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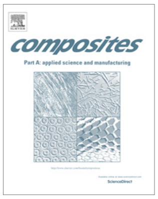

Stiffness control in adaptive thin-walled laminate composite beams

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ABSTRACT

The aim of this paper is to verify the control of the stiffness that is feasible to achieve in a thin-walled box-beam made from a laminate by including an adaptive material with variable stiffness. In this work, a material having a strongly varying Young Modulus under minor temperature changes was included in the cross-section. An analytical model was used to estimate the position of shear centre and the axial, bending, torsional, and shear stiffnesses of the cross-section. Two cross-sections were analysed, one with an adaptive wall and another with two adaptive walls. In both sections, the torsional stiffness could be strongly altered with minor temperature variations. In the section with one adaptive wall, the shear centre and thus the bending–twist coupling was also strongly modified. A study was made of the influence on the control of stiffnesses exerted by the overall cross-section thickness and the thickness of the adaptive walls.

1. Introduction

The interest in developing new smart structures capable to self-adapting to external stimuli that modify their shape or change their mechanical properties has increased considerably in recent decades. In this context, understanding and controlling the response of structures to the changes occurring in their environment is key to improving their performances.

The configuration of the structures can be controlled using different technologies, such as conventional mechanisms or compliant mechanisms [1,2]. In some cases, mounted or embedded sensors need to be incorporated into the structures to provide them the ability to detect changes and take corrective actions [3].

One possible alternative is to control the configuration of a structure using materials having shape memory. These materials are able to remember their original shape and size and can recover it after being deformed after the application of an external condition, such as a temperature change [2].

Another alternative is the use of piezoelectric actuators, generally for shape control and vibration control of structures [3–6]. When mechanical loads are applied on a piezoelectric material, an electric field or a voltage is generated which is used to active shape and vibration control. On the other hand, the reverse effect also occurs: when an electric field or a voltage is applied to the piezoelectric material, it undergoes changes in stress and strains.

To meet the requirements of structures, a control technique that allows for great adaptability of the structure and its stiffness is necessary [2,7]. A variable–stiffness material is one with elastic properties that can be controlled over time by varying some external stimulus. If the variable-stiffness material is part of a structure, the variation in its properties leads to a change in the properties of the overall structure. Such materials can be activated thermally, electrically, magnetically or chemically. These materials have great potential for use in aerospace structures. For example, Raither et al. [8], highlight the potential of shape-adaptable airfoils for the control of the aerodynamic loads on wings by continuous deformations. Also, Gandhi and Kang [9] have studied the variation in the flexural stiffness of a multi-layered beam when varying the temperature of the polymer layers that formed it by applying heat with ultra-thin electric heating blankets.

In many structural applications, i.e. aircraft structures, where weight is an important variable, thin-walled structures are used, such as box-beams for their great stiffness (especially the torsional stiffness). Typical examples are wing spars and helicopter blades.

Not enough information is available in the scientific literature concerning box-beams with walls made of a laminate when one or more walls are made from a variable-stiffness material. Especially scarce is the information on the influence of the thickness of the walls on the control of the beam stiffness of laminate box-beams.

Isotropic beams have been analysed elsewhere [10], where the authors study a beam made of aluminium with a variable-stiffness

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web. In another work [11], the authors examine an airfoil section made of composite material where several interfaces with controllable shear stiffness (PVC) are placed and the concept is based in variable bending–twist coupling.

Raither [12] analysed a shape-adaptable airfoil made of composite material following an adaptive-twist concept. The variable-stiffness control in this study is based on two different systems: temperature control and voltage-regulated control. This research contains a comparison between the elastic behaviour of composite variable-stiffness beams (with elastic couplings) and the one of isotropic cross-sections.

Several theories have been developed to estimate the stiffnesses and movements of thin-walled composite beams by analytical models. However, an exhaustive review of such models is beyond the scope of the present paper. Smith and Chopra [13] have developed an analytical beam formulation to predict the effective elastic stiffness of tailored composite box-beams, being aware of the advantages of this section. Kim and Shin [14] derive the shear stiffness of a thin-walled composite beam in several open-section profiles. Volovoi and Hodges [15] predict the torsional stiffness of beams with closed sections of both a single-cell and multi-cell profile. Pluzsik and Kollár [16] present a theory that takes into account the transverse shear and the restrained warping when calculating the bending and torsional stiffnesses of the section. Massa and Barbero [17] developed a theory for the study of thin-walled beams made from laminates and the calculation of the stiffnesses of sections of any geometry.

