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Non-linear load-deflection response of SMA composite plate resting on winkler-pasternak type elastic foundation under various mechanical and thermal loading

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ABSTRACT

This study investigates the non-linear load-deflection behavior of a composite plate reinforced with Shape Memory Alloy (SMA) fibers. The plate is subjected to the uniform lateral pressure and thermo-mechanical loading while resting on a Winkler-Pasternak type elastic foundation. In SMA fibers, simple one-dimensional Brinson's model is implemented to determine tensile recovery stresses due to the phase transformation. The non-linear semi-analytical solution is formulated for the examination of the large deflections including the preliminary geometrical imperfection. The governing equations of equilibrium are derived in terms of displacement and stress function. The Galerkin technique is chosen to solve the nonlinear partial differential equations of motions. A detailed parametric study including different SMA material properties, SMA fiber pre-strain values, SMA fiber volume fraction, foundation stiffness, and activation temperature are examined.

1. Introduction

In recent years, enormous progresses have been made to use smart materials for reinforcing structural systems. Shape memory alloys are greatly used in the engineering applications such as actuators, sensors, and damping devices. Researchers have focused on two main features of the SMA which are large transformation strain recovery and huge energy absorption capacity. The first one is known as shape memory effect and the second one is recognized as superelasticity characteristics. The shape memory effect (SME) can be used to generate the largely tensile recovery forces; these forces can reduce the deflection of structures under different loading conditions, enhance vibration response, and improve stability in reinforced composite structures. The other feature, the superelasticity effect, can be used in structural applications which require energy absorption. The shape memory alloys, through the SME feature, show temperature dependent properties that can be used to enhance the load-deflection behavior of composite structures. Composite plates are used in the airplane structural components, ships, aero vehicles, and cars. In such structures, the behavior of the plate under various thermo-mechanical loads is a major issue. Composite plates are employed in structural components, which are subjected to in-plane loading such as, wing skin structures, aircraft fuselage sections, and launch vehicle booster tankages. Also, Composite plates can be used in nuclear and petrochemical industries because of their inherent highly specific stiffness and strength. In some structural plate components such as plate elements in the bottom of ships, lateral pressure significantly decreases the strength of the plate. This type of loading occurs due to the aerodynamic forces in aerospace vehicles, hydrostatic water pressure, and uniform blast load. Therefore, SMA reinforced plates can be used to enhance their load bearing capacity or stability.

Composite plates containing embedded SMA fibers with simple configurations and desired features can be manufactured in a laboratory.

Some literature survey about the static and dynamic response of SMA composite plates and shells is as follows:

Thompson & Loughlan [1,2] conducted an experimental study on the post-buckling response of SMA composite plate. They inserted SMA wires through rubber sleeve tubes located in the plate's midplane. In addition, they performed a numerical investigation on linear thermal buckling based on FEM using NASTRAN finite element package. The authors reported that in load levels nearly three times of critical buckling load, deflections were reduced considerably. The reduction happened even by incorporating a relatively low-volume fraction of SMA wires. Also, Thompson & Loughlan [3] carried out the control of post-buckling behavior in thin composite plates using the smart material. Hassanli and Samali [4] investigated the buckling of curved laminated composite panels reinforced with SMA fibers. The panels were studied under different geometric conditions. Ho et al. [5] performed

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Nomenclature

x, y, z	Cartesian coordinates
a, b, c	Length, width, and total thickness of the plate
ξ, ξ_s, ξ_T	Total, stress-induced, and temperature induced martensite fraction
ξ_0, ξ_{s0}, ξ_{T0}	Initial total, Initial stress-induced, and Initial temperature induced martensite fraction
$E_s(\xi)$, E_A, E_M	SMA's Young modulus, SMA's Young modulus in austenite phase, and SMA's Young modulus in martensite phase
$G_s(\xi)$	Shear modulus of SMA
A_s, A_f	Austenite start temperature, austenite finish temperature
M_s, M_f	Martensite start temperature, martensite finish temperature
C_A, C_M	Brinson's model constant parameters
σ_{cr}^s, σ_{cr}^f	Critical phase transformation stresses
σ	Stress in SMA
ε,ε_L, ε_0	Strain, maximum recoverable strain, and initial residual strain of SMA
Θ	Thermo-elastic tensor in SMA
T, ΔT, ΔT^*	Temperature, temperature change (activation temprature), reference buckling temperature
α_s, V_s	SMA thermal expansion coefficient, SMA volume fraction
E_1, E_{1m}	Young modulus and matrix Young modulus in direction 1
E_2, E_{2m}	Young modulus and matrix Young modulus in direction 2
G_{12}, G_{12m}	Shear modulus and shear modulus of matrix
α_1, α_{1m}	Thermal expansion coefficient and matrix thermal expansion coefficient in direction 1
α_2, α_{2m}	Thermal expansion coefficient and matrix thermal expansion coefficient in direction 2
υ_{12}, υ_{12m}, υ_s	Poisson's ratio, matrix Poisson's ratio, and SMA Poisson's ratio
u_0, v_0, w_0	Displacement components of mid-surface
ε_x, ε_y, γ_{xy}	Strain components
ε_x^0, ε_y^0, γ_{xy}^0	Strain components of mid-surface
κ_x^0, κ_y^0, κ_{xy}^0	Curvatures
φ_x, φ_y	Rotation terms about the y-axis and x-axis
γ_{xz}, γ_{yz}	Transverse shear strains
σ_x, σ_y, τ_{xy}	Stress components in the laminate
$\overline{Q}_{ij}$ (i, j = 1, 2, 6)	Reduced stiffness matrix
α_x, α_y	Thermal expansion coefficient in direction x and y
α_0	Reference thermal expansion coefficient
σ_x^r, σ_x^r, σ^r	SMA recovery stress in x and y direction, SMA recovery stress in its fiber direction
N_x, N_y, N_{xy}	In-plane force resultants of the plate
M_x, M_y, M_{xy}	Moment resultants of the plate
N_x^r, N_y^r	Recovery force of the SMA fibers
N_x^T, N_y^T	Thermal force resultants of the plate
N_{x0}, N_{y0}	Uniform edge compressive loads
Q_x, Q_y	Shear force resultants
A_{ij}, D_{ij}(i, j = 1, 2, 4, 5, 6)	Total extensional (in-plane) and bending plate stiffness
a_{ij}	Inverse of total extensional stiffness
t_p, N	Thickness of ply, total number of plies
K	Shear correction factor
w_0^*	Initial geometric imperfection
μ	Imperfection amplitude
Φ_x, Φ_y	Functions of displacements in rotation function
m, n	Number of half-waves in x and y directions
q_{ef}, K_1, K_2	Foundation reaction, Winkler and Pasternak elastic foundation modulus
k_1, k_2	Dimensionless forms of Winkler and Pasternak elastic foundation modulus
Q	Uniform lateral pressure
F	Airy stress function
Δx, Δy	Average end-shortening displacement
E	Young modulus of isotropic material
λ_T, λ_x	Dimensionless forms of Thermal and in-plane compressive load
R	Biaxial ratio, N_y/N_x

an experimental study to investigate the thermal post-buckling of isotropic and composite panels embedded with shape memory alloy. The experiment revealed that when the temperature increased above the critical buckling level, the passive plates with embedded SMA strips showed less deformation than that of plates without SMA. Promising results were obtained by reduction in buckling deflection of Aluminum/SMA sandwich panels. Asadi et al. [6] studied the nonlinear thermal stability of imperfect laminated composite plates based on higher order shear deformation theory. They presented a closed-form formulation to determine the load-deflection path for a rectangular plate with simply supported edges. They also reported that SMA fibers could stabilize imperfect composite plates when they were embedded with relatively high SMA volume fraction. When the critical buckling temperature was lower than the austenite start temperature, SMA recovery forces stabilized the plate. Shiau et al. [7] studied the post-buckling reinforced laminated plates with SMA by utilizing nonlinear finite element method. They used experimental data for SMA recovery stress. The results revealed that an increase in SMA fiber volume fraction and prestrain led to generate higher tensile recovery force. The recovery force increased the plate stiffness in the post-buckling region. The concentration of SMA fibers in the center of the plate was more effective than the other locations. The response of an SMA composite plate under the effect of thermal and aerodynamic loads was examined by Ibrahim et al. [8]. Rasid et al. [9] and Park et al. [10] used finite element method to study thermal post-buckling of SMA composite plates. A different finite element method was used by Tawfik et al. [11] to examine the stability behavior of SMA composite panels. In addition, Von-Karman nonlinear strains were considered in the formulations. A 3-D layer-wise displacement theory was applied by Kumar and Singh [12] to analyze the thermal post-buckling composite plate reinforced with SMA fibers. Turner [13] examined a finite element analysis on the thermoelastic response of SMA hybrid structures. Duan et al. [14] implemented the finite element method for predicting critical buckling temperature and post-buckling deflection of composite plates reinforced with the shape memory alloys. An incremental method consisting of small temperature increment was presented in the study. Another FEM method was employed to determine critical buckling temperature, post-buckling behavior, and vibration about the buckled equilibrium position of SMA composite plate by Guo and Lee [15]. The results demonstrated that it was feasible to suppress the thermal deformation by using a suitable percentage of SMA volume fraction. Peraza Hernandez et al. [16] studied the structurally stable