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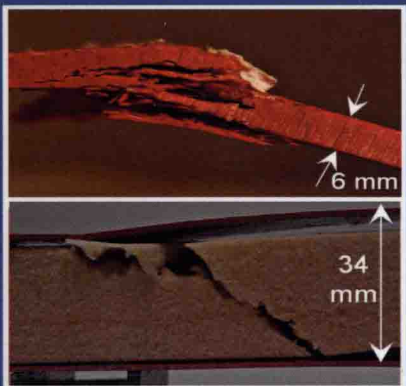

Dynamic Response and Failure of Composite Materials and Structures

Edited by Valentina Lopresto,
Antonio Langella and Serge Abrate

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Part One

Dynamic behavior of composite structures

2D thermo-elastic solutions for laminates and sandwiches with interlayer delaminations and imperfect thermal contact

1

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1.1 Introduction

Laminated, sandwich, and layered composites are largely used in different areas of technology and industry. Their application in primary structures of mechanical devices and vehicles, such as turbines, wind blades, aircrafts, automobiles, or ships, is progressively increasing. The interest in the use of composite materials is due to the fact that their mechanical properties can be tailored, by proper selection of the materials and design of the layups, to meet the stringent design requirements of modern mechanical devices. Current applications require withstanding severe mechanical loadings and surviving aggressive environments characterized for instance by very high or very low temperatures.

The focus of this chapter is on layered composite beams and wide plates subjected to stationary thermo-mechanical loading. Three-dimensional thermo-elasticity provides exact solutions which can be used to confidently design the plates in the elastic regime or validate approximate structural theories. Exact solutions in the literature are mostly limited to simple geometries and loading and boundary conditions; in addition, these solutions typically require extensive computational work when the number of layers is large and this limits their utilization by the design community. In this chapter, a matrix technique will be used, along with the linear theory of 2D thermo-elasticity, to efficiently solve the thermo-mechanical problem in simply supported multilayered wide plates and beams with an arbitrary number of imperfectly bonded layers and thermally imperfect interfaces. The technique and the explicit formulas derived in the chapter simplify the solution procedure and provide a framework for other researchers to easily generate any desirable benchmark solutions.

Section 1.2 presents a literature review on two- and three-dimensional thermo-elasticity models for laminated and sandwich structures with thermally and mechanically perfect and imperfect interfaces. In Section 1.3 the thermo-elasticity model formulated in Ref. [1] for simply supported wide plates with imperfect interfaces is recalled and a matrix technique based on the transfer matrix method is formulated to derive explicit formulas, which allow the efficient closed-form solution of the

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problem with an arbitrary number of layers. Exemplary benchmark solutions are presented in Sections 1.4 and 1.5 and some conclusions in Section 1.6.

1.2 Thermo-elasticity solutions for laminated and sandwich plates with imperfect interfaces: state of the art

In an early paper [2], Pagano used the Airy stress function method to obtain an exact solution in the framework of the linear theory of elasticity for simply supported cross-ply laminates composed of perfectly bonded orthotropic/isotropic layers. The solution was given for plates subjected to sinusoidal transverse loads under plane-strain conditions. The theory was extended to include uniformly distributed and concentrated loads described by means of Fourier series in Ref. [3], and in Ref. [4] to treat stationary sinusoidally distributed thermal loads, under the simplifying assumption of linear thickness-wise temperature distribution. Thanks to these exact solutions, the limitations of classical laminated plate theory for the analysis of laminates with low span-to-thickness ratios were first revealed and the solutions are still used nowadays to assess the range of validity of approximate theories and numerical models. Recently, Pagano's solution was completed in Ref. [5], using the displacement method, for cases where the characteristic equation of the problem has complex conjugate roots, as it occurs in sandwich plates with honeycomb cores having transverse stiffness much higher than the in-plane stiffnesses. An exact stationary thermo-elasticity solution for simply supported plates in plane-strain and subjected to arbitrary thermo-mechanical loading was obtained in Ref. [6] using the method of the displacement potentials and assuming perfect thermal contact at the layer interfaces.

In a later study by Pagano [7], three-dimensional elasticity solutions were obtained for simply supported rectangular bidirectional laminated and sandwich plates composed of perfectly bonded orthotropic/isotropic layers. The characteristic equation of this problem was restated in the form of a cubic equation whose discriminant controls the nature of the solution. Pagano obtained closed-form solutions for the cases of negative and zero discriminants, for example, isotropic layers. Solutions for the case of a positive discriminant were presented later in Ref. [8]. These exact solutions proved the faster convergence to the exact solution of classical plate theory on increasing the number of layers [9]. In parallel with Pagano's work, Srinivas et al. [10,11] obtained elasticity solutions for simply supported perfectly bonded cross-ply laminates under arbitrary loading by expressing the displacement and stress components in terms of infinite series. The thermo-elastic problem was studied in Refs. [12–14] for plates with perfect thermal contact between the layers, by assuming a prescribed temperature distribution with a through-the-thickness linear variation in Ref. [13] and through the exact solution of the heat conduction problem in Refs. [12,14]. Solutions for plates with boundary conditions other than the simple supports were obtained in the form of infinite series in Refs. [15,16] and through the extended Kantorovich method in Ref. [17].

All the aforementioned thermo-elasticity theories are based on two main steps. First, the general forms of the field variables, which satisfy the edge boundary conditions and the governing field equations, are obtained for a generic layer. Then, the unknown constants in the solutions of each layer are calculated by imposing continuity conditions at the layer interfaces and boundary conditions at the top and bottom surfaces of the plate. For a plate composed of n layers, a system of $4 \times n$ and $6 \times n$ algebraic equations needs to be solved for plane-strain and general plate problems, respectively [2,7]. Solving the system of equations becomes cumbersome when the number of layers increases and this restricts the applicability of the models.

The transfer matrix method was originally proposed by Thomson and Haskell [18,19] for the problem of wave propagation in multilayered media. In Ref. [20], the method was employed, along with a mixed formulation of elasticity, to efficiently study statics and dynamics of simply supported bidirectional laminated plates. The basic idea of the method relies on the introduction of a local transfer matrix, which relates the field variables at the bottom of a layer to those at the top; the local matrices of the layers are then coupled through continuity conditions at the interfaces to obtain a global transfer matrix, which relates field quantities of the bottom and top surfaces of the medium. Using the transfer matrix method, the continuity conditions at the interfaces are then satisfied a priori and the field variables in each layer are obtained through the application of the relevant boundary conditions. The number of coupled algebraic equations which need to be solved becomes independent of the number of layers and equal to four or six, for plane-strain or general plate problems, as it would be for a single-layer plate solved with the classical approach. The transfer matrix method was applied for the solution of the thermo-elasticity problems in simply supported laminated plates and arches in Refs. [21,22]. Applications of the method in the ultrasonic and seismology fields are presented in the review paper [23].

The thermo-elasticity models mentioned above assume the layers to be perfectly bonded and in perfect thermal contact, which imply continuity of displacements, tractions, temperature, and heat flux at the layer interfaces. This assumption does not describe systems with damaged interfaces or delaminations between the layers or systems where the plies are connected by thin adhesive layers which are not described as regular layers in the formulation. Flaws and delaminations may develop during the manufacturing processes and/or in service due to, for instance, fatigue loads, impacts, or environmental effects, such as temperature or humidity. They modify the continuity conditions at the layer interfaces and may result in stiffness and heat conductivity degradation and in reduction of the load-carrying capacity of the plates [24].

From a mechanical point of view, an imperfect interface or a very thin interlayer can be represented as a zero-thickness surface across which the interfacial tractions are continuous, while the displacements are discontinuous. The interfacial tractions can then be related to the relative displacements of the layers at the interfaces using interfacial traction laws able to describe different interfacial mechanisms. Linear interfacial traction laws have been frequently used in the literature; they assume that the interfacial tractions are proportional to the corresponding relative sliding and opening displacements and the proportionality factors are the interfacial tangential and normal stiffnesses. These laws well describe the response of thin adhesive elastic layers and the initial branch of more general interfacial traction laws, such as those which are typically used to model cohesive delamination fracture. In addition, these laws can be used to describe the limiting cases of perfectly bonded and fully debonded layers [1].

To the authors' knowledge, Williams and Addessio [25] were the first to employ the concept of linear interfacial traction law in conjunction with Pagano's model [2] in order to obtain exact elasticity solutions for the laminates with imperfect interfaces in plane-strain and subjected to mechanical loading. The extension is straightforward since the general solutions for stresses and displacements in each layer are unchanged, while the interfacial continuity conditions must account for the assumed interfacial traction laws. The same idea was applied in Ref. [26] to verify structural models based on a zigzag homogenization used to improve classical structural theories; in Refs. [27,28] it was used along with the state-space approach, for the bending and free vibrations of simply supported cross-ply laminates and cylindrical panels with imperfect interfaces; in Ref. [29] it was applied to study plates subjected to arbitrary boundary conditions.

From a thermal point of view, heat transfer through the layers of a plate with interfacial imperfections is a rather complex process. Microcracks, voids, and delaminations reduce the areas of actual physical contact between adjacent layers and create regions separated by air gaps which prevent the heat flow across the interface. Heat transfer across the imperfect interfaces takes place through conduction at the contact spots and conduction and/or radiation through the air gaps. These mechanisms control and reduce the interfacial thermal conductance, which also depends on other factors, such as the applied pressure and the mean temperature. The consequence of this behavior is a jump in the temperatures of the layers at the interface [30]. Hence for laminates with interfacial imperfections, the assumption of perfect thermal contact between the layers, which implies a continuous temperature at the interface, is not valid.

The concept of thermally imperfect interface characterized by an interfacial thermal resistance has been frequently used in the literature to account for the behavior described above [1,31–33]. This model enforces the equality of the heat fluxes, which enter and leave the interface, and assumes that the heat flux through the interface is proportional to the interfacial temperature jump; the interfacial thermal conductance H is the proportionality factor and should then account for the various modes of heat transfer through the interface mentioned previously [30]. An interfacial thermal resistance is then introduced, which is the reciprocal of the interfacial thermal conductance, $R=1/H$. If $R=0$, the model describes perfect interfaces, where the temperature is continuous at the interface. Impermeable interfaces, where the heat flux vanishes, can be modeled by setting $H=0$. The model can also be used to efficiently describe the thermal behavior of thin adhesive layers when they are represented as interfaces and H will then be related to the conductivity and thickness of the adhesive. Pelassa et al. [1] employed the concept of interfacial thermal resistance and assumed the interfaces to be mechanically imperfect and described by linear traction laws to extend the thermo-elasticity model presented in Ref. [14] to multilayered plates with thermally and/or mechanically imperfect interfaces.