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Experimental response of additively manufactured metallic pentamode materials confined between stiffening plates

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ABSTRACT

An experimental investigation on the mechanical response of confined pentamode lattices in the elastic and post-yield regimes is presented. An Electron Beam Melting facility is employed to additively manufacture pentamode lattices confined by terminal plates in a titanium alloy. The given experimental results show that the geometry of the microstructure, and the macroscopic aspect ratio of the confined lattices strongly influence the lateral and vertical stiffness properties of the structure. The post-elastic response of the analyzed materials features acceptable energy dissipation capacity. The presented results highlight several analogies between the mechanical response of confined pentamode lattices and that of elastomeric bearings formed by soft rubber pads and stiffening steel or fiber-reinforced composite layers. They pave the way to future studies on the use of pentamode materials for the fabrication of innovative seismic isolation devices and/or shear-wave band gap systems.

1. Introduction

Extremal materials that are receiving increasing interest are the so-called pentamode lattices, which consist of diamond-like lattices featuring five soft modes of deformation (unit cell with four rods meeting at a point) [1]. Such lattices exhibit very low shear moduli (theoretically equal to zero) [1], and may be able to stop or dramatically attenuate shear waves [2]. Physical models of pentamode materials have been fabricated through additive manufacturing (AM) techniques over the last few years, both at the macro- [3] and at the micro-scale [4]. Schittny et al. [3] have studied the experimental behavior of macroscopic, polymeric samples of pentamode lattices in the elastic regime: the results obtained by such authors prove that the elastic moduli of pentamode materials are strongly related to the geometry of the lattice micro-structure, being markedly affected by the dimensions of the rods forming the lattice, and particularly sensitive to the ratio between the diameter d of the connections between the rods and the lattice constant a. The experimental Young's modulus E of the lattice has been found approximately three times stiffer than the experimental shear modulus G. The results presented in [3] also show that the ratio between the bulk modulus B and the shear modulus G strongly increases by reducing the contact area between the rods. Similar results have been found at the micro-scale by Kadic et al. [4]. Polymeric samples of pentamode lattices have been fabricated by such authors using dip-in direct-laser-writing (DLW) optical lithography, a technique well suited to build three-dimensional structures across a range of scales from micro to small [5]. Experimental and numerical results given in [3,4] demonstrate that the mechanical behavior of pentamode lattices replicates that of fluids in the limit of $d \to 0$, when the shear modulus G tends to zero. For finite, nonzero values of d, it has been found that the B/G ratio is extremely high, even if G is positive and nonzero [3,4]. Because of their unusual mechanical features, pentamode materials have been proposed for transformation acoustics and elasto-mechanical cloak (refer, e.g., to the recent paper [6] and the references therein), but their potential in different engineering fields is still only partially explored.

The present study investigates the elastic and post-elastic responses of additively manufactured pentamode lattices confined between stiffening plates. We analyze metallic samples obtained through additive manufacturing by Electron Beam Melting (EBM) of a powder of the titanium alloy Ti–6Al–4V [7,8,10], for different aspect ratios of the unit-cell, and two macroscale aspect ratios

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(slender and thick samples). We find that the confinement of pentamode lattices between stiffening plates greatly affects the elastic response of the overall structure, compared with the case of unconfined, infinite pentamode lattices [11]. The obtained results highlight several similarities between the elastic response of confined pentamode materials and the analogous response of elastomeric bearings composed of rigid steel or fiber-reinforced composite layers and soft layers of natural or synthetic rubber [12–18]. Concerning the post-elastic response, we observe that the examined pentamode materials feature acceptable energy dissipation capacity, and ranges of supplemental damping in line with values of common isolation devices. The remainder of the paper is structured as follows. We begin in Section 2.1 by illustrating the EBM-manufactured pentamode materials analyzed in the present study. Next, we provide a description of the in-house experimental setup employed to subject such materials to lateral and vertical force–displacement tests (Section 2.2). Section 3 presents the results of laboratory tests aimed at determining the elastic moduli (Section 3.1) and the post-elastic energy dissipation properties (Section 3.2) of the analyzed materials. Concluding remarks and directions for future research are presented in Section 4.

