

Contents

Editorial	IX
1 Introduction.....	1
2 Actions on wind turbines	5
2.1 Permanent actions.....	5
2.2 Turbine operation (rotor and nacelle)	5
2.3 Wind loads.....	5
2.3.1 Wind loads for onshore wind turbines	5
2.3.1.1 Wind loads according to the DIBt guideline	6
2.3.1.2 Checking the susceptibility to vibration	8
2.3.1.3 Example of application.....	9
2.3.2 Wind loads for offshore wind turbines	21
2.3.2.1 Classification of wind turbines	21
2.3.2.2 Determining the wind conditions (wind climate)	22
2.3.2.3 Normal wind conditions	23
2.3.2.4 Extreme wind conditions	25
2.3.2.5 Wind farm influence	30
2.4 Height of sea level	31
2.5 Hydrodynamic environmental conditions.....	32
2.5.1 Sea currents.....	32
2.5.2 Natural sea state.....	34
2.5.3 Harmonic primary wave	35
2.5.4 Waves of finite steepness	38
2.5.5 Statistical description of the sea state	40
2.5.6 Short-term statistics for the sea state	41
2.5.7 Long-term statistics for the sea state	47
2.5.8 Extreme sea state values	50
2.5.9 Breaking waves.....	52
2.6 Hydrodynamic analysis	53
2.6.1 General.....	53
2.6.2 Morison formula	54
2.6.3 Potential theory method – linear motion behaviour	60
2.6.4 Integral equation method (singularity method)	62
2.6.5 Vertical cylinders (MacCamy and Fuchs).....	66
2.6.6 Higher-order potential theory	70
2.6.7 Wave loads on large-volume offshore structures.....	72
2.7 Thermal actions	77
2.8 Sea ice.....	78
2.9 Icing-up of structural members.....	83

3	Non-linear material behaviour	85
3.1	General.....	85
3.2	Material laws for reinforced and prestressed concrete	86
3.2.1	Non-linear stress-strain curve for concrete.....	86
3.2.2	Non-linear stress-strain curve for reinforcing steel	87
3.2.3	Non-linear stress-strain curve for prestressing steel	90
3.3	Bending moment-curvature relationships.....	91
3.3.1	Reinforced concrete cross-sections in general.....	91
3.3.2	Prestressed concrete cross-sections in general	92
3.3.3	Annular reinforced concrete cross-sections.....	94
3.4	Deformations and bending moments according to second-order theory	97
3.5	Design of cross-section for ultimate limit state	98
3.5.1	Material resistance of concrete	98
3.5.2	Material resistance of reinforcement	99
3.6	Three-dimensional mechanical models for concrete.....	100
3.6.1	Failure envelopes and stress invariants.....	101
3.6.2	Common failure models for concrete	102
3.6.3	Three-phase model	103
3.6.4	Constitutive models	105
4	Loadbearing structures and detailed design	107
4.1	Basis for design.....	107
4.2	Structural model for tower shaft.....	108
4.2.1	Rotation of the foundation.....	108
4.2.2	Stability of towers on soft subsoils	110
4.3	Investigating vibrations	111
4.3.1	Mass-spring systems with single/multiple degrees of freedom.....	111
4.3.2	The energy method	113
4.3.2.1	Practical vibration analysis.....	114
4.3.2.2	Example of application.....	114
4.3.3	Natural frequency analysis of loadbearing structure	116
4.4	Prestressing.....	118
4.4.1.1	Prestressing with grouted post-tensioned tendons.....	119
4.4.1.2	External prestressing with unbonded tendons	119
4.5	Design of onshore wind turbine support structures	120
4.5.1	Total dynamic analysis	120
4.5.2	Simplified analysis	121
4.5.2.1	Sensitivity to vibration.....	121
4.5.2.2	Vibration damping	122
4.5.3	Design load cases according to DIBt guideline (onshore).....	122
4.5.3.1	Critical design load cases	122
4.5.4	Partial safety factors according to DIBt guideline.....	124
4.6	Design of offshore wind turbine structures.....	125
4.6.1	Control and safety systems	125
4.6.2	Design situations and load cases.....	127

