

Contents

<i>Preface</i>	<i>page</i> xvii
<i>Acknowledgments</i>	xxi
Introduction	1
I.1 History of Fatigue	1
I.2 Examples of Fatigue Failures of Marine Structures	9
I.2.1 The <i>Alexander L. Kielland</i> Accident	9
I.2.2 Fatigue and Fracture of a Mooring Chain	11
I.2.3 Fatigue Cracking in Ship Side of a Shuttle Tanker	11
I.3 Types of Marine Structures	13
I.4 Design Methodology for Marine Structures	13
I.5 Overview of Fatigue Analysis Examples in This Book	17
1 Fatigue Degradation Mechanism and Failure Modes	19
1.1 General	19
1.2 Low Cycle and High Cycle Fatigue	20
1.3 Failure Modes due to Fatigue	22
1.3.1 Fatigue Crack Growth from the Weld Toe into the Base Material	22
1.3.2 Fatigue Crack Growth from the Weld Root through the Fillet Weld	23
1.3.3 Fatigue Crack Growth from the Weld Root into the Section under the Weld	23
1.3.4 Fatigue Crack Growth from a Surface Irregularity or Notch into the Base Material	25
2 Fatigue Testing and Assessment of Test Data	26
2.1 Planning of Testing	26
2.1.1 Constant Amplitude versus Variable Amplitude Testing	26
2.1.2 Fabrication of Test Specimens	27
2.1.3 Residual Stresses and Stress Ratio during Testing	27
2.1.4 Number of Tests	30

2.1.5	Instrumentation	30
2.1.6	Test Frequency	31
2.1.7	Measurements and Documentation of Test Data	32
2.1.8	Assessment of Test Data	32
2.2	Butt Welds in Piles	32
2.2.1	Material Data and Fabrication of Test Specimens	33
2.2.2	Measured Residual Stresses	36
2.2.3	Assessment of the Test Data	37
2.3	Details in Ship Structures	39
2.3.1	Fatigue Testing	39
2.3.2	Geometry and Fabrication of Specimens	43
2.3.3	Additional Test Results for Model 4	43
2.3.4	Additional Test Results for Model 5	44
2.3.5	Effect of Stress Gradient at Weld Toe	45
2.3.6	Hot Spot Stress for the Tested Specimens	48
2.4	Side Longitudinals in Ships	52
2.4.1	Test Arrangement	54
2.4.2	Instrumentation	55
2.4.3	Testing	56
2.4.4	Assessment of Fatigue Test Data	57
2.4.5	Comparison of Calculated Stress by Finite Element Analysis and Measured Data	60
2.5	Fillet Welded Connections	61
2.5.1	Fillet Welds Subjected to Axial Load	61
2.5.2	Fillet Welded Tubular Members Subjected to Combined Axial and Shear Load	64
2.5.3	Correction of Test Data for Measured Misalignment	66
2.5.4	Assessment of Test Data	69
2.5.5	Comparison of Design Equations with Test Data for Combined Loading	72
2.6	Doubling Plates or Cover Plates	74
2.6.1	Background	74
2.6.2	Test Program and Preparation of Test Specimens	75
2.6.3	Fatigue Testing	77
2.6.4	Assessment of Test Data	82
2.7	Effect of Stress Direction Relative to Weld Toe	84
2.7.1	Constant Stress Direction	84
2.7.2	Fatigue Test Data	84
2.7.3	Design Procedures in Different Design Standards	85
2.7.4	Comparison of Design Procedures with Fatigue Test Data	88
2.7.5	Varying Stress Direction during a Load Cycle	94
3	Fatigue Design Approaches	95
3.1	Methodology for Assessment of Low Cycle Fatigue	95
3.1.1	Cyclic Strain and Fatigue Strength	95
3.1.2	Cyclic Stress-Strain Curve	96
3.1.3	Strain-Based Approach for Assessment of Fatigue Life	98

