



Advanced Multifunctional Lightweight Aerostructures

Design, Development, and Implementation

Kamran Behdinan and Rasool Moradi-Dastjerdi



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University of Toronto, Toronto, Canada

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Professor Kamran Behdinin affectionately dedicates this book to his wife, Nasrin, without her love, patience and sacrifices, this and much else would not be possible, and to his dear daughters, Dr. Tina Behdinin and Dr. Asha Behdinin, for their love and unwavering support.

Dr. Rasool Moradi-Dastjerdi warmly dedicates this book to his wife, Arezou, and to his parents for their encouragement, love, and unlimited support.

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Preface

In the aerospace industry, innovative designs, which can simultaneously address concerns about safety and fuel efficiency, have created demands for novel materials and structures. These demands have persuaded researchers to propose and investigate advanced structures made of multifunctional lightweight materials. Some notable mentions include porous, composite, nanocomposite, ultra-high temperature ceramic, piezoelectric, and functionally graded materials.

In the design of aerostructures, strength to weight ratio is the key point where the use of lightweight materials results in a considerable reduction in structural weight. However, the decrease of structural strength usually comes with an ordinary reduction in the weight of the utilized materials such as embedding porosity, or use of lighter materials. This reduction in the structural strength can be compensated using multifunctional materials or by improving the design of the structures. These facts were the key drivers in the development of new lightweight technologies where traditional composite materials as lightweight materials have seen greater integration into aerostructure applications over the past two decades. Furthermore, the introduction of nanotechnology into the design of composite materials presents another leap in the increasing effort to reduce weight and tailor the material properties to suit specific aerostructure applications. In this new generation of composites, nanoscale fillers highly affect the overall properties of the resulting nanocomposite materials.

Another class of multifunctional materials which can have specific applications in the aerospace industry are piezoelectric materials. Employing piezoelectric components with the ability to convert electrical charge to mechanical load or vice versa provides self-controlling property with fast response for the whole structure. This converting ability also provides the benefit of harvesting energy, strain measurements, and damage detection in the structures.

Moreover, aerostructures are mainly subjected to either mechanical or thermal loads where ceramic materials can be prospective candidates. Among them, ultra-high temperature ceramics are an advanced class of material that experience superior structural and thermal stability, reaching temperature over 3000 °C without a noticeable sacrifice in strength.

In aerostructures, the use of architected structures along with multifunctional lightweight materials has opened up possibilities for designs previously unimaginable. The analysis of such advanced materials and structures necessitates the application of novel methods which are precise, reliable, and computationally efficient. The necessity

of utilizing advanced methods complement complex geometrical shapes, different applied loads, a multi-physics environment, and a wide range of scales from nano up to macro scales.

To cover recent developments about the aforementioned concerns and their most exciting aspects, this book is divided into two parts with 10 chapters overall where the state of the art in the respective fields are comprehensively discussed.

The first part deals with multi-disciplinary modeling and characterization of some advanced materials and structures by developing new methods. This part is composed of four chapters. Specifically, layer arrangement impact on deflections of a proposed five-layer smart sandwich plate subjected to electromechanical loads is investigated in Chapter 1. The layers of the sandwich plates are assumed to be made of three different advanced multifunctional materials including porous, graphene-reinforced nanocomposite, and piezoelectric materials. In Chapter 2, heat transfer analysis of sandwich cylinders consisting of a polymeric core and functionally graded graphene-reinforced faces is studied. Chapter 3 presents the application of a new multiscale approach in the modeling and design of lightweight materials and structures that demonstrate complex phenomena that span multiple spatial and temporal scales. In Chapter 4, chemical kinetics and the multiscale characterization of crystallinity in ultra-high temperature ceramics, polymorphic structures and their composites are described.

