Thin-Walled Composite Beams

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Thin-Walled Composite Beams

Theory and Application

by

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Liviu Librescu: To my wife Marilena Librescu, M. D., for her devotion, love, support and encouragement. Her patience and her contributions to technical matters in the book are greatly appreciated.

Ohseop Song: To my wife Bokyong Chun for her endless love and support.

Motto

I will bless the Lord at all times; his praise shall continually be in my mouth.
David, Psalm 34 verse 2.

To the glory of God who inspired us to believe, and gave us the ability to think and the wisdom to write this book for others to read and to use. Blessed be the Lord. It is with gratitude and happiness that we serve the community.

Thanks be to God.

Liviu Librescu and Ohseop Song

CONTENTS

PREFACE

There has been a growing interest in the foundation of the theory of thin-walled composite beams and of their incorporation in aeronautical/aerospace, automotive, helicopter and turbomachinery rotor blades, mechanical, civil and naval constructions in the last two decades or so.

The proliferation of the specialized literature, mainly in the form of journal/ proceedings papers, and the activity in terms of workshops devoted to this topic attest this interest. A decisive factor that has fueled this growing activity was generated by high diversity and severity of demands and operating conditions imposed on structural elements involved in the advanced technology. In order to be able to survive and fulfill their mission in the extreme environmental conditions in which they operate, new materials and new structural paradigms are required.

The new exotic structures have to provide higher performances, unattainable by the classical structures built of traditional materials. The advent of advanced composite materials, of smart materials and functionally graded materials (FGMs), have constituted the strongest stimuli for such developments. Moreover, their incorporation is likely to expand the use and capabilities of thin-walled beam structures. The new and stringent requirements imposed on aeronautical/aerospace, turbomachinery and shaft structural systems will be best met by such new types of material structures.

However, incorporation of these new material structures in the various areas of advanced technology and the solution of many challenging problems involving their static/dynamic response, stability and control, require a good understanding of the various aspects of their modeling and computational methodologies. While the directionality property of composite materials provides new degrees of freedom to the designer, enabling him to achieve greater structural efficiency, it constitutes an enormous challenge for someone who is not familiar with the capabilities that the implementation of the tailoring technology can provide.

For these structures, a good knowledge is also mandatory when dealing with the use of FGMs, and of smart materials in conjunction with feedback control.

For the authors of this book it was a pleasure to contribute to this most challenging and modern field of structural mechanics with a monograph on composite thin-walled beams, the first in the overall specialized literature.

Issues of the modeling and behavior of such structures composed of fiber composite materials and of FGMs, as well as appropriate feedback control methodologies have been developed and applied to many important problems, to alleviate and contain the oscillations generated by explosive blasts impacting the structure.

The monograph is concerned not only with the foundation and formulation of modern linear and nonlinear theories of composite thin-walled beams developed by the authors with their collaborators, but also provides powerful mathematical tools to address issues of free vibration, dynamic response to external excitation, stability and control of gyroscopic and aeroelastic systems. Special care was exercised to show the power of the tailoring technique in the specific problems treated in the monograph. The effects of transverse shear, warping inhibition, and of various elastic couplings on the behavior of these structures, have been highlighted. The two theories, shearable and unshearable, have been compared from the point of view of their mathematical description and of their static, dynamic and stability predictions, and proper conclusions have been drawn. No effort has been spared to compare our predictions with those available in the literature.

Regarding the foundation and formulation of the 1-D theory of composite thin-walled beams, an effort was made to derive the related field equations from the three-dimensional equations of elasticity theory. This approach has enabled us to present a unified treatment of the general theory of thin-walled beams, and provide a number of theorems with counterparts in the 3-D elasticity theory.

In order to provide a unified formulation and approach to both the linear and nonlinear problems, Chapters 2 through 5 are devoted to the foundation of the theory of thin-walled composite beams. While Chapter 1 has an introductory role, highlighting the importance of the topics treated in this monograph and presenting the basic milestones along the developments of thin-walled beam theory, Chapter 2 deals with the kinematics of open/closed cross-sections, and of uni/multicell TWBs. The issue of free and constrained warping, as well as of those related to the geometrically nonlinear and higher-order kinematics are elaborated.

Chapter 3 is concerned with the derivations of the equations of motion and of the related boundary conditions of open/closed cross-section beams. Since Hamilton's principle was used in their derivation, the associated boundary conditions have been obtained in a consistent manner. This was done for both the shearable/nonshearable and for the linear/nonlinear TWBs theories. The equations associated with the higher-order geometrically linear theory and with dissipative effects have been also accounted for.

Chapter 4 deals with some additional equations associated with the linear theory. The kinetic and strain energies associated with the shearable/unshearable TWBs models are presented. The governing equations are expressed in terms of 1-D displacement quantities for the anisotropic TWBs. It is shown that two decoupling types of the governing equations, each of which involving different elastic couplings, can be obtained through the implementation of two special lay-up configurations; this is presented for both shearable and unshearable TWBs.

Chapter 5 is devoted to the formulation of a few theorems in TWBs having counterparts in the 3-D elasticity theory. Beyond their academic importance, these theorems reveal the affiliation of the derived equations with those in the 3-D elasticity theory, from which they were obtained. Applications emerging from some of these theorems have been used in various parts of the monograph.

Chapter 6 deals with the free vibration of TWBs. Two basic solution methodologies used in the monograph in general, and in free vibration problems in particular, are presented. Related problems for non-uniform cross-section beams, validation of predictions, incorporation of the concept of *smart* TWBs, pertinent results and conclusions are provided.

