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GEOMETRICAL IMPERFECTIONS IN LATTICE STRUCTURES:

A SIMULATION STRATEGY TO PREDICT STRENGTH VARIABILITY

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Abstract. The additive manufacturing process (i.e. Selective Laser Melting) allow us to produce lattice structures which have less weight, higher impact absorption capacity and better thermal exchange property compared to the classical structures. Unfortunately, geometrical imperfections in the lattice structures are by-product results of the manufacturing process. These imperfections decrease the lifetime and the strength of the lattice structures and alterate their mechanical responses.

The objective of the paper is to present a simulation strategy which allows us to take into account the effect of the geometrical imperfections on the mechanical response of the lattice structure. In the first part, an identification method of geometrical parameters of the lattice structure based on tomography measurements is presented. In the second part, a finite element model for the lattice structure with the simplified geometrical imperfections is obtained. In what follows, based on experimental tests, distributions of geometrical imperfections are proposed. Based on these distributions, a mathematical approach is presented to propagate the effect of uncertainties of the geometrical imperfections on the strength variability of the lattice structure.

1 INTRODUCTION

With the growth of additive manufacturing (AM) technologies, lattice structures have become popular to enhance the minimal use of material, shorter production recycle, high impact absorption capacity, and good thermal exchanger property [1, 2, 3]. Because of these properties, the structures have high added value in aeronautical and aerospace applications. There are several types of lattice structures based on the form of their unit cells. These cells have different forms such as octet truss, body centred cubic (BCC), body centred cubic with z struts (BCCz), face centred cubic (FCC), face centred cubic with z struts (FCCz), etc [1]. These types of unit cell are composed by micro-beams. AM process can introduce geometric defects such as porosity, surface roughness, and waviness [4]. The geometric defects can have considerable impact on lattice structure mechanical strength [5]. Thus, these defects are important to be investigated. Thanks to X-ray computed tomography (CT) technologies, irradiation is used to produce 3D internal and external representations of a scanned object [6]. The scanned object can be treated and determined its surface as cloud points. Numerically, the cloud points can be extracted and segmented to individual struts to compute specific geometric defects such as shape defects (elliptic shape) [7, 8].

This paper deals with lattice structures where the technical issues are mainly weight reduction for aerospace market. This work has been done in an R&D French project: the DSL (Durabilité des Structures Lattices) project with industrial partners. The main focus of the project was to answer the following question: “How to introduce geometric defects in mechanical models for prediction in nonlinear domain?” In the project, the structures are manufactured with the SLM (Selective Laser Melting) additive layer manufacturing process. The unit cell of the structure is BCC. For the simulations, the Scalmalloy material is considered.

The lattice structures are 3x3x3 cell manufactured in different conditions on a plate in the machine. In this paper, X-ray CT process will be first presented for defect characterization. Then, the statistical defect results for a 3x3x3 lattice structure will be showed. A modelling strategy for the simulation of the mechanical behavior will be presented. Finally, the uncertainty propagation process of geometric defects will be described.

2 X-TOMOGRAPHY PROCESS FOR DEFECT CHARACTERISATION

In this work, X-ray CT is used to scan the structures. A reconstruction is then done with a voxel representation. Surface determination process is followed to extract a point cloud representation of the entire structure. The segmentation of this point cloud allows to build a point cloud representation of each micro-beam of the structure [7, 8]. The CT workflow is represented in figure 1.

