# Index

## Introduction

1. **Conservation of the architectural heritage: structural, seismic and geotechnical aspects**
   1.1 Structural engineering and architectural heritage: national and international deontological guidelines
   1.1.1 International and deontological guidelines
   1.1.2 The Italian scene
   1.2 The path of knowledge: historic, geometric, structural and geotechnical aspects
   1.2.1 Geometric data gathering
   1.2.2 History of the structures
   1.2.3 Survey of constructive materials and state of conservation
   1.2.4 Mechanical characterisation of the materials
   1.2.5 Soil and foundation analysis
   1.2.6 Structural health monitoring
   1.3 Safety assessment of the architectural heritage
   1.3.1 Evolution of the safety levels
   1.3.2 Nominal life
   1.3.3 Modelling

## Seismic risk and safety assessment of the architectural heritage

2.1 Seismic hazard and cultural heritage: geological, geomorphological and geotechnical aspects
   2.1.1 Local site effects and amplification
   2.1.2 Soil-structure interaction
   2.1.3 Liquefaction
   2.2 Seismic vulnerability of architectural heritage: experiences learned from past earthquakes
   2.2.1 Earthquakes and architectural heritage in Europe and Middle East
   2.2.2 Earthquakes and architectural heritage in the Far East
   2.3 Performance-based approaches in structural engineering problems and codes
   2.3.1 Performance-based approach for existing buildings
   2.3.2 Towards a performance-based assessment of historical buildings?
   2.4 Structural health monitoring of historic structures in seismic regions
   2.4.1 SHM technologies

## Experimental modal analysis of masonry buildings

3.1 System identification
3.1.1 Linear system identification and classification of methods 47
3.1.2 Time domain methods 49
3.1.3 Frequency domain methods 53
3.1.4 Time-frequency domain methods 54
3.2 Assimilating experimental results in numerical models (model updating) 70
3.2.1 Model-driven approaches 70
3.2.2 Direct methods and sensitivity analysis 71
3.2.3 Parameterisation of the model 72
3.2.4 Comparison between identified and analytical data: MAC and COMAC 73
3.2.5 Data-driven approaches 74
3.2.6 Perspectives and remarks 74
3.2.7 Stochastic model updating 75
3.3 Examples of experimental modal analysis of masonry structures 76
3.3.1 Experimental modal analysis in buildings 76
3.3.2 SS. Annunziata Bell-Tower in Roccaverano 78
3.3.3 Bell-Tower of Alba’s Cathedral 82
3.3.4 Dome of S.Gaudenzio in Novara 84
3.3.5 Matilde’s tower in San Miniato 88

4. Analysis and monitoring of oval domes 101
4.1 Geometry and structural peculiarities of oval domes 101
4.1.1 Domes in historical architecture 101
4.1.2 Oval geometry in historical architecture 105
4.1.3 Structural monitoring of domes 107
4.2 The oval dome of the Sanctuary of Vicoforte 113
4.2.1 History of the building 113
4.2.2 Geometry survey of the dome oval shape 114
4.2.3 Structural monitoring and dynamic characterisation 117
4.3 The oval dome of the church of Santa Caterina in Casale Monferrato 133
4.3.1 Testing campaign 134
4.3.2 Dynamic identification 137
4.3.3 Model updating 139
4.4 The oval dome of the church of Sant’Agostino in L’Aquila 141
4.4.1 Technical history of the building 141
4.4.2 Damages caused by the 2009 earthquake 141
4.4.3 Dynamic analysis of the church 142

5. Nonlinear and hysteretic models for masonry 151
5.1 Constitutive models for static analysis 151
5.1.1 Discrete models 151
5.1.2 Continuous models 154
5.2 Constitutive models for dynamic analysis 159
5.2.1 Hysteretic models and operators 159
5.2.1.1 Piecewise-linear hysteretic models 161
5.3 Nonlinear models for multiple degrees of freedom systems: recent theories and extensions 181
6. **Identification of nonlinear and hysteretic systems** 193
   6.1 Identification of nonlinear and evolving systems 193
   6.2 Models and methods for the identification of nonlinear and evolving systems 196
      6.2.1 Direct Parameter Estimation 196
      6.2.2 Restoring Force Surface method (RFS) 198
      6.2.3 NARMAX modelling 199
      6.2.4 Reverse Path method and Conditioned Reverse Path method 201
      6.2.5 Nonlinear identification through feedback and output (NIFO) 203
      6.2.6 Volterra series and higher order frequency response functions 205
      6.2.7 Neural Networks 207
   6.3 Instantaneous and on-line methods for nonlinear identification 208
      6.3.1 Hilbert transform 210
      6.3.2 Instantaneous identification with time-frequency estimators 213
         6.3.2.1 Polynomial identification in the time-frequency domain 214
         6.3.2.2 Instantaneous identification of a polynomial form 219
         6.3.2.3 Parametric identification in the time-frequency domain 227
      6.3.3 Kalman filter and its application to nonlinear systems 233
         6.3.3.1 The Extended Kalman Filter (EKF) 234
         6.3.3.2 The Unscented Kalman Filter (UKF) 235
         6.3.3.3 The Iterated Unscented Kalman Filter (UKF) 240
   7. **Experimental identification of non-linear and hysteretic models for masonry structures** 251
      7.1 Scaled model of a masonry twin-arch bridge 251
         7.1.1 Material characterisation tests 253
         7.1.2 Flume tests 254
         7.1.3 Numerical models 254
      7.2 Dynamic experimental tests 255
         7.2.1 Experimental test program 255
         7.2.2 Experimental setups 257
         7.2.3 Accelerometers 258
         7.2.4 Strain gauges 258
         7.2.5 Visually detectable damage 259
      7.3 Identification campaign 259
         7.3.1 Data analysis and assimilation 259
            7.3.1.1 Modal parameters and symptoms evolution 259
         7.3.2 Study of the transient after the application of settlements 261
      7.4 Dynamic monitoring of the parameters at different damage levels 262
         7.4.1 Non-linear identification in principal coordinates 262
         7.4.2 Identification algorithm 264
         7.4.3 Non-linear identification from shaker tests 264
         7.4.4 Perspectives in non-linear model updating 267