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Global sensitivity analysis for the elastic properties of hollow spheres filled syntactic foams using high dimensional model representation method

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ABSTRACT

An accurate prediction of the bulk properties of syntactic foams, even for the elastic properties, is difficult due to the microstructure being composed of constituents with strong distinctions in mechanical properties. Moreover, it is very costly and time-consuming to characterize the influence of various parameters on the bulk properties of syntactic foams by experiments. In this study, a microstructure-based finite element simulation approach was developed to predict the elastic mechanical behaviors of hollow spheres filled syntactic foams. Three-dimensional cubic unit cell model with interface simulated by cohesive elements was constructed to capture the microstructure and stress/strain fields in mesoscale. The effective elastic properties of syntactic foams in terms of Young's modulus and Poisson's ratio were calculated by means of homogenization method. To get an enhanced understanding of property–structure relations, a global sensitivity analysis was performed based on the high dimensional model representation (HDMR) method. Ten parameters, including geometry and mechanical properties of constituent phases, were selected as input parameters. Independent and cooperative effects of the input parameters on the elastic properties of syntactic foams were investigated by first- and second-order sensitivity indices, respectively. An importance ranking of the input parameters for Young's modulus and Poisson's ratio could then be obtained. The procedure proposed in this work provides a powerful tool for design and optimization of syntactic foams.

1. Introduction

Syntactic foams, manufactured by filling a polymeric matrix with hollow spheres called microspheres or microballoons, are generally classified as particle reinforced composites. In general, epoxy resins, polyesters, silicones, polyurethanes, and several other polymers are used as binders, while the fillers have been made of glass, carbon, ceramics, polymers, and even metals [1]. A general microstructure of syntactic foams is illustrated in Fig. 1 [2]. Compared with standard foams (containing blown gas bubbles only), syntactic foams are preferred when high specific mechanical properties are required, rather than just low density [3]. Due to many advantages over other materials, e.g., low density, high specific strength, excellent compressive properties, low conductivity, low thermal expansion, no corrosion effects, fire resistance, low moisture absorption [1,3], syntactic foams have been employed in many engineering applications, ranging from marine equipments for deep sea operations to impact energy absorption components in automotive industry, core materials of sandwiches. And more recently, syntactic foams are also used as manufacturing material of missile canister cover in aerospace industry.

Generally, the levels of the description of material behavior can be divided into nano-, micro-, meso- and macrolevel [4]. Following the pioneering work of Eshelby [5] on the stress field in an isolated ellipsoidal inclusion within an infinite elastic matrix, the mesomechanics has been developing rapidly. Many analytical models were developed to calculate the elastic constants of two-phase composites, e.g., the Mori–Tanaka estimate [6], the Hashin–Shtrikman bounds [7], the self-consistent scheme [8]. Most of the analytical models are simple and explicitly formulated; however, they are limited in scope because of the special assumption for the geometry of reinforcing phase and failure to express the details of the stress and strain fields in mesoscale. Besides, almost all of the analytical models are based on the assumption that the inclusions are perfectly bonded to the matrix material. Actually, it has been well known that an interfacial transition zone (ITZ) may form between inclusions and matrix due to complex chemical and physical actions during the manufacturing process of composites. The interfacial transition zone regarded as an individual interphase whose properties differing from those of constituent phases plays a vital

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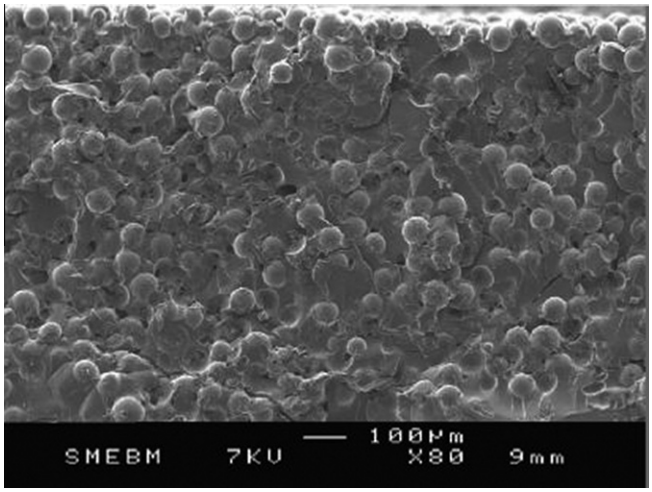

Fig. 1. General microstructure of syntactic foams.

role in the mechanical behaviors of composites. Marur [9] and Bhuiyan et al. [10] demonstrated that analytical models based on perfect interface assumption overestimated the experimentally determined elastic modulus. Rjafiallah and Guessasma [2] and Marur [11] analyzed the interface effect on the elastic properties of syntactic foams.

