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Review

State of the art of composite structures in non-deterministic framework: A review

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ABSTRACT

The main objective of the present paper is to draw the attention of researchers towards the analyses of composite structures in non-deterministic environment. The various distinguishing features of the stochastic finite element methodologies for the analysis of composite structures have been discussed. A thorough literature review has been carried out while emphasizing on the bending, buckling, vibration analysis and failure analysis of composite structures by considering the uncertain behavior of material properties, mechanical loadings and others. This paper also presents an overview of various micromechanical models in the deterministic and stochastic domains, plate theories and impact of uncertainties on the processing techniques of various composite structures. The future research directions have been discussed which will be prolific to the material, design, civil, mechanical and aerospace engineers.

1. Introduction

The development in engineering materials have been going since several decades. Now we are living in the era of "hybrid materials" and composites is one of them. Composite is a class of the material which is composed by integrating two or more materials macroscopically. Basically, composites are heterogeneous materials, which can be tailored according to their intended application. This is due to the fact that composites have high specific modulus, specific strength, low thermal conductivity, high temperature resistance as compared to other traditional materials.

One unique characteristic of composite is that the constituent materials can be arranged to give the strength in a particular direction such as a reinforced column. In recent years composites are widely used for the aerospace applications where composites made by grading the material properties from one face to other such as a cross section of a bamboo tree [1]. The evolution of engineering materials has been started from the base materials of the periodic table to hybrid materials. Fig. 1 shows the comparison of various ceramic metal composites on the basis of the metal and ceramic phase [2].

From the above discussion it can be presumed that the process of modeling, analysis and manufacturing of composites are of great importance. One well-known fact regarding the composite is that the full control of all aspects of manufacturing processes is practically not possible. This will lead us to the addition of non-deterministic or probabilistic behavior in the modeling of composite structures. The probabilistic behavior is triggered in composite structures due to diverse loading conditions, directional material properties etc. Conventionally, structural analysis of the composite structures is performed by assuming the deterministic behavior of design parameters. However, uncertain behavior of various design and manufacturing parameters bring forth the need to model the system in the non-deterministic way. In the present paper, we have focused to review on the analysis of the composite structures having the non-deterministic framework.

In order to solve the various structural problems, various deterministic methodologies have been recorded in the literature, but these existing procedures tends to find the closed-form analytical solutions for the structures. As closed form applications can be applied for the specific cases, numerical techniques must be used for complex structural problem. The stochastic methodologies are available for the simple structures [3], and to solve the real world problems it is mandatory to combine the numerical methods with the stochastic environment. Among all the numerical procedures that are available, the stochastic computational mechanics [4,5,123] and stochastic finite element method (SFEM) [6] are proved to be useful. These numerical procedures have been developed as a significant tool to perform the reliability and response assessment analysis of system. The modeling of

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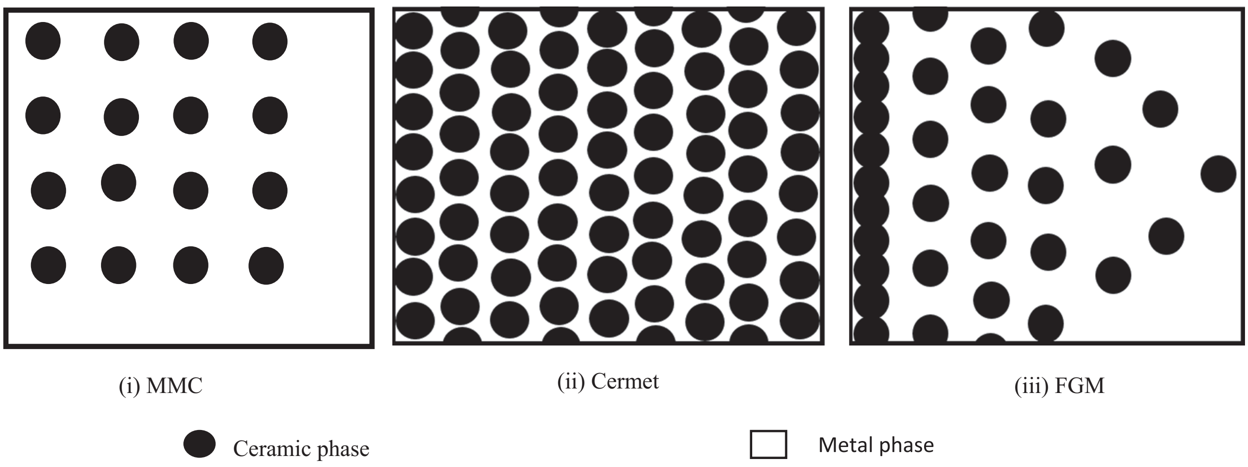
(i) MMC (ii) Cermet (iii) FGM

