



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

ARCHIVIO ISTITUZIONALE
DELLA RICERCA

Alma Mater Studiorum Università di Bologna Archivio istituzionale della ricerca

Structural Analysis of Voxel-Based Lattices Using 1D Approach

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Bacciaglia, A., Ceruti, A., Liverani, A. (2022). Structural Analysis of Voxel-Based Lattices Using 1D Approach. 3D PRINTING AND ADDITIVE MANUFACTURING, 9(5), 365-379 [10.1089/3dp.2020.0178].

Availability:

This version is available at: <https://hdl.handle.net/11585/820605> since: 2024-07-15

Published:

DOI: <http://doi.org/10.1089/3dp.2020.0178>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:

Structural Analysis of Voxel-Based Lattices Using 1D Approach

Antonio Bacciaglia, Alessandro Ceruti, and Alfredo Liverani

3D Printing and Additive Manufacturing 2022 9:5, 365-379

The final published version is available online at:

<https://www.liebertpub.com/doi/10.1089/3dp.2020.0178>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

When citing, please refer to the published version.

2 **Structural analysis of voxel-based lattices using 1D** 3 **approach**

4 **Antonio Bacciaglia** ^{1*}, **Alessandro Ceruti** ¹ and **Alfredo Liverani** ¹,

5 ¹ Department of Industrial Engineering – DIN, University of Bologna, Italy

6 * Correspondence: antonio.bacciaglia2@unibo.it

7

8 Received: ...; Accepted: ...; Published: ...

9 **Abstract:** Lightweight bio-inspired structures are extremely interesting in industrial applications
10 for their known advantages, especially when Additive Manufacturing technologies are used.
11 Lattices are composed by axial elements called ligaments: several unit cells are repeated in three
12 directions to form bodies. However, their inherent structure complexity leads to several problems
13 when lattices need to be designed or numerically simulated. The computational power needed to
14 capture the overall component is extremely high. For this reason, some alternative methodologies
15 called homogenization methods were developed in the literature. However, following these
16 approaches, the designers do not have a local visual overview of the lattice behaviour, especially at
17 the ligament level. For this reason, an alternative 1D modelling approach, called lattice-to-1D is
18 proposed in this work. This method approximates the ligament element with its beam axis, uses the
19 real material characteristics and gives the cross-section information directly to the solver. Several
20 linear elastic simulations, involving both stretching and bending dominated unit cells, are
21 performed to compare this approach with other alternatives in literature. The results show a
22 comparable agreement of the 1D simulations compared to homogenization methods for real 3D
23 objects, with a dramatic decrease of computational power needed for a 3D analysis of the whole
24 body.

25 **Keywords:** lattice structure; periodic structure; homogenization; voxel; structural analysis.

26

27 **1. Introduction**

28 Nowadays, Additive Manufacturing (AM) is considered an important alternative to traditional
29 processes based on chip removal, casting, milling, and lathing processes where several design
30 constraints must be respected ¹. AM technology reveals several advantages which are highlighted in
31 the literature, and its use is increasing in aerospace, automotive ², biomedicine year after year ³ and
32 even in niche applications such as musical instruments ⁴. Time drop-in design-to-manufacturing
33 cycle, design flexibility, ability to generate complex shapes in one piece and capability to imitate
34 low-weight bio-inspired shapes are the advantages of designs based on AM ⁵. On the other hand, to
35 date the main weaknesses of AM technology can be found in: material anisotropic properties for
36 some AM processes; high surface roughness; limitations of CAD software in the integration of
37 design, technology, optimization, smoothing processes; limited material portfolio; problems of
38 inspection and maintenance in complex assemblies made in one piece; high costs and slow
39 certification process; high structural performances variability due to changes of properties in raw
40 materials lots, changes (sometimes even small) in machines settings or environmental
41 characteristics; behaviour of AM structure with fatiguing loads.

42 Bio-inspired cellular structures, also called hierarchic structures, can be included in AM
43 components, where lightweight, stiffness and high strength to mass ratios are essential. There are
44 different types of cellular structures such as foams, which are stochastic, honeycombs and lattices ⁶
45 which are periodic and are the object of this research. Periodic lattice structures are composed of

46 elongated elements, such as cylindrical beams, called ligaments, beams or struts, connected with
47 other similar elements to form a unit cell that is repeated thousands of times along the body.

48 Even if the density is much lower compared to a traditional fully dense part, lattices are
49 manufactured using metallic materials such as aluminium, titanium or steel to have stiff components
50 adopting selective laser melting (SLM)^{7,8} or electron beam melting (EBM)⁹ technologies. Thanks to
51 their strength/weight ratio and good absorption energy, nowadays lattice structures replace other
52 cellular materials such as foams used in sandwich structures in aerospace or automotive
53 applications, due to the capacity to absorb mechanical vibrations and sound waves. The aerospace
54 industries are interested in these types of components to increase the crashworthiness. Just to
55 provide the reader with an example, the Boeing Model 360 helicopter is built using some sandwich
56 structures made of lattices to achieve a lightweight design and to reduce the number of mechanical
57 joints thus reducing maintenance costs¹⁰. Another interesting application of optimized lattice
58 structure is contained in¹¹: an automotive engine mounting bracket has been topologically
59 optimized and in the following partially filled with lattice structure to reduce the weight of the
60 component still maintaining sufficient strength and stiffness. Moreover, thanks to the ability to
61 absorb thermal energy due to a higher surface area for heat exchange, lattice structures are suitable
62 for application where thermal insulation is important as well.

63 After listing the advantages of lattices, it is important to discuss the problems arising when
64 these structures need to be designed and simulated. Common design tools available to the engineer,
65 such as CAD software, still show large limitations because the boundary representation technology
66 (B-rep) is used: it is not well suited for lattices where the external surface is extremely complex¹².

67 Another important problem arises when lattice mechanical behaviour is investigated through
68 numerical analysis. In literature, several contributions deal with the application of Finite Element
69 (FE) analysis to periodic structures for different purposes, such as: material characterization of
70 titanium alloy structures fabricated via EBM¹³, prediction of fatigue behaviour applied on porous
71 metallic biomaterials¹⁴ and non-linear analysis of lattice structures to predict the energy absorption
72¹⁵. In case of components with a simple shape such as the beams used in the aforementioned
73 contribution, the 3D FE analysis assures consistent and reliable results. However, to capture the
74 lattice behaviour, especially when dealing with complex real-life components, due to its high
75 structure complexity, FE analysis requires a huge amount of computational power to discretize the
76 structure in billions of meshing elements, The dimension of the mesh is similar or lower than the
77 diameter of ligaments, which is typically small. This is the reason why alternative methods, such as
78 homogenization algorithms, have been developed in literature¹⁶.

79 Several methods to cope with the time reduction of structural analyses are available in the
80 literature, a non-inclusive list includes:

- 81 • Closed-form expression based on the Euler-Bernoulli beam¹⁷
- 82 • Matrix-based techniques based on Bloch's theory¹⁸
- 83 • Micropolar elasticity theory¹⁹
- 84 • High-frequency homogenization²⁰
- 85 • Discrete homogenization technique²¹
- 86 • Asymptotic homogenization (AH)^{22, 23}

87 AH shows good results in validation tests for a lot of applications, because determines
88 accurately stress distributions in the unit cell without limitations on unit cell topology or relative
89 density (defined as the density of a certain volume of lattice structure over the density of the material
90 that composes the ligaments)²⁴.

91 The AH algorithm aims to speed up the mechanical analysis, and to do that, it replaces a lattice
92 structure with a fully dense homogenous solid, with equivalent mechanical properties, same
93 occupied volume, maintaining same loads and point of applications. In this way, the computational
94 power needed to solve numerically the mechanical behaviour of periodic structures decreases
95 exponentially. The most important assumption behind AH method is that each field quantity
96 depends on two different scales: the macroscopic scale and the microscopic one.

97 Moreover, each field quantity (i.e. strain, displacement) varies smoothly at the macroscopic
98 scale, while it is periodic at microscopic one. Therefore, field quantities can be expressed as an
99 asymptotic expansion based on power series with terms that depend only on macroscopic scale and
100 terms that describe microscopic perturbations. A detailed description of the mathematical model of
101 AH is beyond the scope of this paper, but the reader is addressed to the source ²⁵ in Section 2.10 for a
102 more detailed description.