Contents

vii

3.1.4	Relationship between Elastic Strain and Nonlinear Elastic Strain	101
3.1.5	Notch Sensitivity and Fatigue Strength of Notched Specimens	106
3.1.6	Combination of Fatigue Damage from Low Cycle and High Cycle Fatigue	106
3.2	Methodology for Assessment of High Cycle Fatigue	107
3.2.1	Calculation of Stresses and Relation to Different S-N Curves	107
3.2.2	Guidance Regarding When Detailed Fatigue Analysis Is Required	112
3.2.3	Fatigue Damage Accumulation – Palmgren-Miner Rule	114
3.3	Residual Stresses	116
3.3.1	Residual Stresses due to Fabrication	116
3.3.2	Shakedown of Residual Stresses	116
3.3.3	Mean Stress Reduction Factor for Base Material	118
3.3.4	Residual Stress in Shell Plates in Tubular Towers after Cold Forming	118
3.3.5	Mean Stress Reduction Factor for Post-Weld Heat-Treated Welds	120
3.3.6	Mean Stress Reduction Factor for Inspection Planning for Fatigue Cracks in As-Welded Structures	120
4	S-N Curves	123
4.1	Design S-N Curves	123
4.1.1	General	123
4.1.2	S-N Curves and Joint Classification Using Nominal Stresses	123
4.1.3	S-N Curves for Steel Details in Air	125
4.1.4	Comparison of S-N Curves for Details in Air in Design Standards	126
4.1.5	S-N Curves for Material with High-Strength Steel	127
4.1.6	S-N Curves for Details in Seawater with Cathodic Protection	128
4.1.7	S-N Curves for Details in Seawater with Free Corrosion	130
4.1.8	S-N Curves for Sour Environment	131
4.1.9	S-N Curves for the Notch Stress Method	131
4.1.10	S-N Curves for Stainless Steel	131
4.1.11	S-N Curves for Umbilicals	132
4.1.12	S-N Curves for Copper Wires	134
4.1.13	S-N Curves for Aluminum Structures	134
4.1.14	S-N Curves for Titanium Risers	135
4.1.15	S-N Curves for Chains	135
4.1.16	S-N Curves for Wires	136
4.1.17	S-N Curves for Concrete Structures	136
4.2	Failure Criteria Inherent in S-N Curves	136
4.3	Mean Stress Effect	137

4.4	Effect of Material Yield Strength	137
4.4.1	Base Material	137
4.4.2	Welded Structures	137
4.5	Effect of Fabrication Tolerances	138
4.6	Initial Defects and Defects Inherent in S-N Data	138
4.6.1	Types of Defects in Welded Connections	138
4.6.2	Acceptance Criteria and Link to Design S-N Curves	140
4.7	Size and Thickness Effects	142
4.7.1	Base Material	142
4.7.2	Welded Connections	142
4.7.3	Size Effect in Design Standards	147
4.7.4	Calibration of Analysis Methods to Fatigue Test Data	148
4.7.5	Cast Joints	150
4.7.6	Weld Length Effect	150
4.8	Effect of Temperature on Fatigue Strength	153
4.9	Effect of Environment on Fatigue Strength	154
4.9.1	Condition in Fresh Water	154
4.9.2	Effect of Cathodic Protection in Seawater	154
4.9.3	Corrosion Fatigue	155
4.9.4	Effect of Coating	156
4.10	Selection of S-N Curves for Piles	157
4.10.1	S-N Curves for Pile Driving	157
4.10.2	S-N Curves for Installed Condition	157
4.11	Derivation of Characteristic and Design S-N Curves	157
4.11.1	General	157
4.11.2	Requirements for Confidence for Fatigue Assessment in the Literature and in Design Standards	158
4.12	Requirements for Confidence Levels, as Calculated by Probabilistic Methods	163
4.12.1	Probabilistic Analysis	163
4.12.2	Analysis Results for a Design-Life Approach to Safety	163
4.12.3	Analysis Results for a Per Annum Approach to Safety	164
4.12.4	Effect of Uncertainty in Loading Included	165
4.12.5	Case with Known Standard Deviation	166
4.12.6	Combination of Cases	167
4.13	Justifying the Use of a Given Design S-N Curve from a New Data Set	167
4.13.1	Methodology	167
4.13.2	Example of Analysis of Testing of Connectors, Case A	168
4.13.3	Example of Analysis, Case B	170
4.13.4	Example of Fatigue Proof Testing of Connector in Tethers of a Tension Leg Platform	173
5	Stresses in Plated Structures	174
5.1	Butt Welds in Unstiffened Plates	174
5.2	Fillet Welds	176
5.3	Butt Welds in Stiffened Plates	177

