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Original Research Article

Optimal arrangement of reinforcement in composites

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ABSTRACT

In the paper the problem of the optimal arrangement of the reinforcement in particulate reinforced composites is considered. The criterion of the optimization is the maximization of the stiffness of composites represented by the effective elastic Young modulus. The coupled boundary and finite element method (BEM/FEM) is used to model and analyze representative volume elements (RVEs) of the material. A matrix is modelled by the BEM and reinforcement by the FEM by means of beam finite elements. The optimization problem is solved by the evolutionary algorithm. In numerical examples, composites with aligned and uniformly distributed reinforcement in the matrix are studied. The assumed material properties and the dimensions of constituents are typical for nanocomposites with single and two-layer platelet-like particles, however, the method can be used for different kinds of particulate composites. As a result of the optimization, an improvement of the stiffness is obtained in comparison with the initial microstructures. The presented approach allows the efficient optimization of both structures on a macro level and the microstructures of materials by analyzing RVEs.

1. Introduction

Problems dealing with the optimal design of composites are important from the practical point of view, however, the literature mainly deals with structural composites and not with particulate reinforced composites. Using numerical methods, one can efficiently optimize a microstructure of existing materials or design new ones by analyzing their representative volume elements (RVEs). Changing parameters characterizing the microstructure, like volume fraction, shape, orientation and the arrangement of reinforcement, one can obtain a material of better properties than the initial microstructure, for instance the material of a higher stiffness.

The review of the literature dealing with composites shows the importance of the problem and the possible future research may concern designing of new materials, especially nanomaterials. The results obtained by many researchers show that continuum models give a useful insight into the behaviour of different nanomaterials, despite of their discrete

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atomistic nature, provided that appropriate models are used. The continuum methods, ranging from closed-form expressions to complex micromechanical models and numerical methods, including the finite element method (FEM) [26] and the boundary element method (BEM) [2,3,12], were successfully applied in the prediction of the effective properties of different composites, including nanocomposites (see for example [6,7,22,24]). The solutions are more or less consistent with the results obtained by different analytical models or experiments.

Many papers focus on the optimization of structural composites, analyzed mainly by the finite element method Beluch [1], for instance, has identified the material constants and optimized stacking sequence in laminates. The evolutionary algorithm has been applied as an optimization tool and the FEM for the analysis of structures. Duvaut et al. [9] have optimized the direction and volume fraction of fibres in fibre reinforced composites using variational formulations and the FEM. They have minimized a certain functional in the domain of each finite element which resulted in decreasing the functional value for the whole composite and, in a consequence, in obtaining the optimal structure. Legrand et al. [20] and Huang and Haftka [18] have optimized the orientation of fibres in composite laminates using evolutionary methods (genetic algorithm) and the FEM. Zhu and Narh [25] have investigated the influence of the arrangement of clay platelets on strains, stresses and the tensile modulus of polymer nanocomposites using the FEM. They have studied, among others, the platelet overlap length, the different number of platelets in a stack, the lateral distance between them and also the properties of incorporated phases. Recently, Gong et al. [13] have experimentally examined and monitored interfacial stress transfer mechanisms in graphene monolayer nanocomposites and have concluded that the problem can be also analyzed by using continuum mechanics and the shear-lag theory. The same authors [14] have made the studies of the same nanocomposites but consisting multilayer graphene. They have remarked that the optimum number of graphene layers can be determined for the best reinforcing and the stress transfer efficiency. They have also noticed that the optimum number of layers in a multilayer graphene depends on a separation of graphene flakes in the nanocomposite.

The BEM has been applied in the optimization of structures in a macro scale by several authors, for instance, for homogeneous bodies by Burczyński [4], Burczyński and Fedeliński [5], for non-homogeneous and reinforced structures by Fedeliński and Górski [10,16] and in the optimization of composite structures (orthotropic bodies) by Konderla [19]. The motivation of the present study comes of the fact that most of the publications are focused on the optimization of structural composites, and not on the microstructures of the materials. The study is mainly influenced by the research papers of Zhu and Narh [25] and Gong et al. [13,14] and deals with the optimal design of composite's microstructures.

The optimization problem is solved by the evolutionary algorithm and microstructures are modelled and analyzed by the coupled BEM/FEM. The approach is a new field of application of the BEM and FEM, which have been usually used separately to analyze composites, and it allows exploiting their advantages. Earlier, the coupled BEM/FEM has been successfully applied for the prediction of the effective properties of polymer/clay nanocomposites with straight platelets [8,11]. The results are concurrent with the FEM solutions and the experimental data. It shows that the continuum assumption is an acceptable simplification for the determination of elastic Young's module, characterizing the stiffness of the considered microstructures.

2. The coupled BEM/FEM

A two-dimensional body made of a homogeneous, isotropic and linear elastic material in a plane stress or plane strain state is considered [8]. The body is a plate situated in the global Cartesian coordinate system defined by x_1 and x_2 axes, as shown in Fig. 1. The external boundary of the body and its domain is denoted by Γ and Ω, respectively. The body is statically loaded along the boundary Γ by boundary tractions t and inside the domain Ω by body forces b, displacements of the body are denoted by u.

The relation between the loading of the body and its displacements can be expressed by the boundary integral equation (the Somigliana identity) in the following form [2,12]:

$$c_{ij}(x')u_j(x') + \int_\Gamma T_{ij}(x',x)u_j(x)d\Gamma(x) = \int_\Gamma U_{ij}(x',x)t_j(x)d\Gamma(x) + \int_\Omega U_{ij}(x',X)b_j(X)d\Omega(X), \quad (1)$$

where x' is a collocation point, which can be an internal or a boundary point, for which the above integral equation is applied, x and X is a point on the external boundary Γ and inside the domain Ω, respectively, a coefficient c_{ij} depends on the location of the point x', U_{ij} and T_{ij} are fundamental solutions of elastostatics. The summation convention is used in the equation (the indices for a 2D problem are $i,j = 1,2$).

It is assumed that there are N deformable inclusions (fibres, platelets, etc.) along the lines inside the plate as shown in Fig. 1. The resultant structure presents a model of a composite material, where the plate and the lines play the role of a matrix and a fibre-like reinforcement, respectively.

In the present formulation, the fibres are modelled by deformable beam finite elements attached to the matrix. Thus, fibre-like as well as flake-like reinforcement of an arbitrary shape, size, orientation and cross-section can be easily modelled. In the computer code, quadratic boundary elements

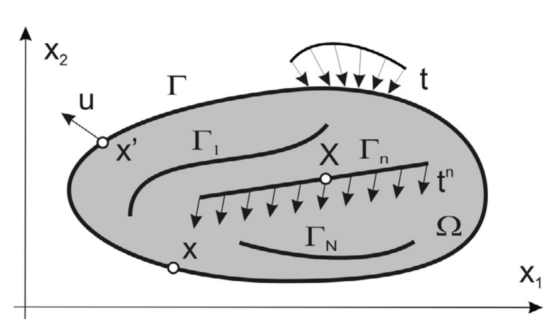

Fig. 1 – A two-dimensional elastic body containing deformable fibres.