4.6.3	Fundamental considerations regarding the safety concept	128
4.6.3.1	Safety analysis	128
4.6.3.2	Combined sea state and wind	130
4.6.4	Design load cases according to GL guideline.....	131
4.6.4.1	Commentary to Table 4.4	135
4.6.5	Partial safety factors according to GL guideline	138
4.7	Ultimate limit state	138
4.7.1	Deformation calculations according to second-order theory.....	138
4.7.2	Linear analysis of internal forces.....	143
4.7.3	Analysis of stresses in tower shaft	144
4.7.4	Special characteristics of prefabricated construction	145
4.7.4.1	Terminology.....	145
4.7.4.2	Shear force transfer across opening joints	146
4.7.4.3	Detailed design	149
4.7.4.4	Transferring prestressing forces	149
4.7.4.5	Erecting and prestressing precast concrete elements.....	149
4.7.4.6	Design of openings	151
4.8	Analysis of serviceability limit state	153
4.8.1	Action effects in tower shaft due to external actions.....	153
4.8.1.1	Limiting the deformations	153
4.8.1.2	Limiting the stresses	153
4.8.1.3	Limiting crack widths and decompression limit state	153
4.8.2	Restraint stresses acting on shaft wall	154
4.8.3	Special aspects of construction with precast concrete elements	155
4.9	Fatigue limit state	156
4.9.1	Fatigue-inducing actions on wind turbine support structures.....	157
4.9.1.1	Actions due to wind and turbine operation.....	157
4.9.1.2	Actions due to waves and sea state	158
4.9.2	Fatigue analyses according to DIBt wind turbine guideline.....	159
4.9.2.1	Simplified analyses for concrete.....	159
4.9.2.2	Direct analysis according to DIBt guideline.....	161
4.9.3	Multi-stage fatigue loads	164
4.9.4	Numbers of fatigue cycles to failure for multi-axial fatigue loads	164
4.9.4.1	Procedure	164
4.9.4.2	Derivation of damage variables κ_c^{fat} and κ_t^{fat}	166
4.9.4.3	Failure envelope for fatigue load	170
4.9.4.4	Failure curves for biaxial fatigue loads	171
4.9.5	Design proposal for multi-axial fatigue.....	174
4.9.5.1	Procedure for designing on the basis of the linear accumulation hypothesis	174
4.9.5.2	Derivation of modification factor $\lambda_{c3}(N, r)$ for fatigue loads on compression meridian.....	175
4.9.5.3	Derivation of modification factors $\lambda_{c2}(N, \alpha)$ for biaxial fatigue loads.....	177
4.10	Design of construction nodes.....	180
4.10.1	Loads on nodes	180

4.10.2	Composition of forces at the ultimate limit state.....	180
4.10.3	Characteristic values for loads.....	181
4.10.4	Example of calculation	184
4.10.5	Load on circular ring beam at ultimate limit state.....	187
4.10.6	Design of circular ring beam	188
4.11	Foundation design.....	188
4.11.1	Calculating the internal forces.....	188
5	Construction of prestressed concrete towers	191
5.1	Introduction	191
5.2	Hybrid structures of steel and prestressed concrete.....	191
5.3	Prestressed concrete towers with precast concrete segments	193
5.3.1	Examples of design and construction	193
5.3.2	Further developments in precast concrete construction.....	197
5.4	Offshore substructures in concrete	198
5.4.1	Compact substructures with ice cones.....	199
5.4.1.1	Middelgrunden offshore wind farm.....	199
5.4.1.2	Sequence of operations on site	202
5.4.2	Design, construction, transport and erection of concrete substructures	202
5.4.2.1	Special design criteria.....	203
5.4.2.2	Construction.....	203
5.4.2.3	Transport and erection	204
5.4.2.4	Spread and deep foundations	205
5.4.2.5	Innovations	207
	References.....	209
	Index.....	217