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Two-scale identification of composites' material constants by means of computational intelligence methods

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ABSTRACT

The paper deals with the two-scale approach to the identification of material constants in composite materials. Structures made of unidirectionally fibre-reinforced composites are examined. Composite constituents' elastic constants in a micro scale are identified on the basis of measurements performed in a macro scale. Numerical homogenization methods using a representative volume element are employed. Static (displacements in sensor points) and dynamic (eigenfrequencies) data are considered as measurements. Ideal and disturbed measurements are taken into account. Computational intelligence methods in the form of evolutionary algorithms and artificial immune systems are used to perform the identification procedure. Finite element method is used to solve the boundary-value problem for composites in both scales. Numerical examples presenting the effectiveness of the proposed approach are attached. Statistical data are considered to compare the efficiency of the identification procedure for both algorithms and different measurement data.

1. Introduction

Composites are heterogeneous structural materials of increasing popularity due to their properties, especially the high stiffness-to-weight ratio, comparing with traditional, typically isotropic structural materials, like metals. It is possible to design the properties of composite materials to tailor them to the designer's requirements. Such approach requires optimization methods which allow one to obtain the optimal (or sub-optimal) properties of designed material [28,31].

Composite elements are often produced in short series or individually, resulting in the need for non-destructive testing methods in order to identify the parameters of the obtained material. The common attitude applied in one-scale identification is to determine the material properties of the whole composite. The macro-scale identification problem was successfully solved for composites' parameters identification, e.g. in [4,6]. In a two-scale approach it is possible to identify the properties of the constituents of the composite if the micro-scale structure of the composite is known.

The identification is performed for the data obtained from the measurements of the structure response to given

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excitations, static or dynamic ones. Identification tasks belong to inverse problems, which are mathematically ill-posed [7]. In such tasks the type of measurements as well as the number and location of sensor points are crucial. In many practical tasks the amount of data possible to obtain is limited which can result in an indeterminate system of equations. Otherwise, too many sensor points can be impractical and expensive. To reduce the number of sensors it is possible to employ dynamic data. Measurements in the form of eigenfrequencies or frequency response data allow for a significant reduction of the number of sensors by collecting a set of data in one point [16].

The identification of material properties in a micro-scale level is performed on the basis of the measurements of state field values made on the macro level. The significant advantage of numerical homogenization techniques is that they allow for simultaneous consideration of the structure in more than one scale with acceptable computational effort.

2. Formulation of the identification problem

Structures made of fibre-reinforced composites are considered. It is assumed that fibres are unidirectionally and uniformly located in the matrix – as a result the structure can be treated as orthotropic one [20]. The aim of the study is to identify elastic constants of the composite constituents on the microscopic level having measured the values of the state field on the macroscopic level. It is assumed that the geometrical properties of considered structures in a micro scale are known.

The identification can be treated as a maximization of a functional $J_0(\mathbf{x})$ depending on state field values: measured m_i and calculated from the numerical model $q_i(\mathbf{x})$:

$$\arg\max\left\{J_0(\mathbf{x}) = -\frac{1}{N}\sum_{i=1}^{N}(m_i - q_i(\mathbf{x}))^2; \quad \mathbf{x}\in\mathbf{D}\right\}, \tag{1}$$

where: $\mathbf{x} = (x^j)$ – vector of parameters representing identified material constants, $\mathbf{D}$ – a set of admissible solutions being a subset of design space $\mathbf{X}$, N – number of measurements.

To calculate the objective function value in real optimization problems, the boundary-value problem has to be solved for each potential solution. To solve the two-scale boundary-value problem different approximate numerical methods, like boundary element method (BEM), finite element method (FEM) or finite difference method (FDM) can be used in each scale. In the presented attitude the commercial FEM software is employed [30] in both scales.

Each constituent of the composite state a homogenous material fully described by two parameters: Young modulus E and Poisson ratio ν. All measurements are simulated numerically (numerical experiment on the numerical model of the structure).

Two variants of measurements are considered:

(i) the measurements are precise (measurement error is equal to 0);
(ii) the measurements are disturbed by the measurement error of Gaussian distribution.

In the second variant it is assumed that the expected value is equal to the not disturbed value of the measurement while the standard deviation does not exceed 1/120 of the expected value, which denotes that the error is not greater than 5%.

3. Applied computation intelligence methods

Traditional identification methods, like gradient methods, often meet difficulties connected with the probability of stacking in the local optima or problems with the calculation of the fitness function gradient. In the present paper computational intelligence methods in form of the evolutionary algorithm and the artificial immune system are applied to solve identification tasks. They both belong to bio-inspired global optimization methods and do not require information about fitness function gradient, but only about the value of the objective function. Both algorithms simultaneously process a set of potential solutions in each iteration, which radically increases their exploration abilities comparing to algorithms processing only one solution [11,29]. In both global optimization algorithms the real-value coding of design variables is applied. As a result, the vector of design variables has the form:

$$\mathbf{x} = (E_m, \upsilon_m, E_f, \upsilon_f) \tag{2}$$

where superscripts m and f refer to matrix and fibres, respectively.

Special programming interfaces have been developed in order to combine global optimization methods with commercial FEM software.

3.1. *Distributed evolutionary algorithm*

Evolutionary algorithms (EAs) and genetic algorithms (GAs) are optimization methods inspired by a process of Darwinian natural evolution and selection [2,3]. The first papers about simple genetic algorithm and its applications were published in the 1970s [13,22]. EAs are global optimization methods which process in each iteration (generation) a set of individuals, being potential solutions of the optimization task. In EAs one individual usually contains only one chromosome, consisting of genes representing design variables. Evolutionary operators allow the production of new individuals while selection procedure promotes solutions with the higher value of the objective function [1]. The evolutionary operators have typically different forms of crossovers and mutation. The whole procedure is repeated until the termination condition is satisfied. The optimization by means of EA is searching for the individual best fitted to the environment represented by objective (fitness) function.

In the present paper distributed evolutionary algorithm (DEA) is applied [9]. DEA is based on the concept of co-evolutionary algorithms – the whole population of individuals is divided into two or more subpopulations, typically with the identical number of individuals in each one. Each subpopulation evolves almost independently, interchanging some information with other subpopulations during migration phase (Fig. 1).

The following evolutionary operators are employed in DEA [14]: