IMPACT ABSORPTION IN AUXETIC DAMAGEABLE MATERIALS

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Summary In this work we study the behaviour of elastic and quasi-brittle auxetic metamaterial under impact. Particular reference is made to the use of these structured materials for facial protector devices for sport activities. Impact analyses of a ball over an auxetic and a non-auxetic honeycomb material show the potential benefit of the densification mechanism occurring in the auxetic material below the impacted region. Moreover, when the bulk material is assumed to have a brittle behaviour, the auxetic lattice in compression develops a smaller damage with respect to the honeycomb, non-auxetic lattice. This can be another advantage in impact absorption applications.

AUXETIC AND NON-AUXETIC STRUCTURED MATERIALS

Auxetic metamaterials, i.e. micro-structured materials with the unusual negative Poisson's rate property, thanks to a significant densification mechanism occurring when they are compressed, have extremely good performances under impact, [1]. We consider two different periodic lattice materials, with two-dimensional (2D) and three-dimensional (3D) microstructures, that may exhibit an equivalent global auxetic behaviour and traditional (non-auxetic), behaviour. The lattices and the unit cells for the re-entrant honeycomb (RHC), originally proposed in [2], and the honeycomb (HC) structures are shown in Figs.1a,c and Figs.1b,d, respectively. For fixed geometries of these lattices, an equivalent density, ρ_{eq}, defined as the mass of the unit cell divided by the volume, can be easily computed.

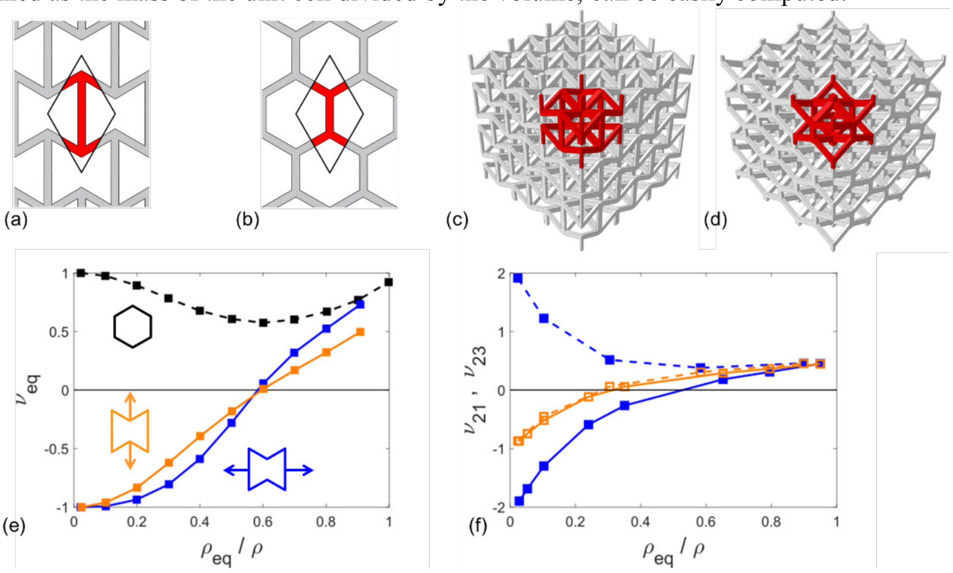

Figure 1. Lattice with unit cell in red of: (a) 2D RHC, (b) 2D HC, (c) 3D RHC, (d) 3D HC. Equivalent Poisson's ratios versus normalized equivalent mass density: (e) 2D lattices, plane strain conditions, (f) 3D lattices (dotted lines: HC, solid lines: RHC, ν_{21} in blue, ν_{23} in orange).

Elastic behaviour: equivalent Poisson's ratio

Several lattices, endowed with different thickness of the beam elements inside the cell, are considered and a linear-elastic analysis allows computing the equivalent Poisson's ratios. The results are shown in Figs. 1e and 1f in terms of equivalent Poisson's ratio versus normalized equivalent density. Note that the microstructure makes the homogenized or equivalent behaviour non-isotropic, with the exception of the 2D HC. For low values of the equivalent density, the 2D RHC lattice exhibits auxetic behaviour in both directions (orange and blu curves in Fig. 1e) and the same holds true for the 3D RHC lattice (solid lines in Fig. 1f). While in the 2D case the HC lattice always has a non-auxetic behaviour (black curve in Fig. 1e), the 3D HC lattice, which is transversally isotropic, can have an auxetic behaviour (i.e. $\nu_{23}<0$) in the horizontal plane of isotropy.

Damageable 2D-lattice micro-structured materials

With the aim to study the effect of damage on the different lattices, we consider the geometries shown in Fig. 1a with ρ_{eq}=0.27ρ and in Fig. 1b with ρ_{eq}=0.22ρ and we assume that the constituent bulk material is brittle, with a tensile strength of 10 MPa and a mode I fracture energy of 0.01 Nmm. In compression, the behaviour of the bulk material is assumed linear elastic. We numerically simulate the response of the two damageable metamaterials under compression. A specimen constituted by 5 x 5 cells is considered, a uniform displacement, inducing shortening, is imposed on the upper boundary and the global reaction is computed. A brittle-crack model is used in the finite element code, with the option of element deletion to avoid over distorted mesh. Figure 2 shows the obtained force vs displacement curves that

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can be interpreted as uniaxial compression stress-strain curves of the structured materials. For comparison, the linear elastic response is also shown (dashed line). One can observe that the auxetic effect provides an additional strength mechanism in compression that results in a higher global force, with a reduced equivalent damage at equal global displacement. The equivalent damage at the peak of the force, estimated from the secant stiffness, is 0.23 for the RHC and 0.41 for the HC. The global behaviour is however quite brittle. The plots in Fig. 2 (right) show the failure patterns corresponding to the points marked in the global curves.

