Analysis and modelling of damage mechanism in FDM 3D-printed Lattice structure during compression loading

Alberto Corvi[1], Luca Collini[1], Corrado Sciancalepore[1] and Ajeet Kumar[2]

[1]Università di Parma – Dipartimento di Ingegneria e Architettura, Viale delle Scienze 181/A, 43124 Parma, Italy,

[2]*High Speed 3D Printing Research Center, National Taiwan University of Science and Technology, Keelung Rd, Taipei, 106 – Taiwan, ROC*

(Received 000 0, 2020; Revised 000 0, 2020; Accepted 000 0, 2020)

Keywords: Failure mechanism; Fused filament fabrication; Lattice structure; Numerical simulation;

Correspondence to: Alberto Corvi alberto.corvi@unipr.it

Abstract Fused Deposition Modeling (FDM), also known as fused filament fabrication, is a widely spread 3D printing process that uses a continuous filament of a thermoplastic material. In this work, the anisotropy of cellular "open-cell" structures printed in ABS by the FDM technology is studied and a model of mechanical response up to the damage regime is tried. The present investigation starts from the analysis of the anisotropic effect due to the directional material deposition, which is preliminary studied on simple prismatic samples at various filament orientations. Then, the research goes through the observation of damage at the micro-scale of a sample cell structure loaded in compression, and tries to reproduce the anisotropy at both elastic and plastic regimes by FE modelling in ABAQUS© environment.

1. Introduction

The risen of additive manufacturing techniques has deeply changed the prototyping process, reducing the cycle-time and the cost of product development. AM allows the creation of objects with really complex geometries, otherwise impossible to obtain with traditional manufacturing methods. The most commonly used technology is Fused Deposition Modeling (FDM): compact size, low cost, and no need of a controlled atmosphere are just some of the aspects for which FDM is considered the most suitable technique for rapid prototyping. Nowadays this technology is no more confined into strictly prototyping but progressed to creating final products for advanced applications in many different areas, from aerospace to bioengineering.

Being a layer-by-layer stacking process, FDM presents some pitfalls: building parts from bottom to top, the material in the current layer can present a high level of solidification before the next one is placed on it, causing incomplete inter-layer adhesion and leaving voids in the solidified structure. This result of course affects the mechanical performance of the printed product, resulting non-homogeneous at the meso- and macro-scale [1], but it is also responsible of a different material response depending on the direction of the testing with respect to the direction of material deposition: this leads to directional properties that allow to classify FDM parts as anisotropic, differing from the isotropic bulk material (the anisotropy is indeed intrinsic of this manufacturing process). [2,3]

Regarding this issue, some work has been carried out to determine the effects of production parameters on the mechanical properties [4-7]. Ismail et al studied the influence of raster angle and orientation on the mechanical properties of ABS printed parts [8].

Various grades of anisotropy in elastic and plastic [9-12] regime have been recently studied, finding their difficult predictability being extremely various the combinations of printing parameters' set.

Lattice structures are a result of the AM application to process complex structures and have gained at date big consideration [13]. Many structures are mimicked from natural designs [14], according to the principles of biomimetics, and are generated through an edge-to-edge tessellation of the unit cell in the three-dimensional space [15]. Lattice structures are light in weight and optimize the effective stiffness ratio. Depending on their morphology and size, lattice structures show properties that can differ a lot from the bulk material of which they are made [16]; in particular, lowering the relative density of the cell, they behave as meta-materials, extending their applicability to several applications, as dampers, shells, and functionally graded structures, thanks to their capacity to absorb a huge amount of energy before failing. More, the possibility of 3D printing with no-support makes these structures effective meta-materials [17-18].

In this work, the anisotropy of sea-urchin-inspired lattice structure printed in ABS by the FDM technology is studied and a model of mechanical response up to the damage regime is tried. The present investigation starts from the observation of damage at the micro-scale of 4x4x4 cell structures loaded in compression, and tries to reproduce the anisotropy at both elastic and plastic regimes by FE modelling in ABAQUS© environment.

