Mechanical characterization and numerical modelling of additively manufactured thermoplastics

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Introduction

3D printing technologies allow the production of components with a much higher degree of intricacy and with near net shape, substantially reducing material wastage. This work aims to present a novel study on the numerical simulation of 3D printed honeycomb structures under compression, that serves as a validation for further simulation of additively manufactured energy absorption structures (EAS).

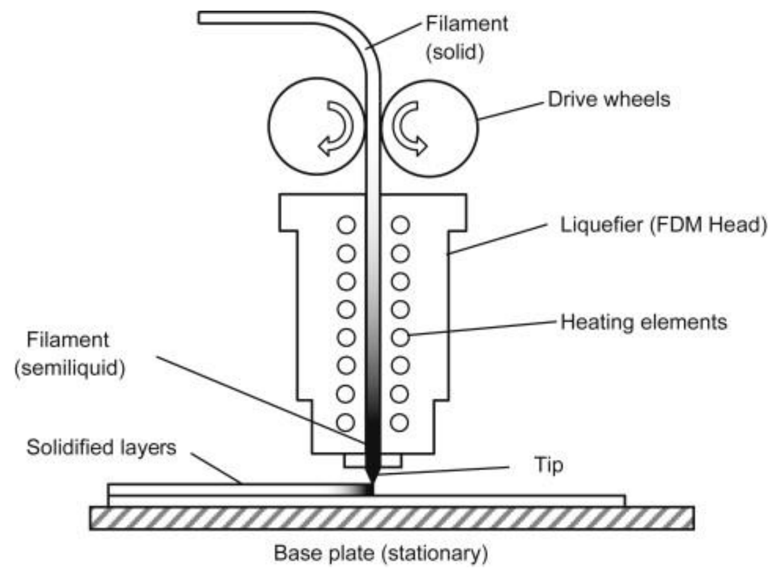


Figure 1 – Fused filament fabrication process representation.

There are many additive manufacturing technologies. Fused filament fabrication (FFF) technology is the most widely implemented due to its process simplicity, cost-effectiveness, and high printing speed [1]. FFF printers use a thermoplastic filament that is heated to its melting temperature and extruded layer-by-layer to create a 3D structure. The mechanical properties and appearance of FFF printed parts are substantially affected by the definition of printing parameters, such as build orientation and raster angle. Hence, the materials were characterized, regarding three different raster orientations - 0°, 45° and 90°.

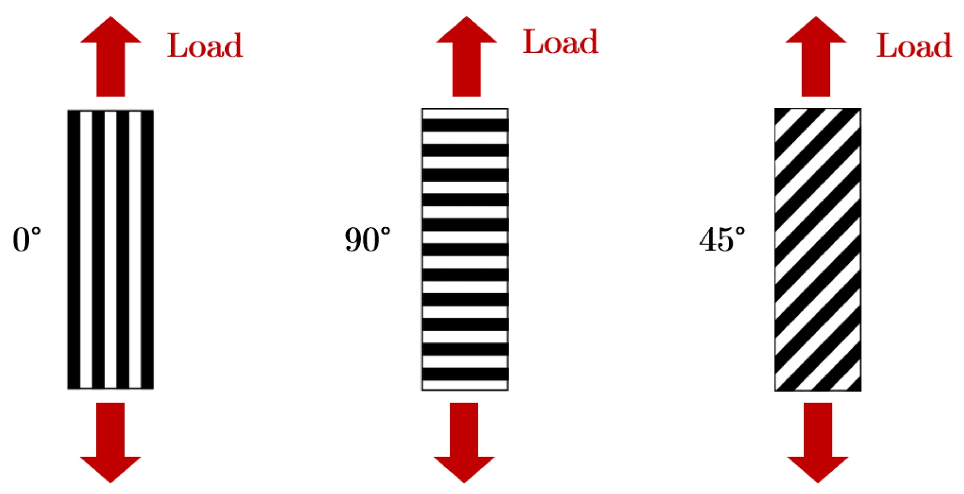
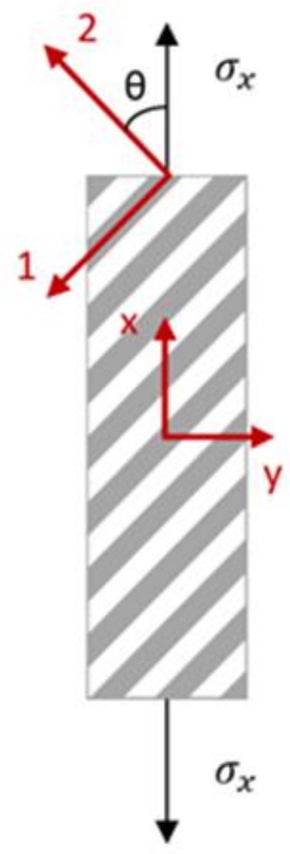


Figure 2 – Raster angle, regarding the applied load.

Anisotropy modelling

Hill's yield criterion is used to model the anisotropic yield of a material. For a orthotropic, transversely isotropic (plane 23) material under plane stress, Hill's criterion can be written as follows:

$$\sigma_\theta = \sigma_x = \left[\frac{sin^4\theta}{X^2} + \frac{cos^4\theta}{Y^2} + \left(\frac{1}{W^2} - \frac{1}{Y^2}\right) sin^2\theta\ cos^2\theta\right]^{-\frac{1}{2}}$$



Where X, Y are the ultimate tensile strength in the 0° and 90° directions, respectively, and W is the ultimate shear strength in plane 12. While X and Y can be directly obtained from tensile tests, W is obtained from applying the previous equation. From X, Y and W parameters, it is possible to calculate F, G, H and N - Hill's model parameters, that depend on the state of anisotropy. In turn, these allow the calculation of the anisotropy coefficients needed for the Abaqus input - R_{11}, R_{22}, R_{33}, R_{12}, R_{13}, R_{23}.

Damage modelling

Due to their straightforward formulation and calibration method, uncoupled fracture criteria have found extensive use in metal forming processes. The formulation of the damage accumulation function in these criteria is based on macroscopic variables, such as the hydrostatic stress, σ_m, the equivalent stress, $\bar{\sigma}$, the maximum principal stress, σ_{max}, the stress triaxiality, η, and the normalized Lode angle parameter, $\bar{\theta}$.

$$D = \int_0^{\bar{\varepsilon}_p} f(macroscopic\ variables) d\bar{\varepsilon}_p$$

In this study, the normalized Cockroft-Latham, Brozzo and McClintock criteria were employed. A hybrid experimental-numerical method was utilized, where these criteria are incorporated into the finite element simulations of the tests conducted on the printed materials. This approach allows for the determination of the critical damage value at the displacement where failure initiates in the experimental tests.

Reference structure

A small-sized reference structure (Figure 4) with a honeycomb cellular geometry was printed in two different build orientations and tested to quasi-static in-plane compression. The performed tests would then be used to validate the numerical model when applied to compression, by numerically simulating the quasi-static compression tests and comparing with the experimental data.

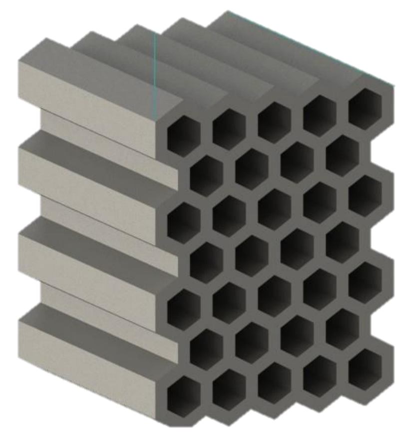


Figure 4 – Reference honeycomb structure.

Finite element analysis

Numerical simulations of the tensile tests were conducted in order to calibrate the true stress vs. plastic strain curves. Once the materials were accurately modelled, a defined user subroutine was used to obtain the damage values at the point at which there was rupture of the tensile specimens - critical damage values -, according to the employed ductile damage criteria. The values obtained were then employed to model crack initiation and propagation in the simulation of the compression of a reference honeycomb structure. Element deletion was activated when the damage function reached its critical value in a specific element. The best agreement was reached when employing the normalized Cockroft-Latham criterion.

