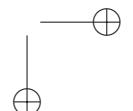
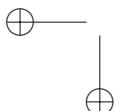
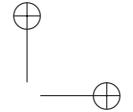


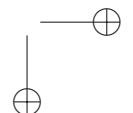
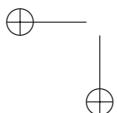
Contents

Foreword	xv
Preface	xvii
Chapter 1. Introduction	1
1.1 An old history	1
1.2 A modern attitude	3
1.3 Reliability: a definition	6
1.4 Which risk is acceptable?	6
1.5 Today	10
1.6 A little glossary	12
1.7 The structure of this book	15
Chapter 2. Preliminary Approach to Reliability in Mechanics	19
2.1 General points	19
2.1.1 Reliability methods in mechanics	19
2.1.2 A new attitude: overcoming obstacles	20
2.2 Theoretical reliability in mechanics	21
2.2.1 Reliability approach in mechanics	21
2.2.2 Variables-component-system chain	21
2.2.3 Theoretical reliability	22
2.3 Stochastic modeling	23
2.3.1 Modeling based on available information	23
2.3.2 Construction of a stochastic model	24
2.3.3 Random variable or stochastic process	26
2.4 Mechanical modeling	28
2.4.1 Representation model of physics	28
2.4.2 Balance between resources and needs	29
2.5 Mechanical-reliability coupling	29
2.5.1 Reliability sensitivity analysis	30
2.5.2 Reliability analysis	31





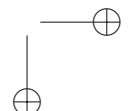
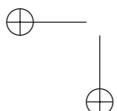
2.5.3	Complexity of mechanical-reliability coupling	33
2.5.4	Actors in mechanical-reliability coupling	33
2.6	Fields of application	34
2.6.1	Reliability of offshore marine structures	35
2.6.2	Soil mechanics	35
2.6.3	Regulation	35
2.6.4	Stochastic dynamics	36
2.6.5	Integrity of structures	36
2.6.6	Stability	36
2.7	Conclusion	37
Chapter 3. Elementary $R - S$ Case		39
3.1	Presentation of the problem	39
3.1.1	Variables	39
3.1.2	Design model	40
3.1.3	Illustration	42
3.2	Definitions and assumptions	42
3.3	Random vector: a reminder	44
3.3.1	Random vector	44
3.3.2	Joint probability density	45
3.3.3	Moments and correlation	45
3.3.4	Independence and correlation	47
3.4	Expressions of the probability of failure	48
3.4.1	Probability of failure	48
3.4.2	Distributions of R and S and probability P_f	48
3.4.3	First expression of P_f	50
3.4.4	Second expression of P_f	51
3.4.5	Illustration	52
3.4.6	Generalization of the probability of failure	53
3.5	Calculation of the probability of failure	53
3.5.1	Calculation of P_f by direct integration	53
3.5.2	Calculation of P_f by numerical integration	54
3.5.3	Calculation of P_f by simulation	54
3.5.4	Calculation of P_f by sampling and integration	55
3.6	Rod under tension	57
3.6.1	Data	57
3.6.2	Probability of failure	58
3.6.3	Analytical integration	58
3.6.4	Simulation	60
3.7	Concept of reliability index	60
3.7.1	Rjanitzyn-Cornell index	61
3.7.2	Hasofer-Lind index	63
3.7.3	Naming point P^*	64

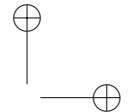
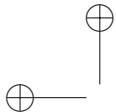




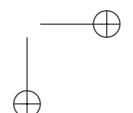
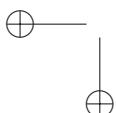
Contents vii

3.7.4	Application to the elementary Gaussian case	65
3.7.5	Rod under tension: Hasofer and Lind index	66
3.8	Equation $P_f = \Phi(-\beta)$	68
3.9	Exercises for illustration	68
3.9.1	Study of a frame	69
3.9.2	Resistance-stress problem	72
Chapter 4. Isoprobabilistic Transformation		77
4.1	Recapitulation of the problem and the notation	77
4.2	Case of independent variables	79
4.2.1	Gaussian variables	79
4.2.2	Independent variables	80
4.3	Rosenblatt transformation	82
4.3.1	Recapitulation	82
4.3.2	Formulation	83
4.3.3	Calculation of P_f	85
4.3.4	Example: double exponential	85
4.3.5	A warning about notation!	87
4.3.6	Gaussian variable couple	87
4.4	Approximation using a normal distribution	89
4.4.1	Principle	89
4.4.2	Uncorrelated variables	90
4.4.3	Correlated variables	91
4.5	Nataf transformation	92
4.5.1	Two random variables	92
4.5.2	Calculation of the correlation $\rho_{0,ij}$	93
4.5.3	Generalization to n variables	95
4.6	Example: correlated loads on a beam	98
4.6.1	Limit-state and design	98
4.6.2	Decorrelation of variables	99
4.6.3	Application of the Rosenblatt transformation	100
4.6.4	Application of the Nataf transformation	100
4.6.5	The uselessness of these calculations	101
4.6.6	Linear limit-state and Gaussian variables	101
4.7	Nataf transformation: example	101
4.8	Transformation by Hermite polynomials	102
4.8.1	Hermite polynomials	102
4.8.2	Isoprobabilistic transformation	104
4.8.3	Winterstein approximation [Win87, Win88]	106
4.8.4	Example: two uniform distributions	109
4.8.5	Conclusion on Hermite transformation	111
4.9	Conclusion	112





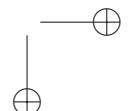
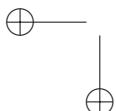
Chapter 5. Reliability Index	115
5.1 An optimization problem	115
5.1.1 Mechanical-reliability coupling	115
5.1.2 Formulation of the optimization problem	116
5.1.3 Optimality conditions	118
5.2 Optimization algorithms	119
5.2.1 Convergence [PW88]	119
5.2.2 Quality criteria	120
5.2.3 Principle of optimization algorithms	121
5.3 First order methods	124
5.3.1 Projected gradient method [HK85]	124
5.3.2 Penalty methods [HK85]	126
5.3.3 Augmented Lagrangian [PW88]	127
5.4 First order algorithms for the SDP	128
5.4.1 Hasofer-Lind-Rackwitz-Fiessler algorithm	128
5.4.2 Complements to first-order methods	131
5.5 Second order algorithms for the SDP	135
5.5.1 Newton method [PW88, HK85]	135
5.5.2 Sequential quadratic programming	136
5.5.3 Hybrid methods	137
5.6 Special problems	138
5.6.1 Limit-state with several minima	138
5.6.2 Search strategy for active constraints	139
5.7 Illustration using a simple example	140
5.7.1 HLRF algorithm	141
5.7.2 SQP, Abdo-Rackwitz and step control algorithms	143
5.8 Conclusion	144
Chapter 6. Products of Reliability Analysis	147
6.1 Sensitivity factors	147
6.1.1 Definitions	147
6.1.2 Mechanical sensitivity	148
6.2 Importance factors in reliability	149
6.2.1 Sensitivity of the reliability index	149
6.2.2 Sensitivity of β with respect to the distribution parameters $p_{i\gamma}$	152
6.2.3 Sensitivity of β with respect to the performance function parameters	155
6.2.4 Sensitivity of the probability of failure [MKL86]	156
6.2.5 Elasticity of parameters	156
6.3 Omission factors	157
6.3.1 Linear limit-state	157
6.3.2 Non-linear limit-state	159

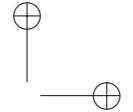




Contents ix

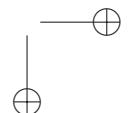
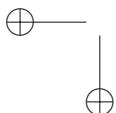
6.4	Representation of the results: an example	161
6.5	Conclusion	163
Chapter 7. Probability of Failure		165
7.1	Methodological framework	167
7.2	Approximation using a hyperplane: FORM	168
7.2.1	Principle of linear approximation	168
7.2.2	Expression of the probability of failure	169
7.2.3	Counter-example	172
7.2.4	Accuracy of the approximation	173
7.2.5	Reference example	174
7.3	Approximation using a second-order hypersurface	175
7.3.1	Curvature at the design point	176
7.3.2	Principle of approximations	177
7.3.3	Quadratic approximation	179
7.3.4	Elements of the approximation quadric	181
7.3.5	Parabolic approximation	183
7.3.6	Quadratic approximation	185
7.3.7	Reference example	185
7.3.8	Complement on quadratic approximations	186
7.3.9	Conclusion	189
7.4	‘Asymptotic’ SORM method	190
7.4.1	Breitung’s formula	190
7.4.2	Reference example	194
7.4.3	Hohenbichler approximation	194
7.4.4	Tvedt approximation	194
7.4.5	Comments and conclusion	195
7.5	Exact SORM method in quadratic form	196
7.5.1	Characteristic function	196
7.5.2	Characteristic functions of quadratic forms	198
7.5.3	Results	199
7.5.4	Inversion of the characteristic function	200
7.5.5	Optimization of numerical calculation	200
7.5.6	Reference example	202
7.6	RGMR method	203
7.6.1	Motivation	203
7.6.2	Introduction to RGMR	204
7.6.3	Notion of solid angle	205
7.6.4	Integral of the solid angle	205
7.6.5	SORM integral	207
7.6.6	Calculation of the solid angle	208
7.6.7	Numerical aspects	211
7.6.8	Solid angle in the FORM approximation	212





