

A Simplified Modelling Strategy for the Analysis of Lattice Structures with Manufacturing Defects

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Abstract. The response of additively manufactured lattices is strongly affected by manufacturing induced imperfections. This work presents a numerical framework to model and assess these imperfections effectively. A simplified beam model is developed starting from accurate three-dimensional finite element analyses carried out on struts where the imperfections are modeled explicitly. The results show that the simplified models proposed here are capable of obtaining good matching with 3D simulations in terms of stiffness and strength, while requiring significantly lower computational cost.

Introduction

Lattice structures present attractive features for space applications. They are characterized by high structural efficiency and their cost is limited even for low production volumes [1, 2]. Furthermore, their production via additive manufacturing (AM) allows innovative configurations to be designed. So peculiar requirements of space structures can be met with larger flexibility. However, the AM process inevitably introduces dimensional inaccuracies, surface defects, and porosity [3]. Several studies have investigated these issues, particularly geometric defects in selective laser melting (SLM) of metallic parts [4, 5, 6]. The waviness and radius variation of struts have been analyzed with several models, including variable elliptical cross-sections [7], imperfect beams [8], and FEM incorporating scan-based data [9].

Despite the relatively vast literature on the topic, the modelling of defects is often based on costly analyses, which are unsuitable for preliminary assessments, where multiple configurations need to be analyzed. In particular, typical geometrical defects due to AM can have a drastic impact on both the linear and nonlinear structural response of lattices. Therefore, an effective modelling technique is crucial to simplify and speed-up the preliminary design phase, fully exploiting the potential of these structures.

In this paper, geometrical defects are modelled referring to the strategy proposed in Ref. [10], the KRK model: the struts are represented as the union of multiple spheres, each characterized by random variation in radius, axial offset, and penetration between adjacent spheres. Previous studies proved the impact of these features on the mechanical response of imperfect lattice structures.

Simplified beam models are developed to represent the structural behavior of lattice panels, using the KRK model to extract the constitutive laws for imperfect struts from three-dimensional finite element analyses. These models enable a rapid assessment of the non-linear response of complete lattice structures, making them particularly suitable for exploring different configurations and performing preliminary optimization.

Modelling of imperfections

Due to the relevance of manufacturing-induced defects, their explicit modelling is first addressed using 3D finite elements. With this purpose, a code has been developed to create either single struts or lattice configurations with multiple struts using Abaqus with Python scripting. The geometry is



generated automatically by assigning random distributions to the model parameters. Specifically, the parameters of the model are associated with a normal distribution whose average value and deviation can be determined from CT images [5, 10, 11]. Multiple struts are then merged together to form lattice cells. Once the geometry is generated, the component is meshed with tetrahedral C3D4 elements.

In addition to geometric imperfection, porosity caused by unmelted powder is modelled by generating spheres with diameters between 30 – 40 μm , uniformly distributed along the strut axis, radial offset, and angular coordinate. To avoid excessive mesh refinement, the elements located within these porosity spheres are identified, and their Young's modulus is reduced by a factor of one thousand with respect to the nominal material. This approach greatly simplifies the meshing process.

Simplified models

The 3D models just presented provide a refined description of the manufacturing imperfections. However, the large number of degrees of freedom resulting from the generation restricts the applicability of this approach. For this purpose, a simplified modelling strategy based on 1D beam elements is proposed herein. Two different techniques are investigated to capture the initial stiffness of the structure, the critical load, and the post-critical behavior of the structure under compressive loading.

The first class of simplified models relies on a 1-element-per-strut modelling. In this case, both the material and geometric nonlinearities are embedded in the constitutive law, which is defined by the force–displacement response of an imperfect strut under tension or compression. Two different strategies are investigated in this context: one using truss elements and the other using beam elements. To determine the section properties of the beam elements, a reduced section is considered. Specifically, it is obtained as the equivalent circular section of a perfect beam that undergoes the same deflection u of the imperfect strut in a cantilever bending test. The equivalent radius R_{eq} is obtained by inverting the formula from the vertical displacement of a linear elastic beam:

$$R_{eq} = \left(\frac{FL^3}{3\pi Eu} \right)^{\frac{1}{4}} \quad (1)$$

A second class of beam models considers multiple elements per strut. In these models, the constitutive law of the elements is obtained from a traction test. The presence of multiple elements allows a more accurate representation of the compressive deformation. Two of these models are analyzed: one includes regions near the nodes with artificially increased Young's modulus to account for local material accumulation, as in [10], while the other neglects these regions. The section of the beam elements is assigned with the equivalent radius R_{eq} of Eq. 1.

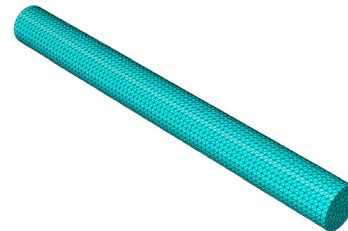
Numerical results

A set of analyses is conducted on both the single strut and the periodic octet cell. This latter is a cell composed by 24 struts merged at their intersection. The aim of the analyses is to evaluate the influence of imperfections and to assess the predictive capabilities of the simplified models. A bilinear constitutive law is adopted for the material, with Young's modulus $E = 70000 \text{ MPa}$, yield strain $\epsilon = 0.002$, Poisson's ratio $\nu = 0.33$ and plastic modulus $E_p = E/50$.

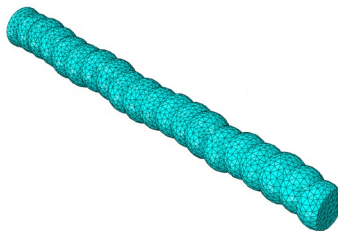
To illustrate the impact of AM-induced defects, three FE models of a single strut with nominal radius $R = 0.1 \text{ mm}$ and length 2 mm , are analyzed, consistent with the dimensions of the CT data. In the first case, Fig. 1a, a strut is generated with the ideal geometry. In the second, Fig. 1b, the defects are introduced by considering a typical distribution with radius average $R_{avg} = 0.1 \text{ mm}$ and deviation $R_{dev} = 0.028 R_{avg}$, offset from the axis average $A_{d,avg} = 0.01 \text{ mm}$ and deviation $A_{d,dev}$

$= 0.012 R_{avg}$, penetration average $L_{p,avg} = R_{avg}$ and deviation $L_{p,dev} = R_{dev}$. An even clearer representation of the imperfect strut is provided in Fig. 1c, where the defects are introduced with the offset from the center $A_{d,avg}$ and all deviations doubled, hence leading to an even rougher surface.

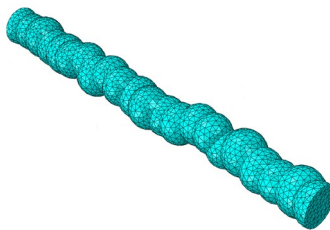
A compression analysis is performed for all three struts. The introduction of geometric imperfections significantly reduces the critical load, which shows a reduction of 20% and 29% for the two defective cases shown in Figs. 1b and 1c, respectively.



(a) *Ideal strut.*



(b) *Strut with typical defects.*



(c) *Strut with larger defects.*

Figure 1: Comparison of struts with different imperfections.

The effect of porosity is evaluated by a set of traction tests on single struts from 0% to 10% of volumetric porosity. For each percentage, 10 different struts are generated and the mean force-displacement curve is obtained. As expected, increasing porosity leads to lower yield and plastic loads.

The influence of strut length is also investigated, as imperfections affect both the stress-strain response in tension and the equivalent section properties in bending. A set of 100 3 struts is generated varying the length in the range of $L = 0.2 - 10$ mm. Each strut is clamped at one end and subjected to a prescribed displacement $u = 0.18L$ on the opposite side. The stress is reconstructed for a circular section of radius R_{avg} . From the results is clear how longer struts are characterized by smaller yield stress. This effect is ascribed to the more extensive role played by imperfections. For the assessment of the equivalent section, each strut is fixed at one end and loaded transversely at the other end with a force F . The equivalent radius is then obtained with Eq. 1. The results of these analyses show that the equivalent radius stays in the range of $R_{eq} = 0.5 - 0.65 R_{avg}$, noticeably lower than the nominal radius.

Finally, a compression analysis of the periodic octet cell is performed to assess the performance of the simplified models. The cell consists of 24 struts with the typical defect distribution. A reference point is associated with the nodes at each exterior intersection to impose the periodic boundary conditions. Each pair of reference points on opposite faces is constrained to have equal in-plane displacements. Along the compression axis, a shortening Δ is applied. Free displacements are allowed along the remaining two axes, with identical values for each face.

The results of the compression analysis are presented in Fig. 2. As shown, for the single element-per-strut models, the initial stiffness and maximum load are captured accurately. However, the post-critical deformation is not represented correctly, as the model is inherently limited by the adoption of a single element per strut. The truss model performs particularly well, as expected for a stretch-dominated cell. Among the multi-element-per-strut models, only the configuration with a stiffer region near each vertex reproduces the initial stiffness accurately. Both multi-element models, however, capture the post-critical deformation with good agreement to the 3D solid-element model. For comparison, results from an ideal beam model with the nominal material and section properties are also reported; this model clearly overestimates the overall structural strength.

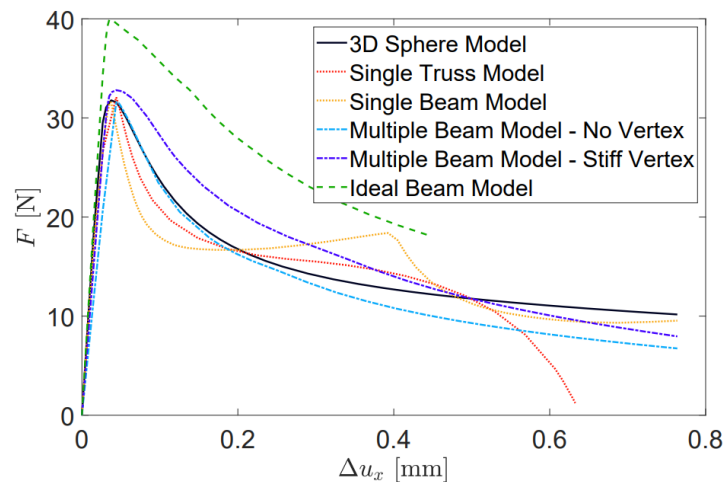


Figure 2: Comparison of struts with different imperfections.

Conclusions

The results demonstrate that geometric imperfections significantly reduce the critical load under compression, while porosity lowers the yield point of the material. The mechanical response is also affected by the strut length: longer members exhibit larger sensitivity to defects and lower yield stresses. The equivalent radius obtained from bending tests was found to be significantly lower than the nominal value.

The simplified 1D models reproduced the overall compression behavior of the octet cell in good agreement with high-fidelity 3D solid models, while requiring drastically lower computational cost. Therefore, the proposed approach is a promising way to account for manufacturing-induced defects, while preserving computational effectiveness.

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