In the second part of this book, behaviors of some critical parts of aircraft are discussed as practical benchmark problems. Chapter 5 presents an optimization study on the design of a novel shimmy damper mechanism for aircraft nose landing gears as a practical case in aerostructures. In Chapter 6, a widely used component of helicopters, jet engines and aircraft, a flexible rotor supported by viscoelastic bearings, is modeled to study its nonlinear dynamic behavior. Chapter 7 proposes an innovative analytical–numerical method to efficiently predict the real-time temperature of belt drive systems. Chapter 8 develops an efficient and reliable physics-based approach to predict noise at the far-field of a nose landing gear of an aircraft. Another important part of aircraft is the aeroengine. In the aeroengine, the vibrations and noises can be transferred to the aircraft fuselage and this transmissibility significantly affects the aircraft crew and passenger comfort and safety. In this regard, Chapter 9 develops and implements a reliable analytical transmissibility method to analyze and investigate the vibration energy propagation in an aeroengine structure. This method results in design guidelines which can significantly reduce the development costs as well as the ability of addressing noise and vibration problems in the structure. Chapter 10 also utilizes the developed method in Chapter 9 to perform structural health monitoring to detect and classify the importance of defects and damage in the considered aeroengine using the obtained frequency response functions. Accordingly, this chapter proposes design guidelines which significantly improve the reliability and operational lifetime of the aeroengine at the lowest possible cost.

This book delivers extensive updated investigations and information to address the latest demands for the effective and efficient design and precise characterization of advanced multifunctional lightweight aerostructures. The authors believe that it is a comprehensive and useful reference for graduate students who want to increase their knowledge. This book provides innovative and practical solutions for active engineers, especially in the aerospace

industry, who are looking for alternative materials, structures or methodologies to solve their current problems.

All contributions to this book are the result of years of research and development conducted by the research team under the direct supervision of the principal investigator, Professor Kamran Behdinin, in the Advanced Research Laboratory for Multifunctional Lightweight Structures (ARL-MLS) at the University of Toronto. We would like to acknowledge the funding received from the Canadian Foundation for Innovation as well as the Natural Science Engineering Research Council of Canada in support of the ARL-MLS facilities and training of highly qualified personnel. Furthermore, we wish to take this opportunity to sincerely express our appreciation to the ARL-MLS graduate students and postdoctoral fellows for their outstanding research in addressing problems of utmost significance to the aerospace research community/industry in the field of advanced multifunctional lightweight aerostructures. Their informative contributions have allowed our ideas and dreams to become a reality in this book. We are also grateful to Wiley and its team of editors for helping us to finalize this book.

Toronto, June 2020

Kamran Behdinin
Rasool Moradi-Dastjerdi

Biographies

Professor Kamran Behdinan

Professor Behdinan earned his PhD in Mechanical Engineering from the University of Victoria in British Columbia in 1996 and has considerable experience in both academic and industrial settings. He was appointed to the academic staff of Ryerson University in 1998, tenured and promoted to the level of associate professor in 2002 and subsequently to the level of professor in 2007 and served as the director of the aerospace engineering program (2002–2003), and the founding Chair of the newly established Department of Aerospace Engineering (July 2003–July 2011). Professor Behdinan was a founding member and the Executive Director of the Ryerson Institute for Aerospace Design and Innovation (2003–2011). He was also a founding member and the coordinator of the Canadian–European Graduate Student Exchange Program in Aerospace Engineering at Ryerson University. He held the NSERC Design Chair in “Engineering Design and Innovation,” 2010–2012, sponsored by Bombardier Aerospace and Pratt and Whitney Canada. He joined the Department of Mechanical and Industrial Engineering, University of Toronto, as a professor in September 2011. He is the NSERC Design Chair in “Multidisciplinary Design and Innovation – UT IMDI,” sponsored by NSERC, University of Toronto, and 13 companies including Bombardier Aerospace, Pratt and Whitney Canada, United Technology Aerospace Systems, Magna International, Honeywell, SPP Canada Aircraft, Ford, and DRDC Toronto. He is the founding director of the “University of Toronto Institute for Multidisciplinary Design and Innovation,” an industry-centered, project-based learning institute in partnership with major aerospace and automotive companies.

