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Dynamic behaviour of soft core sandwich beam structures using kriging-based layerwise models

M.A.R. Loja [a,b,*], J.I. Barbosa [a,b], C.M. Mota Soares [b]

[a] ISEL, IPL, Av. Conselheiro Emídio Navarro, 1, 1959-007 Lisboa, Portugal
[b] LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-01 Lisboa, Portugal

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ABSTRACT

Sandwich structures with soft cores are widely used in applications where a high bending stiffness is required without compromising the global weight of the structure, as well as in situations where good thermal and damping properties are important parameters to observe. As equivalent single layer approaches are not the more adequate to describe realistically the kinematics and the stresses distributions as well as the dynamic behaviour of this type of sandwiches, where shear deformations and the extensibility of the core can be very significant, layerwise models may provide better solutions. Additionally and in connection with this multilayer approach, the selection of different shear deformation theories according to the nature of the material that constitutes the core and the outer skins can predict more accurately the sandwich behaviour.

In the present work the authors consider the use of different shear deformation theories to formulate different layerwise models, implemented through kriging-based finite elements. The viscoelastic material behaviour, associated to the sandwich core, is modelled using the complex approach and the dynamic problem is solved in the frequency domain. The outer elastic layers considered in this work may also be made from different nanocomposites. The performance of the models developed is illustrated through a set of test cases.

1. Introduction

The increasing use of sandwich structures in many different industries, such as construction, shipbuilding, aerospace, automobile among others, may be attributed not only to a favourable relation between stiffness and global weight but also because of their damping characteristics. Damping is an important parameter for vibration control, fatigue endurance, and impact resistance, being the reason for the selection of high damping materials. Viscoelastic materials with high loss factors are known to enable an improvement of the dynamic answer of the structure and to reduce its fatigue failure occurrence. Therefore, to cope with this increasing need of highly damped structures, it is important not only to provide computational tools able to achieve an effective dynamic response prediction, but also capable of proposing efficient solutions to obtain the desired performance.

A number of researchers have worked on this field, considering different approaches. Among them, one can refer the work presented by Barkanov and Gassan [1] which developed an integrated finite element method for the calculation of damping modelling by uniting the laminate and structural damping theories. In their work the damping in the system is represented by using the complex stiffness approach which derives from the elastic–viscoelastic correspondence principle. Sainsbury and Zhang [2] presented a finite element for damped sandwich beam structures, combining the polynomial shape functions of conventional finite element analysis with Galerkin orthogonal functions. These beam functions are selected for fast convergence and for the prediction of higher order vibration modes using few elements. The authors imposed displacement consistency over the interfaces between the damping layer and the elastic layers to ensure a conforming element and results accuracy. A numerical method for the exact solution of nonlinear eigenvalue problems was later proposed by Daya and Pottier-Ferry [3]. Their method associated homotopy and asymptotic techniques to obtain the natural frequencies and loss factors of viscoelastically damped sandwich structures, which were compared to other analytical and experimental results. A layerwise model devoted to the study of thin soft core sandwich plates was formulated by Moreira and Rodrigues [4]. The results were compared with those obtained using a layered combination of plate and solid finite elements. Cai et al. [5] developed an

* Corresponding author at: ISEL, IPL, Av. Conselheiro Emídio Navarro, 1, 1959-007 Lisboa, Portugal.

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analytical study on the vibration response of beams with single passive constrained layer damping, wherein a third admissible function was considered to represent longitudinal displacements of the constraining layer patches, in addition to the two functions used in conventional analytical approaches. The results were compared with commercial finite element solutions, in order to conclude on the damping effects of these patches. Araújo et al. [6], formulated a finite element model using a mixed layerwise approach, by considering a higher order shear deformation theory to represent the displacement field of the viscoelastic core, and a first order shear deformation theory for the displacement fields of adjacent laminated face layers. The viscoelastic material behaviour was modeled using the complex approach and the dynamic problem was solved in the frequency domain, assuming fractional derivative constitutive models. Constrained optimization of passive damping was also carried out for the maximisation of modal loss factors. More recently, Arvin [7] formulated a sandwich beam model based on a higher order theory, which considers independent transverse displacements for the face sheets with linear variations along the depth of the core. The author carried out a study on the fibre angle effects on the frequency response, and on the core Young's modulus and the beam rotary inertia contributions to the frequency response analysis of the beam. The static and free vibration of three-layer composite shells, was carried out by Maturi et al. [8], through the use of radial basis functions collocation. This method is based on a new layerwise theory that considers independent layer rotations, accounting for through-thickness deformation. All displacements are considered to vary linearly with each layer thickness coordinate. The equations of motion and the boundary conditions are obtained by the Carrera's Unified Formulation, and further interpolated by collocation with radial basis functions.

