

Thin-Walled Composite Beams

SOLID MECHANICS AND ITS APPLICATIONS

Volume 131

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Thin-Walled Composite Beams

Theory and Application

by

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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	xxi
1. Introduction	1
1.1 Preliminary Remarks. Importance of the Topic	1
1.2 Contents of the Monograph	4
References	6
2. Kinematics of Thin Walled Beams	7
2.1 Geometrically Linear Theory	7
2.1-1 General Considerations	7
2.1-2 General Definitions. Coordinate Systems	8
2.1-3 Basic Assumptions	10
2.1-4 Displacement Field	11
2.1-5 Free and Constrained Warping	13
2.1-6 Open Cross-Section Beams	14
2.1-7 Single-Cell Closed Beam Cross-Sections	18
2.1-8 Saint-Venant Free Twist of Closed Cross-Section Beams	22
2.1-9 Unified Form of the Warping Function	23
2.1-10 The Strain Field	24
2.1-11 Open Versus Closed Section Beams	26
2.2 Kinematics of Geometrically Nonlinear Thin-Walled Beams	27
2.2-1 Preliminaries	27
2.2-2 Coordinate Systems. Assumptions	28
2.2-3 Displacement Field	28
2.2-4 Strain Field	30

2.3	Multicell Thin-Walled Beams	33
2.3-1	Preliminaries	33
2.3-2	Torsion of Multi-Cell Beams	33
2.3-3	Warping Functions	37
2.4	High-Order Thin-Walled Beam Theory	44
2.4-1	Preliminaries	44
2.4-2	Assumptions and Basic Equations	45
2.5	Bibliographical Comments	48
	References	48
3.	The Equations of Motion of Open/Closed Cross-Section Beams	53
3.1	Nonlinear Formulation	53
3.1-1	Preliminaries	53
3.1-2	General Background	53
3.1-3	Application of Hamilton's Principle to Thin-Walled Beams	55
3.1-4	Equations of Motion	64
3.1-5	The Boundary Conditions	64
3.1-6	The Equations for Non-Shearable Beam Model	65
3.1-7	Remarks	66
3.2	Linear Formulation	67
3.2-1	Energy Quantities in Linear Beam Theory	67
3.2-2	Dissipative Effects	69
3.2-3	Equations of Motion and Boundary Conditions	71
3.2-4	Remarks	72
3.3	Higher-Order Theory: Geometrically Linear Thin-Walled Beams	73
	References	75
4.	Additional Equations of the Linear Beam Theory	77
4.1	Kinetic Energy	77
4.2	Rayleigh's Dissipation Function	79
4.3	Strain Energy	80
4.4	The Governing System	81
4.4-1	Displacement Formulation	82
4.4-2	A Few Comments	86
4.4-3	Unshearable Thin-Walled Beams	87

<i>Contents</i>	xi
4.4-4 Two Structural Coupling Configurations	88
4.4-5 Other Special Cases	94
4.4-6 Unshearable CAS and CUS Beam Configurations	96
4.4-7 Cross-Ply Beam Configuration	99
4.4-8 Spanwise Beam Uniformity	101
4.5 Discussion	102
References	103
5. Several Theorems in Linear Thin-Walled Beam Theory	107
5.1 Theorem of Power and Energy	107
5.2 Uniqueness of Solution	109
5.3 Virtual Work Principle	110
5.4 Clapeyron's Theorem (Theorem of Work and Energy)	111
5.5 Bilinear Form Associated with the Strain Energy \mathcal{W}	111
5.6 Betti's Reciprocal Theorem	112
5.7 Self-Adjointness of the Boundary-Value Problem	113
5.8 Orthogonality of Modes of Free Vibration	114
5.9 Dynamic Response	116
Bibliographical Comments	118
References	118
6. Free Vibration	121
6.1 Introduction	121
6.2 Basic Assumptions and Governing Equations	122
6.3 The Eigenvalue Problem	125
6.3-1 Preliminary Considerations	125
6.3-2 The Laplace Transform Method (LTM)	126
6.3-3 Extended Galerkin Method (EGM)	128
6.4 Results	131
6.4-1 General Considerations	131
6.4-2 Results for the CUS Beam Configuration	132
6.4-3 Results for the CAS Beam Configuration	136

