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On the dynamic performance of additively manufactured visco-elastic meta-materials

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ABSTRACT

Additive manufacturing (AM) has revolutionized the production of structures with tailored material properties, including elastomer polyurethanes (EPU) which exhibit exceptional mechanical performance. EPU possesses unique characteristics, such as high elongation at break, efficient energy dissipation, and superior specific strength, making it well-suited for applications requiring resilience to dynamic loadings. By combining the advantages of AM and EPU, enhanced and customized meta-materials can be created, surpassing the mechanical performance of traditional bulk materials. However, because of the non-linear stress-strain response of both the constitutive material and the structure, designing such meta-materials for high strain-rates can be challenging. In this work, therefore, quasi-static and dynamic experiments were conducted to evaluate a meta-material architecture. The investigation revealed a strong positive rate dependency. The mechanical performances, including strength, and dissipated energy, increased with increasing loading rate. The EPU meta-materials demonstrate their suitability for dynamic applications where high energy dissipation is crucial for reducing transmitted loads.

1. Introduction

Additive manufacturing (AM) has emerged as a transformative technique for producing structures with tailored material properties to meet the evolving demands of various sectors, including automotive, aerospace, and sports [1,2]. Among the materials used, elastomer polyurethanes (EPU) have garnered attention due to their exceptional mechanical performance. EPU exhibits remarkable characteristics such as high elongation at break, efficient energy dissipation, low wave impedance, and a superior specific strength. These properties render EPU well-suited for applications requiring protective systems or resilience to high dynamic loadings.

However, the pursuit of material conservation and the creation of even lighter structures are imperative in today's industrial landscape. To this end, a synergy can be achieved by combining the advantages of AM and EPU, leading to the creation of enhanced and customized meta-materials with improved mechanical characteristics distinctively different to their constituent material. These mechanical meta-materials possess the potential to be lightweight, flexible, with exceptional energy dissipation capabilities, surpassing the mechanical performance of traditional materials [3,4]. The macroscopic performance of these meta-

materials is predominantly defined by the specific architectures on the meso-scale (e.g. truss, surface) as opposed to the chemical and physical properties of the constitutive material at micro- and nano-scale (e.g. constituent phase, grains) – see Fig. 1. By harnessing the benefits of both AM and EPU, novel structures can be developed contributing to enhanced durability in demanding environments without compromising safety and protection.

Motivated by these prospects, this work aims to further advance the characteristics of EPU by creating mechanical meta-materials ensuring high energy dissipation and superior mechanical performance. Hence, an EPU-based constitutive material is quasi-statically tested and assessed on its effect on the mechanical performance for high energy dissipation. This provides valuable information for investigating mechanical meta-materials. Additionally, different unit cells are examined to understand their impact on mechanical performance, with one cell geometry used to investigate the influence of varied loading rates. To assess the meta-materials' impact resistance, the specific energy dissipation is investigated closely. This provides important information on the architecture's influence on the mechanical performance for especially impact-prone applications.

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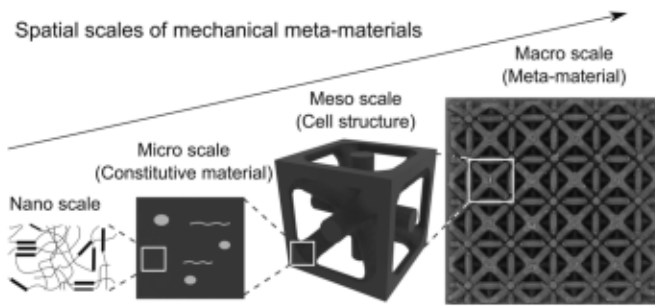


Fig. 1. Graphical illustration of the spatial scales of mechanical meta-materials.

