Numerical characterisation of additively manufactured components

Giuseppe Mantegna[1,a *], Davide Tumino[1,b], Calogero Orlando[2,c] and Andrea Alaimo[1,d]

[1]Kore University of Enna - Department of Engineering and Architecture, 94100, Enna (EN), Italy

[a]giuseppe.mantegna@unikore.it, [b]davide.tumino@unikore.it, [c]calogero.orlando@unikore.it, [d]andrea.alaimo@unikore.it

Keywords: Additive Manufacturing, FEM, Lattice

Abstract. Additive manufacturing (AM) technologies are gaining widespread adoption across multiple engineering sectors due to their ability to create customised components with tailored mechanical properties and reduced material waste. This work presents different innovative Finite Element Method (FEM) models to characterise the behaviour of AM structures. A numerical model is presented to characterise AM porosity defects using the Representative Volume Element (RVE) concept; additionally, different unit cell approaches to study the behaviour of lattice structures are presented. The procedures and methodologies presented offer a range of tools, each with different trade-offs between accuracy and computational cost.

Introduction

Additive Manufacturing (AM), commonly referred to as 3D printing, is a process that involves building objects by incrementally adding material layer-by-layer based on a Computer-Aided Design (CAD) model. One of the major advantages of AM is its ability to produce finished components using a single tool, and the capability to create complex geometric shapes while minimising material waste. Moreover, studies have highlighted the cost savings associated with AM, particularly for small-volume production runs, as well as a shorter design-to-development cycle time [1]. AM technologies have facilitated the integration of lattice structures into complex structural components, enabling weight optimisation while simultaneously maximising mechanical performance tailored to specific functional requirements. Indeed, the fabrication of such complex structures using traditional manufacturing techniques would be highly complex or infeasible. Despite the numerous advantages offered by AM technologies, it must be acknowledged that AM components can exhibit defects and imperfections that may adversely affect their mechanical properties. These defects can arise due to various factors, such as process parameters and/or material characteristics. Consequently, it is essential to be able to forecast the behaviour of AM components. Numerical models not only provide valuable insights into the structure-property relationships but also enable the optimisation of design parameters and manufacturing processes.

Finite Element Model Porosity Characterisation

Internal defects, such as porosity, are common in additively manufactured components, and they can lead to inferior mechanical properties, potentially compromising the structural integrity and safety of the entire system. To address this challenge, a numerical model based on the concept of the Representative Volume Element (RVE) is presented to predict the macroscopic behaviour of the structure. By capturing the microscale defects within the RVE, is possible to predict the macroscopic effects through a homogenization procedure, which significantly reduces the computational costs associated with the macro-scale analysis [2].

The study of Cai et al. [3] is considered as reference for the pore size distribution inside SLM AlSi10Mg components. The developed RVE model uses hollow spheres to simulate pores inside the component. Isolated spheres represent metallurgical pores, while the shapes generated from their overlap simulate keyhole pores generated by the coalescence of multiple pores during the SLM manufacturing process. An in-house APDL (Ansys Parametric Design Language) code is developed to generate the RVE with pores, Figure 1.

