Contents

PREFACE xi

PART 1. TECHNOLOGIES AND CONSTRUCTION PROCESS 1

CHAPTER 1. INTRODUCTION TO SUSTAINABLE MASONRY 3

1.1. Definitions of sustainable masonry 3
1.1.1. Sustainable constructions 3
1.1.2. Masonry structures 4
1.2. Challenges of sustainable development in construction 5
1.2.1. Socio-economic aspects 5
1.2.2. Environmental impact 5
1.2.3. Sustainability. 6
1.2.4. Recycling and reuse. 7
1.3. Past (civil engineering and architecture), present and future (design tools) practices 7
1.3.1. Architectural heritage. 7
1.3.2. Cultural heritage. 8
1.3.3. Rehabilitation, strengthening 8
1.3.4. New constructions. 9
1.4. Durability, deformation and possible movement 10
1.5. Importance of expertise (complexity of cases and history of the structure, evolution over time) 11
1.6. Rationalization and calculation methods 12
1.7. Presentation of the outline of this book. 13
1.8. Bibliography 13

CHAPTER 2. EARTH AND STONE MATERIALS 17

2.1. Stone 17
2.1.1. Geological considerations 17
2.1.2. Stone supply 18
2.1.3. Rheology and mechanical strength 19
2.2. Earth 26
2.2.1. Geological and geotechnical considerations 26
2.2.2. Supply of earth 26
2.2.3. Manufacturing of material by compaction (dry) 27
2.2.4. Implementation of earth in plastic state (wet) 38
2.2.5. Physicochemical considerations 43
2.3. Measurement of dry density 43
2.3.1. Hydrostatic weighing 43
2.3.2. Gamma densitometer weighing 46
2.4. Bibliography 46

CHAPTER 3. BLOCKS: THE ELEMENTS OF MASONRY 49

3.1 Compression of blocks of uncut stone, dry stone masonry 49
3.1.1. Cylindrical samples with dry joints 49
3.1.2. Compression of rough blocks 50
3.2. Shear strength of rubble stones 51
3.2.1. Shear tests of one bed of stone on another 52
3.2.2. Shear tests on rubble stone (uncut) on an inclined plane 53
3.2.3. Conclusion 54
3.3. Compression of earth blocks 55
3.3.1. Compressive strength tests of clay bricks and concrete masonry units 56
3.3.2. Test on directly flat earth block 57
3.3.3. Test developed under RILEM 58
3.3.4. Indirect tests 60
3.3.5. Features of the compressive strength of earth blocks 60
3.3.6. Conclusion 66
3.4. Bibliography 66

CHAPTER 4. ARRANGEMENT OF BLOCKS 69

4.1. Dry assembling, or the art of arranging irregular blocks to make a wall 69
4.1.1. The area of influence of a dry stone retaining wall 69
4.1.2. Quality of the material 70

4.1.3. Elevation 70
4.1.4. Conclusion 74
4.2. Mortars of earth blocks and rubble stone masonry 74
4.2.1. Measurements in the fresh state 76
4.2.2. Drying shrinkage measurements 83
4.2.3. Tests on hardened mortars 84
4.3. Masonry of earth blocks 84
4.4. Stone blocks and mortars 85
4.5. Bibliography 87

PART 2. GRAPHIC STATICS 91

CHAPTER 5. THE FOUNDATIONS OF GRAPHIC STATICS 93

5.1. Introduction 93
5.2. Concepts and principles of statics 94
5.2.1. Hypotheses and basic concepts 94
5.2.2. The principle of the parallelogram of forces 103
5.2.3. The principle of equilibrium and its consequences 104
5.2.4. The principle of reciprocal actions (or action and reaction) 109
5.3. Layout plan and force plan 110
5.3.1. Layout plan 110
5.3.2. Force plan 112
5.4. Bibliography 113

CHAPTER 6. REDUCTION AND EQUILIBRIUM OF A SYSTEM OF FORCES IN A PLANE 115

6.1. Goals for the reduction of a system of forces 115
6.2. Concurrent forces in the plane 116
6.2.1. Reduction of concurrent forces 116
6.2.2. Equilibrium condition of *n* concurrent forces 119
6.2.3. Decomposition of a force into several concurrent forces 120
6.2.4. Theorem of three forces 124
6.3. Arbitrary forces in a plane 125
6.3.1. Method of successive applications of the theorem of the parallelogram of forces 125
6.3.2. Resultant couple 127
6.3.3. Equilibrium condition of *n* arbitrary forces 128
6.4. Bibliography 129

