

ASM[®] HANDBOOK

Volume

21

Composites



The Materials
Information Society

Contents

Introduction to Composites	1	Fabrics and Preforms	59
<i>Chairpersons: Daniel B. Miracle and</i>		Unidirectional and Two-Directional Fabrics.....	59
<i>Steven L. Donaldson, Air Force Research Laboratory</i>		Hybrid Fabrics.....	60
Introduction to Composites	3	Multidirectionally Reinforced Fabrics.....	60
A Brief History of Composite Materials.....	4	Prepreg Resins.....	62
General Use Considerations.....	5	Woven Fabric Prepregs.....	63
Technology Overview.....	7	Unidirectional Tape Prepregs.....	64
Applications.....	12	Multidirectional Tape Prepregs.....	65
View of the Future.....	16	Tape Manufacturing Processes.....	65
Constituent Materials	19	Prepreg Tow.....	66
<i>Chairperson: Steven R. Nutt, University of Southern California</i>		Braiding	69
Introduction to Constituent Materials	21	Braiding Classifications.....	70
Constituent Material Forms.....	21	Two-Dimensional Braiding.....	70
Selection Factors.....	22	Three-Dimensional Braiding.....	72
Introduction to Reinforcing Fibers	23	Properties of Braided Composites.....	74
Overview.....	23	Epoxy Resins	78
PMC Reinforcing Fibers.....	24	Base Resins.....	78
CMC and MMC Reinforcing Fibers.....	25	Epoxy Resin Curatives.....	80
Summary and Conclusions.....	25	Modifiers.....	84
Glass Fibers	27	Epoxy Resin Model Formulations.....	86
Glass Fiber Types.....	27	Safety.....	88
General-Purpose Glass Fibers.....	28	Future Trends.....	88
Special-Purpose Glass Fibers.....	29	Polyester Resins	90
Glass Melting and Fiber Forming.....	30	Polyester Resin Chemistry.....	90
Important Commercial Products.....	31	Mechanical Properties.....	91
Carbon Fibers	35	Thermal and Oxidative Stability.....	92
History.....	35	Chemical Resistance.....	93
Manufacture of Carbon Fibers.....	35	Ultraviolet (UV) Resistance.....	94
Properties and Characteristics of Carbon Fibers.....	36	Electrical Properties.....	94
Typical Applications of Carbon Fibers.....	38	Flame-Retardant Polyester Resins.....	95
Anticipated Developments in Carbon Fibers.....	39	Bismaleimide Resins	97
Aramid Fibers	41	BMI Resin Chemistry.....	97
Fiber Manufacturing.....	41	Bismaleimide Building Blocks.....	97
Fiber Forms and Applications.....	41	Bismaleimide Resin Systems.....	98
Materials Properties.....	43	BMI Composites	100
Future Developments.....	45	Mechanical Properties.....	101
Ceramic Fibers	46	Composite Applications.....	101
Fiber Production.....	46	Resin Transfer Molding.....	103
Composite Applications.....	46	Cure and Post Cure Requirements.....	103
Properties of Commercial Fibers.....	46	Elevated-Temperature Applications.....	103
Fibers for High-Temperature CMC Applications.....	48	Conclusions.....	104
Future Directions.....	49	Polyimide Resins	105
Discontinuous Reinforcements for Metal-Matrix Composites	51	Properties and Applications.....	105
Reinforcement Roles.....	51	Chemistry of Condensation-Type Polyimides.....	107
DRMMC Reinforcements.....	51	Chemistry of Addition-Type Polyimides.....	109
Reinforcement Chemistry.....	55	Preparation of Nadic End-Capped Amic Acid	
Continuous Fiber Reinforcements for Metal-Matrix Composites	56	Oligomer Resin Solutions.....	112
Aluminum Oxide Fibers.....	56	Constituent Properties of PMR-15.....	113
Silicon Carbide Fibers.....	56	Current State of the Art.....	113
Boron Fibers.....	56	Outlook.....	113
Carbon Fibers.....	56	Phenolic Resins	120
Future Outlook.....	57	Phenolic Resin Chemistry.....	120
		Phenolic Prepregs.....	121
		Phenolic Honeycomb.....	121
		Phenolic Pultrusion.....	122

