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A NUMERICAL HYBRID FINITE ELEMENT MODEL FOR LATTICE STRUCTURES USING 3D/BEAM ELEMENTS

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ABSTRACT

In this work, a numerically hybrid model is presented for the lattice structures to reduce the computational cost of the simulations. This approach consists of utilization of solid elements for the junctions and beam elements for the microbeams connecting the corresponding junctions to each other. To take into account the geometric defects, for each microbeam of the lattice structures, an ellipse is fitted to capture the effect of shape variation and roughness. Having the parameters of the ellipses, the lattice structures are constructed in Spaceclaim (ANSYS) using the geometrical hybrid approach. When the global response of the structure is linear, the results from the hybrid models are in good agreement with the ones from the 3D models. However, the hybrid models have difficulty to converge when the effect of large deformation and local plasticity are considerable in the BCCZ structures. For BCCZ lattice structures, the results are not affected by the junction's size. This is also valid for BCC lattice structures as long as the ratio of the junction's size to the diameter of the microbeams is greater than 2.

Keywords: Additive Manufacturing, ANSYS, Geometric defects, Hybrid Finite Element Model, Lattice Structure.

1. INTRODUCTION

Thanks to the additive manufacturing process [1], lattice structures are replacing the traditional structures in aeronautic and automobile industries. Due to their particular design, these structures display enhanced mechanical and thermal properties [2] while their weight is reduced considerably [3].

The lattice structures are manufactured by deploying the fusion process in which powder material is deposited and then melted on the previously made layer of the same material [4]. Nevertheless, there are some drawbacks to this process. The lattice structures that are made using additive manufacturing are not geometrically perfect structures compared to their nominal CAD models. These geometric defects influence the life of the lattice structures and alter their mechanical responses [5]. Thus, it is of great interest to investigate these geometric defects. In the literature, body-centered cubic with z-struts (BCCZ) and body-centered cubic without z-struts (BCC) lattice structures are commonly used in the simulations [5], as they are easy to be made in the additive manufacturing process.

In order to evaluate the effects of the geometric defects in the least costly way, one has to resort to numerical techniques to simulate the behavior of the lattice structures including defects. ANSYS and Abaqus are globally well-known and trusted commercial software that allow us to model the lattice structures and analyze their mechanical responses using either solid or beam elements. In both software, a script may be used to systematically generate the lattice structures for any size and number. However, the inclusion of the geometric defects, a priori, is not implemented in these software, and a strategy is sought to model these defects in either Ansys or Abaqus. In the work of Gümürük and Mines [6], beam and solid elements were used to model the lattice structures. It was shown that there was a considerable discrepancy between the two models due to incapability of the beam elements to model the intersections and variation of the diameters of the beams.

The geometric defects in the lattice structures due to the additive manufacturing are categorized as roughness, waviness and shape variation [5]. There are many works done on modelization and parametrization of these defects. To include the effect of geometric defects, Xiao [7] reconstructed the FE model using the UCT scanned images for a lattice structure. He reported that the disparities changed the mechanical behavior of the lattice structures considerably. Ravari [8] took into account the variation of the beams' diameters in the CAD model via the revolution of a spline around the longitudinal axis of the beams. The drawback of this technique is that the shape variation of the sections as well as the waviness of the microbeams cannot be modelled. Tsopanos et al. [9] modelled the defects by merging several spheres with different diameters and centroid positions relative to the beams' longitudinal axis. In another work, Campoli et al [10] included the variation of the beams' diameters by introducing beam elements with different cross-sections that were obtained via Gaussian distribution of SEM calculated diameters. For lattice structures, Rathore et al. [11] proposed to fit ellipses on the 2D projections of the point clouds based on tomography measurements. In this approach, one ellipse, with a distinguished set of parameters (semi-major/semi-minor axes and angle of rotation), was considered for each microbeam in the lattice structure.