CHAPTER 7. FUNICULAR POLYGONS 131

7.1. Reduction of a system of parallel forces 131
7.1.1. Reduction by adding two directly opposing forces. 131
7.1.2. Reduction by decomposition of forces using a pole and construction of the funicular polygon 133
7.2. Funicular polygon of a system of *n* arbitrary forces 137
7.3. Properties of funicular polygons 141
7.3.1. Funicular polygons of subsystems of forces 141
7.3.2. Funicular polygon through two *a priori* fixed points 142
7.3.3. Relationship between funicular polygons constructed from two distinct poles 144
7.4. Applying the properties of funicular polygons 148
7.4.1. Relationships between a tensed cable and compressed arc 148
7.4.2. Condition on the magnitude of forces 150
7.4.3. Passage of a funicular through three points 152
7.5. Bibliography 153

CHAPTER 8. PROJECTIVE PROPERTIES AND DUALITY 155

8.1. Projective properties and graphic statics 155
8.1.1. The Desargues theorem and equilibrium of three forces 157
8.1.2. Steiner's theorem and equilibrium of *n* forces 161
8.1.3. Scope of geometric properties in constructions using graphic statics 164
8.2. Reciprocal figures and projections of polyhedra 165
8.2.1. Reciprocal plane figures 165
8.2.2. Reciprocal figures seen as projections of polyhedra 169
8.3. Duality in graphic statics 176
8.3.1. Interpretation of reciprocal figures in the case of reticulated structures 176
8.3.2. Reciprocal figures and funicular polygons 178
8.3.3. Application in the search for tensile planar structure shapes 181
8.3.4. Search for support reactions of a solid 184
8.3.5. Application to the calculation of reticulated structures loaded at the nodes 187
8.4. Bibliography 190

PART 3. YIELD DESIGN APPLIED TO MASONRY 191

CHAPTER 9. PRINCIPLES OF YIELD DESIGN 193

9.1. Objective and position of the yield design problem 193
9.2. Potential stability and potentially bearable loads 194
9.2.1. Notion of potential stability, domain of potentially bearable loads and extreme loads. 194
9.2.2. Potentially bearable loads in a reticulated structure 196
9.3. Search for domain K of potentially bearable loads 198
9.3.1. Static approach from the inside 198
9.3.2. Static approach from the outside 199
9.3.3. Kinematic approach from the outside 200
9.4. Bibliography 201

CHAPTER 10. STABILITY OF CURVILINEAR MASONRY. 203

10.1. Yield design applied to planar curvilinear masonry. 203
10.1.1. Geometric definition of planar curvilinear masonry 204
10.1.2. Strength criteria 207
10.1.3. Strength criteria expressed in terms of generalized stresses. 209
10.1.4. Yield design and limit analysis 217
10.2. Line of thrust 219
10.2.1. Definition of a line of thrust 220
10.2.2. Systems with one support: example of corbelled stacks under their own weight 223
10.2.3. Systems with two supports: example of the semi-circular arch under its own weight 227
10.2.4. Extreme lines of thrust, joints and associated mechanisms. 234
10.2.5. Minimum thickness and geometric factor of safety 236
10.2.6. Dimensional similitude 237
10.3. Construction of lines of thrust in graphic statics. 241
10.3.1. Construction of lines of thrust using funicular polygons 241
10.3.2. Parametric study of the semi-circular arch and pointed arches under their own weight. 248
10.3.3. Case of an earthquake: quasi-static approach 252
10.3.4. Pseudo 3D study of arches or domes 252

10.4. Numerical methods for the construction of lines of thrust . . . 253
10.4.1. Force network method. 253
10.4.2. Complex systems. 256
10.5. Bibliography 258

CHAPTER 11. HOMOGENIZATION AND YIELD DESIGN OF MASONRY 261

11.1. 2D understanding of masonry walls 262
11.2. 2D model developed by De Buhan and De Felice 264
11.3. Application to structures under plane stress 268
11.4. Application to structures under plane strain 271
11.4.1. Retaining walls 271
11.4.2. Masonry dams 272
11.4.3. Mixed rockfill and masonry dams. 273
11.5. Conclusion 276
11.6. Bibliography 277

CONCLUSION 279

INDEX 281