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Multiscale homogenization for nearly periodic structures

Akinori Yoshimura [a,b,*], Anthony M. Waas [b], Yoshiyasu Hirano [a]

[a] Aeronautical Technology Directorate, Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka, Tokyo 181-0015, Japan
[b] William E. Boeing Department of Aeronautics and Astronautics, University of Washington, Guggenheim Hall, Seattle, WA 98195, USA

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ABSTRACT

In this paper, we propose a new numerical multiscale homogenization method for nearly periodic structures, where perfect periodicity is disturbed due to unintended geometrical imperfections. Geometrical imperfection is introduced as an input to the calculation, and the calculation is always done using the idealized perfect geometry. This has a distinct advantage in numerical calculations where the same mesh can be used for a series of imperfect geometries. The method is implemented using commercially available finite element code ABAQUS. The proposed method is validated by comparing the results to those of a conventional calculation. The results demonstrate that the proposed method can accurately capture the stress distribution when the amplitude of the imperfection is small. Finally, the method is applied to the analysis of the effect of fiber waviness on the mechanical properties of a low cost CFRP. The simulation results reveal that the fiber waviness has little effect on the macroscopic stiffness, but significantly degrades the uniaxial tensile strength.

1. Introduction

Materials with microstructure require multiscale analysis methods in order to capture effects at different length scales. This is significant in a wide variety of engineering materials, including structural foams and carbon fiber reinforced plastic (CFRP) laminates. In many instances, the microstructure geometry contains symmetries and repeat units, which allows simplifying the resulting analysis through the choice of a representative repeat unit cell. This has lead to a vast literature that deals with the mechanics of periodic structures and the resulting homogenization analysis methods were pioneered by a number of researchers, including, Babuška [1], Bensoussan [2], Sanchez-Palencia [3], Bakhvalov and Panasenko [4], etc.

In many structural materials with microstructure, it is not unusual to find internal microscopic imperfections including tow distortion, voids, or resin pockets. Low-cost CFRP manufacturing techniques such as vacuum-assisted resin transfer molding (VaRTM) [5–8] or Out-of-Autoclave (OoA) prepreg [9] have been studied to apply these techniques to large aerospace structures [10–14]. Compared to prepreg-autoclave process, composites produced using low-cost manufacturing techniques tend to contain more imperfections in the microstructure.

These microscopic imperfections significantly affect the macroscopic material properties, such as stiffness and strength. A number of researchers have conducted studies on the compressive strength of polymer composites [15–21]. These studies have revealed that initial fiber misalignment has significant effect on the failure process and compressive strength of composites, which includes kink banding and fiber–matrix splitting instabilities. Moreover, Cox et al. [22] and Mouritz and Cox [23] revealed that fiber misalignment can have significant effect on the tensile failure process and strength of 3D woven CFRP and stitched CFRP. For VaRTM specimens, Hirano et al. [12] compared the macroscopic material properties between VaRTM and conventional prepreg-autoclave CFRP specimens. Compressive strengths of VaRTM specimens were significantly lower than those of the conventional CFRP laminates. For OoA CFRP, Agius and Fox [24] investigated the relationship between void content and fracture toughness, and revealed that mode-II interlaminar fracture toughness was significantly increased by reducing void content. As described above, microscopic geometrical imperfections in the composites significantly affect macroscopic material properties. Therefore, observation and evaluation techniques of microscopic imperfections and their effects on macroscopic material properties are very important for characterizing low cost CFRP as they are used in large aerospace structures.

Past studies have reported results on the observation of microscopic imperfection by utilizing micro-focus X-ray computed tomography (CT). Schell et al. [25] produced 3D images of glass fiber reinforced plastic woven composites from 3D X-ray CT images.

* Corresponding author at: Aeronautical Technology Directorate, Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka, Tokyo 181-0015, Japan.
E-mail address: yoshimura.akinori@jaxa.jp (A. Yoshimura).

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Djukic et al. [26–28] applied contrast enhancement methods to CFRP and measured tow architecture of the woven materials. Iida et al. [29] also applied a similar method to measure the distribution of fiber orientation in short-fiber CFRP. Centea and Hubert [30] acquired X-ray CT images for several out-of-autoclave CFRP samples which were partially processed, and investigated the porosity in the material during out-of-autoclave curing process. Scott et al. [31] employed micro-focus X-ray CT together with synchrotron radiation X-ray CT, and observed microscopic voids and damage processes of Aluminum-CFRP-GFRP structure. Yoshimura et al. [32] applied image processing technique to the micro-focus X-ray CT images and measured microscopic fiber orientation and its deviation in CFRP. In summary, detailed observation of the microscopic imperfection in composite materials are possible because of advances in micro-focus X-ray CT devices in recent years, together with the innovative methods developed by researchers.