In present work the model proposed by Massa and Barbero [17] was used because it allows a variable-stiffness material to be easily incorporated into the calculation of the stiffnesses of the thin-walled composite beam. This analytical model is applicable to sections of different geometries, both open and closed, and thus offers the possibility of analysing different sections with relatively few modifications in the calculation process.

A phenomenon that appears in composite beams is the bending–twist coupling or extension-twist coupling. These couplings are caused partly by the anisotropy of composite materials, depending for example on the fibre orientation or the stacking sequence. Sometimes the coupling is undesirable, but on the other hand, these couplings appear to have great potential for various applications, prompting interest in the study of such problems. For example, the twist angle plays an important role in aerospace applications because it directly influences the angle of attack in aircraft wings and helicopter blades [18]. For this reason, knowledge and quantification of couplings is crucial because, if they can be controlled or caused to an appropriate extent, they can contribute to the structural response of the beam. Some authors have studied the coupling phenomenon; for example, Raither et al. [1] have investigated the concept of adaptive bending–twist coupling stiffness of laminated composite plates based on the variation of shear-stress transfer at layer interfaces.

The aim of the present paper is to determine the stiffness control that is possible to achieve in a thin-walled box-beam made from laminates when, due to a temperature variation, one of the walls undergoes a change in its properties. The variation of such properties, in addition to varying the stiffnesses of the section, also causes a displacement in the position of the shear centre of the cross-section and therefore results in a bend–twist coupling that also has been studied because of the importance mentioned above. The thickness of a thin-walled section is a relevant parameter in calculating cross-section stiffness. For this reason, the global stiffnesses variation of the section (axial, bending, torsional, and shear) has been analysed when the thickness of the entire section and the thickness of the wall made of adaptive material vary.

2. Problem description

Two cross-sections were analysed: a box-section with one adaptive wall, Fig. 1a, and a section with the same overall geometry but with two adaptive walls, Fig. 1b. The first cross-section allows an analysis of the case in which torsional stiffness undergoes large variations associated with the change in properties of the adaptive material (i.e. when the temperature increases, the section behaves almost like an open section). The second cross-section has lower shear stiffness due to the position of the adaptive walls, and thus the influence of temperature in the shear stiffness is high. The two sections have no variable-stiffness flanges, since in some applications (as in aircraft structures) the principal bending stiffnesses should be affected as little as possible [10].

Variations in the adaptive material properties induce changes in the position of shear centre of the cross-section, so that when a vertical load is applied at the shear centre at one temperature, a torque appears when the temperature changes.

For this reason the position of shear centre was also analysed. The reference case study corresponds to a temperature of 20 °C, and variations of ±20 °C with respect to the reference temperature have been considered. Higher temperature variations are difficult to reach in real applications.

The time course of the cross-section stiffnesses with the change in adaptive material properties was studied. The axial stiffness, bending stiffness with respect to the principal axes of section, shear stiffness, and torsional stiffness were analysed. Also the displacement of the shear centre was examined.

The adaptive material used is the elastomer Soundcoat Dyad 609 with a variation of the elastic constants taken from the literature [1]. A glass fibre/LY556 epoxy laminate with a $[0/90]_{2S}$ stacking sequence was selected. The mechanical properties of this composite material were taken from the literature [20].

In the present study, since the range of temperature variation is narrow, the variation of the composite material properties with temperature was not considered.

3. Analytical model

For the calculation of the stiffnesses of the thin-walled beam, the model proposed by Massa and Barbero [17] was used. Because this paper examines the influence of the presence of the adaptive material in the beam response, hygrothermal effects on the composite material are not considered in the model formulation.

Each flat wall of the thin-walled composite beam, which was a laminated plate, was described by one segment. Each had its corresponding associated stiffness matrices and constitutive equations. If these equations are inverted and the undeformability of the contour assumption of the classical theory of thin-walled beams is applied together with the assumption of no coupling between normal and shearing effects [17], a reduced expression results, leading to the reduced constitutive equations of each i-th segment in terms of the segment stiffness:

$$\begin{Bmatrix} N_x \\ M_x \\ N_{xs} \\ M_{xs} \end{Bmatrix}^i = \begin{bmatrix} A_i & B_i & 0 & 0 \\ B_i & D_i & 0 & 0 \\ 0 & 0 & F_i & C_i \\ 0 & 0 & C_i & H_i \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \kappa_x \\ \gamma_{xs} \\ \kappa_{xs} \end{Bmatrix}^i \tag{1}$$

where the s-axis and x-axis define the laminate plane and the superscript i refers to each of the four segments. A description of the model and the variables used can be found in Massa and Barbero [17]. In Eq. (1), A_i is the axial stiffness per unit length of the segment (in N/m), B_i is the coupling between bending curvature and extensional force (in N), D_i is the bending stiffness of the