

Handbook of Structural Life Assessment

Raouf A. Ibrahim

*Professor
Wayne State University, USA*

WILEY

Contents

Acknowledgements *xi*

Introduction *xiii*

Part I Fracture Mechanics Dynamics and Peridynamics *1*

1	Fundamentals of Fracture Mechanics	3
1.1	Introduction and Historical Background	3
1.2	Classical Theory of Solid Mechanics	6
1.3	Stress Intensity Factor	12
1.3.1	Analytical Development	12
1.3.2	Evaluation of Stress Intensity Factors	15
1.4	Linear Elastic Fracture Mechanics (LEFM)	17
1.4.1	Griffith's Criterion	18
1.5	Nonlinear Fracture Mechanics	19
1.5.1	Irwin's Modification	20
1.5.2	Crack Tip Element Method	22
1.5.3	Paris-Erdogan Law	23
1.5.4	AFGROW Program	25
1.5.5	Energy Release Integrals	26
1.5.6	Mechanisms of Crack Propagation	35
1.6	Boundary-Layer Effect of Composites	38
1.6.1	Introduction	38
1.6.2	Analytical Treatment	40
1.6.3	Thermal Loading Stress Field	48
1.7	Closing Remarks	55
2	Applications of Fracture Mechanics	59
2.1	Introduction	59
2.2	Fracture Mechanics of Metallic Structures	59
2.2.1	Steel Structures	59
2.2.2	Aluminum Alloys	62
2.3	Damage of Composite Structures	70
2.3.1	Preliminaries	70
2.3.2	Assessment of Composites Mechanics	71

2.3.3	Damage of Sandwich Structures	76
2.3.4	Sandwich Plates under Normal Loads	78
2.3.5	Thermo-Mechanical Coupling of Sandwich Plates	90
2.3.6	Mechanics of Solid Foams	108
2.4	Closing Remarks	127
3	Dynamic Fracture and Peridynamics	129
3.1	Introduction	129
3.2	Fracture Dynamics	131
3.2.1	Features of Dynamic Fracture	131
3.2.2	Instability of Cracks and Microbranching	133
3.2.3	Experimental Techniques	139
3.2.4	Dynamic Crack Propagation Using Optical Caustics	142
3.3	Fracture Dynamics of Metals	148
3.3.1	Spalling of Metals	148
3.3.2	Dynamic Crack Propagation in Metals	149
3.3.3	Melting Metals	154
3.4	Dynamic Fracture of Composites	155
3.4.1	Functionally Graded Materials and Bi-Materials	157
3.4.2	Polymer and PMMA Materials	163
3.4.3	Fiber-Reinforced Composites	169
3.5	Peridynamics	171
3.5.1	Ingredients of Peridynamic Theory	171
3.5.2	Remarks and Restrictions	181
3.5.3	Numerical Simulation	185
3.5.4	Horizon Convergence	190
3.5.5	Application	192
3.6	Closing Remarks	208

Part II Introduction to Structural Health Monitoring 211

4	Structural Health Monitoring Basic Ingredients and Sensors	213
4.1	Introduction	213
4.2	Between Structural Life Assessment and Health Monitoring	213
4.3	Basic Ingredients of SHM	216
4.3.1	Non-Destructive Evaluation	217
4.3.2	Lamb Waves	220
4.3.3	Acoustic Emission	227
4.3.4	Damage Location using Smart Sensors	241
4.3.5	Electric Resistance and Capacitance Techniques	251
4.3.6	Impact Resonance Method	253
4.3.7	Optimal Sensor Location	256
4.4	Closing Remarks	261

5	Statistical Pattern Recognition and Vibration-Based Techniques	263
5.1	Introduction	263
5.2	The Statistical Pattern Recognition Paradigm	264
5.2.1	Basic Concept	264
5.2.2	Damage Index and Outlier Analysis	267
5.2.3	Case Study: Impact Tests of Composite Plates	269
5.3	Vibration-Based Techniques	276
5.3.1	Overview	276
5.3.2	Damage Detection Using Strain Energy Method	278
5.3.3	Damage Detection and Location Using Modal Properties	280
5.3.4	Damage Detection Using Frequency Response Function	285
5.3.5	Damage Index and Modal Assurance Criterion	286
5.3.6	Applications	292
5.3.7	Operational Deflection Shapes/Vibration Deflection Shapes	324
5.4	Closing Remarks and Conclusions	356
	Part III Reliability and Fatigue under Extreme Loading	359
6	Fatigue Life and Reliability Assessment	361
6.1	Introduction	361
6.2	Fatigue Life Assessment	362
6.2.1	Fatigue Crack Propagation	362
6.2.2	Fatigue Cumulative Damage	363
6.2.3	Half-Cycle Fatigue Life Approach	369
6.2.4	Thermal Fatigue	372
6.2.5	Acoustical Fatigue	377
6.2.6	Fatigue of Structural Joints	379
6.2.7	Design Considerations	386
6.3	Design Based on Ultimate Strength of Ship Structures	388
6.3.1	Modes of Ship Failure	394
6.3.2	Modes of Hull Failure	395
6.4	Probabilistic Models of Load Effects	398
6.4.1	Reliability Index	401
6.4.2	Limit State Function	403
6.4.3	Risk Analysis	408
6.4.4	Ultimate Limit State (ULS)	410
6.4.5	Reliability and Uncertainty	415
6.4.6	Reliability-Based Fatigue Assessment	418
6.4.7	Probabilistic Fracture Mechanics Assessment	421
6.5	Climate and Environmental Effects	425
6.6	Closing Remarks	428

