

Table of contents

1	Introduction	16	2	The development of cable-stayed bridges	46
1.1	Design fundamentals	17	2.1	The precursors of cable-stayed bridges	47
1.1.1	General	17	2.1.1	Introduction	47
1.1.2	Overall system	19	2.1.2	Historical development	47
1.1.2.1	Cable arrangement	19	2.1.2.1	Historical designs	47
1.1.2.2	Cable stiffness	20	2.1.2.2	First examples and failures	48
1.1.2.3	Geometry	21	2.1.2.3	John Roebling and stiffened suspension bridges	51
1.1.2.4	Support conditions	21	2.1.2.4	Transporter bridges	52
1.1.3	Tower shapes	23	2.1.2.5	Approaching the modern form	55
1.1.3.1	Two outer cable planes	23	2.2	Steel cable-stayed bridges	58
1.1.3.2	One central cable plane	23	2.2.1	Introduction	58
1.1.3.3	Spread central cable planes	24	2.2.2	Beginnings	58
1.1.4	Beam cross-sections	24	2.2.3	The Düsseldorf Bridge Family	59
1.1.4.1	Steel cross-sections	24	2.2.4	Further Rhine river bridges	62
1.1.4.2	Concrete cross-sections	25	2.2.5	Special steel cable-stayed bridges	70
1.1.4.3	Composite cross-sections	25	2.2.6	Cable-stayed bridges with record spans	76
1.1.4.4	Hybrid beams (steel/concrete)	26	2.3	Concrete cable-stayed bridges	80
1.1.4.5	Double deck cross-section	26	2.3.1	General	80
1.1.5	Stay cables	26	2.3.2	Development of concrete cable-stayed bridges	81
1.1.5.1	Systems	26	2.3.3	Bridges with concrete stays	92
1.1.5.2	Cable anchorages	26	2.3.3.1	Riccardo Morandi's bridges	92
1.2	Aesthetic guidelines for bridge design	30	2.3.3.2	Later examples	92
1.2.1	Introduction	30	2.3.3.3	Bridges with concrete walls	94
1.2.2	Aesthetic guidelines	30	2.3.4	Cable-stayed bridges with thin concrete beams	94
1.2.2.1	Guideline 1: Clear structural system	30	2.3.5	Record spans	98
1.2.2.2	Guideline 2: Good proportions	31	2.4	Composite cable-stayed bridges	101
1.2.2.3	Guideline 3: Good order	33	2.4.1	General	101
1.2.2.4	Guideline 4: Integration into the environment	34	2.4.2	Cross-sections	101
1.2.2.5	Guideline 5: Choice of material	35	2.4.3	Special details	104
1.2.2.6	Guideline 6: Coloring	36	2.4.4	Economic span lengths	104
1.2.2.7	Guideline 7: Space above the bridge	38	2.4.5	Beginnings	105
1.2.2.8	Guideline 8: Recognizable flow of forces	38	2.4.6	Record spans	105
1.2.2.9	Guideline 9: Lighting	41	2.4.7	Latest examples	111
1.2.2.10	Guideline 10: Simplicity	41	2.5	Special systems of cable-stayed bridges	118
1.2.3	Collaboration	42	2.5.1	Series of cable-stayed bridges	118
			2.5.1.1	Load transfer	118
			2.5.1.2	Intermediate piers	118
			2.5.1.3	Stiff towers	118
			2.5.1.4	Stayed towers	118
			2.5.1.5	Frames	121
			2.5.1.6	Accommodation of longitudinal deformations	121
			2.5.1.7	Examples	123
			2.5.2	Stayed beams	130
			2.5.2.1	Stayed from underneath	130
			2.5.2.2	Stayed from above (extradosed)	130
			2.5.3	Cable-stayed pedestrian bridges	133

3	Stay cables	140
3.1	General	141
3.2	Locked coil ropes	141
3.2.1	System	141
3.2.2	Fabrication	142
3.2.3	Modern corrosion protection systems	142
3.2.3.1	General	142
3.2.3.2	Galvanizing of the wires	142
3.2.3.3	Filling	142
3.2.3.4	Paint	143
3.2.4	Inspection and maintenance	143
3.2.5	Damage	143
3.2.5.1	Köhlbrand Bridge	143
3.2.5.2	Maracaibo Bridge, Venezuela	145
3.2.5.3	Flehe Rhine River Bridge	146
3.2.5.4	Lessons from the damage	146
3.3	Parallel bar cables	146
3.4	Parallel wire cables	147
3.4.1	System	147
3.4.2	Corrosion protection	148
3.4.2.1	Polyethylene (PE) pipes	148
3.4.2.2	Wrappings	150
3.4.2.3	Grouting	150
3.4.2.4	Damage	151
3.4.2.5	Petroleum wax	151
3.4.3	Fabrication	152
3.5	Parallel strand cables	153
3.5.1	General	153
3.5.2	System	153
3.5.3	Corrosion protection	153
3.5.3.1	Traditional	153
3.5.3.2	With dry air	153
3.5.4	Fabrication	154
3.5.5	Durability tests	154
3.5.5.1	Tensile strength and fatigue strength	154
3.5.5.2	Water tightness	154
3.5.5.3	Sustainability	154
3.5.6	Monitoring	154
3.6	Cable anchorages	156
3.6.1	General	156
3.6.2	Support of anchor heads	156
3.6.3	Anchorage at the tower	158
3.6.3.1	Continuous	158
3.6.3.2	Composite cable anchorages at tower head	158
3.6.3.3	Cable anchorage in concrete	158
3.7	Cable sizing	160
3.7.1	General	160
3.7.2	Sizing by permissible stresses	160
3.7.2.1	Permissible stresses for static loads	160
3.7.2.2	Permissible fatigue range	160
3.7.2.3	Permissible stresses during cable exchange	161
3.7.3	Sizing in ultimate limit state	161
3.7.3.1	Ultimate limit state	161
3.7.3.2	Fatigue	161
3.7.3.3	Cable exchange	162
3.7.3.4	Service limit state	162
3.7.4	Summary	162
3.8	Cable dynamics	163
3.8.1	General	163
3.8.2	Fundamental parameters	164
3.8.2.1	Static wind load	164
3.8.2.2	Natural frequencies	165
3.8.3	Dynamic excitation	165
3.8.3.1	Galloping oscillations	165
3.8.3.2	Anchorage excitation	166
3.8.3.3	Parametric resonance	168
3.8.3.4	Buffeting	168
3.8.3.5	Vortex-induced vibrations	169
3.8.4	Countermeasures	169
3.8.4.1	Dampers	169
3.8.4.2	Surface profiling	174
3.8.4.3	Cross ties	174
3.9	Cable installation	175
3.9.1	General	175
3.9.2	Locked coil ropes	175
3.9.2.1	General	175
3.9.2.2	Example	175
3.9.3	Parallel wire cables	178
3.9.3.1	General	178
3.9.3.2	Example	178
3.9.4	Parallel strand cables	179
3.9.4.1	General	179
3.9.4.2	Example	179
3.9.5	Cable calculations	184
3.9.5.1	Cable deformations	184
3.9.5.2	Measuring of cable forces	184

