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"On the Use of Cellular Materials for the Design of Innovative Seismic Isolations Devices"

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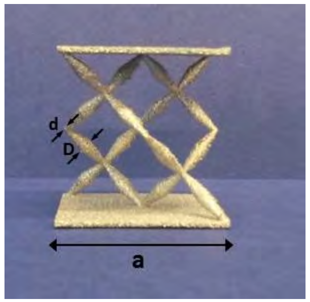
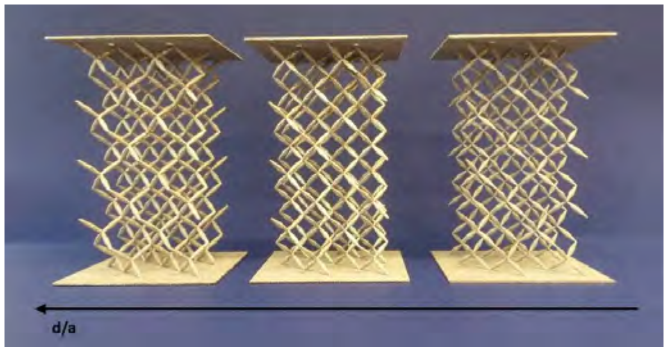
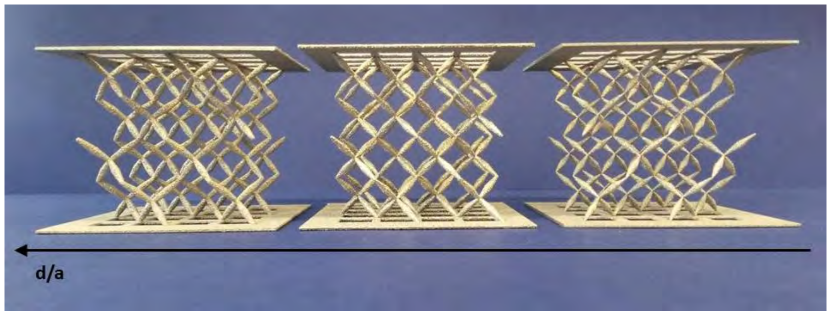






Outline

On the Use of Cellular Materials for the Design of Innovative Seismic Isolations Devices

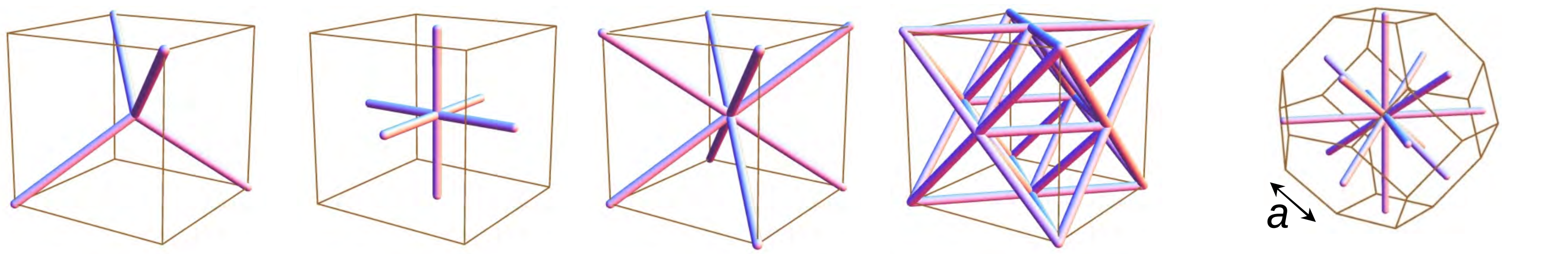
1) Part 1: Introduction
2) Part 2: Elastic Moduli of Lattice Materials
3) Part 3: Use of Pentamode Lattices for Base Isolation Devices
4) Part 4: Practical examples
5) Part 5: Conclusions

Introduction 1/3

Mechanical metamaterials simultaneously can show very soft and very stiff deformation modes (unimode, bimode, trimode, quadramode and pentamode materials, depending on the number of soft modes) [*A.N. Norris, Proceedings of the Royal Society of London A, 470, 20140522, 2014; G.W. Milton, A.V. Cherkaev, Journal of Engineering Materials and Technology, 117, 4, 483-493, 1995*].

