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Degradation of thermal postbuckling behaviors of functionally graded material in aero-hygrothermal environments

Chang-Yull Lee [a], Ji-Hwan Kim [b,*]

[a] Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea
[b] Institute of Advanced Aerospace Technology, Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, South Korea

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ABSTRACT

This paper presents aero-elastic analysis for the characteristics of functionally graded material (FGM) panel exposed to hygrothermal environments. The analysis is performed to study the behaviors due to the variation of temperature and moisture on the structure. To consider the supersonic aerodynamic flow, the first-order piston theory is adopted. Equations of motions are derived by the principle of virtual work, and Newton–Raphson iterative method is applied to solve the nonlinear equations. To verify the present work, numerical results are compared with previous data in the literatures. Finally, the influences of temperature, moisture concentration, aspect ratio and volume fraction index of the model are investigated in detail. Especially, the results show that absorbed moisture and high temperature degrade the structural performance.

1. Introduction

Composite materials have been used in civil, aerospace and other engineering fields due to the high modulus, high strength, light weight and excellent thermal resistant characteristics. The various structures are often in severe environmental conditions such as high temperature as well as moisture absorption. Thermal and hygroscopic conditions may induce residual stresses and extensional strains, and then the strength and stiffness of the structure can be reduced. Thus, the absorbed moisture and high temperature degrade the performance of the structures. Generally, simultaneous condition due to the changes of temperature and moisture concentration is referred to as hygrothermal condition, and the effects on the mechanical system have been a hot issue.

The previous research works on the hygrothermal effects were investigated earlier for composite structures. Effects of the conditions for the static and vibration of laminated panels was considered by Whitney and Ashton [1] using the Ritz method. Eslami and Maerz [2] investigated vibration of symmetric cross-ply laminated plates under unsteady temperature and moisture loading. Shen [3] also presented effects on the postbuckling of shear deformable laminated plates subjected to a uniaxial compression. Patel et al. [4] performed the linear free vibration of structures using first and high order theory. Kalamkarov and Georgiades [5] studied the smart composite models on account of actuation, thermal conductivity and hygroscopic absorption. Benkhedda et al. [6] suggested an analytical analysis for the stresses of the plate and the mechanical characteristics of the model due to moisture and temperature. Additionally, Singh and Verma [7] investigated the hygrothermal buckling of laminated composite plates with random geometric and material properties. Also, Lo et al. [8] performed the analysis using the global–local higher order plate theory, and presented a method on the concentration effects of the temperature and moisture.

On the other hand, the concepts of FGM was proposed in 1984 by the material scientists in Japan as a means of thermal barrier materials [9]. It can be overcome drawbacks of the composite materials such as delamination and other damage mechanisms due to mismatch between the layers. Since then, an effort to investigate the FGMs as a heat-resistant materials have been continued. Many engineers have studied the characteristics of FGM and manufacturing skills of various models using various approach. Javaheri and Eslami [10] derived equilibrium and stability equations of a rectangular plate made of FGM based on the classical plate theory. Vel and Batra [11] investigated the exact solution for thermoelastic deformations of a simply supported thick rectangular plate subjected to mechanical and thermal loads. Lee and Kim [12] studied thermal postbuckling and snap-through phenomena of the panels in hypersonic flows. Also, Lee and Kim [13] investigated the stability boundaries and flutter behaviors for P-, S- and E-FGMs. Mantari

* Corresponding author. Address: Gwanak-ro 1, Gwanak-gu, Seoul 151-744, South Korea.
E-mail address: jwhkim@snu.ac.kr (J.-H. Kim).

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and Soares [14] presented an analytical solution to the static analysis of the plates including stretching effect by a trigonometric higher-order theory. Nie et al. [15] performed the analytical solution for the beam with arbitrary graded material properties by the displacement function approach. Furthermore, some researchers tried to obtain the experimental results. Kapuria et al. [16] performed static and free vibration response of the beam model using experimental results. Jin et al. [17] also validated the variation of elastic modulus of the FGMs using modified Mori–Tanaka model experimentally and theoretically. Additionally, Kumar et al. [18] made FG composite models, and then studied for thermo-mechanical behaviors of the models. Especially, in the hygrothermal point of view, Zenkour [19] presented the static analysis of FGM plate resting on elastic foundations according to the sinusoidal plate theory. Additionally, Lee and Kim [20] performed hygrothermal behaviors of FGM model in detail.

