Journal Club April 2010: Negative Poisson's ratio materials

Metamaterials are artificial materials engineered to provide properties which may not be readily available in nature and are attracting increasing attention. These materials usually gain their properties from structure rather than composition. Although the first metamaterials were photonic (i.e. artificially fabricated, sub-wavelength, periodic structures, designed to interact with optical frequencies) and acoustic (i.e. artificially fabricated materials designed to control, direct, and manipulate sound), the idea may be extended to the mechanical properties of materials defining mechanical metamaterials as artificially fabricated structures designed to achieve unusual mechanical properties. Interesting examples of mechanical metamaterials are provided by negative Poisson's ratio and negative thermal expansion materials. Here I will focus on negative Poisson's ratio materials, while inspiring results for negative thermal expansion materials were reported by Sigmund and Torquato (1997) and Steeves et al. (2007).

When materials are compressed (stretched) along a particular axis they are most commonly observed to expand (contract) in directions orthogonal to the applied load (Fig. 1 - left). The property that characterizes this behavior is the Poisson's ratio which is defined as the ratio between the negative transverse and longitudinal strains. The majority of materials are characterized by a positive Poisson's ratio which is approximately 0.5 for rubber and 0.3 for glass and steel. Materials with a negative Poisson's ratio will contract (expand) in the transverse direction when compressed (stretched) (Fig. 1 - right) and, although they can exist in principle, demonstration of practical examples is relatively recent.

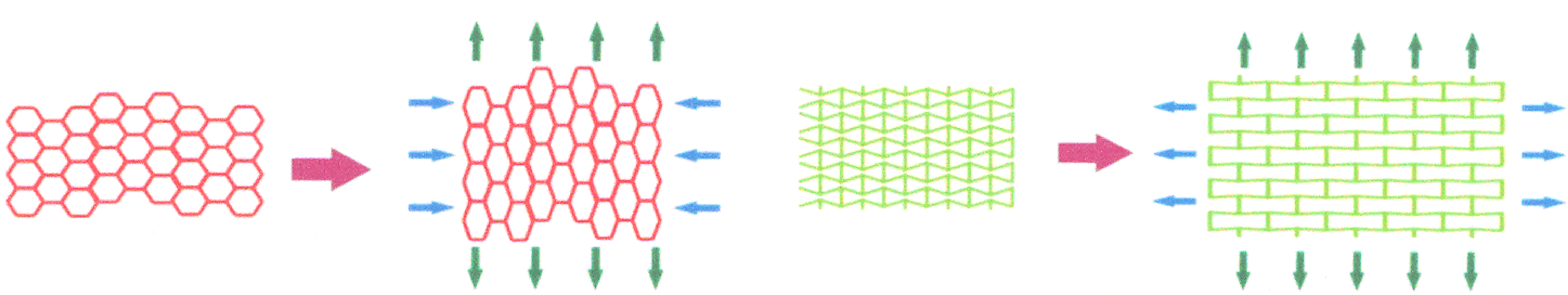

Figure1: Left: The material elongates and contracts when stretched, leading to a positive Poisson's ratio. Right: The structure unfolds when stretched, causing lateral expansion and a negative Poisson's ratio.

There is significant interest in the development of negative Poisson's ratio materials because of potential in applications in areas such the design of novel fasteners (Choi and Lakes, 1991), prostheses (Scarpa, 2008), piezocomposites with optimal performance (Sigmund et al, 1998) and foams with superior damping and acoustic properties (Scarpa et al., 2004). Moreover, auxetic materials may lead to the design of stronger composite materials. The primary failure mechanism of composite materials is through reinforcement "pull-out", a tensile failure caused by the reinforcing fibers getting narrower and pulling away from the matrix. Due to the fact that auxetic materials expand when stretched, however, the load required to cause structural failure will significantly increase.

Discovery and development of materials with negative Poisson's ratio, also called auxetics, was first reported in the seminal work of Lakes in 1987 (Lakes, 1987). The auxetic behavior was achieved using a novel foam characterized by a reentrant microstructure (Fig. 2) that unfolds when stretched (Fig. 1-right), causing lateral expansion and negative Poisson's ratio. In the case of thermoplastic foams the transformation from the conventional to auxetic form is achieved by triaxial compression followed by heating of the compressed foam to above the softening point.

Lakes, R.S. Negative Poisson's ratio materials. Science, 235, 1987.

