International Journal of Sciences
Research Article Volume 3 - November 2014 (11)

Paper-based Metamaterials: Honeycomb and Auxetic Structures

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Abstract: Metamaterials are engineered materials that gain their properties from the repeating patterns of their structures. Here we discuss paper-based metamaterials, with the honeycomb structure, and a possible auxetic design of them.

Keywords: Honeycomb cells, Auxetic structures, Metamaterials, Paper, Cardboards.

1. Introduction

Metamaterials are engineered materials, usually considered made of metals or plastics, that gain their properties from the repeating patterns of their structures. The prefix "meta", from a Greek preposition meaning "after" or "beyond", is used to indicate a concept, which is an abstraction from another concept. Then, the "metamaterials" are materials that are "beyond" common materials. This means that they are artificial objects engineered to have properties different from the original materials of which they are composed. Sometimes, these properties are not found in nature or are unusual.
As beehives are composed of a regular multitude of honeycomb cells, the metamaterials are composed of many individual elements, which are usually arranged in periodic patterns. These assemblies do not gain their mechanical, thermal, electrical or optical features from the materials they are made of, but from the manner their structure is designed [1,2]. Therefore, researches on metamaterials are requiring high level of interdisciplinary, where engineers, physicists, chemists and others, are joining their efforts to produce devices which are not only able to deflect light or sound for instance, but also to create phenomena impossible to observe in ordinary materials, such as the negative refraction and the metamaterial cloaking [3,4,5]. This last process concerns the use of invisibility cloaks, which create specific paths of electromagnetic waves through them, able of shielding an object from view. The metamaterial guides the incident waves around it so that they are not able of detecting its presence.

As told in [6], the history of metamaterials can have several starting points, which are depending on the properties of interest. However, it is generally supposed that this history began with the study of microwave engineering, just after World War II, when it was started the development of certain manufactured devices, able of interacting with radio frequencies and microwaves. Metamaterials, created to interact with electromagnetic waves and composed of periodic dielectric or metal-dielectric micro- or nanostructures, are known as photonic crystals.

However, metamaterials are not only those interacting with electromagnetic waves. Acoustic metamaterials exist too; the first materials of such kind were the sonic crystals, objects exhibiting bandgaps that prevent the transmission of acoustic waves at given frequencies [7]. Sonic crystals, and their evolution, the phononic crystals, are belonging to the huge family of mechanical metamaterials, which have their mechanical properties tuned by their structures.

As told in [8], there are several materials of common use, such as those for the paper-based packaging and cardboards, which could be considered mechanical metamaterials too. Here we will discuss paper and cardboards, proposing for them an auxetic design, besides the commonly used honeycomb one.

2. The paper

Paper is a term that indicates, generally, a thin foil of material produced by pressing moist fibers. The fibers used for it are contained in the cellulose pulp derived from wood or other materials, for instance, by recycling used textiles. Drying the pressed pulp, flexible foils are obtained. Paper and the process of making it of cellulose pulp had been probably developed in China during the early 2nd century AD [9].

Of course, due to their importance, several scientific and industrial researches had been performed to increase the properties of paper-based products. The structure of paper, in particular, is the subject of several scientific investigations. For instance, in [10,11], we find a discussion of paper elasticity and

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models for explaining the experimental measurements of its Young's modulus.

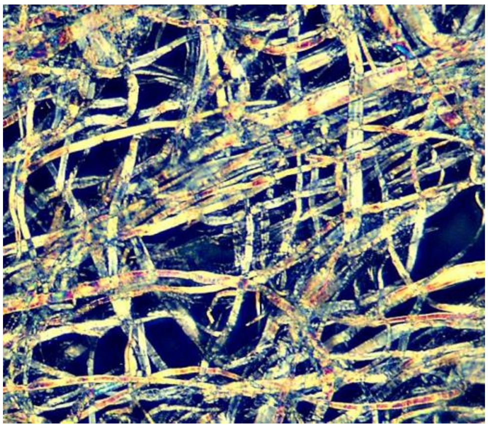

Figure 1: Fibrous structure of a disposable paper tissue (Image 200x, Courtesy: Wikipedia, Jan Homann).