Phenolic Filament Winding.....	122	Analysis	197
Phenolic Sheet Molding Compounds.....	123	Design.....	197
Phenolics for Hand Lay-Up	124	Micromechanics	199
Conclusions	124	Physical Properties of Fiber Composites:	
Cyanate Ester Resins	126	General Concepts.....	199
Cyanate Ester Chemistry.....	126	Elastic Properties	199
Properties and Characteristics.....	127	Thermal Expansion and Moisture Swelling.....	202
Processing.....	129	Viscoelastic Properties.....	204
Properties for Selected Applications.....	129	Conduction and Moisture Diffusion	205
Outlook	131	Macromechanics Analysis of Laminate Properties.....	207
Thermoplastic Resins.....	132	Lamina Stress-Strain Relations	207
Background.....	132	Lamination Theory	209
Categories and Characteristics	133	Laminate Properties	211
Product Forms.....	134	Thermal and Hygroscopic Analysis.....	215
Impregnation.....	134	Laminate Stress Analysis	216
Processing.....	135	Strength and Failure.....	219
Costs	136	Intra- and Interlaminar Cracking	224
Properties.....	137	Characterizing Strength from a Structural Design	
Applications	137	Perspective.....	230
Future Directions	138	Background on Characterization	230
Molding Compounds	141	The Strength of Embedded Fibers under Arbitrary	
Sheet Molding Compounds.....	141	Biaxial Loads.....	231
Bulk Molding Compounds.....	144	The Strength of Embedded Fibers Characterized	
Injection Molding Compounds	145	at the Lamina Level.....	233
Metallic Matrices.....	150	Strength Properties for Polymer Matrices Confined	
Aluminum Alloys.....	151	Between Fibers.....	235
Titanium Alloys.....	156	Effects of Combined Loading on Matrix Failure	
Conclusions.....	158	Envelope	237
Ceramic Matrices.....	160	Characterization of Progressive Matrix Damage.....	236
Pressure-Assisted Densification.....	160	Empirical Failure Envelopes for Multidirectional	
Chemical Vapor Infiltration	160	Laminates	238
Melt Infiltration	160	Conclusions	240
Polymer Infiltration and Pyrolysis	161	Fracture Mechanics of Composite Delamination	241
Sol-Gel Processing	162	Delamination Characterization.....	241
Carbon Matrices.....	164	Delamination Analysis.....	242
Pure Carbon Forms.....	164	Delamination Prediction.....	242
Matrix Formation Methods	165	Hygrothermal Behavior	246
Matrix Contribution to Composite Properties.....	167	General Considerations in Assessing Hygrothermal	
Future Directions and Needs	168	Behavior.....	246
Interfaces and Interphases.....	169	Resins or Matrices.....	247
Interface and Interphase	169	Reinforcements.....	247
Interphase Thermodynamics.....	170	Processing.....	247
Surface Modification Strategies.....	171	Diffusion	247
Surface Modification Examples	172	Hygrothermal Testing and Conditioning.....	248
Fiber-Matrix Adhesion Measurements	173	Degradation Mechanisms and Failure Modes	249
Interphase Processing.....	175	Properties	249
Interphase Effects on Fiber-Matrix Adhesion.....	175	Fatigue and Life Prediction	252
Interphase and Fiber-Matrix Adhesion Effects		Fatigue Damage.....	252
on Composite Mechanical Properties.....	175	Fatigue Methodologies	253
Conclusions.....	178	Delamination	256
Lightweight Structural Cores	180	Life Prediction Models	256
Honeycomb	180	Damping Properties.....	259
Balsa	182	Unidirectional Composites.....	259
Foam	182	Beams Cut From Laminated Plates	262
Specifying Structural Core.....	182	Laminated Plates.....	262
Sandwich Structures	182	Woven Fibrous Composites	266
Bio-Based Resins and Natural Fibers.....	184	Sandwich Laminates	266
Bio-Based Resins	184	Effect of Temperature	266
Neat Resin Properties.....	187	Relationship Between Damping and Strength	268
Triglyceride-Based Composite Materials	188	Composites Versus Metals.....	269
AESO and HSO/MA Glass-Fiber Composites	189	Bolted and Bonded Joints	271
Natural-Fiber Composites.....	189	Fundamentals of Shear Load Transfer through	
Ballistic Impact Resistance of Soy-Resin Composites.....	191	Adhesively Bonded Joints	272
Biodegradable Composites	191	Nonuniformity of Load Transfer through	
Conclusions.....	192	Adhesive Bonds.....	274
Engineering Mechanics, Analysis, and Design.....	195	Elastic-Plastic Adhesive Shear Model.....	277
<i>Chairperson: Scott Reeve, National Composite Center</i>		Single-Lap Adhesively Bonded Joints	278
Introduction to Engineering Mechanics, Analysis, and Design.....	197	Stepped-Lap Adhesively Bonded Joints	278
Mechanics.....	197	Load Redistributions with Flawed and Damaged	
		Adhesively Bonded Joints	280

