Numerical modeling of selective laser melting lattice structures: A review of approaches

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Abstract. With the recent development of metal additive manufacturing processes, the fabrication of lattice structures became more feasible. Mainly, with the selective laser melting process, lattices of various topologies have been designed and manufactured with superior properties. Their excellent characteristics have drawn the attention of major leading industrial sectors. Nevertheless, their full-scale adoption is still limited, owing to the lack of a standard numerical model that can accurately represent the lattices’ mechanical and failure response. The main challenge in developing such a model is the high computational cost associated with the fine three-dimensional meshes of the struts. Besides, the need to incorporate the struts’ defects into the finite element model while also accounting for the material behavior significantly increases the complexity of the model. In this context, this paper presents a review of the numerical models explicitly developed to simulate the lattices’ behavior. The potential of modeling lattices at the macro-scale level using reduce order elements will also be discussed. Overall, the aim of this paper is first to identify the important numerical parameters needed to construct the optimum numerical setup, and second to pinpoint the gaps that can be worked upon to develop a more reliable and computationally effective model.

1. Introduction
Metal Additive Manufacturing (MAM) technology allows for the realization of complex meta-material lattice structures across several length scales using a wide range of metals and alloys [1]. Lattice structures fabricated via Selective Laser Melting (SLM) have particularly drawn the interest of the leading industrial sectors owing to their diverse applications and commercial usefulness [2–5]. Without a doubt, the adoption of these types of structures is proliferating in engineering applications; however, at a slow pace. It is currently impossible to predict the mechanical behavior of lattice structures, both accurately and with low computational expenses. So far, only experimental testing can provide an accurate representation of the lattice structures’ behavior. Nonetheless, the design space is restricted to that of the testing machine, and the experimental approach itself is expensive in terms of time and cost. Other methods, such as the Gibson-Ashby [2] and the analytical models [6–12], can be used as predictive tools to estimate the lattice structures’ mechanical properties, but they are not enough. Subsequently, it is of particular importance to have a standard numerical approach that can provide full-field stress and strain distribution within the lattice microstructure.

Essentially, it is prohibitively difficult to develop a numerical model that is computationally inexpensive due to the high aspect ratio of the strut elements, which necessitates the use of 3D fine meshes [13]. Additionally, the SLM layer by layer material deposition, along with the repetitive melting and cooling process, introduces some irregularities and weak spots within the structure [14–
These imperfections are more pronounced in the case of lattice structures as they are built close to the SLM manufacturing limits. The SLM process-induced defects can be reduced to some extent through the optimization of the process parameters and the use of high-quality metallic powder. However, they can never be totally eradicated [17]. Therefore, to develop a model that can accurately reflect the lattice structures' behavior, the implementation of defects is a must.

Several unique approaches have been developed to physically incorporate the struts imperfections within a Computer-Aided Design (CAD) or Finite Element (FE) model using either a three-dimensional solid or a one-dimensional beam element. Alternatively, the irregularities can be accounted for by using an appropriate material model. At the moment, there is no single standard FE approach to follow. In this review, the aim is to focus on the key differences between the newly established numerical models and find the gaps that can be worked upon to speed up the process of developing a standard methodology or approach suitable for lattices of different topologies and designs. Special attention will also be given to the macro-scale modeling of lattices.

2. Micro-Scale Modeling Parameters
The modeling strategy for lattices changes depending on the scale considered. At the cellular level, the lattice is treated as a simple structure where the typical finite element method is used to model and simulate its behavior. In the literature, many FE models have been developed to evaluate the compressive behavior of lattice structures. Each follows a distinctive methodology. The lack of continuity and progressiveness between the published works are slowing down the expansion and the full-scale adoption of lattice structures. This is attributed to the complexity of lattices’ simulations, as many parameters have to be considered. Among those parameters, the element type, the material model, and the frictional contact constitute the main aspects of the SLM lattice structures numerical models [18]. Each one of those parameters can be accounted for in various ways.

2.1. Element Type
The struts of the lattice structures can be modeled using a three-dimensional solid or one-dimensional beam element (Euler-Bernoulli or Timoshenko). The selection of the proper element is related to the deformation and the aspect ratio (AR=d/L) of the lattice [19], as shown in figure 1. In the case of a small deformation or a lattice with high AR, both elements provide similar results. Evidently, to decrease the computational cost, it is better to use the beam-based model under the conditions that the imperfections are accurately represented. In the other cases, where the deformation is large (i.e., impact applications) or the lattice is of a small AR, the three-dimensional solid-based model is the better choice since the beam-based model tends in this situation to underestimate the mechanical properties [9,10].

