

# Table of Contents

<b>Abbreviations . . . . .</b>	<b>xv</b>
<b>PART I. Common Practice . . . . .</b>	<b>1</b>
<b>Chapter 1. Introduction . . . . .</b>	<b>3</b>
1.1. The importance of welded joints and their fatigue behavior . . . . .	3
1.2. Objectives and scope of the book . . . . .	4
1.3. The content of the various chapters . . . . .	5
1.4. Other literature in the field . . . . .	7
1.5. Why should the practicing engineer apply reliability methods? . . . . .	8
1.6. How to work with this book . . . . .	9
1.7. About the authors . . . . .	10
<b>Chapter 2. Basic Characterization of the Fatigue Behavior of Welded Joints . . . . .</b>	<b>11</b>
2.1. Introduction and objectives . . . . .	11
2.2. Fatigue failures . . . . .	11
2.3. Basic mechanisms of metal fatigue . . . . .	15
2.4. Parameters that are important to the fatigue damage process . . . . .	17
2.4.1. External loading and stresses in an item . . . . .	17
2.4.2. Geometry, stress and strain concentrations . . . . .	19
2.4.3. Material parameters . . . . .	20
2.4.4. Residual stresses . . . . .	24
2.4.5. Fabrication quality and surface finish . . . . .	25
2.4.6. Influence of the environment . . . . .	25
2.5. Important topics for welded joints . . . . .	26
2.5.1. General overview . . . . .	26

2.6. Various types of joints . . . . .	30
2.6.1. Plated joints . . . . .	30
2.6.2. Tubular joints . . . . .	34
2.7. References . . . . .	35
<b>Chapter 3. Experimental Methods and Data Analysis . . . . .</b>	<b>37</b>
3.1. Introduction and objectives . . . . .	37
3.2. Overview of various types of tests . . . . .	38
3.3. Stress-life testing (S-N testing) of welded joints . . . . .	38
3.3.1. Test specimens and test setup . . . . .	38
3.3.2. Preparations and measurements . . . . .	41
3.3.3. Test results . . . . .	46
3.4. Testing to determine the parameters in the strain-life equation . . . . .	49
3.5. Crack growth tests – guidelines for test setup and specimen monitoring . . . . .	50
3.6. Elementary statistical methods . . . . .	55
3.6.1. Linear regression analyses . . . . .	55
3.7. References . . . . .	60
<b>Chapter 4. Definition and Description of Fatigue Loading . . . . .</b>	<b>61</b>
4.1. Introduction and objectives . . . . .	61
4.2. Constant amplitude loading . . . . .	62
4.3. Variable amplitude loading . . . . .	63
4.3.1. Overview . . . . .	63
4.3.2. Rain-flow cycle counting of time series . . . . .	64
4.3.3. The energy spectrum approach . . . . .	69
4.4. References . . . . .	73
<b>Chapter 5. The S-N Approach . . . . .</b>	<b>75</b>
5.1. Introduction and objectives . . . . .	75
5.2. Method, assumptions and important factors . . . . .	76
5.2.1. Statistics for the S-N approach, median and percentile curves . .	76
5.2.2. Discussion of S-N curves-important factors . . . . .	78
5.2.2.1. The threshold phenomenon . . . . .	78
5.2.2.2. Mean stress and loading ratio . . . . .	79
5.2.2.3. Stress relieving . . . . .	79
5.2.2.4. The thickness effect . . . . .	80
5.2.2.5. Misalignment . . . . .	81
5.2.2.6. Post-weld improvement techniques . . . . .	82
5.2.2.7. Corrosive environment . . . . .	83
5.3. Mathematics for damage calculations . . . . .	84
5.3.1. Linear damage accumulation; load spectrum on a histogram format . . . . .	84

