Contents

Preface —— V

Chapter 1
Introduction to composite materials —— 1
1.1 Introduction to materials —— **3**
1.1.1 Classification of materials —— **3**
1.2 Introduction to composite materials —— **3**
1.2.1 What are composites? —— **3**
1.2.2 History of composite materials —— **4**
1.2.3 Advantages and disadvantages —— **5**
1.2.3.1 Advantages of composite materials —— **5**
1.2.3.2 Disadvantages of composite materials —— **6**
1.2.4 Applications of composite materials —— **7**
1.2.4.1 Space applications —— **8**
1.2.4.2 Automotive applications —— **9**
1.2.4.3 Sporting industry applications —— **9**
1.2.4.4 Marine applications —— **10**
1.2.4.5 What can be made using composite materials? —— **10**
1.2.4.6 What is the world market for composites? —— **10**
1.2.5 Classification of composite materials —— **11**
1.2.5.1 Particulate composites —— **11**
1.2.5.2 Flake composites —— **11**
1.2.5.3 Fiber composites —— **12**
1.2.5.4 Polymer matrix composites —— **13**
1.2.5.5 Metal matrix composites —— **13**
1.2.5.6 Ceramic matrix composites —— **13**
1.2.5.7 Carbon–carbon composites —— **13**

Chapter 2
Basic concepts and terminology —— 15
2.1 Fibers and matrix —— **15**
2.1.1 Matrix materials —— **15**
2.1.2 Functions of a matrix —— **15**
2.1.3 Properties of a matrix —— **16**
2.1.4 Factors considered for the selection of matrix —— **16**
2.1.5 General types of matrix materials —— **17**
2.1.5.1 Thermosetting matrices (resin) —— **17**
2.1.5.1.1 Comparison of common thermosetting resins —— **17**
2.1.5.2 Thermoplastic matrices (resin) —— **18**
2.1.6 Fiber materials —— **20**

2.1.7 Functions of a fibers — **20**
2.1.7.1 Glass fibers — **21**
2.1.7.2 Carbon fibers — **21**
2.1.7.3 Aramid fibers — **21**
2.1.7.4 Silicon carbide — **21**
2.1.7.5 Organic fibers — **22**
2.2 Styles of reinforcement — **23**

Chapter 3
Design concepts for composite materials/structures — 24
3.1 Introduction — **24**
3.1.1 Design considerations — **24**
3.1.2 Designing the laminate — **25**
3.1.3 Establishing property data — **25**
3.1.4 Designing for the environment — **26**
3.1.5 Designing for joints and assemblies — **26**
3.1.6 Designing for robustness and through-life performance — **27**
3.1.7 Designing for manufacture — **27**
3.1.8 Designing for cost — **27**
3.2 The need for design management — **28**
3.3 The design process — **28**

Chapter 4
Composite manufacturing, fabrication, and processing — 32
4.1 Introduction — **32**
4.2 Classification of manufacturing processes — **33**
4.2.1 Open mold process — **33**
4.2.1.1 Wet layup/hand layup — **33**
4.2.1.2 Spray layup — **35**
4.2.1.3 Filament winding — **35**
4.2.1.4 Sheet molding compound — **37**
4.2.1.5 Expansion tool molding — **37**
4.2.1.6 Contact molding — **38**
4.2.2 Closed mold process — **39**
4.2.2.1 Compression molding — **39**
4.2.2.2 Vacuum bag processing — **40**
4.2.2.3 Pressure bag molding — **40**
4.2.2.4 Injection molding — **41**
4.2.2.5 Cold press molding — **41**
4.2.2.6 Resin transfer molding — **41**

4.2.2.7 Autoclave molding — **42**
4.2.3 Continuous processes — **43**
4.2.3.1 Pultrusion — **43**
4.2.3.2 Continuous laminating processes — **43**
4.2.3.3 Braiding — **44**
4.3 Defects in manufactured polymeric composites — **45**

