Contents

Foreword of the series editors	
Foreword vii	
Preface ix	

Section A Physical models from ancient times to the 1880s $\, {\it 1} \,$

1	Models in civil engineering from ancient times to the industrial
	Revolution 3
	Dirk Bühler
1.1	Introduction 3
1.2	Engineering models in classical times 4
1.3	The Master Builders of the Renaissance and their engineering
	models 5
1.3.1	Phillipo Brunelleschi and Florence cathedral 5
1.3.2	Leonardo da Vinci 6
1.3.3	Andrea Palladio 7
1.3.4	Domenico Fontana and moving the Vatican obelisk 7
1.3.5	The Fleischbrücke: a case study in technology transfer 9
1.4	The first collections of engineering models 11
1.4.1	Elias Holl and the Augsburg model chamber 12
1.4.2	Caspar Walter and hydraulic engineering in Augsburg 15
1.5	Models in the Age of Enlightenment 19
1.5.1	Cabinets of curiosities 19
1.5.2	The models of Hans Ulrich Grubenmann 20
1.5.3	The models of John Smeaton 22
1.6	Final remarks 26
	References 26
2	Block models of the masonry arch and vault 31
	Santiago Huerta
2.1	The beginnings of arch construction 31
2.2	The use of block models from 1400 to 1700 32
2.2.1	Leonardo da Vinci 34



xiv	Contents	

2.2.2	Robert Hooke and Christopher Wren 37
2.3	Block models in eighteenth- and nineteenth-century France 38
2.3.1	Henri Gautier, 1717 39
2.3.2	Augustin Danyzy, 1732 40
2.3.3	François-Michel Lecreulx, 1774 41
2.3.4	Louis-Charles Boistard, 1797 43
2.3.5	Émiland-Marie Gauthey, 1798 45
2.3.6	Jean-Baptiste Rondelet, 1797-1813 47
2.3.7	Louis Vicat, 1832 50
2.3.8	Édouard-Henri-François Méry, 1828 and 1840 50
2.4	Block models in nineteenth-century Britain 53
2.4.1	John Robison, 1801 53
2.4.2	Thomas Young, 1807-1824 55
2.4.3	William Bland, 1836-1839 58
2.4.4	Henry Moseley, 1833-1837 59
2.4.5	William Henry Barlow, 1846 60
2.4.6	Henry Charles Fleeming Jenkin, 1876 62
2.5	Block models in the late nineteenth and twentieth centuries 64
2.5.1	Modelling the elastic behaviour of masonry arches 64
2.5.2	Alfred Pippard, 1936-1938 67
2.5.3	Epilogue – the 'plastic' theory of masonry structures 70
	References 71
3	The catenary and the line of thrust as a means for shaping
3	The catenary and the line of thrust as a means for shaping arches and vaults 79
3	
3.1	arches and vaults 79
	arches and vaults 79 Rainer Graefe
3.1	arches and vaults 79 Rainer Graefe Introduction 79
3.1 3.1.1	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79
3.1 3.1.1 3.1.2	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81
3.1 3.1.1 3.1.2 3.1.3	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81
3.1 3.1.1 3.1.2 3.1.3 3.1.4	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2 3.3.3	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96 Hanging models and the design of arch bridges 98
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2 3.3.3	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96 Hanging models and the design of arch bridges 98 Hanging models for architectural designs 99
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2 3.3.3 3.4 3.4.1	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96 Hanging models and the design of arch bridges 98 Hanging models for architectural designs 99 Heinrich Hübsch 99
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2 3.3.3 3.4 3.4.1 3.4.2	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96 Hanging models and the design of arch bridges 98 Hanging models for architectural designs 99 Heinrich Hübsch 99 Carl-Anton Henschel 101
3.1 3.1.1 3.1.2 3.1.3 3.1.4 3.2 3.2.1 3.2.2 3.2.3 3.2.4 3.2.5 3.2.6 3.3 3.3.1 3.3.2 3.3.3 3.4 3.4.1	arches and vaults 79 Rainer Graefe Introduction 79 Robert Hooke's theory 79 Early arch forms 81 Circular and spherical shapes 81 The special shape of the catenary 83 The early use of the catenary in construction 84 Hooke and Wren – theory and construction practice 84 Hidden or on view? 86 Poleni's hanging experiment for St. Peter's Basilica, Rome 89 Kulibin's Bridge over the River Neva 91 Silberschlag's hanging models 92 Rondelet's dome for Sainte Geneviève 93 Catenary models in the early nineteenth century 95 Models of upright catenary arches 95 Rejection of the catenary as an arch form 96 Hanging models and the design of arch bridges 98 Hanging models for architectural designs 99 Heinrich Hübsch 99