![Figure 1. Diagram illustrating the proper FE element model for different types of deformation and aspect ratio.](image-url)
2.2. Material Model
A critical aspect of the FE analysis is the material model. For SLM lattice structures, different approaches have been used to model the material behavior. The first approach is directly derived from the stress-strain curve of the lattice structure’s constituent material [20,21]. This approach is simple yet requires the physical implementation of the geometric imperfections to obtain accurate results; otherwise, the numerical outcomes would be far off from their experimental counterparts. The second approach is the ductile damage model calibration, which can be utilized to predict the evolution of plastic strain at failure as a function of triaxiality over a wide range of stress states [22–25]. The third approach relies on the stress-strain data derived from an AM representative single strut [10,26]. The advantage of this approach is that the effects of all imperfections are already included in the model. The downside, on the other hand, is the lack of a standard procedure to perform a tensile test on a micro-strut. Furthermore, the stress-strain curve of a representative micro-strut might not be identical for struts of dissimilar orientations. For instance, horizontal struts are usually oversized, whereas the vertical struts are thinner in comparison with the nominal design [27,28].

2.3. Frictional Contact
The frictional contact between the struts and the plates or the struts themselves can potentially affect the response of lattice structures. For example, Smith et al. [29] showed that the frictional effect is more apparent for lattice structures of high density. Also, Galarreta et al. [19] proved that the modulus of elasticity increases as the frictional coefficient increases. The authors found a 22.5% difference in modulus between a frictionless model and one with a frictional coefficient of 0.3. On the other hand, Lozanovski et al. [30] found a negligible difference in the mechanical properties for models having tangential coefficients of 0.3, 0.6, and 0.9 at the lattice-plates interface.

3. SLM Lattice Structures Numerical Approaches: Potentials and Limitations
Various methods have been specifically developed to implement the SLM process-induced defects while taking into consideration the above-mentioned parameters. Herein, the most promising approaches are extensively discussed. The focus is on the setup and the combination of parameters employed, as well as the reliability, effectiveness, and applicability of the model for full-scale lattice structures simulations. The limitations of each model are also highlighted.

Campoli et al. [31] focused on studying the effects of the irregularities caused by the SLM technique on the mechanical properties of Ti6Al4V cube, diamond, rhombic dodecahedron, and truncated octahedron lattices. The authors based their research on two types of irregularities (1) strut thickness variations and (2) cavities. The struts’ thickness variation was implemented into a Timoshenko beam element of various diameters drawn from a Gaussian distribution, as depicted in figure 2. Furthermore, the Eshelby theory of ellipsoidal inclusions was employed to implement the effect of material porosity. No frictional coefficient or penalty factor had been applied. Concerning the material model, the distribution of porosity was included in the material matrix. From the reported outcomes, the significance of irregularities on the mechanical properties was clearly observed. As seen in figure 3, the model was better suited for structures of low apparent density. As the apparent density increases, the error between the experimental and the numerical results increases significantly. Overall, the Eshelby theory used in this model can be an effective tool to improve the accuracy of other models, especially those that focused only on the geometric imperfections and neglects the other types of defects.

Amani et al. [32] developed a heterogeneous model that accounts for the macroscopic void-cell structure and the micro-porosity within the nodes and the struts. Local tomography and double detector techniques were used to quantify the different levels of porosities. Then, a standard Gurson-Tvergaard-Needleman (GTN) model was used to include the quantified micro-porosities in each mesh element. The heterogeneous model was tested on two face-centered cubic (FCC) structures of different struts thicknesses. A comparison between x-ray tomography images at fracture and the numerical results proved the reliability of this model, especially in the prediction of the fracture location. The
drawback of this approach is primarily the heavy computational cost associated with the three-dimensional solid elements used to incorporate the micro-porosities. Consequently, the full-scale lattice structures simulation using this particular model would be rather difficult.

Figure 2. Struts irregularities modeled using beam elements of various diameters.

Figure 3. Modulus of elasticity results comparison after the implementation of the irregularity on a lattice with rhombic dodecahedron unit cells [31].

Liu et al. [28] established a beam-based model featuring a statistical representation of imperfections within the struts of rhombi-cuboctahedron and octet cells. The defects morphology, location, and distribution were quantified using computer tomography, and the geometric mismatches were obtained by generating a series of parallel planes which intersect with the strut at equidistant points along the axis, a schematic of this procedure is depicted in figure 4. A statistical analysis of the geometric irregularities based on the building direction (horizontal, vertical, and diagonal struts) was performed. Accordingly, probability density functions for each set were generated and applied to the beam model using a code. The authors considered small deformation (elastic region) and utilized the asymptotic homogenization approach to calculate the effective stiffness matrices of the lattices. This model was much better in predicting the elastic response of lattice structures in comparison with the as-designed geometrical model (slender beam), specifically for the rhombi-cuboctahedron cell. Generally, the statistical representation of defects can be easily implemented into full-scale lattice structure simulations and possibly combined with a plastic damage model to improve its functionality.

Figure 4. Schematic of the CT image extraction process [28].
Lozanovski et al. [30] created a new approach consisting of a series of elliptical cross-sections. The ellipse principal area moment of inertia and the axis of rotations were derived from a micro-computer tomography analysis of SLM fabricated struts. Concerning the material model, the experimental test data for the SLM-manufactured Inconel 625 was used, and for the frictional coefficient, a value of 0.9 was set. The behavior of a single strut modeled with elliptical cross-sections was compared with a representative volume element and an idealized strut to verify the proposed approach. The idealized geometry over-predicts the results, while the ellipse-based model under-predicts them yet with a smaller margin of error. According to the authors, this small error is attributed to the shrink-wrapping method utilized to mesh the μCT reconstruction model. This ellipse-based model was afterwards used to investigate the elastic response of FCC and FCCZ and compare it with the experimental outcomes. The results shown in figure 5 indicated that this model is quantitatively accurate but a little bit off qualitatively. As the number of cells increases, the qualitative results became more precise; nevertheless, this model cannot be used with large structures due to the massive computational cost associated with the simulations of millions of 3D solid elements.

![Figure 5. Numerical-experimental comparison of the stress-strain curves of (a) FCCZ and (b) FCC AM representative lattice structure of different sizes [30].](image)

Lozanovski et al. [13] also developed a computationally effective beam-based model. The main objective of this approach is to extract the effective diameters of AM struts and then use them for the simulation of full-scale lattice structures. A combination of the Markov Chain model and Monte Carlo Simulation techniques were used to generate the realization’s geometric properties and to establish the effective diameters based on the struts building angle and the CAD dimensions. The authors modeled the lattices with the mean strut diameter found using the Monte Carlo Simulation method. The outcomes of the simulations showed that the stiffness of the BCC and FCC lattice structures is underestimated. A better agreement towards the experiment results was obtained after increasing the beam diameters near the nodes by 40% (to account for the agglomeration of materials).

Galarreta et al. [19] used the stress-strain data of a representative micro-strut to derive two bilinear elastoplastic models. In the first one, the intersection between the slopes of the initial stiffness and the plastic hardening modulus was represented by the yield strength, while in the second, a 0.2% yield strength offset was used. The results of the mechanical properties were reasonably accurate in comparison with the experimental test, as shown in figure 6. The authors were able to achieve an error difference as low as 11% and 18% in stiffness and yield strength, respectively.
4. Macro-Scale Modeling

At the macro-scale level, the lattice is treated as a continuum or homogenized materials with its own set of effective properties [33]. Therefore, it is potentially possible to establish a relevant constitutive equation for lattice structures. This approach has not been particularly addressed for metallic lattices; however, some phenomenological models for solid foams have already been developed. For instance, Liu and Subhash [34] created a phenomenological model which is capable of capturing the entire non-linear stress-strain characteristics of porous materials (polymer foams) under large deformation. Similarly, Goga and Hučko [35,36] modeled a solid foam under pure compression using three basic systems in parallel, as shown in figure 7. The first system is composed of spring with stiffness $k$ connected in series with a dashpot of viscosity $c$. This system is referred to as the Maxwell model, and it was used to describe the linear elastic region of the compressive stress-strain curve. The other two systems consist of springs ($k_P$ and $k_D$). One spring represents the slope of the plateau stress, and the other is used to model the densification region. Accordingly, the following stress-strain relationship was established for modeling the compressive curve of solid foams.

$$\sigma(\varepsilon) = e^{-kE \varepsilon^2} \left( -1 + e^{kE \varepsilon} \right) c + [k_P + y(1 - e^n)] \varepsilon$$

The most important aspect of this phenomenological model is the direct relationship between the independent parameters ($k_0, k_P, y$ except $n$) and the relative density of the foam. This can be extremely useful if potentially exploited in the modeling of lattice structures. A similar methodology can be practically followed for metallic lattices under compression with some modifications in the modeling part of the plateau region (in the case of softening and hardening behavior). The capability of representing the lattices’ behavior using a constitutive equation and subsequently introducing it into a
FE model might drastically reduce the computational cost, and therefore allows for the accurate simulation of full-scale lattice structures.

