ELSEVIER

Composite Structures 60 (2003) 145–157

COMPOSITE STRUCTURES

www.elsevier.com/locate/compstruct

A sensitivity analysis of the dynamic performance of a composite plate with shape memory alloy wires

Arkadiusz J. Żak [a,*], Matthew P. Cartmell [a,1], W.M. Ostachowicz [b,2]

[a] *Department of Mechanical Engineering, University of Glasgow, James Watt Building, G12 8QQ, Glasgow, UK*

[b] *Institute of Fluid-Flow Machinery PASci, Gdańsk, 14 ul. Fiszera 80-952, Poland*

Abstract

In this paper the dynamic performance of a multi-layered composite plate with embedded shape memory alloy (SMA) wires has been investigated in terms of the changes in its relative fundamental natural frequency. A sensitivity analysis has been carried out on the influence of various geometrical parameters and material properties on the plate's dynamic performance, as well as the influence of the form of boundary condition. The use of the active property tuning (APT) method and the active strain energy tuning (ASET) method has also been discussed within the paper. The finite element method has been used for the analysis, and a new element has been exploited for modelling multi-layered composite plates. It has been found that the dynamic performance of the multi-layered composite plate with embedded SMA wires strongly depends on the plate geometry and the form of boundary condition, however, the dynamics can be successfully controlled and influenced by an optimal selection of the geometrical parameters and material properties.

Keywords: Sensitivity analysis; Composite multi-layered plate; SMA wires; Fundamental natural frequency; Finite element method

1. Introduction

Over the past few decades various types of composite material have been extensively used in many fields of civil and mechanical engineering. This can be particularly clearly seen in the case of the civil and military aircraft industries, where numerous structural elements made of composite materials are now in common use [1–3]. Because of their extensive use the guarantee of high durability and long-term performance of structural elements made of composite materials is a very important issue. One of many methods used to achieve this objective could be the integration of composite materials with another class of high performance material, such as one of the various alloys exhibiting the shape memory effect [4]. It has been found that under certain conditions selected material properties of such alloys can be precisely controlled; for example their Young's modulus [4,5] and damping coefficient [4,6,7]. Moreover, the shape memory alloys (SMAs) also possess two unique abilities for recovering large non-linear strains [4], and for generation of large internal forces [8] during their activation. These arise from the superelastic and shape memory effects, respectively. Due to their exceptional properties components made of SMAs in the form of wires, strips, or tubes, integrated within, or bonded to, the composite material element offer great capabilities for active control of the static and dynamic behaviour of the overall integrated structures [8,9]. The principal static and dynamic characteristics of structural components made from composite materials can be manipulated and enhanced by the introduction of embedded SMA wires or strips. The results presented in the literature report changes in deflection and shape [10–17], natural frequencies [17–21], forced vibration amplitude [22,23], buckling load [20,24–26], and damping behaviour [27,28] in such installations.

However, despite the fact that the use of SMA components has been extensively exploited in the literature, as shown above, very little information can be found regarding sensitivity studies in which the different influences on the performance of the composite structural

* Corresponding author. Tel.: +44-141-330-4351; fax: +44-141-330-4343.

E-mail addresses: azak@mech.gla.ac.uk (A.J. Żak), matthewc@mech.gla.ac.uk (M.P. Cartmell), wieslaw@imp.gda.pl (W.M. Ostachowicz).

[1] Tel.: +44-141-330-4337; fax: +44-141-330-4343.

[2] Tel.: +48-58-341-1285; fax: +48-58-346-0881.

