Extending two dimensional auxetic structures into three dimensions:

The 'bolt and nut' mechanism

Pierre S. Farrugia and Joseph N. Grima

Faculty of Science, University of Malta, Msida MSD 2080

Auxetic behaviour refers to the ability of material and structures to expand laterally when stretched and contract laterally when compressed. This results as a combined effect originating from the geometry of the system and the way this deforms when subjected to a load. There are various structures that deform through prescribed mechanisms that have been identified to result in auxetic behaviour. These include re-entrant and chiral honeycomb deforming through deforming through flexure [1], the rotation of rigid units in 2D and 3D (e.g. squares [2], rectangles [3], triangles [4], tetrahedral [5], etc.) as well as structures deforming through dilation-type mechanisms [6].

In this work we propose a new concept that can transform existing auxetic two dimensions lattices that involve rotation of units to three dimensional auxetics which may exhibit negative Poisson's ratios in 3D for loading in any direction.

To illustrate the proposed concept we consider a structure consisting of two parallel layers of 'rotating squares' that are attached via a "bolt" and a "nut" where the "bolt" is attached to one layer while the "nut" is attached to the other. The two layers are aligned in such a way that the square unit connected to the 'bolt' rotates in an opposite direction to the square unit attached to the "nut". When the system is uniaxially compressed in a direction in the 'rotating squares' plane, the structure will contract in this plane as a result of the 'rotating squares' mechanism. Furthermore, the "bolts" and the "nuts" will rotate in different directions in such a way that they will 'tighten up', thus decreasing the length in the third dimension.

[1] L. J. Gibson, M. F. Ashby, G. S. Schajer, and C. I. Robertson, Proc. R. Soc. Lond. A 382 (1982) 25.; D. Prall and R. S. Lakes, Int. J. of Mechanical Sciences 39 (1996) 305.
[2] J. N. Grima, A. Alderson and K. E. Evans, Zeolites with negative Poisson's ratios, Paper presented at the 4th Materials Chemistry conference, Dublin (Ireland), July 1999 (P81); J. N. Grima and K. E. Evans, J. Mater. Sci. Lett. 19 (2000) 1563; Y. Ishibahi and M. Iwata, J. Phys. Soc. Japan 69 (2000) 2702.
[3] J. N. Grima, A. Alderson and K. E. Evans, Phys. Stat. Sol. (b) 242 (2005) 561.
[4] J. N. Grima and K. E. Evans, J. Mater. Sci. 41 (2006) 3193.
[5] A. Alderson and K. E. Evans, Phys. Chem. Minerals 28 (2001) 711..
[6] K. W. Wojciechowski, Mol. Phys. 61 (1987) 1247; K. W. Wojciechowski and A. C. Branka, Phys. Rev. A 40 (1989) 7222; K. W. Wojciechowski, J. Phys. A: Math. Gen. 36 (2003b) 11765.

Extending 2D auxetic structures into 3D: The "bolt and nut" mechanism

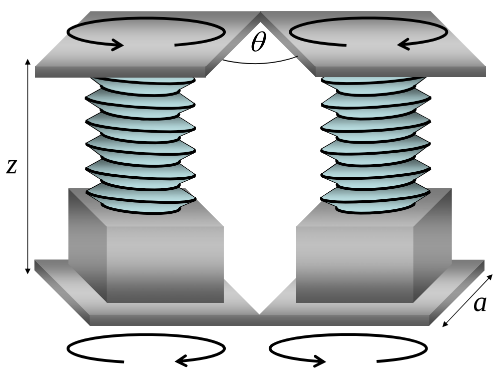
Pierre S. Farrugia and Joseph N. Grima
Faculty of Science, University of Malta

Auxetic behaviour refers to the ability of materials and structures to expand laterally when stretched and contract laterally when compressed. This results as a combined effect originating from the geometry of the system and the way this deforms when subjected to a load. There are various structures that deform through prescribed mechanisms that have been identified to result in auxetic behaviour. These include re-entrant and chiral honeycombs deforming through flexure [1], rotation of rigid units in 2D and 3D (e.g. squares [2], rectangles [3], triangles [4], tetrahedral [5], etc.) as well as systems deforming through dilation-type mechanisms [6].