2. Materials & Methods

2.1. Samples manufacturing

Samples for investigating the mechanical performance of the constitutive material and of the different architectures were additively manufactured by Erpro using the Carbon3D technology which is a resin-based AM printing process. The constitutive material is the resin EPU45, which is an elastomeric polyurethane consisting of hard and soft polymer blocks. According to the manufacturer, EPU45 has a density of $\rho_{EPU45} = 1060 \text{ kg m}^{-3}$, a glass transition temperature of $T_g = 30^\circ\text{C}$, and a tensile modulus of 17 MPa together with an elongation at break of 290% when tested at ASTM D412. The investigated meta-materials are represented by different unit cell geometries which were designed with the software Ntopology. The chosen architectures are strut-based lattices (Iso-truss, Octet-truss (OC), Rhombic Dodecahedron (RD)) and Sheet Triply Periodic Minimal Surfaces based lattices (Gyroid). The samples are made of $5 \times 5 \times 5$ unit cells in which each cell is 6 mm large, resulting in $30 \times 30 \times 30 \text{ mm}$ samples. The resulting relative densities are between 0.23 and 0.35. The as received samples were measured and weighted before testing.

2.2. Mechanical testing

Different experimental setups are used to investigate quasi-static (QS) and high-rate (HR) mechanical responses of constitutive material and meta-materials.

2.2.1. Quasi-static compression

An electro-mechanical screw-driven machine (Zwick Roell Z010) was used to load and unload the samples under uniaxial compression. A 10kN force sensor together with the experimental setup device

displacement allowed the measurement of the mechanical performance. The displacement speed was 30 mm/min corresponding to a macroscopic strain-rate of 0.017 s^{-1} . All samples were tested in the fabrication direction z (through-thickness) at 20°C . Three samples were used.

2.2.2. High-rate compression

Similarly to the QS-experiments, three samples of meta-materials with Isotruss unit cells are loaded and unloaded using the fly-wheel setup. This is a specific setup developed for HR-experiments at intermediate strain rates. It consists of a heavy metallic wheel (1 m diameter, 617 kg) that is set in motion. Its rotation velocity is controlled by an asynchronous motor. A hammer which is fixed on the wheel is the impactor and can impose either tensile loading on metallic and composite materials or compression loading on cellular materials. The reader is referred to [5] for more details of the setup. The resulting displacement speed was 4.4 m/s corresponding to a macroscopic strain rate of 155 s^{-1} .

The compression force is measured by a Kistler piezoelectric sensor (model 9011A, force range 15 kN) placed between the rigid cross-head and the upper punch. The displacement of the lower punch is measured by a laser displacement sensor (model OptoNCDT LD 1607-20) with a 20 mm range of displacement.

3. Results & Discussions

3.1. Mechanical performance of the constitutive material

The investigated constitutive material EPU45 in uniaxial compression demonstrates a higher stiffness when compared to compression responses of other materials [6–8] suitable for high energy dissipative applications – see Fig. 2a. This higher stiffness can result in improved energy dissipation suitable for impact-prone applications.

3.2. Effect of unit cell geometry

The meta-materials reveal a classical behavior of cellular materials in their stress–strain responses as shown in Fig. 2b. An initial linear elastic deformation is observed, followed by a nonlinear transition at an intermediate stress. It then exhibits a large strain under a plateau stress until densification. Furthermore, all tested meta-materials demonstrate a smooth transition between linear elastic and plateau region which is usually linked to bending-dominated structures. Furthermore, Fig. 2c reveals that the specific energy dissipation of meta-materials with strut-based lattice unit cells is higher when compared to Gyroid unit cells.