Fundamentals of Shear Load Transfer through Mechanical Fasteners	281	Factors Affecting Design Allowables	360
Single-Hole Bolted Composite Joints	282	Lamina Versus Laminate Allowables	361
Multirow Bolted Composite Joints	284	Extending Laminate Results	362
Practical Considerations	286	Statistical Determination of Allowables	363
Instability Considerations	290	Ensuring the Validity of Allowables	365
Background	290	Computer-Aided Design and Manufacturing	366
Orthotropic Plates	290	Overview	366
Finite Stack Effects	291	Composite Draping Simulation	366
Anisotropic Plates	291	Composite Hierarchy	367
Unsymmetric Plates	292	Core Sample and Ply Analysis	368
Transverse Shear Stiffness Effects	292	Producibility and Flat-Pattern Evaluations	368
Hygrothermal Buckling	293	Laminate Surface Offset	368
Composite Sandwich Panels	293	Engineering Documentation	369
Computer Codes	293	Flat-Pattern Export	369
Shell Panel Instability	293	Structural Analysis Interface	370
Damage Tolerance	295	Resin Transfer Molding Interface	371
Definitions	295	Fiber Placement and Tape-Laying Interfaces	371
Durability and Damage Tolerance Criteria	295	Laser Projection Interface	371
Specific Criteria	295	Design, Tooling, and Manufacturing Interaction	373
Damage Tolerance Philosophy	296	Selection of Composites Manufacturing Processes	373
Compression After Impact Failure Mode	297	Process Considerations	374
Damage Tolerance Allowables Development	299	Preparation	374
Implementation of a Damage Tolerance Analysis Methodology	300	Forming Processes	375
Out-of-Plane Analysis	302	Post-Processing and Fabrication	376
The Challenge	302	Repair	377
Out-of-Plane Analysis Techniques	303	Conclusions	377
Conclusion	306	Cost Analysis	379
Analysis of Sandwich Structures	308	Composite Cost Tools	379
Sandwich Panel Failure Modes	308	Cost Savings	381
Nomenclature and Definitions for Loads, Geometry, and Material Properties	309	Rapid Prototyping	383
Strength Checks	309	Review of Processes	383
Stiffness and Internal Loads	310	Direct Fabrication of Composite Structures	385
Flat Panel Internal Loads and Stresses—Pressure Loading	313	Freeform Tooling for Composite Part Lay-Up	386
Curved Sandwich Panel Internal Loads and Stresses	316	Design Guidelines	388
Local Strength Analysis Methods	317	Definition of Composites	388
Flat Panel Stability Analysis Methods	319	Analysis of a Composite Laminate	389
Finite Element Analysis	321	Mold Design	391
Overview of Finite Element Analysis	321	Matrix-Resin Selection	391
Homogenization	322	Typical PMC Processes	391
3-D Solid Elements	323	Electromagnetic Interference (EMI) Shielding and Electrostatic Discharge (ESD) Protection	393
2-D Cylindrical Shell Elements	324	Metal Plating	393
1-D Beam Elements	326	Fire Resistance	393
Commercial Finite Element Analyses Codes	328	Thermal Conductivity	394
Numerical Examples	328	Corrosion	395
Computer Programs	334	Fasteners	395
Evaluation Criteria	334	Engineering Mechanics and Analysis of Metal-Matrix Composites	396
Reviews of Available Programs	335	Micromechanics of Fiber-Reinforced MMCs	396
Internet Resources	343	Micromechanics of Discontinuously Reinforced MMCs	400
Testing and Analysis Correlation	344	Local Failures of Fiber-Reinforced MMCs	401
The "Building Block" Approach to Structural Qualification	344	Macromechanics	402
Design Allowables Coupons	345	Fracture Toughness	403
Bolted Joints	347	Software	405
Elements and Subcomponents	349	Fracture Analysis of Fiber-Reinforced Ceramic-Matrix Composites	407
Conclusions	351	General Framework for Fracture Analysis	408
Design Criteria	353	Classes of Material Behavior	408
Overview of Design Criteria for Composites	353	Constitutive Laws for Inelastic Straining	409
Cost	354	Stress Distributions in Notched Specimens	411
Size	355	Fracture Initiation	412
Mechanical Properties	355	Crack Propagation	413
Repeatability and Precision	357	Environmental Degradation	415
Damage Tolerance and Durability	357	Conclusions	416
Environmental Constraints	358	Manufacturing Processes	419
Conclusions	359	<i>Chairperson: B. Tomas Åström, IFP SICOMP AB, Sweden</i>	
Design Allowables	360	Introduction to Manufacturing of Polymer-Matrix Composites	421
Need for Design Allowables	360	Outlook	422
Development of Design Allowables	360		

