IMAGE BASED STOCHASTIC MULTISCALE ANALYSIS OF METAL FOAM

Carsten Proppe[*]
[*]*Institute of Engineering Mechanics, Karlsruhe Institute of Technology, Karlsruhe, 76131, Germany*

Summary Metal foam may consist of a very heterogeneous structure, such that the size of the representative volume element is rather large. Therefore, macroscopic properties of components made of metal foams might show a large scatter. In order to predict the scatter of eigenfrequencies for bending beam structures, a consistent formulation from digital image based analysis to the distribution of macroscopic properties is developed. With the help of computed tomography, statistical characteristics of the cell geometry of open cell foams are estimated. This information allows for the calibration of a random mosaic generator that reproduces the statistical properties of the cell geometry. In order to compute the linear elastic properties as well as the mass density of metal foam, three dimensional volume elements from random samples of the mosaic generator are analyzed and distributions of apparent properties are computed. The covariance function is estimated by considering volume elements at different locations of the macrostructure. Having a description of random fields for the apparent properties at hand, Monte Carlo simulations are applied to predict the eigenfrequencies, their scatter and the associated eigenforms of beams made of metal foam. The results are validated by experiments.

INTRODUCTION

Metal foam has many distinct advantages over other materials:

- its high stiffness to mass ratio allows its application in lightweight constructions;
- its excellent energy absorbing properties make it a material of choice in crash boxes;
- due to its huge surface to volume ratio, metal foams come into play in filters or catalytic converters.

In machine tools, metal foams are used for vibration isolation. In this regard, it is necessary to determine the vibration behavior, especially the eigenfrequencies of structures made of metal foam. Due to the heterogeneous structure of metal foam, the eigenfrequencies exhibit a large scatter. In order to determine the scatter in the eigenfrequencies, a multiscale stochastic computational approach has been implemented that calibrates a microstructure generator from image based analysis, generates realizations of elastic material properties, identifies random field models for the elastic properties and finally computes the scatter in the eigenfrequencies from finite element (FE) analyses. The procedure is illustrated in Figure 1.

COMPUTATIONAL PROCEDURE

Cubes of metal foam were imaged by CT. The obtained images of the cell wall system were converted to binary (i.e. black-and-white) images by applying a global threshold. To these images, the Euclidean distance transform was applied, which assigns to each cell pixel its distance to the nearest strut. Ideally, this leads to local maxima at the cell center points. In praxis, a cell can contain several local maxima due to discretization effects and irregular cell shapes. These were removed using an adaptable h-maxima transform. Finally, the watershed algorithm was applied to the inverted distance image to separate the single cells. From the reconstructed images, statistical properties of the geometry, such as mean value and standard deviation of the cell diameter, surface area, volume and facets are obtained.

A three-dimensional microstructure generator for metal foams has been developed based on random Laguerre tesselation [1]. The distribution of the radii of the underlying spheres is calibrated such that the statistical properties of the obtained geometry match those obtained by analyzing computer tomography images of open cell metal foam. In the same way, statistical characteristics of the struts can be estimated. It has been checked that the microstructure generator reproduces the statistics of the geometric properties as obtained from the digital images.

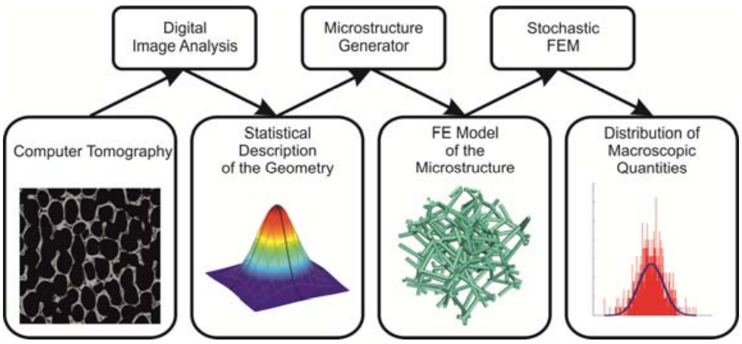

Figure 1: Proposed computational procedure.

Since the basic deformation mechanism of metal foams is bending dominated, the mechanical model is based on the hypothesis that foam consists of a three dimensional network of connected Timoshenko type beams with the material properties of the solid structure. Linear elastic properties are computed from FE analyses of random samples of the network obtained with the microstructure generator. Because of the heterogeneity inherent in the microstructure, the size of the representative volume element is large and not smaller than the macroscopic length scale such that scale coupling occurs. As a consequence, a size effect exists both for the mean value and the standard deviation of the elastic properties. In order to separate the influence of the boundary conditions from the influence of the microstructure heterogeneity, boundary conditions are applied to large volume elements and averaging is carried out only on smaller volume elements lying inside these large elements, cf. [2]. The elastic properties of these volume elements are estimated and evaluated.

From the realizations of the elastic material properties, a random field model for the mechanical properties is identified [3]. To this end, one-point-distributions are computed and the covariance function is determined by moving volume elements through a larger volume. The random fields can be decomposed by means of the Karhunen-Loève expansion or the Spectral Representation method. It becomes then possible to apply the stochastic FE method in order to investigate the influence of the microstructure geometry on the macroscopic behavior of the structure.

With the proposed procedure, it can be shown how randomness of the microscale influences randomness on the macroscale. The effect of strut geometry and pre-deformation, missing nodes or broken struts can be evaluated. It can be seen that the cross section geometry and missing nodes have a great influence on the linear elastic behavior.

EXAMPLE

The eigenfrequencies of beams made of Cu Duocel® are predicted and compared with experimental values. Therefore, 25 beams of size 25 mm x 25 mm x 250 mm were investigated experimentally in two ways. First, the density was determined via optical measurements and second, experimental modal analysis was performed.

The input parameter for the simulation model were the material data of copper, the geometric characteristics estimated from the CT data of 10 Cu Duocel® cubes of length 25 mm, and the cross section shape of the beam network.

Table 1 compares experimental and simulation results for the first bending eigenfrequencies. While there is good agreement on the coefficient of variation, there is a larger deviation of the mean values. This could be related to experimental conditions or to a simplified microstructure geometry of the model (e.g., ignoring the anisotropy). For this case, the generated microstructure model had a more homogeneous structure than the real foam which exhibited large variations in the strut thickness. The observed deviations between experimental and simulated values could be reduced by a refined model that takes the anisotropy as well as the inhomogeneities of the real foam structure into account.

Table 1 : First eigenfrequencies for beams of Cu Duocel® (25 mm x 25 mm x 250 mm).

	Bending Eigenfrequencies [Hz] (COV)			
	Simulation		Experiments	
1.	327	(1.9%)	314	(2.8%)
2.	834	(3.5%)	762	(3.4%)

References

[1] Lautensack C.: Fitting Three-Dimensional Laguerre Tessellations to Foam Structures. J. Appl Stat 35:985–995, 2008.

[2] Di Paola F.: Modélisation multi-échelles du comportement thermo-élastique de composites à particules sphériques. PhD Thesis, Ecole Centrale de Paris, 2011.

[3] Liebscher A., Proppe C., Redenbach C., Schwarzer D.: Uncertainty Quantification for Metal Foam Structures by Means of Digital Image Based Analysis. *Prob Eng Mech*, doi:10.1016/j.probengmech.2011.08.015, 2011.