Professor Behdinan is a past President of the Canadian Society of Mechanical Engineering (CSME), and served as a member of the International Union of Theoretical and Applied Mechanics (IUTAM) – General Assembly and the IUTAM Canadian National Committee, and a member of technical and scholarship committees of the High-Performance Computing Virtual Laboratory (HPCVL). He is the founding director and principal investigator of the University of Toronto, Department of Mechanical and Industrial Engineering “Advanced Research Laboratory for Multifunctional Lightweight Structures,” funded by the Canadian Foundation for Innovation as well as Ontario Research Fund. His research interests include Design and Development of Light-weight Structures and Systems for biomedical, aerospace, automotive, and nuclear applications, Multidisciplinary Design Optimization of Aerospace and Automotive Systems, Multi-scale Simulation of

Nano-structured Materials and Composites. He has supervised 32 PhDs, 120 Masters, and 40 Post-Doctoral Fellows and Scholars. He has also published more than 370 peer-reviewed journal and conference papers, and 9 book chapters. He has been the recipient of many prestigious awards and recognitions such as the Research Fellow of Pratt and Whitney Canada and Fellows of the CSME, ASME, the Canadian Academy of Engineering, EIC, AAAS, as well as Associate Fellow of AIAA.

Dr. Rasool Moradi-Dastjerdi

Dr. Moradi-Dastjerdi is currently a postdoctoral fellow in the Advanced Research Laboratory for Multifunctional Lightweight Structures at the University of Toronto. He obtained his PhD degree in Mechanics at Shahid Rajaei Teacher Training University, Tehran, Iran in 2016.

His research focuses on the coupled thermo-electro-mechanical analysis of smart multifunctional lightweight structures made of advanced materials such as piezoelectric materials, nanocomposites, functionally graded materials, and foams. He mainly utilizes advanced numerical methods including mesh-free and finite element methods. He has been an advisor for two PhD and six MSc theses. He has also contributed to more than 50 peer-reviewed journal papers. He was the recipient of the best researcher award from the Young Researcher and Elite Club of Isfahan Azad University in 2011, 2012, 2013, and 2016.

Part I

Multi-Disciplinary Modeling and Characterization

1

Layer Arrangement Impact on the Electromechanical Performance of a Five-Layer Multifunctional Smart Sandwich Plate

Rasool Moradi-Dastjerdi and Kamran Behdinan

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1.1 Introduction

The reversible effect of piezoelectricity is the ability to generate electrical charge as a result of subjecting to mechanical loads. This active effect is observed in some specific materials called piezoelectric materials. Such active materials are usually employed as attachments or layers in passive structures to provide a self-controlling property with fast response in the resulting smart structures [1]. The application of such active materials mainly relies on their passive structures. In the design of aerostructures, weight and strength are two key points which can be addressed using sandwich structures as they generally contain a thick lightweight core for stabilizing the structures and two thin stiff faces to provide structural strength [2–4]. In this regard, attaching thin layers made of polymer base nanocomposites onto the faces of polymeric porous cores results in multifunctional sandwich structures [5]. Moreover, the use of such passive structures as the host of piezoceramic attachments reduces failure risks due to the brittle structure of piezoceramics. Depending on the application, a wide range of nanofillers with astonishing thermomechanical properties have been proposed and utilized in nanocomposites. Among them, the extraordinary nanofillers of graphene and carbon nanotubes (CNTs) have aroused the interest of researchers in both academia and industry [6–8]. Although there are different parameters in the electromechanical design of five-layer multifunctional smart sandwich plates (5LMSSPs), protecting brittle layers of piezoceramic is also an important issue. Changing the location of piezoceramic layers from faces to middle layers (i.e. between porous core and nanocomposite faces) provides protecting layers. This change in layer arrangements can affect both the mechanical and electrical response of such structures.

In recent literature, different passive structures have been considered as host for piezoelectric sensors/actuators to introduce smart structures with potential applications in energy harvesters [9], noise and vibration reduction [10], fluid delivery [11, 12] and structural damage monitoring [13] where piezoelectricity plays an essential role. In these structures, piezoelectric components come as attached pieces, separate layers or