5.3.2. Discussion of the validity of the linear damage accumulation . . . . .	86
5.3.3. Definition of the equivalent stress range . . . . .	88
5.3.4. Load spectrum on the format of a Weibull distribution. . . . .	88
5.4. S-N curves related to various stress definitions. . . . .	91
5.4.1. Nominal stress, geometrical stress and weld notch stresses . . . . .	92
5.4.2. Geometrical stresses in tubular joints . . . . .	96
5.4.3. Fatigue life estimate based on the weld notch stress approach . .	98
5.4.4. Conclusions on the various stress approaches . . . . .	101
5.5. Some comments on finite element analysis . . . . .	104
5.6. Current rule and regulations . . . . .	110
5.6.1. General considerations . . . . .	110
5.6.2. The original fatigue classes and S-N curves from DoE . . . . .	112
5.6.3. S-N life predictions according to Eurocode 3-Air environment . . . . .	117
5.6.4. S-N life predictions according to HSE . . . . .	119
5.6.5. S-N life predictions according to NORSOK and DNV . . . . .	120
5.6.6. S-N life predictions for ship structures . . . . .	122
5.7. The industrial case: an offshore loading buoy . . . . .	130
5.8. References . . . . .	136
<b>Chapter 6. Applied Fracture Mechanics . . . . .</b>	<b>139</b>
6.1. Introduction. . . . .	139
6.2. Objectives of this chapter . . . . .	142
6.3. Basic concepts of linear elastic fracture mechanics . . . . .	142
6.3.1. The local stress field ahead of the crack front . . . . .	142
6.4. Fracture criterion due to extreme load . . . . .	152
6.4.1. Mixed mode rupture . . . . .	153
6.4.2. The R6 criterion and critical crack size . . . . .	154
6.5. Fatigue threshold and fatigue crack growth . . . . .	156
6.5.1. Crack growth models. . . . .	156
6.5.2. Parameters C and m . . . . .	159
6.5.3. Residual stresses . . . . .	160
6.5.4. Some notes on the size of the initial cracks. . . . .	161
6.6. Geometry function and growth parameters given in BS7910 . . . . .	161
6.6.1. The geometry function . . . . .	162
6.6.2. Parameters C and m . . . . .	163
6.7. Fracture mechanics model for a fillet welded plate joint . . . . .	165
6.7.1. Basic assumptions and criteria for the model. . . . .	165
6.7.2. Data for crack growth measurements (database 1) . . . . .	166
6.7.3. Data for fatigue lives at low stress levels (database 2) . . . . .	167
6.7.4. Procedure and curve fitting . . . . .	167
6.7.5. Growth parameters C and m. . . . .	169
6.7.6. The initial crack depth $a_0$ . . . . .	172

6.7.7. Prediction of crack growth histories and construction of S-N curves . . . . .	173
6.7.8. Conclusions for fillet joints with cracks at the weld toe . . . . .	175
6.8. Fatigue crack growth in tubular joints . . . . .	176
6.8.1. Discussion of current models . . . . .	179
6.8.2. Conclusion on the empirical fracture mechanics model . . . . .	183
6.8.3. Proposal for model improvements . . . . .	183
6.9. A brief overview of stiffened panels . . . . .	184
6.10. Units and conversion for fracture mechanics parameters . . . . .	186
6.11. Industrial case: fatigue re-assessment of a welded pipe . . . . .	186
6.11.1. Introduction . . . . .	186
6.11.2. Description of the loading buoy with steel pipe . . . . .	187
6.11.3. Replacement and inspection strategy . . . . .	189
6.11.4. Re-assessment based on the S-N approach . . . . .	190
6.11.5. Re-assessment based on fracture mechanics . . . . .	191
6.12. References . . . . .	193
<b>PART II. Stochastic Modeling . . . . .</b>	<b>197</b>
<b>Chapter 7. Stochastic Modeling . . . . .</b>	<b>199</b>
7.1. Introduction and objectives . . . . .	199
7.2. Overview of models and methodology . . . . .	200
7.2.1. Sources of uncertainty . . . . .	200
7.2.2. Introduction to the random variable model and related methods . . . . .	201
7.2.3. Requirements for a stochastic model . . . . .	203
7.2.4. The concept of the limit state function and the safety margin . . . . .	204
7.2.5. The first and second order reliability methods (FORM/SORM) . . . . .	206
7.3. Elementary reliability models . . . . .	207
7.3.1. General considerations . . . . .	207
7.3.2. The Lognormal distribution . . . . .	208
7.3.3. The Weibull distribution . . . . .	209
7.4. The random variable model using simulation methods . . . . .	212
7.4.1. General considerations . . . . .	212
7.4.2. The realization of a random variable by the Monte Carlo method . . . . .	213
7.5. Random variable models based on the S-N approach . . . . .	215
7.5.1. The lognormal format for the S-N fatigue life . . . . .	215
7.5.1.1. Example: full-penetration butt joint in an offshore structure . . . . .	217
7.5.2. Monte Carlo Simulation of the S-N fatigue life . . . . .	219
7.6. Random variable models based on fracture mechanics . . . . .	220
7.6.1. General considerations . . . . .	220
7.6.2. Taking account for future inspections and inspection results . . . . .	221
7.6.3. Characterization of the performance of the non-destructive inspection technique . . . . .	223

7.6.4. Simulation with account for future planned inspections . . . . .	225
7.6.4.1. A first approximation to the inspection problem . . . . .	225
7.6.4.2. Full stochastic simulation . . . . .	226
7.6.5. Simulation of planned inspections for a fillet welded joint. . . . .	229
7.6.6. Updating based on inspections results. . . . .	231
7.7. The Markov chain model. . . . .	235
7.7.1. Basic concepts. . . . .	235
7.7.2. Simple illustration on how the model works . . . . .	235
7.7.3. Elaboration of the model. . . . .	242
7.7.4. Influence of scheduled inspection and repair. . . . .	244
7.7.5. Parameter estimation . . . . .	246
7.7.6. Hybrid model to account for additional scatter. . . . .	248
7.7.7. Analysis of a fillet welded joint. . . . .	249
7.7.7.1. Short review and elaboration of database 1 . . . . .	250
7.7.7.2. Determination of parameters in the Markov model. . . . .	251
7.7.7.3. Reliability results and discussion . . . . .	253
7.8. A damage tolerance supplement to rules and regulation . . . . .	255
7.8.1. Introduction . . . . .	255
7.8.2. An industrial case study: single anchor loading system . . . . .	260
7.8.2.1. Example 1: butt weld in upper pipeline. . . . .	262
7.8.2.2. Example 2: welded brackets on the main plates. . . . .	263
7.8.3. Conclusions for the damage tolerance supplement . . . . .	263
7.9. Risk assessments and cost benefit analysis . . . . .	264
7.10. Reliability and risk assessment for the riser steel pipe. . . . .	267
7.11. References. . . . .	268
<b>PART III. Recent Advances . . . . .</b>	<b>271</b>
<b>Chapter 8. Proposal for a New Type of S-N Curve . . . . .</b>	<b>273</b>
8.1. Introduction and objectives . . . . .	273
8.2. General considerations for the conventional S-N approach. . . . .	275
8.2.1. Basic assumptions . . . . .	275
8.2.2. The S-N approach based on BS5400 and Eurocode 3. . . . .	275
8.3. S-N curves based on a random fatigue limit model . . . . .	277
8.4. Experimental data for model calibration. . . . .	278
8.4.1. Data for fatigue life at high stress levels (database 1). . . . .	278
8.4.2. Data for fatigue lives at low stress levels (database 2) . . . . .	279
8.5. Comparison between the F-class curve, the RFLM-based curve and the data . . . . .	279
8.6. Conclusions. . . . .	284
8.7. References . . . . .	284