103 Thanks to AH, it's possible to obtain a closed-form expression for the equivalent stiffness matrix
104 for several unit cell topologies, exploiting the results available in the literature ^{26,27}. Then it is possible
105 to analyze the fully dense solid, using a finite element method, with same dimensions but with
106 equivalent mechanical properties compared to the original object, obtaining a mesh with a lower
107 number of nodes and decreasing the FE problem dimensions. This reflects on the speed-up of the
108 numerical process, with a confined error on the numerical results. When FE analysis is applied to
109 components made by isotropic materials, 5% error with experimental data can be expected with a
110 proper modelling and accurate material properties definition ²⁸. When dealing with orthotropic or
111 anisotropic materials and complex shapes such as lattice structures, a higher difference between
112 numerical and experimental tests can be noticed. However, the L1D approach has been developed to
113 be applied during preliminary and conceptual design phases, where FE assures the capability to
114 explore many design scenario in short times, and higher errors than what introduced by [28] are
115 accepted. However, the main drawback of AH algorithm, that is its high computational cost in case of
116 complex shapes due to a multiscale problem that must handle a lot of variables in case of
117 non-closed-form results. This is the reason why, in case of complex unit cell topologies, the research
118 community still has to develop different simplification methods to speed up the material analysis.

119 Moreover, this kind of procedure moves away from the real object towards a fully dense object
120 and the designer may lose the geometrical lattice characteristics by using a bulk component instead
121 of a periodic structure.

122 The aim of this research is a comparison of three techniques which can be used for FEM
123 analyses on lattice structures: innovative 1D representation and simulation, 3D analyses of the lattice
124 structure and asymptotic homogenization. The first method tries to solve this problem by modelling
125 the tridimensional lattice with 1D elements to decrease the computational effort (nearly 90% less
126 compared to the full 3D model), with limited estimation error (about 15-20%) together with the
127 capability of giving to the designer a visual idea of the periodic lattice.

128 Such an approach hasn't been yet investigated in detail, but it can offer to the designer several
129 advantages such as light computation efforts, better lattice geometry understanding in a context of
130 preliminary design phase where several scenarios have to be investigated in a fast way with
131 reasonable results and limited estimation error compared to the real 3D lattice behaviour. Using the
132 terminology of ²⁹, the herein investigated approach is still limited to uniform strut-and-node
133 arrangement lattices and not for Triply Periodic Minimal Surface (TPMS) structures ³⁰. The
134 strut-and-node arrangement perfectly fits the approximation, which is at the basis of this work,
135 where the ligaments are approximated with their beam axis.

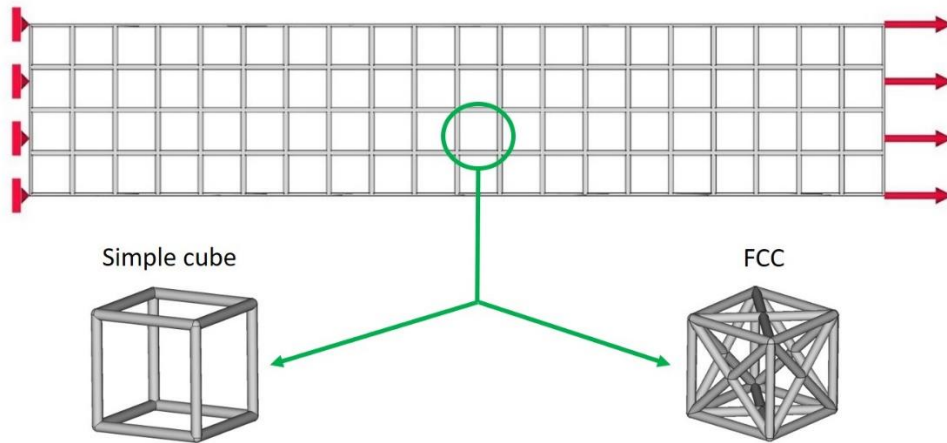
136 A numerical analysis scenario has been implemented to assess the differences in terms of
137 maximum and mean deformation estimation and understand if this approach can be a valid
138 alternative to AH and 3D lattice analysis. The performance of the innovative approach has been
139 tested in terms of maximum and mean deformation and not regarding the comparison of stresses
140 (e.g. Von Mises criterion for isotropic materials) because in this latter case possible numerical
141 instabilities can introduce fictitious values of maximum stress for the FE analysis of 3D and 1D
142 models. This aspect will be better investigated in the further, but it is out of the scope of the present
143 paper.

144 After this initial introduction, the second section presents the methodology based on the
145 innovative approach. Then, the results of finite element analysis will be shown in section three. In
146 section four the results are discussed. Finally, section 5 lists conclusions and future developments.

147 2. Methodology

148 In this section, the methodology to generate the 1D model of the lattice structure and to
149 compare the mechanical behaviour of 3D lattice, 1D lattice and AH approach is described.

150 To assess the suitability of this alternative approach, which is called L1D (Lattice to 1D) and
151 described in this work, several numerical analyses are performed using Patran/Nastran software with
152 a tensile load case, applied on a cantilevered rectangular beam which is filled with uniform lattice
153 (Figure 1).



154
155 **Figure 1.** 3D cantilevered beam filled with a uniform lattice; a tensile load is applied on the free end.
156 Two different unit cells are examined in this work: simple cube unit cell which is bending
157 dominated; FCC unit cell which is stretching dominated.

158 These preliminary simulations have been used to assess the capability of the L1D approach and
159 investigate how some design parameters (unit cell type, cross-section type) may affect the results.
160 Then, the L1D approach is applied on a real-life object such as an aircraft engine bracket designed with
161 uniform and periodic lattice. The material chosen for these simulations is the Ti6Al4V ELI-0406
162 powder for AM applications with high specific strength (strength to weight ratio) which makes it an
163 ideal choice where weight saving load structures are required³¹. The unit cells of the periodic structure
164 are based on cubic shape. Two different unit cells are used for the scope of this paper in the
165 cantilevered beam example: the simple cube unit cell and the Face Centered Cubic one (FCC). A
166 similar approach could be carried out with other lattice structures.

167 This choice comes from the necessity to investigate the efficiency of the L1D for both bending
168 (simple cube) and stretching dominated (FCC) lattice unit cells. In this way, it is possible to understand
169 how this kind of modelling lattice structures influences the approach performances in terms of
170 accuracy of results and computational time. Stretch-dominated unit cells are characterized by high
171 stiffness while bending dominated cells have lower stiffness but achieve higher strain values that
172 make them appropriate for energy-absorbing applications³². Moreover, for the sake of this research,
173 the ligaments composing the lattice are modelled using both square and circular beam cross-section to
174 investigate all the possible settings which may affect the lattice design. For simplicity, only the simple
175 cube unit cell is used in the engine bracket simulation.

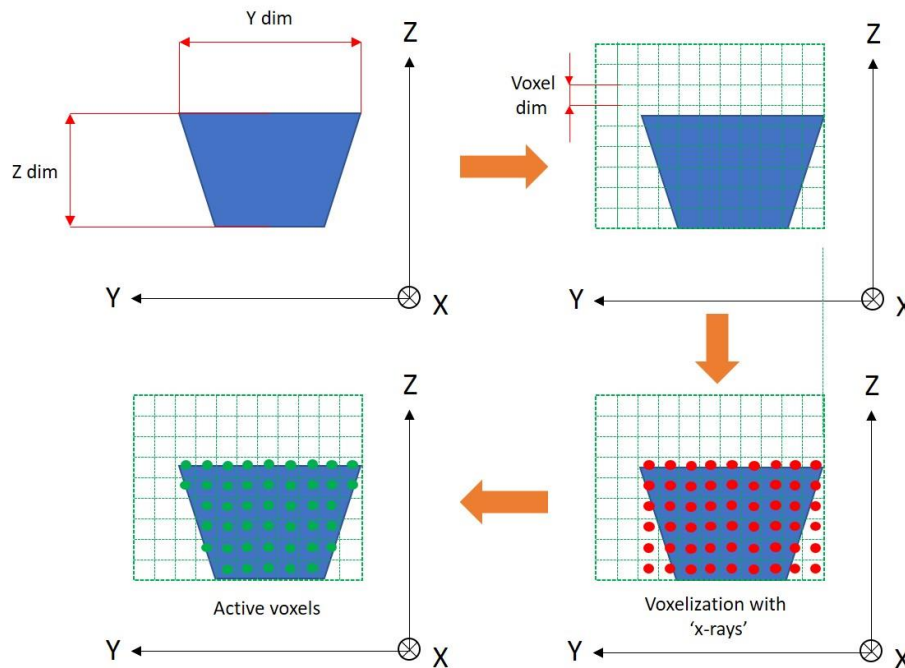
176 To obtain the mono-dimensional lattice structure, only the periodic uniform lattices were
177 considered in this research. At first, a dense 3D model of the part in lattice structure is sketched, and
178 saved in STL format. In the following, an algorithm has been developed to fill the dense part with a
179 periodic structure which is obtained thanks to a 1D wireframe modelling: the orientation and size of
180 this 1D modelling are equal to the lattice cell properties. In this way, the 3D dense part is converted
181 into a 1D lattice using the axis of ligaments through a voxel-based approach; the geometrical
182 cross-section data and material properties are given to the solver in a second moment inside the
183 software itself. The resulting geometry is only made by mono-dimensional geometrical entities as lines
184 connected to different points according to the unit cell geometry. It is worth noting that, thanks to this
185 methodology, is not necessary to model the complete 3D part with lattice structure, but only a dense
186 part is sketched. In the following, the designer can do simulations to assess the behaviour as if the

187 body was in lattice structure. Different cell size, ligaments shape and dimensions and orientation can
188 be tested to tune the model depending on the final application. Finally, the body can be automatically
189 sketched in lattice structure for manufacturing purposes.

190 2.1. Methodology to get the 1D geometry

191 To simulate the 3D lattice, an original MATLAB code was written by authors. The code is capable
192 to read a .STL file describing a fully dense 3D object and get the facet and the coordinates of the
193 vertices composing the triangle mesh of the external surface. Then, using the ray intersection method
194 ³³, a voxelized representation of the original object is achieved and a logical matrix made by 0 and 1
195 (B/W representation) is available to the user, knowing the voxel resolution the designer want (which
196 imitates the lattice structure features). The ray intersection method is the more diffused and easy
197 method to voxelize a 3D object. In particular, the mesh is ray-traced in each of the x, y, z directions,
198 with the overall result being a combination of the result from each direction (Figure 2). The
199 voxelization approach applied for each triangle of the .STL mesh can be divided into these steps:

- 200 • Take each edge of the facet in turn
- 201 • Find the position of the opposing vertex to that edge
- 202 • Find the position of the ray relative to that edge
- 203 • Check if the ray is on the same side of the edge as the opposing vertex
- 204 • If this is true for all three edges, then the ray passes through the facet.



205

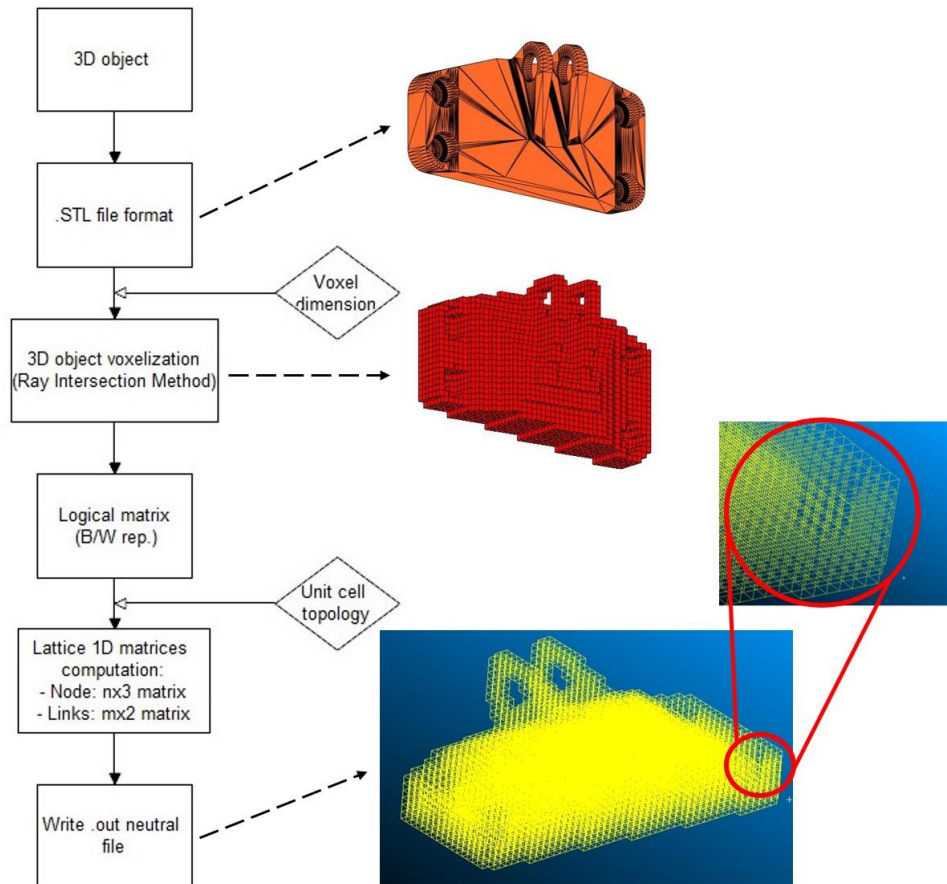
206 **Figure 2.** Ray intersection method for object's voxelization: in this picture only the rays in the
207 x -direction are shown; the algorithm passes sorted rays along the X -axis incrementing Y and Z
208 coordinates and finds their intersections with the facets. Adapted from ³³

209 The proposed methodology matches the unit cell of the lattice structure with the voxels used to
210 represent the 3D object, by setting size and orientation. After the unit cell topology is set, the own code
211 is capable to generate two distinct matrices which describe the uniform and periodic lattice. The first
212 matrix of dimensions $n \times 3$ contains all the coordinates of the vertices of the lattice cells belonging to
213 active voxels, while the second matrix of dimensions $m \times 2$ contains the information regarding the
214 IDs of two vertices composing a ligament. The final step of the code is to write a .out neutral file. The
215 neutral file contains the coordinates of the lattice points and the index of vertices linked together,
216 according to the neutral file format ³⁴ structure. Several types of geometry file formats were
217 investigated, but the neutral file format of Patran software has been set as the best one due to
218 importation, geometrical description, and formatting easiness. A flowchart describing the

219 methodology developed to get the 1D geometry is shown in Figure 3, in which it is possible to see
 220 different stages of this approach, applied to a model of an aircraft engine bracket in lattice structure.
 221 The conversion from 3D to 1D is performed in MATLAB on a workstation with 32GB RAM and an
 222 Intel Zeon CPU @ 3.50 GHz. The overall time needed for the conversion of the sample part given by
 223 the aircraft engine bracket is listed in Table 1.

224
 225
 226
 227
 228
 229

As it can be expected, the more the dimension of the discretization element decreases, the more
 the number of active voxels and the computational time increase. However, values of computational
 time around seconds or minutes in case of complex shapes suits the scenarios where the L1D approach
 is expected to be used: the preliminary and conceptual design stages.



