Multiscale global identification of porous structures

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Abstract

The paper is devoted to the evolutionary identification of the material constants of porous structures based on measurements conducted on a macro scale. Numerical homogenization with the RVE concept is used to determine the equivalent properties of a macroscopically homogeneous material. Finite element method software is applied to solve a boundary-value problem in both scales. Global optimization methods in form of evolutionary algorithm are employed to solve the identification task. Modal analysis is performed to collect the data necessary for the identification. A numerical example presenting the effectiveness of proposed attitude is attached.

Keywords: identification, porous material, numerical homogenization, evolutionary algorithm,

1. Introduction

Porous materials, defined as solids containing pores, are microscopically inhomogeneous materials. They can be classified by different criteria like: pore size, pore shape, materials and production methods. Various porous materials: metals, ceramics and glasses are used in biotechnology, mechanical engineering, electronics and chemistry [4]. The non-destructive identification of material parameters of porous structures is necessary due to the manufacturing process, which results in material properties' uncertainties.

The micro-scale structure of porous media must be considered to model them with proper accuracy. To obtain macroscopically homogenous material equivalent to the microscopically inhomogeneous one, different homogenization methods may be applied. In the present paper, numerical homogenization method is employed to obtain the equivalent elastic material properties values of porous material. The boundary-value problem is solved in both scales by means of the finite element method (FEM) commercial software. Modal analysis is carried out to obtain necessary measurement data.

The aim of the paper is to perform the identification of the microscale material properties of porous media based on the measurements performed at a macro scale. As the identification is usually considered as an optimization problem, different optimization methods may be applied. In the present paper, the identification is performed by means of the global optimization method.

2. Formulation of the identification problem

Different problems in the mechanics of materials and structures may be described as identification ones. Identification problems belong to the class of inverse problems which are mathematically ill-posed ones (the lack of a unique solution) [2]. The identification is performed by measuring the response of the system to the given excitations. The number as well as the type of measurement data may strongly influence the identification results.

The identification is performed as the minimization of an objective function J_0 with respect to the vector of the design variables $\mathbf{x}$:

$$\min : J_0(\mathbf{x}) = \frac{1}{N}\sum_{i=1}^{N}(h_i - q_i)^2 \tag{1}$$

where: $\mathbf{x} = (x_i)$ – a vector of identified parameters; h_i – measured values of state fields; q_i – values of the same state fields calculated for the numerical model, N – a number of measurement data.

3. Global optimization methods

Gradient optimization methods are fast and precise, but usually lead to local optima. To increase the possibility of reaching the global optimum, the global optimization methods, e.g. evolutionary algorithms, particle swarm optimizers or artificial immune systems, are usually employed. As global optimization algorithms work on a set (population) of possible problem solutions, the searching is multidirectional. Such algorithms are commonly applied if objective function gradient is hard or impossible to obtain, as the only necessary information for them to work is the objective function value [7].

To solve the identification problem, MOGA evolutionary algorithm, embedded in the ANSYS Workbench software package, is used. MOGA is a hybrid variant of NSGA-II algorithm [3] and can be applied for single- and multi-objective optimization problems with both binary end floating-point input parameters. The application of the EAs to the multi-objective and multi-scale optimization of inhomogeneous materials is presented in [1].

4. Numerical homogenization

The direct application of more than one scale for the numerical calculations performed by means of FEM leads to an enormously large system of equations. The problem may be surmounted by means of different homogenization methods like mean-field approach, variational methods or numerical homogenization method [5].