x Structural Reliability

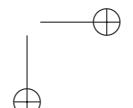
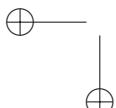
7.6.9	Special two-dimensional case	215
7.6.10	Reference example	215
7.6.11	Conclusion	216
7.7	Numerical examples	218
7.7.1	Reference example: conclusions	218
7.7.2	Rod under tension	219
7.7.3	Plastic failure of a section	221
7.7.4	Approximations of the probability of failure	222
7.7.5	Example: double exponential	227
7.8	Conclusions	232
Chapter 8. Simulation Methods		233
8.1	Introduction	233
8.2	Uniform pseudo-random numbers	234
8.2.1	Composite congruential generator	234
8.2.2	Multiplicative generator	236
8.2.3	Congruential additive generator	237
8.2.4	Some generators as examples	237
8.2.5	How to test a generator	239
8.2.6	Conclusion	239
8.3	Generators of non-uniform distributions [Rub81, Dea90]	240
8.3.1	Inverse transformation method	240
8.3.2	Composition method [But56]	240
8.3.3	Rejection-acceptance method [VN51]	241
8.3.4	Gaussian distribution	242
8.3.5	Lognormal distribution	244
8.3.6	Weibull distribution with two parameters	244
8.3.7	Generation of a random vector	244
8.3.8	Conclusion	247
8.4	Simulation methods	247
8.4.1	Introduction	247
8.4.2	Crude Monte Carlo simulations	249
8.4.3	Directional simulations (DS) [Dea80, DBOH88, DMG90, Bje88]	253
8.5	Sampling methods using P^*	255
8.5.1	Importance sampling (IS) [Mel90]	255
8.5.2	Conditional sampling (CS) [BF87]	256
8.5.3	Latin hypercube (LH)	258
8.5.4	Adaptive sampling (AS) [Buc88]	259
8.5.5	Conditional importance sampling method	259
8.5.6	Stratified sampling method [Rub81]	260
8.6	Illustration of the methods	260
8.6.1	Crude Monte Carlo (MC)	260





Contents xi

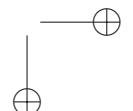
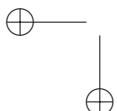
8.6.2	Directional simulations (DS)	260
8.6.3	Conditional sampling with the knowledge of P^* (IS, CS, LH)	261
8.6.4	Outcome of the illustration	263
8.7	Conclusion	263
Chapter 9. Reliability of Systems		265
9.1	Combination of failure modes	265
9.1.1	Series combination	266
9.1.2	Parallel combination	266
9.1.3	Series combination of parallel systems	267
9.1.4	Parallel combination of series systems	268
9.1.5	Conditional parallel combination	268
9.1.6	Implementation and application	269
9.2	Bounds of the failure probability of a system	273
9.2.1	Hypothesis	273
9.2.2	A classic approximation	274
9.2.3	Correlation of events E_i and E_j	274
9.2.4	Uni-modal bounds	275
9.2.5	Bi-modal bounds	276
9.3	First-order approximation bounds	277
9.3.1	Hypothesis	277
9.3.2	Probability bounds of the intersection $P(E_i \cap E_j)$	277
9.3.3	Equivalent hyperplane	279
9.4	First-order system probability	281
9.4.1	Parallel system	282
9.4.2	Series system	282
9.4.3	Multinormal distribution function	282
9.5	Second-order system probability	286
9.6	System of two bars in parallel	289
9.6.1	Statement of the problem and data	290
9.6.2	Solution	291
9.6.3	First-order solution	293
9.6.4	Second-order solution	296
9.6.5	Conclusion of the illustration	296
9.7	Conclusion	297
Chapter 10. ‘Safety’ Coefficients		299
10.1	Bases of design	299
10.1.1	General information	299
10.1.2	Values associated with a variable	300
10.1.3	Design rule	303
10.1.4	Levels in the design approach	304

