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Buckling analysis of laminated composite curved panels reinforced with linear and non-linear distribution of Shape Memory Alloys

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ABSTRACT

In the present study, the buckling of laminated composite curved panels embedded with Shape Memory Alloy (SMA) fibers under different geometrical conditions was studied. The buckling load of curved panels subjected to axial, lateral and mixed loads was analyzed. Different distributions of SMA fibers were considered. The optimized reinforcement of curved panel using SMA fibers based on different opening angles was studied. The sensitivity analysis was performed to investigate the effect of the variables of fiber distribution function on critical buckling load of the panel. The results indicate that by increasing the radius, the buckling load for both axial and lateral loadings decreases, while the share of SMA fibers on buckling load increases. The result shows the possibility of buckling load enhancement by optimized distribution of SMA fibers in both flat and curved panels. In addition, sensitivity analysis shows that critical buckling is very sensitive to the coefficient of higher non-uniform distributions.

1. Introduction

The interest in lightweight and durable structures in infrastructure industry has been growing substantially in the past decades. The industry has moved its research focus to lightweight composite panels and shells and the integration into commercial structures. To further this approach, researchers have recently been investigating the potential of using smart materials incorporated in hybrid composite structures for reinforcement, active and passive control. The characteristics of these materials can be exploited to bring functionality to the structure while reducing the complexity and weight. Shape Memory Alloys belong to a class of smart materials, which have many interesting features to enhance civil engineering structures. A basic description of their highly nonlinear material behavior in terms of shape memory effect, pseudoelasticity, martensite damping and variable stiffness has been studied extensively [1,2]. Shape memory effect is described as the ability to recover the original shape (memorizing) at certain characteristic temperatures, even under high applied loads and large inelastic deformations. Pseudoelasticity refers to isothermal large strain recovery due to the phase change in SMAs [3]. The other characteristics of SMAs are extracted from these two main behaviors. The interest in using SMA Hybrid Composites (SMAHC) in civil and architectural engineering has been growing due to shape control capability of SMAs as well as buckling and vibration control. While architectural concepts are moving toward designing curved and geometrically non-linear structures, the conventional methods of reinforcement with common materials cannot keep pace with this approach. For example, while in common post-tensioning techniques using steel cables the stresses are distributed non-uniformly, SMAs provide the opportunity for uniform development of the recovery stresses along the entire length of the tensioning element [1]. Due to high recovery stress generation under pre-strain and temperature in SMAs, they are a suitable choice to enhance the stability of composite panels in civil structures.

The lateral buckling of NiTi reinforced composite beams was studied by Baz and Chen [4]. The results indicated that by implementing the SMA, critical buckling increases by up to 400% for active controlled beam. Zhang and coworkers [5,6] studied the thermal buckling and post-buckling behavior of composite plates with embedded SMA using finite element method. The other approach is suggested by Ro and Baz [7–9]. In this approach, the active control of the buckling characteristics of flexible NiTi reinforced composite plates using finite element method was investigated. It is found that reinforcing composite plates with NiTi fibers can dramatically enhance their critical buckling loads even when these plates are clamped around all their edges. An extensive experimental and numerical study on controlling the post buckling response of thin composite plates using shape memory alloy was performed by Thompson and Loughlan [10,11]. Lee and Lee [12] performed the analysis of buckling and post-buckling NiTi reinforced composite plates using ABAQUS. The results show that

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for simply supported boundary condition the critical buckling increases. However, if SMA fibers are aligned in inappropriate direction, the critical buckling load reduces. The analytical solution for post-buckling behavior of laminated composite beam reinforced with SMA fibers was found by Asadi et al. [13]. After validation, a comprehensive study was performed to investigate the effect of different geometrical parameters, material properties, boundary and loading conditions. Kuo and coworkers [14,15] presented finite element method for vibration and buckling analysis of SMA embedded composite laminates. Results show that active strain tuning is much better than active property tuning. In addition, when SMA fibers are concentrated, the buckling load will be improved considerably. However, this is not the case for curved panels. The mode of buckling for curved panels is not always the first mode. Therefore, the higher concentration of SMA fibers in the middle of the panel may not always result in enhancing the buckling load. For a panel with a certain radius of curvature, a particular distribution of SMA fiber is appropriate for a better reinforcement. While in previous research studies, the distribution of SMA fibers is not considered for curved panels, in this paper an appropriate distribution function with variable coefficients is introduced to account for different radius of curvature and consequently for different mode of buckling. In addition, the need for the optimization of SMA fiber distribution also arises from economics point of view due to the high cost of SMAs. While the price of SMA has been reduced substantially as a result of its use in a wide range of applications and implementations, it is still considered as an expensive material, especially for infrastructure engineering applications. In the present study, different techniques such as pre-straining the SMA fibers and different SMA volume fractions as well as different fiber distributions are applied to obtain a better buckling performance under axial, lateral and mixed loadings while keeping the SMA usage to minimum.