2. Materials and Methods

2.1 Material test

The effect of the material deposition process on the level of anisotropy of the printed part is analysed. Process parameters are indeed the key aspect to understand and predict the resulting mechanical properties of the component. The final product has a direction-depending resistant section, because of a worse bonding between filaments of different layers rather than between those of the same layer: this aspect is influenced by many parameters and the printing path is one of the principals, the shorter the deposition path, the higher the temperature of filaments, and the better the consequent bonding and sintering between two adjacent filaments.

Small rectangular specimens have been fabricated in all the different possible configurations of building orientation.

Configurations are reported in Fig.1. Samples are tested for bending strength on a (AMETEK) Chatillon TCD225 Series Force Measurement System© with 1kN load cell as follows: i) printed sample is placed into the test machine, with a span of 50 mm; ii) necessary data are inserted in the test machine: strain rate of 5 mm/min and maximum displacement of 5 mm; iii) tests are carried out and load-displacement data are written down.

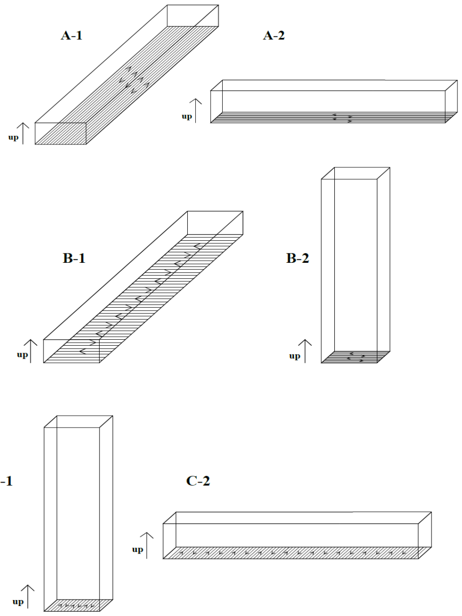

Fig.1. Unit cell and tessellated structure

2.2 Cellular structure

Cellular structures are originated from a tessellation of a unit cell in the three-dimensional space. The unit cell is nature-inspired, trying to reproduce the morphology of the sea-urchin skeleton, but in an "open" configuration with holes in the planar faces. Again, considering biomimetic theory, the final structure is obtained through a process of tessellation of the unit cell. In particular, a face-to-face tessellation is adopted, same as the one observed in bee honeycomb.

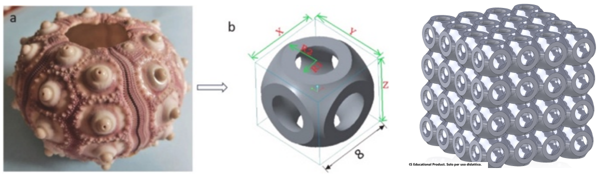

Fig.2. Unit cell and tessellated structure

2.3 Finite Elements simulation

A numerical simulation of the compressive test is developed in ABAQUS© environment, with the aim to reproduce the failure of the lattice structure and so to predict the material level of integrity to prevent failure. The constitutive model of the printed ABS must be orthotropic, according to what observed relate to the material deposition process. In particular, a transversely isotropic constitutive model is the most suitable for FDMed components. Material properties are symmetric about an axis that is normal to a plane of isotropy: the plane of isotropy coincides with planes parallel to the basis of the structure, meaning that the material inside each layer is almost isotropic.

The constitutive matrix for transversely isotropic elasticity is reported, with indexes *p* and *t* for the plane of isotropy and the transverse direction, respectively.

