Honeycomb and auxetic paper-based metamaterials

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Amelia Carolina Sparavigna
Department of Applied Science and Technology, Politecnico di Torino, Italy

Honeycomb papers are metamaterials gaining their features from their structures. Let us talk about them and about possible new auxetic designs.

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"Meta", from the Greek preposition meaning "after" or "beyond", is a prefix used to indicate a concept which is an abstraction from another concept. It is used in the sense of "about" too. Then, the "metamaterials" are materials which are "beyond" common materials, that is, they are artificial objects engineered to have properties different from the original materials by which they are composed, properties that sometimes are not found in nature.

The metamaterials are assemblies of several individual elements obtained from materials such as metals or plastics, usually arranged in periodic patterns. They have then their mechanical, thermal, electric or optic features not from their composition, but from the manner their structure is designed [1,2]. These structures can deflect light or sound, creating phenomena which are impossible to have in ordinary materials, such as the recently investigated phenomenon of negative refraction [3] and the metamaterial cloaking [4,5].

It is generally supposed that the history of metamaterials begins with the study of microwave engineering, just after World War II [6]. This history seems then to follow, essentially, the development of certain manufactured objects, which interact at radio frequency and microwave. However, the research on metamaterials includes, and included, a high level of interdisciplinary, involving mechanical and electrical engineering, electromagnetism, solid state physics and materials science, optics, optoelectronics and others.

It could be surprising but one of the first applications of metamaterials was obtained in the developments and applications of cardboard materials, and this happened at the same time of radio and microwaves applications. These metamaterials were the honeycomb papers and cardboard panels. During the Second World War, honeycomb paper was used in the aerospace industry [7]. It seems that Dakota aircraft fuel tanks were wrapped with honeycomb paper, to prevent problems after mechanical shocks. However, the history of such paper structures could be probably rather older, linked to some decorative papermaking in China. Nowadays, the honeycomb paper is used in the manufacture of light structures used for interior partitions and furniture industry, being strong and light, and as a packaging material, protecting the brittle loads during transport. Glued with paper on both sides, it makes an excellent protecting material for all types of items.

The paper-based "metamaterial" is built by sandwiching a recycled material having a honeycomb structure between two layers of thick paper. This sandwich is used to build a board that being made of recycled paper is an eco-friendly object too. Besides being used in furniture for homes, these boards can be used for architectural structures, exhibition shelves, and light walls and so on. Therefore the paper and cardboard honeycomb have recently entered the area of artistic and architectural design. Let us stress that the honeycomb cardboard is a metamaterial – this fact is probably undervalued – because it is gaining a high mechanical strength from its structure, not from the materials it is made from.

Honeycomb structures have a high strength-to-weight ratio. Natural or man-made, these structures minimize the amount of used material to reach minimal weight and minimal material cost. As previously told, a man-made honeycomb structures is usually a lattice of hollow cells between thin walls that provide strength in tension, in a plate-like shape. Natural honeycomb structures include beehives made of wax and nest of wasp made of paper. Probably it was the hexagonal lattice created by honey-bees, a structure admired from ancient times, which suggested Euclid the hexagonal shape as making the most efficient use of space and building materials.

Fig.1 A natural honecomb structure, a nest of wasps made of paper (Courtesy: Wikipedia)

Paper honeycombs and the related production process had been invented in Germany by Hans Heilbrun in 1901 for decorative applications [8]. Nowadays, the three basic honeycomb production techniques are still used (expansion, corrugation and moulding), those that had been developed by 1901 for non-sandwich applications. Let us remember that a corrugated board is a paper-based material consisting of a fluted corrugated sheet and one or two flat linerboards [9]. It is widely used in the manufacture of corrugated boxes and shipping containers; using the so-called flute lamination machines. A pile of corrugated cardboards is shown in the Figure 2.

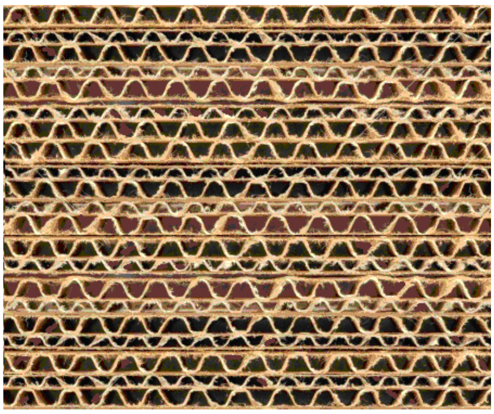

Fig.2 Piled corrugates cardboards.