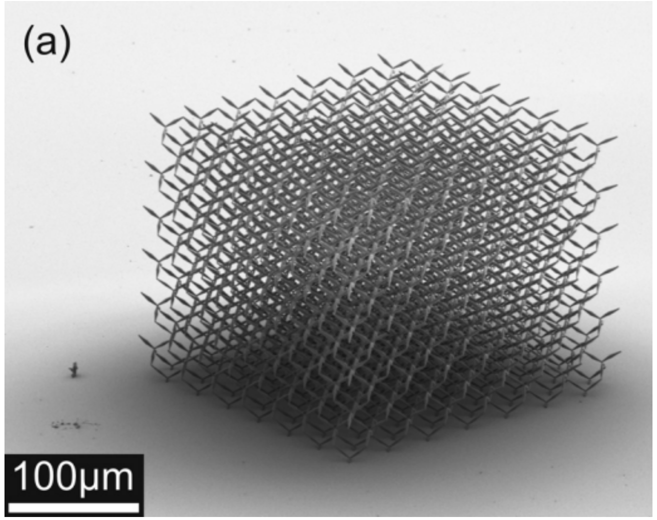
This definition applies to a special class of mechanical metamaterials – composite materials, structural foams, cellular materials, etc. – which feature special mechanical properties.

"pentamode" *"simple cubic"* *"BCC"* *"FCC octet truss"* *"tetrakaidecahedral"*

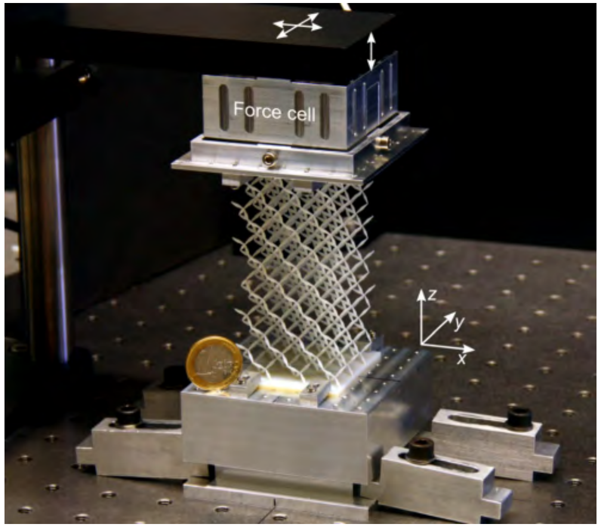


Introduction 2/3

Rapid prototyping techniques for the manufacture of materials with near-pentamode behavior have been recently presented in literature at both macroscale and microscale [*M. Schittny, et al., Applied Physics Letters, 103, 231905, 2013; M. Kadic et al., Applied Physics Letters, 100, 191901, 2012*].



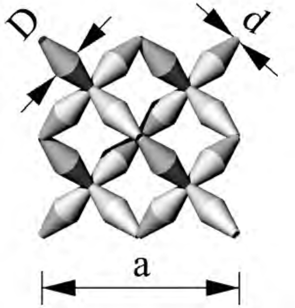
M. Kadic et al., Applied Physics Letters, 100, 191901, 2012

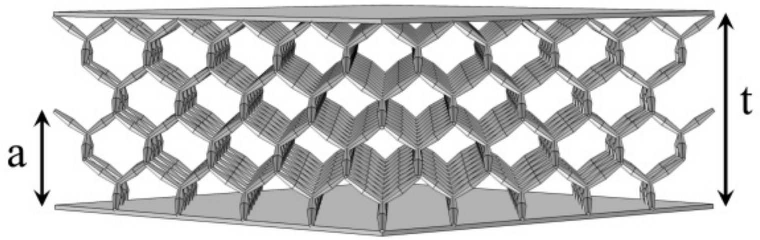


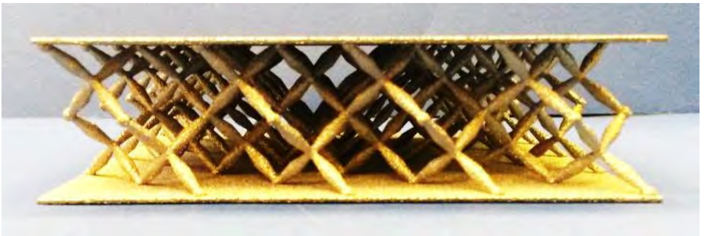
M. Schittny, et al., Applied Physics Letters, 103, 231905, 2013

