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Mechanical Properties of 3D Auxetic Structures Produced by Additive Manufacturing

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Abstract: Three distinct auxetic structures were produced by direct 3D printing based on parametric CAD models. Mechanical properties of the structures were established by static compression tests where strain fields on the surface of the specimens was measured by non-contact optical method. Parametric finite element (FE) model of each structure was then subjected to a virtual compression test and mechanical properties obtained from the FE simulations were compared to the experimentally assessed values. After verification, the parametric FE models were used to establish relationships between various design parameters (porosity, rod thickness, internal angles, etc.) and overall mechanical properties (particularly stiffness).

Introduction

Auxetic materials are materials with negative Poisson's ratio, i.e. unlike other materials, auxetics become thicker in the direction perpendicular to the applied strain when stretched. This phenomena is caused by their specific microstructure either at the molecular or macroscopic level. Auxetics thus posses interesting properties such as high energy absorption and fracture resistance [1]. This predetermines them for applications such as body armor, padding and robust shock absorbing material.

Methods

Three different types of auxetic structures were designed and printed (see Fig. 1): i) two-dimensional cut missing-rib, ii) two-dimensional inverted (re-entrant) honeycomb and iii) three-dimensional inverted honeycomb. These structures were then printed using VisiJet EX200 (3D Systems, USA) UV curable acrylic material suitable for high resolution 3D printing with accuracy approx. $328 \times 328 \times 606\,$DPI ($25 - 50\,\mu$m resolution). The samples were tested in uni-axial compression experiments to obtain stress-strain response of each microstructure.

Parametric FE model of each auxetic structure has been developed. The geometries have been discretized either with linear 3D hexahedral solid elements or with beam elements, each having 6 degrees of freedom at every nodal point. Beam elements were based on Timoshenko beam theory which includes shear-deformation effects. To inversely calculate the stress-strain relationship of the structures the model must include both geometric and material nonlinearities. In this study material model was considered elasto-plastic with von Mises yield criteria coupled with bilinear isotropic work hardening. Loading has been prescribed in 100 loading steps, i.e. in each step $0.1\,\%$ deformation was applied. Furthermore to take post-buckling behaviour of the thin beams subjected to the large compression into account used strain measures have to also account for higher order terms. Thus in our analyses material stress-strain properties were input in terms of true stress versus logarithmic strain. In every loading step reaction forces originating at the supports have been calculated and the true stresses and strains have been derived.

The FE models were used for description of deformation behaviour of auxetic structures which allows for easy and fast prediction and optimization of the effective mechanical characteristics that

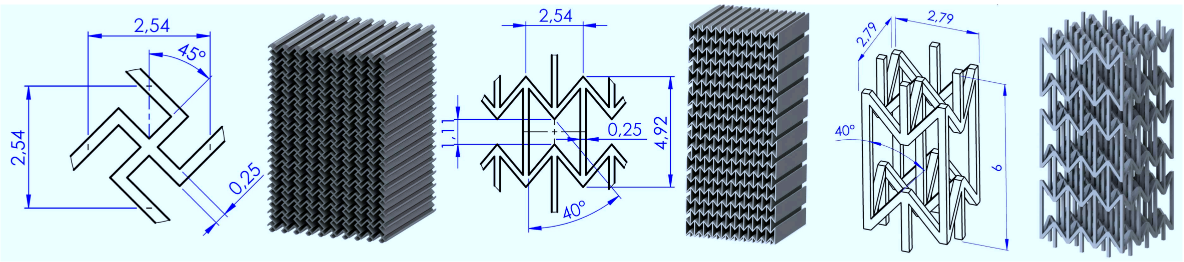

Fig. 1: Auxetic structures used in the study: a) cut missing-rib structure, b) 2D re-entrant structure, c) 3D re-entrant structure

facilitates material's design for specific application. Although there are many analytical models available in the literature, here we used numerical approach only. One reason is that the analytical models assume small deflections neglecting axial deformation of the struts [2]. The other reason is that for investigation of very large deformations one must include for the self-contact between the individual struts. The analytical models are effective only when simplifying assumptions such as small deflection theory and linear elastic material properties are used. In contrary FE approach can be used to prove not only the concept of negative Poisson's ratio and/or to optimize parameters of the structure (e.g. the re-entrant angle, relative density, struts' thickness) but also to maximize the effective parameters of resulting constructs (i.e. deformation energy per unit volume, yield strength of the structure, compressive strength) according to specific requirements.

Stress-strain curves were assessed from the FE simulations inversely, i.e. from reaction forces calculated at the restrained side of the sample. Using such inverse FE simulations it is relatively easy to obtain not only the stress-strain curves for each considered sample, but it is also possible to establish the stresses and strains arising at individual struts from the deformation of the structure. Hence strains can be easily compared to the experimentally obtained values from the digital image correlation at the same positions (i.e. individual markers).

Results

Mechanical behaviour of three different porous microarchitectures exhibiting in-plane and volumetric negative Poisson's ratio was studied both experimentally and numerically. True stress - true strain diagrams in compression were derived and compared for each structure. FE models of all considered microarchitectures were developed and their ability to predict mechanical response of the studied constructs was assessed by comparing numerically and experimentally obtained stress-strain diagrams. Deformation response of the cut missing-rib structure was well captured by the FE model up to 20 % strain. Simulations of re-entrant honeycomb structures showed good correlation of yield point and strain softening characteristics up to 10 % strain. The FE models can be readily used for optimization of the auxetic structures for a specific application.

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