Chapter 5
The mechanical behavior of composite materials — 46
5.1 Introduction — **46**
5.1.1 Isotropic material — **46**
5.1.2 Orthotropic material — **46**
5.1.3 Anisotropic material — **46**
5.2 Lamina and laminates — **47**
5.3 Failure modes of composite materials — **48**
5.3.1 Microcracking of the matrix — **48**
5.3.2 Fiber pull-out and debonding (separation of fibers and matrix) — **49**
5.3.3 Delamination — **49**
5.3.4 Breaking of fibers — **50**
5.4 Failure mechanisms of composite materials — **51**
5.5 Fatigue behavior of composite materials — **52**
5.6 Factors affecting the fatigue behavior of composite materials — **54**
5.7 Failure criteria of fatigue loading — **54**

Chapter 6
Structural health monitoring of composite structures — 57
6.1 Introduction — **57**
6.1.1 Capability of nondestructive testing techniques for structural health monitoring — **59**
6.1.2 Characteristics of piezoelectric sensors for structural health monitoring — **59**
6.2 Lamb wave technique-based structural health monitoring of composite structures — **65**
6.2.1 History and literature behind the Lamb wave technique — **66**
6.2.2 Lamb wave modeling and simulation — **68**
6.2.3 Lamb wave application in structural health monitoring — **70**
6.2.4 Optimal number and configuration of piezoelectric transducers — **71**
6.2.5 Lamb wave-based damage identification principle — **72**
6.3 Electrical capacitance sensor technique-based structural health monitoring of composite structures — **77**

6.3.1 History and literature behind the electrical capacitance sensor technique — **79**
6.3.2 Electrical capacitance sensor modeling and simulation — **80**
6.3.3 Electrical capacitance sensor electrode excitation strategy — **82**
6.3.4 3D electrical capacitance sensor governing equation — **82**
6.3.5 Factors affecting the electrical capacitance sensor technique — **84**
6.3.6 Effect of the number of electrodes on the performance of electrical capacitance sensors — **84**
6.3.7 The life of electrical capacitance sensor — **84**
6.4 Fiber-optic sensor technique-based structural health monitoring of composite structures — **85**
6.4.1 History and literature behind the fiber-optic technique — **88**
6.4.2 Common types of fiber-optic sensors — **88**
6.4.3 Description of fiber Bragg grating sensors — **89**
6.4.4 Working principle of fiber Bragg grating sensors — **89**
6.4.5 Improve the design of the fiber Bragg grating for large-strain sensor — **91**
6.5 Artificial intelligence — **92**
6.5.1 Machine learning — **93**
6.5.2 Deep learning — **96**
6.5.3 Artificial neural networks — **96**
6.5.4 Damage identification with artificial neural networks in composite structures — **98**
6.5.4.1 Gray-box model — **98**

Chapter 7
Case studies on structural health monitoring of composite structures — 103
7.1 Structural health monitoring of composite pipelines — **103**
7.1.1 Case study (1): predicting water absorption in composite pipes using electrical capacitance sensors integrated with deep learning approach — **103**
7.1.2 Methodology — **104**
7.1.2.1 The geometric model — **104**
7.1.2.2 Numerical work — **107**
7.1.2.2.1 System assumptions — **107**
7.1.2.3 The structural–thermal–electrostatic (multi-physics) coupled field modeling — **107**
7.1.2.3.1 The static model analysis — **107**
7.1.2.3.2 Electrostatic field results — **108**
7.1.2.4 The mass of water absorption (*M*%) monitoring — **109**
7.1.2.5 Deep neural networks — **112**