Introduction 3/3

We design novel versions of pentamode materials whose bulk and shear moduli are controlled by adjusting the dimensions of the struts and nodal junctions and the material properties.

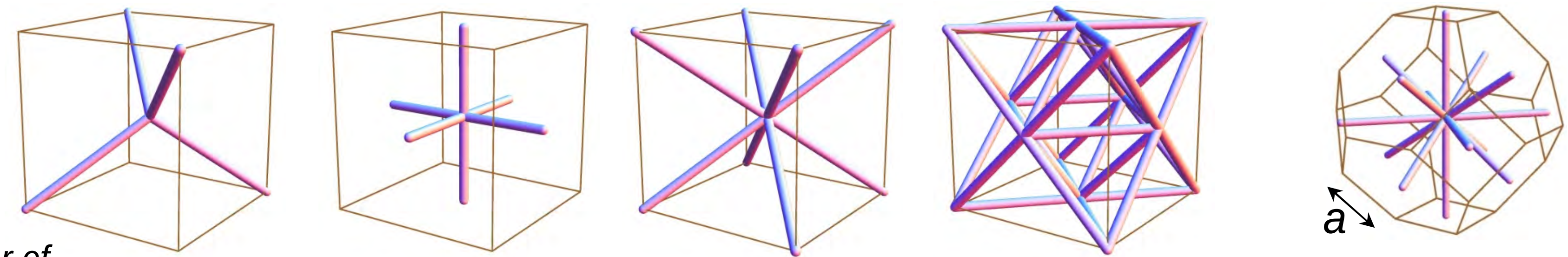






Pentamode materials have been proposed for transformation acoustics and elasto-mechanical cloak (refer, e.g., to the recent paper [T. Bückmann et al. Nature Communications, 5, 4130, 2014.] and the references therein), but their potential in different engineering fields is still only partially explored.
The present study with the use of pentamode lattices as tunable seismic isolation devices, making profit from the control of the soft modes of such materials through the tuning of the bending moduli of members and junctions.

Unit cells of 3D lattices ($d = 3$)

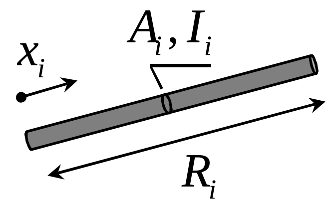


	"pentamode"	"simple cubic"	"BCC"	"FCC octet truss"	"tetrakaidecahedral"
"number of members"	$Z=4$	$Z=6$	$Z=8$	$Z=12$	$Z=14$
"volume"	$\frac{64}{3\sqrt{3}}R^3$	$8R^3$	$\frac{32}{3\sqrt{3}}R^3$	$4\sqrt{2}R^3$	$8\sqrt{2}a^3$

Young modulus: E_i

Bending compliance of i^th members of the unit cell: $N_i = \int_0^{R_i} \frac{x^2 dx}{E_i I_i}, i = 1,\dots,Z$

Axial compliance of i^th members of the unit cell: $M_i = \int_0^{R_i} \frac{dx}{E_i A_i}, i = 1,\dots,Z$



Mechanical properties of 3D lattices

$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon}$ symmetries: $\begin{cases} C_{ijkl} = C_{jikl} \\ C_{ijkl} = C_{klij} \end{cases}$

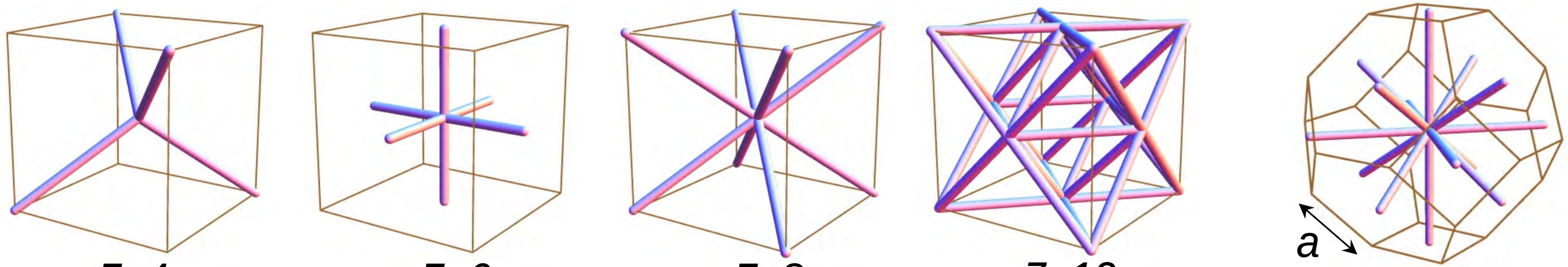
Voigt notation: $C_{ijkl} = C_{IJ} = C_{JI}$

independent stiffness constant: C_{11}, C_{44}, C_{12}

Bulk modulus: $K = \dfrac{C_{11} + 2C_{12}}{3}$

Shear modulus: $G = \mu_1 = C_{44}$

Shear modulus: $\mu_2 = \dfrac{C_{11} - C_{12}}{2}$



	"pentamode"	"simple cubic"	"BCC"	"FCC octet truss"	"tetrakaidecahedral"
	$Z=4$	$Z=6$	$Z=8$	$Z=12$	$Z=14$
K	$\dfrac{4R^2}{9MV}$	$\dfrac{2R^2}{3MV}$	$\dfrac{8R^2}{9MV}$	$\dfrac{4R^2}{3MV}$	$\dfrac{1}{9V}\left[\dfrac{6R_1^2}{M_1} + \dfrac{8R_2^2}{M_2}\right]$
G/K	$\dfrac{9M}{4M+2N}$	$\dfrac{3M}{2N}$	$1+\dfrac{M}{2N}$	$\dfrac{3}{4}+\dfrac{3M}{4N}$	$\dfrac{3}{2}\dfrac{1/M_1 + 1/N_2}{1/M_1 + 1/M_2}$

Pentamode Lattices for Base Isolation Devices

It is worth comparing the analytic prediction of the ratio, with the numerical estimate of the same ratio given in [*M. Kadic et al., Applied Physics Letters, 100, 191901, 2012*], which has been obtained by fitting the results of finite element simulations of pentamode lattices under hydrostatic pressure and simple-shear loading:

$$\frac{G}{K} = \left[\left(\frac{R}{d} \right)^2 \sqrt{\frac{R}{D}} \right]^{-1}$$

We compare our analytical prediction with the Kadic results, assuming the lattice constant a = 15 mm, different ratios D/a ($D/a = 0.174, 0.087, 0.044$), and letting the ratio d/D vary from zero to one. The limiting cases with d/D = 0 and d/D = 1 respectively correspond to a stretch-dominated pentamode lattice (no bending effects), and a pentamode lattice showing rods with constant cross-section (cylindrical rods).

Numerical results

lattice constant: $a = \frac{4R}{\sqrt{3}}$

radii $\begin{cases} r(x) = r_{\min} + \left(\frac{r_{\max} - r_{\min}}{R/2}\right)x, & 0 \le x < \frac{R}{2} \\ r(x) = r_{\max} - \left(\frac{r_{\max} - r_{\min}}{R/2}\right)\left(x - \frac{R}{2}\right), & \frac{R}{2} \le x \le R \end{cases}$

axial and bending compliances:

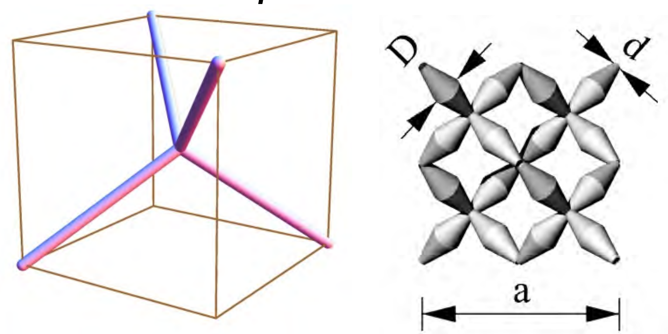
$$M = \frac{R}{\pi E\, r_{\max} r_{\min}} \qquad N = \frac{R^3\left(2r_{\max}^2 + r_{\max} r_{\min} + r_{\min}^2\right)}{3\pi E\, r_{\max}^3 r_{\min}^3}$$

bulk modulus: $K = \frac{4R^2}{9VM} = \frac{\pi E d D}{64\sqrt{3}R^2}$

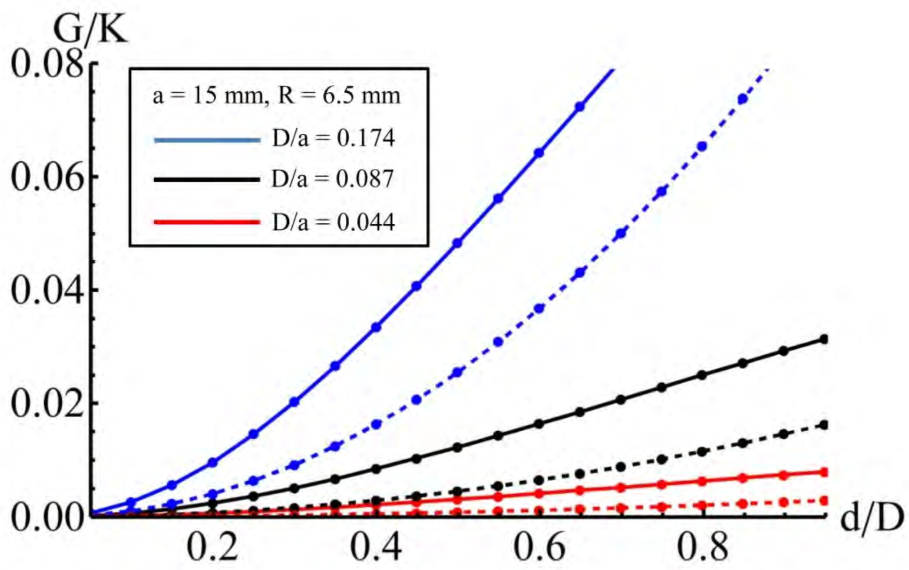
shear modulus: $G = \frac{9\sqrt{3}\pi (dD)^3 E}{768(dDR)^2 + 512\left(d^2 + 2D^2 + dD\right)R^4}$

FE simulations by *M. Kadic et al., Applied Physics Letters, 100, 191901, 2012* : $\frac{G}{K} = \left[\left(\frac{R}{d}\right)^2 \sqrt{\frac{R}{D}}\right]^{-1}$

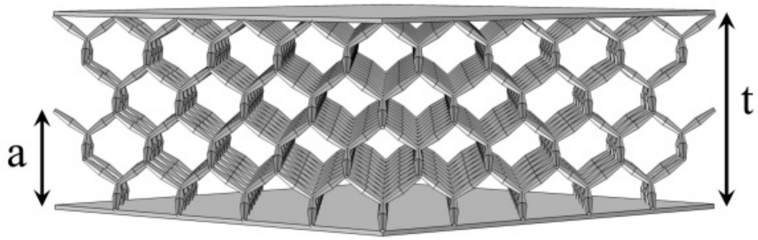
"pentamode"



$r_{\min} = d/2$
$r_{\max} = D/2$



Design of pentamode seismic isolators



Let us compare the mechanical response of pentamode lattices with that of a commercial rubber bearing (isolator Type E [RB-800] produced by Dynamic Isolation Systems, Inc, McCarran, NV, USA).