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{bmatrix} 1/E_p & -v_p/E_p & -v_{tp}/E_t & 0 & 0 & 0 \\ -v_p/E_p & 1/E_p & -v_{tp}/E_t & 0 & 0 & 0 \\ -v_{pt}/E_p & -v_{pt}/E_p & 1/E_t & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_t & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_t \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}$$

Through proper user subroutine, damage is introduced: local strains at the centroid of each element are recalled and put inside the formulation of the damage variable. More in details, two different damage variables independent from each other are defined, in order to develop an anisotropic damage, different from the plane of isotropy to the transversely isotropic direction. A threshold strain value ε_{th} is defined: when the local deformation is smaller than the set value, the material is perfectly integer, and the damage variable is equal to zero. When the strain exceeds the condition of damage initiation, the damage variable is computed and the material starts to change/degrade its elastic properties.

Damage initiation condition:

$$\varepsilon_i = (\varepsilon_{th})_i$$

Damage evolution law:

$$\text{for} \quad (\varepsilon_{th})_i < \varepsilon_i < (\varepsilon_f)_i \qquad D_i = 1 - \left(1 - \frac{\ln \frac{\varepsilon_i}{(\varepsilon_{th})_i}}{\ln \frac{(\varepsilon_f)_i}{(\varepsilon_{th})_i}} \right)^{\alpha_i}$$

$$\text{for } i = p, t \qquad E_i = (E_0)_i \left(1 - {D_i}^2\right)$$

The strain in a specific direction is responsible of the damage in that direction, creating a one-to-one correspondence between strain and elastic properties in the considered direction. When the damage variable reaches unit value, i.e. the failure strain value ε_f is reached, the element is supposed not to carry any load and can be suppressed from the analysis.

3. Results

3.1 Experimental test

Results of the flexural modulus and of the maximum bending stress up to failure for the three-point-bending test are shown in Fig.3, together with their error bands. As expected, the A-group, where the material deposition direction coincides with the stress direction, is the stiffest and the most resistant. This result is important because it provides a ratio between the elastic properties of FDMed ABS tested in different orientations, confirming the importance of the printing parameters' proper setting.

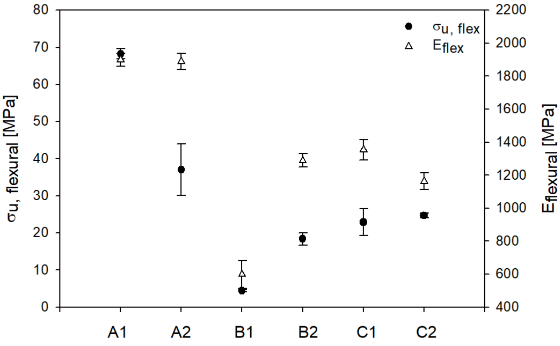

Fig.3. Flexural modulus and maximum bending stress

At the beginning of the compressive test the structure behaves as a spring so the first region is linear elastic until 6.6% deformation. The linear region is followed by a decrease in the load when first failures occur.

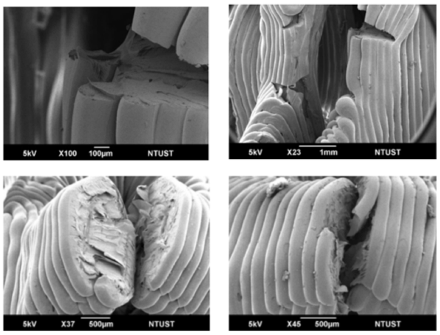

Fig.4. Different failure mechanisms

In Fig.5 it is possible to notice both initiation of a crack in the external wall of the cell and a damage between cells, caused by the increase in width of the structure. From there on, some cells completely crash and the response curve goes on decreasing, until 19% deformation, where the whole structure is functionally crashed and the material stack to the lower level so the mechanical curve rises again. This region is not considered since the test is considered as ended.

