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Introductory Chapter: Laminations - Theory and Applications

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1. Introduction

Historically, the earliest use of laminated materials was by the Mesopotamians around 3400 BC. Similarly, plywood laminates from wood strips glued together at different angles were constructed for structural applications. Nevertheless, for several centuries, primitive lamination methods were used for the construction of bows and canoes. Specifically, the invention of Bakelite in 1907 heralded a new era for composite and laminated material applications. For instance, at the inception of the aircraft by the Orville and Wilbur Wright brothers, it was made with wood and fabrics. The need for better aerodynamic performance and efficiency supported by advances in aerospace engineering led to the use of lighter materials with strength that matches that of steel. The development of this field has progressed significantly to the point of the ubiquitous availability of laminates in materials for aviation, civil structures and automotive uses. In particular, carbon fiber reinforced plastics are in use in modern aircraft aerospace systems. In modern engineering practices, the use of layered sandwich structural flat plate members is increasing steadily in aerospace, civil, mechanical and offshore structures due to their high specific strength and stiffness. Such structural applications have significantly led to reduction in vulnerability of warships to blasts, ballistics, bombs and fire attacks and to enhance superior resistance to fatigue crack propagation, impact damage and local buckling.

From the viewpoint of structural mechanics, an interface slip motion between two laminated structures, such as beam, beam plate and plate in the presence of dry friction can be utilized for slip damping systems. By scientific definition, slip damping is a mechanism exploited for dissipating noise and vibration energy in machine structures and systems. There are several engineering procedures to effect or simulate such a damping phenomenon. For example, the introduction of constrained, unconstrained and even viscoelastic layers has been very helpful in this respect. One good technique is layered construction

made possible by externally applied pressure at the interface of two structural members. An arrangement of this nature could either be jointed or fastened by appropriate bolting methods. Within that concept, interface pressure profiles must assume a significant role subject to interfacial slip motion to waste or dissipate energy from the induced vibration arising from any form of excitation.

Within this context, researchers have developed a number of interesting mathematical models to derive the advantages discussed above for noise dissipation, minimization or complete vibration isolation. For instance, in the paper published by Osheku et al. [1], they employed a mathematical model to discuss the effect of structural vibration on the propagation of acoustic pressure waves through a cantilevered 3D laminated beam-plate enclosure. On the other hand, slip damping with heterogeneous sandwich composite viscoelastic beam-plate smart systems as a model for dissipation of vibration and active noise control mechanism in ship and floating structures was studied effectively by Olunloyo and Osheku in [2]. A scientific discussion of interfacial slip through layered laminates is described as shown in **Figure 1**.

As a demonstration of the application of laminations to noise reduction, **Figure 2** shows the problem geometry subject to governing equations as derived in [1]:

$$\nabla^2 P - \frac{\partial^2 P}{c_1^2 \partial t^2} - \frac{2u_x \partial^2 P}{c_1^2 \partial t \partial x} - \frac{u_x^2 \partial^2 P}{c_1^2 \partial x^2} = -\frac{\partial^2 W_1}{\rho \partial t^2} \quad (1)$$

while the governing equations for each vibrating boundary are namely:

For the case Ω_1 ,

Figure 1. Mechanism of interfacial slip geometry.

Figure 2. Problem geometry of 3D composite structure.

$$D \left(\frac{\partial^4 W_1}{\partial x^4} + 2 \frac{\partial^4 W_1}{\partial x^2 \partial y^2} + \frac{\partial^4 W_1}{\partial y^4} \right) + \rho_1 h \frac{\partial^2 W_1}{\partial t^2} - \left(\frac{\mu H_2}{2} \frac{\partial p(x, 0)}{\partial x} + \frac{\mu H_2}{2} \frac{\partial p(0, y)}{\partial y} \right) = 0 \quad (2)$$

For the case Ω_2 ,

$$\frac{\partial^2 W_2}{\partial x^2} + \beta_2 \frac{\partial^2 W_2}{\partial t^2} = \alpha_2 \frac{\partial P(x, 0)}{\partial x} \quad (3)$$

For the case Ω_3 ,

$$D \left(\frac{\partial^4 W_3}{\partial x^4} + 2 \frac{\partial^4 W_3}{\partial x^2 \partial y^2} + \frac{\partial^4 W_3}{\partial y^4} \right) + \rho_1 h \frac{\partial^2 W_3}{\partial t^2} - \left(\frac{\mu H_2}{2} \frac{\partial p(x, 0)}{\partial x} + \frac{\mu H_2}{2} \frac{\partial p(0, y)}{\partial y} \right) = 0 \quad (4)$$

For the case Ω_4 ,

$$\frac{\partial^2 W_4}{\partial x^2} + \beta_2 \frac{\partial^2 W_4}{\partial t^2} = \alpha_4 \frac{\partial P(x, 0)}{\partial x} \quad (5)$$

$$\forall \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \frac{6\mu}{Eh^2}; \beta_1 = \beta_2 = \beta_3 = \beta_4 = \frac{\rho b h}{EI} \quad (6)$$

The boundary stresses through the domains Ω_1, Ω_2 and Ω_3 are evaluated from the following equations in Fourier finite double sine transforms plane, viz.:

$$\begin{aligned}\tilde{P}^{F_y F_z}(0, \lambda_m, \lambda_k, s) &= \int_0^b \int_0^c [\mu P_{av}] \sin\left(\frac{m\pi y}{b}\right) \sin\left(\frac{k\pi z}{c}\right) dy dz, \\ \tilde{P}^{F_y F_z}(a, \lambda_m, \lambda_k, s) &= \int_0^b \int_0^c [\mu P_{av}] \sin\left(\frac{m\pi y}{b}\right) \sin\left(\frac{k\pi z}{c}\right) dy dz\end{aligned}\quad (7)$$

$$\begin{aligned}\tilde{P}^{F_x F_y}(\lambda_n, \lambda_m, 0, s) &= \int_0^b \int_0^c \left[\frac{P_{av}}{s}\right] \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{m\pi y}{b}\right) dx dy, \\ \tilde{P}^{F_x F_y}(\lambda_n, \lambda_m, c, s) &= - \int_0^b \int_0^a \left[\frac{P_{av}}{s}\right] \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{k\pi y}{b}\right) dx dy,\end{aligned}\quad (8)$$

$$\tilde{P}^{F_x F_z}(\lambda_n, b, \lambda_k, s) = \int_0^a \int_0^c \left[\frac{P_{av}}{s}\right] \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{k\pi z}{c}\right) dx dz, \quad (9)$$

$$\tilde{P}^{F_x F_z}(\lambda_n, 0, \lambda_k, s) = - \int_0^a \int_0^c \left[\frac{P_{av}}{s}\right] \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{k\pi z}{c}\right) dx dz, \quad (10)$$

subject to interfacial slip mechanism as modulated by the pressure profile as discussed in the paper. In the meantime, when such a slip mechanism is to be examined under the influence of an electromagnetic field, the details of such a problem were discussed in Osheku [3].

The underlying principle is such that during bending, each half of the sandwich elastic in transverse magnetic field has its neutral plane that does not necessarily coincide with the geometric mid-plane through the interface because of the frictional stresses. These are located at $z = \alpha_1(x)\frac{h}{2}$ and $z = \alpha_2(x)\frac{h}{2}$ on layers (1) and (2) respectively, where $\alpha_1(x)$ and $\alpha_2(x)$ are generalized functions of x . The use of Taylor series approximation leads to the following expressions for the microscopic slip or displacements of the two adjacent opposite points A_1 and A_2 to the corresponding A_1^1 and A_2^1 namely:

$$\begin{aligned}\Delta U_1(x, z, t) &= \Delta U_1(0, 0+, t) + \left(z - \alpha_1(x)\frac{h}{2}\right) \frac{\partial W(x, t)}{\partial x} + \frac{1}{2} \left(z - \alpha_1(x)\frac{h}{2}\right)^2 \frac{\partial^2 W(x, t)}{\partial x^2} \\ &+ \frac{1}{6} \left(z - \alpha_1(x)\frac{h}{2}\right)^3 \frac{\partial^3 W(x, t)}{\partial x^3}\end{aligned}\quad (11)$$

and

$$\begin{aligned}\Delta U_2(x, z, t) &= \Delta U_2(0, 0-, t) - \left(z + \alpha_2(x)\frac{h}{2}\right) \frac{\partial W(x, t)}{\partial x} - \frac{1}{2} \left(z + \alpha_1(x)\frac{h}{2}\right)^2 \frac{\partial^2 W(x, t)}{\partial x^2} \\ &- \frac{1}{6} \left(z + \alpha_1(x)\frac{h}{2}\right)^3 \frac{\partial^3 W(x, t)}{\partial x^3}\end{aligned}\quad (12)$$