Paper is a fibrous material (see for instance Figure 1), and its properties depend on the orientation of fibers [10]. This orientation is determined by the method of manufacture [12], and therefore, the papers made in industrial conditions show a consequent oriented distribution of mechanical properties [12]. The main axes of this distribution, where extreme values of breaking stresses, deformations at the moment of break and Young's modulus are achieved, almost overlap with directions imposed by machines producing paper. Two of these directions are the Machine Direction (MD) and the Cross Direction (CD). MD is the direction along which paper moves, and in this direction we find the highest values of Young's modulus. CD is perpendicular to MD. The third direction is the Thickness Direction (TD), perpendicular to the plane determined by MD and CD.

Besides the Young's modulus, another elastic parameter is important: it is the Poisson's ratio, which is given by the negative ratio of transverse to axial strain. The Poisson's ratio is usually positive, and then, when the material is stretched, it becomes narrower in its cross section. However, materials with negative Poisson's ratio exist, where the cross section is larger when the material is stretched. In [13], it is reported of a negative value of the Poisson's ratio; the negative value is supposed being produced by the network of fibers. This is shown also in a more recent research [14], which demonstrates that fibrous paper increases in thickness when stretched in planar direction. By measuring the thickness variation for different types of paper, the researchers find the Poisson's ratio to be negative (0 to -3.0). This behavior is caused by the non-woven network structure of cellulose fibers having rich hydroxyl surface. "During compressive stages of papermaking, hydrogen bonding between fibers locks them into a crumpled microstructure which expands when stretched" [14].

Materials having a negative Poisson's ratio are known as "auxetics". We will discuss them with more details in a following section.

3. Paper as metamaterial

Several paper-based materials exist. Among them, we can find some products that could be considered metamaterials, such as the honeycomb papers and cardboards (Figure 2). It could be surprising but one of the first applications of them as "metamaterials" was contemporary to radio and microwaves applications. It seems that honeycomb papers were used during Second World War in the aerospace industry [15]; Dakota aircraft fuel tanks were wrapped with them, being strong and light materials, to prevent problems after mechanical shocks. Of course, the history of such paper structures is older, linked to the creation and use of them for decorative papermaking.

Nowadays, the honeycomb paper is used in the manufacture of light structures for interior partitions and furniture industry and as a packaging material, protecting the brittle loads during transport. Glued with paper on both sides, the honeycomb paper makes an excellent packaging material to protect all types of items.

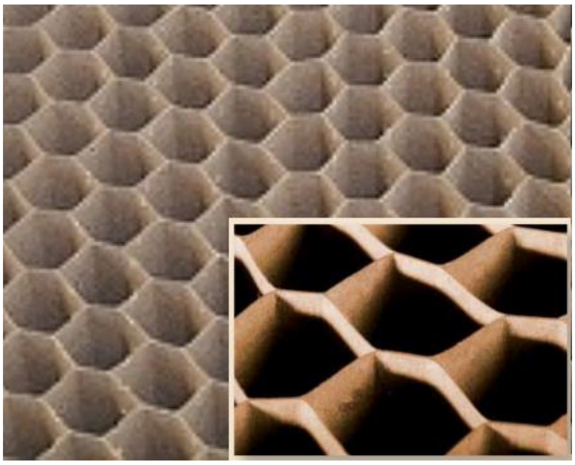

Figure 2: Honeycomb cells made of paper.

The paper-based "metamaterial" is built by sandwiching a recycled material having a honeycomb structure between two layers of thick paper. This sandwich creates 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. In this manner, honeycomb papers and cardboards have entered the area of artistic and architectural design for interior rooms of public and private houses.

Let us stress another time a fact, which is probably undervalued: the honeycomb cardboard is a metamaterial because it is gaining high mechanical strengths from its structure, not from the materials it is made of. It is a honeycomb metamaterial, in a plate-like shape, with a lattice of hollow cells, inserted between thin walls. These walls are providing the required strength when a tension is applied.

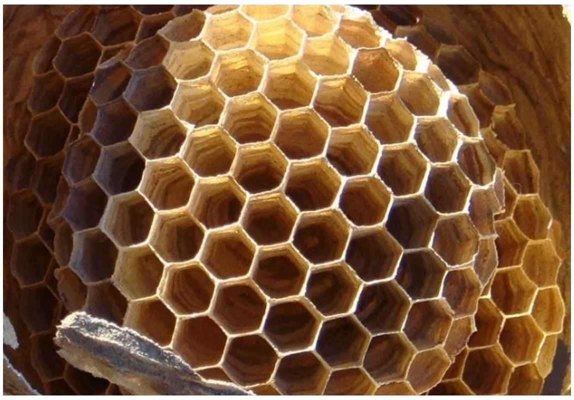

Figure 3: A natural honeycomb structure, a nest of wasps made of paper (Courtesy: Wikipedia).

