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Multiscale modeling of free-surface effect on crack formation in unidirectional off-axis laminates

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ABSTRACT

A multiscale approach based on the mesh superposition method is applied to unidirectional CFRP laminates to evaluate the influence of the deformation field near the free-surface region on crack formation. Our approach employs two different scale analyses: local analysis utilizing a model composed of carbon fibers with micron-scale diameter and matrix resin, and global analysis employing a homogenized model assumed to be an anisotropic elasto-plastic body. Global analysis is conducted to evaluate the macroscopic deformation behavior of laminates. The local model is superimposed on the global model, maintaining the continuity of the displacement field between global and local domains. Local analysis is then performed to predict crack initiation and crack propagation, using the displacement field obtained from the global analysis. Our simulated results indicate that the initial crack occurring on the free-surface region does not affect the final failure strain.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been widely used in the aerospace industry to reduce the structural weight of aircraft, because their mechanical properties (e.g., specific strength and specific stiffness) are superior to those of conventional metal materials. CFRPs are broadly applied as laminate. Laminate is made from prepreg sheets consisting of micron-order diameter carbon fibers and matrix resin, stacked at different fiber angles. The initial cracking strain of the CFRP laminate is used as the design criteria for structures made of CFRPs. However, it is difficult to predict the initial cracking strain because of the complex failure mechanism caused by the characteristic structure of laminate. This difficulty increases the safety factor of structural components, and it hinders reducing structural weight. Therefore, an accurate method of predicting the initial cracking strain is desired to utilize CFRPs more efficiently.

The characteristic structures of CFRP laminate affecting failure of the laminate can be classified into macroscopic and microscopic scales. On the macroscopic scale, laminate configurations influence failure prediction of laminate. The appropriate laminate configuration improves mechanical properties and laminate reliability. However, different-angle stacking causes mechanical property differences between laminae, and this generates inhomogeneous stress and strain fields. The free-edge effect that occurs near the interlaminar region on the laminate edge is one of the critical issues of different-angle-stacked laminate, and was reported experimentally in several laminate configurations. Lecomte-Grosbras et al. [1,2] evaluated strain fields on the free edge of angle-ply laminates using the digital image correlation (DIC) technique [3]. They observed a high shear strain gradient near the interface between laminae, which leads to crack formation or delamination, due to mechanical property differences between laminae. Okabe et al. [4] measured the free-edge effect in cross-ply laminates and reported high thickness-direction strain near the interface between laminae under longitudinal tension. They pointed out that the strain field near the interface causes the biaxial stress state, and transverse cracking, reported by many researchers [5–8], occurs from the interface. On the microscopic scale, a microscopic structure composed of thin carbon fibers and matrix resin causes a microscopic stress/strain field, and local stress concentration causes micron-scale crack formation in composites. Hobbiebrunken et al. [9] observed microscopic crack formation in CFRP laminate subjected to transverse tensile loading. In recent years, microscopic CT observation has been conducted to precisely clarify damage accumulation [10–12]. This small damage can grow to a large crack that results in final failure. Therefore, prediction of crack formation considering macroscopic deformation and microscopic structure is important to accurately evaluate structural safety.

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The multiscale approach, which consists of microscopic analysis considering the heterogeneity of the material and macroscopic analysis assuming a homogeneous body, is applied to CFRP laminates to predict the initial cracking strain. Okabe et al. [4] performed multiscale analysis to predict the cracking strain of cross-ply laminates. Sato et al. [13] applied the multiscale approach to tensile tests of unidirectional CFRP laminates under off-axis loading to evaluate the fiber-direction dependence of the initial cracking strain. In their work, periodic unit cell (PUC) analysis was used as the microscopic analysis to predict crack initiation on the free surface. However, this analysis cannot accurately reproduce the deformation field near the free surface because there is no periodicity in that region. The singular stress field that occurs on the free-surface region is one of the causes of crack initiation [6]. To evaluate the effect of the singular deformation field near the free-surface region on crack formation, another multiscale approach is needed.

The mesh superposition method is used as the multiscale approach to evaluate non-periodic stress fields. This method is based on the s-version finite-element method proposed by Fish [14] and was applied to heterogeneous materials by Takano et al. [15]. This method utilizes two different meshes: a local mesh that considers the heterogeneity of the material and a global mesh modeled as a homogeneous body. The local model is superimposed on the global mesh to reproduce the local heterogeneity of the material, maintaining the continuity of the displacement field between local and global analysis domains. This superposition enables us to consider the interaction between the deformation behavior of the overall structure and the heterogeneity of the materials. Takano et al. [16] evaluated the stress field near the interface crack between a porous thin film and its substrate using the mesh superposition method. Their analysis captures microscopic stress distribution caused by the macroscopic crack and microscopic structure well. This simulated result indicates that the mesh superposition method can evaluate the non-periodic stress distribution near the free-surface region.

In the present study, a multiscale approach based on the mesh superposition method is developed to predict initial cracking strains under appropriate boundary conditions. Our approach utilizes two different scale analyses: local analysis using a mesh consisting of carbon fibers with micron-scale diameter and matrix resin, and global analysis employing a mesh assumed to be a homogeneous and anisotropic elasto-plastic body. Global finite-element analysis is conducted to obtain the macroscopic deformation behavior of the overall structure. The local mesh is superimposed on the global mesh where crack initiation is expected, maintaining the continuity of the displacement field between global and local domains. Local analysis is then performed to predict crack initiation. Two failure criteria, which correspond to brittle failure and ductile failure, are applied to matrix resin to predict matrix cracking under elastic deformation and plastic deformation. Global and local analyses are repeated until the result converges. This study focuses on unidirectional laminate to validate our developed multiscale approach, and shows the effect of non-periodic stress fields near the free surface on crack formation in unidirectional laminate, which will contribute to understanding the complex laminate failure mechanism. Predicted initial cracking strains are compared with experiment data and simulated results that did not consider the free surface to assess the free-surface stress effect.

2. Multiscale modeling

Multiscale analysis based on the mesh superposition method is performed to predict the initial cracking strain of unidirectional CFRP laminates under off-axis tensile loading. To reduce the computational cost of multiscale analysis, our analysis is developed based on the micro–macro decoupling approach [17]. The analysis consists of local analysis that considers heterogeneity of materials and global analysis assuming a homogeneous body. To evaluate the effect of free-surface singularity on the cracking strain, we analyze the same problem as that conducted by Sato et al. [13], and compare our simulated results with their results obtained from multiscale analysis that did not consider the free-surface effect. In this section, we explain global and local analyses, and finite-element formulation for multiscale analysis based on the mesh superposition method. Material parameters shown in this section correspond to the experiment and simulated results reported by Sato et al. [13]; our simulated results are compared with their results in the next section.

2.1. Global analysis

Under off-axis loading, unidirectional CFRP laminate exhibits nonlinear stress–strain behavior because of the plastic deformation of matrix resin [13,18,19]. Heterogeneous deformation fields due to the end-tab constraint and the orthotropy of laminate were also observed in off-axis tensile tests [20]. To reproduce the nonlinear behavior and the heterogeneous deformation fields, global analysis is conducted based on an anisotropic elasto-plastic constitutive law proposed by Yokozeki et al. [18,19]. In this constitutive law, effective stress $\bar{\sigma}_{\mathrm{eff}}$ and the yield function f are defined by stress components associated with material principal axes.

$$\bar{\sigma}_{\mathrm{eff}} = \sqrt{\frac{3}{2}\left[(\sigma_{22}-\sigma_{33})^2 + 2a_{44}\sigma_{23}^2 + 2a_{66}\left(\sigma_{12}^2+\sigma_{13}^2\right)\right] + a_1^2\sigma_{11}^2} \\ + a_1(\sigma_{11}+\sigma_{22}+\sigma_{33}) \tag{1}$$

$$\bar{\sigma}_{\mathrm{eff}} = \sqrt{3f} \tag{2}$$

Here, 1 represents the fiber axis direction, 2 represents the in-plain transverse direction, and 3 represents the out-of-plain transverse direction. f given by Eq. (2) is used as the plastic potential for the flow rule; and a_{44}, a_{66}, and a_1 are parameters determining plastic behavior. We employed $a_{44} = 2.0$, $a_{66} = 1.6$, and $a_1 = 0.01$, referring to the literature [13].

The relationship between effective stress $\bar{\sigma}_{\mathrm{eff}}$ and effective plastic strain $\bar{\varepsilon}^{\mathrm{p}}_{\mathrm{eff}}$ is approximated by the following power law.

$$\begin{cases} \bar{\varepsilon}^{\mathrm{p}}_{\mathrm{eff}} = A_1(\bar{\sigma}_{\mathrm{eff}})^{n_1} & \text{for} \quad \bar{\sigma}_{\mathrm{eff}} < \bar{\sigma}^{\mathrm{threshold}}_{\mathrm{eff}} \\ \bar{\varepsilon}^{\mathrm{p}}_{\mathrm{eff}} = A_2(\bar{\sigma}_{\mathrm{eff}})^{n_2} & \text{for} \quad \bar{\sigma}_{\mathrm{eff}} \geqslant \bar{\sigma}^{\mathrm{threshold}}_{\mathrm{eff}} \end{cases} \tag{3}$$

Here, A_1, n_1, A_2, and n_2 are fitting parameters. To reproduce nonlinear behavior accurately, two sets of parameters are used in the same way as in the literature [21]. In this study, we employ $A_1 = 3.2 \times 10^{-11}$, $n_1 = 3.8$, $A_2 = 4.5 \times 10^{-18}$, $n_2 = 7.0$, and $\bar{\sigma}^{\mathrm{threshold}}_{\mathrm{eff}} = 138$ MPa, referring to the literature [13]. The material properties used in the global analysis are listed in Table 1.

A schematic view of the computational model is presented in Fig. 1. The fiber angles of unidirectional laminates are 15°, 20°, 30°, 45°, 60°, 75°, and 90°. The length of the

Table 1
Material properties of unidirectional laminates used in global analysis.

Longitudinal Young's modulus E_1	130 GPa
Transverse Young's modulus E_2, E_3	8.21 GPa
Shear modulus G_{12}, G_{13}	4.00 GPa
Shear modulus G_{23}	2.77 GPa
Poisson's ratio ν_{12}, ν_{13}	0.26
Poisson's ratio ν_{23}	0.48
Coefficient of thermal expansion α_1	0.4×10^{-6}/K
Coefficient of thermal expansion α_2, α_3	36×10^{-6}/K