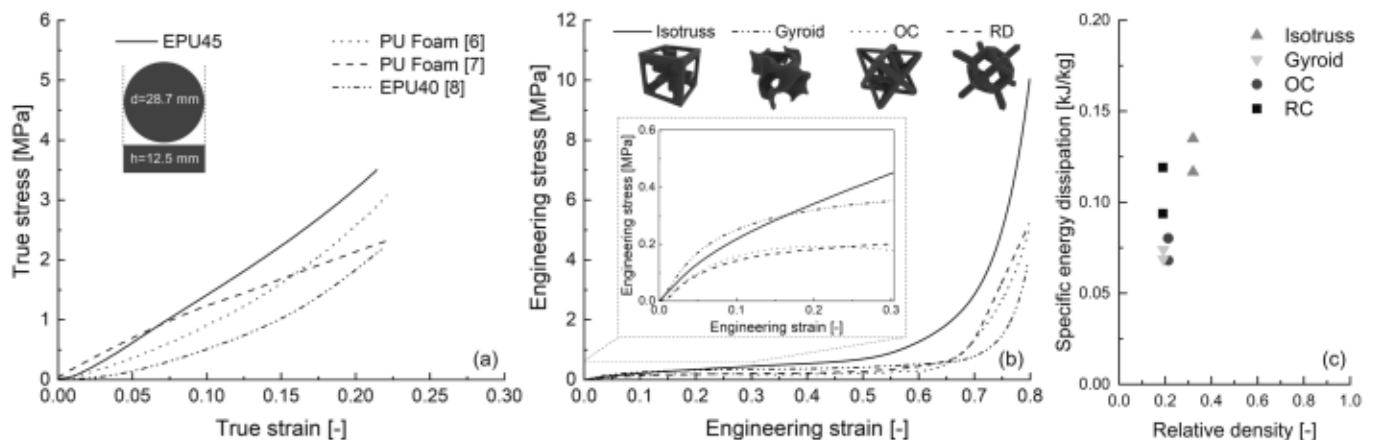
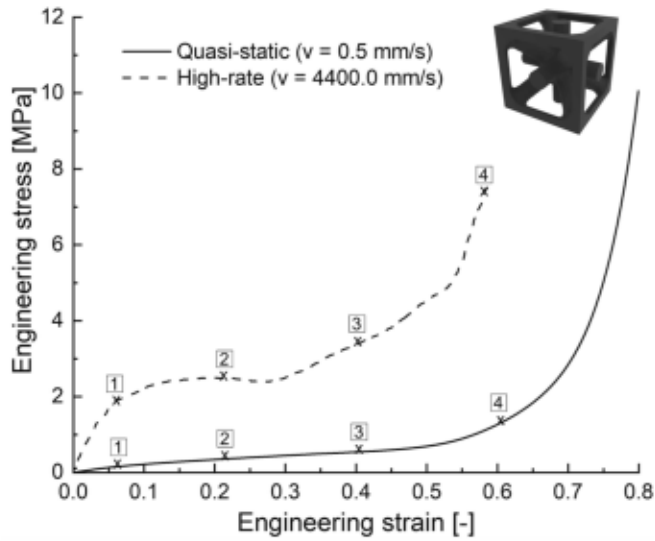


Fig. 2. Experimental results for (a) stress–strain behavior of constitutive materials, (b) stress–strain behavior of meta-materials, and (c) specific energy dissipation of different meta-materials.