Aerospace structure may be operated in moist and thermal environments, and thus hygrothermal and aerodynamic forces are applied simultaneously. In this paper, postbuckling behaviors of the FGM with a type of simple power-law of mixture are investigated under hygrothermal as well as aerodynamic effects. The structural models are based on the first-order shear deformation plate theory, and von Karman strain–displacement relations are adopted. Further, first-order piston theory is applied to consider the effect of supersonic airflow. Newton–Raphson iterative method is used, and then numerical results are compared with the previous data. Further, the hygrothermal effects on the degradation of thermal postbuckling behaviors of FGM structure are discussed.

2. Formulations of FGMs

Fig. 1 shows a rectangular FGM plate model with length a, width b and thickness h, respectively. Typically, the material properties are assumed to be made up of a mixture of ceramic and metal, and the properties are changed continuously as well as smoothly in the thickness direction.

2.1. FGM properties

The upper surface of a FGM plate is ceramic rich, while the bottom portion is metal rich. In this study, a simple power-law distribution is adopted, thus the volume fractions of the ceramic $V_c(z)$ and metal $V_m(z)$ are expressed as in Ref. [10].

$$V_c(z) = (z/h + 0.5)^k \quad (0 \leqslant k < \infty), \quad V_m(z) = 1 - V_c(z) \tag{1}$$

where z and h are coordinate in the thickness direction and the thickness of the plate such as $-h/2 \leqslant z \leqslant h/2$. Additionally, $V_c(z)$, superscript k, the subscripts c and m represent the volume fraction of ceramic, the volume fraction index, ceramic and metal, respectively. Young's Modulus and density are assumed to the rule of mixture as

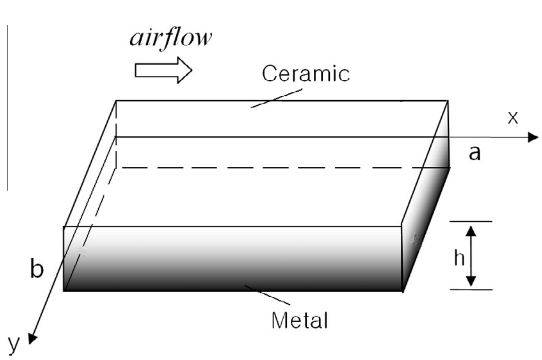

Fig. 1. Geometry of a functionally graded plate.

$$P_{\text{eff}}(z) = P_c(z)V_c(z) + P_m(z)(1 - V_c(z)) \tag{2}$$

where $P_{eff}(z)$, $P_c(z)$ and $P_m(z)$ stands for effective material properties of the FGM, the properties of the ceramic and metal, respectively.

2.2. Constitutive equations

Basically, the first-order shear deformation theory of the plate is employed:

$$u = u_0 + z\phi_x, \quad v = v_0 + z\phi_y, \quad w = w_0 \tag{3}$$

where u, v and w are the displacements in the x, y, and z directions, while ϕ_x and ϕ_y are the rotation of originally perpendicular to the longitudinal plane.

In this study, the von Karman strain–displacement relations are adopted, thus the in-plane strain vectors are derived as

$$\varepsilon_{xx} = u_{,x} + \frac{1}{2}w_{,x}^2, \quad \varepsilon_{yy} = v_{,y} + \frac{1}{2}w_{,y}^2, \quad \gamma_{xy} = u_{,y} + v_{,x} + w_{,x}w_{,y} \tag{4}$$