The goal of this paper is to study the critical buckling of hybrid composite panels reinforced by SMAs and analyze the effect of parameters including opening angle of panel, temperature, prestrain and distribution of SMA fibers on critical buckling load. To achieve this, the first order shear deformation theory with linear deformation is assumed. The Finite Element Method (FEM) is chosen and the codes are generated in MATLAB. Writing FEM in MATLAB brings flexibility and robustness as simultaneous varying of parameters (e.g. temperature points, pre-strain levels, opening angles, coefficients of distribution functions) can be included into the loops. By this method, a classified metadata of buckling loads based on a wide range of parameters can be determined by onestep analysis, unlike common solver packages, which need a separate analysis for each geometry or material property. This is an important advantage, especially when conducting geometric parametric study and optimization study in which many changing geometrical and material parameters are involved. The other advantage is in having more control over applying changes in governing equations or defining unusual material properties such as Shape Memory Alloys' behavior. Overall, the program code generated in MATLAB saves a lot of time and computational cost while it provides a comprehensive database for influential parameters related to buckling load. The code has been developed to accommodate variations in geometric parameters and material properties including different lay-ups, fiber orientations, material properties, commonly used boundary conditions as well as variation in radius of a double curvature panel. Therefore, the main advantages of the code would lie in geometric parametric study, geometric optimization and integration of thermomechanical constitutive model of SMAs into the code.

2. Shape memory alloy overview

Although the solid phase transformation of SMAs was found by Ölaner in 1932 [16] and NiTi was first discovered by William Buehler in 1959, the potential to commercialize its application did not appear until the shape memory effect (SME) was revealed by William Buehler and Fredrick Wang in 1962 [17,18]. Due to lack of clear understanding of the behavior, inconsistency in the properties and high cost, SMAs have not been implemented in the medical, commercial and aerospace industries until the past decade when these deficiencies could be overcome and manufacturing cost decreased [19].

SMAs exhibit two distinguishing characteristics based on their solid-solid phase transformation. As a result of this transformation, the observable macroscopic thermo-mechanical behavior of SMAs can be separated into two categories: shape memory effect and pseudoelasticity.

2.1. Shape memory effect

The shape memory effect (SME) is the capability of SMAs to recover their original state after sequential thermo-mechanical loadings (Fig. 1). In this phenomenon, SMA specimen is cooled from its parent phase austenite at a temperature above austenite finish temperature (A_f) to below the forward transformation temperatures (M_s and M_f) in a stress-free situation which results in the formation of twinned martensite $.(A - B)$. The specimen is then subjected to loading above the critical level (σ_s) followed by unloading which forms detwinned martensite and results in a large inelastic residual strain $(B - C - E)$. Finally, by increasing the temperature of the specimen, it completely recovers the residual deformation and springs back to its original state (parent phase) $(E - A)$. This process is a one way shape memory effect (OWSME) which needs an external force and a heating process. In addition to OWSME, a two way shape memory effect (TWSME) can be achieved by a training process. In TWSME, the material recovers half of strain recovery in OWSME at two different temperatures. One way and two way shape memory effect of SMAs can be exploited mainly for sensing and actuating devices.

2.2. Pseudoelasticity

The pseudoelasticity is the capability of SMA to undergo a large inelastic deformation due to loading and full recovery upon unloading (Fig. 2). When an SMA specimen is subjected to a load in

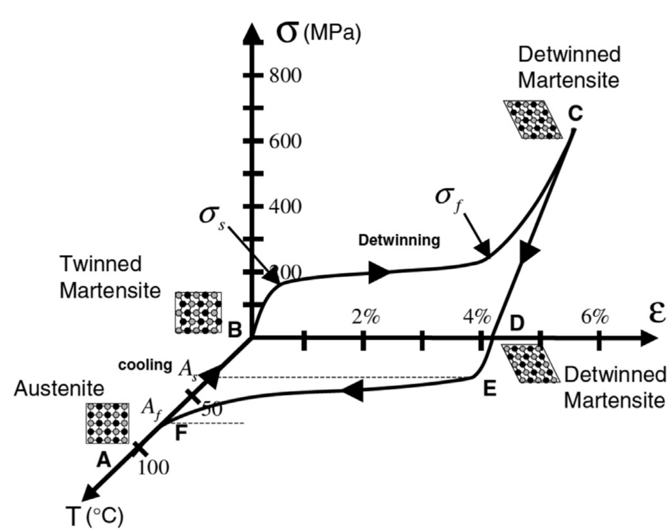

Fig. 1. Shape Memory Effect for a typical SMA, Ref. [21].