It is well recognized that microstructure drives the performance of a material. Thus, once the state of the microstructure is identified, analysis methods need to be developed to understand and predict the effect of the microstructure on performance. An effective method is finite element analysis using a three-dimensional finite element model constructed from 3D micro-focus X-ray CT images. Naouar et al. [33] proposed a method to produce a meso-scale finite element model directly from micro-focus X-ray CT image and conducted nonlinear simulations. Czabaj et al. [34] proposed image processing algorithm for detecting the positions of the fiber in the CT image, and applied it to small CFRP sample. They then constructed microscale (fiber and matrix) finite element model which contains realistic fiber orientation distortion. These methods can introduce realistic microscopic geometrical imperfection into the finite element model. However, in order to produce the finite element mesh directly from 3D X-ray CT image, many nodes and elements are necessary so as to trace the details of the microscopic imperfection. This can lead to large computational costs. Additionally, the mesh generation algorithm might produce distorted elements because of the CT data. In order to avoid such distorted elements, the meshing operation becomes a time-consuming process. When considering the structural simulation of a large aerospace structure, the imperfection pattern is different in each part of the structure. Therefore, it is necessary to conduct multiple calculations which include many imperfection patterns. However, it is very difficult to conduct multiple analyses based on these methods because of difficulty in meshing and the resulting large degrees of freedom (DoF).

In this paper, we propose a method to overcome these issues by developing a calculation method in which a single idealized mesh is used, and each imperfection pattern is introduced to the model as input. The theoretical developments that are needed to facilitate this method are presented, based on the classical homogenization method for periodic structures. A new numerical simulation method is developed for a plate structure, in which unintended initial geometrical imperfections are considered. The method is implemented using the finite element (FE) method and a regular perturbation method. The geometrical imperfection is introduced as input for the calculation, and the calculation is always done using an idealized regular mesh. For large aerospace structural simulations, multiscale analysis is necessary because the characteristic length of the structure is much larger than the microstructure of the material. A number of researches have reported multiscale simulation methods for composite structures [35–40], which are relevant to the present study.

The paper is organized as follows: In Section 2, formulation of new method is introduced. In Section 3 the proposed method is validated by comparing the results of the proposed method to the conventional calculation method. In Section 4, the proposed method is applied to the analysis of the effect of the imperfection on the properties of VaRTM CFRP laminate. Conclusions from the present study are reported in the final section.

2. Formulation

2.1. Problem setting

Fig. 1 shows the schematic of the problem considered in this study. Consider a macroscopic plate Ω that includes an in-plane periodic microscopic inhomogeneity. It is assumed that deformation in Ω can be described by Kirchhoff–Love's plate theory. Let Y denote the representative volume (RUC; Representative unit cell) of the in-plane periodic inhomogenity. Geometrical imperfection is considered only in the RUC.

Orthogonal coordinate system $O - X_1X_2X_3$ is used in order to indicate reference configuration of domain Ω. On the other hand, another orthogonal coordinate system $O' - Y_1Y_2Y_3$ is used for reference configuration of the RUC. Note that basis vectors of these two coordinate systems are respectively parallel. Scales of X_1 and X_2 are much larger than those of Y_1 and Y_2. The scale of thickness direction X_3 is the same as that of Y_3.

In the macroscopic domain, the current configuration x_i and reference configuration X_i are related by,

$$x_i = X_i + u_i^G(\boldsymbol{X}) \tag{1}$$

where u_i^G denotes macroscopic displacement, which depends on macroscopic position.

In the microscopic domain Y, geometrical imperfection $e\hat{u}_i^L(\boldsymbol{Y})$ is considered. Scalar parameter e is used as perturbation parameter in the latter part of the paper. In order to consider geometrical imperfection, we used three configurations: reference configuration, imperfect configuration and current configuration (see Fig. 2). In the finite element analysis, reference configuration corresponds to regular mesh, and imperfect configuration corresponds to a distorted mesh. As described in Section 1, in order to reduce meshing cost, formulation using reference configuration is preferred. Positions in reference configuration, imperfect configuration, and current configuration are expressed by vector $Y_i, \bar{Y}_i$ and y_i, respectively. These vectors are related as,

$$\bar{Y}_i = Y_i + e\hat{u}_i^L(\boldsymbol{Y}) \tag{2}$$

$$y_i = Y_i + u_i^L(\boldsymbol{Y}) \tag{3}$$

where u_i^L denotes microscopic displacement, which depends on microscopic position. Because of the in-plane periodicity of Y, both $\hat{u}_i^L$ and u_i^L has in-plane periodicity.

2.2. Strain and stress tensor

Infinitesimal mechanical strain tensor is calculated as,

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i^G}{\partial X_j} + \frac{\partial u_j^G}{\partial X_i}\right) + \frac{1}{2}\left(\frac{\partial\left(u_i^L - e\hat{u}_i^L\right)}{\partial \bar{Y}_j} + \frac{\partial\left(u_j^L - e\hat{u}_j^L\right)}{\partial \bar{Y}_i}\right) \tag{4}$$

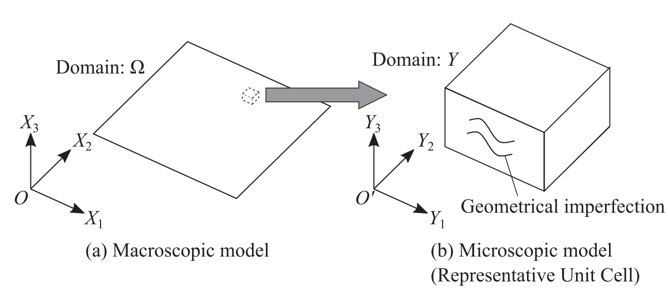

Fig. 1. Schematic showing the problem considered.