0263-8223/03/$ - see front matter
doi:10.1016/S0263-8223(02)00316-1

elements with the embedded SMA components are considered. In many studies SMA-embedded composite components are characterised by very low thickness-to-length ratios [10,13,15,18,21,24,27]. Although such structures can have very good performance characteristics their engineering applications are very limited due to their low stiffness and low critical loads. Many researchers have considered structural composite elements with embedded SMA components for which the ratio of the composite material Young's modulus to the Young's modulus of the SMA components is very low. As a consequence generally high performance of these structural elements has been widely reported [10,14,15,18,21]. Furthermore, in certain cases the performance of such structures is enhanced by the high assumed relative volume fraction of the SMA components [10,15], or by the very high level of recovery stresses arising from activation of the SMA components [24].

As can be seen from the above literature review the performance of various composite structural elements with embedded SMA components is determined by a number of different factors. One such factor is the ratio of the SMA Young's modulus to that of the composite material reinforcing fibres (glass, kevlar, graphite, boron, etc.), as well as the relative volume fraction of the SMA components. In addition the relative volume fraction of the reinforcing fibres, the structural geometry, the location and the orientation of the SMA components within the host structures, temperature, moisture, etc. are also of great importance. It should be emphasised here that the high relative volume fraction of the SMA components is in many cases not desirable. Since the SMA components are temperature activated to undergo their phase transformation considerable amounts of heat can be released at that time. Although this could easily result in the softening of the composite material, the effect can be avoided by appropriate selection of the SMA transformation temperatures, which can be adjusted accurately over a wide range (refer to Shape Memory Application, Inc. at http://www.sma-inc.com).

In this paper certain results have been presented for a sensitivity analysis of the dynamic performance of a multi-layered composite plate with embedded SMA wires. The performance criterion is based on calculating relative changes in the fundamental natural frequency of the plate. For this analysis the finite element method has been chosen and a new finite element for modelling multi-layered composite plates has been applied. The use of the active property tuning (APT) method and the active strain energy tuning method (ASET) [9,15,17,21] have also been investigated in this work. The influences of the plate geometry on the relative fundamental frequency, as well as various material properties and the form of boundary condition, have been all investigated.

It should be emphasised here that the results presented for the APT method have been obtained under the assumption that activation of the SMA wires leads only to changes in the plate's stiffness matrix, due to changes in the Young's modulus of the SMA wires. In the case of the ASET method the in-plane loads produced by recovery stresses resulting from the activation of the SMA wires have also been included within the plate's geometrical stiffness matrix [19,20]. Selected properties of the SMA wires, as well as appropriate values of recovery stress levels have been taken from Dynalloy, Inc. and are summarised in Table 1—for more details see http://www.dynaloy.com.

Table 1
Selected properties of the Flexinol™ actuator wires

Property	Value
Wire diameter	0.025–0.4 mm
Recovery stress	135.5–180 MPa
Wire resistance[a]	1780–7.87 Ω/m
Contraction	4%
Activation current[b]	20–2750 mA
Contraction time[b]	1 s
Off time	0.06–10 s

[a] For martensitic phase.
[b] At room temperature.

It should also be noted that in this study, thermal and hygrothermal effects have not been taken into account due to limited data available in the literature as required for such a complex analysis. However, it should also be emphasised that these effects could have a great influence on dynamic performance in specific conditions, and cannot therefore be arbitrarily neglected.

2. FEM modelling

A finite element for modelling multi-layered composite plates has been proposed and applied throughout this paper. The element is based on a classical plate finite element, however two additional degrees of freedom have been added in order to include shear deformation. The element proposed possesses 8 nodes and 7 degrees of freedom per node, as shown in Fig. 1. These degrees of freedom are defined as the longitudinal in-plane displacements u and v, the transverse displacement w, the rotations φ_x and φ_y due to the transverse displacement w, and the independent correction rotations θ_x and θ_y for the rotations φ_x and φ_y, and due to shearing effects. The length of the element is L, the width is B, and H is its thickness. The element consists of N layers made of a unidirectional composite material. Reinforcing fibres, or SMA wires, are arbitrarily orientated within the layers, and their orientation angles α or β are measured within the x–y plane of the element.

According to first-order shear deformation theory the displacement field within a single layer of the element can be expressed as follows: