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EFFECT OF POLYMERIC FILLERS ON POISSON'S FUNCTION IN ADDITIVELY MANUFACTURED AUXETICS

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Abstract: *In this study, the relation between the presence of the filler in different types of open auxetic lattices and their Poisson's functions was investigated using optical strain measurement technique and Digital Image Correlation (DIC) algorithms.*
Three different types of auxetics were manufactured using Selective Laser Sintering (SLS) technique from 316L–040 stainless steel alloy: (i) 2D re-entrant, (ii) 3D re-entrant and (iii) 2D missing rib structure. All types of SLS printed auxetics were then divided into three different groups according to the presence of the filler: (a) unfilled and filled with (b) porous polyurethane foam and (c) ordnance gelatin. All groups of samples were tested in uniaxial compression mode under both quasi-static and high strain rates in the range of thousands strains per second using the Split Hopkinson pressure bar.
During the loading tests, the deforming structure was observed optically and from the captured image data, the in-plane displacements were calculated using DIC. Based on these displacements, Poisson's functions among the tested groups were compared.
The results show that in the case of both types of polymeric fillers, the auxetic behaviour is suppressed with increasing values of longitudinal strain.

Keywords: Auxetics, Impact energy absorption, Interpenetration phase composites.

1. Introduction

Auxetics are a class of meta-materials, which exhibit mechanical properties beyond the ranges of the base material due to geometrical properties of their lattice. Their lattice is constructed in such a way to exhibit negative Poisson's ratio, as decribed e.g., by Lakes (1987) or Evans (1991). Due to this, the auxetic lattices have a high potential in impact protection, e.g. in a protective panel design. Performance of auxetic lattices exhibiting enhanced protection against impacts together with their lightweight nature may be further improved with strain rate sensitive fillers as was shown in our previous studies, (Doktor et al., 2015; Fila et al., 2017) as well as by other authors, e.g., Novak et al. (2020). On the other hand, the presence of the filler affects Poisson's function of such an auxetic structure.

2. Materials and methods

To assess the effect of the filling materials under higher strain-rate impact loading, a series of auxetic, additively manufactured, structures were tested at strain-rates reaching $2000\,\mathrm{s}^{-1}$. The contribution of each considered filling to the strain energy density was assessed. From the images of the deforming loading scene captured using a high speed camera, the strain fields were obtained to assess the effect of the filling on Poisson's function.

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2.1. Specimens' design and manufacturing

For this experimental campaign, three types of auxetics were designed and produced by selective laser sintering (SLS), two of which exhibited an in-plane auxetic behaviour, while the third structure posed negative Poisson's ratio in three dimensions: (i) a missing rib (cross-chiral) structure, (ii) a 2D re-entrant (inverted honeycomb) and (iii) a fully re-entrant structure. The used lattices are depicted in Figure 1. These representatives of auxetics were selected based on the capabilities of the SLS to produce the samples with satisfactory resolution and with reasonable dimensions of the unit cell. As the overall dimensions are limited by the design parameters of the used SHPB, only 3-by-3 (or, in the case of three-dimensionally auxetic structure 3-by-3-by-3) might be used, which enabled one unit cell without direct connection to the samples' endplate which was used for load transfer purposes.

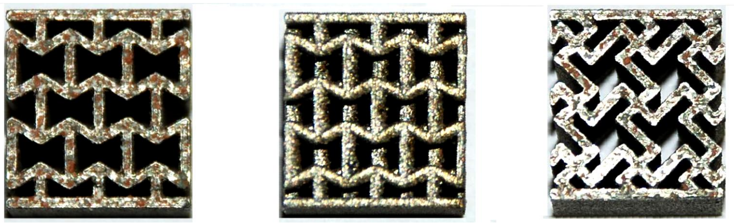


Fig. 1: Samples of auxetics tested with fillings (SLS printed). 2d re-entrant (left), 3d re-enrant (middle), missing-rib (right).

The dimension of the designed samples (w $\times$ d $\times$ h) were $12 \times 12 \times 13\,\mathrm{mm}$. The nominal values of porosity were $53.1\,\%$, $52.3\,\%$ and $74.0\,\%$, respectively. The samples were manufactured by SLS from an austenitic stainless steel alloy 316L-0407.

To assess the effect of the filling materials on the mechanical response at high strain-rates, the manufactured samples were then divided into three groups: (i) unfilled group, (ii) filled with a polyurethane foam and (iii) filled with an ordnance gelatin.