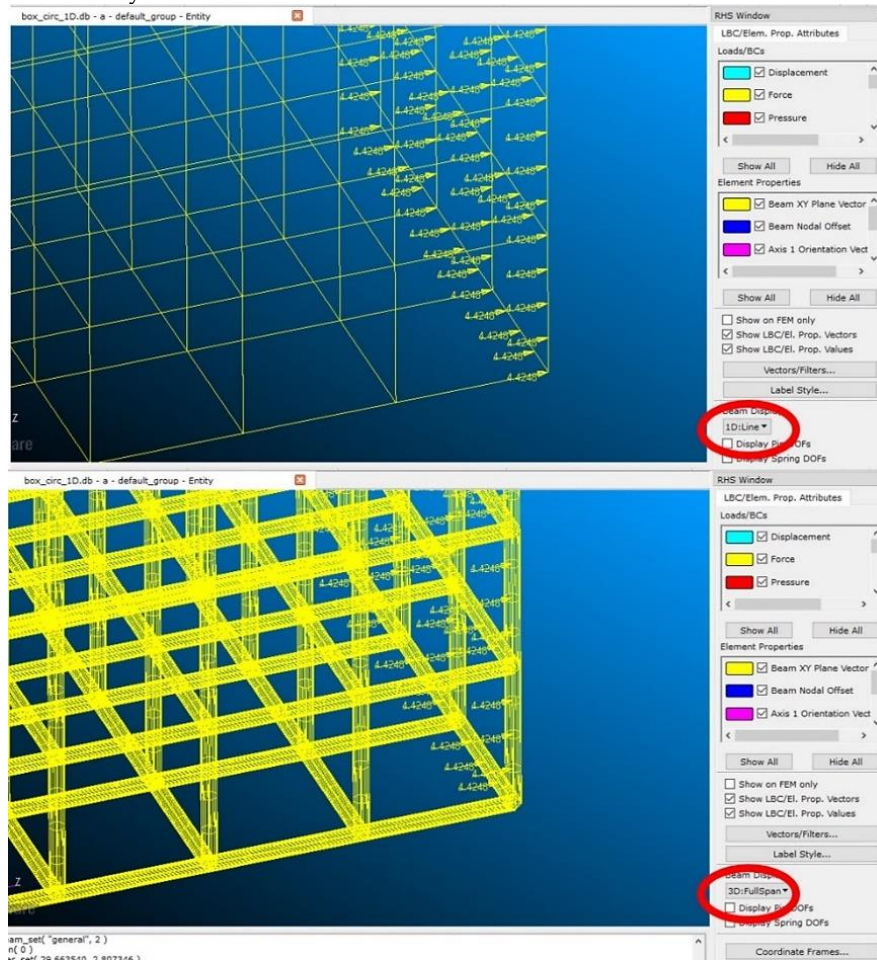
230 **Figure 3.** Flowchart describing the algorithm to get the 1D model in Patran from a 3D object in .STL
 231 file format. The L1D methodology is applied to an aircraft engine bracket: from the .STL mesh of the
 232 dense part, the algorithm obtains a voxelized model of the object; finally, the 1D lattice structure in
 233 Patran is depicted.

234 2.2. Methodology to compare the 3D, 1D and AH analyses

235 After importing the mono-dimensional lattice geometry as .out format file in Patran/Nastran, it is
 236 possible to provide the software with the material properties which are the effective ones and not the
 237 equivalent properties coming from AH methods of a hypothetical fully dense object. Moreover, the user
 238 can define in the solver the beams cross-section characteristics inside the Patran “Properties” menu
 239 since the neutral file does not contain this information. For the scope of this work, the “beam” 1D
 240 property was chosen to characterize all the ligaments which make the lattice. A rod option would
 241 neglect the bending effects. The great advantage of Patran software is the capability to show the
 242 resulting structure by selecting the element properties display option: going from the “1D: Line”
 243 option to the “3D: FullSpan” option, the user can understand if the lattice properties are correct

244
245

without increasing the computational power needed to model a 3D structure, as can be seen in Figure 4 where a close to reality 3D lattice structure visualization is obtained without efforts.



246
247

Figure 4. Same 1D lattice with two different displaying options in Patran

248
249
250
251
252
253
254
255
256
257

In this research, the lattice 3D models of the cantilever beam used for the simulation herein described were designed using a lattice structure exploiting the LSWM workbench of FreeCAD³⁵, developed by authors. On the other hand, the 3D full lattice model of the engine bracket was designed using the commercial Element software by nTopology³⁶. This software can be used to obtain a 3D model based on lattice structures and save it in CAD formats. The geometry is then imported as .step file in Patran. Other commercial software codes could be used for lattice modelling as well. This to highlight that nowadays alternative software to design 3D models, filled by lattice structures with properties set by the user, are available to the community. However, several problems arise when such complex structures need to be structurally investigated through mechanical simulations, as already cited in the previous sections.

258
259
260
261
262
263
264
265
266
267
268
269

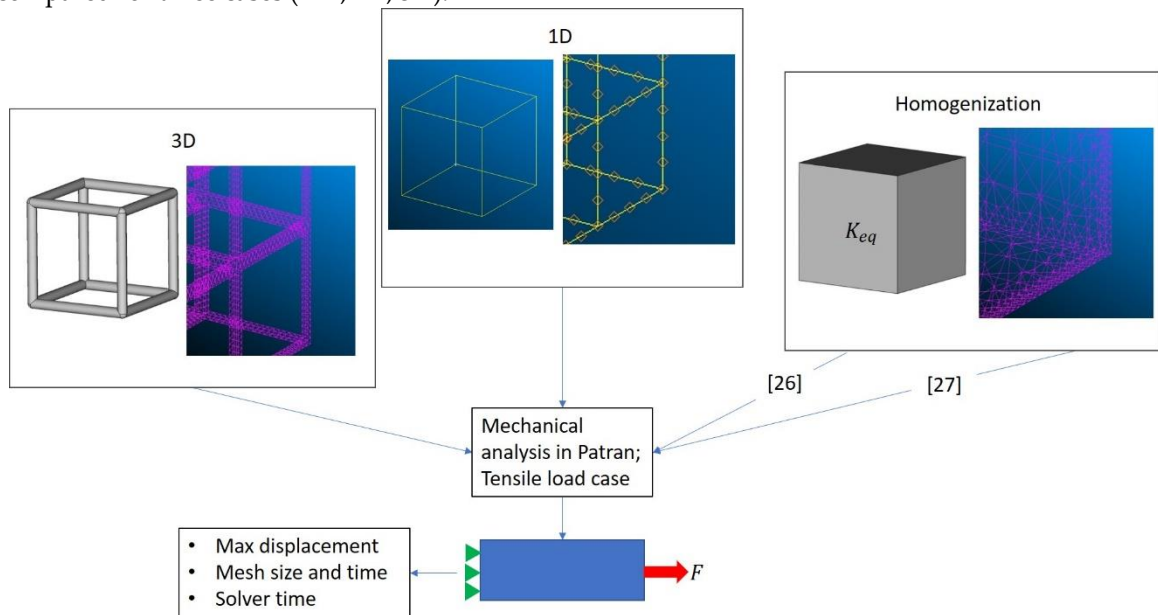
As last methodology useful to understand the goodness of the L1D approach, AH closed-form results coming from two different literature contributions^{26,27} are used as entries for the stiffness matrix of the equivalent 3D fully dense homogenized material. In the following, AH results are compared with 1D analysis. The source²⁶ uses a multiscale approach to determine the macroscopic stiffness of different lattice topologies. The results are given as different stiffness matrices depending on the geometrical unit cell characteristics, as ligament length, cross-sectional dimension, cross-sectional area and material characteristics as Young's modulus (E) and Poisson ratio (ν). These results can be applied only if a slenderness ratio (ligament length over cross-sectional dimension) of 10 at least is guaranteed to verify the slender beam assumption at the basis of this method. On the other hand, the research²⁷ developed a MATLAB code by using a voxel-based approach to analyze different unit cell lattice topologies, based on the procedure described by Andreassen³⁷. The code is capable to return the lattice stiffness matrix knowing the unit cell dimensions, the unit cell topology in terms of

270 point position and relative links, the material properties (E and ν). However, this method is limited in
 271 terms of cross-sectional topologies and only circular ones are modelled.

272 For both selected contributions ^(26,27), the resulting lattice stiffness matrix has a different scheme
 273 concerning common isotropic materials, where the matrix is defined using only two parameters,
 274 namely Young's modulus and Poisson ratio. For periodic structures, the stiffness matrix K_{lat} can be
 275 written as a function of three parameters α, β and γ (Eq. 1) ³⁸. These are functions of geometric
 276 characteristics of the unit cell topology and the beam elements. Each unit cell type will have different
 277 eigenvalues that bring to different mechanical characteristics. It's important to underline that this
 278 method can be applied only if the Euler-Bernoulli beam assumptions are valid, that reflects on a
 279 limited unit cell edge slenderness ratio. Otherwise, some instabilities could arise in case of local
 280 compressive loads, as well described by ³⁹.

$$K_{lat} = \begin{bmatrix} \alpha & \beta & \beta & 0 & 0 & 0 \\ \beta & \alpha & \beta & 0 & 0 & 0 \\ \beta & \beta & \alpha & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & \gamma \end{bmatrix} \quad (1)$$

281 As previously said, the scope of this work is to compare and understand if the L1D approach can
 282 be a valid alternative to AH methodology for lattice structural analysis. To do that a set of simulations
 283 has been carried out in Patran/Nastran MSC software following the layout proposed in Figure 5: the
 284 maximum and mean displacement, the mesh size, the meshing time, and the solving time are
 285 compared for three cases (AH, 1D, 3D).