In these studies, the viscoelastic nature of the core is the central issue however it may also be relevant to devote some attention to the skins contribution to the overall performance. Assuming that these layers are made from elastic materials, not only their selection may be an important subject but the potential use of nano-inclusions to modify its characteristics may be something to address. Concerning to this later aspect, one can refer some published works related to processing methodologies to enable and improve the dispersion of carbon nanotubes into polymeric, ceramic or metallic matrices, and related to the influence of these inclusions on the structure mechanical response. In Thostenson et al. [9], an overview of the advances in nanocomposites research, was carried out and an attempt was made to point key research opportunities. The development of structural and functional nanocomposites was addressed in the context of traditional fibre composites, being presented a state of the art in processing, characterization, and analysis/modeling of nanocomposites and identified critical issues in nanocomposites research as well as promising techniques. A review study in the field of carbon nanotube (CNT) metal matrix composites (MMCs) was developed by Bakshi et al. [10]. This review focuses on the critical issues of CNT-reinforced MMCs that include processing techniques, nanotube dispersion, interface, strengthening mechanisms and mechanical properties. The mechanical property improvements achieved by addition of CNTs in various metal matrix systems are summarized and future necessary research work is addressed. Another recent review work in the field of nanocomposites, is due to Zapata-Solvas et al. [11] and it concerns to the use of CNT as a promising reinforcement for ceramic matrix composites (CMCs). The current status of the research and the description of different approaches used to disperse carbon nanotubes throughout ceramic matrices, is presented, enabling also an overview of composites microstructure and mechanical, electrical and thermal properties. Concerning to studies devoted to the analysis of structures containing CNT's one can refer among others, the work developed by Zu et al. [12]. These authors analysed thin to moderately thick composite plates reinforced by single-walled carbon nanotubes. The bending and free vibration analyses are carried using first order shear deformation theory. Different types of distributions of the uniaxially aligned reinforcement material are considered, being the effective material properties of the nanocomposite plates, estimated using the rule of mixtures. Parametric studies were carried out and results are compared to the solutions obtained using a commercial finite element application. Rafiee et al. [13] presented a work on the modelling and nonlinear stress analysis of piezolaminated CNTs/fibre/polymer composite plates under a combined mechanical and electrical loading. The governing equations of the plates are based on first-order shear deformation plate theory (FSDT) and considering von Kármán geometric nonlinearity. The macroscopic composite properties are predicted through the hierarchical use of Halpin–Tsai equations and fibre micromechanics. Numerical examples are shown for simply supported plates submitted to different loadings and nanocomposites composition.

In the present work, one aims to study the dynamic behaviour of sandwich beam structures with a viscoelastic core. To this purpose, a set of layerwise models based on kriging finite element models were developed and implemented. As far as the author's knowledge, no published works were found considering the use of kriging functions applied to the study of viscoelastic core sandwiches, nor considering its use along with layerwise approaches. The models developed are based on different shear deformation theories. The outer layers are made from elastic materials, which can be nanocomposites, and the core of the sandwich is made from viscoelastic materials. In this latter situation, the corresponding elastic properties are modelled using the complex approach and the dynamic problem is solved in the frequency domain. Parametric studies are carried out to characterise the influence of different parameters on the dynamic response of the sandwich structure.

2. Layerwise shear deformation models

In this work, we have considered different shear deformation models and some of their combinations, to model the sandwich structure. To achieve the layerwise sandwich model it is assumed displacement continuity at adjacent layers interfaces as well as that no slipping occurs between layers. The skins are assumed to be made from elastic materials and the core is from a viscoelastic material.

The simplest and less expensive approach corresponds to the use of the first order shear deformation theory to model both the skins and the core kinematics. According to this, the displacement fields for the viscoelastic core (v) and for the outer elastic layers ($e1, e2$), are respectively given as:

$$\begin{aligned} u^v(x,z,t) &= u^{0v}(x,t) + z.\theta_x^{0v}(x,t) \\ w^v(x,t) &= w^{0v}(x,t) \\ u^e(x,z,t) &= u^{0e}(x,t) + (z - z^e).\theta_x^{0e}(x,t) \\ w^e(x,t) &= w^{0e}(x,t) \end{aligned} \tag{1}$$

where the superscripts, (v) stands for viscoelastic and is related to the core, and (e) represents each of the elastic layers, where $e = e1, e2$ according to Fig. 1. The parameter z^e denotes the thickness coordinate associated to the mid-plane of an elastic layer, described in the sandwich coordinate system, being for each case, given as:

$$z^{e1} = \frac{h_v}{2} + \frac{h_{e1}}{2}; \quad z^{e2} = -\frac{h_v}{2} - \frac{h_{e2}}{2} \tag{2}$$