Process Modeling	423	Control Systems.....	489
Classification Based on Dominant Flow Process	423	Other Process Cures.....	490
Usefulness of Process Models	424	Thermoplastic Composites.....	491
Ingredients of a Process Model.....	425	Resin Transfer Molding and Structural Reaction Injection	
Formulation of Models	429	Molding.....	492
Composite Tooling.....	434	Technique Characteristics	492
Advantages of Composite Tools.....	434	Applications	493
Disadvantages of Composite Tools	435	Technique Description.....	494
Tool Design Overview	435	Material Types and Forms.....	495
Master Model or Pattern Design.....	437	Representative Component Properties.....	497
Fiber and Fabric Selection.....	437	Design Guidelines	497
Resins	437	Outlook	499
Surface Coat and Surface Ply	437	Vacuum Infusion.....	501
Tool Laminate Construction Techniques	438	Technique Characteristics.....	501
Curing and Demolding	438	Applications	503
Cutting and Trimming	438	Technique Description: Theory and Background	505
Substructure Design.....	438	Technique Description: How Parts Are Made.....	508
Future Outlook	440	Equipment and Material Types and Forms.....	510
Electroformed Nickel Tooling.....	441	Representative Component Properties.....	513
Electroforming Process.....	441	Design Guidelines	513
Mandrel Cost and Design Considerations	442	Outlook	514
Comparison of Nickel and Other Tooling Materials	443	Compression Molding.....	516
Future Developments	444	Process Description and Characteristics	516
Elastomeric Tooling	445	Part Design and Process Engineering	517
Bag-Side Elastomeric Cauls.....	445	Compression Molding of Glass Mat Thermoplastics.....	518
Thermal Expansion Molding Methods	447	Compression Molding of Long-Fiber Thermoplastics	522
Volumetric Analysis	448	Compression Molding of Sheet Molding Compounds	525
Open Molding: Hand Lay-Up and Spray-Up.....	450	Filament Winding	536
Process Characteristics	450	Advantages and Disadvantages	537
Applications	450	Effects of Fiber Tension	538
Process Description	451	Materials.....	539
Materials.....	453	Shapes.....	540
Component Properties and Characteristics	453	Winding Patterns	541
Basic Design Guidelines	455	Tooling and Equipment	542
Outlook	456	Applications	544
Custom Sailing Yacht Design and Manufacture.....	457	Representative Component Properties.....	545
Yacht Structure.....	457	Design Guidelines	546
Design Guidelines	458	Fabrication Recommendations	547
Material Types and Forms.....	460	Outlook	548
Technique Characteristics.....	461	Pultrusion	550
Outlook	465	Technique Characteristics.....	550
Prepreg and Ply Cutting	466	Process Advantages	550
History of Composites Ply Cutting	466	Applications	551
Creating the Data	466	Key Technology Areas	552
Nesting the Pieces	467	Process Equipment	552
Kitting.....	467	Process Tooling	555
Cutting.....	468	Materials.....	555
Labeling	469	Properties of Pultruded Products	559
Manual Prepreg Lay-Up.....	470	Design Guidelines	561
Technique Characteristics and Applications	470	Future Outlook	562
Technique Description.....	471	Tube Rolling	565
Component Properties	474	Process Description	565
Design Guidelines	475	Process Equipment and Techniques	565
Outlook	475	Material Forms.....	566
Fiber Placement	477	Wrapping Techniques	567
Applications	477	Outlook	569
Materials.....	478	Thermoplastic Composites Manufacturing.....	570
Part Design Considerations	478	Characteristics of Thermoplastic Composites.....	570
Outlook	479	Material Forms.....	571
Automated Tape Laying.....	480	Technique Descriptions	571
History	480	Outlook	577
Process Overview.....	480	Processing of Metal-Matrix Composites	579
Applications	481	Processing of Discontinuously Reinforced Aluminum.....	579
Description of Equipment.....	481	Processing of Continuous Fiber-Reinforced	
Tape Laying Process Description	483	Aluminum.....	584
Typical Material Types and Forms	484	Processing of Discontinuously Reinforced Titanium.....	585
Design Guidelines	484	Processing of Continuous Fiber-Reinforced Titanium	585
Outlook	484	Processing of Other Metal-Matrix Composites.....	586
Curing	486		
Preparation for Curing.....	486		
Autoclave Cure Systems	487		