6.5	Free Vibration of Non-Uniform Cross-Section Beams	139
6.5-1	Preliminaries	139
6.5-2	Basic Assumptions	139
6.5-3	A Few Numerical Results	141
6.5-4	Validation of the Accuracy of the Extended Galerkin Method	142
6.6	Adaptive/Smart Thin-Walled Beams	144
6.6-1	Introduction	144
6.6-2	Piezoelectrically Induced Bending Moments. Piezoactuator Location	144
6.6-3	Governing Equations of Smart Thin-Walled Beams	146
6.6-4	Sensing and Actuation Feedback Control	149
6.6-5	The Discretized Governing Equations of Adaptive Beams	150
6.6-6	Numerical Simulations	151
6.7	Closing Remarks	159
	References	160
7.	Dynamic Response to Time-Dependent External Excitation	165
7.1	Introduction	165
7.2	Governing Equations	166
7.2-1	Shearable Model	166
7.2-2	Purely Bending Shearable Beam Model	167
7.2-3	Unshearable Beam Model	169
7.3	Time-Dependent External Excitations	170
7.3-1	Explosive Pressure Pulses	170
7.3-2	Time-Dependent Harmonic Excitation	172
7.4	Solution Methodology	173
7.4-1	Preliminaries	173
7.4-2	Laplace Transform Method	173
7.4-3	Extended Galerkin Method	177
7.4-4	Normal Mode Approach	178
7.5	Numerical Simulations	180
7.5-1	Preliminaries	180
7.5-2	Box-Beam in Pure Transverse Bending	180
7.5-3	Bi-Convex Symmetric Cross-Section Beams Featuring Bending-Twist Cross-Coupling	183

<i>Contents</i>	xiii
7.6 Closed-Loop Dynamic Response	188
7.6-1 Preliminaries	188
7.6-2 Closed-Loop Response to Harmonic Loads	189
7.6-3 Dynamic Response Control	189
7.6-4 Numerical Simulations and Discussion	191
7.7 Instantaneous Optimal Feedback Control	195
7.7-1 Preliminaries	195
7.7-2 Control Law	195
7.7-3 Saturation Constraint	198
7.7-4 Sensor Output Equation	199
7.8 Expressions of Matrices M and K	200
7.9 Results	202
7.9-1 Preliminaries	202
7.9-2 Case (B) coupled with Case (a)	202
7.9-3 Case (B) coupled with Case (b)	204
References	208
8. Thin-Walled Beams Carrying Stores	213
8.1 Preliminaries	213
8.2 Transverse Bending of Beams Carrying Distributed Stores	213
8.2-1 Basic Assumptions	213
8.2-2 Equations of Motion and Boundary Conditions. Shearable Beams	215
8.2-3 Unshearable Beams	217
8.3 Adaptive Beams Carrying External Stores	219
8.3-1 Preliminaries	219
8.3-2 Governing Equations	219
8.3-3 Static and Dynamic Feedback Control	221
8.3-4 Results	224
References	230
9. Rotating Thin-Walled Anisotropic Beams	233
9.1 Untwisted Beams	233
9.1-1 Introduction	233
9.1-2 Preliminaries	234
9.1-3 Kinematic Equations	235
9.1-4 The Equations of Motion and Boundary Conditions	238
9.1-5 Several Remarks on the Equations of Motion and	

