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Thermo-mechanical loading of laminates with imperfect interfaces

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Abstract

Composite laminates are currently being pursued for structures which may be subjected to explosive threats in aggressive environments, characterized by extreme temperatures and seawater. A mechanical model is formulated for laminated plates subjected to thermo-mechanical loading and deforming in cylindrical bending; the layers are assumed to be imperfectly bonded, with sliding interfaces and delaminations. The model derives dynamic equilibrium equations which depend on only three unknown displacement functions for arbitrary numbers of layers/interfaces. Close form solutions are obtained which highlight accuracy and limitations of the approach and the influence of the imperfect interfaces on stress and displacement fields.

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Keywords: composite laminates, structural theories, dynamic loading, delamamination

1. Introduction

Composite laminates are currently being pursued for structures which may be subjected to explosive threats in aggressive environments, characterized by the presence of extreme temperatures and seawater. Under such conditions the structural systems may exit the elastic regime and the response if then controlled by progressive inter- and intra-layer damage up to final failure. Temperature variations and moisture absorption generate strains and stresses which are controlled by the thermal/hygroscopic properties of the layers and their connections and by the stacking sequence; these stresses may affect the elastic/post-elastic behaviour of the structural systems. Modelling of composite systems in aggressive environments must then account for hygro-thermo-mechanical loading.

The surfaces connecting adjacent layers in composite laminates and multi-layered systems, also known as interfaces, may be perfect, as in fully bonded systems, or imperfect, as in systems where the interfacial tractions are

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continuous but relative displacements between the layers are allowed. Imperfect interfaces are typically described in the theoretical models by interfacial traction laws, which relate the interfacial tractions, normal ad tangential to the interfaces, to the relative displacements of the layers. Linear-elastic interfacial traction laws are used to describe thin elastic interlayers [1] or to approximate, in numerical solutions of the problems, perfect adhesion of the layers, in which case the interfacial tractions are described by very steep functions of the interfacial jumps [2,3]. More complex laws are used in the post-elastic regime to describe the different nonlinear mechanisms which take place at the interfaces and include material rupture, cohesive/bridging mechanisms acting along the wake of delaminations or ahead of their front and contact between delamination surfaces [4]. Nonlinear interfacial traction laws can be approximated by piece-wise linear functions and each piece of the laws is an affine function of the interfacial jumps.

The displacement/stress fields in multilayered systems with imperfect interfaces are characterized by large variations, zigzag patterns and discontinuities. These fields are accurately predicted by recently developed theories, which derive a homogenized displacement field depending on a limited number of variables [5-7]. The theories corrects the models proposed in [1,8-10], which were energetically inconsistent. They extend the original models to describe affine interfacial traction laws, so setting up the bases for the solution of nonlinear problems. In this paper, the model formulated in [6] for plates deforming in cylindrical bending is extended to account for thermo-mechanical problems. Modified dynamic equilibrium equations are derived, which depend on the applied temperature field and the thermo-elastic constants of the material.

2. Model

A mechanical model has been formulated by the authors in [5] for laminated plates with imperfect interfaces characterized by affine interfacial traction laws and subjected to static and dynamic loading. The model has been particularized to plates deforming in cylindrical bending in [6]. The accuracy of the models has been verified through a comparison with exact 2D solutions [11,5,6]. Stresses and displacements are accurately predicted over the whole range of interfacial stiffnesses. The transverse displacements are underestimated in thick highly anisotropic plates with very compliant interfaces, as a consequence of the assumed interfacial conditions [5,6]; a modification of the shear factor is expected to resolve the problem (work in progress). Applications to plates with clamped edges [7] highlight the consistency/accuracy of the solution in the domain with the exception of boundary regions, near the clamped edges, where internal resultants, couples and global displacements are correctly predicted while inaccuracies are found in the local displacements and stresses in the layers.

In this paper the formulation presented in [6] is extended to account for thermo-mechanical loading. The model refer to the schematic shown in Fig. (1), which depicts a plate of thickness h and in-plane dimensions L_1 and $L_2 = L$, with $L_1 >> L_2$. A system of Cartesian coordinates, $x_1 - x_2 - x_3$, is introduced with the axis x_3 normal to the reference surface of the plate, which is arbitrarily chosen, and measured from it. The plate consists of n layers joined by $n-1$ interfaces. The layer *k,* where the index $k = 1,..,n$ is numbered from bottom to top, is defined by the coordinates x_3^{k-1} and x_3^k of its lower and upper interfaces, ${}^{(k)}\mathscr{S}^-$ and ${}^{(k)}\mathscr{S}^+$, and has thickness ${}^{(k)}h$, Fig. 1 (the k superscript in brackets identifies affiliation with layer k). Each layer is linearly elastic, homogeneous and orthotropic with material axes parallel to the geometrical axes. The displacement vector of an arbitrary point of the plate at the coordinate $\mathbf{x} = \{x_1, x_2, x_3\}^T$ is $\mathbf{v} = \{v_1, v_2, v_3 = w\}^T$.

The plate is subjected to distributed loads acting on the upper and lower surfaces, $\mathscr{S}^+$ and $\mathscr{S}^-$, and on the lateral bounding surface, $\mathscr{B}$, and to thermal loads applied so as to satisfy plane strain conditions parallel to the plane $x_2 - x_3$; the plate then deforms in cylindrical bending. In addition, the plate is assumed to be incompressible in the thickness direction and the interfaces to be rigid against mode I (opening) relative displacements. This latter assumption, which is often used in the literature, is rigorously correct only in problems where the conditions along the interfaces are purely mode II. The assumption, however, is acceptable in the presence of continuous interfaces, when the interfacial normal tractions are small compared to the tangential tractions and interfacial opening is prevented, e.g. by a through-thickness reinforcement or other means. Based on the assumptions above, the displacement components then simplify in $v_1 = 0$, $v_2 = v_2(x_2, x_3)$ and $v_3 = w(x_2)$.