286
 287 **Figure 5.** Methodology layout used to compare and estimate in terms of accuracy the performances
 288 of the alternative 1D modelling for uniform periodic structures along with a detailed view of
 289 meshing elements of 3D full model, 1D model and 3D homogenized model.

290 *2.3. Case studies: geometry, load material definition*

291 The first part used to assess the L1D methodology capabilities is a cantilevered beam with a
 292 rectangular cross-section with a 500N axial load to the free extremity applied on the overall surface
 293 (Figure 1). The beam dimensions are 30mm (thickness), 40mm (height) and 200mm (length): this
 294 slenderness has been set to comply with the hypothesis of the classic beam theory ⁴⁰. The applied
 295 load is at first modelled as a set of nodal forces distributed on the structure nodes of the free end.
 296 Additional simulations have been performed by applying nodal forces in the mesh nodes instead of

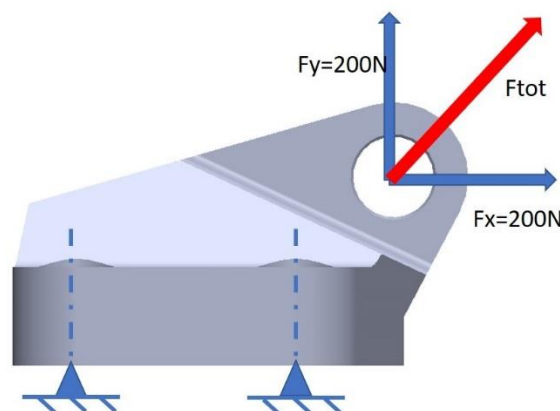
297 structure ones to detect possible differences in terms of structural deformation. As an alternative,
298 kinematic link (e.g. RBE2 or RBE3) could have been used to distribute loads within the model in a
299 similar manner to what suggested in ⁴¹.

300 As previously said, two different unit cell topologies are investigated to understand if both
301 stretching (FCC) and bending dominated (simple cube) lattices are well modelled by the L1D
302 approach. For each unit cell type, both squared and circular cross-section are modelled; in this way,
303 even the cross-section variable is investigated for the scope of the research. On the one hand, the unit
304 cell characteristics are chosen to guarantee a slenderness ratio of 10 to comply with the
305 Euler-Bernoulli assumption. On the other hand, the size is set to limit the computational power
306 needed to design and model the 3D lattice structure. In fact, by increasing the ligament length, the
307 meshing procedure can take longer time or evenly fail or return a low-quality discretization. For the
308 above-mentioned reasons, the unit cell topology characteristics set for the cantilever beam case study
309 can be summarized as:

- 310 • Ligament length: 10mm
- 311 • Cross-section dimension:
 - 312 ○ squared: edge of 1mm;
 - 313 ○ circular: radius of 0.5mm

314 The average mesh size for the full 3D model is 0.5mm, while for the homogenized one is 1mm
315 made by Tet10 elements. The 1D models have a mesh average size of 2.5mm, made of Bar2 elements.
316 The 3D homogenized component is modelled as a dense part with an orthotropic material according
317 to eq.1 with matrix entries coming from ^{26,27} references. An isotropic material using the bulk
318 characteristics is employed to model the full 3D lattice and the 1D wireframe.

319 The L1D approach is applied in the following also on a real component, namely an aircraft
320 engine bracket. This bracket has been designed with uniform and periodic lattice in other to
321 understand the L1D performances in a significant industrial engineering context. The investigated
322 component is a bracket sketched for a famous challenge organized by General Electric and Grabcad
323 ⁴². About FE analysis, for sake of simplicity, the constraints applied on the bracket consist of four
324 holes on a base, fully constrained for all the 6 degrees of freedom. In the opposite part of the bracket,
325 there are two vertical holes where a tensile load is applied in the form of nodal force distributed on
326 the cylindrical hole surface. The simulated load is composed of a vertical component of 200N and a
327 horizontal one of the same amount (Figure 6).



328
329 **Figure 6.** Schematic view of loads and constraints applied on the aircraft engine bracket
330

331 The bracket is filled with uniform and non-conformal lattice, using for simplicity only the
332 simple cube unit cell topology. To verify the slenderness ratio imposed by the investigated AH
333 methodologies, the unit cell characteristics are:

- 334 • Ligament length: 4mm

- 335 • Cross-section dimension:
- 336 ○ squared: edge of 0.4mm;
- 337 ○ circular: radius of 0.2mm

338 The average mesh size for the homogenized models is 2mm made by Tet10 elements, while the
 339 meshing procedure failed for the full 3D model. On the other hand, the 1D models have a mesh
 340 average size of 2mm, made of Bar2 elements. In this case study, the 3D homogenized component is
 341 modelled with an orthotropic material according to ^{26,27}; an isotropic material using the bulk
 342 characteristics is employed to model the 1D wireframe material as well.

343 Such unit cell dimension has been set to have at least two layers of lattice cells in the support
 344 region where the tensile load is applied: a trade-off has been carried out using a voxel size which is
 345 not highly demanding for the computational power available to us. As for the cantilevered beam, the
 346 material used for these simulations is Ti6Al4V ELI-0406 powder for AM applications with a Young's
 347 Modulus of 126 GPa and a Poisson ratio of 0.3.

348 The unit cell size changes in the two case studies due to computational power burden
 349 limitation. In the cantilever beam example, the unit cell size has been set to limit the computational
 350 power as much as possible, thus limiting the number of unit cells, also satisfying the imposed
 351 limitations in the lattice geometry in terms of slenderness ratio.

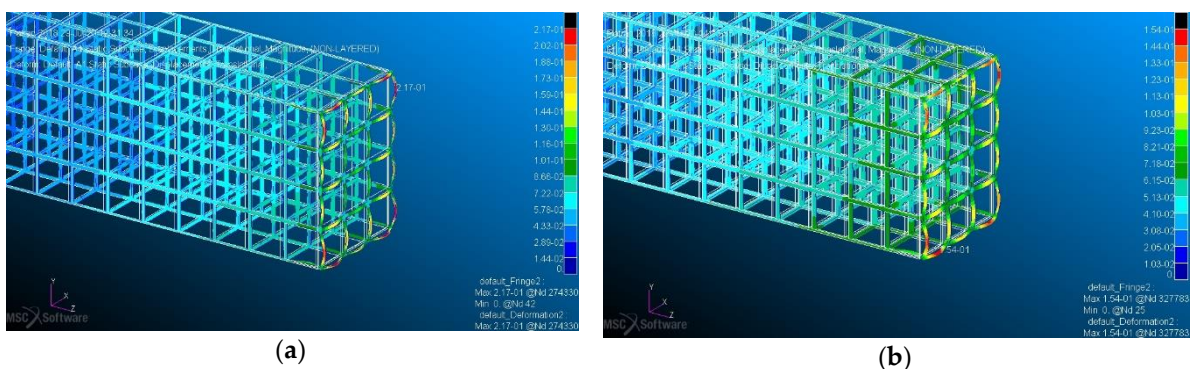
352 The lattice dimension used to fill the bracket has been set to limit the computational power, thus
 353 limiting the overall number of unit cells, and satisfying at the same time two conditions: the
 354 geometry limitations to the slenderness ratio, and to guarantee at least two layers of unit cells in the
 355 region where the load is applied.

356 3. Results

357 In this section, the features of the mechanical simulations and the results are collected, leaving
 358 Sec. 4 for its discussion. The linear elastic numerical simulations have been performed in
 359 Patran/Nastran on a workstation with 32GB RAM and an Intel Zeon CPU @ 3.50 GHz.