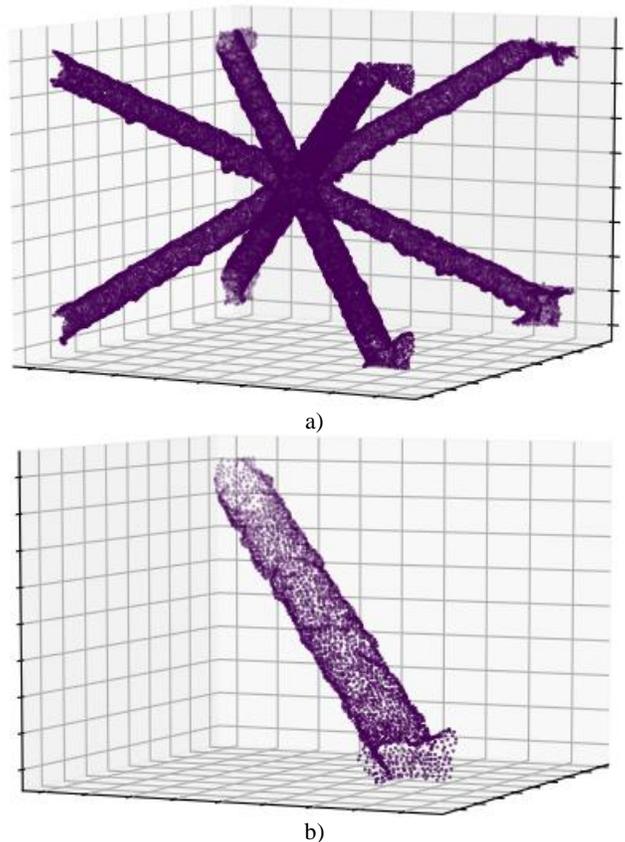
A suitable finite element (FE) model that is not costly yet efficient to take into account the geometric defects is a challenging task. While solid elements allow us to correctly model the contact between the substrates and the lattice structure, the local plasticity and the intersection of the microbeams, the computational cost is considerable for a large lattice structure. On the other hand, using beam elements reduce the computational cost drastically. The problem with the beam model is that we cannot correctly model the contact between the lattice structures and the substrates. Also, the notion of local plasticity is not valid anymore; moreover, the beam elements cannot model the intersection of the microbeams correctly (as mentioned by Gümrük and Mines [6]).

In this work, to reduce the computational cost, we propose a novel hybrid model in which the intersections are modelled using solid elements and the remaining microbeams are model using beam elements. Due to the solid nature of the junctions, the contact between the lattice structure and the substrates can correctly be modelled. Firstly, as proposed by Rathore et al. [11], we deploy the ellipse fit strategy to parametrize the point clouds of the lattice structures. To do that, we use LATANA platform, developed by "Institut de Recherche Technologique SystemX" (IRT-SystemX), to read the point clouds of the lattice structures, and then to parametrized them. Once the ellipses' parameters are calculated, we create the corresponding hybrid models. For the simulations, we consider two types of lattice structures; 1- Body-centered cubic with z-struts (BCCZ), and body-centered cubic without z-struts (BCC). The results show that the mechanical response of the hybrid model in the linear domain (where there is a small local plasticity and small deformation) is in good agreement with the full 3D model for both BCCZ and BCC lattice structures. However, in the nonlinear domain (where there

is a considerable plasticity and large deformation), the mechanical responses are not matched with the ones from the 3D models. Moreover, in the nonlinear domain, the numerical solutions of the hybrid models fail to converge. For BCCZ lattice structures, the results are not affected by the junction's size. This is also valid for BCC lattice structures as long as the ratio of the junction's size to the diameter of the microbeams should be more than 2. Due to lack of experimental results of the lattice structures, the results of the proposed hybrid models are only compared to those of the 3D models (taken as the reference models) and not to those of the experimental results.

2. CALCULATION OF ELLIPSE'S PARAMETERS

At IRT-SystemX, we developed the LATANA platform (LATtice ANALysis) in which the point clouds of the lattice structures are manipulated and parametrized. Firstly, the point clouds in text format are read; then, they are repositioned and partitioned cell by cell based on the type of the lattice structure. Next, beam by beam, the point cloud of each cell are partitioned again and then they are reoriented in vertical direction (Figure 1).



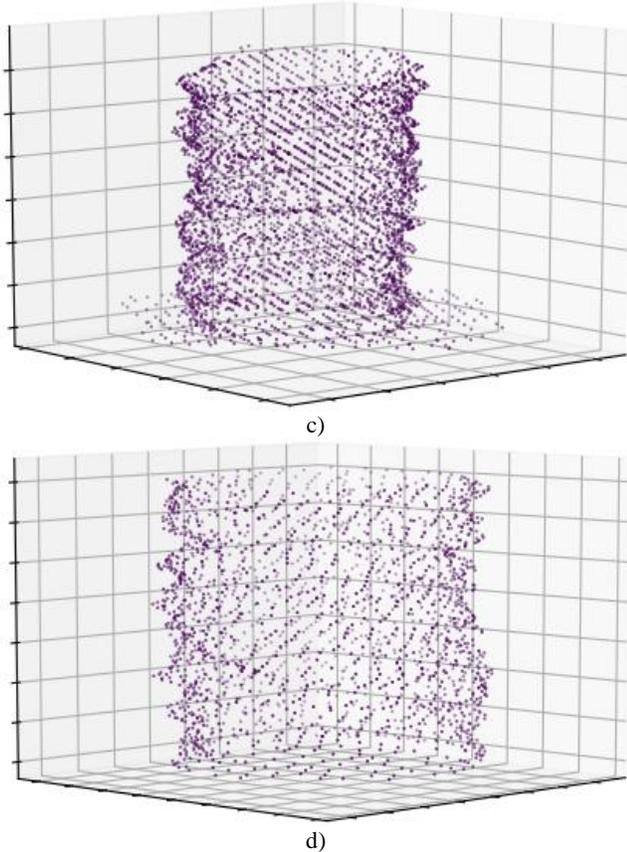


FIGURE 1: MANIPULATION OF THE POINT CLOUD OF A BCC LATTICE STRUCTURE IN LATANA, A) A CELL IS PARTITIONED, B) A MICROBEAM OF THE CELL IS PARTITIONED, C) THE MICROBEAM IS VERTICALLY REORIENTED, AND D) THE MICROBEAM IS CLEANED

In what follows, the point clouds are projected onto a 2D surface and finally the ellipse parameters are calculated. In figure 2, the distance of the center of the ellipse with regard to the local coordinates is noted by c , the angle of rotation between the ellipse's axis and the local coordinate is represented by φ , and semi-major and semi-minor axes of the ellipse are a and b , respectively. A review of ellipse fitting approach for lattice structures is discussed in Ref. [11]. The output of platform LATANA is an excel sheet in which the ellipse parameters are presented for each beam. This file is read in the Spaceclaim script (Spaceclaim is a module in Ansys workbench to create geometries) to create the geometries.

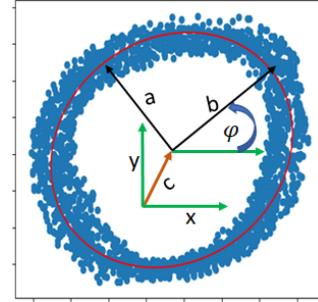


FIGURE 2: PROJECTION OF THE POINT CLOUD OF A BEAM ON A 2D SURFACE WITH CALCULATED ELLIPSE'S PARAMETERS

3. HYBRID MODEL

In this section, we present the methodology to create the hybrid model in ANSYS. This process has two parts; the creation of the geometry using a script in Spaceclaim, and setting up the hybrid model in ANSYS mechanical.

3.1 Geometry creation in Spaceclaim

In the hybrid model, the junctions are 3D geometries while the beams connecting the junctions are represented by beam elements. It is worth noting that the terms beam elements and 1D elements are used interchangeably in this work. To create the hybrid model, we wrote two Spaceclaim scripts; in the first script, the 3D junctions are created while in the second script, the 1D beams are made. In both scripts, the models are based on the ellipse parameters obtained from LATANA platform. By assembling the beams and junctions, we get the whole structure in which the connections of the beams and the junctions are not defined yet. We will define these connections later in Ansys mechanical. Using another script, we cut the surfaces of the top and bottom junctions of the lattice structure and then we add the substrates. The substrates represent the jaws of the compression device in which the lattice structures undergo compression. Having finished creating the hybrid model, we export it to Ansys mechanical of Ansys workbench. Figure 3 shows the three different models of a BCCZ lattice structure, i.e. the 3D model, the 1D model and the hybrid model. Also, the definition of the size of junctions is shown in figure 3-d.