	Boundary Conditions	242
9.1-6	The Governing System	243
9.1-7	Decoupled Natural Frequencies of Rotating Beams	247
9.1-8	Comparisons with Available Predictions	249
9.1-9	Numerical Simulations-Extended Galerkin Method Applied to Rotating Beams	252
9.1-10	Numerical Simulations and Behavior	258
9.2	Pretwisted Rotating Beams	263
9.2-1	Preliminaries	263
9.2-2	Basic Assumptions	264
9.2-3	The Governing System	266
9.2-4	Several Comments on the Governing System	270
9.2-5	Numerical Results and Discussion	274
9.2-6	Adaptive Rotating Thin-Walled Beams	279
9.3	Pretwisted Rotating Thin-Walled Beams Operating in a Temperature Environment	285
9.3-1	Preliminaries	285
9.3-2	Basic Assumptions	286
9.3-3	Numerical Simulations	288
9.3-4	Final Remarks	296
9.4	Effects of Presetting on Coupled Vibrations of Rotating Blades	296
9.4-1	Preliminaries	296
9.4-2	A Special Case	298
9.4-3	Comparisons with Available Numerical Predictions	299
9.4-4	Results and Discussion	302
9.5	Rotating Blades Made-up of Functionally Graded Materials	310
9.5-1	Preliminaries	310
9.5-2	Structural Model. Basic Assumptions	310
9.5-3	3-D Constitutive Equations	311
9.5-4	Governing System	313
9.5-5	Validation of the Model and of the Solution Methodology	315
9.5-6	Numerical Results and Discussion	317
9.6	Rotating Blades Carrying a Tip Mass	330
9.6-1	Preliminaries	330
9.6-2	Kinematics, Equations of Motion and Boundary Conditions	331
9.6-3	The Governing System	334
9.6-4	Numerical Simulations	337
9.6-5	Influence of the Induced Strain Actuation	345

9.7	Pretwisted Rotating Blades Featuring Extension-Twist Elastic Coupling	353
9.7-1	Preliminaries	353
9.7-2	Kinematics	354
9.7-3	The Equations of Motion and Boundary Conditions	357
9.7-4	Validation of the Structural Model and Solution Methodology	364
9.7-5	Results and Discussion	364
9.7-6	A Few Comments about Washizu's Approach	372
9.8	A Few Results on Geometrically Nonlinear Rotating Beams	375
9.8-1	Preliminaries	375
9.8-2	Kinematics	375
9.8-3	Equations of Motion and Boundary Conditions	376
9.8-4	Special Cases	381
9.8-5	A Few Results	384
	References	385
10.	Spinning Thin-Walled Anisotropic Beams	395
10.1	Untwisted Beams	395
10.1-1	Introduction	395
10.1-2	Coordinate Systems and Basic Assumptions	396
10.1-3	Kinematics	397
10.1-4	Governing Equations	397
10.1-5	Special Cases	399
10.1-6	Solution of the Eigenvalue Problem of Gyroscopic Systems	401
10.1-7	Closed-Form Solutions	402
10.1-8	Comparisons with Available Predictions	404
10.1-9	Numerical Simulations	406
10.1-10	Concluding Remarks	408
10.2	Vibrations and Stability of Spinning Circular Cylindrical Shaft	409
10.2-1	Preliminaries	409
10.2-2	Governing Equations	409
10.2-3	Two Alternative Representations of Governing Equations	410
10.2-4	The Eigenvalue and Instability of the Spinning Shaft	411
10.2-5	Results	411
10.2-6	Concluding Remarks	417
10.3	Pretwisted Spinning Beams	417
10.3-1	Basic Assumptions	417
10.3-2	Governing System	418

10.3-3	Nonshearable Beam Counterpart	419
10.3-4	Comparisons with Other Results	420
10.3-5	Numerical Simulation and Discussion	421
10.3-6	Concluding Remarks	425
10.4	Functionally Graded Thin-Walled Beams	426
10.4-1	Preliminaries	426
10.4-2	Basic Assumptions	426
10.4-3	Governing System	426
10.4-4	Results	428
10.5	A Beam Carrying a Spinning Tip Rotor	436
10.5-1	Preliminaries	436
10.5-2	Basic Assumptions	437
10.5-3	Kinematics	438
10.5-4	Governing Equations	439
10.5-5	Explicit Derivation of Eq. (10.5-5)	443
10.5-6	Solution Methodology	444
10.5-7	Results	447
10.5-8	Concluding Remarks	452
10.6	Smart Thin-Walled Spinning Beams	453
10.6-1	Preliminaries	453
10.6-2	Results	455
10.6-3	Concluding Remarks	467
10.7	Geometrically Nonlinear Spinning Beams	467
10.7-1	Preliminaries	467
10.7-2	Governing Equations	467
10.7-3	Numerical Results	470
	References	470
11.	Thermally Induced Vibration and Control of Spacecraft Booms	475
11.1	Introduction	475
11.2	Non-Stationary Thermal-Loading	476
11.3	Thermally Induced Vibration	480
11.4	Governing System	481
11.4-1	Shearable Booms	481
11.4-2	Unshearable Booms	482
11.4-3	Alternative Form of Equations for Transverse Bending	483