In the meantime, a first-order approximation follows as:

$$\Delta U_1(x, z, t) = \Delta U_1(0, 0+, t) + \left(z - \alpha_1(x) \frac{h}{2} \right) \frac{\partial W(x, t)}{\partial x} \quad (13)$$

$$\Delta U_2(x, z, t) = \Delta U_2(0, 0-, t) - \left(z + \alpha_2(x) \frac{h}{2} \right) \frac{\partial W(x, t)}{\partial x} \quad (14)$$

Here, $\Delta U_1(0, 0+, t)$ and $\Delta U_2(0, 0-, t)$ must be zero at the fixed end.

$$\Delta U(x, z, t) = \Delta U_1(x, z, t) - \Delta U_2(x, z, t) \quad (15)$$

The associated interfacial slip motion is then given by the equation below which on following Goodman and Klumpp [4] becomes:

$$\Delta U(x, 0) = E^{-1} \int_0^x [(\sigma_x)_1(\xi, 0+, t) - (\sigma_x)_2(\xi, 0-, t)] d\xi \quad (16)$$

where ξ is a dummy axial spatial variable of integration across the interface and $0+$, $0-$ denote the origin of the transverse spatial variable for each layer; while subscripts 1 and 2 refer to the upper and lower laminates.

For the contrived geometry, the derived corresponding spatial bending stresses are namely:

$$(\sigma_x)_1(x, z, t) = -\frac{E}{2}(2z - h) \frac{\partial^2 W(x, t)}{\partial x^2} + \frac{B_0^2}{\mu_0} \left(1 - \frac{\mu_0}{\mu_m} \right) [W(x, t) - W(L, t)] + \mu P_0(1 + \varepsilon \bar{x}) \frac{(x - L)}{h} \quad (17)$$

and

$$(\sigma_x)_2(x, z, t) = -\frac{E}{2}(2z + h) \frac{\partial^2 W(x, t)}{\partial x^2} + \frac{B_0^2}{\mu_0} \left(1 - \frac{\mu_0}{\mu_m} \right) [W(x, t) - W(L, t)] - \mu P_0(1 - \varepsilon \bar{x}) \frac{(x - L)}{h} \quad (18)$$

This gives Eq. (11) as:

$$\Delta U(\bar{x}) = \int_0^x \left[\frac{\partial^2 \bar{W}(\bar{x}, \tau)}{\partial \bar{\xi}^2} + \bar{B}^2 \left(1 - \frac{\mu_0}{\mu_m} \right) [\bar{W}(\bar{\xi}, \tau) - \bar{W}(1, \tau)] + 2\mu P_0(1 + \varepsilon \bar{\xi})(\bar{\xi} - 1) \right] d\bar{\xi} \quad (19)$$

and on introducing the nondimensionalized parameters, viz.:

$$\Delta U = \frac{\Delta U(\bar{x}) E b h^2}{L^2 F}; \bar{P}_0 = \frac{P_0}{F/bh}; t = \frac{2\pi\tau}{\omega_0} \quad (20)$$

For the static case, the governing differential equation is described in [2] as

$$EI \frac{d^4 W}{dx^4} + \frac{bh}{\mu_0} \left(1 - \frac{\mu_0}{\mu_m}\right) B_o^2 \frac{d^2 W}{dx^2} = \frac{1}{2} bh \mu \frac{dP}{dx} \quad (21)$$

subject to the form computed as in [3] as:

$$\bar{P}_{av} = \bar{P}_o \int_0^1 (1 + \varepsilon \bar{x}) d\bar{x} = \bar{P}_o \left(1 + \frac{\varepsilon}{2}\right) \quad (22)$$

In the meantime, several derivatives of this analysis can be conjured for comparative analysis with literature.

For the case of a layer of sandwich homogenous magnetoelastic beam-plate of thickness h with non-uniform pressure at the interface, the formulated equation governing the vibration takes the form:

$$D \frac{\partial^4 W}{\partial x^4} + \frac{h}{\mu_0} \left(1 - \frac{\mu_0}{\mu_m}\right) B_o^2 \frac{\partial^2 W}{\partial x^2} - \frac{\sigma_c h^3 B_o^2}{12} \frac{\partial^3 W}{\partial t \partial x^2} + \rho h \frac{\partial^2 W}{\partial t^2} = \frac{1}{2} h \mu \frac{\partial P}{\partial x} \quad (23)$$

$$\forall D = \frac{Eh^3}{12(1 - \nu^2)} \quad (24)$$

so that for the case corresponding to uniform interfacial pressure, Eq. (23) reduces to the following:

$$D \frac{\partial^4 W}{\partial x^4} + \frac{h}{\mu_0} \left(1 - \frac{\mu_0}{\mu_m}\right) B_o^2 \frac{\partial^2 W}{\partial x^2} - \frac{\sigma_c h^3 B_o^2}{12} \frac{\partial^3 W}{\partial t \partial x^2} + \rho h \frac{\partial^2 W}{\partial t^2} = 0 \quad (25)$$