Contents

ix

5.3.1	Background	177
5.3.2	Finite Element Analysis of Stiffened Plates	178
5.3.3	Analytical Equations for Stress Concentrations at Butt Welds in Plated Structures	183
5.3.4	Effect of Fabrication Tolerances in Plated Structures in Fatigue Design Standards	184
5.4	Openings with and without Reinforcements	188
5.4.1	Circular Hole in a Plate	188
5.4.2	Elliptical Hole in a Plate	188
5.4.3	Rectangular Holes	190
5.4.4	Scallops or Cope Holes	190
5.5	Fatigue Assessment Procedure for Welded Penetrations	191
5.5.1	Critical Hot Spot Areas	191
5.5.2	Stress Direction Relative to Weld Toe	191
5.5.3	Stress Concentration Factors for Holes with Reinforcement	193
5.5.4	Procedure for Fatigue Assessment	194
5.5.5	Comparison of Analysis Procedure with Fatigue Test Data	199
5.5.6	Example Calculation of the Fillet Welds in the <i>Alexander L. Kielland</i> Platform	203
6	Stress Concentration Factors for Tubular and Shell Structures Subjected to Axial Loads	205
6.1	Classical Shell Theory	205
6.2	Girth Welds	206
6.2.1	Circumferential Welds in Tubular Members	206
6.2.2	Closure Welds at Stubs	209
6.3	SCFs for Girth Welds in Tubular Members	210
6.4	Recommended SCFs for Tubular Girth Welds	212
6.5	Application of Eccentricity to Achieve an Improved Fatigue Strength	214
6.6	Example of Fatigue Assessment of Anode Attachment Close to a Circumferential Weld in a Jacket Leg	215
6.7	Ring Stiffeners	218
6.7.1	Example: Assessment of Stress Concentration Inherent in Nominal Stress S-N Curves	220
6.7.2	Example: Fatigue Assessment of a Drum	221
6.8	Conical Transitions	222
6.8.1	Weld at Conical Junction	222
6.8.2	Example of Conical Transition in Monopile for Wind Turbine Structure	224
6.8.3	Conical Transition with Ring Stiffeners at the Junctions	225
6.8.4	Conical Transition with Ring Stiffener Placed Eccentrically at Junction	226
6.9	Tethers and Risers Subjected to Axial Tension	227
6.9.1	Example: Pretensioned Riser	229

7	Stresses at Welds in Pipelines, Risers, and Storage Tanks	231
7.1	Stresses at Girth Welds and Ring Stiffeners due to Axial Force	231
7.1.1	General	231
7.1.2	Circumferential Butt Welds in Pipes at Thickness Transitions and with Fabrication Tolerances	232
7.1.3	Nominal Stress in Pipe Wall and Derivation of Hot Spot Stresses	235
7.1.4	Stress Distribution in Pipe Away from a Butt Weld with Fabrication Tolerances	236
7.2	Stresses at Seam Weld due to Out-of-Roundness of Fabricated Pipes and Internal Pressure	237
7.3	Stresses at Ring Stiffeners due to Internal Pressure	241
7.4	Stresses at Thickness Transitions due to Internal Pressure	244
7.4.1	Circumferential Butt Welds in Pipes with Different Thicknesses	244
7.5	Stresses in Cylinders Subjected to Internal Pressure	248
7.5.1	Classical Theory for Spherical Shells	248
7.5.2	Stresses at Girth Weld between Cylinder and Sphere in Storage Tank with Internal Pressure	249
8	Stress Concentration Factor for Joints	252
8.1	General	252
8.2	Simple Tubular Joints	253
8.2.1	Definitions of Geometry Parameters and Stresses	253
8.2.2	Influence of Diameter Ratio β on Stress Concentration	257
8.2.3	Influence of Radius-to-Thickness Ratio of Chord, γ , on Stress Concentration	257
8.2.4	Influence of Thickness Ratio, τ , on Stress Concentration	257
8.2.5	Influence of Chord-Length-to-Diameter, α , on Stress Concentration	259
8.2.6	Assessment of Accuracy of SCFs	264
8.2.7	Combination of Stresses from Different Load Conditions	264
8.3	Single-Sided Welded Tubular Joints	266
8.3.1	Background	266
8.3.2	Design S-N Curves	267
8.3.3	Design Fatigue Factor	268
8.3.4	SCFs for Inside Hot Spots	268
8.4	Overlap Joints	270
8.5	Stiffened Tubular Joints	270
8.6	Grout-Reinforced Joints	271
8.6.1	General	271
8.6.2	Chord Filled with Grout	271
8.6.3	Annulus between Tubular Members Filled with Grout	272
8.7	Cast Nodes	272
8.8	Joints with Gusset Plates	272
8.9	Rectangular Hollow Sections	273

Contents

xi

8.10	Fillet-Welded Bearing Supports	273
8.11	Cutouts and Pipe Penetrations in Plated Structures	274
8.12	Details in Ship Structures	275
8.12.1	Lugs at Side Longitudinals	275
8.12.2	Asymmetric Sections Subjected to Dynamic Sideway Loading	275
8.12.3	Example of Calculated SCFs for an Asymmetric Section	278
9	Finite Element Analysis	279
9.1	Welded Connections in Plated Structures	279
9.1.1	General	279
9.1.2	Finite Element Modeling for Structural Stress Analysis	281
9.1.3	Derivation of Hot Spot Stress from Finite Element Analysis	284
9.1.4	Effective Hot Spot Stress	288
9.1.5	Hot Spot S-N Curves	288
9.1.6	Analysis Methodology for Fillet Welds	291
9.1.7	Verification of Analysis Methodology	292
9.1.8	Examples of Finite Element Models in Ship Structures	292
9.2	Alternative Procedure for Analysis of Web-Stiffened Cruciform Connections	294
9.2.1	General	294
9.2.2	Plate Thickness to Be Used in Analysis Procedure	296
9.2.3	Procedure for Analysis Using a Shell Element Model	297
9.3	Joint with Gusset Plates	299
9.4	Welded Penetrations in Plates	301
9.4.1	General	301
9.4.2	Stresses for Fatigue Design at Position a	302
9.4.3	Stresses for Fatigue Design at Position b	302
9.4.4	Stresses for Fatigue Design at Position c	303
9.5	Tubular Joints	304
9.6	Notch Stress Method	305
9.6.1	General	305
9.6.2	The Notch Stress Method	306
9.6.3	Calculation of Notch Stress	308
9.6.4	Example of Validation of Analysis Methodology	308
10	Fatigue Assessment Based on Stress Range Distributions	310
10.1	Weibull Distribution of Long-Term Stress Ranges	310
10.2	Closed-Form Expressions for Fatigue Damage Based on the Weibull Distribution of Stress Ranges	312
10.3	Closed-Form Expressions for Fatigue Damage Based on the Rayleigh Distribution of Stress Ranges	314
10.4	Example of Use of Closed-Form Expressions for Fatigue Damage in Calculation Sheets Based on a Bilinear S-N Curve	315
10.5	Probability of Being Exceeded	317