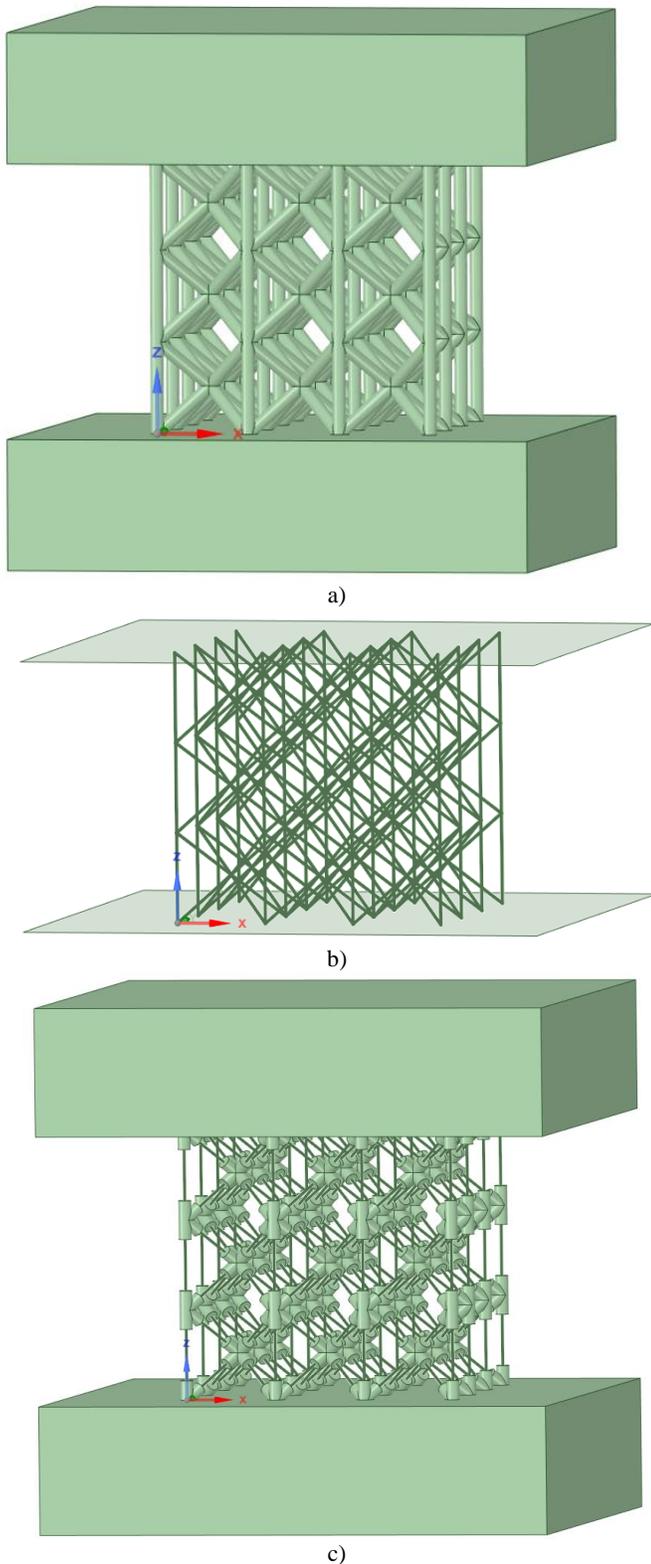


FIGURE 3: A) 3D MODEL, B) 1D MODEL, C) HYBRID MODEL OF A BCCZ LATTICE STRUCTURE WITH D) DEFINITION OF THE JUNCTION'S SIZE

3.2 Setting the parameters in ANSYS mechanical

After importing the created hybrid model from the previous section, we set the analysis parameters in Ansys mechanical. To take into account the effect of the plasticity, we opt for nonlinear behavior of the material. Also, we consider the effect of large deformation. Finally, we define frictional contacts between the lattice and the substrates, and we also define contacts between the beams and the corresponding junctions using the MPC type of contact (multipoint constraint-all direction). For the MPC type, we need to define the pinball region in which Ansys searches for nodes of elements. As a rule of thumb, the radius of the pinball region should be equal the maximum equivalent radius of the beams. As the boundary conditions, we consider zero displacement in all three directions on the bottom surface of the bottom substrate whereas on the top surface of the top substrate, we impose a displacement in $-z$ direction.

4. RESULTS AND DISCUSSION

In this section, the results obtained using the hybrid, 3D, and 1D models are presented. Firstly, we validate the hybrid model by comparing the obtained results with those of 3D and 1D models. The models (3D, 1D and hybrid) are nominal models, i.e. every microbeam has a circular cross-section with a radius of 0.5mm, and for the hybrid model, and the size of junctions is 1.5mm. The bottom 3D substrate is fixed while there is an imposed displacement in $-z$ direction on the top 3D substrate. For the 1D model, the 3D substrates are replaced by 2D plates and the nodes of the lattice structure, that are in contact with the substrates, are additionally limited to rotate in x and y directions. Between the substrates and the 3D parts (junctions in case of hybrid models), we assume unilateral contact with a 0.3 for the friction coefficient. The element size of the substrate and the 3D parts are 0,001mm and 0.00035mm, respectively; also 10 elements are used to mesh each microbeam. Furthermore, the size of each cell in the structures is 7mmx7mmx7mm. For the lattice structures, the elastic-plastic constitutive law with

multilinear isotropic hardening for an ideal Inconel 718 is used, while for the substrate (considered as a linear material with no plasticity) the Young's Modulus and Poisson's coefficients are 210 (GPa) and 0.33, respectively. In all the simulations the effects of large deformation and the plasticity are taken into account. In the hybrid models, we use Multi Point Constraint (MPC) method to define the bonded contacts between the surfaces of the junctions and the corresponding nodes of the microbeams. In this method, we chose 0.5mm for the radius of the pinball region. Lastly, we refer to the domain in which the global response of the structures is linear as "linear domain" and to the domain in which the global response of the structures is nonlinear as "nonlinear domain".

The results for reaction force (z direction) versus the imposed displacement (-z direction) for 3D, 1D and hybrid models are shown in figure 4.

As can be seen from figure 4-a, the results from the hybrid model match well with those of the 3D model for the BCCZ lattice structure. However, when the imposed displacement is about 0.00025mm, the hybrid model encounters difficulty to converge. We tried with different size of junctions and different number of elements but to no avail. Moreover, we can see that the results of 1D model correspond to the results of hybrid and 3D models in the linear domain. From figure 4-b for the BCC lattice structure, we can see that while there is a good agreement between the hybrid and 3D models in the linear domain, a considerable gap exists between the results in the nonlinear domain. It is worth noting that the results of the 1D model, even in the linear domain, are not matched well with those of hybrid or 3D models. However, for the nominal BCC lattice structure, the hybrid model did not face any problem during the solution and it converged even in the nonlinear domain. The total displacements of the 3D, 1D and hybrid models for the BCCZ and BCC lattice structure are depicted in figures 5 and 6.