![Characteristic shape of compressive foam curve represented by a system of basic mechanical components](image)

Figure 7. Characteristic shape of compressive foam curve represented by a system of basic mechanical components [35].

5. Conclusion
The interest in the superior properties and characteristics of SLM lattice structures is consistently increasing. Their broad applications and multi functionalities attracted much research attention aiming at exploring these characteristics to the fullest. The main challenge in doing so is to account for the complexity of the lattice structures using a numerical model characterized by its low computational cost and good accuracy. This paper provides a review of novel approaches explicitly developed for the numerical assessment of the lattice structures at micro- and macro-scale level as well as an overview of the main numerical aspects that must be considered in each FE setup and simulation. The main conclusions of this review are summarized as follows.

- The main aspects of the SLM lattice structures numerical models are identified as the finite element type, the material model, the frictional effect, and the process-induced defects. The lattice’s numerical models are highly dependent on these parameters, and they must be carefully introduced into the FE model to obtain an accurate representation of the lattice’s behavior.
- The proper selection of the FE element type is dependent on the type of deformation and the lattice’s aspect ratio.
- The material model derived from the stress-strain curve of the constituent material necessitates the physical implementation of imperfections.
- The material model based on the tensile test of a representative micro-strut typically includes all the geometric imperfections. However, there is no standard to perform such a test. Additionally, for struts with different orientations, the stress-strain curves might not be identical.
- There is the potential to represent the lattices’ behavior using a constitutive equation established via macro-scale modeling of the structure. The constitutive equation can then be introduced into an FE model allowing for the simulations of full-scale lattice structures with a considerably low computational cost.
References

[1] Surjadi J U, Gao L, Du H, Li X, Xiong X, Fang N X and Lu Y 2019 Mechanical Metamaterials and Their Engineering Applications Adv. Eng. Mater. 21

[2] Ashby M F, Evans A G, Fleck N A, Gibson L J, Hutchinson J W and Wadley H N G 2000 “Metal Foams: A Design Guide Library of Congress Cataloguing-in-Publication Data”

[3] Wadley H N G 2006 Multifunctional periodic cellular metals Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 364 31–68

[4] Cabras L and Brun M 2016 A class of auxetic three-dimensional lattices J. Mech. Phys. Solids 91 56–72

[5] Evans A G, Hutchinson J W and Ashby M F 1998 Multifunctionality of cellular metal systems Prog. Mater. Sci. 43 171–221

[6] Ushijima K and Smith M 2010 An investigation into the compressive properties of stainless steel micro-lattice structures Artic. J. Sandw. Struct. Mater. 13 303–29

[7] Hedayati R, Sadighi M, Mohammadi-Aghdam M and Zadpoor A A 2016 Mechanical behavior of additively manufactured porous biomaterials made from truncated cuboctahedron unit cells Int. J. Mech. Sci. 106 19–38

[8] Babae S, Jahromi B H, Ajdari A, Nayeb-Hashemi H and Vaziri R 2012 Mechanical properties of open-cell rhombic dodecahedron cellular structures Acta Mater. 60 2873–85

[9] Zhang M, Yang Z, Lu Z, Liao B and He X 2018 Effective elastic properties and initial yield surfaces of two 3D lattice structures Int. J. Mech. Sci.

[10] Gümrück R and Mines R A W 2013 Compressive behaviour of stainless steel micro-lattice structures Int. J. Mech. Sci. 68 125–39

[11] Tancogne-Dejean T and Mohr D 2018 Stiffness and specific energy absorption of additively-manufactured metallic BCC metamaterials composed of tapered beams Int. J. Mech. Sci. 141 101–16

[12] Alañà M, Lopez-Arancibia A, Pradera-Mallabiaarrena A and Ruiz de Galarreta S 2019 Analytical model of the elastic behavior of a modified face-centered cubic lattice structure J. Mech. Behav. Biomed. Mater.

