

Contents

Preface — V

Acknowledgments — VII

Part I: Fundamentals

Chapter 1

Introduction to composite materials, laminate theory, and extended laminate theory — 3

- 1.1 General — 3
- 1.2 Characteristics of fiber-reinforced epoxy composite materials (from manufacturing considerations) — 3
 - 1.2.1 Transformation behavior of thermoset resin during curing — 5
 - 1.2.2 Coefficients of thermal expansion (or contraction) — 7
 - 1.2.3 Prepregs — 7
- 1.3 Lay-up sequences — 8
- 1.4 Composite behavior during curing and cooling — 10
 - 1.4.1 Material behavior during curing — 11
- 1.5 Laminate theory — 13
 - 1.5.1 General formulation — 13
 - 1.5.2 Deformed shape — 18
- 1.6 Extended laminate theory by Hyer — 20
- 1.7 Physical explanation for the occurrence of different shapes — 24
- 1.8 Laminates made of lay-up sequences $[0_{2m}/90_{2n}]$ — 26
 - 1.8.1 For 0° layers — 26
 - 1.8.2 For 90° layers — 26
 - 1.8.3 For the special case where $m = n = p$ — 28
 - 1.8.4 In eqs. (1.58)–(1.65), if $p = 0.5$ (the case of the $[0/90]$ laminate) — 28
 - 1.8.5 Experiments — 31
- 1.9 Effect of geometrical dimensions on the bifurcation point — 32
 - 1.9.1 Finite element simulation to illustrate the change in shape — 33
- 1.10 Conclusions — 34
- References — 35

Chapter 2

Differences between regular 4D printing (4DP) and 4D printing of composites (4DPC) — 37

- 2.1 Differences between short, discontinuous fibers and long, continuous fibers — 37

2.2	Differences in the method of deposition of materials —	39
2.3	Secondary processes —	40
2.4	The mechanism for the change of shape —	41
2.4.1	For 4DP —	41
2.4.2	For 4DPC —	42
2.5	Conclusion —	44
	References —	44

Chapter 3

Procedure for 4D printing of composites — 45

3.1	Determination of the feasibility of whether the part can be made using 4DPC —	45
3.2	Determination of the lay-up sequence —	47
3.3	Deposition of layers or strips of prepregs on a flat mold —	47
3.3.1	Hand lay-up (HLU) —	47
3.3.2	Automated fiber placement (AFP) —	48
3.4	Bagging the stack of layers —	49
3.5	Heating and curing the stack of layers —	50
3.5.1	Heating and curing multiple samples simultaneously —	52
3.6	Using the structure as is after curing —	52
3.7	Constrained structures —	53
3.8	A-structures —	53
3.9	Conclusion —	54
	References —	54

Chapter 4

Nonlinear aspects of the shape transformation of composite structures made by 4D printing of composites — 55

4.1	Proposed procedure —	57
4.1.1	First increment —	58
4.1.2	Second increment —	58
4.1.3	Third increment —	59
	Reference —	60

Part II: Different structures

Chapter 5

U-structures — 65

5.1	S-shaped structures —	65
5.2	Composite flower —	66
5.3	Leaf springs —	68

5.3.1	Procedure to develop the composite leaf spring using 4DPC —	71
5.3.2	Elastic axis —	73
5.3.3	Equivalent flexural stiffness —	75
5.3.4	Effect of different stacking sequences on the radius of curvature using laminate theory: selection of lay-up sequence for leaf spring —	75
5.3.5	Explanation for the behavior of the composite spring made by 4DPC —	78
5.4	Letters of the alphabet —	85
5.4.1	Principles of the mechanism —	85
5.4.2	Letter “a” —	86
5.4.3	Letter “b” —	87
5.4.4	Letter “C” —	88
5.4.5	Letter “d” —	90
5.5	Composite structures made of fiber orientations other than 0° or 90° —	92
5.5.1	Laminate made of $[45^\circ/-45^\circ]$ stacking sequence —	93
5.5.2	Laminate made of $[0/45]$ stacking sequence —	97
5.6	Conclusion —	107
5.7	Environmental effects —	108
5.7.1	Effect of heat —	108
5.7.2	Effect of moisture absorption on radius of curvature —	117
	Appendix —	124
	References —	126

Chapter 6

C-structures — 127

6.1	Composite omega stiffener —	127
6.1.1	General —	127
6.1.2	Lay-up sequence —	128
6.1.3	Discussion —	130
6.2	Corrugated cores for sandwich constructions —	131
6.2.1	Introduction —	131
6.2.2	Application example —	133
6.2.3	Conclusion —	135
	References —	135

Chapter 7

A-structures — 137

7.1	General aspects —	137
7.2	A-circular cylinders —	137
7.2.1	Comparison with other tubes of equivalent weight —	142

7.3	A-cones with circular cross section —	143
7.3.1	Introduction —	143
7.3.2	Manufacturing procedure using 4DPC —	144
7.3.3	Lay-up sequences —	148
7.3.4	Relationship between dimensions of the flat stack and those of the cone shape —	148
7.3.5	Mechanical testing for compression properties —	149
7.3.6	Discussion —	154
7.3.7	Strain results —	155
7.3.8	Finite element method for the determination of the deformed shape —	157
7.3.9	Comparison between straight fiber finite element method and curved fiber finite element method —	169
7.4	Conclusion —	171
	References —	171

Part III: Design space

Chapter 8

Expansion of design space — 175

8.1	Methods to affect the radius of curvature —	175
8.1.1	Decreasing the radius of curvature —	175
8.1.2	Changing the radius of curvature by modifying the lay-up sequence —	176
8.2	Variation in mechanical properties —	179
8.3	A-cylinder with an elliptical cross section —	180
	References —	182

Index — 183