3.4.5 3.5 3.5.1 3.5.2	Aesthetics of the catenary 106 Hanging models become three-dimensional 108 Three-dimensional net models by Karl Mohrmann 109 The Reichstag Project by Fritz Gösling 109
3.5.3 3.6	The legendary model of Colònia Güell built by Antoni Gaudí 113 Epilogue 118 References 120
4	Leonhard Euler and the model tests for a 300-metre timber arch bridge in St. Petersburg 127 Andreas Kahlow
4.1	Timber bridges and material experiments in the eighteenth century 127
4.1.1	Timber bridges in the mid-eighteenth century 127
4.1.2	Experimental testing of material properties 129
4.2	Proposals for a bridge across the River Neva in St Petersburg 131
4.2.1	The first design proposals by Ivan Kulibin 131
4.2.2	The bridge design competition of 1771 137
4.2.3	Kulibin's experimental model from 1776 138
4.3	Euler's 'Simple rule' for assessing the strength of bridges 140
4.4	Competition between rival designs for the Neva Bridge 143
4.4.1	The models of Kulibin and de Ribas 143
4.4.2	The Academy is required to judge between the designs 145
4.5	Further work by Euler 146
4.5.1	Euler's work on column buckling of 1776 146
4.5.2	Definition of the modulus of elasticity 148
4.5.3	Calculation of the modulus of elasticity h from the data of Musschenbroek's buckling tests 149
4.6	The practical solution to the academic question: Kulibin's experiment 150
4.7	Final remarks 151
	Abbreviations and citation methods 153 References 154
5	The use of models in early nineteenth-century British
	suspension bridge design 161 Denis Smith
5.1	Suspension bridges in the early nineteenth century 161
5.2	The proposed suspension bridge at Runcorn 162
5.3	The proposed suspension bridge at Montrose 166
5.4	The Menai suspension bridge – chain geometry model 167
5.5	Wood as a material for suspension chains 167
5.6	James Dredge and the taper chain controversy 170
5.6.1	The Dredge and Clive correspondence 177
5.6.2	The Ballee Khal bridge – Calcutta 179

Contents

5.7	Final remarks 182
	Acknowledgements 183 References 183
6	Models used during the design of the Conway and Britannia tubular bridges 187 Bill Addis
6.1	The Chester to Holyhead railway 187
6.2	Bridge engineering around 1840 188
6.3	The first set of model tests – Fairbairn in Millwall 188
6.4	The second set of model tests - Hodgkinson in Manchester 192
6.5	The third series of tests, on the large model – Fairbairn in Manchester 193
6.6	Discussion of similarity 198
6.7	Final remarks 199
	References 201
	Section B Physical models used in structural design, 1890s-1930s 205
7	The use of models to inform the structural design of dams,
	1890s-1930s 207
	Mike Chrimes
7.1	Introduction – the British experimental approach in the nineteenth century 207
7.2	Masonry dam design before 1900 207
7.3	The Aswan Dam 210
7.3.1	The genesis of the First Aswan Dam scheme 210
7.3.2	Raising the Aswan dam and the stability controversy 211
7.4	Responses to Baker's call for the use of models for the Aswan dam 215
7.4.1	The introduction of India-rubber models 215
7.4.2	The mathematicians respond 215
7.5	The ICE debate in January 1908 216
7.5.1	Wilson and Gore's studies with mechanical models 217
7.5.2	Ottley and Brightmore's studies with Plasticine models 222
7.5.3	Further contributions to the debate 224
7.6	After Wilson and Gore 225
7.6.1	The use of physical models for designing dams between the Wars 225
7.6.2	Physical and numerical models – post-war developments 226
7.7	Conclusions 228
	Further reading 228
	Acknowledgements 228
	References 228

8	Models used during the design of the Boulder Dam 233 Bill Addis
8.1	The US Bureau of Reclamation dams: 1925-1940 233
8.2	Preliminary model studies 233
8.2.1	Stevenson Creek Experimental Dam 233
8.2.2	Gibson Dam 236
8.3	Boulder Dam – structural model studies 236
8.3.1	The 1:240 scale plaster-Celite model 236
8.3.2	The 1:240 scale, 2-D plaster-Celite cantilever model 242
8.3.3	The 1:120 scale, 2-D plaster-Celite arch model 245
8.3.4	The 1:180 scale 3-D rubber-litharge model 251
8.4	Boulder Dam – hydraulic model studies 255
8.4.1	Model studies for design of the spillways 255
8.4.2	Model studies for design of the penstocks and intake tower 258
8.4.3	Model studies for design of the outlet works 260
8.5	Final remarks 263
	Acknowledgements 266
	References 266
9	The role of models in the early development of Zeiss-Dywidag
	shells 269
	Roland May
9.1	Zeiss-Dywidag shells: an absence of empiricism? 269
9.2	The Jena models: domes 270
9.3	The Jena models: cylindrical shells 274
9.4	Basic research in Biebrich 278
9.5	Models of large-scale buildings 282
9.6	The 'white temple' of Biebrich 289
9.7	Outlook and conclusion 292
	References 294
10	Model testing of structures in pre-war Italy: the School of
	Arturo Danusso 299
10.1	Mario Alberto Chiorino and Gabriele Neri
10.1	The beginning of model testing in Italy 299 The Laboratoria Prove Modellia Controllia in the Polytoch via of
10.2	The Laboratorio Prove Modelli e Costruzioni at the Polytechnic of Milan 300
10.2.1	Arturo Danusso and Guido Oberti 300
10.2.2	Models for concrete dam design in the 1930s 304
10.3	The encounter between Arturo Danusso and Pier Luigi Nervi 306
10.4	Model analysis and structural intuition in the work of Pier Luigi Nervi 308
10.5	Further experimental model studies by Nervi and Oberti 310
10.5.1	The monumental arch for the 1942 Universal Exhibition in Rome 310
10.5.2	Pavilion for the 1947 Milan Trade Fair 312
10.5.3	Civic Centre for Tucumán, Argentina 314

cviii	Contents
-------	----------

10.6	Final remarks 316
	Further reading 316
	References 317
11	Eduardo Torroja and his use of models up to 1936 321
	Joaquín Antuña
11.1	Introduction 321
11.2	Tests on full-scale models 324
11.2.1	The Hospital Clínico in the University City in Madrid 324
11.2.2	Courtyard roof at the <i>Escuela elemental de trabajo</i> (Elementary
	Technical School), Madrid 326
11.2.3	Roof of the grandstands of the Zarzuela Hippodrome, Madrid 327
11.3	Tests on equivalent reduced-size models 328
11.3.1	The roofs of operating theatres at the <i>Hospital Clínico</i> in the University
	City in Madrid 329
11.3.2	The market hall in Algeciras, Spain 330
11.3.3	The Frontón Recoletos, Madrid 333
11.3.3.1	Description of the model 335
11.3.3.2	Description of the test, application of loads 336
11.4	Final remarks 340
	Further reading 341
	References 341
12	Photoelastic stress analysis 343
	Bill Addis
12.1	The principles of photoelastic stress analysis 343
12.1.1	Photoelasticity 343
12.1.2	The basic photoelastic image 345
12.1.3	Analysing the results of a photoelastic model test 345
12.1.4	Photoelastic materials 346
12.2	History of photoelastic stress analysis 348
12.2.1	Birefringence, or double refraction 348
12.2.2	The beginnings of photoelastic analysis in construction 349
12.2.3	The growth of photoelastic stress analysis after 1930 352
12.3	Technical developments in photoelastic stress analysis 354
12.3.1	Three-dimensional model analysis – stress freezing 354
12.3.2	Three-dimensional model analysis – scattered light method 355
12.3.3	The photoelastic interferometer 355
12.3.4	Photoelastic analysis using birefringent coatings 356
12.4	Some case studies 356
12.4.1	Studies of the Vierendeel girder (1936) 356
12.4.2	Oleftal Dam (1956-1959) 357
12.4.3	3D photoelastic study for a strong road base, using stress-freezing
10.5	(1960s) 359
12.5	Conclusion 361
	Acknowledgements 362
	References 362

Section C Physical models used in structural design, 1940s to 1980s 367

13	Structural modelling technique 369
	Bernard Espion and Bill Addis
13.1	Introduction 369
13.2	Dimensionless numbers and similitude 370
13.2.1	The beginning – fluid dynamics in the nineteenth century 370
13.2.2	Dimensionless numbers for structural model testing 372
13.3	Experimental stress analysis using measurement models 374
13.3.1	Manuals on experimental stress analysis using measurement models 374
13.3.2	Structural model-testing procedure 375
13.4	The measurement of strain 376
13.4.1	Extensometry 376
13.4.2	Mechanical strain measurement 380
13.4.3	Acoustic strain gauges 384
13.4.4	Electrical-resistance strain gauges 387
13.4.5	The bonded electrical-resistance strain gauge 390
13.4.6	Some miscellaneous measuring techniques 395
13.5	The Beggs Deformeter 397
13.6	Concluding remarks 405
	References 405
14	Physical modelling at the University of Stuttgart 415
14	Physical modelling at the University of Stuttgart 415 Christiane Weber
14 14.1	
	Christiane Weber
	Christiane Weber The Materials Testing Institute at the Technical University of
14.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415
14.1 14.1.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416
14.1 14.1.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in
14.1 14.1.1 14.1.2	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417
14.1.1 14.1.1 14.1.2 14.2	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420
14.1.1 14.1.1 14.1.2 14.2	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for
14.1.1 14.1.1 14.1.2 14.2	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422
14.1.1 14.1.1 14.1.2 14.2 14.2.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421
14.1 14.1.1 14.1.2 14.2 14.2.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422
14.1.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425
14.1.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3 14.3.1	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425 Form-finding models with soap films and soap bubbles 425
14.1.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3.1 14.3.1 14.3.2	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425 Form-finding models with soap films and soap bubbles 425 The IL Pavilion, University of Stuttgart 426
14.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3 14.3.1 14.3.2 14.3.3 14.3.4 14.3.5	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425 Form-finding models with soap films and soap bubbles 425 The IL Pavilion, University of Stuttgart 426 The German pavilion at Montreal. 427
14.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3 14.3.1 14.3.2 14.3.3 14.3.4	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425 Form-finding models with soap films and soap bubbles 425 The IL Pavilion, University of Stuttgart 426 The German pavilion at Montreal. 427 The cablenet roofs for the Munich Olympic Games 431 Hanging models 434 The sports hall in Jeddah 435
14.1 14.1.1 14.1.2 14.2 14.2.1 14.2.2 14.3 14.3.1 14.3.2 14.3.3 14.3.4 14.3.5	Christiane Weber The Materials Testing Institute at the Technical University of Stuttgart 415 Model-testing of bridges for the Reichsautobahn 416 Model tests for a dome proposed for the new main station in Munich 417 Model testing after the Second World War 420 The Institut für Spannungsoptik und Modellmessungen (Institute for Photoelasticity and Model Measurement) at the Faculty of Construction 421 Model tests for the roof of the Alster swimming baths, Hamburg 422 The Institut für Leichte Flächentragwerke, University of Stuttgart 425 Form-finding models with soap films and soap bubbles 425 The IL Pavilion, University of Stuttgart 426 The German pavilion at Montreal. 427 The cablenet roofs for the Munich Olympic Games 431 Hanging models 434

15.	Model testing of structures in post-war Italy. The activity of
	ISMES, 1951-1974 441
	Mario Alberto Chiorino and Gabriele Neri
15.1	Istituto Sperimentale Modelli e Strutture (ISMES) 441
15.1.1	The founding of ISMES 441
15.1.2	The facilities and fields of research at ISMES 442
15.2	ISMES' activity 1951-1961 445
15.2.1	Large dams 445
15.2.2	High-rise buildings 449
15.2.3	I modelli nella tecnica (1955): an important conference for structural
10.2.0	modelling in Italy 454
15.3	1964-1974. Changes for ISMES: new guidance, new horizons 457
15.4	Nervi's projects at ISMES 461
15.5	Other structures tested at ISMES 464
15.6	From physical to virtual models 468
15.7	Concluding remarks 470
13.7	Further reading 471
	References 471
	References 4/1
16	Eduardo Torroja and his use of models from 1939 477
	Joaquín Atuña
16.1	Introduction 477
16.2	The Central Laboratory for Testing Construction Materials
	(LCEMC) 477
16.2.1	The new organization and staff 478
16.2.2	The objectives of the new laboratory 478
16.2.3	Types of tests performed 479
16.2.4	Works carried out 480
16.3	Photoelastic stress analysis 480
16.3.1	Three-dimensional problems: grillages 480
16.3.2	Three-dimensional problems: stresses in solid materials 481
16.4	Tests on reduced-scale physical models 481
16.4.1	Initial investigations 482
16.4.2	Innovation in shell structures 483
16.4.3	The roof of the church of Saints Felix and Régula, Zurich 485
16.4.4	An experimental shell roof 487
16.5	Model studies for concrete dams 489
16.6	Reduced-scale roof models. 491
16.6.1	The Haas shell roof for a factory in Nadam Havenwerke, Delft 491
16.6.2	The Labour University of Tarragona 493
16.6.3	Club Táchira, Caracas, Venezuela 494
16.6.4	The roof of Bacardi's offices in Havana 498
16.6.5	The Church of La Paz, Barcelona 500
16.6.6	The grandstand canopy for the Madrid Canódromo (dog track) 502
	<u> </u>
16.6.7 16.7	Reflections on model testing by Carlos Benito 503

Further reading		506
References	507	

17	Scale models for structural testing at the Cement and Concrete		
	Association, UK: 1951-1973 511		
	Edwin Trout		
17.1	Introduction 511		
17.2	The Morice years (1951-1957): establishing a reputation for expertise 511		
17.2.1	Shell roofs (1951-1953) 512		
17.2.2	Prestressed road bridges (1953-1956) 513		
17.2.3	Clifton Bridge, Nottingham (1954-1955) 517		
17.2.4	1957 519		
17.3	The Rowe years I (1958-1966): model testing on a cost repayment basis 520		
17.3.1	Shell roofs (1958-1961) 521		
17.3.2	Symposium on Models for Structural Design (1959) 526		
17.3.3	Bridges and multi-span structures (1959-1962) 526		
17.3.4	Commonwealth projects overseas (1961-1962) 527		
17.3.5	Metropolitan Cathedral at Liverpool (1961-1964) 529		
17.3.6	Cumberland Basin scheme, Bristol (1962) 531		
17.3.7	The Manchester Skyway Bridge / Mancunian Way (1963-1964) 534		
17.3.8	Meeting on Model Testing, 1964 535		
17.3.9	Elevated roads (1964-1966) 536		
17.3.10	CEGB cooling tower (1965) 538		
17.4	The Rowe Years II (1966-1973): applying and reporting research 539		
17.4.1	Viaducts (1967-1970) 539		
17.4.2	Three-year research programme supported by CIRIA		
	(1967-1970) 541		
17.4.3	Model techniques (1969-1973) 542		
17.5	Final remarks 543		
	Appendix 544		
	References 546		
18	Heinz Hossdorf: his contribution to the development of		
	physical model testing 551		
	Pepa Cassinello		
18.1	Introduction 551		
18.2	Tests using physical scale models 552		
18.3	The construction of scale models 553		
18.3.1	Models made with wood 553		
18.3.2	Models made with micro-concrete 554		
18.3.3	Models made with acrylic or epoxy resin 556		
18.3.4	Models made with aluminium 560		
18.3.5	A model made with steel and a polyester membrane 561		
18.4	Evolution of his experimental laboratory 563		

xxii	Contents
------	----------

18.4.1	New equipment 563	
18.4.2	Computers and the Hybrid Test 564	
18.4.3	Hybrid tests with acrylic models 564	
18.5	Final remarks 566	
	Acknowledgements 567	
	References 567	
	Note that the same of the same	
19	Soap-film and soap-bubble models 569	
	Berthold Burkhardt	
19.1	Some historical notes 569	
19.2	Manufacture of soap films and bubbles 570	
19.3	Creating soap film surfaces 574	
19.3.1	The soap film as a minimal surface area 574	
19.3.2	Support of surfaces 575	
19.4	Other forms of film and bubble 577	
19.4.1	Minimal net surfaces 577	
19.5	Air-inflated structures – the pneus 578	
19.6	Bubbles with free edges 579	
19.7		
19.7	1	
	σ	
19.9	Concluding remarks 582 References 584	
	References 504	
20	The model as a concent: the origins of the design methods of	
20	The model as a concept: the origins of the design methods of	
20	Sergio Musmeci 587	
	Sergio Musmeci 587 Lukas Ingold	
20.1	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587	
20.1 20.2	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588	
20.1 20.2 20.2.1	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588	
20.1 20.2 20.2.1 20.2.2	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589	
20.1 20.2 20.2.1 20.2.2 20.2.3	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2 20.3.3	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2 20.3.3 20.3.4	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2 20.3.3 20.3.4	Sergio Musmeci 587 Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2 20.5	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601 The origin of the method 604	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2 20.5 20.5.1	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601 The origin of the method 604 Form-finding in a history of ideas 604	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2 20.5 20.5.1 20.5.2	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601 The origin of the method 604 Form-finding in a history of ideas 604 Between theory and empiricism 606	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2 20.5 20.5.1	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601 The origin of the method 604 Form-finding in a history of ideas 604 Between theory and empiricism 606 The scientification of the design 607	
20.1 20.2 20.2.1 20.2.2 20.2.3 20.3.1 20.3.2 20.3.3 20.3.4 20.4 20.4.1 20.4.2 20.5 20.5.1 20.5.2	Lukas Ingold The interdependence of form and method 587 The quest for the form 588 Scarcity as potential 588 Continuity of force and form 589 Between economic construction and material efficiency 592 The physical model as instrument 593 Visualizing mathematics: the soap-film model 594 Measuring the geometry: the rubber-membrane model 595 Gauging stresses and strains: the methacrylate model 597 Analysing the material behaviour: the reinforced micro-concrete model 598 The development of the method 599 Genealogy of conceptions 600 Emergence of a motif 601 The origin of the method 604 Form-finding in a history of ideas 604 Between theory and empiricism 606	

21	Heinz Isler and his use of physical models 613 John Chilton
21.1	Introduction 613
21.2	Modelling techniques 614
21.2.1	The freely-shaped hill 614
21.2.2	Membrane under pressure 614
21.2.3	Hanging cloth reversed 615
21.2.4	Expansion forms 618
21.2.4	Modelling rules and need for precision 618
21.3	The application of physical models in Isler's design process 618
21.3.1	Exploratory models 619
21.3.2	Form-finding models 622
21.3.3	Structural verification/validation models 625
21.3.4	Is enlargement of models allowed? 628
21.3.4	Isler's use of models in teaching student engineers and architects 629
21.5	Dissemination of Isler's modelling techniques to engineers and
21.5	architects 630
21.6	Isler's contribution to the use of models in structural design 632
	References 633
22	Models for the design development, engineering and
	construction of the Multihalle for the 1975 Bundesgartenschau
	in Mannheim 639
	lan Liddell
22.1	Introduction 639
22.2	Early gridshells 639
22.3	Initial design for the Mannheim shells 640
22.3.1	The hanging-chain model 641
22.3.2	Initial engineering work 644
22.4	Wind loads 644
22.4.1	Wind pressure and scale modelling 644
22.4.2	Wind-tunnel tests 645
22.4.3	Determination of pressures. 647
22.5	Structural model testing: the Essen model 648
22.6	Predicting failure loads from model tests 650
22.6.1	Scale factors 650
22.6.2	Prediction of collapse loads 651
22.7	Structural model testing: the Multihalle model 652
22.7.1	
2272	The Perspex model 652
22.7.2	The Perspex model 652 Testing of the timber joint details 654
22.7.2	Testing of the timber joint details 654 Comparison with computer results 654
	Testing of the timber joint details 654
22.7.3	Testing of the timber joint details 654 Comparison with computer results 654