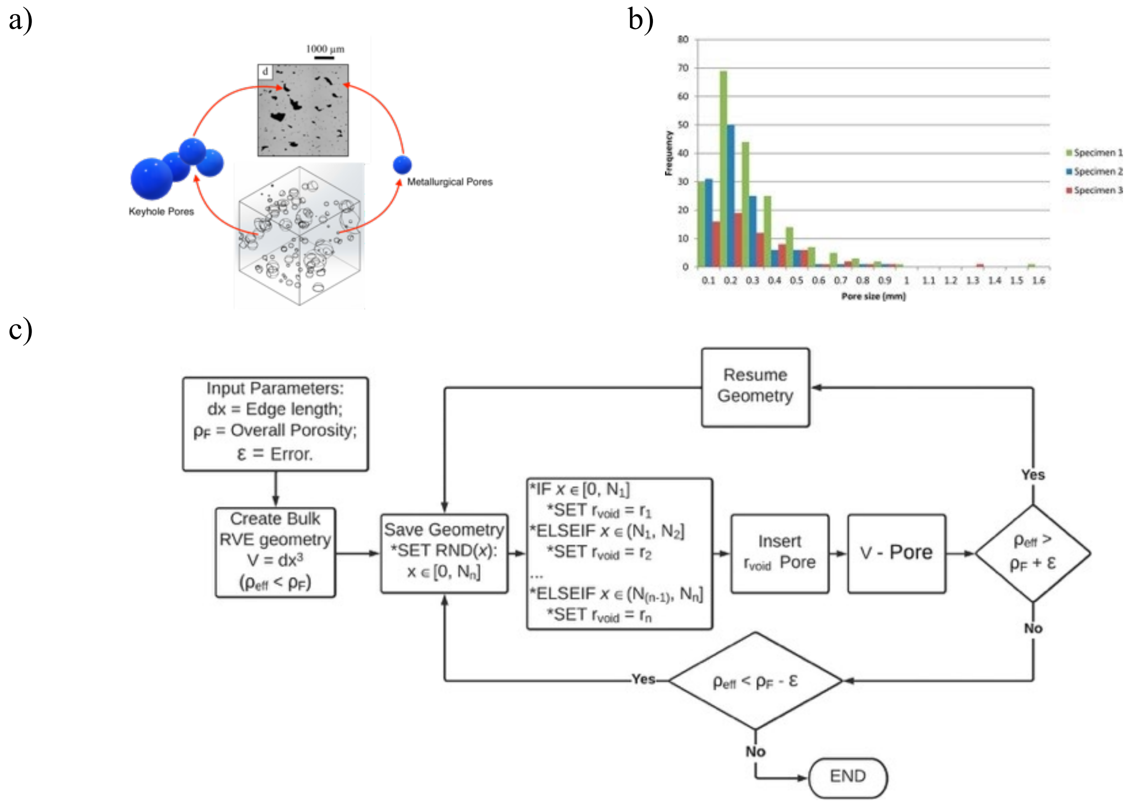


Figure 1 – RVE porosity scheme. a) Pores idealisation, b) Pores size distribution ***[3]****, c) APDL flow chart diagram.*

Compression and shear numerical tests are performed on the RVE to characterise its mechanical behaviour. To ensure accurate results, double periodic boundary conditions are imposed by coupling the displacement of each node on two opposing faces that share the same relative position with two pilot nodes, Np. The periodic conditions along the x-direction are:

$$\begin{aligned} u_{i(0,y_i,z_i)} - u_{i'(dx,y_i,z_i)} &= \Delta u_{Np} \\ v_{i(0,y_i,z_i)} - v_{i'(dx,y_i,z_i)} &= \Delta v_{Np} \\ w_{i(0,y_i,z_i)} - w_{i'(dx,y_i,z_i)} &= \Delta w_{Np} \end{aligned} \tag{1}$$

As expected, as porosity increases, key mechanical properties decrease, including the elastic modulus, the shear modulus, yield strength and Poisson's coefficient, Figure 2.

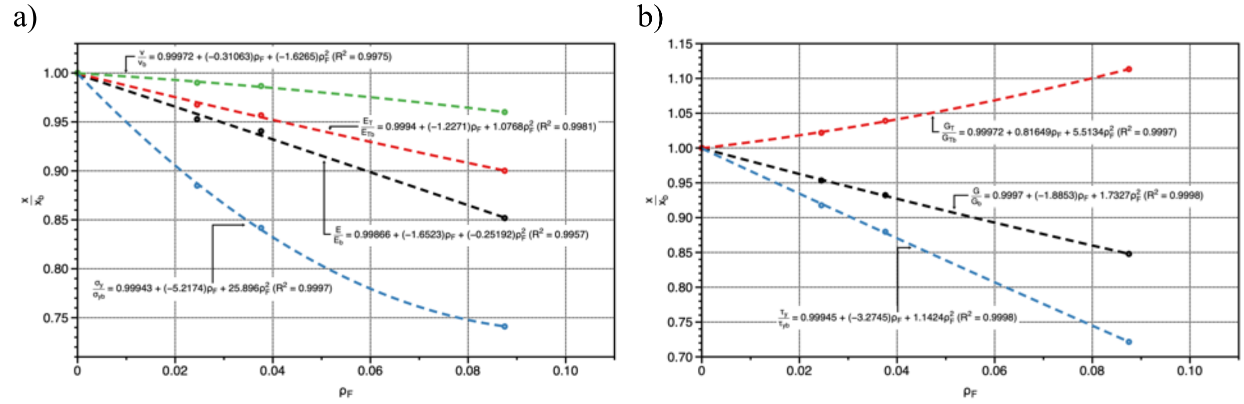
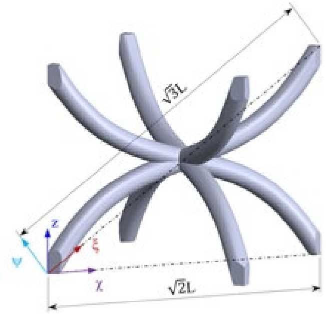


Figure 2 – Normalised properties respect with defect-free material [2]. a) Compression Test, b) Shear test.

Waved Body-Centred Cubic Cell

Lattice structures are formed by the ordered repetition of unit cells in three-dimensional space to create the final component. Among the different cell topologies, strut-based cells are often used to their manufacturing and modelling simplicity. The standard BCC cell has been extensively studied in the literature [4], [5]. A new variant of the BCC cell has been developed by the authors [6], wherein the straight struts of the traditional BCC cell are replaced by sinusoidal struts, making to the new cell orthotropic:



$$\psi = a \sin\left(\frac{2\pi\xi}{\sqrt{3}L}\right) \tag{2}$$

Figure 3 – Waved Body-Centred Cell.