Processing of Ceramic-Matrix Composites	589	Environmental Protection and Sealing	659
Cold Pressing and Sintering	589	Corrosion Control	659
Hot Pressing	589	Design Considerations	660
Reaction-Bonding Processes	590	Sealing	660
Infiltration	590	Primer and Topcoat Systems	663
Directed Oxidation (Lanxide) Process	591	Extrusion of Particle-Reinforced Aluminum Composites	666
In Situ Chemical Reaction Techniques	592	Dies and Shapes	666
Sol-Gel Techniques	595	Effects of Reinforcements	667
Polymer Infiltration and Pyrolysis	595	Post-Processing and Assembly of Ceramic-Matrix	
Self-Propagating High-Temperature Synthesis	597	Composites	668
Electrophoretic Deposition	598	Machining and Finishing of CMCs	668
Processing of Carbon-Carbon Composites	600	Coating and Surface Treatments for CMCs	669
Preform Fabrication	600	Joining of CMCs	669
Densification Processing	601	Assembly of CMCs	670
Protective Coatings	603	Nondestructive Evaluation	670
Joining	605	Quality Assurance	675
Properties of Carbon-Carbon Composites	606	<i>Chairperson: G. Aaron Henson III, Design Alternatives Inc.</i>	
Post-Processing and Assembly	613	Introduction to Quality Assurance	677
<i>Chairperson: Flake C. Campbell, The Boeing Company</i>		In-Process Monitoring	677
Introduction to Post-Processing and Assembly	615	Quality Assurance Factors	677
Polymer-Matrix Composites	615	Tooling and Assembly Considerations	677
Metal-Matrix and Ceramic-Matrix Composites	615	Quality Assurance for Commercial Applications	678
Machining, Trimming, and Routing of Polymer-Matrix		Nondestructive Testing and Data Fusion	678
Composites	616	Conclusions	678
Machining Operations	616	Resin Properties Analysis	679
Cutting Tools For Machining	616	Component Material Tests	679
Peripheral Milling	617	Mixed Resin System Tests	680
Face Milling	617	Prepreg Tests	680
Trimming	618	Cured Resin and Prepreg Mechanical Properties	681
Secondary Adhesive Bonding of Polymer-Matrix		Tooling and Assembly Quality Control	682
Composites	620	Tooling Quality Control	682
Adhesive Joint Design	620	Documentation	682
Selection Criteria	620	Hand-Faired Master Models	682
Highly Loaded Joint Considerations	622	Machined Master Models	683
Epoxy Adhesives	624	Second-Generation Patterns	683
Surface Preparation	626	Composite Tooling	683
Sandwich Structures	627	Metallic Tooling	683
Honeycomb Core	628	Composites Assembly Quality Control	683
Honeycomb Processing	628	Methods for Simplifying and Improving Assembly	
Syntactic Core	628	Operations	684
Foam Core	628	Assembly Process Monitoring	684
Adhesive-Bonding Process	628	Outlook for Composites Assembly	684
Adhesive Application	629	Reinforcing Material Lay-Up Quality Control	685
Tooling	630	Facilities and Equipment	685
Inspection	632	Material Control	687
Processing and Joining of Thermoplastic Composites	633	Lay-Up	687
Economic Considerations	633	Automated Tape Laying and Fiber Placement	690
Material Options	634	Numerically Aided Lay-Up	690
Processing Methods	636	Cure Monitoring and Control	692
Joining	638	Process Control	692
Hole Drilling in Polymer-Matrix Composites	646	Resin Cure Sensing	692
Part Fit-Up	646	Flow Sensing	697
Drilling Considerations	647	Practical Issues in Sensing Resin Cure and Flow	698
Reaming	649	Nondestructive Testing	699
Countersinking	649	Ultrasonics	699
Hole Quality	649	Air-Coupled Ultrasonics	702
Mechanical Fastener Selection	651	Laser Ultrasound	703
Corrosion Compatibility	651	Ultrasonic Spectroscopy	707
Fastener Materials and Strength Considerations	651	Lamb Waves	708
Bolt Bending	652	Nonlinear Ultrasonics	711
Head Configuration Selection	652	Acousto-Ultrasonics	711
Clamp-Up	653	Radiography	712
Chamfering of Holes	653	Computed Tomography	715
Interference Fit Fasteners	654	Thermography	717
Lightning-Strike Protection	655	Low-Frequency Vibration Methods	718
Hi-Lok and Lockbolt Fasteners	656	Acoustic Emission	718
Eddie-Bolt Fasteners	657	Eddy Current	719
Blind Fasteners in Composite Structures	657	Optical Holography and Shearography	719
Screws and Nutplates in Composite Structures	658	Data Fusion	720
		Standards	721