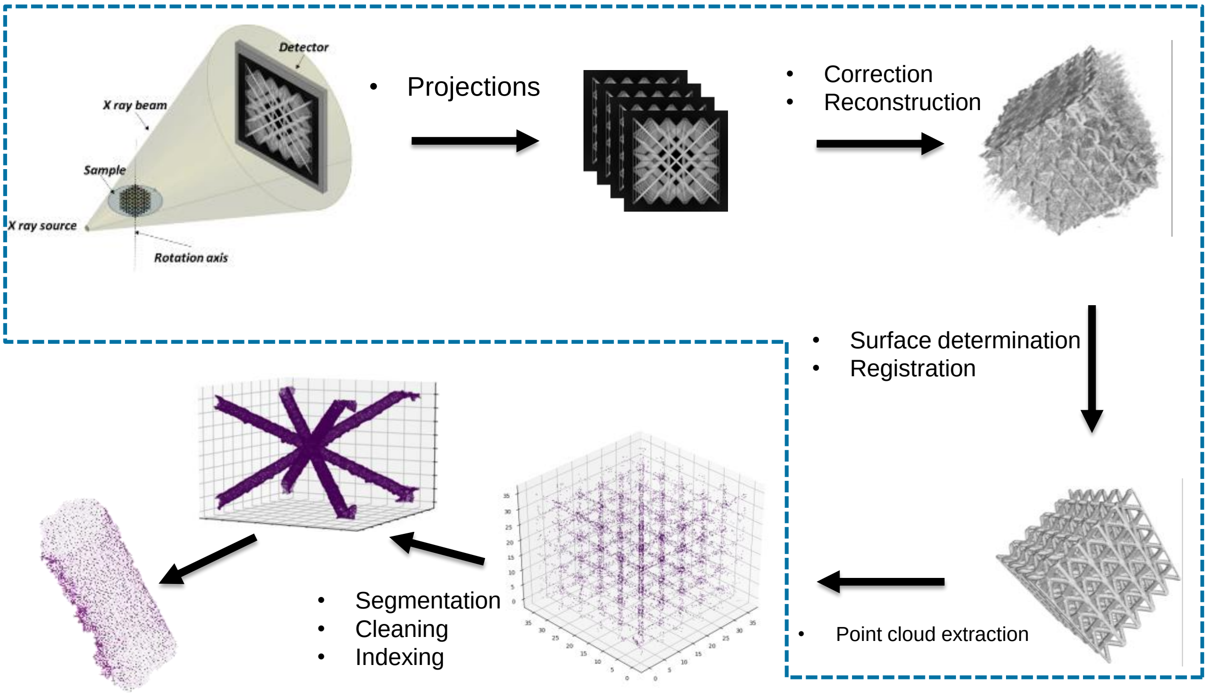

Figure 1: X-ray CT workflow and methodology to characterise geometric defects

A projection of a beam point cloud is done along the beam axis, and then an ellipse is fitted on a 2D plane projection (Fig. 2). This fitting allows to describe completely the geometric defect through three parameters: Eccentricity, area and angle. The eccentricity is defined as $e = \sqrt{1-\left(\frac{b}{a}\right)^2}$ where a, b are major and minor radius of the ellipse, respectively.

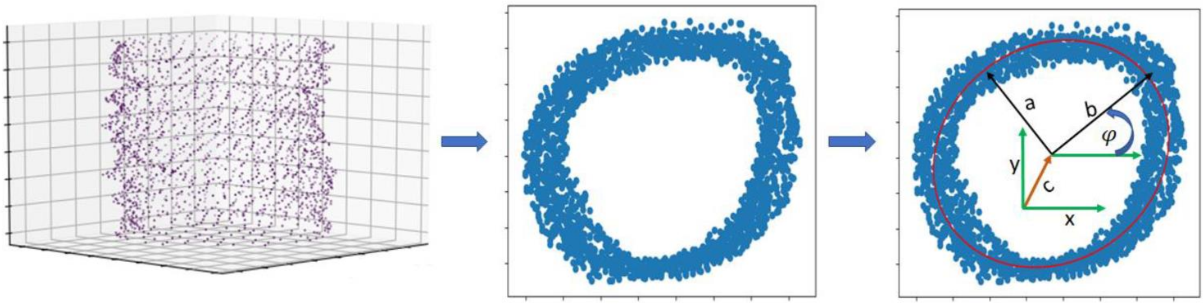

Figure 2: Ellipse fitting from 2D plane projection

3 STATISTICAL DEFECT RESULTS FOR A 3X3X3 LATTICE STRUCTURE

The aforementioned process has been applied to all the beams of one complete 3x3x3 lattice structure. An exemplary of a BCC cell is presented in figure 3. Four classes of coaxial beams has been defined from experimental results. Four colors has been chosen to plot the parameters which describe the geometric defects. The colors represent each class of the coaxial beams. The dark & light colors represent each beam of a same group. From the results, we can see that similar statistic behavior of the coaxial beam classes is observed.