2. Materials and methods

2.1. Physical models of confined pentamode materials

We manufactured pentamode lattices confined by stiffening plates and made by the titanium alloy Ti–6Al–4V (hereafter simply denoted by Ti6Al4V) through the Arcam S12 EBM facility at the Department of Materials Science and Engineering, University of Sheffield. Such an additive manufacturing (AM) technology allows the manufacture of features with size down to 0.4 mm by progressively depositing, heating and melting layers of Ti6Al4V powder, with the melted regions in each layer defined according to a CAD model of the specimen to be manufactured [7,8]. It is worth noting that the size of the specimen designed by CAD does not correspond perfectly to the built object. The beam scan strategies and the surface roughness can result in larger (in diameter) printed members [10]. The main properties of the employed titanium alloy, when in the fully dense state, are given in Table 1 [19]. The EBM process has also been shown to fabricate lattice structures with certain members that are undersized [20]. But here it was also shown that this affect can be completely alleviated for thin members if the use of perimeter melting (known as contouring) is excluded. Therefore all of the pentamode lattice specimens were fabricated using a back-and-forth raster melt pattern only (known as hatching).

Fig. 1 shows the extended face-centered-cubic (fcc) unit cell of a pentamode lattice formed by sixteen rods that are composed of two truncated bi-cones featuring large diameter D at the mid-span and small diameter d at the extremities [2–6]. Upon selecting the lattice constant $a = 30$ mm and $D = 2.72$ mm ($D/a \approx 9\%$), we manufactured pentamode specimens with the unit cell shown in Fig. 1, using three different values of d: $d_1 = 0.49$ mm ($d_1/a = 1.6\%$); $d_2 = 1.04$ mm ($d_2/a = 3.5\%$); and $d_3 = 1.43$ mm ($d_3/a = 4.8\%$, cf. Table 2). It is worth remarking that the limit $d/a \rightarrow 0$ corresponds to a perfectly pin-jointed lattice (stretching-dominated response), while the case with $d/a > 0$ corresponds to a lattice featuring nonzero bending rigidities of nodal junctions and rods, which deforms through both stretching of rods and bending of rods and nodes [11].

Table 1
Main physical and mechanical properties of the fully dense isotropic polycrystalline Ti6Al4V titanium alloy [19].

Mass density [g/cm^3]	4.42
Yield strength [MPa]	910.00
Young's modulus [GPa]	120.00
Poisson's ratio	0.342

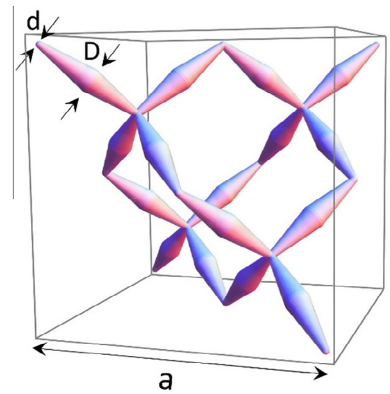

Fig. 1. Extended fcc unit cell of the pentamode lattices analyzed in the present study.

Table 2
Geometrical parameters of the EBM built pentamode materials (CAD sizes in brackets).

	a [mm]	D [mm]	d_1 [mm]	d_2 [mm]	d_3 [mm]
Built size	30	2.72	0.49	1.04	1.43
(CAD size)	(30)	(2.71)	(0.45)	(0.90)	(1.35)

We additively manufactured two different sets of pentamode specimens:

(a) "*Slender pentamode materials*" (SPM): obtained by replicating the extended fcc unit cell of Fig. 1 2×2 times in the horizontal plane, 4 times along the vertical axis, and confining the $2 \times 2 \times 4$ lattice between Ti6Al4V plates with 80 mm edge and $t_p = 1$ mm thickness (see Fig. 2);
(b) "*Thick pentamode materials*" (TPM): obtained by replicating the extended fcc unit cell of Fig. 1 2×2 times in the horizontal plane, 2 times along the vertical axis, and confining the $2 \times 2 \times 2$ lattice between the above mentioned plates (see Fig. 3).

Hereafter, we name SPM1, SPM2 and SPM3 the SPM-specimens with $d = d_1$, $d = d_2$, and $d = d_3$, respectively. Similarly, we name TPM1, TPM2 and TPM3 the TPM-specimens with $d = d_1$, $d = d_2$, and $d = d_3$, respectively. We built three different SPM specimens and one TPM specimen for each analyzed d/a ratio.

It is well known that the EBM manufacturing process creates solid material with some level of porosity (typically below 0.2% if suitable parameters for the alloy are used in the machine) instead of fully dense materials for both solid structures [9] and those intended to contain free space [8]. Based on a recent, detailed study of porosity in EBM titanium made with the same conditions used for the current material [9], we hereafter assume the internal porosity of such a material is of the order of 0.2%, and its Young modulus E_m is therefore approximately equal to that of the fully dense Ti6Al4V alloy (Table 1).

2.2. Experimental setup

An in-house experimental setup was assembled to apply lateral force–displacement histories under constant vertical load on the pentamode specimens described in the previous section (Fig. 4).

An L-shaped plate, sliding vertically over linear bearings, allows the application of the vertical load through calibrated weights. The