Quality Assurance of Metal-Matrix Composites.....	726	Properties and Performance of Ceramic-Matrix and	
Characterization Techniques	726	Carbon-Carbon Composites	859
Mechanical Testing.....	727	Discontinuously Reinforced Ceramic-Matrix	
Nondestructive Evaluation.....	728	Composites.....	859
Testing and Certification	731	Continuous Fiber Ceramic Composites	862
<i>Chairperson: Richard E. Fields, Lockheed Martin Missiles</i>		Carbon-Carbon Composites	865
<i>and Fire Control</i>		Product Reliability, Maintainability, and Repair	869
Introduction to Testing and Certification.....	733	<i>Chairpersons: Michael J. Hoke, Abaris Training Resources, Inc.</i>	
Section on Testing and Certification.....	733	<i>Rikard B. Heslehurst, Australian Defence Force Academy</i>	
Overview of Testing and Certification.....	734	Introduction to Product Reliability, Maintainability,	
Differences Between Testing of Composites and		and Repair	871
Testing of Isotropic Materials.....	734	Facilitating Effective Repair of Composite Structures ..	871
Involvement of Certification Agencies.....	734	Repair Issues for Specific Applications	871
Understanding the Building-Block Approach.....	735	Repair Standardization and Reliability Considerations ..	871
Building-Block Levels.....	735	Designing for Repairability	872
Determining the Purposes of Testing.....	736	Introduction to Designing for Repairability	872
Data Normalization.....	736	Design Guidelines	874
Statistical Data Reduction.....	738	Design for Supportability	880
Test Program Planning.....	741	Specific Examples	882
Development of Test Matrices.....	741	Repair Engineering and Design Considerations	885
Testing Standards.....	742	Types of Repairs to Composite Structures	885
Specimen Preparation.....	743	Repair Requirements.....	885
Environmental Conditioning	745	Considerations Prior to, During, and After Repair	
Instrumentation and Data Acquisition.....	747	Action.....	887
Failure Modes	747	Validation and Certification of Repairs	888
Data Interpretation and Recording	747	Design Guidelines	889
Constituent Materials Testing.....	749	Pitfalls and Problems	891
Tests for Reinforcement Fibers and Fabrics	749	Repair Applications, Quality Control, and Inspection	893
Tests for Matrix Resins and Prepregs	751	Types of Damage.....	893
Lamina and Laminate Nonmechanical Testing	759	Damage Detection in Field Conditions	893
Per Ply Thickness.....	759	Component Identification	894
Constituent Content	759	Paint Removal.....	895
Density.....	760	Repair Design	895
Coefficient of Thermal Expansion and Coefficient		Repair Design Considerations.....	896
of Moisture Expansion	760	Repair Instructions	897
Glass Transition Temperature.....	761	Repair Materials	897
Thermal Conductivity, Diffusivity, and Specific Heat ..	762	Curing Methods	897
Lamina and Laminate Mechanical Testing	766	Ship Structure Repairs	899
Failure Mode Analysis	766	Repair Classification, Characterization, and Cycle	899
Tensile Property Test Methods	767	Repair to Gel Coats	900
Compressive Property Test Methods	769	Composite Patch Repairs.....	901
Shear Property Test Methods	772	Scarf Repairs	901
Flexure Property Test Methods	774	Step Repairs	903
Fracture Toughness Test Methods	775	Resin-Infusion Repairs	904
Fatigue Property Test Methods	776	Rehabilitation of Reinforced Concrete Structures	
Element and Subcomponent Testing	778	Using Fiber-Reinforced Polymer Composites	906
Test Methodology and Considerations	778	Structural Assessment	906
Standard Elements.....	781	Composite Materials Reinforcing Systems for Concrete	
Nonstandard Elements and Subcomponents	789	Strengthening.....	907
Durability and Damage-Tolerance Testing.....	790	Properties of Polymer Composite Reinforcing	
Full-Scale Structural Testing.....	794	Systems	908
Static Test	795	Materials Property Requirements for Design	909
Durability (Fatigue) Test.....	798	FRP-Reinforced Concrete Behavior	910
Damage Tolerance Test	798	Surface Preparation.....	912
Properties and Performance.....	801	Composite Materials Applications	912
<i>Chairperson: Jeffrey Schaff, United Technologies Research Center</i>		Records	912
Properties and Performance of Polymer-Matrix		Acceptance Criteria	912
Composites.....	803	Maintainability Issues	914
Materials and Properties Description	803	Types of Composite Structures	914
Axes Definitions, Symbols, and Special Property		Designing for Maintainability.....	915
Calculations.....	805	Sources of Defects and Damage.....	915
Overview of Constituent Materials	806	Nondestructive Inspection Requirements	916
Thermoplastic-Matrix Composites	807	Design Recommendations	917
Thermoset-Matrix Composites	807	Personnel, Facilities, and Equipment	918
Properties of Metal-Matrix Composites	838	Bonded Repair of Metal Structures Using Composites	922
Discontinuously Reinforced MMCs	838	Damage Assessment	922
Hybrid Laminated Metal and Ductile Phase		Repair Design	922
Composites.....	848	Repair Application	924
Continuous Fiber Reinforced Composites.....	851	Repair Certification.....	926