Chapter 7 is devoted to the dynamic response of TWBs to time-dependent external excitations generated by an explosive blast or by a sonic-boom pulse. The two solution methodologies presented in Chapter 6 are extended to address this problem. In addition, the approach based on the orthogonality property of eigenmodes that was obtained in Chapter 5 by simply applying the reciprocal theorem, is also presented. We discuss the dynamic response of TWBs without/with incorporation of adaptive capabilities in conjunction with the piezoelectric induced strain actuation and of a feedback control methodology, and present results highlighting the beneficial and synergistic effects of tailoring and active feedback control technologies.

Chapter 8 deals with the behavior of TWBs carrying external stores. The problem is treated in the context of the transverse bending only. Issues of the feedback control of smart beams with external stores are addressed and results are reported.

Chapter 9, the largest chapter, deals with rotating TWBs. It addresses issues related to their modeling and incorporation of a number of important effects such as pretwist, presetting, anisotropy of constituent materials, temperature degradation of material properties for turbomachinery blades operating in a high temperature environment, transverse shear, tennis-racket, tension-torsion, geometrical nonlinearities. The model of a rotating blade made up of functionally graded materials (FGMs) is developed, and its performances are supplied.

Models of rotating blades carrying a tip mass, featuring extension-twist elastic coupling that is important for helicopter blades and tilt-rotor aircraft are developed in a general context. Feedback control of smart rotating beams is considered. The validity and complete agreement of the kinematic equations of pretwisted rotating blades as obtained via application of Wagner's multifilamentary concept and through Washizu's most accurate modeling are demonstrated.

Chapter 10 deals with the modeling and behavior of spinning TWBs. It is shown that centrifugal effects generated by the spinning speed produce a bifurcation of eigenfrequencies. Although conservative in nature, in some conditions, such systems can feature instabilities by divergence and flutter that are proper to non-conservative systems. We consider issues related the effects of pretwist, transverse shear, anisotropy, cross-sectional shape, boundary conditions, geometrical nonlinearities on their behavior. We develop the concept of FGMs in this type of structure and emphasize its usefulness in the presence of a high temperature during operating conditions. In this chapter we model the robotic gyroscopic system consisting of a TWB carrying a spinning tip rotor, and discuss its behavior with respect to the instabilities by divergence and flutter. We note the beneficial effects of piezoelectric induced strain actuation and of the tailoring technique.

Chapter 11 is devoted to the vibration and feedback control of spacecraft booms modeled as TWBs exposed to solar radiation. It is well-known that these structural systems are susceptible to flutter instability. This instability can jeopardize the mission of the spacecraft or satellite. An advanced model of spacecraft booms is developed, and issues of vibration, instability, feedback control and thermal compensation are addressed.

Chapter 12 is devoted to the aeroelasticity of aircraft wings modeled as anisotropic thin-walled beams. We develop an advanced model of anisotropic straight/swept wing structures and address issues of static aeroelastic instability and response, and feedback control. In the context of the same structural model, a few results on flutter and dynamic aeroelastic response of aircraft wings in various flight speed regimes are included.

Chapter 13 deals exclusively with the modeling and the static/dynamic behavior of open-section anisotropic beams of the I-profile.

In order to avoid any interruption in the description of the main topics treated in the monograph, the Appendix provides the background for the study of the anisotropy and heterogeneity of TWBs.

Lists of references are included at the end of each chapter.

We trust that this preview will give to the reader an idea on the topics covered by this monograph.

We hope that the monograph will prove useful to many researchers working in industry and academia in applied mechanics and aeronautics, for practicing engineers in the field of aeronautical/aerospace, mechanical, civil, nuclear and naval engineering, and for graduate students also.

All symbols are defined when first introduced. We tried to maintain a complete uniformity in notations. In some instances the same symbol has been used in different contexts. In such cases, the proper indications will avoid any possibility of confusion.

In the preparation of this book, we are indebted to many colleagues, scientists and former doctoral students who, through numerous discussions and research collaborations over many years, have helped us to mature our insight into the subject matter and enrich this work. It is virtually impossible to quantify how much we owe to them.

In particular, Chapters 6 through 8 contain results obtained during a close and fruitful scientific cooperation with Professor Sungsoo Na from Korea University in Seoul, Korea. Chapters 9 and 10 have been greatly influenced by close cooperation with Dr. Sang-Yong Oh, a Research Scientist at Virginia Tech; some issues in Chapter 10 were developed in cooperation with Dr. Nam-Hui Jeong from Chungnam National University in Daejeon, Korea; the parts from Chapters 2 and 3 addressing geometrically non-linear theories of TWBs have been influenced by cooperation with Professor Kanaan Bhaskar from the Indian Institute of Technology, Madras, India, during his working visit at Virginia Tech; the issues of higher-order theory and its applications to rotating blades were developed with Professor Naresh K. Chandiramani and his students, among others Mr. Shete C.D., from the Indian Institute of Technology, Guwahati, India; Chapter 12, in particular, was influenced by joint research with Dr. Zhanming Qin, a multidisciplinary Research Scientist at Virginia Tech who validated predictions generated from our developed structural model against those available in literature, while Chapter 10 benefited from the cooperation with Dr. Hyuck-Dong Kwon, Yonsei University, Seoul, South Korea, now a visting Research Scientist at Virginia Tech.

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