[13] Lozanovski B, Downing D, Tran P, Shidid D, Qian M, Choong P, Brandt M and Leary M 2020 A Monte Carlo simulation-based approach to realistic modelling of additively manufactured lattice structures Addit. Manuf. 32

[14] Sing S L, Yeong W Y, Wiria F E and Tay B Y 2016 Characterization of Titanium Lattice Structures Fabricated by Selective Laser Melting Using an Adapted Compressive Test Method Exp. Mech. 56 735–48

[15] Yasa E, Deckers J, Kruth J P, Rombouts M and Luyten J 2010 Charpy impact testing of metallic selective laser melting parts Virtual Phys. Prototyp. 5 89–98

[16] Van Bael S, Kerckhofs G, Moesen M, Pyka G, Schrooten J and Kruth J P 2011 Micro-CT-based improvement of geometrical and mechanical controllability of selective laser melted Ti6Al4V porous structures Mater. Sci. Eng. A 528 7423–31

[17] Kozak J and Zakrzewski T 2018 Accuracy problems of additive manufacturing using SLS/SLM processes AIP Conference Proceedings vol 2017 (American Institute of Physics Inc.) p.20010

[18] Alomar Z and Concli F 2020 A Review of the SLM Lattice Structures and Their Numerical Models Adv. Eng. Mater. 2000611

[19] Ruiz de Galarreta S, Jeffer J R T and Ghouse S 2020 A validated finite element analysis procedure for porous structures Mater. Des. 189

[20] Melancon D, Bagheri Z S, Johnston R B, Liu L, Tanzer M and Pasini D 2017 Mechanical characterization of structurally porous biomaterials built via additive manufacturing: experiments, predictive models, and design maps for load-bearing bone replacement implants Acta Biomater. 63 350–68

[21] Meboob H, Tarlochan F, Meboob A and Chang S H 2018 Finite element modelling and
characterization of 3D cellular microstructures for the design of a cementless biomimetic porous hip stem Mater. Des. 149 101–12
[22] Concli F and Gilioli A 2019 Numerical and experimental assessment of the mechanical properties of 3D printed 18-Ni300 steel trabecular structures produced by Selective Laser Melting—a lean design approach Virtual Phys. Prototyp. 14 267–76
[23] Zhao M, Zhang D Z, Liu F, Li Z, Ma Z and Ren Z 2020 Mechanical and energy absorption characteristics of additively manufactured functionally graded sheet lattice structures with minimal surfaces Int. J. Mech. Sci. 167
[24] Jin N, Wang F, Wang Y, Zhang B, Cheng H and Zhang H 2019 Failure and energy absorption characteristics of four lattice structures under dynamic loading Mater. Des. 169
[25] Concli F, Gilioli A and Nalli F 2019 Experimental–numerical assessment of ductile failure of Additive Manufacturing selective laser melting reticular structures made of Al A357 Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.
[26] Li P, Wang Z, Petrinic N and Siviour C R 2014 Deformation behaviour of stainless steel microlattice structures by selective laser melting Mater. Sci. Eng. A 614 116–21
[27] Arabnejad S, Burnett Johnston R, Pura J A, Singh B, Tanzer M and Pasini D 2016 High-strength porous biomaterials for bone replacement: A strategy to assess the interplay between cell morphology, mechanical properties, bone ingrowth and manufacturing constraints Acta Biomater. 30 345–56
[28] Liu L, Kamm P, Garcia-Moreno F, Banhart J and Pasini D 2017 Elastic and failure response of imperfect three-dimensional metallic lattices: the role of geometric defects induced by Selective Laser Melting J. Mech. Phys. Solids J. homepage 107 160–84
[29] Smith M, Guan Z and Cantwell W J 2013 Finite element modelling of the compressive response of lattice structures manufactured using the selective laser melting technique Int. J. Mech. Sci. 67 28–41
[30] Lozanovski B, Leary M, Tran P, Shidid D, Qian M, Choong P and Brandt M 2019 Computational modelling of strut defects in SLM manufactured lattice structures Mater. Des. 171
[31] Campoli G, Borleffs M S, Amin Yavari S, Wauthle R, Weinans H and Zadpoor A A 2013 Mechanical properties of open-cell metallic biomaterials manufactured using additive manufacturing Mater. Des. 49 957–65
[32] Amani Y, Dancette S, Delroisse P, Simar A and Maire E 2018 Compression behavior of lattice structures produced by selective laser melting: X-ray tomography based experimental and finite element approaches Acta Mater. 159 395–407
[33] Amin Yavari S, Ahmadi S M, Wauthle R, Pouran B, Schrooten J, Weinans H and Zadpoor A A 2015 Relationship between unit cell type and porosity and the fatigue behavior of selective laser melted meta-biomaterials J. Mech. Behav. Biomed. Mater. 43 91–100
[34] Liu Q and Subhash G 2004 A phenomenological constitutive model for foams under large deformations Polym. Eng. Sci. 44 463–73
[35] Goga V and Hučko B 2016 Phenomenological Material Model of Foam Solids Strojnicky Cas. – J. Mech. Eng. 65 5–20
[36] Goga V 2011 New phenomenological model for solid foams Computational Methods in Applied Sciences vol 24 (Springer Netherland) pp 67–82