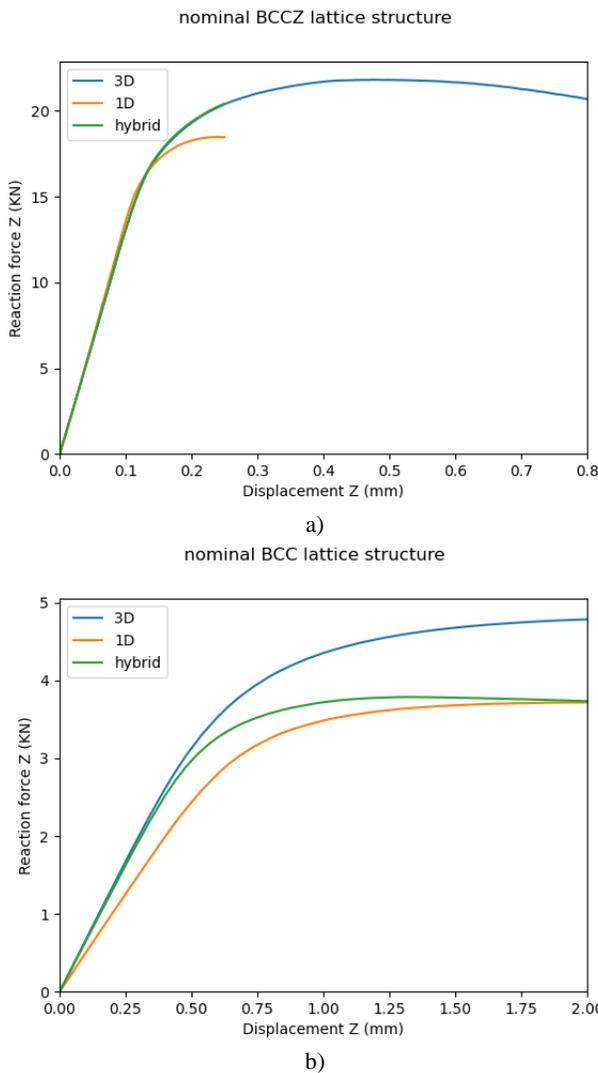
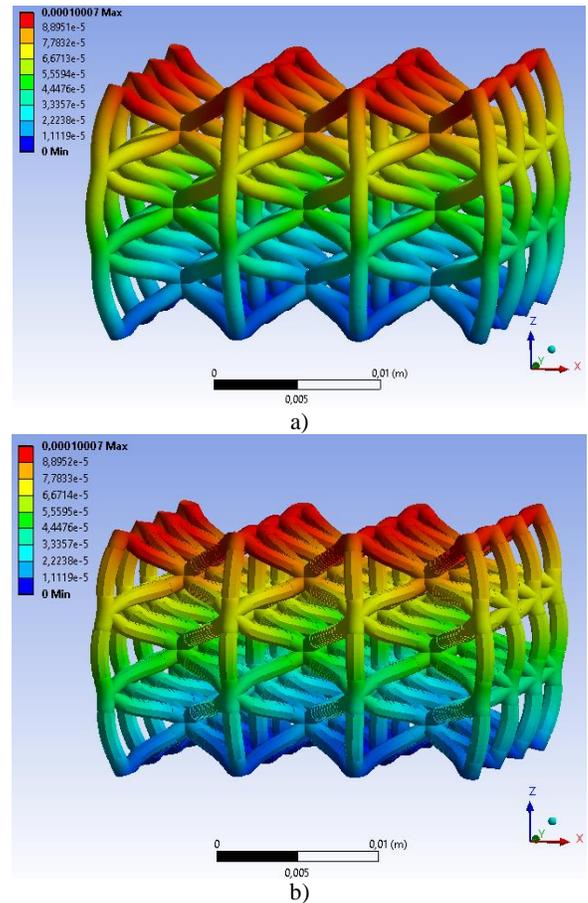


FIGURE 4: REACTION FORCE Z VERSUS IMPOSED DISPLACEMENT $-Z$ FOR A NOMINAL ($R=0.5\text{MM}$) LATTICE STRUCTURE; A) BCCZ, B) BCC



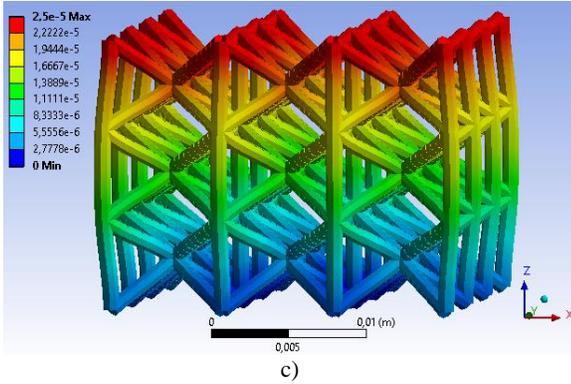


FIGURE 5: TOTAL DISPLACEMENT (M) OF A NOMINAL ($R=0.5\text{MM}$) BCCZ LATTICE STRUCTURE FOR AN IMPOSED DISPLACEMENT $-Z$ (0.1MM); A) 3D MODEL (X39), B) HYBRID MODEL (X39), AND C) 1D MODEL (X150)

As depicted in figures 5 and 6 in which the total displacements are exaggerated, we can see that the overall deformation of the hybrid and 3D models are very similar while the deformation of the 1D model is different from the other two models.