10.6	Maximum Allowable Stress Range	319
10.6.1	Design Charts	319
10.6.2	Effect of Design Fatigue Factor and Other Design Lives	319
10.6.3	Some Guidance on Selection of a Weibull Shape Parameter	320
10.6.4	Example of Use of Design Charts	321
10.7	Combined Load and Response Processes	322
10.7.1	General	322
10.7.2	Example of Fatigue Analysis of Pipes on a Floating Production Vessel	322
10.8	Long-Term Loading Accounting for the Mean Stress Effect	324
11	Fabrication	327
11.1	General	327
11.2	Selection of Material	327
11.3	Welding	328
11.4	Defects	329
11.5	Fabrication Tolerances	330
11.6	Non-Destructive Testing for Defects	331
11.6.1	General	331
11.6.2	Visual Inspection	333
11.6.3	Probability of Detection by Visual Inspection	333
11.6.4	Magnetic Particle Inspection	333
11.6.5	Penetrant Testing	334
11.6.6	Ultrasonic Testing	334
11.6.7	Probability of Detection for Ultrasonic Testing	336
11.6.8	Radiographic Testing	336
11.6.9	Eddy Current	336
11.6.10	Alternating Current Field Measurement and Alternating Current Potential Drop Methods	337
11.6.11	Probability of Detection Curves for EC, MPI, and ACFM	337
11.6.12	Methodology to Provide Reliable PoD Curves for Other Inspection Methods	338
11.7	Improvement Methods	339
11.7.1	General	339
11.7.2	Weld Profiling by Machining and Grinding	340
11.7.3	Weld Toe Grinding	342
11.7.4	Workmanship	343
11.7.5	Example of Effect of Grinding a Weld	344
11.7.6	TIG Dressing	345
11.7.7	Hammer Peening	345
11.7.8	High-Frequency Mechanical Impact Treatment	347
11.7.9	Post-Weld Heat Treatment	347
11.7.10	Extended Fatigue Life	348
11.7.11	Stop Holes	348

<i>Contents</i>	<i>xiii</i>
11.7.12 Grind Repair of Fatigue Cracks	349
11.7.13 S-N Curves for Improved Areas	350
11.8 Measurement of Surface Roughness	350
11.9 Effect of Surface Roughness on Fatigue Capacity	353
12 Probability of Fatigue Failure	355
12.1 Failure Probability at the Design Stage	355
12.1.1 General	355
12.1.2 Accumulated and Annual Failure Probability	356
12.1.3 Time-Limited Failure Probability	356
12.2 Uncertainties in Fatigue Analysis	357
12.3 Requirements for In-Service Inspection for Fatigue Cracks	359
12.4 Target Safety Level for Structural Design	360
12.5 Residual Strength of Structures with a Fatigue Crack	362
12.6 System Reliability Method	364
12.6.1 Robustness	364
12.6.2 Assessment of Collapse Capacity in Jacket Structures	365
12.6.3 Simplified Method for Estimation of Probability of System Failure	365
12.7 Design Fatigue Factors	366
12.7.1 Structures	367
12.7.2 Piles	368
12.7.3 Example of Design Methodology for Storage Pipes for Compressed Gas	369
12.8 Example of Calculation of Probability of Fatigue Failure Using an Analytical Approach	376
13 Design of Bolted and Threaded Connections	379
13.1 Introduction	379
13.2 Failure Modes of Bolts and Bolted Connections Subjected to Dynamic Loading	381
13.3 Stress Corrosion and Embrittlements	382
13.4 Fatigue Capacity of Bolts	384
13.4.1 Geometry	384
13.4.2 Chemistry	386
13.4.3 Material Strength	386
13.4.4 Effective Bolt Area	387
13.4.5 Fitted Bolts	388
13.4.6 Thread Forming	388
13.4.7 Tolerances	389
13.4.8 Surface Treatment	389
13.4.9 Effect of Mean Stress	391
13.5 Slip-Resistant Connections	391
13.6 Tension-Type Connections	392
13.6.1 Application	392
13.6.2 Structural Mechanics for Design of Bolted Connections	393