<b>Chapter 9. Physical Modeling of the Entire Fatigue Process . . . . .</b>	287
9.1. Introduction and objectives . . . . .	287
9.2. Modeling the fatigue crack initiation period . . . . .	289
9.2.1. Basic concept and equations for the local stress-strain approach . . . . .	289
9.2.2. Definition of the initiation phase and determination of parameters . . . . .	292
9.2.3. Local toe geometry and stress concentration factor . . . . .	292
9.2.4. Transition depth . . . . .	294
9.2.5. Cyclic mechanical properties and parameters in Coffin-Manson equation . . . . .	295
9.3. Constructing the S-N curve from the two-phase model . . . . .	297
9.4. Damage accumulation using the TPM . . . . .	301
9.5. The practical consequences of the TPM . . . . .	302
9.5.1. General considerations . . . . .	302
9.5.2. Life predictions and dimensions . . . . .	302
9.5.3. Predicted crack evolution and inspection planning . . . . .	303
9.6. Conclusions . . . . .	306
9.7. Suggestions for future work . . . . .	307
9.8. References . . . . .	308
<b>Chapter 10. A Notch Stress Field Approach to the Prediction of Fatigue Life . . . . .</b>	309
10.1. A modified S-N approach . . . . .	309
10.1.1. General considerations . . . . .	309
10.1.2. The basic theory for the notch stress intensity factor . . . . .	311
10.1.3. S-N data analysis for fillet welded joints . . . . .	313
10.2. A modified crack growth approach . . . . .	315
10.3. References . . . . .	317
<b>Chapter 11. Multi-Axial Fatigue of Welded Joints . . . . .</b>	319
11.1. Introduction and objectives . . . . .	319
11.2. Overview of theory and crack-extension criteria . . . . .	321
11.3. The crack box technique . . . . .	322
11.3.1. General considerations for finite element analysis and element mesh . . . . .	322
11.3.2. Methodology . . . . .	322
11.3.3. Examples . . . . .	324
11.4. Tentative mixed-mode model to crack propagation in welded joints . . . . .	325
11.4.1. Modeling the effect of the loading mode on the crack growth rate . . . . .	327
11.4.2. Modeling the effect of the residual stress due to the weld on the crack growth rate . . . . .	328

11.4.3. Measured effect of the loading angle on the crack growth rate . . . . .	329
11.4.4. Measured effect of weld on the crack growth rate . . . . .	331
11.4.5. Measured crack extension angle under mixed mode loading. . . . .	332
11.5. Validation of the model . . . . .	333
11.5.1. Verification of the models for non-welded steel specimens under mixed-mode loading . . . . .	334
11.5.2. Verification of the models for non-welded and welded steel specimens under mode I loading . . . . .	336
11.5.3. Verification of the models for welded steel specimens under mixed-mode loading . . . . .	337
11.5.4. Verification of the effect of the welded residual stress on the fatigue life . . . . .	338
11.5.5. Discussion and conclusions . . . . .	339
11.6. Extension to full test. . . . .	340
11.6.1. Modeling methodology. . . . .	341
11.6.2. Global calculation scheme . . . . .	341
11.6.3. The crack box technique . . . . .	343
11.6.4. Crack-propagation rate . . . . .	344
11.6.5. Description of experiments carried out . . . . .	345
11.6.6. Results. . . . .	345
11.6.7. Weld toe geometry . . . . .	346
11.6.8. Numerical calculations . . . . .	347
11.6.8.1. Crack initiation . . . . .	347
11.6.8.2. Crack growth . . . . .	349
11.7. References. . . . .	351
<b>Chapter 12. The Effect of Overloads on the Fatigue Life. . . . .</b>	<b>355</b>
12.1. Introduction and objectives. . . . .	355
12.2. Residual stress opening approach at the crack tip following an overload during fatigue. . . . .	359
12.3. Numerical modeling. . . . .	362
12.3.1. Modeling aspects . . . . .	362
12.3.2. Finite element modeling choices . . . . .	363
12.4. Proposed deterministic approach to fatigue crack growth following an overload. . . . .	366
12.5. Reliability modeling including the effect of an overload . . . . .	370
12.6. Application of the reliability model to a fillet welded joint. . . . .	371
12.7. References. . . . .	375
<b>Appendix A. Short Overview of the Foundations of Fracture Mechanics .</b>	<b>381</b>
A1. Introduction. . . . .	381
A2. Elementary failure modes and stress situations. . . . .	383
A3. Foundations of fracture mechanics . . . . .	383
A4. Parameters characterizing the singular zone. . . . .	385

A4.1. The stress intensity factor (SIF), $K$ . . . . .	385
A4.2. The energy release rate, $G$ . . . . .	387
A4.3. The J-integral . . . . .	388
A4.4. The crack-opening displacement (COD) . . . . .	389
A5. Asymptotic stress field in elastic-plastic media. . . . .	390
A5. References . . . . .	391
<b>Appendix B. Spreadsheet for Fatigue Life Estimates . . . . .</b>	<b>393</b>
<b>Appendix C. CG – Crack Growth Based on Fracture Mechanics . . . . .</b>	<b>395</b>
<b>Appendix D. CI – Crack Initiation Based on Coffin-Manson . . . . .</b>	<b>399</b>
<b>Index . . . . .</b>	<b>403</b>