Repair Examples.....	927
Future Trends.....	928
Worldwide Repair Standardization.....	931
Repair Types and Materials.....	931
Training.....	932
Major Standardization Issues.....	932
Product Reliability, In-Service Experience, and	
Lessons Learned.....	934
Reliability.....	934
Context of In-Service Experiences within Aircraft	
Operations.....	935
Failure Modes.....	935
Part-Specific In-Service Experiences.....	937
Lessons Learned.....	943
Failure Analysis.....	947
<i>Chairperson: Patricia L. Stumpff, Hartzell Propeller Inc.</i>	
Introduction to Failure Analysis.....	949
Overview of Failure Analysis.....	949
Coverage of this Section.....	949
Failure Causes.....	951
Design.....	951
Manufacturing.....	951
Improper Use.....	952
Failure Analysis Procedures.....	953
Review of Available In-Service Records, Materials	
and Processing Methods, Print Requirements, and	
Manufacturing Records.....	953
Visual Analysis and Nondestructive Examination.....	953
Verification of Materials and Processing Methods.....	954
Determination of Fiber, Matrix, and Void Volume	
Fractions and Verification of Ply Lay-Up	
and Orientation.....	955
Review of Composites Processing Parameters.....	956
Fractography and Surface Analysis.....	956
Mechanical Testing and Stress Analysis.....	956
Conclusions.....	957
Visual Analysis, Nondestructive Testing, and Destructive	
Testing.....	958
Visual Analysis.....	958
Nondestructive Test Techniques.....	960
Destructive Test Techniques.....	962
Microscopy.....	964
Sample Preparation.....	964
Rough Grinding and Polishing.....	966
Thin-Section Preparation.....	967
Viewing the Specimen.....	969
Thermal Analysis.....	973
Composite Failure Modes Affected by Matrix Resin.....	973
Testing Approach.....	973
Thermal Analysis Techniques.....	973
Fractography.....	977
Interlaminar Fracture Features.....	978
Translaminar Fracture Features.....	985
Conclusion.....	986
Case Histories.....	988
Helicopter Rotor Blade Failure.....	988
Composite Wing Spar Failure.....	990
Aircraft Rudder Failure.....	991
Fatigue Properties and Quantitative Fractography	
of Metal-Matrix Composites.....	994
Fatigue Properties of Metal-Matrix Composites.....	994
Fatigue Testing of MMCs.....	995
Fractography of MMCs under Plane-Strain	
Conditions.....	996
Failure Analysis of Ceramic-Matrix Composites.....	1000
Characteristic Failure.....	1000
Evidence of Failure Mechanisms.....	1001