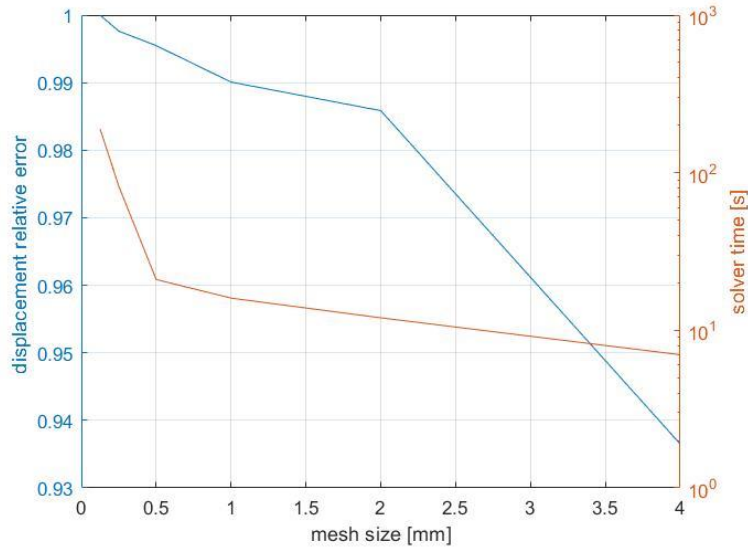
360 3.1. Cantilever beam

361 *Simple cube unit cell.* In this paragraph, all the simulation results are collected. Starting from the
 362 simple cube unit cell topology, two distinct simulations are completed to analyze the periodic
 363 structure modelled with the complete 3D geometry for the circular (Figure 7a) and square
 364 cross-sections (Figure 7b).
 365



366 **Figure 7.** View of strain field of 3D period structure with simple cube unit cells: (a) zoom view for the
 367 circular cross-section; (b) detailed view for the square cross-section

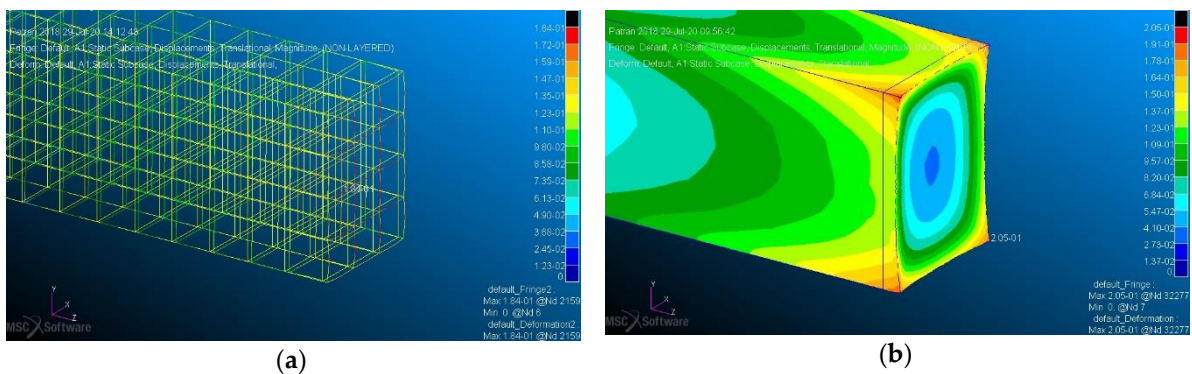
368 Before doing that, a complete mesh size convergence study was performed to optimize the
 369 minimum element size of the discretization process on a simplified (less lattice unit cells) version of
 370 the 3D full model, which is the more critical one in terms of computational requirements (Figure 8).



371
372 **Figure 8.** Mesh size convergence study on a simplified version of the full 3D lattice model of the cantilever
373 beam with simple cube and square cross-section geometry
374

375 In particular, reducing the average mesh size from 4mm to 0.125mm, it was found out that an
376 average mesh size of 0.5mm is detailed enough to capture the mechanical behaviour of the
377 component with confined computational costs (less than 0.5% of error and 89% of saved time
378 compared to 0.125mm average mesh size). The simulation of the 3D complete model is the most
379 critical since it gives benchmarking results to compare alternative approaches to study periodic
380 structures.

381 The same is done for the 1D model of the periodic structure (i.e. circular cross-section type
382 shown in Figure 9a) and for the 3D fully dense equivalent model (see as example Figure 9b for the
383 case with circular cross-section using closed-form results coming from ²⁶). Two distinct simulations
384 of the 1D model with the same geometry are performed to assess the behaviour of the L1D approach
385 in case of nodal forces applied on FE nodes or structure ones, as previously described.
386



387 **Figure 9.** View of strain field of period structure with simple cube unit cells: (a) detailed view for
388 circular cross-section for the 1D lattice model; (b) zoom view for the 3D equivalent fully dense
389 material using AH method from ²⁶

390 It is important to pinpoint that ²⁷ does not provide closed-form results in terms of stiffness
391 matrix when the square beam section is used so that only one simulation is performed using the
392 closed-form entries for the stiffness matrix coming from this contribution.

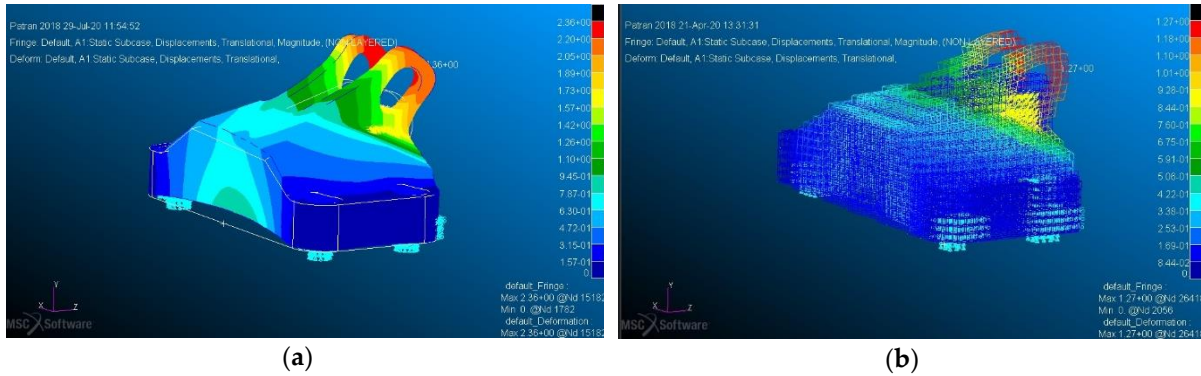
393 To have a comprehensive view of all the results, Table 2 and Table 3, respectively for circular
394 and square cross-section, contain the results coming from the simulations performed using the
395 simple cube unit cell for the periodic structure under investigation. The 3D analysis of lattice
396 structure has been considered the reference benchmark for other techniques.

397 *Face centred cubic unit cell*. The same procedure was followed to investigate the periodic
 398 structure behaviour when a stretching dominated unit cell is chosen to fill the component. Same
 399 boundary conditions and same scheme of numerical simulations are used: 2 distinct simulations for
 400 the 3D complete model (one for circular cross-section and one for the square type), 2 simulations
 401 using the 1D model coming from the L1D approach (respectively for circular cross-section and
 402 square) and 3 simulations with the 3D fully dense beam (two simulations using the results coming
 403 from ²⁶ for circular and square topologies and one using the results from ²⁷ for the circular
 404 cross-section). Also in this case, two distinct simulations of the 1D model are performed depending
 405 on the nodal forces point of application. All the results are collected in Table 4 and Table 5.

406 3.2. G.E. Aircraft engine bracket

407 The same approach to compare the L1D methodology against AH methods and 3D full model
 408 has been followed in the case study represented by the GE bracket. However, at this step, we
 409 encountered some issues to numerically simulate the 3D full model of the engine bracket filled with
 410 uniform lattice. The resulting lattice structure is made by 28712 ligaments and using a discretization
 411 with a minimum element size of half of the lattice cross-section dimension, the computational power
 412 at our disposal was not enough and at the end, the meshing procedure failed. This is exactly the
 413 context where alternative methods need to be used to simulate the mechanical behaviour of a
 414 complex lattice structure because of limited computational power. Knowing the number of nodes,
 415 elements and the meshing time applied to a single 3D ligament, it was possible to estimate the
 416 number of elements and the meshing time of the entire lattice structure. Thanks to this evaluation,
 417 assuming a linear trend, we were able to estimate about 30 million of elements in the mesh and 4
 418 hours of meshing time for the 3D full model with squared cross-section ligaments.

