

Contents

<i>Preface</i>	page 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

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

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