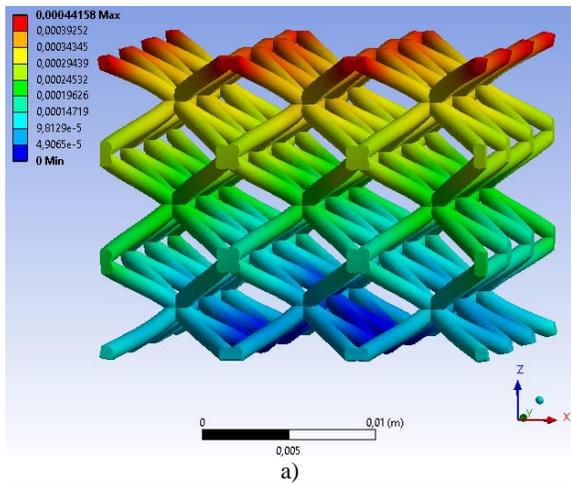


FIGURE 6: TOTAL DISPLACEMENT (M) OF A NOMINAL ($R=0.5\text{MM}$) BCC LATTICE STRUCTURE FOR AN IMPOSED DISPLACEMENT $-Z$ (0.4MM); A) 3D MODEL (X8.7), B) HYBRID MODEL (X8.7), AND C) 1D MODEL (X9.4)

The computational times for the three models are presented in Tables 1 and 2. In order to bypass the problem of convergence in the nonlinear domain, we used different maximum imposed displacements in a way that the global behaviors of the 3D and hybrid models remain in the linear domain. The calculations were carried out on a workstation with an Intel(R) core(TM) i7-7800X clocked at 3.5GHz and 64 gigabytes of RAM. As can be seen from Tables 1 and 2, the hybrid model decreases the computational time for both BCCZ and BCC lattice structures.

TABLE 1: COMPUTATIONAL TIME OF THE THREE MODELS OF A NOMINAL BCCZ LATTICE STRUCTURE WITH A MAXIMUM IMPOSED DISPLACEMENT OF -0.1MM (APPLIED IN 10 STEPS) IN Z DIRECTION

	3D model	Hybrid model	1D model
Computational time (minutes)	32	27	2

TABLE 2: COMPUTATIONAL TIME OF THE THREE MODELS OF A NOMINAL BCC LATTICE STRUCTURE WITH A MAXIMUM IMPOSED DISPLACEMENT OF -0.5MM (APPLIED IN 3 STEPS) IN Z DIRECTION

	3D model	Hybrid model	1D model
Computational time (minutes)	21	17	1

The simulation result for another BCC structure is shown in figure 7. In this structure, the size of the cells, the diameters of the microbeams, and the junctions' sizes are about 8mm, 0.6mm, and 1.5mm, respectively. Moreover, the other parameters are the same as the parameters for the previous cases. Also, the computational time of the 3D and hybrid models are presented in Table 3.

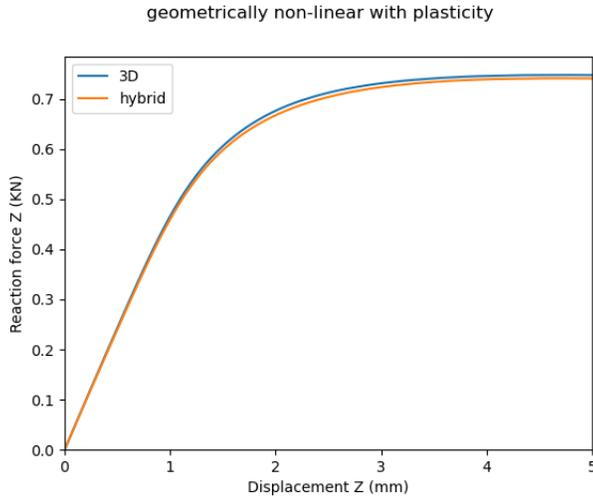


FIGURE 7: SIMULATION RESULT FOR A BCC STRUCTURE WITH A CELL'S SIZE OF 8MM, A DIAMETER OF 0.6MM, AND A JUNCTION'S SIZE OF 1.5MM

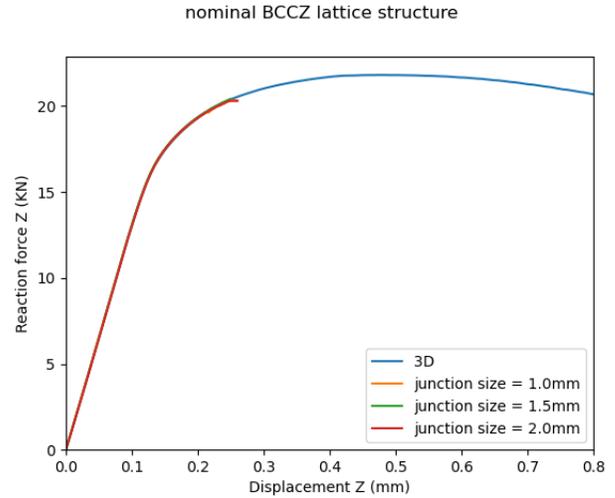
TABLE 3: COMPUTATIONAL TIME OF THE TWO MODELS OF A NOMINAL BCC LATTICE STRUCTURE WITH A MAXIMUM IMPOSED DISPLACEMENT OF -5MM (50 STEPS) IN Z DIRECTION

	3D model	Hybrid model
Computational time (hours)	46	20

We can see that for this simulation the hybrid model is considerably faster (more than 2 times) than 3D model, while for the previous cases, the computational time difference between the 3D models and the hybrid models were less.

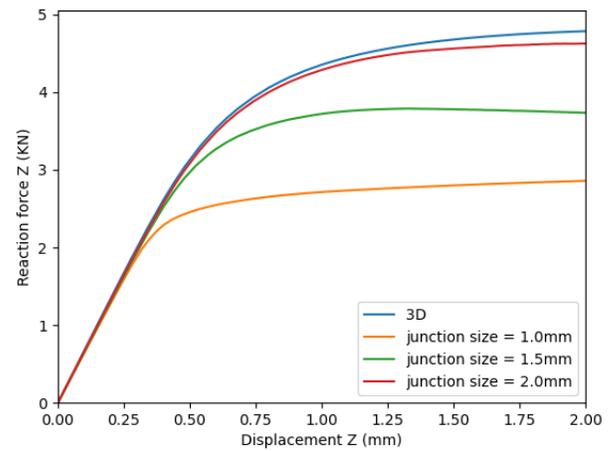
We observed that in the linear domain, the hybrid model is considerably faster than the 3D model however, when the nonlinear domain starts, it becomes harder for the solution of the hybrid model to converge. It has a direct effect of the computational time of the hybrid model and in some cases, e.g. for BCCz lattice structures, the solution of the hybrid model doesn't converge. We realized that there are a few solid elements around the junction-beam connections that become considerably distorted. This is due the different formulations (i.e. different number of degrees of freedom and different hypotheses used to derive beam and solid elements) used for solid and beam elements when the plasticity and large deformations happen. The location and the number of distorted elements vary for each simulation with different load steps, geometry, constitutive law, type, etc.

To analyze the effect of the junctions' size on the results, we chose three different size of the junctions for both BCCZ and BBC lattice structures. The results are shown in figure 8.



a)

nominal BCC lattice structure



b)

FIGURE 8: REACTION FORCE Z VERSUS IMPOSED DISPLACEMENT $-Z$ FOR A NOMINAL ($R=0.5\text{MM}$) LATTICE STRUCTURE; A) BCCZ, B) BCC

From figure 8-a, by changing the size of the junctions, the results don't change for the BCCZ structure. On the other hand, for the BCC structure, the size of the junctions has a considerable effect on the response of the lattice structure in the non-linear domain. From figure 8-b, we can see that by increasing the size of the junctions, the results of the hybrid model becomes closer to the results of 3D model. By a simple calculation, we see that when the ratio of the size of the junctions to the diameter of the microbeams is more than 2 for BCC lattice structures, the results of hybrid models are close to the results of 3D models in the nonlinear domain. For the BCCZ lattice structures, this ratio is not important, however, the hybrid model has difficulty converging in the nonlinear domain.

Lastly, to investigate the performance of the hybrid model for the lattice structure in which the geometric defects are taken in to account, we created three models based on the ellipse parameters that were calculated for the lattice structure A8KA01.

For the hybrid model, the size of the junctions was chosen as 1.5mm. The results are presented in figure 9. It is worth mentioning that the BCC lattice A8KA01 is the same as the BCCZ lattice A8KA01 in which the vertical beams are removed.