"Computational mesomechanics of materials" that is a generalizing term suggested by Mishnaevsky and Schmauder [4] aims at achieving a much better resolution of mesoscale stress and strain fields than is possible with analytical models, typically by investigating suitable model geometries by means of numerical engineering techniques, especially the finite element method (FEM) [12–14]. Syntactic foams can be regarded as macroscopically homogeneous and isotropic medium due to the random distribution of microspheres, while in mesoscale, syntactic foams are heterogeneous materials. Multi-scale unit cell analysis based on homogenization method is applicable to such materials to compute the effective mechanical properties given the microstructures and material properties of constituent phases. The unit cell homogenization methods treat the bulk material as a periodic array of particles suspended in the matrix and solve only a representative volume. Recently, several types of unit cell have been developed and used successfully to model particle reinforced composites, including periodic two-dimensional cylindrical and spherical unit cells [15,16], three-dimensional cubic unit cell [15–19], three-dimensional random unit cells [18–20]. To better understand the bulk properties of syntactic foams, and characterize the influence of various parameters (e.g., volume fraction, wall thickness, inclusion diameter), sensitivity analysis is required. However, the literatures are limited to the independent effects of a few mesoscale parameters on the mechanical properties of syntactic foams, usually by material experiments [21–25]. To our best knowledge, a global sensitivity analysis considering the interacting effects of mesoscale parameters for the elastic properties of syntactic foams based on numerical simulation has not been reported.

The aim of the present work is to develop a three-dimensional FE unit cell model considering the interface effect to predict the elastic properties of syntactic foams in terms of Young's modulus and Poisson's ratio. And a global sensitivity analysis based on the high dimensional model representation (HDMR) method is performed to quantify the importance of various mesoscale parameters and characterize the independent and cooperative effects of these parameters on the elastic properties of syntactic foams.

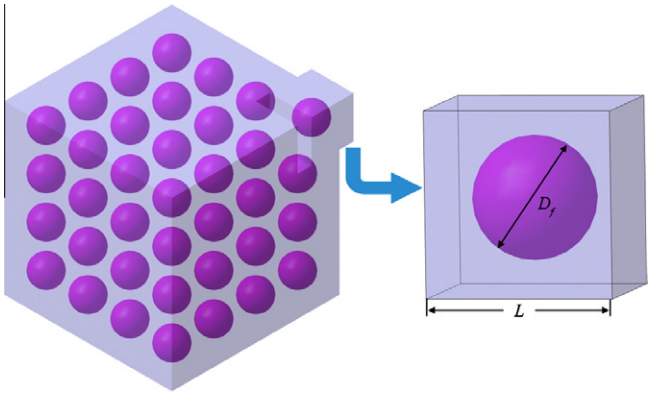

Fig. 2. Schematic of idealized microstructure and 3D cubic unit cell.

2. Finite element simulation

2.1. Unit cell homogenization method

It is generally recognized that the unit cell homogenization method widely used in analysis of particulate composites with solid inclusions is especially applicable to syntactic foams. The unit cell method treats the bulk material as a periodic array of particular type of unit cells and takes only one cell element for analysis. The cell element took for analysis is also called representative volume element (RVE). Fig. 2 illustrates the idealized microstructure of syntactic foams and a 3D unit cell being composed of one hollow sphere centered in cubic matrix.

The essence of unit cell homogenization for heterogeneous, periodic medium is applying an average stress or average deformation to a detailed model (unit cell) on a given length scale at which the material is heterogeneous; and for each loading, computing detailed, equilibrium mesoscale stress and strain fields; finally, taking the spatial average of the mesoscale stress and strain fields to get their macroscopic correspondents. The mesoscale tensors can be split into an average value and a fluctuating term associated with the periodic local fields. Thus, the mesoscale stress and strain fields in the unit cell are governed by the following equations:

$$\sigma(\mathbf{x}) = \Sigma + \sigma^*(\mathbf{x}) \tag{1}$$

$$\varepsilon(\mathbf{x}) = \mathrm{E} + \varepsilon^*(\mathbf{x}) \tag{2}$$

where Σ and E are macroscopic effective stress and strain, respectively, $\sigma^*(\mathbf{x})$ and $\varepsilon^*(\mathbf{x})$ are periodic parts of stress and strain fields in mesoscale. Spatial averages of $\sigma^*(\mathbf{x})$ and $\varepsilon^*(\mathbf{x})$ are both equal to zero. The periodicity of mesoscale stress and strain fields is described as:

$$\sigma(\mathbf{x} + n\lambda_i\mathbf{e}_i) = \sigma(\mathbf{x}) \tag{3}$$

$$\varepsilon(\mathbf{x} + n\lambda_i\mathbf{e}_i) = \varepsilon(\mathbf{x}) \tag{4}$$

λ_i is the length of unit cell in three directions of the coordinate system; $\mathbf{e}_i$ is the unit vector; n is a positive integer. The spatial average of the mesoscale stress and strain fields are defined by:

$$\mathbf{\Sigma} = \langle \boldsymbol{\sigma} \rangle = \frac{1}{V}\int_V \boldsymbol{\sigma} dV \tag{5}$$

$$\mathbf{E} = \langle \boldsymbol{\varepsilon} \rangle = \frac{1}{V}\int_V \boldsymbol{\varepsilon} dV \tag{6}$$

2.2. Finite element modeling

Idealized unit cell studies by Iung and Grange [26] and Ganser et al. [27] indicated that two-dimensional models may lead to