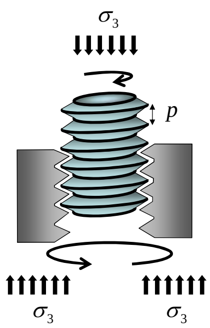
In this work we propose a new concept that can transform existing auxetic two dimensions lattices that involve rotation of units to three dimensional auxetics that may exhibit negative Poisson's ratios in 3D for loading in any direction.

The Idea

Consider a structure consisting of two parallel layers of "rotating squares" that are attached *via* a "bolt" and a "nut" where the "bolt" is attached to one layer while the "nut" is attached to the other as shown below. The two layers are aligned in such a way that the square unit connected to the "bolt" rotates in an opposite direction to the square unit attached to the "nut." When the system is uniaxially compressed in a direction in the "rotating squares" plane, under the right conditions, the structure will contract in this plane as a result of the "rotating squares" mechanism. Furthermore, the "bolts" and the "nuts" will rotate in different directions in such a way that they will "tighten up," thus decreasing the length in the third dimension.



Also, provided that the pitch of the tread is sufficiently large, when loaded in the third direction the "bolt" and the "nut" will slide past each other causing a decrease in the third dimension together with a rotation of the "bolt" and the "nut". This will cause the squares connected to them to rotate, that under the right conditions, will induce a decrease in size in the orthogonal directions.



Equations

Analysis of the situation indicates that:

- The Poisson's ratios are,

$$\nu_{12} = \nu_{21} = -1 \qquad \nu_{13} = \nu_{23} = (\nu_{31})^{-1} = (\nu_{32})^{-1} = -\frac{2p}{\pi z}\tan\left(\frac{\theta + \frac{1}{2}\pi}{2}\right)$$

- The Young's moduli are,

$$E_1 = E_2 = \frac{16K_h}{a^2 z[1-\sin(\theta)]} \qquad E_3 = \frac{4z\pi^2 K_h}{p^2 a^2[1-\sin(\theta)]}$$

where z is the height in the third direction, p is the pitch, K_h is the stiffness constant of the rotating squares and a is the length of one of the sides of the squares.

- The Shear Modulus is infinite in all three orthogonal directions.

Conclusions

The above shows that it is possible to use twisting in order to achieve a decrease in length. If this is coupled with two layers of auxetic materials that have rotating units vertically above each other that rotate in opposite directions it is possible to straightforwardly extend 2D auxetics into 3D. The "bolt and nut" mechanism is just one possible example that is simple to construct and understand. However, there are other possible ways of achieving the same result that we are currently considering. These include helixes and simple line elements.

References

[1] L. J. Gibson, M. F. Ashby, G. S. Schajer, and C. I. Robertson, *Proc. R. Soc. Lond. A,* 382 (1982) 25.; D. Prall and R. S. Lakes, *Int. J. of Mechanical Sciences*, 39 (1996) 305.
[2] J. N. Grima, A. Alderson and K.E. Evans, Zeolites with negative Poisson's ratios, Paper presented at the 4th Materials Chemistry conference, Dublin (Ireland), July 1999 (P81); J. N. Grima and K. E. Evans, *J. Mater. Sci. Lett.,* 19 (2000) 1563; Y. Ishibahi and M. Iwata, J. Phys. Soc. Japan 69 (2000) 2702.
[3] J. N. Grima, A. Alderson and K. E. Evans, *Phys. Stat. Sol. (b)*, 242 (2005) 561.
[4] J. N. Grima and K. E. Evans, *J. Mater. Sci.*, 41 (2006) 3193.
[5] A. Alderson and K. E. Evans, *Phys. Chem. Minerals*, 28 (2001) 711.
[6] K. W. Wojciechowski, *Mol. Phys.,* 61 (1987) 1247; K. W. Wojciechowski andA. C. Branka, *Phys. Rev. A*, 40 (1989) 7222; K. W. Wojciechowski, *J. Phys. A: Math. Gen.,* 36 (2003) 11765.

http://www.auxetic.info