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Pantographic metamaterials: smart materials and their simulation methods

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Mechanical metamaterials

The inner structure determines the mechanical properties of materials. By using specific geometries on the scale below a material bodies dimension the behavior can be systematically influenced. The emerging characteristics are often very distinct from continuous materials, so that a new class of materials, the metamaterials, emerges.

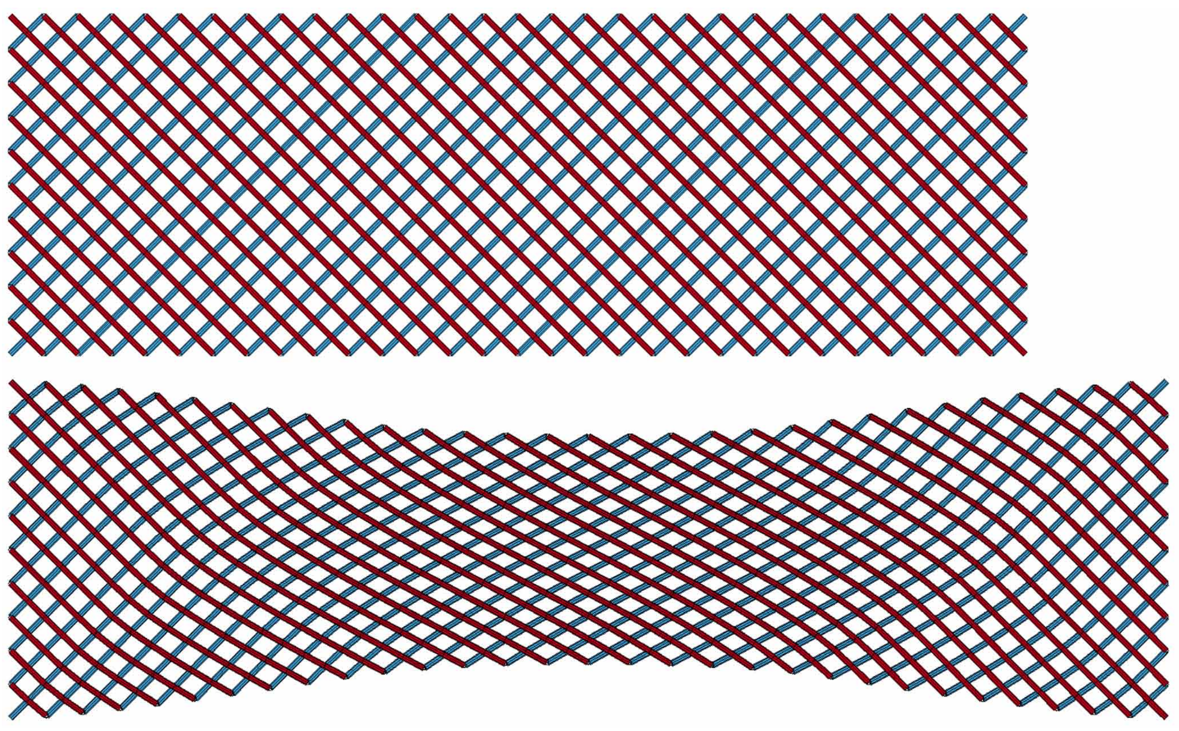

Figure 1: The pantographic sheet in its undeformed state and during bias extension.

Pantographic sheets

Connecting two layers of orthogonal fibers with a pivot results in a sheet simple in its structure yet complex its mechanical response, *see Figure 1*. Even with metallic materials a high flexibility can be realized. This makes it a suitable and interesting study object to explore some of the principles of metamaterials. This raises, among others, two basic questions:

- How can we further design metamaterial behavior?
- What are suitable computational methods to predict these behaviors?

Bistability and actuators

The pantographic sheet's mobility is mainly determined by its pivots. By systematically changing their features one can configure the overall reactions. Through bistability there can be additional equilibrium configurations and therefore shapes that are retained without external load or damage.

