Title:
Mesoscale Modeling of Cellular Materials for Finite Element Analysis

Authors:
Michele Bici, michele.bici@uniroma1.it, Sapienza University, Roma, Italy
Francesca Campana, francesca.campana@uniroma1.it, Sapienza University, Roma, Italy
Micaela de Michelis, Sapienza University, Roma, Italy

Keywords:
Cellular materials, Finite Element Analysis, Voronoi Diagram, Representative Volume Element, Reverse Engineering

DOI: 10.14733/cadconfP.2016.268-273

Aim of the work:

Mesoscale modeling of cellular materials is not strictly related to tomography reconstruction, but it can be applied also in Finite Element Analysis: (a) to better understand load distribution at the interfaces; (b) to develop and calibrate material models; (c) for sensitivity analysis to different loads or shape parameters. This paper aims to survey some of the most applied techniques to model cellular materials at a mesoscale level discussing their advantages and disadvantages for modeling in Finite Element Analysis. Among them, two of the most applied techniques, the Voronoi approach and the reverse engineering reconstruction, are here applied to simulate the behavior of aluminum foams under compression. These applications compared to some experimental evidences confirm the capability of mesoscale analysis, highlighting possible enhancement of the modeling techniques.

Introduction:

Cellular materials cover a wide range of materials from metallic to biological. They consist with a non-homogeneous structure defined by pores or voids, named also cells, which are distributed with different shape and dimension. According to [5], "porous materials" have a bulk matrix with small pores in an amount of less than 30-40% while "cellular materials" have a larger amount of voids. Generally speaking, they can be classified according to the cells distribution: thus they can be regular distributed cells or stochastic; open or closed cells; polyhedral or elliptical. Honeycomb and lattice structure are two examples of regular distributed cells. The first one is an open structure closed by two laminated panels (sandwich structure), the second one defines an open structure. They allow weight reduction without drop of stiffness and strength so that they are applied as structural panels in aeronautical applications or bumpers. Metallic foams made by powder technology represent stochastic closed cells. Typically, they are rather spherical or elliptical. On the contrary, foaming through infiltration in a salt pattern produces open cells structures that can be extremely small (pore size is related to salt granulometry), and may assume polyhedral shapes.

Modeling must face different problems considering what it has to accomplish. Two modeling scenarios may be defined: one is related to the reconstruction from direct experimental acquisition (e.g. X-ray tomography or metallographic cross sections), the second one concerns with numerical generation from registered data. Reconstruction from direct experimental acquisition is derived from medical practice and it is common in bioengineering. In this case, material cells (of both bone and metallic component) have length ranging from 1 to 5 mm and are distributed according to load paths [7], thus direct acquisition is required to capture the specific test case related to the patient. The same approach has been applied also to mechanical investigation of metallic foams [5]. Since void density and morphology has been demonstrated as the leading parameters of mechanical response, tomography reconstructions have been made to quantify foam's porosity and to investigate its mechanical behavior via FEA. From the design point of view this approach is not effective because it requires the experimental investigation on the materials thus the second modeling scenario (numerical generation from registered data) seems to be the most appropriate. In this case, some hypothesis about cell shape and size distribution are made according to experimental observations, then a pattern of voids is generated and subtracted to the bulk materials. Doing so both regular pattern and stochastic distribution can be made according to the hypothesis applied.

In both scenarios, many difficulties have been faced and discussed in literature. In the case of reconstruction from direct experimental acquisition, main problems concern with: (a) data acquisition and image analysis post-processing, (b) surface/volume discretization. In the case of numerical generation from registered data, they mainly concern with: (a) the consistency of the assumption related to cell shape and (b) the ability of reproducing the actual stochastic void variability, which is intrinsically due to the manufacturing process. In all cases, the final result must be processed according to the specific requirement of the research, e.g. as a stl or FEA model file or as surface model. In every case, it may ask for large model processing and checking, steps often discharged or undervalued with regard to the reliability of the results.

Modeling strategies:

Modeling from direct experimental acquisition are usually based on the concept of voxel processing of a 3D-tomography. It requires the subtraction of the voxels included in the scanned porosity, as defined through image analysis techniques. In the field of mechanical characterization, it is also associated to the Representative Volume Element (RVE) technique [4]. RVE defines a mesoscale model able to include the interesting material discontinuity, so that the global description of the material can be computed. The choice of the RVE length represents the core of the procedure when FEA must be carried from the model directly. In [5] it was related to the reliability of the stress distribution achieved importing the voxel structure directly as FEA model. Because increasing RVE length means reducing the number of nodes, passing from $273x10^3$ to $14x10^3$ nodes, the error from the experimental value of the Young modulus passes from 28% to 42%, demonstrating a loss of accuracy of the specimen stiffness due to the merge of some voids, whereas the local evaluation of stress at the thicker walls remains the same. RVE is used in bioengineering where the length ratio between meso/macro-scale is of about 1:100-1:50 mm/mm according to porosity volume fraction of 0.30-0.49. Void granulometry from image analysis has allowed also RVE reconstruction from registered data. It has been made in [7] assuming two strategies: in a control volume (e.g. the specimen) RVE is inserted from blank iteratively, if porosity volume fraction is higher than 0.50, or subtracted, if it is lower. The iterations work from the center of the control volume to the edges. At the end, check and refinement are performed to evaluate the discrepancy from the input porosity volume fraction and the hypothesis on the cell shape (close or open).

Another approach to measure voids distribution is through metallographic cross-sections. Also in this case, image analysis may allow contour segmentation that in [6] is used to obtain a 3D FE model by stacking the cross-sections. Although it was not mentioned in the paper, the reconstruction process followed a typical reverse engineering process, since the scanned sections were imported as cloud of points in a CAD environment to obtain the void surfaces.

Regular cells may be modeled through pattern replication of a basic volume (the cell). It requires the definition of a cell geometry and its subtraction from the component bulk shape according to the required density. The most adopted cells are polyhedric (e.g. Kelvin cell), elliptical or a lattice structure [8]. In this last case, open regular cells are obtained. Although many works are present in literature, for metallic foam characterization, this approach may not be able to take into account realistic changes of cell shape, being more adapt for regular cell distributions. Due to this problem, mixed approaches have been defined to introduce probabilistic distribution in a regular cell morphology. An example is given in [1]. Doing so volume subtraction may build also stochastic cells according to probabilistic distributions related to cell's length and position.

Another possible approach is the Voronoi cell [3]. It is a computational geometry construct related to the space partitioning according to the near-neighbor rule. Each cell can be associated to a point, thus the region of the space that is the closest to its convex hull, represents the void edge. Many applications have been derived from this approach (and some of them are also related to RVE applications, for example see [4], because Voronoi diagram concerns with the geometrical description of the problem). The general procedure consists of defining a Pore Volume Fraction (PVF) so to derive the number of cells (N) that must be included in the specimen volume according to their shape and average dimension. For spherical cells, with radius R, the relation is:

$$PVF = N\frac{4}{3}\pi R^3 \qquad (1)$$

Assuming a stochastic distribution for the cell's center the space tessellation is not regular thus irregular voids are defined although the hypothesis of Eqn. (1).

Applications and comparison:
Tab. 1 summarizes the documented approaches according to some evaluation criteria. Pattern Replication can be seen as a solid modeling technique. Its outputs are surfaces and volumes thus the FE models may be derived with minor post-processing (e.g. mid-surfacing in case of shell elements), after neutral format data exchange. On the contrary major efforts are required to insert stochastic variation of cell distributions, like shape transition from ellipsoidal to polyhedral.

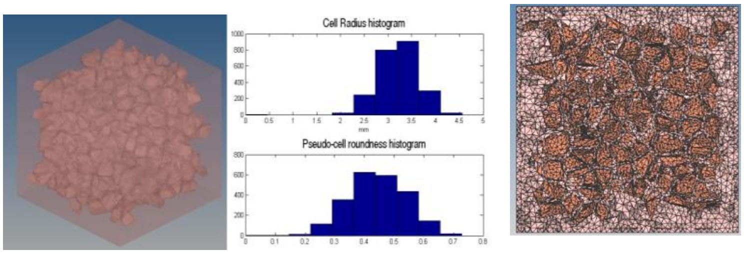
	RVE	*Reverse Engineering*	*Pattern Replication*	*Voronoi Cell*
direct from experimental	yes/no	yes	no	no
cell shape	open/close also polyhedral	as experimented	open/close also polyhedral	open/close polyhedral
stochastic	yes	as experimented	no/yes with major efforts	yes
type of model	discrete	discrete/surface	surface	discrete
field of application	bioengineering, mechanical	mechanical	mechanical	multipurpose
post-proc time	medium	high	low	medium
FEA aptitude	good	low	good	medium

Tab. 1: Comparison among documented approaches.

Reverse Engineering, intended as derived from point-cloud segmentation and not from voxel reconstruction, is intrinsically laborious because of the 3D nature of the voids. Without reliable automatic segmentation and careful checks of the tessellation quality, is rather difficult to achieve good FEA models from the stl file, systematically. The advantage may concern with the capability of reach smooth void shapes, if the resolution of the acquisition is good enough.

RVE and Voronoi cell approaches seems to be the most versatile in terms of cell shape and distribution. Void surface is discrete. In the case of RVE, it can be automatically associated to a FE solid mesh, while in the case of the Voronoi cell it can be more difficult. If the mesoscale model can be simulated by shells, the association of a uniform thickness on the tessellation of the void surfaces is trivial. On the contrary, if a FE solid model is required a proper map of the void surface mesh must be defined [4].

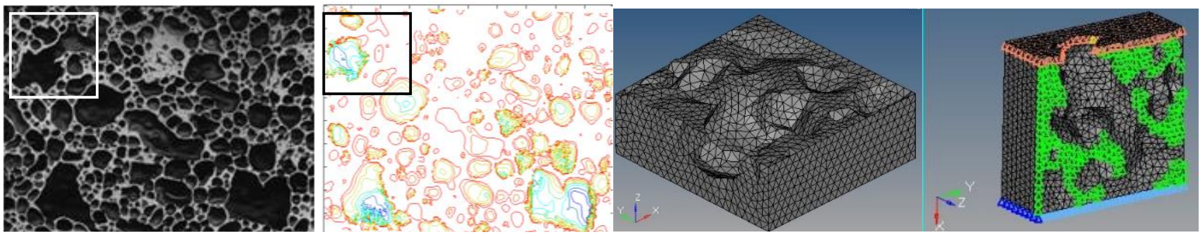
By two test cases Voronoi approach and Reverse Engineering approach have been compared. The Voronoi model has been applied on a virtual specimen 60x60x60 mm (Fig. 1). It has been built starting from a nominal PVF of 41%, a number of seeds equal to 3261 and a nominal wall thickness of 2 mm. These input lead to an effective PVF of 25% accepting 2300 seeds in the volume. The effective density amount to 2.05×10^{-6} kg/mm^3, which means a relative density ratio equal to 0.76. The FEA model is made by 138000 nodes and 565000 elements.



(a) (b) (c)

Fig. 1: (a) STL final model; (b) cell frequency histograms; (c) tetramesh, section view.

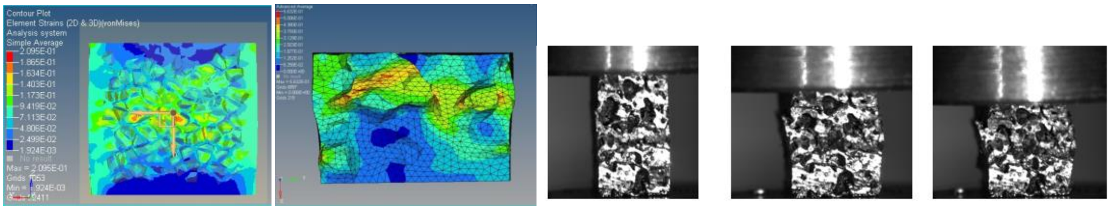
The Reverse Engineering approach has been tested on a subset of points taken from a laser scanner acquisition of the cross-section of an Al7075 specimen, as reported in the box of Fig. 2(a). In this test case only one half of a cut is investigated through its cross-section, with the aim of evaluating the operations necessary without taking into account the slice stacking. To capture cell shapes, 52000 points have been resampled on a planar surface of 12x13 mm. After hole filling, the 2D STL mesh has been optimized and the volume corresponding to the slice has been derived, assuming a cut height equal to 4 mm, since the maximum depth of the cavities is of about 3.42 mm. The FEA model has 26980 elements with mesh max element size set to 1.5 mm and aspect ratio to 0.8.



(a) (b) (c) (d)

Fig. 2: Reverse engineering test case: (a) experimental cross-section; (b) iso-level curves of the acquisition; (c) tetramesh of the slice; (d) FEA constraints and imposed displacements.

As shown by the contour plots of the two test cases (Fig. 3(a). and Fig. 3(b).), the mesoscale FEA confirms its capability to describe plastic hinge and the local collapse of cells. In Fig. 3(c) some experimental evidences of the plastic hinge are given according to a quasi-static test. The collapse is localized at sections where minimum stiffness is present, not necessary where larger cells are.



(a) (b) (c)

Fig. 3: (a) Voronoi test case: strain contour at 25 mm of compression; (b) Reverse Engineering test case: strain contour at 20%; (c) Quasi-static compression test: sequence of deformation.