(nano)fillers. Askeri et al. [14] proposed attaching two lead zirconate titanate (PZT) layers on the faces of a transversely isotropic nonpiezoelectric plate to introduce a smart plate. Functionally graded (FG) metal/ceramic materials, as advanced materials, have been considered as the passive part of smart structures activated by piezoelectric materials. In this regard, passive plates and shells made of such FG materials and PZT-activated layer(s) were considered under thermo-electro-mechanical loads to study their nonlinear dynamic responses in [15–17]. The deflections of FG titanium/aluminum oxide plates integrated between PZT faces under static and dynamic electromechanical loads were presented in [18]. Khoa et al. [19] covered the outer layer of imperfect FG metal/ceramic cylindrical shells with a PZT layer and studied its buckling resistance. In another setting, laminated composites have been also employed as the passive part of piezoelectric activated smart structures. Talebitooti et al. [20] considered such plates covered with PZT sensor and actuator layers to optimally control the vibrations of the obtained smart plates using a feedback algorithm. By developing an isogeometric finite element method (FEM), Phung-Van et al. [21] aimed to outline the static deflections and vibrations of the same composite plates actuated by PZT layers. To reduce structural weight, nanocomposite materials have also been used as the host of piezoelectric actuated smart structures. In addition, there are different types of nanofillers that can be utilized in specific applications. The use of composite plates enhanced with wavy CNTs and carbon fibers as the multifunctional host of two piezoelectric patches was proposed by Kundalwal et al. [10]. They utilized piezoelectric patches made of piezoceramic fibers embedded in a polymer to provide smart damping property for host plates. Mohammadimehr et al. [22] employed nanofillers of CNTs and piezoelectric nanotubes of boron nitride in passive and active polymers and considered double sandwich plates. They presented the vibration behaviors of such smart structures subjected to magnetic and electric fields. Moradi-Dastjerdi et al. [23] proposed the use of nanocomposite plates enhanced with nanoclays in aggregated and intercalated forms as the passive layers of a smart plate with two PZT faces. Arani et al. [24] utilized two piezoelectric faces made of polyvinylidene fluoride to control the frequencies of CNT/polymer microplates under magnetic field and located on an elastic foundation. Malekzadeh et al. [25] considered a graphene/polymer multi-layered circular plate with a randomly located hole activated with two PZT faces and outlined its vibration behavior. For further reduction of structural weight in the passive layer, porous material can be utilized. Jabbari et al. [26, 27] suggested the use of circular plates with FG dispersions of embedded porosities for passive layers activated by attaching two PZT faces and investigated the stability resistances of the obtained smart circular plates. Askari et al. [28] considered rectangular plates with FG patterns of porosity dispersion between two PZT faces to determine porosity impact on the natural frequencies of the resulted active plates. Barati and Zenkour [29] studied the vibrations of active porous plates made of an FG mixture of two different piezoceramics. Mohammadi et al. [30] considered aluminum cylindrical pressure vessels with three patterns of porosity dispersion integrated between two inner and outer PZT faces as sensor and actuator. They presented the electromechanical responses of such smart pressure vessels located in elastic media. In a more advanced setting of smart structures, the combination of nanocomposite and porous materials have been utilized as multifunctional passive structures. Nguyen et al. [31, 32] proposed three-layer smart sandwich plates with a metal porous layer enhanced with graphene platelets (GPLs) as a

passive core integrated between two active PZT faces. They considered FG patterns for the dispersions of GPLs and porosities in the passive layer and obtained two different sets of results including vibrational response and its active control using PZT layers. However, GPLs in the core layer of these three-layer smart plates interfere with the electrical charge and potential field obtained in PZT faces. In addition, according to the concept of sandwich panels, the use of separated layers of nanocomposite and porous materials leads to five-layer multifunctional smart panels with higher structural stiffness to weight ratio. In these regards, Setoodeh et al. [33] proposed such five-layer smart curved shells including two PZT faces, two CNT-enhanced nanocomposite middle layers and one porous core with FG patterns for the dispersions of nanofillers and porosities. Another set of five-layer smart plates including PZT faces, graphene/polymer middle layers and porous core were also proposed and thermo-electro-mechanical behaviors of such 5LMSSPs are presented in [34–37].

Five-layer multifunctional smart sandwich plates with layers made of porous, GPL/polymer and PZT have been proposed in the literature. However, considering piezoceramic layers as the faces of such plates is a challenging point because of their brittle nature. Therefore, in this work, a comparison study has been conducted to explore the impact of changing the location of piezoceramic layers from faces to middle layers on the electromechanical performances of 5LMSSPs. In this regard, a mesh-free solution has been developed based on Reddy's third-order shear deformation theory (TSDT). Moreover, Halpin–Tsai equations with the ability to capture the shape of nanofillers are employed to define the mechanical properties of GPL/polymer nanocomposite layers. In addition to the impact of layer arrangement, the effects of GPL volume and dispersion, porosity volume and the thickness of each layer are investigated in this chapter.