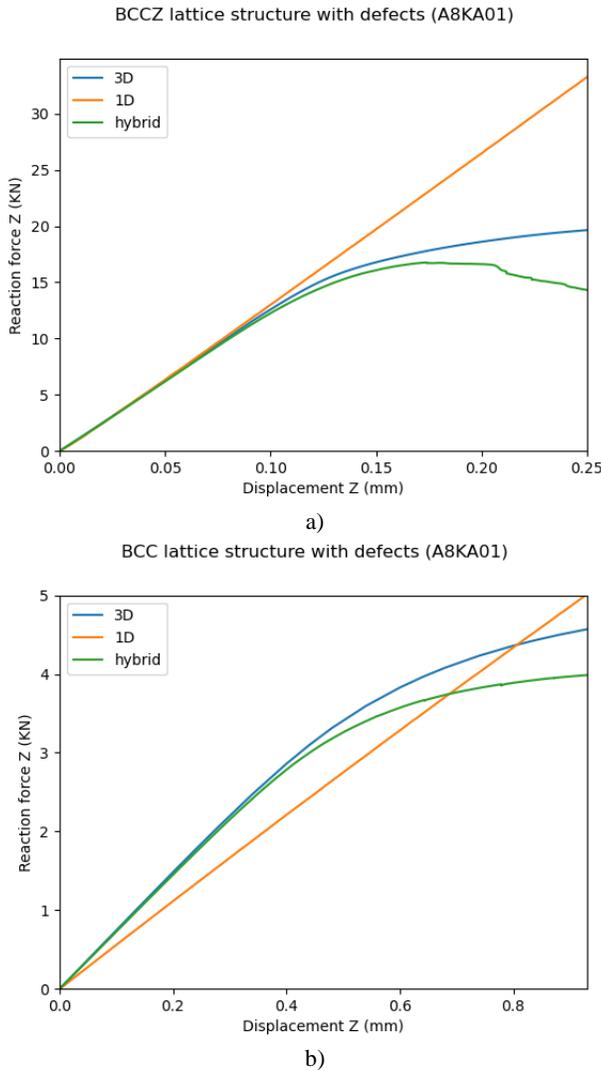


FIGURE 9: REACTION FORCE Z VERSUS IMPOSED DISPLACEMENT $-Z$ FOR A LATTICE STRUCTURE A8KA01; A) BCCZ, B) BCC

As can be seen from figure 9-a, the hybrid model predicts well the reaction force of the BCCZ lattice structure in the linear domain, while it diverges from the results of the 3D model in nonlinear domain. We can see even in the linear domain the three models perform well. For the BCC lattice structure (figure 9-b), we can see that the results of the hybrid and 3D models are similar in the linear domain where the results of 1D model is considerably different. Unfortunately, the hybrid model stopped to converge around an imposed displacement of -1mm for the BCC lattice structure. It is worth mentioning that for this structure, the ratio of the junction's size to the diameters of the microbeams is 1.5. We speculate that if the ratio of the junction's

size to the diameters of the microbeams is more than 2, not only the results are not affected by the junction's size but also there will be no convergence problem for BCC lattice structures. To verify this, we used another BCC lattice structure with defects (LIDA01) where the cell's size is about 8.13mm, the junction's size is 1.5mm, and the diameters of the microbeams are less than 0.7mm. For this simulation we used the constitutive law for Scalmalloy materials.

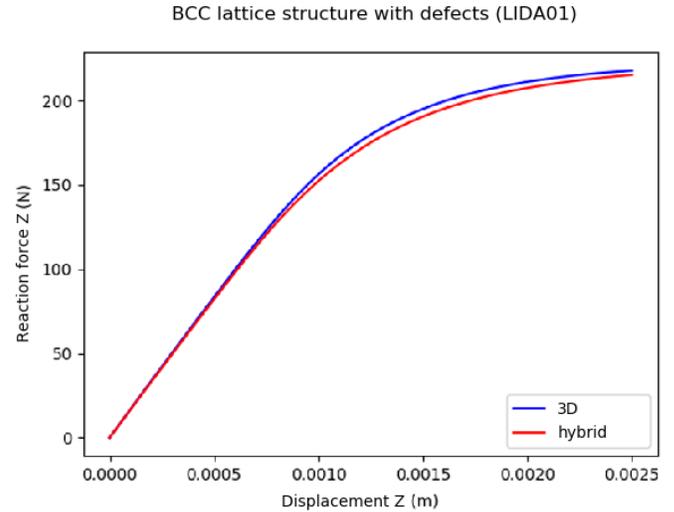


FIGURE 10: SIMULATION RESULT FOR A BCC STRUCTURE WITH A CELL'S SIZE OF 8.13MM, DIAMETERS < 0.7 MM, AND A JUNCTION'S SIZE OF 1.5MM

As can be seen from figure 10, the results from the 3D model match well with the results of the hybrid model in both linear and nonlinear domains. Moreover, there is no convergence problem.

5. CONCLUSION

In this work, to reduce the computational cost, we proposed a numerical hybrid model for lattice structures. Firstly, the lattice structures are translated into sets of point clouds measured by tomography methods. These structures are then parametrized using the ellipse fitting method in which three parameters are introduced; semi-major axis, semi-minor axis and angle of orientation. By use of ellipse parameters, 3D and 1D models of the junctions and the microbeams are presented, respectively. The hybrid model is obtained by assembling the 3D junctions and the 1D microbeams connecting the junctions.

The results show that in the linear domain, there is a good agreement between 3D and hybrid models for any size of the junction for both BCCZ and BCC lattice structures. However, there are two major drawbacks using the hybrid model; 1- the convergence of the numerical model is not always guaranteed, 2- for some particular geometries, the results strongly depend on the junction's size for BCC lattice structures. It is worth mentioning that when the ratio of the size of the junctions to the diameter of the microbeams is more than 2 for BCC lattice structures, the results of hybrid models are similar to the results of 3D models in the nonlinear domain.

Lastly, the deformations of the lattice structures (BCCZ and BCC) using the hybrid models match well with those of the lattice structures (BCCZ and BCC) using 3D models. Therefore, due to properly model the junctions and the contact between the lattice structures and the substrates, the hybrid model is a proper choice to analyze the mechanical responses of the lattice structures with geometric defects in the linear domain for a reduced computational cost.

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