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Table 1: Identification results

	Range	Actual value	Found values					
			Location randomness 5%			Location randomness 10%		
			avg. value	st. dev.	error [%]	avg. value	st. dev.	error [%]
E [GPa]	70÷400	113.8	114.0086	0.4484	0.1833	113.7579	0.4118	0.0370
ν [ ]	0.2÷0.4	0.342	0.3255	0.0295	4.8246	0.3412	0.0276	0.2339

Numerical homogenization method is employed in the present paper as it allows modelling the complex geometry of microstructure. Assuming periodicity of the considered structure, representative volume element (RVE) concept is applied. RVE fully describes the whole structure (global periodicity) or its part (local periodicity)

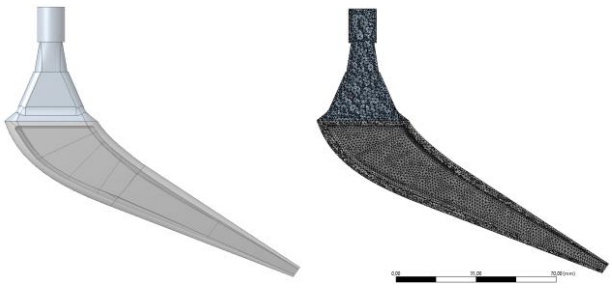
The characteristic dimensions of RVE should be larger than the characteristic dimensions at micro scale and considerably smaller than the macro-scale ones. The additional conditions which must be satisfied for RVE are: i) the Hill-Mandel condition and ii) appropriate boundary conditions (uniform traction conditions, uniform displacement conditions or periodic boundary conditions) [8].

The analysis of the RVE allows the determination of the constitutive relation between averaged field variables, like stresses or strains, of the microscopic model. If the FEM is applied to solve the boundary-value problem, the RVE must be assigned to each integration point at the micro scale. ANSYS Workbench FEM software is applied to solve boundary-value problem in both scales. The application of the FEM software and the optimization tool available in the same software package reduces the time necessary for information exchange between independent systems.

5. Numerical example

Porous metals, like stainless steels and titanium, and porous ceramics (alumina, hydroxyapatite) are commonly used in prostheses. Open pores are required to enhance tissue ingrowth and fixation of the implant.

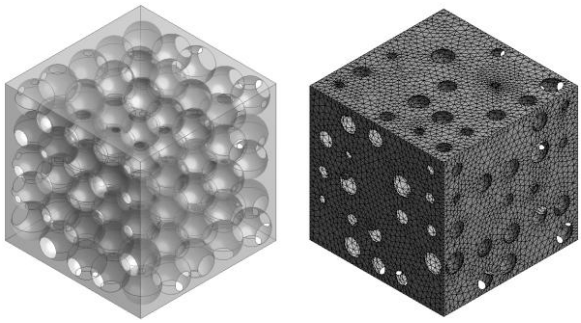
A hip implant made of Ti-6Al-4V alloy is considered [6]. The elastic constants of the alloy are: the Young's modulus E=113.8 GPa, the Poisson's ratio υ=0.342 and the density ρ=4430 kg/m^3. The upper part of the implant is made of the regular alloy while the lower part is made of porous variant of the same alloy (Figure 1). The aim is to identify material elastic constants values for the porous section. The modal numerical experiment has been performed to collect first 10 eigenfrequencies of the structure.



a) b)

Figure 1: a) Geometry and b) FEM mesh (for the intersection)

RVE model contains 125 spherical voids with assumed (5% or 10%) ratio of void location randomness (Figure 2). The parameters of MOGA are: the number of individuals n_i=100, the arithmetical crossover probability p_{ac}=0.98, the uniform mutation probability p_{um}=0.01; the maximum number of generations n_g=40. The identification procedure has been performed 30 times for each RVE variant. The results are collected in Table 1.



a) b)

Figure 2: a) Geometry and b) FEM mesh for the RVE with 10% void location randomness

6. Final conclusions

Multiscale global identification has been conducted. To solve the identification task global optimization methods (EA), FEM commercial software and numerical homogenization algorithm have been combined.

The obtained identification results are satisfactory, although Young's modulus has been identified with higher precision than Poisson's ratio for both RVE variants. It can be also observed that a higher level of location randomness results in lower values of the identification error.

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