Hugo Junkers, a German engineer, was the first to explore the use of a honeycomb core within a laminate structure made of metal. He proposed and patented the first honeycomb cores for aircraft application in 1915, where he describes in detail how to replace the fabric covered aircraft structures by metal sheets, which are supported by a lattice of cells. However, the problem of bonding such a structure led Junkers to produce an open corrugated structure, which could be riveted together.
For what concerns the mechanical properties, a honeycomb lattice has a positive Poisson's ratio; that is, when a honeycomb sample is stretched we have an extension in the direction of the applied load and a contraction in a direction perpendicular to the applied load. This feature of a material having a positive Poisson’s ratio is shown in the Figure 3. However, there is a new class of lattices that do the unexpected, that is they expand transversely when stretched, demonstrating a negative Poisson's ratio. In the Figure 3 we can see on the right a new lattice design called "re-entrant honeycomb", showing this counter intuitive behavior. When the ends of this lattice are pulled in the direction of the red arrows, the scaffold expands perpendicularly to the tension. These new structures are defined as "auxetics".
The term "auxetic" comes from the Greek word "auxetikos", meaning “that which tends to increase” [10]. The theory behind these metamaterials was brought to the researchers’ attention in 1987 by Rod Lakes with the development of auxetic polymeric foam [11]. These materials are of great interest thanks to their potential enhancements of the mechanical properties.

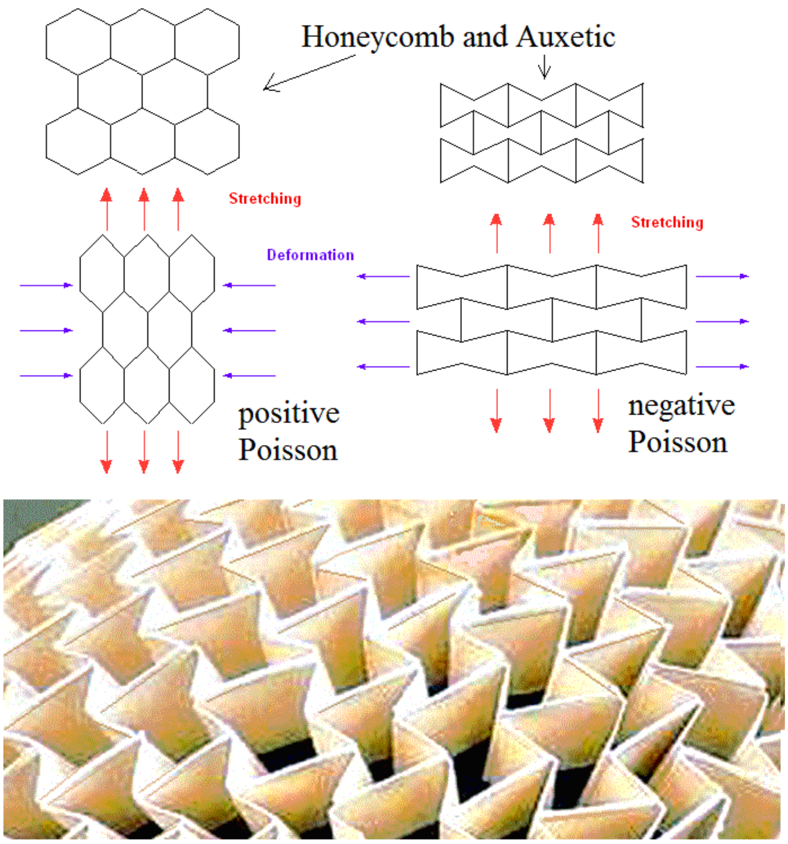

Figure 3 Comparison of the honeycomb and auxetic structures when stretched. In the lower part of the figure, an image adapted from a picture of Joseph Grima’s metamaterial. [15]

An auxetic metamaterial is proven to be more difficult to indent, that is to make notches, grooves, or holes in them, and therefore it is interesting in areas such as the blast protection [12]. We can therefore imagine a panel made of auxetic metamaterials that assists in prevention of damage due to blasts. The material will automatically adjust its mechanical properties in response to external forces. Auxetic materials are also known to have better vibrational absorption [13,14] and then they can be used to reduce sound noise. Moreover, they have a natural tendency to form dome-shaped surfaces (see Figure 3), unlike conventional materials which tend to form saddle-shaped surfaces. As a consequence, the Maltese researchers lead by Joseph Grima [15,16], developed a new way of making helmets using metamaterials, or other advanced protective equipments against sudden collisions.
For all these reasons, it would be interesting the development and tests of auxetic cardboards too, and compare their strength with that of the traditional honeycomb arrangement. Another interesting investigation could be the evaluation of their effective sound absorption. Let us consider that, in the case of using paper-based metamaterials, the reduction of noise level in public and private buildings could be achieved with a relevant weight reduction too.

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