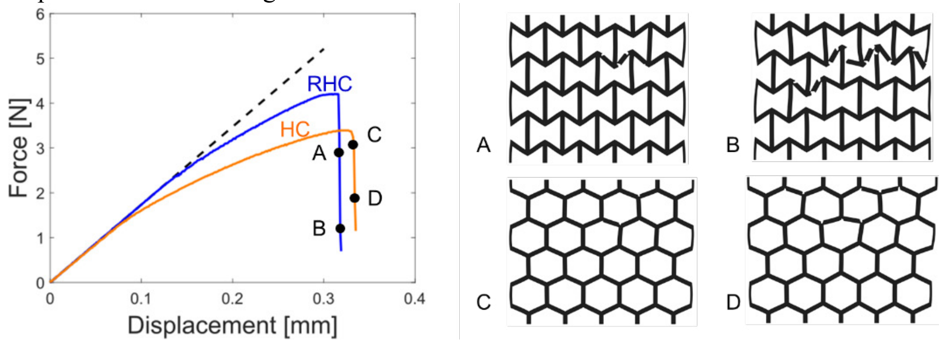

Figure 2. Force vs displacement of 2D-RHC (orange curve) and 2D-HC (blue curve) lattices in compression. Dashed line represents the linear elastic response, solid lines represent the response with a damage model. Failure patterns for RHC and HC materials.

IMPACT ON STRATIFIED MATERIALS WITH AUXETIC CORE

The problem considered is related to the choice of optimal materials for protector facial masks to be used by athletes. The real functional requirement sets a limit on the thickness of the device and a limit to the transmitted force in case of impact. In this context, [3] proposed a mask made of two layers of flexible and rigid ethylene vinyl acetate (EVA) and compared the stresses on the face in case of impact with and without the mask.

In [4], we proposed a different solution, with the inclusion of an intermediate layer of structured material, see Fig. 3a and analysed the impact of a rigid sphere on a small portion of the mask, assuming an elastic behaviour of the bulk material used to fabricate 3D HC and RHC lattices and large deformations. Figure 3b shows the results in terms of the time evolution of the reaction force transmitted to the internal surface. A more efficient impact absorption in obtained with the RHC lattice (lower value of the peak of transmitted force). This is due to the densification of the material in the impacted region, with activation of self-contact inside the highly deformed metamaterial.

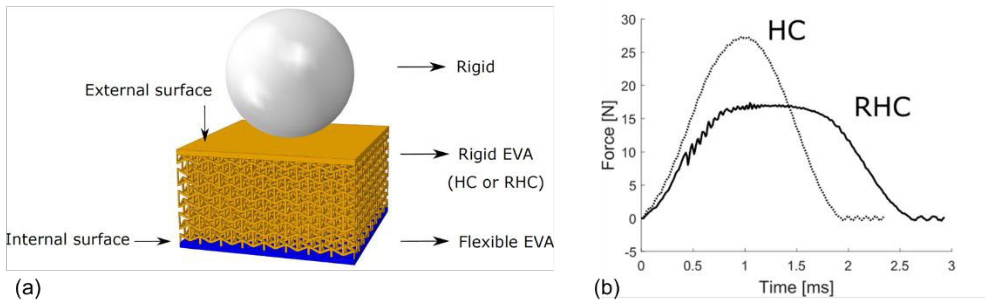

Figure 3. (a) Scheme of analyzed portion of mask. (b) Time evolution of reaction force at internal surface of protector device

To set the safefy margin of a real protector device one has to include also the non-linear behaviour of the bulk material. The effect of non-linear material behaviour, possibly with damage, has to be properly taken into account. As here shown, assuming small strain, the auxetic behaviour can induce additional strength mechanisms to prevent damage development, but can also result in a brittle final failure. The combined effect of large displacements and damage deserves further study and is currently under development.

CONCLUSIONS

The densification mechanism of auxetic material under compression can improve the impact absorption performance and modify the damage mechanism. This opens the way to possible application to protector devices for athletes. The real design of such devices however would require proper identification of the actual nonlinear behavior of the bulk material and the definition of homogenized constitutive law for the micro-structured materials.

References

[1] Lakes, R., Elms, K. Indentability of Conventional and Negative Poisson's Ratio Foams. *Journal of Composite Materials* **27**: 1193–1202, 1193.
[2] Almgren, R.F. An isotropic three-dimensional structure with Poisson'sratio = -1. *Journal of Elasticity* **15**: 427–430, 1985.
[3] Coto, N. P., Meira, J. B. C., Brito e Dias, R., Driemeier, L., de Oliveira Roveri, G., Noritomi, P. Y. Assessment of nose protector for sport activities: Finite element analysis. *Dental Traumatology* **28**: 108–113, 2012.
[4] Faraci, D., Driemeier, L., Comi, C. Bending-dominated auxetic materials for facial protector devices. *Submitted,* 2019.