7.1.2.5.1 Architecture of the developed deep neural network — **112**
7.1.2.5.2 Deep neural network training and test sets — **112**
7.1.2.5.3 The training and testing algorithm — **117**
7.1.2.5.4 The developed deep neural network predicted data of *M*% — **117**
7.1.2.6 Validity of the proposed technique — **118**
7.1.2.6.1 Theoretical validation — **118**
7.1.2.6.2 Experimental validation — **119**
7.1.2.6.3 Evaluation of present algorithm accuracy and reliability — **119**
7.1.2.7 Summary — **121**
7.1.3 Case study (2): predicting long-term creep thermomechanical fatigue behavior monitoring in composite pipelines using electrical capacitance sensors integrated with deep learning approach — **123**
7.1.3.1 Methodology — **124**
7.1.3.2 The geometric model — **124**
7.1.3.3 Numerical work — **126**
7.1.3.3.1 The structural–thermal–electrostatic modeling analysis — **126**
7.1.3.3.2 *S*–*N* curve of fatigue behavior for basalt fiber-reinforced polymer composite pipeline — **127**
7.1.3.3.3 *D*–*N* curve of fatigue damage model for basalt fiber-reinforced polymer composite pipeline — **128**
7.1.3.4 Deep neural networks — **130**
7.1.3.4.1 Deep neural network configuration for LTCTMF behavior in basalt fiber-reinforced polymer composite pipeline — **130**
7.1.3.4.2 Deep neural network training and testing — **132**
7.1.3.4.3 The training and testing algorithms — **135**
7.1.3.5 Electrical capacitance sensor results for LTCTMF behavior in basalt fiber-reinforced polymer composite pipelines — **135**
7.1.3.6 Validity of the proposed technique — **137**
7.1.3.6.1 Theoretical validation — **137**
7.1.3.6.2 Experimental validation — **142**
7.1.3.7 The deep neural network predicted data of $S_f(t)$ — **143**
7.1.3.8 Utilizing the trained deep neural network for predicting nonfinite element model data — **146**
7.1.3.9 Summary — **148**
7.1.4 Case study (3): structural health monitoring of composite pipelines utilizing fiber optic sensors and machine learning approach — **149**
7.1.4.1 Methodology — **150**
7.1.4.2 The geometric model — **150**
7.1.4.2.1 Damaged pipeline system modeling — **152**
7.1.4.2.2 Modal analysis of the pipeline — **154**

7.1.4.2.3 Stress–strain analysis in a stressed thick-walled pipe — **154**
7.1.4.3 Pipeline monitoring-based fiber Bragg grating sensor technology — **156**
7.1.4.4 Design theory of fiber Bragg grating strain sensor array — **157**
7.1.4.5 The basalt fiber-reinforced polymer pipeline damage identification model — **159**
7.1.4.5.1 A k-nearest neighbor algorithm — **161**
7.1.4.5.2 The convolutional neural network modeling — **163**
7.1.4.6 The displacement response identification — **166**
7.1.4.7 Experimental validation of the proposed method — **167**
7.1.4.8 Hybrid convolutional neural network + k-nearest neighbor (ECNN) architecture as a surrogate model — **169**
7.1.4.9 The displacement response prediction based on ECNN — **172**
7.1.4.10 Summary — **174**
7.2 Structural health monitoring of composite ducts — **176**
7.2.1 Case Study (4): structural health monitoring of composite dual-chamber muffler using deep learning algorithm for predicting acoustic behavior — **177**
7.2.1.1 Methodology — **178**
7.2.1.2 Materials and methods — **178**
7.2.1.2.1 The geometric model — **178**
7.2.1.2.2 Basic acoustic equations of the dual-chamber muffler — **179**
7.2.1.2.3 Acoustic properties of composite laminated muffler — **181**
7.2.1.2.4 Acoustic transmission loss — **182**
7.2.1.3 Artificial neural networks — **184**
7.2.1.3.1 Convolutional neural network — **185**
7.2.1.3.2 Recurrent neural network with long short-term memory (RNN-LSTM) blocks — **185**
7.2.1.3.3 Bayesian genetic algorithm optimization — **187**
7.2.1.4 The work description — **187**
7.2.1.5 Validation of the proposed method — **188**
7.2.1.6 Data collection — **190**
7.2.1.7 The established algorithm — **193**
7.2.1.8 Development of artificial neural network models — **193**
7.2.1.9 Performance evaluation of artificial neural network models — **194**
7.2.1.10 Acoustic DCLCM geometry design optimization — **195**
7.2.1.11 Summary — **197**
7.3 Structural health monitoring of composite plates — **199**
7.3.1 Case Study (5): structural health monitoring of composite plates using electrical capacitance sensors and system control theory — **199**
7.3.1.1 Methodology — **199**
7.3.1.2 The geometric model — **200**

7.3.1.3 Damage monitoring of basalt fiber-reinforced polymer composite plate using electrical capacitance sensors — **202**
7.3.1.3.1 Voltage signal analysis in the frequency domain — **203**
7.3.1.3.2 Frequency domain analysis methods — **207**
7.3.1.4 Summary — **208**

Notations — 211

References — 215

Index — 239