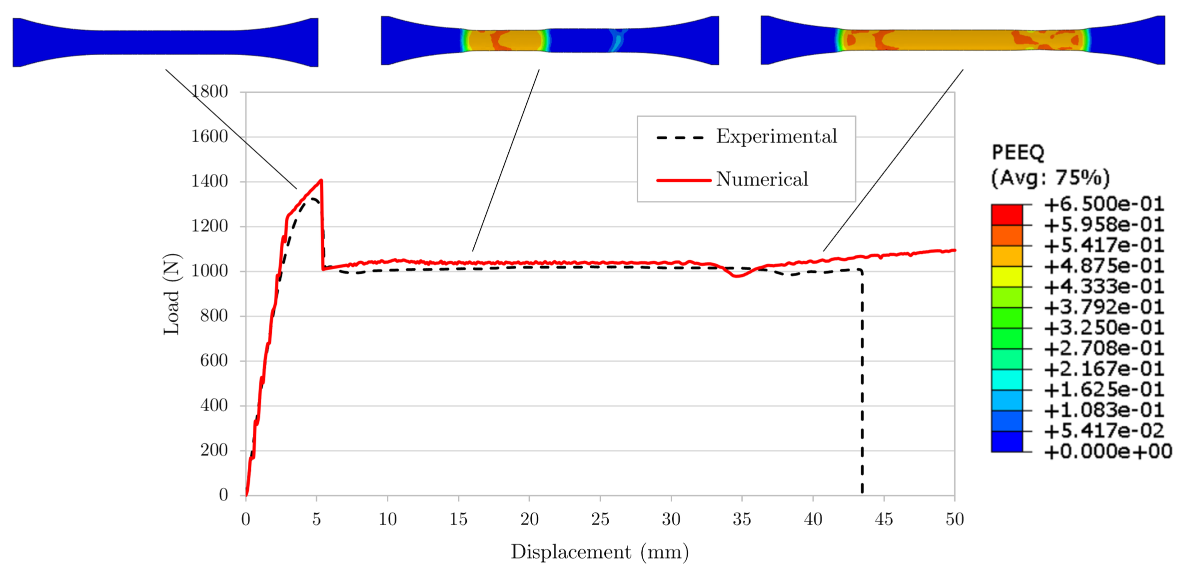


Figure 5 – Comparison between experimental and numerical tensile load-displacement curves for PC 0° specimen.

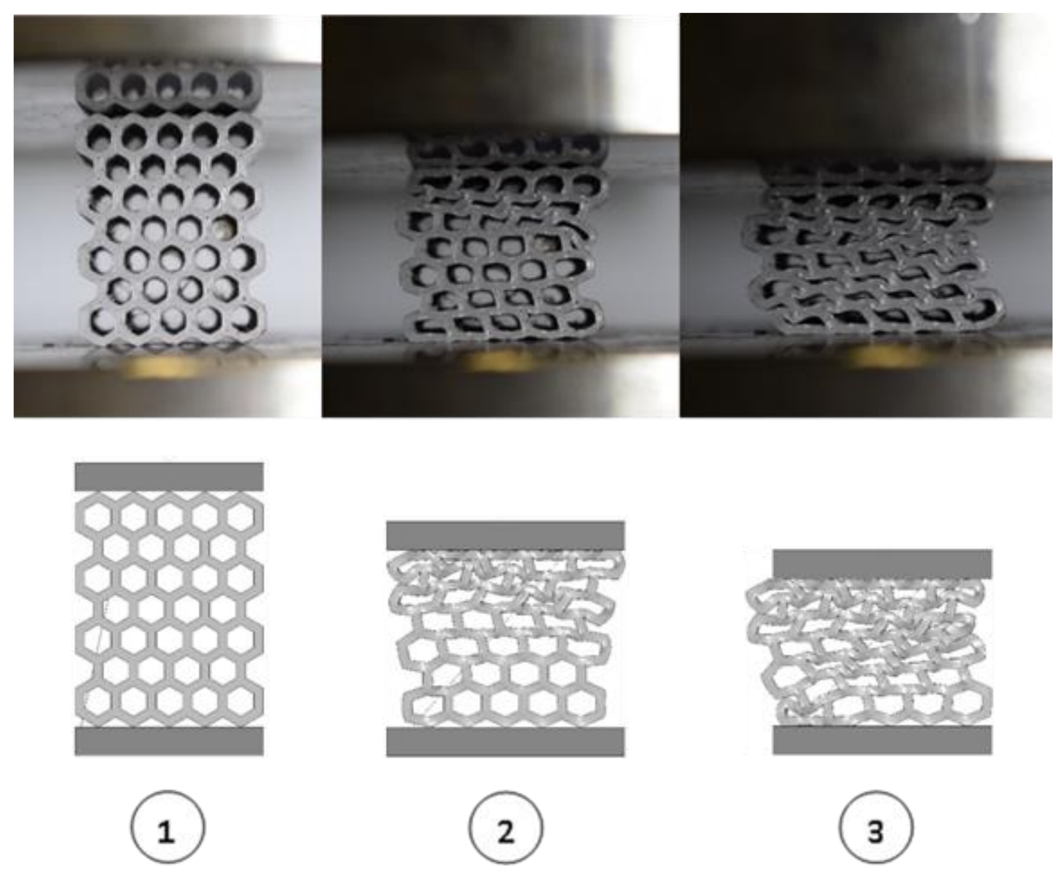


Figure 6 – Comparison between experimental and numerical tensile load-displacement curves for PC 0° specimen.

Conclusions

The anisotropic behaviour of the additively manufactured parts was assessed and modelled successfully, resorting to the Hill's yield model. For all materials, higher mechanical properties were obtained for the 0° raster orientation specimens, whereas a significant deterioration of those was verified when the raster was perpendicularly oriented to the applied load, due to the weak adhesion between adjacent filaments. Overall, the developed model was able to accurately predict the behaviour under compression of the honeycomb structures, for both build orientations. A satisfactory agreement was reached for all the tested materials (PC, PETG and TPU), with a good correlation between the fracture modes of the structures and load-displacements values.

References

[1] - Kristiawan, R., Imaduddin, F., Ariawan, D., Ubaidillah & Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. *Open Engineering*, *11*(1), 639-649.

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