(a) Rate-dependent stress-strain response



(b) Deformation mechanism of the meta-materials

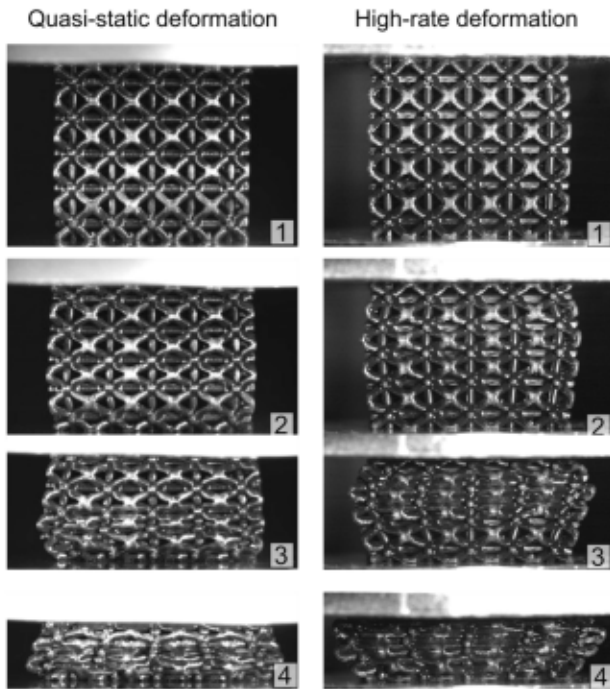


Fig. 3. Experimental observations of (a) the rate-dependent stress-strain response of the Isotruss lattices, and (b) corresponding deformation mechanisms.

Table 1
Mechanical parameters of Isotruss-materials.

Loading regime	E (MPa)	σ_{pl} (MPa)	E_{pl} (MPa)	ϵ_{d0} (-)	SEA (kJ/kg)
Quasi-static	3.3	0.20	1.51	0.40	0.56
High-rate	43	2.26	5	0.37	2.08
Difference	+1203%	+1030%	+231%	-7.5%	+271%

3.3. Effect of loading-rate

The QS and HR experimental results of the Isotruss meta-material revealed a positive rate-dependence of the mechanical performance

(see Fig. 3). The Young's modulus E , the plateau stress σ_{pl} , the plateau modulus E_{pl} and the specific energy dissipation SEA show a strong increase with increasing loading-rate (see Table 1).

This high-rate sensitivity can be related to the glass transition temperature at $T_g=30^\circ\text{C}$ which is close to room temperature. In the glass transition zone (which is in between -20 and 80°C for EPU45 according to Carbon3D) from room temperature to low temperatures or high frequencies, the molecular mobility between chain segments decreases rapidly [2]. This suggests the enhancement of the mechanical strength which corresponds to the stiffness increase of the meta-material.

In Fig. 3b the deformation of the meta-material in QS and HR loading are shown for specific strains as indicated in Fig. 3a. A change in deformation mechanisms between the two types of loading can be observed. In QS, the cell struts start to buckle layer-by-layer near the opposite side of the moving plate. In HR, the whole structure suggests a homogeneous deformation at similar macroscopic strains. Several layers appear to buckle and bend simultaneously in the vicinity of the moving and fixed plate. This can be related to the elastic rate-dependent characteristics of the constitutive material (mostly stiffening). Moreover, the change of deformation mechanism from QS to HR could also corresponds to a more drastic change in large strain constitutive materials stress-strain behavior.

Overall, the rate-dependent performance of the meta-material is based on the combined mechanical response of the constitutive material on the micro-scale and on the localised cell deformation on the meso-scale. In addition, micro-inertia, stress wave propagation in the open-cell material and dynamic buckling might further influence the rate-dependent performance of the mechanical meta-material [9].

4. Conclusion

In this work, the specific energy dissipation of mechanical meta-materials as well as the loading-rate dependence of a single mechanical meta-material based on an elastomeric polyurethane were investigated and assessed. The following conclusions can be drawn:

- Four investigated mechanical meta-materials tested in uniaxial compression quasi-statically reveal a higher specific energy dissipation for strut-based lattice unit cells when compared to Gyroid lattice.
- Quasi-static and high-rate loading tests were conducted which revealed a strong positive rate dependency of the mechanical meta-material with Isotruss unit cells. The mechanical performances such as strength, and dissipated energy increased with increasing loading rate.
- The EPU mechanical meta-material demonstrate its suitability for dynamic applications.
- Further investigations are necessary to elucidate the individual influence of constitutive material and unit cell geometry in rate-dependent environments.

CRedit authorship contribution statement

Louise Le Barbenchon: Conceptualization, Writing - original draft, Visualization, Investigation. **Maria Lißner:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization, Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Louise Le Barbenchon reports equipment, drugs, or supplies was provided by Erpro Group.

Data availability

Data will be made available on request.

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