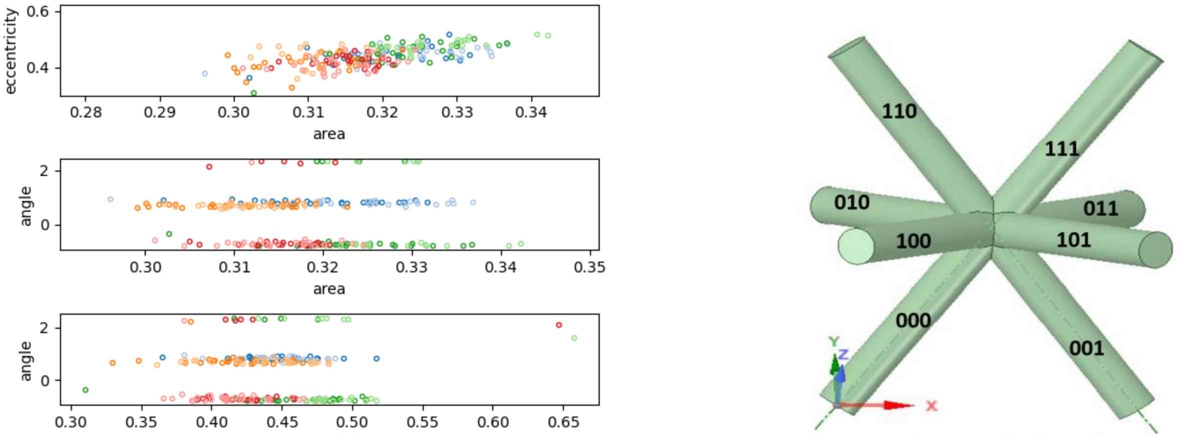

Figure 3: Defect parameter results according to a 3x3x3 Lattice structure & a BCC cell representation

The geometric defect distributions of coaxial beam classes are built from experimental data. A kernel density estimation is used for each coaxial beam class to identify probability laws. Figure 4 depicts the identified distributions for the parameters regarding the angle, area and eccentricity.

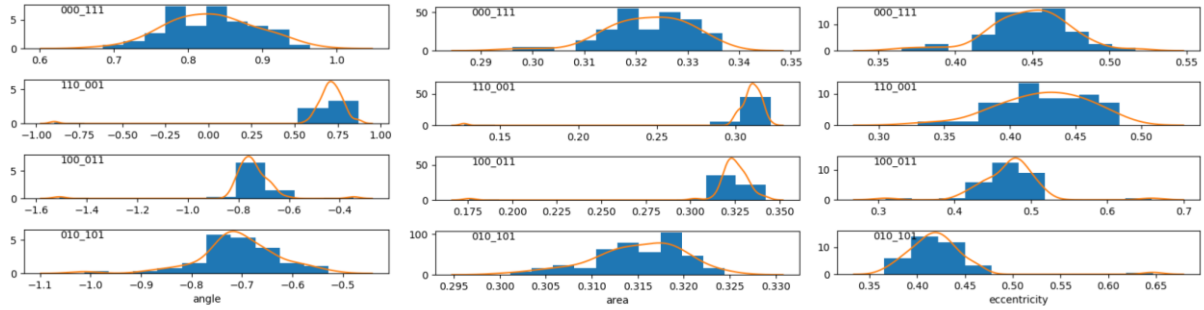

Figure 4: Distribution of defect parameters

4 MODELLING STRATEGY FOR THE SIMULATION OF THE MECHANICAL BEHAVIOUR

The modelling strategy for the simulation of the mechanical behavior is presented here. Figure 5 presents the CAD model of a 3x3x3 BCC structure: a 3D and a hybrid model. The hybrid model is composed of beam models for the micro beams and 3D parts for the junctions.

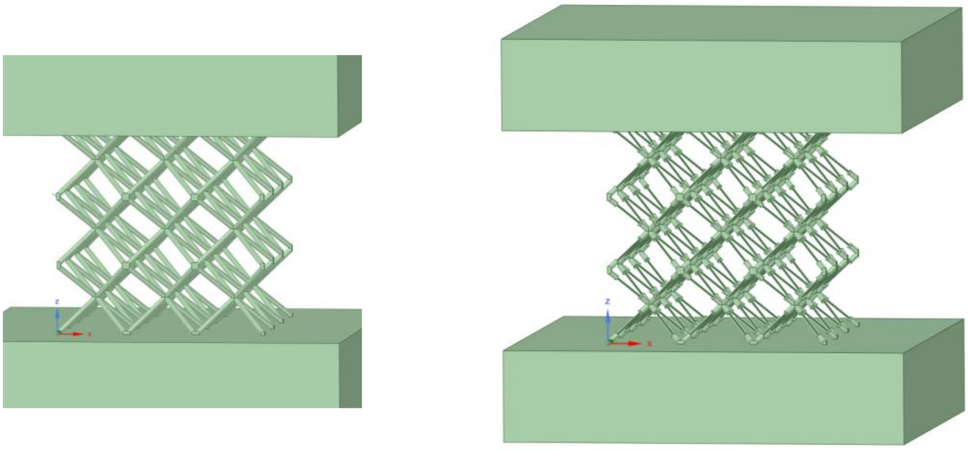

Figure 5 : CAD models of a 3x3x3 BCC structure : 3D model on the left & Hybrid model on the right

A parametric FEM model is adopted for both models. Integration of defect parameters has been done in the ANSYS software. The junctions of the hybrid model are the extensions of the 3D beams with defects. In these models, it is important to note that the elasto-plastic constitutive law of Scalmalloy material has been identified from traction tests on micro beams: it includes the behavior of porosity inside the material.