7	Structural Reliability and Risk Assessment Under Extreme Loading	431
7.1	Introduction	431
7.2	Historic Extreme Loading Events	432
7.2.1	World Trade Center Towers (Terrorist Attack)	432
7.2.2	Ship Collisions and Grounding	436
7.2.3	Bridges under Extreme Loading	438
7.2.4	Collision of Road Tankers	443
7.3	Structural Life Assessment of Ocean Systems	444
7.3.1	Ship Structural Damage due to Slamming Loads	445
7.3.2	Damage Due to Grounding Accidents	472
7.3.3	Risk Assessment	472
7.3.4	Damage Due to Collisions	478
7.3.5	Reliability under Extreme Loading	487
7.4	Road Tanker Rollover	496
7.4.1	Rollover Scenarios and Metrics	497
7.4.2	Quasi-Dynamic Approach	506
7.4.3	Rollover of Road Tankers	508
7.4.4	International Standards of Roll Threshold	512
7.4.5	Directional Stability and Dynamics	513
7.4.6	Collision of Vehicles and Structural Fatigue	516
7.4.7	Coupled Dynamics of Liquid-Tanker Systems	520
7.4.8	Liquid-Vehicle Coupling During Braking	523
7.4.9	Passive Control of Liquid Sloshing	527
7.5	Pipes Conveying Fluids	529
7.5.1	Mechanics of the Linear Problem	530
7.5.2	Mechanics of the Nonlinear Problem	534
7.5.3	Constrained Pipes Conveying Liquid	544
7.6	Closing Remarks	557
	Part IV Environment Conditions, Joints and Crack Propagation Control	561
8	Corrosion and Hydrogen Embrittlement	563
8.1	Introduction	563
8.2	Corrosion of Ocean and Aerospace Structures	564
8.2.1	Corrosion of Ocean Structures	564
8.2.2	Problems of Aluminum Ship Structures	578
8.2.3	Corrosion of Aircraft Structures	582
8.2.4	Corrosion Monitoring	588
8.2.5	Corrosion Control	589
8.2.6	Corrosion Fatigue Cracking	593
8.3	Fretting/Wear in Heat Exchangers	598
8.3.1	Analytical and Computational Models	600
8.3.2	Experimental Investigations	603

8.4	Hydrogen Embrittlement	605
8.4.1	Hydrogen Embrittlement Problems	606
8.4.2	Fatigue Crack Enhancement	608
8.4.3	Crack Growth Modeling	610
8.4.4	Hydrogen Cracking Due to Welding	611
8.5	Closing Remarks and Conclusions	613
9	Joints and Weldments	615
9.1	Introduction	615
9.2	Energy Dissipation and Nonlinearity of Joints	616
9.2.1	Friction Characteristics	616
9.2.2	Energy Dissipation	617
9.2.3	Sources of Nonlinearities	621
9.2.4	Nonlinear Identification	623
9.2.5	Force-State Mapping Technique	626
9.3	Design Considerations	629
9.3.1	Fully and Partially Restrained Joints	634
9.3.2	Sensitivity Analysis to Joint Parameter Variations	636
9.3.3	Stochastic Sensitivity	638
9.3.4	Joint Uncertainties and Relaxation	640
9.3.5	Uncertainty of Boundary Conditions and Material Properties	643
9.3.6	Mechanism of Relaxation and Loosening	645
9.3.7	Case Study A: Elastic Structures with Parameter Uncertainties and Relaxation of Joints	649
9.3.8	Case Study B: Beloiu et al. (2005) – Influence of Boundary Conditions Relaxation	662
9.4	Welded Joints	690
9.4.1	Types of Welding Processes	690
9.4.2	Aluminum Welded Panels	694
9.4.3	Fatigue Assessment of Welded Joints	696
9.4.4	Fracture Mechanics Assessment	699
9.4.5	Fatigue Improvement of Welded Joints	704
9.5	Closing Remarks and Conclusions	706
	Appendix	708
10	Crack Control	711
10.1	Introduction	711
10.2	Basic Concept and Development of Crack Arresters	711
10.2.1	Basic Concept	711
10.2.2	Crack Arrest Toughness	714
10.3	Crack Arresters of Ship Structures	719
10.3.1	Crack Arresters of Metal Ship Structures	720
10.3.2	Crack Arresters of Composite Ship Structures	730
10.4	Crack Control and Repair of Aerospace Structures	737
10.4.1	Crack Control of Metallic Structures	737
10.4.2	Composite Patches	743
10.4.3	Crack Control of Composite Structures	745

10.5	Pipeline Crack Arresters	752
10.5.1	Transmission Pipelines	752
10.5.2	Buckle Arresters of Pipelines	756
10.6	Closing Remarks	763

References	767
-------------------	-----

Index	983
--------------	-----