
Dynamic compression of additively manufactured architected materials

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Abstract

Architected materials produced through additive manufacturing offer unparalleled advantages. This technique enables intricate designs and customizable structures, optimizing material distribution for enhanced strength, weight reduction, and functionality. By precisely layering materials, it allows for geometric complexities that traditional manufacturing methods cannot achieve. One of the family of structures that were previously unachievable through traditional machining but realised by AM, is lattice structures. This category of structure including gyroid, octet truss, re-entrant honeycomb are classified based on their geometry, material, and intended functionality. Each lattice type showcases unique characteristics like energy absorption, compression, and shear resistance in applications ranging from lightweight components to impact-absorbing structures. The Gyroid lattice features interconnected, curved lines, offering optimal strength and minimal material usage. Diamond lattice presents a balanced combination of strength and space efficiency, ideal for load-bearing applications. This study focuses on two different lattice structures made with a thermoplastic polyurethane: the triply periodic minimal surface (TPMS) called Schwarz "D" or more commonly diamond and the re-entrant structure. Re-entrant honeycomb are auxetic cellular structures that exhibit negative Poisson's ratio so that, unlike regular cellular structures, they show lateral shrinkage upon axial compression. This project used a combined experimental and numerical approach to study the mechanical behaviour of two lattice structures fabricated using Additive Manufacturing. The material chosen is Thermoplastic Polyurethane (TPU) (EOS TPU 1301) manufactured using Selective Laser Sintering. TPU is commonly used in 3D printing and injection molding, and finds applications in automotive components for impact absorption, medical devices due to biocompatibility, footwear, flexible seals and gaskets, protective cases for electronics, and sportswear for stretchable and resilient fabric. TPU's unique blend of mechanical properties and processability makes it indispensable in various industries seeking robust yet flexible materials for their energy absorption capacity. Quasistatic and dynamic compression tests were conducted using a universal tester and drop tower respectively. Full field imaging techniques were used to analyse the kinetics of the deformation. MatchID 2D software was used to quantify displacements and strains in materials thanks to the digital image correlation technique. The quasistatic testing was conducted in a universal testing machine (Shimadzu autograph AGS-X). Both structures were first tested under a 10 kN maximum load capacity but as the maximum force measured during the first test for the re-entrant structure is under 1 kN, the setup was changed for this structure under a 1 kN maximum load. The image acquisition frame rate for these

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experiments is set at 1 frame per second while the tests usually lasts about 5 minutes. The dynamic testing was conducted in a drop weight impact testing machine (Instron 9450). The setup for this experiment included a high speed camera and a set of two leds in order to get the highest resolution possible for DIC. The tests duration are both about half a second so the high speed camera frame rate set is 20,000 frames per second. The DIC analysis allows the discussion of the folding happening for the diamond or the collapse of the struts for the re-entrant for instance but it can also measure the strain within each structure. In quasi-static compression, the deformation rate being very slow, the structure has time to respond to the load and to dissipate energy progressively. This leads to a more uniform deformation process. Dynamic compression is characterized by extremely rapid deformation rates. The energy does not have enough time to be dissipated in the structure, hence a less predictable deformation organized in layers. When the drop tower impacts the structure, kinetic energy is transferred to the structure and converted into other forms of energy such as deformation energy or vibration and resonance. Another part of the impact energy could also be reflected and may cause the impacting object to bounce off the structure with a portion of the original energy. To determine which structure would exhibit better absorption capabilities, displacement alone is not sufficient. It is essential to compare force-displacement curves, since the energy absorption (EA) corresponds to the surface below the force-displacement curve, in other words, its integral. Finite element models were created using Abaqus software and a stochastic model was created using Python scripting to account for the variability in material properties introduced by additive manufacturing. TPU behaviour is considered hyperelastic. Hyperelastic materials exhibit only a non-linear elastic behaviour, meaning that the material returns to its initial shape when the stress is removed. They have the ability to experience a large deformation without considerable permanent deformation after load is removed. This type of behaviour can be characterised by the strain energy potential and can be modelled with many different forms (polynomial, Ogden, Arruda-Boyce etc..). The model retrieved for the TPU from is a polynomial form called Mooney-Rivlin. The Python code takes the input file from Abaqus and different arguments. The code takes the information for the material that needs to be modified and writes copies partly modified. For this present work as a first intention, only the Young's modulus is altered but it can be easily be modified to be the yield strength as it is intended to work on elasto-plastic materials. From the arguments information, the name of the part concerned allows to get the number of elements and to distribute them normally and randomly into elements sets that are each assigned a section with a unique material defined before. The results show that the introduction of material uncertainty with the stochastic model reduced the properties of the lattice structures. For the same mean Young's modulus, the stochastic model's response is definitely different and the resulting reaction force is below for the whole displacement. This behaviour is what was expected in the first place when seeing the weakened behaviour of AM structures. However as it is a random distribution, it would be more accurate to run several stochastic models with the same distribution parameters in order to get a mean response and not an isolated one. The validation of the numerical model by comparison with experimental data shows that there is still significant work required to have a good correspondence. By integrating advanced material models based on intricate geometries and microstructures, simulations can replicate the intricate stress distribution, deformation, and failure mechanisms. This enables a deeper understanding of how architected materials respond under various conditions, guiding design optimization and performance prediction. With refined material models, engineers can fine-tune the composition and arrangement of structures to match real-world behaviour.