Actuators further reduce the need of external effects. Previously stored energy can be released as a twisting of selected pivots and an autonomous deformation occurs, *see Figure 2*.

Simulation methods

As cost-effective in the sense of computation time, a beam model in a finite element environment can be applied to pantographic sheets. However, if the number of unit cells or their complexity is increased, a more efficient method is desirable. This usually calls for multiscale modeling with homogenization. Interestingly it becomes apparent that many metamaterials are only insufficiently represented by classical homogenization methods for finite element simulations. Some of these materials are categorized as *second gradient materials* since derivatives of second order in their displacement need to be considered for correct representation as homogeneous matter. The mapping χ in the neighborhood of a material point X can no longer be linearized as the relevant length scale λ of the substructure is no longer infinitesimal compared to the coarse structure, *see Equation 1*.

$$\chi(X+\lambda) = \chi(X) + \lambda\nabla\chi(X) + \frac{\lambda^2}{2}\nabla\nabla\chi(X) + \ldots \tag{1}$$

The usual finite element based code environments are in general not able to replicate these materials as elements with additional degrees of freedom are needed. A problem-specific formulation with energy minimization in an FEM environment is in principal feasible [1]. More comprehensive and versatile methods are yet to be developed.

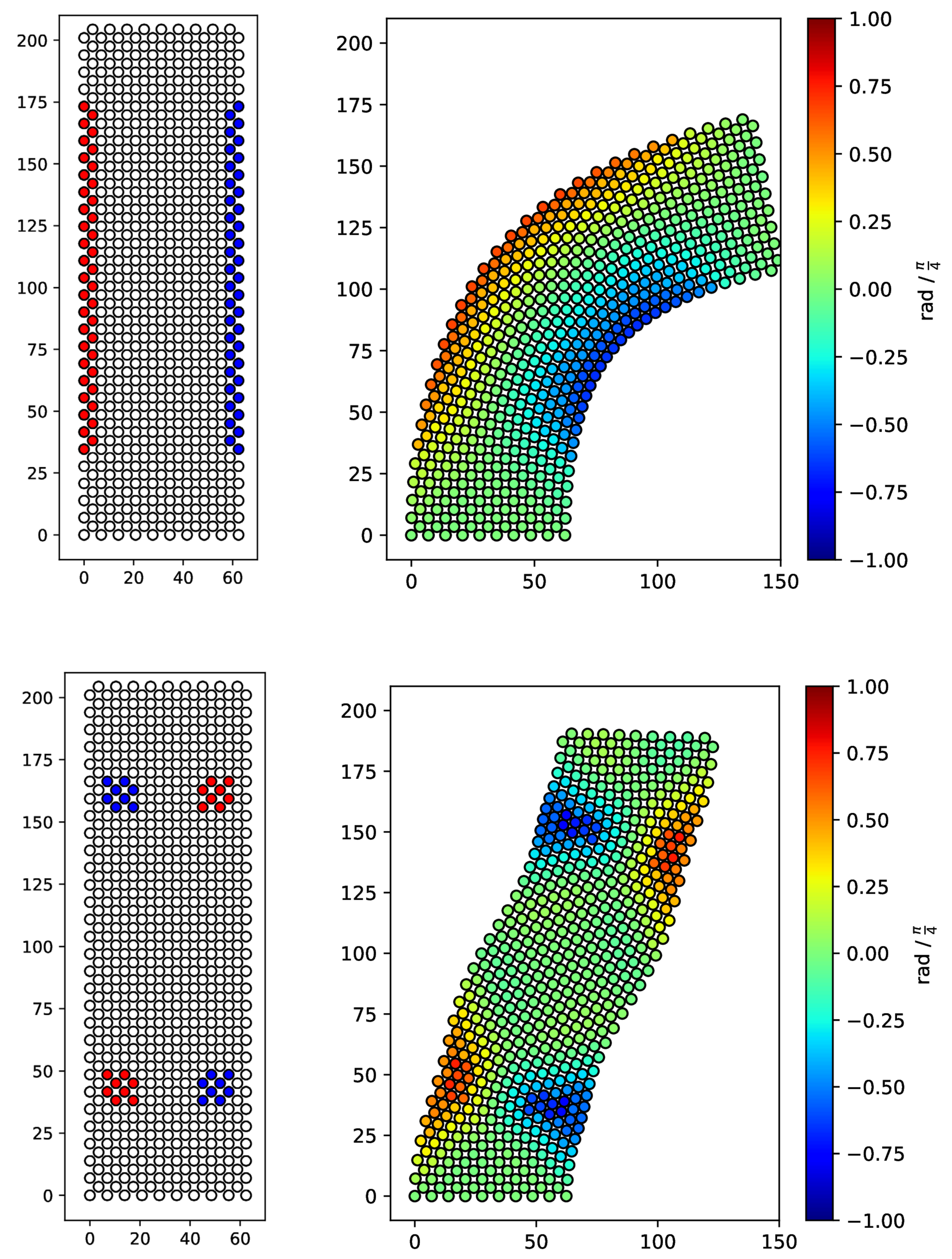

Figure 2: Twisting of certain pivots (left) leads to controlled bending (top) or shearing (bottom) motion.

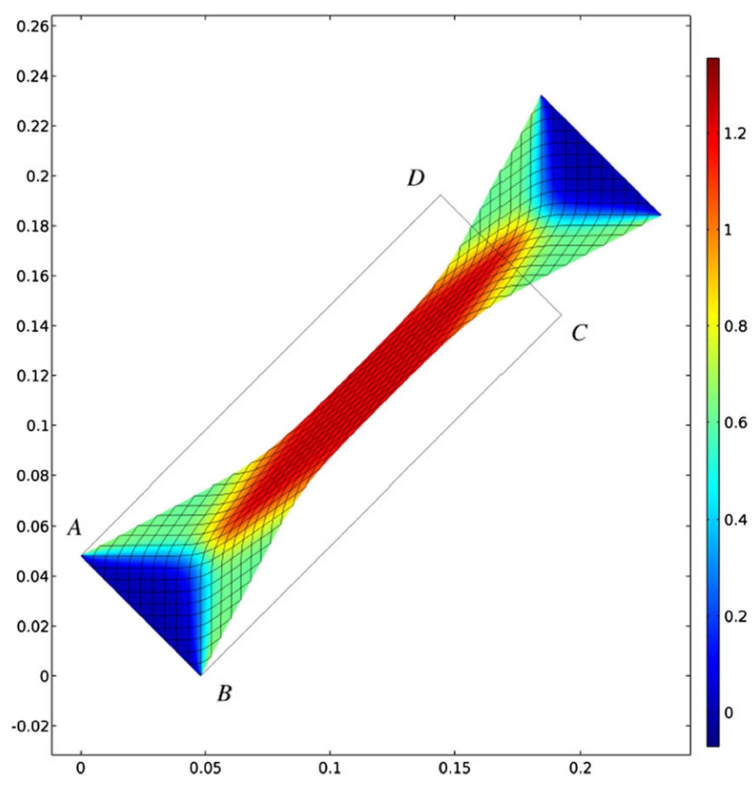

Figure 3: In-plane shear angle of a pantographic sheet simulated as 2D second gradient material [1].

Prospects

Through smart design, metamaterials offer yet unimagined possibilities in their mechanical behavior. Bistabilities and actuators have the ability to further move this towards programmable shape morphing materials.

One of the challenges is to find a suitable numerical method for reliable predictions. The pantographic sheet through its simple structure provides an ideal framework to compare existing and develop new approaches.

References

[1] Dell'Isola et al., Proc. R. Soc. A 472: 20150790 (2016)