Nonetheless, a theoretical investigation by [5] on the proposed uses of lamination theory via slip damping was hinged on the following pictorial representation in **Figure 3**.

Figure 3 illustrates a slip damping theory and its application in ship hull subject to Eq. (26). Detailed solution methods of this boundary value mathematical physics problem are outlined in [5]. The intent here is to demonstrate possible means to enhance moving ocean craft stability subject to turbulent flow conditions in **Figure 4**. Meanwhile, the governing equation is depicted as follows,

$$\left(\frac{c_1 + c_2}{4}\right) \frac{\partial^5 W}{\partial t \partial x^4} + \frac{\partial^4 W}{\partial x^4} + \frac{(\beta_1 \mathcal{A} + \beta_2 \mathcal{B} + \beta_3 + \beta_4)}{4} \frac{\partial^2 W}{\partial t^2} = \frac{(\alpha_1 \mathcal{A} + \alpha_2 \mathcal{B})}{4} \frac{\partial P(x, 0)}{\partial x} + \frac{C_a}{4} \frac{\partial^2 V_a}{\partial x^2} \quad (26)$$

where $\mathcal{A}$ denotes $1 - \nu_1^2$ and β denotes $1 - \nu_2^2$ and the following parameters have been defined viz.:

$$\alpha_1 = \frac{6\mu}{E_{eq1} h_{eq1}^2}, \alpha_2 = \frac{6\mu}{E_{eq2} h_{eq2}^2} \quad (27)$$

$$\beta_1 = \frac{\rho_1 b h_1}{E_1 I_1}, \beta_2 = \frac{\rho_2 b h_2}{E_2 I_2}, \beta_3 = \frac{\rho_a b h_a}{E_a I_{a1}}, \beta_4 = \frac{\rho_s b h_s}{E_s I_s} \quad (28)$$

Figure 3. (a) Preslip geometry for the composite sandwich structure under dynamic load. (b) Layering cross section of composite structure.

Figure 4. (a) A mathematical model of ship/Floating Production Storage and Offloading vessel (FPSO) in ocean environment. (b) An elliptical model representation of a ship/FPSO bottom hull configuration.

$$h_{eq1} = (h_1 + h_a), h_{eq1} = (h_a + h_s), C_a = \frac{1}{2} E_a d_{31} b (h_a + h_s) \quad (29)$$

By utilizing the closed form expression of the interfacial slip motion, the energy dissipation quantification can be evaluated from ongoing equation

$$D = 4\mu b \int_0^{\pi/2\omega} \int_0^L P(x) \Delta u(x, t) f dx dt \quad (30)$$

and nondimensionalized as:

$$\bar{D} = 4\mu \int_0^{1/4} \int_0^1 \bar{P}_{av} \Delta \bar{u} d\bar{x} d\tau, \quad (31)$$

where $\bar{D} = D(\bar{x}, \tau) E b h^3 / L^3 F_0^2$

For the purpose of clarity, some nomenclatures are described. Readers are advised to read the papers in the references for detailed description of symbols in the equations. Theoretical simulated studies of the foregoing based on the generalized energy dissipation equations and possible scientific applications and engineering design purposes are well highlighted in these papers.

2. Proposed applications

A number of technological applications are possible in the areas of machine structures, power plants, ship turbines, military jets and commercial aircrafts with suitable laminated materials in conjunction with intelligent manufacturing systems to produce systems that are more comfortable for use by humans especially in the modern day world with advanced 3D manufacturing techniques. Arising from research results based on lamination theory and applications, the following modern noise dissipation and vibration isolation systems can be incorporated in new aircraft engines and power generating turbo machines to enhance their operational stability are itemized in the following diagrams (**Figures 5–11**).

Figure 5. (a) A commercial airliner with proposed vibration attenuation devices. (b) Proposed 2D cross section of vibration damping system.