bulk modulus: $K = \frac{4R^2}{9VM} = \frac{\pi E d D}{64\sqrt{3}R^2}$

shear modulus: $G = \frac{9\sqrt{3}\pi (dD)^3 E}{768(dDR)^2 + 512\left(d^2 + 2D^2 + dD\right)R^4} = 0.791 MPa$

elastic modulus: $E_c = 6.73\, G\, S_1^2 = 341 MPa$

shape factor: $S_1 = \frac{L}{4t} = \frac{n_a}{4n_v}$

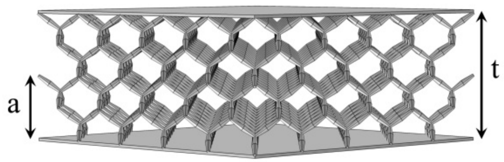
$a = \frac{4R}{\sqrt{3}}$

Case	$t \equiv a\,[mm]$	$R\,[mm]$	n_a	$L = n_a\, a\,[m]$	$d = \frac{D}{2}\,[mm]$
SPMB1	5	2.17	32	0.16	0.19
SPMB2	10	4.33	32	0.32	0.37
PPMB1	5	2.17	32	0.16	0.66
PPMB2	10	4.33	32	0.32	1.32

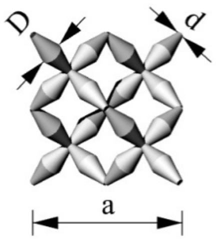
Geometric properties of pentamode pads to be employed to form seismic isolators

SPMB1, SPMB2 (steel): $E = 206\, GPa$

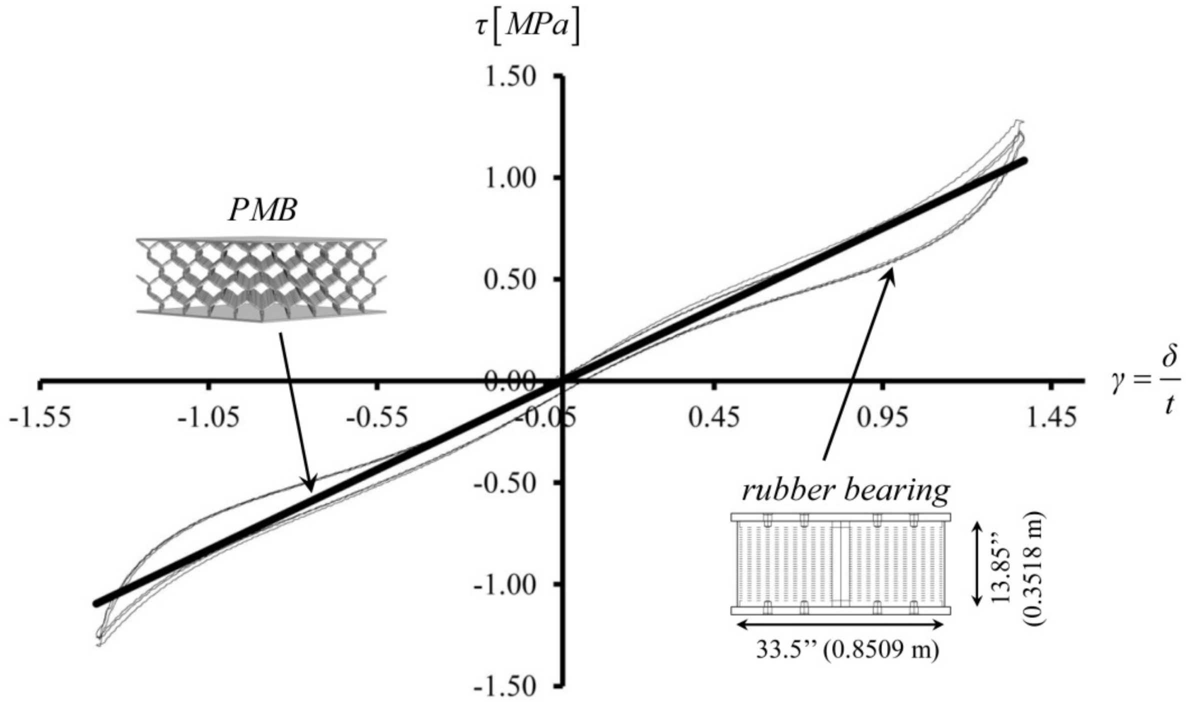
PPMB1, PPMB2 (FullCure850 VeroGray): $E = 1.4\, GPa$