4	Preliminary design of cable-stayed bridges	186	4.4	Protection of bridges against ship collision	248
4.1	Action forces for equivalent systems	187	4.4.1	Introduction	248
4.1.1	General	187	4.4.2	Collision forces	248
4.1.2	System geometry	187	4.4.3	Protective structures	252
4.1.3	Normal forces of articulated system	188	4.4.3.1	General	252
4.1.4	Live loads on elastic foundation	189	4.4.3.2	Out of reach	252
4.1.4.1	Beam on elastic foundation	189	4.4.3.3	Artificial islands	253
4.1.4.2	Buckling – non-linear theory	190	4.4.3.4	Guide structures	253
4.1.5	Permanent loads on rigid supports	192	4.4.3.5	Independent protective structures	258
4.1.5.1	Dead load	192	4.4.3.6	Strong piers	261
4.1.5.2	Post-tensioning	193	4.5	Preliminary design calculations	266
4.1.5.3	Shrinkage and creep	193	4.5.1	General	266
4.1.6	Towers	195	4.5.2	Typical cable-stayed concrete bridge	266
4.1.6.1	In the longitudinal direction	195	4.5.2.1	System and loads	266
4.1.6.2	In the transverse direction	195	4.5.2.2	Normal forces for articulated system	267
4.1.7	Stay cables	197	4.5.2.3	Bending moments	269
4.2	Action forces of actual systems	197	4.5.3	Typical cable-stayed steel bridge	270
4.2.1	Permanent loads	197	4.5.3.1	General	270
4.2.1.1	General	197	4.5.3.2	System	270
4.2.1.2	Concrete bridges	198	4.5.3.3	Section properties and loads	270
4.2.1.3	Steel bridges	199	4.5.3.4	Beam moments from live load	270
4.2.1.4	Towers	202	4.5.3.5	Permissible beam moments	271
4.2.2	Live loads	202	4.5.3.6	Moments from dead load for articulated system	271
4.2.3	Kern point moments	204	4.5.4	Cable-stayed bridge with side spans on piers	272
4.2.4	Non-linear theory (second order theory)	206	4.5.4.1	System and loads	272
4.2.5	Superposition	208	4.5.4.2	Cable forces of articulated system	273
4.2.6	Temperature	208	4.5.4.3	Bending moments for beam	274
4.2.7	Eigenfrequencies	210	4.5.5	Cable-stayed bridge with harp arrangement	275
4.3	Bridge dynamics	211	4.5.5.1	With regular side spans	275
4.3.1	General	211	4.5.5.2	With side spans on piers	276
4.3.2	Overview of wind effects	213	4.5.6	Cable-stayed bridge with longitudinal A-tower	276
4.3.3	Wind profile, turbulence and turbulence-induced oscillations	214	4.5.6.1	System and loads	277
4.3.3.1	Wind parameters	214	4.5.6.2	Normal forces for articulated system	277
4.3.3.2	Natural modes of vibration of structures	216	4.5.6.3	Cable sizing	278
4.3.3.3	Section forces under turbulent excitation	218	4.5.6.4	Bending moments for beam	278
4.3.4	Vortex-induced vibrations	222	4.5.6.5	Post-tensioning	278
4.3.5	Self-excitation and other motion-induced effects	224	4.5.7	Slender cable-stayed concrete bridge	279
4.3.5.1	General description, background	224	4.5.7.1	System and loads	279
4.3.5.2	Practical examples of bending-type galloping	226	4.5.7.2	Stay cables	280
4.3.5.3	Practical examples of torsional galloping	228	4.5.7.3	Beam moments	283
4.3.5.4	Flutter	232	4.5.7.4	Aerodynamic stability	286
4.3.6	Damping measures	236	4.5.7.5	Towers	287
4.3.7	Wind tunnel testing	240			
4.3.7.1	General	240			
4.3.7.2	Overview of important types of wind tunnel testing	240			
4.3.8	Earthquake	244			

5	Construction of cable-stayed bridges	290
5.1	Examples	291
5.1.1	General	291
5.1.2	Tower construction	291
5.1.2.1	Steel towers	291
5.1.2.2	Concrete towers	291
5.1.2.3	Composite towers	291
5.1.3	Beam construction	292
5.1.3.1	General	292
5.1.3.2	Concrete beam	293
	Free cantilevering	293
	Launching	299
	Rotating	299
	Rotating on scaffolding	302
5.1.3.3	Steel beams	304
	Free cantilevering	304
	Launching	304
	Transverse shifting	305
5.1.3.4	Composite beam	305
	Free cantilevering	305
	Launching	309
5.2	Construction engineering	312
5.2.1	General	312
5.2.2	Construction engineering by dismantling	312
5.2.2.1	General	312
5.2.2.2	Dismantling from $t = \infty$ to $t = 1$	313
5.2.2.3	Dismantling of bridge	313
	With floating crane	313
	Dismantling with derrick	314
5.2.2.4	Aerodynamic stability	315
5.2.3	Example for construction engineering	316
5.2.3.1	Forward construction	316
5.2.3.2	Construction engineering	316
5.2.3.3	Construction manual	316
5.2.3.4	Control measurements	316
5.2.4	Design of auxiliary stays	320
5.2.4.1	Symmetrical auxiliary stays for towers	320
5.2.4.2	One-sided auxiliary stays for towers	321
5.2.4.3	Auxiliary stays for beam	321
5.2.4.4	Without auxiliary stays for beam	321
5.2.5	Auxiliary tie-backs for travelers	323