From the cell topology point of view, obviously, the reverse engineering test case fully accomplishes the reproduction of an Al7075 foams made by metallic powder technology. This process uses TiH_2 as foaming agent of compact powders pre-arranged in dies as semifinished. It produces closed cells as shown in Fig. 14(a) and Fig. 4(b), surrounded by dense outer walls made by the contact with the die. To give an example of different cell topology Fig. 4(c) shows the same technology applied to AlSi7, with similar relative density ratio. In this case, the cells are sharper and there is a thicker outside wall.

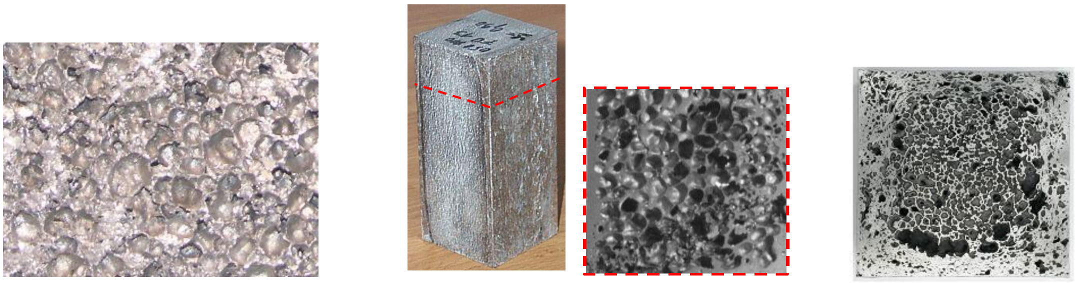

(a) (b) (c)

Fig. 4: Examples of cell topology (a) and (b) Al7075; (c) AlSi7.

Considering the Al7075 cell topology, the implemented Voronoi approach gives sharper edges, rather similar to the Alsi7 cells (Fig. 4(c)). Nevertheless, in Fig.4(c), it can be seen that the cell size and distribution is not normally distributed, but it decreases from the centre of the ingot to the outside, according to the temperature cycle determined by the foaming process, as also studied in [2]. Thus, in case of compact powder technology, more sophisticated cell distributions must be implemented in the Voronoi approach to accomplish a more realistic mesoscale CAD modeling. Moreover, some specific check must be implemented to calibrate the dense volume near the outer surfaces.

Doing so the test case based on the Voronoi approach, may be enhanced to carry out, in the next, a manufacturing-process-driven modeling technique. On the contrary, reconstruction and modeling via Reverse Engineering is more time consuming, although it may reproduce cell cavities with better accuracy. Nevertheless, major efforts must be taken to prepare the cross-section and evaluate the slice stacking.

References:

[1] Carofalo, A.; De Giorgi, M.; Morabito, A.: Geometric modelling of metallic foams, Engineering Computations, 30(7), 2013, 924-935. http://dx.doi.org/10.1108/EC-06-2011-0070

[2] Campana, F.; Cortese, L; Pilone, D.: Property variations in large AlSi7 alloy foam ingots, Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing, 556, 2012, 400-407. http://dx.doi.org/10.1016/j.msea.2012.07.004.

[3] Gil Montoro G. C.; Abascal, J. L. F.: The Voronoi Polyhedra as Tools for Structure Determination in Simple Disordered Systems, The Journal of Physical Chemistry, 97(16), 1993, 4211-4215.

[4] Kanit, T.; Forest, S.; Galliet, I.; Mounoury, V.; Jeulin, D.: Determination of the size of the representative volume element for random composites: statistical and numerical approach, International Journal of Solids and Structures, 40, 2003, 3647–3679. http://dx.doi.org/10.1016/S0020-7683(03)00143-4.

[5] Maire, E.; Fazekas, A.; Salvo, L.; Dendievel, R; Youssef, S.; Cloetens, P.; Letang, J.M.: X-ray tomography applied to the characterization of cellular materials. Related finite element modeling problems, Composites Science and Technology, 63(16), 2003, 2431-2443. http://dx.doi.org/10.1016/S0266-3538(03)00276-8.

[6] Michailidis, N.; Stergioudi, F.; Omar, H.; Tsipas, D.N.: 2010, An image-based reconstruction of the 3D geometry of an Al open-cell foam and FEM modeling of the material response, Mech. Mater. 42, 142–147.

[7] Simoneau, C.; Terriault, P.; Rivard, J.; Brailovski, V.: Modeling of metallic foam morphology using the Representative Volume Element approach: Development and experimental validation, International Journal of Solids and Structures, 51(21–22), 2014, 3633-3641. http://dx.doi.org/10.1016/j.ijsolstr.2014.06.027.

[8] Zhang, J.: The Mechanics of Foams and Honeycombs, Cambridge University Press, Cambridge (UK), 1989.