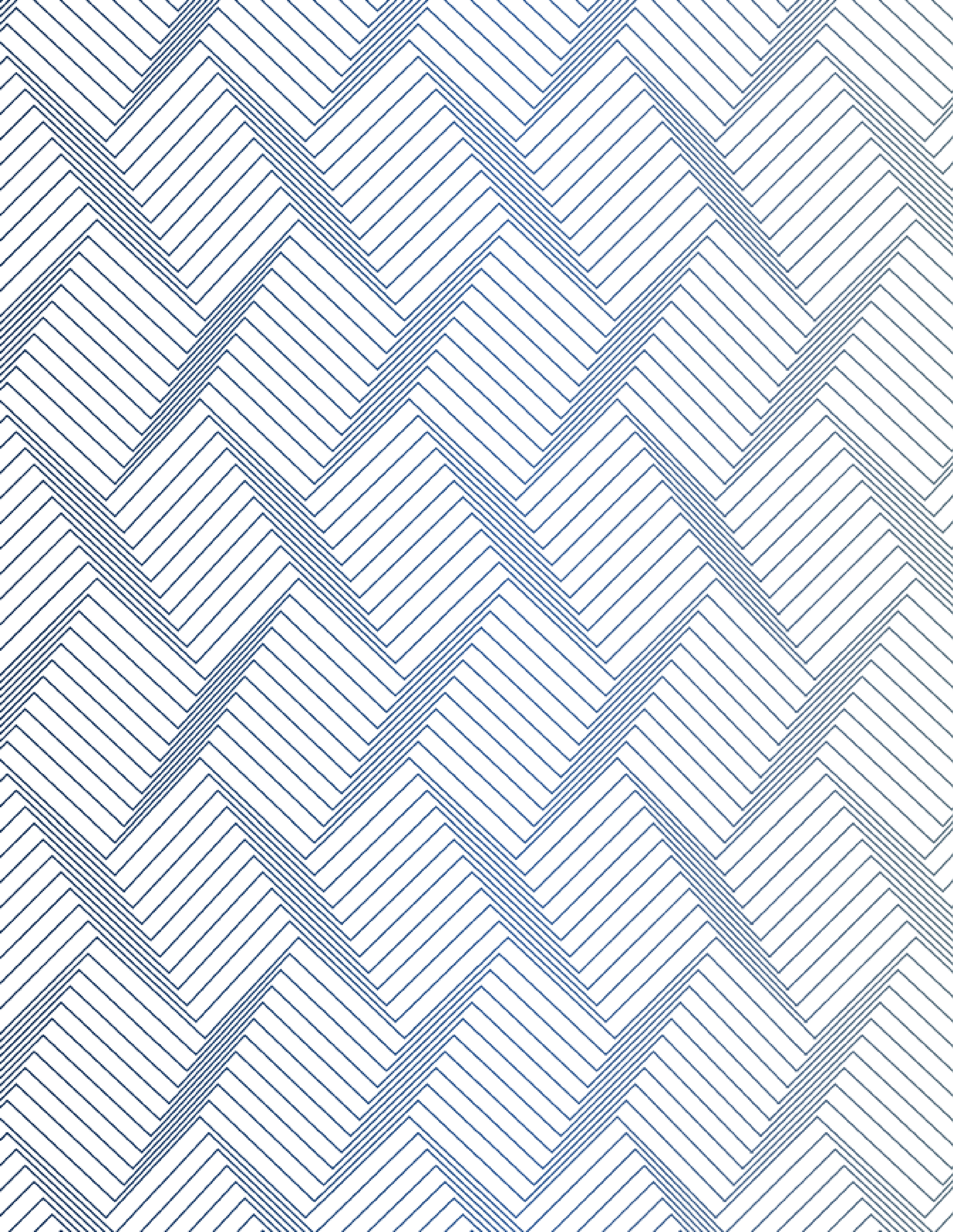
PART I

VISIONS

CHAPTER VI



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Photography by Frank Kaltenbach.

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Photography by Frank Kaltenbach and graphics by ICD/ITKE

Figure 4.
Optimization analysis done with software Millipede for Grasshopper. On the top it is showed the analysis layouts.; the arrows indicate the direction of the inserted forces. Below, it is shown the output and some details. This results are used to better understand the flows of forces inside the structure.

Figure 5.
Optimization analysis done with software Millipede for Grasshopper. On the top it is showed the analysis layouts.; the arrows indicate the direction of the inserted forces. Below, it is shown the output and some details. This results are used to better understand the flows of forces inside the structure.

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Figure 17.
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Figure 18
Building Construction Process

Figure 19
Changing the materials and inserting elements while printing can help in embed other systems into the structure. In this example, electricity is brought through the

use of a polymer mixed with carbonium (high-conductive material) and water is supplied thanks to the insertion of a small tubular element.