1.2 Modeling of 5LMSSP

The considered multifunctional smart sandwich plates have five layers including one porous, two piezoelectric and two GPL-reinforced nanocomposite layers to provide a wide range of industrial applications. There is no doubt in the use of a porous layer as the core because embedding porosity in the core results in a remarkable structural weight reduction without a significant loss of structural stiffness. However, the locations of nanocomposite and piezoelectric layers could be changed based on the operating conditions of 5LMSSPs. As shown in Figure 1.1, two different layer arrangements have been examined: case I, considering piezoceramics as faces; and case II, considering nanocomposite layers as the faces of 5LMSSP to protect the piezoelectric from environmental and loading issues. In both cases, 5LMSSPs are assumed under a uniform mechanical pressure f_0 on their top faces. In addition, the piezoelectric layers are subjected to an electrical input such that their outer faces are connected to a uniform voltage V_0 and their inner faces are grounded to provide a voltage difference of V_0 through the thickness of each piezoelectric layer. In this chapter, square 5LMSSPs with side length of a and thickness of h are considered. The thicknesses of porous, piezoelectric and nanocomposite layers are represented by h_c , h_p , and h_n , respectively.

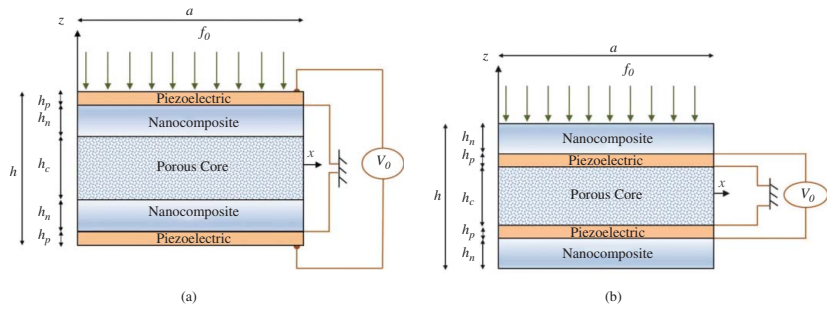


Figure 1.1 Two different layer arrangements of the considered five-layer sandwich plates with one porous, two piezoelectric and two GPL-reinforced nanocomposite layers: (a) SLMSSP case I; and (b) SLMSSP case II.

1.2.1 Porous Layer

Embedding pores in a body affects the material properties of the host body. In this chapter, the distribution of pores is considered as a symmetric profile through the thickness of the core layer such that the outer faces of the core i.e. $z = \pm h_c/2$ has no pores, but the highest volume of pores is located at $z = 0$. Using Gaussian random field technique [38], Young's modulus E^p , density ρ^p and Poisson's ratio ν^p of such porous layer can be estimated as [31]:

$$E^p(z) = \left(1 - q_0 \cos\left(\frac{\pi z}{h_c}\right) \right) E^m \quad (1.1)$$

$$\rho^p(z) = \left(1 - q_m \cos\left(\frac{\pi z}{h_c}\right) \right) \rho^m \quad (1.2)$$

$$\nu^p(z) = 0.221\beta + \nu^m(0.342\beta^2 - 1.21\beta + 1) \quad (1.3)$$

where superscripts m and p show the corresponding properties of perfect polymeric ($q_0 = 0$) and porous ($q_0 \neq 0$) core layer, respectively. In addition, q_0 is the porosity parameter which implies the porosity volume fraction of the core layer. q_m and β are determined as [31]:

$$q_m = \frac{1.121(1 - \sqrt[3]{1 - q_0 \cos(\pi z/h_c)})}{\cos(\pi z/h_c)} \quad (1.4)$$

$$\beta = 1 - \rho^p/\rho^m = q_m \cos(\pi z/h_c) \quad (1.5)$$

1.2.2 Nanocomposite Layers

Graphene platelets are assumed to be dispersed with functionally graded patterns in nanocomposite layers to optimize the volume of GPLs and to improve the structural performance of 5LMSSPs. The FG patterns of nanofillers in cases I and II can be described as the functions of GPL volume fraction V_r versus z location as follows [35]:

Case I:

$$\text{Upper nanocomposite layer: } V_r(z) = [(2z - h_c)/2h_n]^p \times V_r^* \quad (1.6)$$

$$\text{Lower nanocomposite layer: } V_r(z) = [-(2z + h_c)/2h_n]^p \times V_r^* \quad (1.7)$$