The lattice structure is under imposed displacement u and is clamped at the bottom (figure 7- left). Both FE (finite element) models developed in ANSYS software are presented in figure 6. The figure 7- right illustrates the value of force (F) versus displacement (u) between the two models. We conclude that hybrid model gives good results in this case.

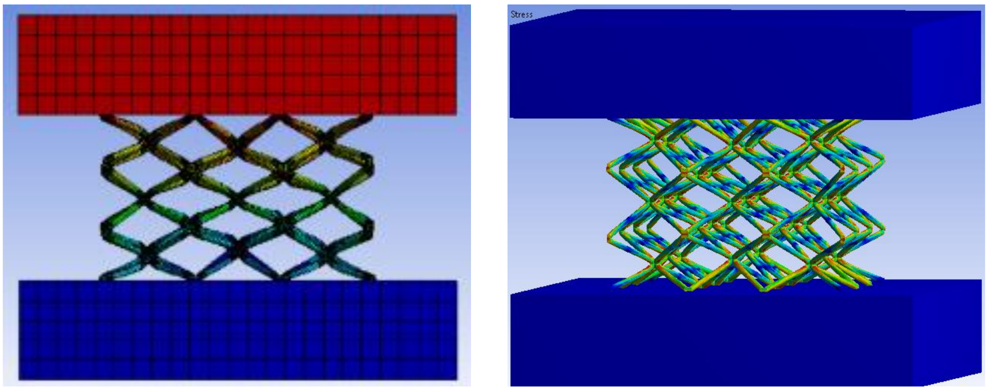

Figure 6: FE models of a 3x3x3 BCC structure

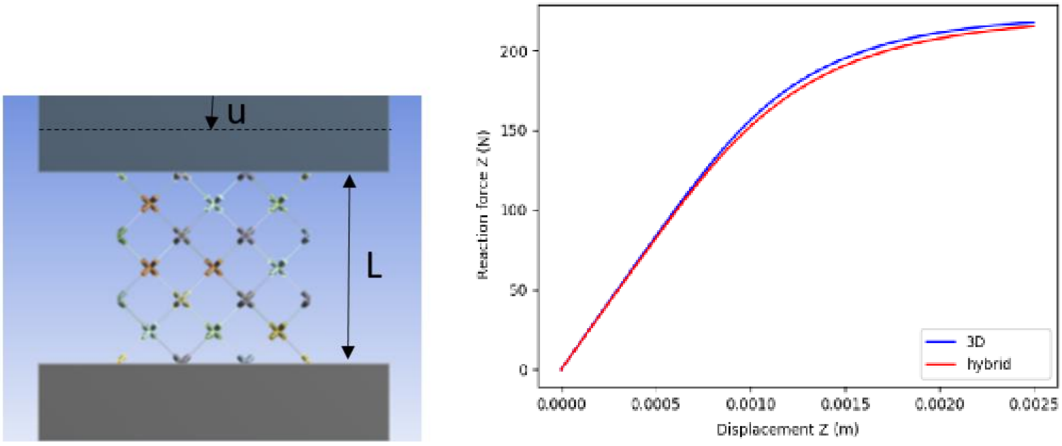

Figure 7: Compression load case presentation and results comparison between both models

From this point forward, we consider now only the hybrid model for simulation. We are specifically interested in the total strength of the structure. To do that, a homogenous equivalent material of the lattice structure has been built. Moreover, homogenous stress and strain quantities have been defined.

From the force/displacement response, the following equivalent stress and strain response can be built:

$$\sigma = \frac{F}{A} \qquad (1)$$

$$\varepsilon = \frac{u}{L} \qquad (2)$$

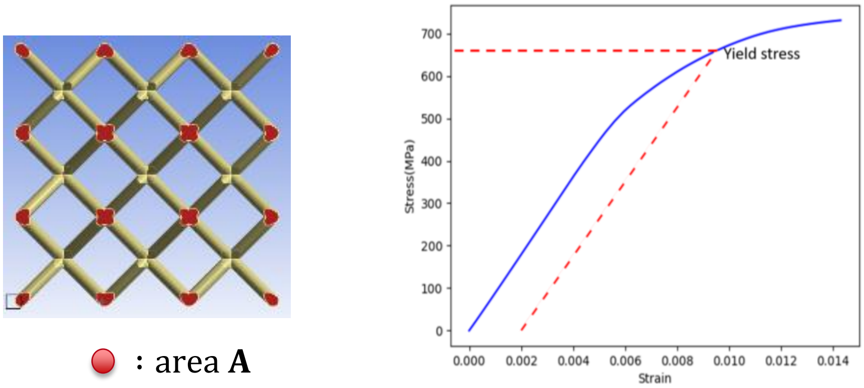

Figure 8: Yield stress identification of equivalent homogeneous material

Equivalent elastic modulus and yield strength can be identified from compression results as presented on figure 8. Yield stress is determined for an equivalent strain of 0.2%.