Section D	Physical models used in non-structural engineering
disciplines	661

22	The biskerian have of about all as all as also at a first or for
23	The historical use of physical model testing in free-surface
	hydraulic engineering 663 Bill Addis
23.1	Introduction 663
23.2	The nineteenth-century pioneers 665
23.2.1	Louis J. Fargue 665
23.2.1	Osborne Reynolds 666
23.2.2	Vernon Harcourt 670
23.2.3	The first hydraulics laboratories 1900-1930 672
23.3.1	Hubert Engels 672
23.3.1	Theodore Rehbock 674
23.3.3	Model testing in the 1920s 675
23.3.4	Hydraulics Research Laboratory, Poona, India, 1916 683
23.4	Hydraulic modelling in the USA in the 1930s 684
23.4.1	Iowa Institute of Hydraulic Research, 1920- 684
23.4.1	·
	The U.S. Army Waterways Experiment Station, 1929-1998 685
23.4.3	The Beach Erosion Board, U.S. Army Corps of Engineers, 1930-1963 688
23.4.4	Current Hydraulic Laboratory Research Reports, 1933-1942 689
23.5	Hydraulic modelling in other countries in the 1930s 689
23.5.1	The Severn Estuary barrage 689
23.5.2	An underwater breakwater for the port of Leixões, Portugal 692
23.6	Some post-war developments in free-surface water modelling 693
23.6.1	The BEB and WES post-war 693
23.6.2	Some developments in Europe 700
23.6.3	The starry sky 701
23.7	Conclusion 704
20	Acknowledgements 705
	References 705
	Notice of the second of the se
24	The historical use of physical model testing in wind
27	engineering 711
	Bill Addis
24.1	The scientific study of wind 711
24.1.1	The force of the wind 711
24.1.2	Early wind tunnels 713
24.1.2	The first measurement of wind-pressure loads on model
2 1 .2	buildings 716
24.2.1	William Charles Kernot, 1893 716
24.2.1	Johann Irminger, 1894 718
24.2.3	National Physical Laboratory, Teddington, UK, 1903-08 720
24.2.3	Making visible the dynamic behaviour of fluids 722
24.3.1	Schlieren photography 722
w r.u.l	ocimeren photography /22

24.3.2	Visualisation of flow lines 723
24.4	Wind-tunnel model studies in the 1920s and 1930s 725
24.4.1	Model studies in Germany 726
24.4.2	Model studies in Denmark 728
24.4.3	Model studies in the USA 728
24.5	The Tacoma Narrows Bridge collapse, November 1940 734
24.5.1	The static model used for the design of the bridge 734
24.5.2	Dynamic model studies undertaken before the collapse 734
24.5.3	Model studies begun immediately after the collapse 736
24.5.4	Studies using the full aerodynamic model of the original bridge, at 1:50
2 F.J. F	scale 738
24.5.5	Studies using a 1:50 scale model for the design of the new Tacoma
21.5.5	Narrows Bridge 741
24.5.6	The legacy of the Tacoma Narrows bridge collapse 742
24.6	The boundary-layer wind tunnel 743
24.6.1	Martin Jensen 743
24.6.2	Alan Davenport 743
24.0.2 24.7	Final remarks 746
27. /	References 746
	References 740
25	The historical use of physical model testing in earthquake
	engineering 753
	Bill Addis
25.1	Early shaking tables 753
25.1.1	Seismology and seismographs in the nineteenth century 753
25.1.2	The Milne-Omori shaking table c.1890 754
25.1.3	F.J. Rogers at Stanford University, 1908 755
25.2	Shaking tables in the 1930s 756
25.2.1	Lydik Jacobsen at Stanford University 756
25.2.2	Nahago Mononobe in Tokyo 759
25.2.3	Arthur Ruge at MIT 760
25.3	Post-war developments in shaking tables 761
25.3.1	More, bigger, better 761
25.3.2	Shaking tables with six degrees of freedom 762
25.4	Final remarks 763
20.1	References 763
26	The historical use of models in the acoustic design of
	buildings 767
	Raf Orlowski
26.1	Early twentieth century 767
26.1.1	Model studies using the sound-pulse method 767
26.1.2	Model studies using the ripple-tank method 770
26.1.3	Three-dimensional model studies using light rays 772
26.1.4	Three-dimensional model studies using sound 776
26.2	Model testing in the 1960s and 1970s 778

xxvi	Content
VV AI	Content.

28.1 28.2

Aesthetic models 821

•		
	26.2.1	Developing new modelling techniques 778
	26.2.2	Sydney Opera House 779
	26.3	Model studies at one-eighth scale in the late-twentieth century 781
	26.3.1	Music studios and auditoria 781
	26.3.2	The Olivier Auditorium, National Theatre, London 782
	26.3.3	The Barbican Concert Hall, London 783
	26.3.4	Assessment of model studies at one-eighth scale 784
	26.4	Model studies at one-fiftieth scale 784
	26.4.1	Glyndebourne Opera House and some concert halls 785
	26.4.2	Factory buildings 786
	26.4.3	Underground railway stations 788
	26.4.4	Corporate and Government Buildings 789
	26.5	Physical modelling of acoustics – the first hundred years 791
		References 791
	27	Geotechnical centrifuge models – a history of their role in
		pre-construction design 793
		William H. Craig
	27.1	Introduction 793
	27.2	Historical review 794
	27.2.1	The beginnings of centrifuge testing of physical models 794
	27.2.2	Early use of physical modelling in geology 798
	27.2.3	The growth of centrifuge modelling in geotechnical engineering 799
	27.2.3	Physical model testing for site-specific prototypes 800
	27.3.1	Excavations 800
	27.3.1	Dams and embankments 801
	27.3.3	Offshore and marine structures 803
	27.3.4	Transmission line pylon foundation 807
	27.3.4	Netherlands national security – coastal defence 807
	27.3.3 27.4	•
	27.4	Centrifuge model testing for more-general geotechnical problems 808
	27 / 1	•
	27.4.1 27.4.2	Pipeline interactions 808 Simulating construction processes 810
		<i>b</i>
	27.4.3	Control and testing modes 811
	27.4.4	Visual observations 812
	27.5	Concluding remarks 812
		References 814
		Section E Physical modelling in the twenty-first century 819
	28	Physical models as powerful weapons in structural
		design 821
		Mamoru Kawaguchi
	28.1	Introduction 821

28.3	Mechanism models 824		
28.4	'Touch and feel' models 825		
28.5	Structural behaviour models 827		
28.5.1	Full-size structural models 827		
28.5.2	Reduced-scale structural models 828		
28.6	Concluding remarks 829		
	References 829		
29	Physical modelling of structures for contemporary		
	building design 831		
	Bruce Martin		
29.1	Introduction 831		
29.2	The canopy – tensegrity then ferrocement 831		
29.3	Column heads with bearings, springs and dampers 838		
29.4	Seismic base isolation 841		
29.5	The wind-tunnel model 843		
29.6	The flexible mast 843		
29.7	The future use of physical models in structural design 843		
	Acknowledgements 844		
	References 845		
30	Models in the design of complex masonry structures 847		
	David Wendland		
30.1	Introduction 847		
30.2	Modelling traditional Iranian vaults 853		
30.3	Experimental construction of a free-form shell structure in masonry 855		
30.4	Reconstruction of the vault in the Chapel of Dresden Castle: a masonry		
30.4	structure with complex geometry 865		
30.5	Conclusion 870		
	Acknowledgements 871		
	References 872		
31	Physical modelling of free surface water – current		
	practice 875		
	James Sutherland		
31.1	Introduction 875		
31.2	Physical model testing 876		
31.2.1	Wave overtopping of structures 876		
31.2.2	Breakwater stability 877		
31.2.3	Loads on structures 877		
31.2.4	Motion of ships and other floating structures 879		
31.2.5	Scour around structures 881		
31.2.6	Other model types 883		
31.3	Combined use of physical and digital models 883		
31.3.1	Model nesting 884		

xxviii Contents	
-------------------	--

31.3.2	Use of a numerical model to design a physical model 884		
31.3.3	Physical model of one component of a system 885		
31.3.4	Model training and calibration 885		
31.4	Conclusion 885		
	Acknowledgements 885		
	References 886		
32	Boundary layer wind tunnel model testing – current		
	practice 889		
	Francesco Dorigatti		
32.1	Introduction 889		
32.2	Recent developments in test facilities 889		
32.2.1	Principles of boundary layer wind tunnel modelling 889		
32.2.2	Modern boundary layer wind tunnels 891		
32.2.3	Novel test facilities 893		
32.3	Recent developments in measuring techniques 894		
	Velocity measurements 895		
	Hot-wire and hot-film anemometers (HWA, HFA) 896		
	Multi-hole pressure probes 896		
	Irwin probes and surface pressure sensors 897		
	Non-intrusive measurements 897		
32.3.2			
	Measurements of overall forces and moments 900		
32.3.4	0 1		
32.4	Wind-tunnel tests on buildings and urban environments 902		
	Wind-induced pressures on building envelopes 902		
	Overall wind-induced responses of buildings 904		
	Structural wind loading and wind-induced motion 904 Rigid-model tests 907		
	Aeroelastic model tests 909		
	A case study: 432 Park Avenue, New York 912		
	Pedestrian level winds in urban environments 914		
	Urban wind flows in proximity to the ground 914		
	Lawson criteria for pedestrian safety and comfort 914		
	Mitigation measurements 915		
	Pedestrian-level wind tests 916		
32.5	Wind-tunnel tests on bridges 919		
	Principles of bridge aerodynamics 919		
32.5.2	Full-aeroelastic bridge model tests 920		
32.5.3	Sectional bridge model tests 923		
32.5.4	Other wind-tunnel tests on bridges 926		
32.6	Wind-tunnel tests on other structures 929		
32.6.1	Long-span roofs 929		
32.6.2	Building appendages and superstructures 930		
32.6.3	Plumes and pollutant dispersion in urban environments 930		
32.7	The future of the BLWT 931		
	References 932		