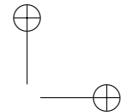




xii Structural Reliability

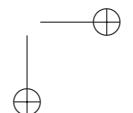
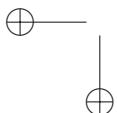
10.1.5 Illustration	305
10.2 Safety coefficients – elementary case	306
10.2.1 Probabilistic design	306
10.2.2 Global characteristic coefficient	309
10.2.3 Designing using partial coefficients	315
10.3 General definition of partial coefficients	319
10.3.1 Case of independent variables	319
10.3.2 Case of dependent variables	321
10.3.3 Comments	321
10.4 Calibration of partial coefficients	322
10.4.1 Calibration principle	322
10.4.2 A calibration method	324
10.4.3 Application example	326
10.5 Application examples	331
10.5.1 Linear fracture mechanics	331
10.5.2 Compound bending of a fragile material	336
10.6 Conclusion	339
Chapter 11. Mechanical-Reliability Coupling	341
11.1 Introduction	341
11.2 General information on the coupling with a FEM code	343
11.2.1 Control of the FEM code	343
11.2.2 Random variables	343
11.2.3 Mechanical-reliability variables	344
11.2.4 Dialog between FEM and reliability procedures	347
11.2.5 Implementation of the procedures	347
11.2.6 Numerical evaluation of gradients	349
11.3 Direct method	352
11.3.1 Description of the method	352
11.3.2 Overview	352
11.4 Response surface method	353
11.4.1 Introduction: polynomial response surface	353
11.4.2 Description of the method	355
11.4.3 Calculation of the coefficients of a QRS	359
11.4.4 Validation	360
11.4.5 Construction of a neural network	364
11.4.6 Summary	367
11.5 Two applications as examples	368
11.5.1 Sphere under pressure	369
11.5.2 Two correlated uniform distributions	371
11.5.3 Conclusion	376
11.6 Optimization method	377
11.6.1 Description of the method	377

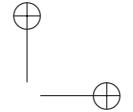




Contents xiii

11.6.2	Overview	380
11.6.3	Application	380
11.7	Example: isostatic truss	380
11.7.1	Data	380
11.7.2	Mechanical analysis	382
11.7.3	Reliability analysis	382
11.8	Conclusion	387
Chapter 12. Stochastic Finite Elements		391
12.1	Introduction	391
12.1.1	Definition and purpose	391
12.1.2	Random variables and random fields	392
12.1.3	Chapter plan	393
12.2	Spatial discretization of a random field	394
12.2.1	Random field [Cau88, CL67]	394
12.2.2	Stochastic mesh	398
12.2.3	A few discretization methods	399
12.2.4	Conclusion	400
12.3	Series expansion of a random field	401
12.3.1	Cholesky decomposition	401
12.3.2	Karhunen-Loève expansion [GS91]	402
12.3.3	Polynomial chaos	402
12.3.4	Conclusion	404
12.4	Finite element method and gradient calculation	405
12.4.1	Assumptions and notations	405
12.4.2	FEM linear equations	405
12.4.3	Gradient calculation with constant mesh	406
12.4.4	Calculation of derivatives with a variable mesh	407
12.5	Perturbation method	410
12.5.1	Taylor expansion	410
12.5.2	Mean and covariance	411
12.5.3	Example: deflection of a beam	412
12.5.4	Neumann expansion	417
12.6	Polynomial chaos expansion	418
12.6.1	Random variable expansion	418
12.6.2	Application to the finite element method	420
12.6.3	Perspectives	424
12.6.4	Conclusion	425
12.7	Continuous random field methods	425
12.7.1	Weighted integral method	425
12.7.2	Spectral method	427
12.7.3	Conclusion	432
12.8	An illustration	432





xiv Structural Reliability

12.8.1 Statement of the problem	432
12.8.2 Case 1: 4 random variables	433
12.8.3 Case 2: stiffness EA is a random field	435
12.9 Conclusion	437
12.9.1 Combination of the coupling and stochastic finite elements	438
12.9.2 Conclusion	439
Chapter 13. A Few Applications	441
13.1 Design of a wind bracing	441
13.2 Modeling of a mandrel	442
13.3 Failure of a cracked plate	443
13.4 Cooling of a cracked plate	444
13.5 Boiler casing subjected to a thermal field	445
13.6 Pressurized tank	446
13.7 Stability of a cylindrical shell	447
13.8 Reliability sensitivity for a cooling tower	448
13.9 Lifespan of an exhaust manifold	450
Chapter 14. Conclusion	453
14.1 Reliability methods in mechanics	453
14.2 Application of the methods	455
14.2.1 Design and maintenance	455
14.2.2 Software tools	458
14.3 Perspectives	459
14.3.1 Stochastic finite elements	460
14.3.2 The time factor	460
14.3.3 Data acquisition and processing	461
14.3.4 Mechanical-reliability optimization	461
14.4 Reliability analysis and sensitivity analysis	463
Bibliography	465
Annotations	481
A.1 Vectors and matrices	481
A.2 Operators	481
A.3 Random values	482
A.3.1 Scalar values and random variable couples	482
A.3.2 Statistical values	482
A.3.3 Vectorial values	483
A.3.4 Mechanical values	484
Index	485