Substituting Eq. (3) into Eq. (4), the in-plane strain can be written

$$\begin{aligned}
\varepsilon_{xx} &= u_{0,x} + \frac{1}{2}w_{0,x}^2 + z\phi_{x,x} \\
\varepsilon_{yy} &= v_{0,y} + \frac{1}{2}w_{0,y}^2 + z\phi_{y,y} \\
\gamma_{xy} &= u_{0,y} + v_{0,x} + w_{0,x}w_{0,y} + z(\phi_{x,y} + \phi_{y,x})
\end{aligned} \tag{5}$$

And, transverse shear strains are defined as

$$\gamma_{xz} = w_{0,x} + \phi_x, \quad \gamma_{yz} = w_{0,y} + \phi_y \tag{6}$$

Further, the stress–strain relations with the hygrothermal effects as in Ref. [19] are

$$\begin{aligned}
\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \end{Bmatrix} &= \frac{E(z)}{1-v^2}\begin{bmatrix} 1 & v \\ v & 1 \end{bmatrix}\begin{Bmatrix} \varepsilon_{xx} - \alpha\Delta T - \beta\Delta C \\ \varepsilon_{yy} - \alpha\Delta T - \beta\Delta C \end{Bmatrix} \\
\{\sigma_{yz}, \sigma_{xz}, \sigma_{xy}\} &= \frac{E}{2(1+v)}\{\varepsilon_{yz}, \varepsilon_{xz}, \varepsilon_{xy}\}
\end{aligned} \tag{7}$$

where $\Delta T = T - T_0$ and $\Delta C = C - C_0$ in here T_0 and C_0 are reference temperature and the reference moisture concentration, respectively. Also, α and β are thermal and moisture expansion coefficients, respectively.

Then, the constitutive equations for the plates in hygrothermal environment are

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix}\begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \end{Bmatrix} - \begin{Bmatrix} \mathbf{N}_{\Delta\mathbf{T}} \\ \mathbf{M}_{\Delta\mathbf{T}} \end{Bmatrix} - \begin{Bmatrix} \mathbf{N}_{\Delta C} \\ \mathbf{M}_{\Delta C} \end{Bmatrix}, \quad \mathbf{Q} = \mathbf{A_s}\boldsymbol{\gamma} \tag{8}$$

where **A**, **B**, **D**, **Q**, $\mathbf{A}_s$ and $\boldsymbol{\gamma}$ are matrixes representing the extensional, bending-extensional, bending, the resultant shear force matrix and shear stiffness matrix, transverse shear strain vector, respectively. Moreover, the matrices are defined as $(\mathbf{A}, \mathbf{B}, \mathbf{D}) = \int_{-h/2}^{h/2} \mathbf{E}(1, z, z^2)dz$ and $\mathbf{A_s} = \kappa_p \int_{-h/2}^{h/2} \frac{E(z)}{2(1+v)}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}dz$. In here, $E(z)$ is the z-dependent Young's modulus of the model in the thickness direction. Additionally, κ_p is the shear correction factor, and constant value for FGM is not appropriated due to the variation of Poisson ratio through the thickness. Thus, the factor for FGM was proposed as in Ref. [21]: $\kappa_p = 5/(6 - (v_m V_m + v_c V_c))$, and v_m and v_c stand for the Poisson ratios of metal and ceramic, respectively. Furthermore, $(\mathbf{N}_{\Delta\mathbf{T}}, \mathbf{M}_{\Delta\mathbf{T}})$ and $(\mathbf{N}_{\Delta C}, \mathbf{M}_{\Delta C})$ are defined as the temperature and moisture dependent quantities as follows

$$\begin{aligned}
(\mathbf{N}_{\Delta\mathbf{T}}, \ \mathbf{M}_{\Delta\mathbf{T}}) &= \int_{-h/2}^{h/2} (1, z)\mathbf{E}\{\alpha(z), \alpha(z), 0\}^T \Delta T(z)\, dz \\
(\mathbf{N}_{\Delta C}, \ \mathbf{M}_{\Delta C}) &= \int_{-h/2}^{h/2} (1, z)\mathbf{E}\{\beta(z), \beta(z), 0\}^T \Delta C(z)\, dz
\end{aligned} \tag{9}$$