Compression and shear tests have been conducted to characterise the behaviour of the new unit cell. To achieve accurate results, the double periodic boundary conditions employed for the RVE, Eq. (1), have been suitably modified. Additionally, a novel procedure has been developed to reduce the computational costs associated with the analysis. This approach utilizes simplified periodic conditions through the implementation of remote points to constrain the lateral faces, as shown in Figure 4.

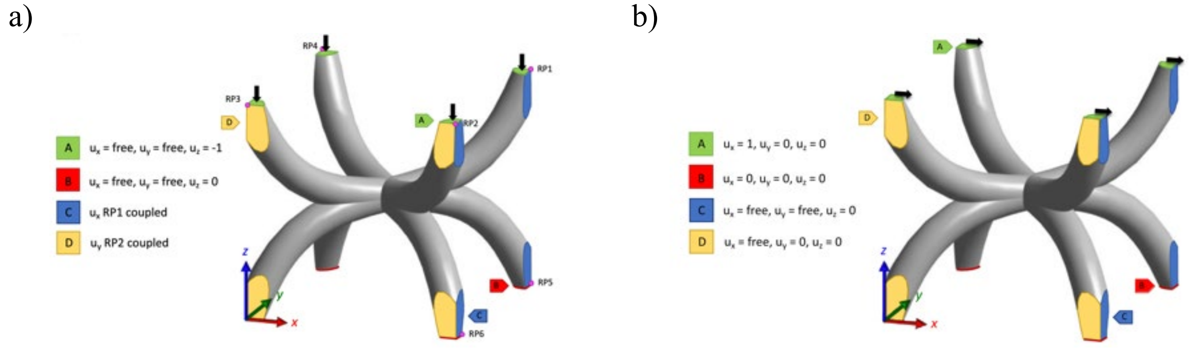


Figure 4 – Simplified periodic boundary conditions [6]. a) Compression test, b) Shear test.

Table 1 summarises the elastic modulus E_z results obtained with the double periodic boundary conditions (2xp) and the simplified periodic conditions (s-p). A good approximation can be outlined with a maximum error of only 2%. Table 2 summarises the mechanical properties of the waved unit cell.

Table 1 – WBCC double periodicity-simplified periodicity E_z modulus comparison.

ϕ [mm]	E_z 2xp [MPa]	E_z s-p [MPa]	e%
1.5	22.12	21.79	-1.5%
1.75	46.5	45.56	-2.0%
2	85.84	83.58	-2.6%
2.25	141.62	138.03	-2.5%
2.75	297.46	290.39	-2.4%

Table 2 – WBCC equivalent elastic properties.

ϕ [mm]	$E_x = E_y$ [MPa]	E_z [MPa]	ν_{12} [ ]	$\nu_{23} = \nu_{13}$ [ ]	G_{12} [MPa]	$G_{23} = G_{13}$ [MPa]
1.5	7.35	22.12	0.721	0.175	38.74	7.33
1.75	14.99	46.5	0.723	0.155	54.54	12.83
2	27.92	85.84	0.719	0.138	73.37	20.51
2.25	48.12	141.62	0.705	0.125	103.97	30.62
2.75	120.62	297.46	0.653	0.1	158.11	58.84

Conclusions

Novel FEM models have been developed to characterise various aspects of additively manufactured structures. The proposed models offer designers a versatile toolset, providing the flexibility to select the optimal balance between accuracy and computational costs, thereby tailoring the approach to specific design requirements.

References

[1] V. Mohanavel, K. S. A. Ali, K. Ranganathan, J. A. Jeffrey, M. M. Ravikumar, and S. Rajkumar, “The roles and applications of additive manufacturing in the aerospace and automobile sector,” *Mater Today Proc*, vol. 47, pp. 405–409, 2021. https://doi.org/10.1016/j.matpr.2021.04.596

[2] G. Mantegna *et al.*, “Representative volume element homogenisation approach to characterise additively manufactured porous metals,” *Mechanics of Advanced Materials and Structures*, vol. 30, no. 5, pp. 1073–1082, 2023. https://doi.org/10.1080/15376494.2022.2124002

[3] X. Cai, A. A. Malcolm, B. S. Wong, and Z. Fan, “Measurement and characterization of porosity in aluminium selective laser melting parts using X-ray CT,” *Virtual Phys Prototyp*, vol. 10, no. 4, pp. 195–206, 2015. https://doi.org/10.1080/17452759.2015.1112412

[4] R. Gümrük and R. A. W. Mines, “Compressive behaviour of stainless steel micro-lattice structures,” *Int J Mech Sci*, vol. 68, pp. 125–139, 2013. https://doi.org/10.1016/j.ijmecsci.2013.01.006

[5] E. Ptochos and G. Labeas, “Shear modulus determination of cuboid metallic open-lattice cellular structures by analytical, numerical and homogenisation methods,” *Strain*, vol. 48, no. 5, pp. 415–429, 2012. https://doi.org/10.1111/j.1475-1305.2012.00837.x

[6] D. Tumino, A. Alaimo, G. Mantegna, C. Orlando, and S. Valvano, “Mechanical properties of BCC lattice cells with waved struts,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2023. https://doi.org/10.1007/s12008-023-01359-9