Recycling and Disposal.....	1003
<i>Chairperson: Nicholas J. Gianaris, Visteon Corporation</i>	
Introduction to Recycling and Disposal of Composites.....	1005
Recycling and Disposal of Polymer-Matrix Composites.....	1006
Driving Forces for Recycling of Composites.....	1006
Disposing of Composite Scrap.....	1007
Recycling of Thermoset-Matrix Composites.....	1008
Recycling of Thermoplastic-Matrix Composites.....	1010
Properties of Recycled Composite Fibers.....	1011
Recycling and Disposal of Metal-Matrix Composites.....	1013
Recycling of Aluminum MMCs.....	1013
Continuous Reinforced Aluminum MMCs.....	1014
Quality Issues.....	1014
Properties of Recycled Aluminum MMCs.....	1015
Disposal of Aluminum MMCs.....	1015
Recycling Other MMCs.....	1015

Applications and Experience..... 1017
Chairpersons: Tia Benson Tolle, Air Force Research Laboratory
Warren H. Hunt, Jr., Aluminum Consultants Group Inc.

Introduction to Applications.....	1019
Advanced Polymer-Matrix Composites.....	1019
Metal-Matrix Composites.....	1019
Ceramic-Matrix Composites.....	1019
Automotive Applications.....	1020
Automotive Composites.....	1021
Design Challenges and Constraints.....	1021
Design Environments.....	1023
Application Drivers and Constraints.....	1023
High-Volume Composite Descriptions, Properties,	
and Processes.....	1024
State-of-the-Art and Developing Technologies.....	1026
Automotive Applications of Metal-Matrix Composites.....	1029
Engine Applications.....	1029
Brake System Applications.....	1031
Driveshaft Applications.....	1031
Other Applications.....	1031
Conclusions.....	1032
Space Applications.....	1033
Design Drivers and Challenges.....	1033
Environments.....	1033
Design Processes and Trade-Offs.....	1033
Composite Materials Properties.....	1035
State-of-the-Art Applications.....	1036
New Developments and Future Needs.....	1041
Aeronautical Applications of Metal-Matrix Composites.....	1043
Aerostructural Applications.....	1044
Aeropropulsion Applications.....	1046
Aeronautical Subsystem Applications.....	1047
Implementation Strategy.....	1048
View of the Future.....	1048
High-Temperature Applications.....	1050
General Characteristics.....	1050
Condensation-Type Polyimides.....	1050
PMR Polyimides.....	1050
Applications of PMR-15.....	1051
Aircraft Applications.....	1057
Early Commercial Applications.....	1057
Current Production Aircraft.....	1058
Military Applications.....	1061
Outlook.....	1065
Applications of Carbon-Carbon Composites.....	1067
Material Properties.....	1067
Applications.....	1067
Conclusions.....	1070
Sports and Recreation Equipment Applications.....	1071
Historical Background.....	1071
Bats, Rackets, and Clubs.....	1071

Bicycling	1072	Civil Infrastructure Applications.....	1091
Winter Sports.....	1072	The Need for Infrastructure Renewal.....	1091
Aquatic Sports.....	1073	Conventional Materials versus Composites	1091
Track and Field Equipment.....	1075	Seismic Retrofit Applications	1092
Archery Equipment	1076	Repair and Strengthening of Beams and Slabs.....	1093
Conclusions	1076	Repair of Large-Diameter Pipes.....	1095
Thermal Management and Electronic Packaging		Replacement Bridge Decks.....	1096
Applications	1078	New Structural Systems.....	1097
Application Requirements and Candidate Materials....	1078	Outlook	1098
Reinforcements.....	1080	Applications of Ceramic-Matrix Composites.....	1101
Thermal Management Composites and Other Advanced		Applications for Discontinuously Reinforced CMCs ..	1101
Materials	1081	Applications for Continuous Fiber Ceramic	
Applications	1082	Composites.....	1106
Future Trends.....	1082	Reference Information	1111
Marine Applications	1085	Glossary of Terms	1113
Naval Applications of FRP Composites	1085	Metric Conversion Guide.....	1137
Leisure, Sporting, and Commercial FRP		Abbreviations and Symbols.....	1140
Composite Craft	1088	Index.....	1143
Offshore Applications of FRP Composites.....	1089		