Fig. 1. Typical characteristics of ceramics and metal composites.

uncertain parameters is usually done by considering the safety factors. It appears that the significance of uncertainty in structural models is an important extension to the present structural analysis techniques. The various second moment approaches such as perturbation techniques [7–9], Spectral SFEM [10] and MCS [11] are used for response of variability assessment of various parameters. An approach known as spatial variability has been addressed as an important modeling tool using the random fields [12]. The fuzzy FEM has been appeared as an alternative to probabilistic formulations, as the uncertain behavior of mechanical models can be easily understood using fuzzy logics [13].

2. Micromechanical models for composites

Composites are microscopically heterogeneous materials which are generally consist of two or more number of phases. Here the term ‘microscopically’ refers to the constituent level (i.e. fibre and matrix level). It is desirable to calculate the effective thermo-mechanical properties of composites materials as properties are dependent on the direction, volume fraction and arrangement of constituent materials to ensure their proper functionality in a particular application. A large number of models have been reported in the past to predict the thermo-mechanical properties of the composites which are as follows:

2.1. Deterministic models

In composites, the materials properties vary in the domain of the structures. Due to which it becomes crucial for us to homogenize the micromechanical material properties in order to observe the effects on macro mechanical behavior of the structures. Some commonly used micromechanical models for the homogenization of material properties across the structures have been explained in this section:

2.2. Voigt approximation

Voigt approximation is widely used in the analysis of the graded composites for the calculation of effective material properties. The basic assumption in this calculation is that the strain throughout the composite remains uniform. Effective material properties *(P*)* for a composites considering two materials can be written as [14],

$$P^* = P_1 V_1 + P_2 V_2 \tag{1}$$

where, V_1, V_2 represents the volume fractions of the constituent material, P_1, P_2 are the elastic properties matrix for constituent materials. *P* can be elastic modulus (E), Poisson's ratio (υ) and coefficient of thermal expansion (α).

2.3. Reuss approximation

In Reuss methodology, it has been assumed that the composites are subjected to uniform average stress. The effective compliance of the material properties (Q^*) can be written as [15],

$$Q^* = Q_1 V_1 + Q_2 V_2 \tag{2}$$

where, Q_1, Q_2 are the compliance matrices for the constituent materials. Though both Voigt and Ruess assumptions are not exactly correct but they give the upper and lower bounds of the effective values.

2.4. Dilute approximation

According to dilute approximation it is assumed that there is no interaction among the particles and they can be considered in a continuous phase. The effective bulk modulus using this method can be written as [14],

$$B^* = B_1 + c(B_2 - B_1)(3B_1 + 4\mu_1)/(3B_2 + 4\mu_1) \tag{3}$$

where $B_i = \lambda_i + 2\frac{\mu_i}{3}$ represents the bulk modulus of the phase and c («1) represents the concentration ratio of the inclusions, λ and μ are the Lame's constant.

2.5. Mori -Tanaka scheme

This scheme was developed in two phases firstly Mori and Tanaka [16] tried to calculate the effective properties through the average internal stresses present in the matrix of the composites. Benveniste [17] made an important contribution in reformulating this theory and explaining the approximation behind it. As it includes the average internal stress calculation, it is also known as equivalent Inclusion-Average Stress (EIAS) method. The effective bulk and shear modulus through EIAS can be written as [18],

$$\begin{gathered}B^* = B_1 + \phi(B_2 - B_1)A_b,\ G^* = G_1 + \phi(G_2 - G_1)A_s\\ \text{Where, } A_b = \frac{B_1}{B_1(1-\phi)(B_2 - B_1)S'_b},\ A_s = \frac{B_1}{G_1(1-\phi)(G_2 - G_1)S'_S},\\ S_b = \frac{1+\upsilon}{2(1-\upsilon)},\ S_s = \frac{8-10\upsilon}{15(1-\upsilon)}\end{gathered} \tag{4}$$

In above expression B_1, G_1 represents the bulk and shear modulus of the matrix. Whereas, B_2, G_2 are the shear and bulk modulus of the inclusions. υ here represents the Poisson's ratio of the matrix.