The ordnance gelatin for this campaign was prepared according to the reports of Jussila (2004). As a base, $260\,\mathrm{Bloom}$ beef gelatin (REMI MB, Ltd., Czech Republic) was used. The gelatin powder was dissolved in warm water (the temperature was $45\,^{\circ}\mathrm{C}$), stirred for $10\,\mathrm{min}$ to remove air bubbles and poured into the SLS printed lattice. The samples were cured for $24\,\mathrm{h}$ at room temperature and subsequently stored for $24\,\mathrm{h}$ in a refrigerator. In the second group, a single component low expansion porous polyurethane foam (Soudal, N.V., Belgium) was used, which, atfer pouring into the lattice, cures under ambient conditions.

2.2. Quasi-static tests

From each of the 9 groups (three structures $\times$ three groups of filling options), one sample was selected for the quasi-static testing. An Instron 3382 uniaxial loading machine (Instron, USA) was used for the displacement controlled compression. The loading rate was $0.5\,\mathrm{mm} \cdot \mathrm{s}^{-1}$ which resulted in a strain-rate of $0.0011\,\mathrm{s}^{-1}$. The loading was conducted up to $50\,\%$ of the overall strain. For the further evaluation of the strain field, the loading scene was captured using a digital camera attached to a telecentric lens. In the acquired images, the displacements were tracked by DIC and then, the in-plane strains were calculated.

2.3. SHPB tests

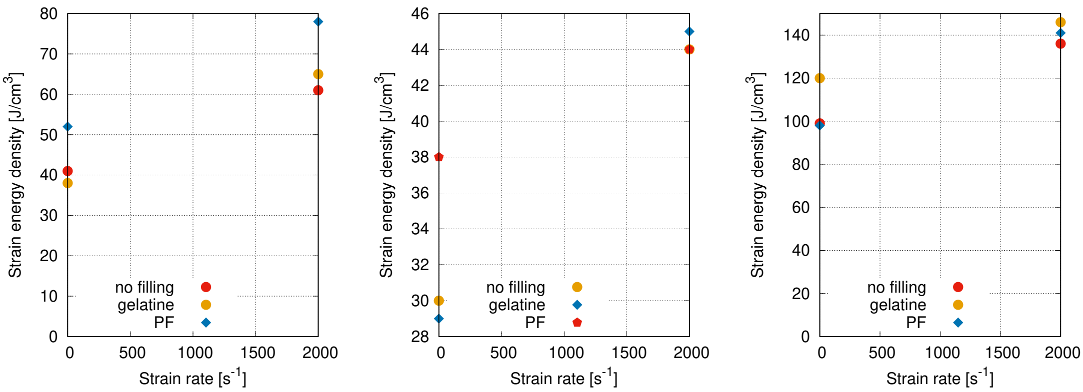
The tests at high strain-rates were performed using an SHPB apparatus. The instrumentation is based on SHPB setup designed in DynLab laboratory at CTU Prague by Fíla (2018b). As the tested samples manufactured from steel exhibited high mechanical impedance, aluminium bars were used in this series of experiments. To adjust the shape of the strain pulses generated in the incident bar and reduce the wave dispersion, pulse shapers were used. Based on the calibration experiments performed prior to this campaign, paper pulse-shapers were used (thickness $2 \times 0.25\,\mathrm{mm}$), which allowed one to achieve nearly constant strain-rates in the plateau regions. All the tests were performed with a unchanged level of a gas gun release pressure of $5\,\mathrm{bar}$. The resulting impact velocity of the striker bar was $33\,\mathrm{m} \cdot \mathrm{s}^{-1}$.

2.4. Poisson's function evaluation

To evaluate the effect of the filling on the auxetic behaviour, in-plane strains were calculated using the captured image data of the deforming samples. In the inteconnection points of the struts, tracking features were placed. Using a tracking algorithm developed by Lucas and Kanade (1981) and implemented by Jandejsek et al. (2010), displacement of the tracking features were obtained. Then, on the grid of the tracking features, a mesh of quadrilaterals was defined. Based on displacements of the nodal points, strains were calculated using equations for linear isoparametric 4-node elements. Poisson's function was calculated as negative of the ratio of transverse strain to axial strain and plotted against the axial strain for each sample.

3. Results

The measured strain gauge signals were evaluated according to the 1-dimensional wave propagation theory in elastic media. The analytical description of the strain waves is implemented by an in-house software (Fíla, 2018a), which allows one to obtain the stress-strain curves as well as the strain-rate-strain dependencies. Strain energy density was then calculated as areas under the stress strain curves. Based on stress-strain curves measured at both quasi-static and impact conditions, strain energy densities were obtained. The comparison is presented in Figure 2.



(a) 2D re-entrant (b) 3D re-entrant (c) missing rib

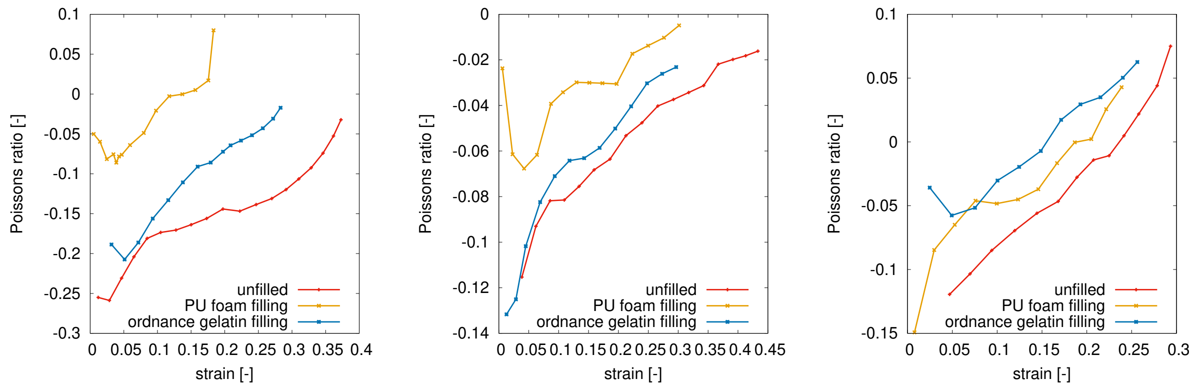
Fig. 2: Comparison of strain energy density measured under quasi-static and impact loading

Based on the image data recorded by the high-speed camera during the SHPB tests, the strains were calculated using DIC. The obtained Poisson's function for each type of auxetic structure is depicted in Figure 3. Due to the small values of the strain in the initial phase of the impact loading, Poisson's ratio corresponding to the first two images differs significantly even in the same groups of samples. However, after this initial phase, the calculated Poisson's function started to be consistent among each group.

In the unfilled samples of the 2D re-entrant structure, Poisson's ratio increases steadily from -0.3 at a 1% strain to -0.08 at a 35% strain. In the samples of the same structure filled with polyurethane foam and ordnance gelatin, the displayed Poisson's ends with a lower strain value. This was determined by the presence of the filling in the loading scene, which, at higher levels of compression, caused strong changes at the samples' surface and a loss of correlation in the optical strain measurement. In the 2D re-entrant samples filled with the polyurethane foam, Poisson's ratio steadily increases from -0.08 at a 1% strain to 0.08 at a 18% strain, while the zero value of Poisson's ratio is reached at a 15% strain. In the 2D re-entrant samples, Poisson's ratio increases steadily from -0.2 at a 1% strain to 0 at a 30% strain.

In the group of 3D re-entrant samples, Poisson's ratio preserves the negative sign up to a 30% strain. In the unfilled samples and the samples filled with ordnance gelatin, Poisson's function exhibits a steady increase, where Poisson's ratio of the unfilled samples is slightly lower. In the samples filled with polyurethane foam, a slight decrease from -0.02 at a 1% strain to -0.07 at 5% strain occurs followed by an increase to -0.005 at a 30% strain.

In the group of 2D missing rib samples, Poisson's function increases for the unfilled samples as well as for both types of filling and, in all cases, reaches the zero value of Poission's ratio at strains of 0.25, 0.18 and 0.15 for the unfilled samples, polyurethane foam filling and ordnance gelatin filling, respectively.



(a) 2D re-entrant (b) 3D re-entrant (c) missing rib

Fig. 3: Poisson's function of the tested groups obtained by DIC

4. Conclusions

Three types of additively manufactured auxetics, 2D and 3D re-entrant structure and 2D missing rib structure were tested at quasi-static and high strain-rate conditions in a compression mode. The influence of two types of filling materials on the energy absorption properties were evaluated as well as the influence on the auxetic behaviour of these lattices. The obtained results at a quasi-static strain-rate show a positive influence on the strain energy density when the polyurethane foam filling was used, while the influence of the ordnance gelatin was negligible. At a strain-rate of $2000\,s^{-1}$, an increase in the absorbed impact energy was observed for both types of filling. Moreover, the influence of the filling on the auxetic behaviour was evaluated using an optical strain measurement. For both types of filling, the auxetic nature was slightly suppressed at high strain-rates.

Acknowledgments

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