Figure 6. (a) Sectional view through a modified aircraft engine. (b) Blown-out section of modified new jet engine concept showing laminated vibration damping mechanism.

Figure 7. (a) Proposed application of lamination for vibration damping and isolating system. (b) Modified axially compressing turbo jet aircraft engines.

Figure 8. (a) 3D section of jet fighter engine showing modified engine. (b) 3D view of jet fighter modified engine.

Figure 9. (a, b) Proposed civilian aircraft with modified engines fitted with laminated vibration attenuation devices. (c) Proposed military jet fighter with modified engine fitted with laminated devices. (d) Proposed aircraft engine ducting with laminated devices.

Figure 10. Jet engine vibration isolation system with laminated devices.

The intention of this book is to describe new concepts of producing laminated structures and possible modern engineering applications as demonstrated in the introductory chapter and other chapters. The introductory chapter of this book offers new engine design concepts on how laminated enclosures can be useful in machine, ocean and aerospace structures. The thrust is to showcase how the world can benefit from these innovative concepts.

Figure 11. (a, b) Proposed 3D view of a modified turbojet engine with laminated enclosure.

In Chapter 1, the focus is on the study of multiscale hierarchical structure and laminated strengthening and toughening mechanisms. Here, the authors emphasize how higher strength can be achieved in titanium matrix composites by adjusting the multiscale hierarchical structure. The chapter further deduced how the elastic properties and yield strength of laminated composites can be modulated through the “rule of average.” It is also discussed in this chapter how impossible it is to predict fracture elongation and toughness via this rule. In addition, the authors pointed out that fracture elongations of laminated composites are closely tied to strain indexing exponent and strain rate parameter.

In Chapter 2, large deflection analysis of laminated composite plates using a higher order zigzag theory is discussed. This proposed refined theory is expected to ease the determination of deflections and stresses in composite sandwich laminate analysis. The presented model which incorporated an efficient C_0 plate finite element (FE) was shown to accurately calculate the deflections as well as stresses for different geometries of composite and sandwich laminates. The results obtained agree with existing exact 3D elasticity solutions for thin, moderately thick composite and sandwich laminates.

In Chapter 3, the dynamic modeling of a serial link robot laminated with plastic film to improve waterproofing and dustproofing of serial link robots is the main focus. It also discusses how to improve lubrication between the links and the film through an insulating fluid that was encapsulated in the plastic film by employing detailed appropriate mathematical analysis. Dynamic performance of the laminated body was validated for flexural rigidities. Through detailed mathematical analysis, the dynamic performance of the laminated body was confirmed for different flexural rigidities.

In Chapter 4, advanced technologies in manufacturing 3D layered structures for defense and aerospace systems is the main focus of the study. It emphasizes the importance of additive manufacturing techniques and their robust applications in aeronautical and defense structural systems. This study further reveals that not all advanced materials and alloys can be automatically layered by rapid prototyping system or machine. It also highlighted how efforts are underway to apply automated layering technology in many materials with potential applications in nowadays plastics and reinforced polymers for ease of manufacturing 3D parts. The discussion in this chapter presented a review of additive manufacturing history and the potential advantages the proposed method would offer.

Nomenclature

b	width of laminated beam
B_0	magnetic flux density
d/dx	differential operator
E	electric field intensity
E	modulus of rigidity
F	applied end force amplitude
h	depth of laminated beam
H	magnetic field intensity
I	moment of inertia
L	length of laminated beam
P	clamping pressure at the interface of the laminated beams
t	time coordinate
u, v	velocity
$\dot{u}, \dot{v}$	acceleration
U_1	displacement of the lower laminate
U_2	displacement of the upper laminate
W	dynamic response
W^F	dynamic response in Laplace transform plane
$\tilde{W}$	dynamic response in Fourier transform plane
$\tilde{W}^F$	dynamic response in Fourier-Laplace transform plane
x	space coordinate along the beam interface
z	space coordinate perpendicular to the beam interface
ε	pressure gradient
μ	dry friction coefficient
μ_m	permeability of the medium
μ_r	relative permeability of the medium
χ	normalized magnetic field intensity
ε_{x1}	axial strain in layer-1

ε_{x2}	axial strain in layer-2
γ_{xz}	angular strain
ρ	density of laminate material
τ_{xz}	shear stress at the interface of the laminates
$(\sigma_x)_1$	bending stress at the upper half of the laminates
$(\sigma_x)_2$	bending stress at the lower half of the laminates
ξ	dummy variable
ν	Poisson's ratio

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