419 Since the results coming from the 3D full model were not available, the AH methodologies were
 420 used as a benchmark to evaluate the L1D capabilities applied on a real-life object. AH methods ²⁶ and
 421 ²⁷ are used with the same scheme to simulate the engine bracket using the simple cube unit cell with
 422 both circular and squared cross-section (Figure 10a). L1D method is applied to the 1D model of the
 423 same object (Figure 10b).
 424



425 **Figure 10.** View of strain field of engine bracket filled with period structure with simple cube unit
 426 cells: (a) view for the 3D equivalent fully dense material using AH method from ²⁶, (b) view for
 427 circular cross-section for the 1D lattice model.

428 Using the values of the relative errors found with the cantilevered beam example, for simplicity
 429 it was assumed a linear trend for the displacement estimation error, just to have a numeric reference
 430 for the 3D model. In this way, it was possible to estimate the maximum displacement of the 3D full
 431 model, knowing the maximum displacements of the AH models of both ²⁶ and ²⁷, according to Eq. 2:

$$\frac{U_{max_{3D}}}{1} = \frac{U_{max_{[25]}}}{1 - err_{[25]}} = \frac{U_{max_{[26]}}}{1 - err_{[26]}} \quad (2)$$

432

433 To have a complete overview of all the results, Table 6 and Table 7, respectively for circular and
434 square cross-section, contain the results coming from the simulations performed using the simple
435 cube unit cell for the aircraft engine bracket under investigation.
436

437 4. Discussion

438 In this section, we will refer to the results reported in the previous Tables. The reader can
439 immediately notice that both 1D modelling and AH approaches decrease more than 90% the time
440 needed for meshing and more than 80% time needed to the solver to converge to a solution whatever
441 is the unit cell or the cross-section type for both cantilevered beam and engine bracket. This result is
442 extremely important in the context of conceptual/preliminary design when several scenarios need to
443 be investigated in a fast way. Along with time reduction, also the number of elements needed to
444 discretize the geometry decreases dramatically. However, this computational power reduction must
445 be combined with good accuracy of the numerical results to provide consistent data.

446 Focusing on the simple cube unit cell topology applied to cantilevered beam and engine
447 bracket, the AH method proposed by ²⁶ estimates with more accuracy the lattice deformations (from
448 3 to 6% of error for both maximum and mean displacement), but the L1D approach shows good
449 results too. Depending on the application of the nodal forces on the 1D simulations, the L1D
450 estimates the structure maximum and mean displacement with sufficient accuracy. In particular,
451 when the forces are applied on the structure nodes, the ligament bending is lower, decreasing the
452 overall maximum displacement of some percentage points, while estimating the mean displacement
453 with higher accuracy compared to 1D simulations with nodal forces applied on mesh nodes
454 (respectively 9% and 23% error compared to 3D full model). The main advantage of the L1D
455 approach is that the designer can have a good overview of the structure geometry and behaviour in
456 terms of single beam element, which is not possible with AH methodologies (See Figures 9 and 10).
457 The AH approach proposed in ²⁷ overestimates the structural behaviour of about 13%, which is a
458 figure still acceptable in the case of conceptual/preliminary design. In case of objects with complex
459 geometry, such as the GE engine bracket, simplification methods such as AH or L1D must be used to
460 decrease the computational time and power needed for mechanical simulations. On the one hand,
461 the 3D full lattice model was so complex and computationally demanding that led to the simulation
462 failure. On the other hand, both AH and L1D approaches decrease up to 99% the time for meshing
463 and the number of elements, while maintaining a satisfactory degree of accuracy which is extremely
464 important in a context of conceptual/preliminary design.

465 Concerning the FCC topology implemented only in the cantilevered beam, the reader can
466 immediately conclude that a complex structure leads to higher computational power and time when
467 the real 3D object is analyzed. This is again a context where approximation methods are extremely
468 important. For example, by using the AH methodology or the 1D modelling, the computational
469 power reduces almost 96%, along with the reduction of the number of elements of the mesh. Even
470 for FCC unit cell type, L1D approach seems a valid alternative because the deformations are
471 overestimated with a limited error for both types of nodal force application points (18%) with
472 respect both AH methodologies in which the maximum deformations are underestimated (50% of
473 error). Even in FCC topology, using the L1D approach the mean displacement is estimated with high
474 accuracy in case the nodal forces are applied on the structure points instead of mesh nodes
475 (respectively 9% and 13% of error).

476 To summarize, the 1D approach can estimate the maximum and mean deformations with a
477 limited error, low computational power, but still giving to the designer an overview of the lattice
478 geometry and behaviour, even at the ligament level for both stretching and bending dominated unit
479 cells, while AH approaches are more precise for bending dominated topologies compared to
480 stretching ones. Moreover, comparing both AH methods, [26] has outstanding estimation
481 performances compared to [27] in all the studied contexts.

482 Both AH and 1D methodologies have similar computational requirements both for meshing
483 and results in convergence if compared to the 3D object.

484 From this study, it is also possible to understand that the cross-section topology does not affect
485 the computational costs and the results accuracy for both AH and 1D approaches, confirming the
486 results obtained in ⁴³. The only main difference is that when the square cross-section is used
487 (whatever is the unit cell type), the computational cost increases for the 3D model.

488 Moreover, from the above results coming especially from the GE engine bracket simulations, it
489 is clear that a simplification method, such as the L1D approach described in this work, is compulsory
490 nowadays in case of mechanical investigation through numerical analysis of 3D lattice structures:
491 this kind of analyses are usually carried out when designing lightweight structures for industrial
492 applications such as aerospace, automotive and automatic machines.

493 The analysis of the results of the simulations carried out in this research, confirms that the L1D
494 approach is a good alternative to homogenization approaches because comparable performances
495 can be achieved, or even better, still giving to the designer the quasi-real geometry view. However,
496 the developed approach still shows some limitations because only node-strut arrangement lattices
497 can be modelled. In the future, it could be of interest comparing the 3 methods explained in this
498 work varying the slenderness ratio of the lattice structure and using different loading conditions.
499 Moreover, only uniform and non-conformal periodic structures can be analyzed.

500 5. Conclusions

501 This paper aimed to investigate alternative methods for numerical simulations of periodic
502 structures. In literature, several contributions use the asymptotic homogenization approach by
503 substituting the lattice with a fully dense material with equivalent mechanical characteristics.
504 However, this approach does not give an overview of the structure behaviour in terms of
505 deformation at ligament levels since a bulk material is used.

506 To fill the gap, this research focused on a 1D modelling for uniform periodic lattices which can
507 give to the designer a good idea of how is behaving the structure in case of static loads. Several linear
508 elastic simulations were performed to compare the maximum deformation of the 1D modelling with
509 the complete 3D model of the lattice structure, which was taken as a benchmark, and two valid AH
510 methods available in the literature. Two different unit cell topologies and two different cross-section
511 types were investigated to understand how these variables influence the performance of the
512 alternative 1D approach. Results show good agreement with the 3D complete model, but with a
513 drastic decrease of the time and computational power required, with comparable or even better
514 performance compared to AH approaches here analyzed. The benefits of the 1D modelling are
515 amplified in case of complex unit cells, while the results show that the cross-section does not
516 influence the accuracy of the methodology herein investigated.

517 However, this approach still shows some limitations because it can model only uniform,
518 non-conformal periodic structures with a strut-and-node arrangement. Moreover, only the tensile
519 load case was investigated; other load scenarios and other slenderness ratios of the lattice structure
520 must be investigated in the future to declare this alternative approach mature for periodic structure
521 analysis. Finally, the conversion from the 3D model to the 1D is based on the voxelization procedure,
522 which is an approximation of the real geometry. For this reason, a certain % of error in terms of
523 maximum displacement can be attributed to the L1D methodology.

524 It is worth noting that the development of methodologies to compute periodic structures in
525 complex geometries is tightly connected to the evolution of computational power which can open
526 new possibilities in coming years. However, nowadays it is not feasible the analysis of complex
527 lattice structures using 3D meshing, using standard computational devices such as a PC. In this
528 research, a solution to address the structural analysis of lattice structures in a typical industrial
529 environment where large PC clusters are not available to each designer is proposed.

530 **Funding:** This research did not receive any specific grant from funding agencies in the public, commercial, or
531 not-for-profit sectors.

532 **Conflicts of Interest:** "The authors declare no conflict of interest."

533 **Data Availability:** "The raw/processed data required to reproduce these findings cannot be shared at this time
534 as the data also forms part of an ongoing study."

535 **References**

- 536 1. Gibson I, Rosen D, Stucker B: Additive Manufacturing Technologies. New York: Springer, 2015.
- 537 2. Bacciaglia A, Ceruti A, Liverani A. Additive Manufacturing Challenges and Future Developments in the
538 Next Ten Years. In: Design Tools and Methods in Industrial Engineering. Springer International
539 Publishing, 2020, pp. 891–902.
- 540 3. Gao W, Zhang Y, Ramanujan D et al. The status, challenges, and future of additive manufacturing in
541 engineering. *Comput.-Aided Des* 2015; 69: 65–89.
- 542 4. Bacciaglia A, Ceruti A, Liverani A, Evaluation of 3D printed mouthpieces for musical instruments. *Rapid*
543 *Prototyp J* 2019; 26: 577–584.
- 544 5. Bacciaglia A, Ceruti A, Liverani A, A systematic review of voxelization method in additive manufacturing.
545 *Mech Ind* 2019; 20: 630.
- 546 6. Sola A, Defanti S, Mantovani S, et al. Technological Feasibility of Lattice Materials by Laser-Based Powder
547 Bed Fusion of A357.0. *3D Print Addit Manuf* 2020; 7: 1–7.
- 548 7. Maskery I, Aboulkhair N T, Aremu A O et al. A mechanical property evaluation of graded density
549 Al-Si10-Mg lattice structures manufactured by selective laser melting. *Mater Sci Eng A* 2016; 670: 264–274.
- 550 8. Leary M, Mazur M, Elambasseril J et al. Selective laser melting (SLM) of AlSi12Mg lattice structures. *Mater*
551 *Des* 2016; 98: 344–357.
- 552 9. Rashed M G, Ashraf M, Mines R A W, et al. Metallic microlattice materials: A current state of the art on
553 manufacturing, mechanical properties and applications. *Mater Des* 2016; 95: 518–533.
- 554 10. Llorente S, Honeycomb sandwich primary structure applications on the Boeing model 360 helicopter. In
555 *International SAMPE Symposium and Exhibition*. SAMPE, Covina, CA, United States, 1989. 34(1): 824–838.
- 556 11. Campo G A, Vettorello A, Giacalone M, Optimization Methodology for Continuous Heterogeneous
557 Structures: A Preliminary Design of an Engine Mounting Bracket. *Key Eng Mater* 2019; 827: 116–121.
- 558 12. McMillan M L, Jurg M, Leary M, et al. Programmatic generation of computationally efficient lattice
559 structures for additive manufacture. *Rapid Prototyp J* 2017; 23: 486–494.
- 560 13. Cansizoglu O, Harrysson O, Cormier D, et al. Properties of Ti–6Al–4V non-stochastic lattice structures
561 fabricated via electron beam melting. *Mater Sci Eng A* 2008; 492: 468–474.

- 562 14. Hedayati R, Hosseini-Toudeshky H, Sadighi M, et al. Computational prediction of the fatigue behavior of
563 additively manufactured porous metallic biomaterials. *Int J Fatigue* 2016; 84: 67–79.
- 564 15. Ozdemir Z, Tyas A, Goodall R, et al. Energy absorption in lattice structures in dynamics: Nonlinear FE
565 simulations. *Int J Impact Eng* 2017; 102: 1–15.
- 566 16. Arabnejad S, Pasini D, Mechanical properties of lattice materials via asymptotic homogenization and
567 comparison with alternative homogenization methods. *Int J Mech Sci* 2013; 77: 249–262.
- 568 17. Gibson L J, Ashby M F. *Cellular solids: structure and properties*. Cambridge Univ. Press, 2001.
- 569 18. Hutchinson R G, Fleck N A, The structural performance of the periodic truss. *J Mech Phys Solids* 2006; 54:
570 756–782.
- 571 19. Chen J, Fracture analysis of cellular materials: A strain gradient model. *J Mech Phys Solids* 1998; 46: 789–
572 828.
- 573 20. Craster R V, Kaplunov J, Pichugin A V, High-frequency homogenization for periodic media. *Proc R Soc*
574 *Math Phys Eng Sci* 2010; 466: 2341–2362.
- 575 21. Florence C, Sab K, A rigorous homogenization method for the determination of the overall ultimate
576 strength of periodic discrete media and an application to general hexagonal lattices of beams. *Eur J Mech -*
577 *A Solids* 2006; 25: 72–97.
- 578 22. Chen C M, Kikuchi N, Rostam-Abadi F, An enhanced asymptotic homogenization method of the static and
579 dynamics of elastic composite laminates. *Comput Struct* 2004; 82: 373–382.
- 580 23. Kalamkarov A L, Andrianov I V, Danishevs'kyi V V, Asymptotic Homogenization of Composite Materials
581 and Structures. *Appl Mech Rev* 2009; 62: 030802.
- 582 24. Guinovart-Díaz R, Bravo-Castillero J, Rodriguez-Ramos R. et al. Modeling of elastic transversely isotropic
583 composite using the asymptotic homogenization method. Some comparisons with other models. *Mater*
584 *Lett* 2002; 56: 889–894.
- 585 25. Bendsøe M P, Sigmund O. *Topology optimization: theory, methods, and applications*. Springer, 2011.
- 586 26. Vigliotti A, Pasini D, Stiffness and strength of tridimensional periodic lattices. *Comput Methods Appl*
587 *Mech Eng* 2012; 229–232: 27–43.
- 588 27. Dong G, Tang Y, Zhao Y F, A 149 Line Homogenization Code for Three-Dimensional Cellular Materials
589 Written in matlab. *J Eng Mater Technol* 2019; 141: 011005.
- 590 28. Pointer J. *Understanding Accuracy and Discretization Error in an FEA Model*. 2004.

- 591 29. Tamburrino F, Graziosi S, Bordegoni M, The Design Process of Additively Manufactured Mesoscale Lattice
592 Structures: A Review. *J Comput Inf Sci Eng* 2018; 18: 040801.
- 593 30. Maskery I, Sturm L, Aremu A O, et al. Insights into the mechanical properties of several triply periodic
594 minimal surface lattice structures made by polymer additive manufacturing. *Polymer* 2018; 152: 62–71.
- 595 31. Renishaw, Ti6Al4V ELL-0406 powder for additive manufacturing Datasheet, 2017.
- 596 32. Choy S Y, Sun C N, Leong K F, et al. Compressive properties of Ti-6Al-4V lattice structures fabricated by
597 selective laser melting: Design, orientation and density. *Addit Manuf* 2017; 16: 213–224.
- 598 33. Patil S, Ravi B, Voxel-based Representation, Display and Thickness Analysis of Intricate Shapes. In: Ninth
599 International Conference on Computer Aided Design and Computer Graphics (CAD-CG'05) 2005. 415–
600 422.
- 601 34. Patran reference manual. The neutral file. 2018.
- 602 35. Ceruti A, Ferrari R, Liverani A, Design for Additive Manufacturing Using LSWM: A CAD Tool for the
603 Modelling of Lightweight and Lattice Structures. In: *Sustainable Design and Manufacturing*. Springer
604 International Publishing, 2017. 68: 756–765.
- 605 36. Element lattice design software. nTopology <https://ntopology.com/blog/2016/04/19/element-free/>. Last
606 access: 10/10/2020.
- 607 37. Andreassen E, Andreassen C S, How to determine composite material properties using numerical
608 homogenization. *Comput Mater Sci* 2014; 83: 488–495.
- 609 38. Asaro R, Lubarda V. *Mechanics of Solids and Materials*. Cambridge University Press, 2006.
- 610 39. Vigliotti A, Pasini D, Mechanical properties of hierarchical lattices. *Mech Mater* 2013; 62: 32–43.
- 611 40. Timoshenko S P. *History of Strength of Materials*. McGraw-Hill Inc., 1953.
- 612 41. Rotondella V, Merulla A, Baldini A, et al. Dynamic Modal Correlation of an Automotive Rear Subframe,
613 with Particular Reference to the Modelling of Welded Joints. *Adv Acoust Vib* 2017; 2017: 1–9.
- 614 42. GE jet engine bracket challenge. <https://grabcad.com/challenges/ge-jet-engine-bracket-challenge>. Last
615 access: 2/10/2020.
- 616 43. Cook R D. *Finite element modeling for stress analysis*. Wiley, 1995.
617