13.7	Technical Specification for Supply of Heavy-Duty Bolts	396
13.8	Pretensioning of Bolts	397
13.9	Connectors for Tubular Structures	398
14	Fatigue Analysis of Jacket Structures	400
14.1	General	400
14.2	Deterministic Fatigue Analysis	402
14.3	Frequency Response Fatigue Analysis	404
15	Fatigue Analysis of Floating Platforms	407
15.1	General	407
15.2	Semi-Submersibles	407
15.3	Floating Production Vessels (FPSOs)	407
16	Fracture Mechanics for Fatigue Crack Growth Analysis and Assessment of Fracture	408
16.1	Brittle and Ductile Failures	408
16.1.1	Introduction	408
16.1.2	Design of Ductile Structures	408
16.1.3	Structural Strength of Connections with Defects	409
16.2	Stress Intensity Factors and Fatigue Crack Growth Equations	410
16.3	Examples of Crack Growth Analysis	413
16.3.1	Assessment of Internal Defects in a Cruciform Joint	413
16.3.2	Example of Crack Growth from the Crack around the Hydrophone Support in the <i>Alexander L. Kielland</i> Platform	416
16.3.3	Example of Crack Growth from the Root of a Partial Penetration Weld	418
16.3.4	Example of Crack Growth from the Root in a Single-Sided Girth Weld in a Pile Supporting a Jacket Structure	420
16.4	Fracture Mechanics Models for Surface Cracks at Weld Toes	424
16.5	Numerical Methods for Derivation of Stress Intensity Factors	427
16.6	Crack Tip Opening Displacement	428
16.7	Fracture Toughness Based on Charpy V Values	429
16.8	Failure Assessment Diagram for Assessment of Fracture	429
16.9	Effect of Post-Weld Heat Treatment and Effect of Crack Closure	431
16.10	Alternative Methods for Derivation of Geometry Functions	431
16.11	Crack Growth Constants	433
16.12	Link between Fracture Mechanics and S-N Data	434
17	Fatigue of Grouted Connections	435
17.1	Jacket Structures	435
17.1.1	Background for Design Standards for Grouted Connections	435
17.1.2	Grouted Connections in Newer Jackets	436
17.1.3	Assessment of Load Effects and Failure Modes	437

<i>Contents</i>		xv
17.1.4	Recommended Design Practice in NORSOK N-004 and DNV-OS-J101	441
17.2	Monopiles	444
17.2.1	Experience with Plain Cylindrical Grouted Connections	444
17.2.2	Moment Capacity of Plain Connections	445
17.2.3	Opening between the Steel and the Grout in the Connections due to Moment Loading	449
17.2.4	Load on Shear Keys in Grouted Connections with Shear Keys	450
17.2.5	Design of Box Test Specimens	458
17.2.6	Comparison of Design Procedure with Test Data	460
17.2.7	Fatigue Tests Data	462
17.2.8	Illustration of Analysis for Long-Term Loads	463
18	Planning of In-Service Inspection for Fatigue Cracks	465
18.1	General	465
18.2	Analysis Tools	468
18.3	Assessment of the Probability of Fatigue Failure	471
18.4	Implementation of Monitoring Data	472
18.5	Inspection Planning and Inspection Program	473
18.6	Reliability Updating	473
18.7	Description of Probabilistic Fatigue Analysis Models	474
18.8	Description of Probabilistic Crack Growth Analysis	475
18.9	Formulation of Reliability Updating	476
18.10	Change in Damage Rate over Service Life	478
18.11	Effect of Correlation	478
18.11.1	General	478
18.11.2	Example of Analysis Where Correlation Is Included in Assessment of an FPSO	479
18.12	Effect of Inspection Findings	480
18.13	Residual Strength of the Structure or System Effects with a Fatigue Crack Present	480
18.14	Inspection for Fatigue Cracks during In-Service Life	481
18.14.1	General	481
18.14.2	Magnetic Particle Inspection Underwater	481
18.14.3	Eddy Current	481
18.14.4	Flooded Member Detection	481
18.14.5	Leakage Detection	482
18.14.6	Acoustic Emission	482
18.14.7	Inspection Methods for Jackets	483
18.14.8	Inspection Methods for Floating Structures	483
18.15	Effect of Measurements of Action Effects	483
APPENDIX A: Examples of Fatigue Analysis		485
A.1	Example of Fatigue Design of a Pin Support for a Bridge between a Flare Platform and a Larger Jacket Structure	485
A.2	Fatigue Design of Ship Side Plates	486

A.3	Fatigue and Unstable Fracture of a Chain	488
A.3.1	Problem Definition	488
A.3.2	Assessment of Unstable Fracture Using Failure Assessment Diagram	489
A.3.3	Fatigue Assessment of the Chain Based on S-N data	491
A.3.4	Fatigue of the Chain Assessed by Fracture Mechanics	492
	APPENDIX B: Stress Intensity Factors	494
	<i>References</i>	499
	<i>Index</i>	521