Case II:

$$\text{Upper nanocomposite layer: } V_r(z) = [(2z - 2h_p - h_c)/2h_n]^p \times V_r^* \quad (1.8)$$

$$\text{Lower nanocomposite layer: } V_r(z) = [-(2z + 2h_p + h_c)/2h_n]^p \times V_r^* \quad (1.9)$$

where V_r^* is the specific GPL volume fraction and p is the exponent of GPL volume fraction which controls the profile of GPL dispersion. The dispersion profiles of GPLs through the thickness of the considered 5LMSSP are illustrated in Figure 1.2.

To determine the effective mechanical properties of nanocomposite layers, Halpin-Tsai's approach [39, 40] capable of considering the rectangular shape of GPLs is employed.

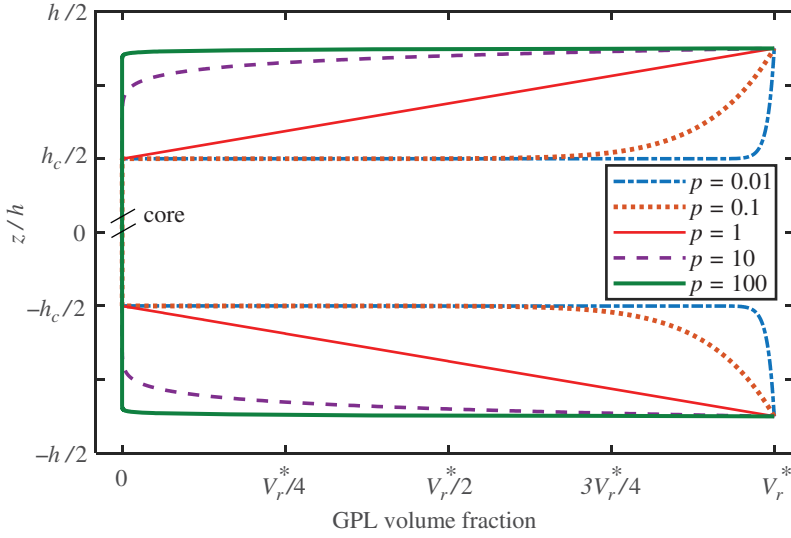


Figure 1.2 The dispersion profiles of GPLs through the thickness.

According to this approach, the effective Young's modulus of GPL/polymer nanocomposite is estimated as follows [39, 40]:

$$E(z) = \frac{3}{8} \left[\frac{1 + 2(a^g/h^g) \gamma_{11}^g V_r}{1 - \gamma_{11}^g V_r} \right] E^m + \frac{5}{8} \left[\frac{1 + 2(b^g/h^g) \gamma_{22}^g V_r}{1 - \gamma_{22}^g V_r} \right] E^m \quad (1.10)$$

where

$$\gamma_{11}^g = \frac{E^g/E^m - 1}{E^g/E^m + 2a^g/h^g}, \gamma_{22}^g = \frac{E^g/E^m - 1}{E^g/E^m + 2b^g/h^g} \quad (1.11)$$

where E^g and E^m are the Young's moduli of GPL and polymeric matrix, respectively. Moreover, a^g , b^g , and h^g are the geometrical dimensions of GPL, respectively.

1.2.3 Governing Equations

To calculate the energy function of the considered 5LMSSPs, displacement field is needed to be defined by a plate theory. It is well established that the increase of the order of plate theory makes the theory more applicable to thicker plates. Therefore, an efficient TSDT reported by Reddy [41] is utilized to determine x , y and z components of displacement field (i.e. u , v , and w) in 5LMSSPs as:

$$\begin{aligned} u(x, y, z) &= u_0(x, y) + z \theta_x(x, y) + z^3 c_1 (\theta_x + w_{0,x}) \\ v(x, y, z) &= v_0(x, y) + z \theta_y(x, y) + z^3 c_1 (\theta_y + w_{0,y}) \\ w(x, y, z) &= w_0(x, y) \end{aligned} \quad (1.12)$$

where $c_1 = -4/3h^2$ and θ_x and θ_y are the rotations of mid-plane around the y and x axes, respectively. As Eq. (1.12) shows, the utilized plate theory has only five unknowns which is