5 UNCERTAINTY PROPAGATION OF GEOMETRIC DEFECTS

The geometric defects in lattice structure are distributed according to the probability distributions of the coaxial beam classes. The defect parameters in this case are uncertain parameters. The goal here is to estimate the dispersion of mechanical strength from distribution of defect parameters.

The numerical design of experiment is determined by the Monte Carlo method and by choosing the samples of lattice structure with defects according to the given probability density law of coaxial beam classes of the lattice structure. Figure 9 depicts samples of geometric defects of a lattice structure that are computed from probability laws which were previously identified.

This process has been applied to identify the probability law for young modulus of the homogeneous model. Ten simulations have been conducted and a distribution has been built and presented figure 10. Same identification can be made for the yield strength of equivalent homogeneous material.

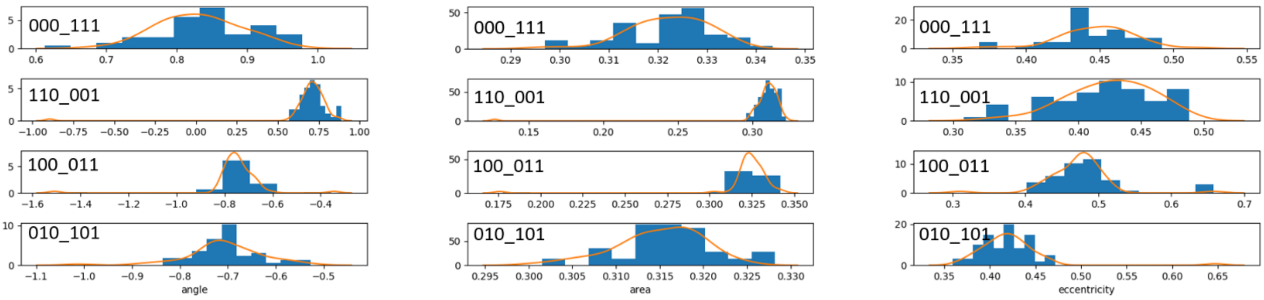

Figure 9: Samples of geometric defects of a lattice structure that are computed from probability laws

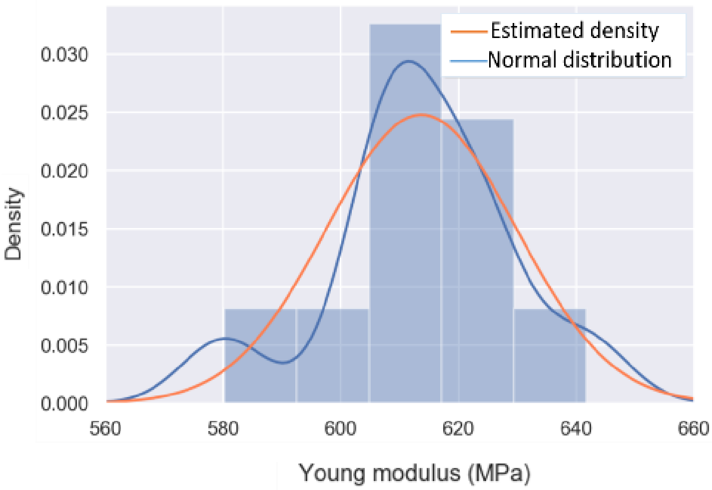

Figure 10: Samples of geometric defects of a lattice structure that are computed from probability laws

6 CONCLUSIONS

In this work, a numerical strategy has been proposed to introduce geometric defects in mechanical models for strength variability estimation of lattice structures. This strategy starts from numerical treatment of X-tomography results. A statistical identification of defect parameters has been conducted. A simplified nonlinear parametric mechanical model of the structure has been built. With this model, it is possible to compute a young modulus and a mechanical strength of an equivalent homogeneous material from a set of defect parameters.
Monte Carlo techniques has been used for young modulus variability estimation with the help of a numerical design of experiment.

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