6	Examples for typical cable-stayed bridges	326
6.1	Cable-stayed concrete bridges with precast beams	327
6.1.1	General	327
6.1.2	Pasco-Kennewick Bridge	327
6.1.2.1	General layout	327
6.1.2.2	Construction engineering	332
6.1.2.3	Completed bridge	344
6.1.3	East Huntington Bridge	346
6.1.3.1	General design considerations	346
6.1.3.2	Construction	346
6.1.3.3	Completed bridge	349
6.2	CIP concrete cable-stayed bridge	
	Helgeland Bridge	352
6.2.1	General layout	352
6.2.1.1	Introduction	352
6.2.1.2	Bridge system	353
6.2.2	Construction	358
6.2.2.1	Climate	358
6.2.2.2	Towers	358
6.2.2.3	Beam	360
6.2.2.4	Stay cables	362
6.2.2.5	Instrumentation	366
6.2.2.6	Completed bridge	367
6.2.3	Summary	367
6.3	Cable-stayed steel bridge	
	Strelasund Crossing	369
6.3.1	Design considerations	369
6.3.1.1	Bridge alternates	369
6.3.1.2	Optimizing the cable-stayed solution	371
6.3.1.3	Structural details	371
6.3.2	The cable-stayed bridge	371
6.3.2.1	Span lengths	371
6.3.2.2	Beam cross-section	371
6.3.2.3	Wind barriers	372
6.3.2.4	Tower	372
6.3.2.5	Stay cables	373
6.3.2.6	Aerodynamic investigation	373
6.3.3	Construction	375
6.3.3.1	Construction engineering	375
6.3.3.2	Construction of the main bridge	376
6.3.3.3	Completed bridge	386

6.4 Composite cable-stayed bridge

Baytown Bridge	387
6.4.1 General layout	387
6.4.1.1 Bridge system	387
6.4.1.2 Composite beam	388
6.4.1.3 Towers	390
6.4.1.4 Stay cables	390
6.4.1.5 Aerodynamic stability	391
6.4.2 Construction	391
6.4.2.1 Foundations	391
6.4.2.2 Towers	391
6.4.2.3 Beam	392
6.4.2.4 Stay cables	398
6.4.2.5 Completed bridge	398
6.4.3 Summary	401

6.5 Hybrid cable-stayed bridge

Normandy Bridge	402
6.5.1 Design considerations	402
6.5.1.1 Structural design	402
6.5.1.2 Cable dynamics	404
6.5.2 Construction	404
6.5.2.1 Tower	404
6.5.2.2 Concrete approach bridges	406
6.5.2.3 Steel main span	408
6.5.2.4 Cable installation	408
6.5.2.5 Completed bridge	410

6.6 Series of cable-stayed bridges 411

Millau Bridge	411
6.6.1.1 General	411
6.6.1.2 Design	412
6.6.1.3 Construction	412
6.6.1.4 Completed bridge	416
6.6.2 Rion-Antirion Bridge	418
6.6.2.1 General	418
6.6.2.2 Design	418
6.6.2.3 Construction	421
6.6.2.4 Completed bridge	425

7 Future development 426**Index** 428

Bridge Index	428
References	431
Figure Origins	439
List of Advertisers	441

Appendix: 40 years of experience with major bridges all over the world 443

Beginnings	443
Bridges in Germany	443
Cable-stayed bridges abroad	445
New developments by competition	446
Checking of bridges	449
Participation in Code Commissions	452
Current projects	452
Summary	453
References	454

Lectures on cable-stayed bridges on DVD 458