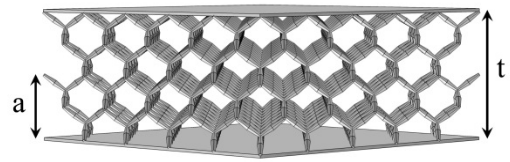
Undeformed configuration



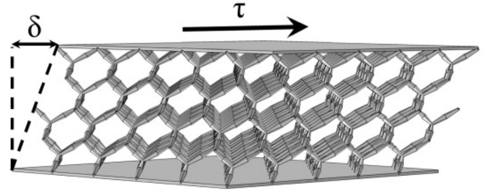
We illustrate the hysteretic (low-damping) response of such an isolator in terms of cyclic shear stress vs. shear strain curves at constant velocity (courtesy of Caltrans Testing Facility, University of California, San Diego).



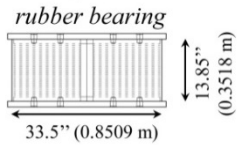
Average shear modulus: $\bar{G} = 0.791\,MPa$



Undeformed configuration

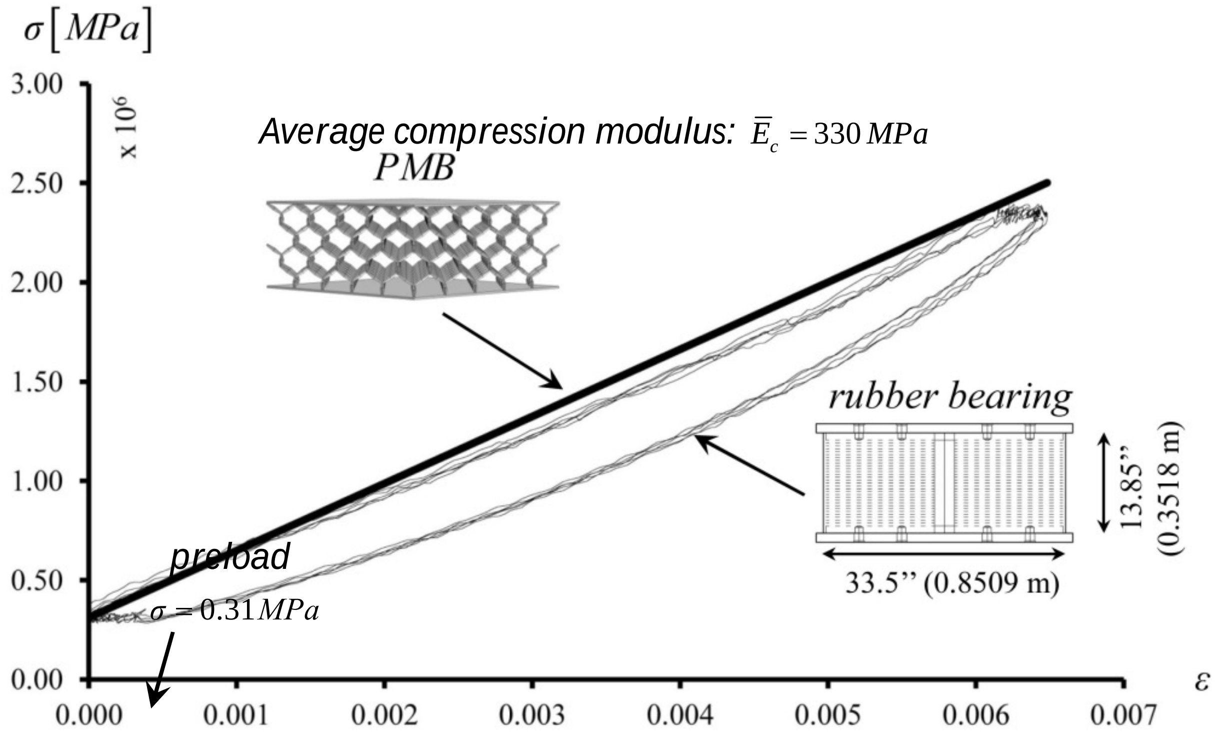


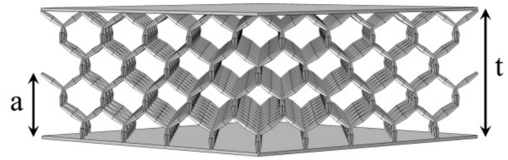
Deformed configuration

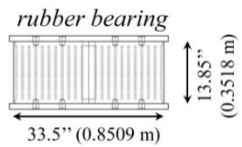
	*number*	*thickness [mm]*
rubber layers	*29*	*7.00*
steel shims (spacers)	*28*	*3.04*

Vertical response

Comparison between the axial stress vs. axial strain responses of the pentamode bearings (pmbs) and a low-damping rubber bearing.





	*number*	*thickness [mm]*
rubber layers	*29*	*7.00*
steel shims (spacers)	*28*	*3.04*

Conclusions / Advantages of pentamode isolators 1

We have designed innovative seismic isolators based on pentamode lattices confined between steel plates, which can be been controlled by tuning the bending moduli and the geometry of members and junctions. We may conclude that the main advantages of pentamode bearings over traditional structural bearings are the following:

- the mechanical properties of the soft layers forming such devices mainly depend on the geometry of the pentamode lattices, more than on the chemical nature of the employed materials (metallic, ceramic, polymeric, etc.);

- it is easy to adjust the mechanical properties of pentamode bearings to those of the structure to be isolated, by playing with the lattice geometry and the nature of the material, as opposed to rubber bearings, where instead the achievement of very low shear moduli implies marked reductions of the vertical load carrying capacity, making such devices not particularly convenient in the case of structures with very high fundamental periods of vibrations (such as, e.g., very tall buildings; highly compliant structures; very soft soils; etc.);

Advantages of pentamode isolators 2

- the dissipation of pentamode bearings can be conveniently designed through an accurate choice of the material to be used for the pentamode lattices, and inserting, - when necessary, an additional dissipative element within the device (such as, e.g., a lead core);