33	Model testing using shake tables – current practice 941 Amarnath Kasalanati
33.1	Introduction 941
33.2	The need for physical testing 942
33.3	Key components of a shake table 943
33.3.1	Mechanical aspects of the shake table 944
33.3.2	Hydraulic system 945
33.3.3	Control systems of a shake table 946
33.3.4	Shake table performance limitations 947
33.4	Notable modern shake tables in the USA 949
33.4.1	The University of California Berkeley shake table 949
33.4.2	The NEES shake tables in the USA 951
33.5	Shake tables in Japan 952
33.5.1	E-Defense shake table 952
33.6	Shake tables in Europe and Asia 954
33.6.1	LNEC 3D Earthquake Simulator, Lisbon 954
33.6.2	Dynamic Testing Laboratory at IZIIS, Skopje 954
33.6.3	EQUALS Laboratory, University of Bristol 954
33.6.4	Multi-Function Shake Table (MFST) Array, Tongji University,
	Shanghai 955
33.7	Some notable projects tested with shake tables 955
33.7.1	Testing of concrete-dam models at UC Berkeley 955
33.7.2	Testing of models of historic buildings, at IZIIS, Macedonia 957
33.7.3	Testing of a curved bridge at University of Nevada, Reno 957
33.7.4	Testing of a wind turbine at UC San Diego 959
33.7.5	Testing of an isolated five-storey building at E-Defense 959
33.8	Concluding remarks 960
	Acknowledgements 961
	References 961
34	Geotechnical centrifuge modelling – current practice 965 David White
34.1	The role of the geotechnical centrifuge 965
34.2	State-of-the-art geotechnical centrifuge facilities 966
34.2.1	Centrifuge machines 966
34.2.2	Modelling technologies 968
34.3	Complex ground improvement – the Rion-Antirion Bridge 970
34.4	Offshore oil and gas platforms – the Yolla and Maari projects 973
34.5	Sub-sea pipelines – modelling of 'whole life' system behaviour 976
34.6	Concluding remarks – Why use geotechnical centrifuge
	modelling? 979
	References 980
35	The use of physical models in acoustic design – current
	practice 985
	Raf Orlowski
35.1	Introduction 985

xx	Contents
~~	Contents

35.2	Elisabeth Murdoch Hall, Melbourne 985
35.3	Concert hall, Krakow Congress Centre 986
35.4	An acoustic scale model on wheels 987
35.5	The ongoing popularity of acoustic models at scale factors of 1:10 or
	similar 988
35.6	Final remarks 989
	References 990
36	Water-bath modelling – small-scale simulation of natural
	ventilation flows 991
	Owen Connick
36.1	Introduction 991
36.2	Historical perspective 991
36.3	Fundamentals and theory – developing the technique 992
36.4	Water-bath modelling 993
36.4.1	Point sources of buoyancy 994
36.4.2	Distributed heat loads 994
36.4.3	Wind and buoyancy 994
36.4.4	Current and future work 995
36.5	Some applications of water-bath modelling in design 995
36.5.1	Breathing Space, Rotherham 995
36.5.2	Aldwyck Housing Group HQ, Houghton Regis, UK 997
36.5.3	Bloomberg European HQ, London 998
36.6	Experimental techniques and flow visualisation 1002
36.6.1	Dye attenuation 1002
36.6.2	Schlieren imaging 1002
36.6.3	PIV, PTV and LIF 1002
36.7	Concluding remarks 1002
	References 1003
37	The use of biological models for building engineering
3/	design 1005
	Jan Knippers
37.1	Historical background 1005
37.1	A new way of thinking in the twenty-first century 1008
37.3	The Elytra Filament Pavilion 1009
37.4	Plant movements as concept generators for adaptive building
37.1	systems 1011
37.5	Concluding remarks 1014
07.0	References 1015
38	Flying a 100-metre long Jumbo Koinobori 1017
20.1	Mamoru Kawaguchi
38.1	Introduction 1017
38.2	Model theory and dimensional analysis 1019

38.3	Othe	r technical issues 1020
38.4	Laun	ching the Jumbo Koinobori 1022
38.5		luding remarks 1024
	Refer	ences 1024
39		gue: A future for models from the past 1025 ühler and Christiane Weber
39.1	Intro	duction 1025
39.2	Histo	rical study of engineering models 1026
39.2.1	Muse	eum collections 1026
39.2.2	Exhib	oitions 1031
39.2.3	Confe	erences 1032
39.3	Some	e surviving models from the twentieth century 1032
39.3.1	Mode	els for designing concrete shells 1033
39.3.2	Frei (Otto models 1035
39.3.3	Misce	ellaneous structural models 1036
39.3.4	Repli	ca structural models 1038
39.3.5	Mode	els from non-structural engineering disciplines 103
39.4		n for the future 1041
	Ackn	owledgements 1042
	Refer	ences 1042
Append	lices	1047
Append	lix A.1	Extract from Vitruvius (c.30-15 BC) 1049
Append	lix A.2	Extract from Galileo (1638) 1051
Append	lix A.3	Leonhard Euler (1766) A simple rule to determine the strength of a bridge or similar structure, on the basis of the known strength of a model 1053
Append	lix A.4	Extract from report: Telford's design for new London Bridge (1801) 1061
Append	lix A.5	Experimental Models, <i>The Builder</i> (1846) 1071
Append	lix A.6	On model experiments, <i>The Civil Engineer and</i> Architects Journal (1847) 1075
Appendix A.7		Osborne Reynolds (1888) Extract from paper: On certain laws relating to the regime of rivers and estuaries 1081

Author biographies 1085

About the series editors 1093

About this series 1095

Index 1097