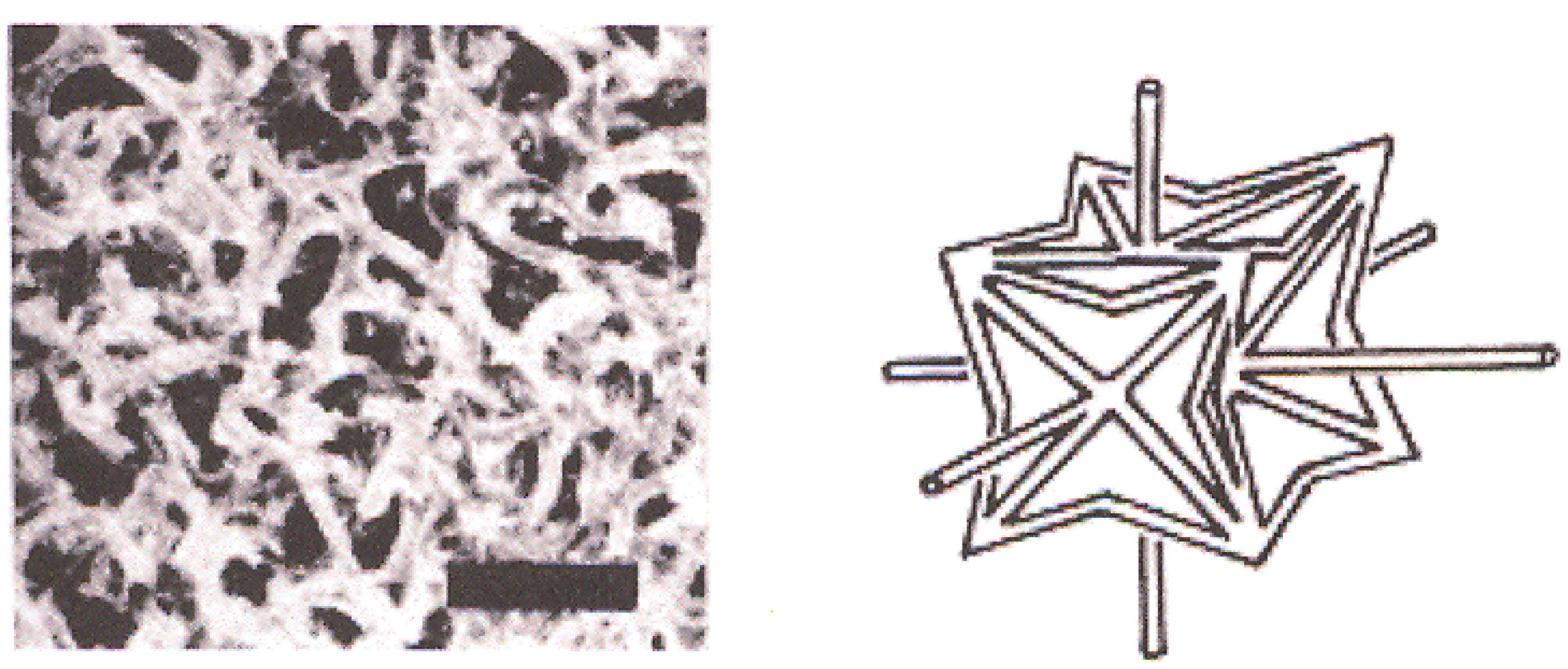

Figure 2. Stereo photograph of a reentrant foam with Poisson's ratio -0.6 (left) and idealized reentrant unit cell (right)(Figure taken from Lakes (1987)

Negative Poisson's ration materials occur also in nature. There are a growing number of natural materials that have been discovered to possess one or more negative Poisson's ratios. Baughman et al. (1998) revealed that 69% of the cubic elemental metals and some face-centered cubic (fcc) rare gas solids are auxetic when stretched along the specific [110] off-axis direction. 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.

Baughman, R. H., Shacklette, J. M., Zakhidov, A. A. and Stafstrom, S. Negative Poisson's ratios

as a common feature of cubic metals. Nature , 392, 362, 1998.

More recently it has been found that natural layered ceramics (Song et al, 2008), ferroelectric polycrystalline ceramics (Tan et al, 2009) and zeolites (Grima et al, 2000) may all exhibit negative Poisson's ratio behavior.

Moreover, several geometries and mechanisms have been proposed to achieve negative values for the Poisson's ratio and a variety of man-made auxetic materials and structures have been fabricated and synthesized from the macroscopic down to the molecular, including foams with reentrant structures (Lakes, 1987), hierarchical laminates (Milton, 1992), polymeric and metallic foams (Friis et al, 1988), microporous polymers (Caddock and Evans, 1991), molecular networks (Evans et al, 1991) and many-body systems with isotropic pair interactions (Rechtsman et al, 2008). Negative Poisson's ratio effects have also been demonstrated at the micron scale using complex materials which were fabricated using soft lithography (Xu et al, 1999) and at the nanoscale with sheets assemblies of carbon nanotubes (Hall et al, 2008). A critical issue related to auxetic material is that their fabrication often requires embedding structures with intricate geometries within a host matrix. However, recently it has been shown that instability induced pattern switches in porous elastomeric structures characterized by an initial simple microstructures may lead to auxetic behavior (Bertoldi e al., 2010).

To conclude I would like to remark the difference between isotropic and anisotropic auxetic materials. From the standpoint of applications Isotropic auxetic materials are more attractive, since negative Poisson's ratio is achieved for loadings applied along any direction. Energy arguments in the theory of elasticity may be used to show that their Poisson's ratio for isotropic materials cannot be lower than -1 and larger than ½. Differently, for anisotropic materials the bounds on Poisson's ratio are wider and Poisson's ratios smaller than -1 have been reported.

This journal entry provides a sampling of the research in a field that is active and growing. Discussion on your experiences in this area and on your perceived future challenges is welcomed :)

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