- the possibility to design and fabricate laminated composite bearings showing layers with different materials, geometries and properties: such a design approach is instead much less effective in the state-of-the-art laminated rubber bearings, where the only lamination variable consists of the type of rubber to be employed for the soft pads (natural rubber or synthetic rubber);

- the freedom in the choice of the materials of the pentamode lattices, by keeping the elastic properties of the device essentially unchanged, allows the designer to adapt the energy dissipation capacity and the life span (i.e., the durability) of the device to the actual use conditions;

Advantages of pentamode isolators 3

- the possibility to replace the fluid components of the structural bearings and energy absorbing devices currently available on the market (such as, e.g., viscous fluid dampers and tuned mass dampers) with pentamode lattices: such a replacement would lead to significantly reduce the technical issues related to fluid leaking and frequent maintenance, which currently affect the state-of-the-art devices involving fluid materials [17-18];

- the mechanical properties of pentamode bearings can be dynamically adjusted and measured, by equipping selected struts of the pentamode lattices with sensors and/or actuators;

- pentamode bearings directly manufactured from computer-aided design data outputted by a computational material design phase, employing advanced and fast additive manufacturing techniques at different scales and single or multiple materials (metals, polymers, etc.).

Future work

Several aspects of the present work pave the way to relevant further investigations and generalizations that we address to future work.

First, mechanical models for composite rubber-steel bearings need to be generalized to pentamode-steel bearings, accounting for the peculiar deformation models of such systems.

Second, physical models of pentamode isolators need to be constructed, employing, e.g., additive manufacturing techniques, and laboratory tested as seismic base-isolation devices, in order to experimentally asses their isolation and dissipation capabilities arising, e.g., from inelastic response and/or material fracture.

Another relevant generalization of the present research regards the design of dynamically tunable systems, with the aim of designing novel metamaterials and bio-inspired lattices tunable by local and global prestress . Future studies will also address the experimentation of pentamode materials as components of new-generation seismic dampers.

3D Printed Models
(collaborative work with the Mercury Centre for Advanced Manufacturing Technology & Production, University of Sheffield, UK)