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. Natural honeycomb structures include beehives made of wax and nests of wasps made of paper (Figure 3). Probably, it was the hexagonal lattice created by honeybees, a structure admired from ancient times, which suggested Euclid the hexagonal shape as the one having the most efficient use of space and building materials.

Honeycomb papers, and the related industrial production processes, had been invented in Germany by Hans Heilbrun, in 1901, for decorative applications [15-17]. Nowadays, the three basic honeycomb production techniques are still used (expansion, corrugation and moulding), including those that had been developed in 1901 for non-sandwich applications. To have a perception of the importance of these processes, let us consider the corrugated boards. They are consisting of fluted corrugated sheets with one or two flat linerboards, and are obtained using the so-called flute lamination machines [17]. Corrugated boards are widely used in the manufacture of boxes and shipping containers, and therefore we find them everywhere (a pile of corrugated cardboards is shown in the Figure 4).

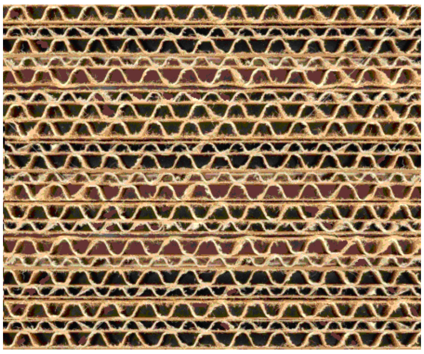

Figure 4: Piled corrugates cardboards.

4. Honeycomb and auxetic structures

For what concerns the ratio of transverse to axial strain, a honeycomb lattice has a positive Poisson's ratio; this means that when a honeycomb sample is stretched, we have an elongation of the lattice in the direction of applied tension and a contraction in the direction perpendicular to it. This is illustrated in the Figure 5, on the left. 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 5, we can see, on the right, a new lattice design called "re-entrant honeycomb", showing this counterintuitive 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 known as "auxetics".

The term "auxetic" comes from the Greek word "auxetikos", meaning "that which tends to increase" [18]. The theory behind these metamaterials was brought to the researchers' attention, in 1987, by Rod Lakes with the development of auxetic polymeric foams [19]. These materials are of great interest because of their potential enhancements of the mechanical properties.

An auxetic metamaterial is proven to be more difficult to indent, that is to make notches, grooves, or holes in it, and therefore, it is interesting in areas such as the blast protection [20]. We can therefore imagine a panel made of auxetic metamaterial 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 a better vibrational absorption [21,22] and then they can be used to reduce sound noise. Moreover, they have a natural tendency to form dome-shaped surfaces, unlike conventional materials, which tend to form saddle-shaped surfaces. As a consequence, the Maltese researchers lead by Joseph Grima [23,24], developed a new way of making helmets using metamaterials, or other advanced protective equipments against sudden collisions.

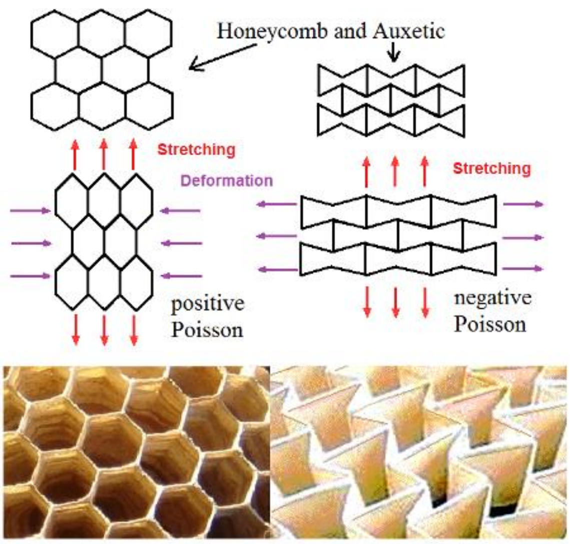

Figure 5: Comparison of the honeycomb and auxetic structures when stretched. In the lower part of the figure, on the right, an image adapted from a picture of Joseph Grima's metamaterial [24,25].

5. Conclusion

For the several reasons discussed above, it would be interesting the development and test 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 reduction of weight too.

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