<i>Contents</i>	xvii
11.5 Solutions for Thermally Induced Vibrations	484
11.5-1 Preliminaries	484
11.5-2 Quasi-Static Solution	485
11.5-3 Vibratory Solution	486
11.6 Numerical Simulations on Dynamic Response	487
11.7 Piezoelectric Vibration Control	489
11.7-1 Preliminaries	489
11.7-2 Open/Closed Loop Dynamic Response	491
11.8 Results	491
11.8-1 Validation of the Solution Methodologies	491
11.8-2 Open/Closed Loop Response and Instability	493
11.9 Conclusions	495
References	495
12. Aeroelasticity of Thin-Walled Aircraft Wings	499
12.1 Preliminaries	499
12.2 Governing Equations	500
12.3 Static Response and Divergence Instability	503
12.3-1 Preliminaries	503
12.3-2 Special Cases	504
12.3-3 Bending-Twist Divergence of Swept-Forward Wings	506
12.4 Numerical Simulations	507
12.4-1 Divergence Instability	508
12.4-2 Subcritical Static Aeroelastic Response	509
12.5 Dynamic Aeroelasticity of Aircraft Wings	512
12.5-1 Preliminaries	512
12.5-2 General Considerations	513
12.5-3 Selected Results	514
12.6 Lifting Surface Control Using Smart Materials Technology	518
12.6-1 Preliminaries	518
12.6-2 Results	519
12.6-3 Concluding Remarks	520
References	520

13. Open-Section Beams	525
13.1 Introduction	525
13.2 Basic Equations	527
13.2-1 Preliminaries	527
13.2-2 Kinematic Equations	527
13.2-3 Equations of Motion and Boundary Conditions	528
13.2-4 CAS Configuration	528
13.2-5 CUS Configuration	535
13.2-6 Results	540
13.3 Conclusions	550
References	551
Appendix A: The Constitutive Equations	557
A.1 Introduction	517
A.2 Linearly Elastic 3-D Anisotropic Continuum	517
A.3 Material Symmetry	559
A.3-1 One Surface of Symmetry (Monclinic Hookean Material)	559
A.3-2 Three Planes of Symmetry (Orthotropic Material)	560
A.3-3 Transverse Isotropy	561
A.3-4 Isotropic Hookean Material	562
A.4 Alternative Form of the 3-D Constitutive Equations	564
A.5 Transformation of Material Coefficients	564
A.6 Alternative Representations	569
A.7 Elastic Coefficients of Orthotropic Materials in Terms of Engineering Constants	571
A.8 Anisotropic Thin-Walled Beams	573
A.8-1 Introduction	573
A.8-2 3-D Equations for a Lamina	574
A.8-3 2-D Stress-Resultants and Stress-Couples	575
A.8-4 A First Step Toward Obtaining the Constitutive Equations of Thin-Walled Open Beams	577
A.8-5 Remarks on Stiffness Quantities	580
A.8-6 Selected Classes of Laminate Configurations	582
A.8-7 Equations for Open Cross-Section Beams	583
A.8-8 2-D Constitutive Equations for Closed Cross-Section	

<i>Contents</i>	xix
Beams	584
A.8-9 Final Form of 2-D Constitutive Equations	586
A.8-10 Unified Form of 2-D Constitutive Equations	587
A.8-11 Two Structural Coupling Configurations – CUS and CAS	588
A.8-12 Additional Remarks	589
A.9 Piezoelectric Constitutive Equations	589
A.9-1 Preliminaries	589
A.9-2 Piezoelectric Medium	590
A.9-3 2-D Piezoelectric Constitutive Equations	591
References	593
Subject Index	595

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 famil-

iar 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 con-

ditions 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, geo-

metrical 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.

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