Through Scanning Electron Microscope (SEM) observation of the fracture surfaces of the structure at the end of the test, two damage mechanisms are identified. The first one, upper images in Fig.4, is related to the comparison and propagation of a crack across a filament, with the macroscopic effect of cracking filaments of different layers in the direction normal to the deposition direction: it is referred to this as the intra-layer damage. The second mechanism, lower in Fig.4, is responsible of the separation of two adjacent layers, breaking the bonds between filaments. This is the first failure to occur during the compressive test, as the material is less resistant in this direction.

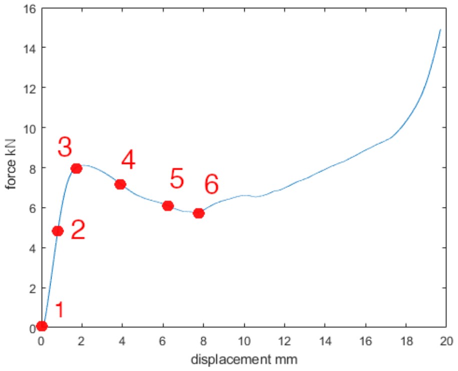

Fig.5. Compressive response of the cellular structure

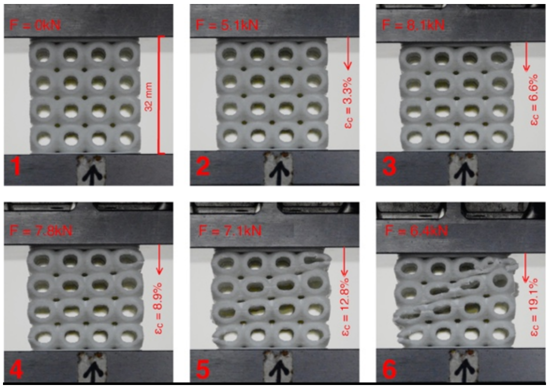

Fig.6. Structure behavior during the compressive test

The intra-layer damage is the first mechanism to occur, despite not being the one causing first failure. As we can see in Fig.6, the second frame presents an incipit of material degradation in the region between two adjacent cells, while only in the third frame a crack starts, when the damage level inside the structure is already significative.

4. Conclusions

Numerical results of the FE simulation show a good match with experimental tests: the two damage mechanisms affect the structure similarly as what observed in Fig.6, allowing to validate the numerical model.

Fig.7 presents at first the comparison of an inter-cell damage, responsible of a local degradation of the mechanical response of the material. Then it is followed by the intra-cell cracks, generated by the bending stress in the external cell wall.

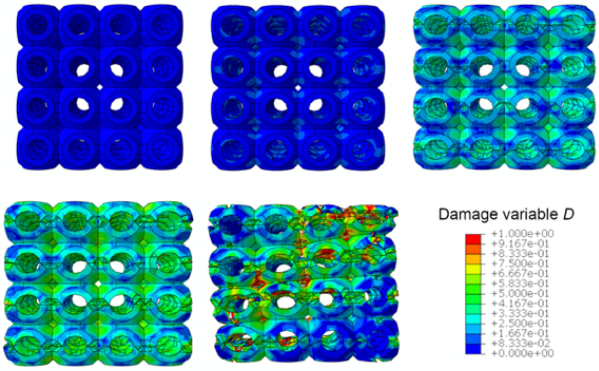

Fig.7. Numerical simulation for the failure of the structure

The main results can be summarized as follows:

- Two different damage mechanisms take place, independent from each other: these affect the structure in different directions.
- The material deposition direction is responsible of the anisotropy of the printed structure, so it is important to properly define the production's parameters according to the stress field the component will be subjected to.
- FE model is a reliable mean to predict failure and to understand the condition of integrity of compressed cellular structures.
- Through an accurate tuning process of the model, the effect of printing parameters will be reflected in different levels both of anisotropy of the component and of damage threshold for crack initiation and for the failure.

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Author information

Alberto Corvi is a Ph.D. student in the University of Parma, Parma, Italy. His research interests include Numerical Modelling, FE simulations and Additive Manufacturing.