

Contents

Preface viii

Acknowledgments ix

About the Authors xi

1 INTRODUCTION TO ANCIENT MASONRY 1

- 1.1 Introduction to Ancient Masonry 1
 - 1.1.1 History of Masonry Materials 2
 - 1.1.1.1 Stone 2
 - 1.1.1.2 Clay Units 4
 - 1.1.1.3 Terra Cotta 6
 - 1.1.1.4 Mortars 7
 - 1.1.2 Early building elements 11
 - 1.1.2.1 Building Up 12
 - 1.1.2.2 Spanning Across 19
 - 1.1.2.3 Enclosing Space 27
 - 1.1.3 Development of building structure 31
 - 1.1.3.1 Posts and lintels 32
 - 1.1.3.2 Vaults and domes 33
 - 1.1.3.3 Gothic 35
 - 1.1.3.4 Single-Story Loadbearing Buildings 37
 - 1.1.3.5 Multistory Loadbearing Buildings 38
- 1.2 Transition from Ancient to Modern 40
 - 1.2.1 Masonry as a Fireproofing Element 41
 - 1.2.2 Masonry Floor Systems 44
 - 1.2.3 Early Concrete Masonry 46
 - 1.2.4 Composite Wall Systems 48
 - 1.2.5 Evolution of the Masonry Cavity Wall 51
 - 1.2.6 Transition to Modern Masonry: Summary 54
- 1.3 Closure 54
- 1.4 References 55

2 INTRODUCTION TO MODERN MASONRY 57

- 2.1 Introduction 57
 - 2.1.1 Types of Modern Masonry Construction 57
 - 2.1.2 Wall Types and Configurations 58
- 2.2 Properties of Masonry Materials 64
 - 2.2.1 Clay Masonry Units 64
 - 2.2.2 Concrete Masonry Units (CMU) 67
 - 2.2.3 Building Stone 69
 - 2.2.4 Special Nonconventional Masonry Units 72
 - 2.2.5 Mortar 74
 - 2.2.6 Masonry Grout 77
 - 2.2.7 Reinforcement 78

2.3	Properties of Masonry Assemblies	79
2.3.1	Compressive Strength	79
2.3.2	Flexural Tensile Strength for Out-of-Plan Bending (Modulus of Rupture)	81
2.3.3	In-Plane Tensile Strength	83
2.3.4	Bed Joint Shear Strength	83
2.4	Summary	84
2.5	References	85

3 EVALUATION AND RETROFIT PROCESS 87

3.1	Introduction	87
3.2	Need for Evaluation	87
3.2.1	Performance of Existing Structures	88
3.3	Code Requirements for Evaluation	92
3.3.1	Building Codes for Existing Construction	92
3.3.2	Guidelines	97
3.3.3	Design Information Summary	99
3.4	Evaluation Process	99
3.4.1	Introduction	99
3.4.2	Seismic Evaluation of Buildings	100
3.4.3	Seismic Evaluation Approach	102
3.4.4	Seismic Damage Assessment	114
3.5	Investigation Plan	118
3.5.1	Introduction	118
3.5.2	State 1: Preliminary Investigation	119
3.5.3	Main Investigation	119
3.5.4	Problem Identification and Decision-Making	120
3.5.5	Recommendation for Retrofit	121
3.6	Documentation and Recording	123
3.7	Information Management	124
3.8	Summary: Evaluation and Retrofit Process	124
3.9	References	124

4 SITE INVESTIGATION AND ANALYSIS 129

4.1	Introduction	129
4.2	Preliminary Site Investigation	129
4.2.1	General	129
4.2.2	Masonry Evaluation Checklist	130
4.2.3	Building Description and Geometry	130
4.2.4	Visual Examination	130
4.2.5	Drones for Façade and Roof Inspection	132
4.2.6	Damage Identification	133
4.2.7	Crack Mapping and Movement	139
4.2.8	Soil Conditions and Foundations	141

4.3	Testing Plan	146
4.3.1	Test Locations	146
4.3.2	Sample Size	146
4.3.2.1	Codes and Guidelines	147
4.3.2.2	Statistical Approach to Choosing a Sample Size	149
4.3.3	Interpreting Test Results	151
4.3.3.1	Strength Correlation	151
4.4	Detailed Site Investigation and In Situ Testing	154
4.4.1	General	154
4.4.2	Standardized Methods	154
4.4.3	Nondestructive Evaluation	155
4.4.4	Minor Destructive Methods	175
4.4.5	In Situ Strength and Deformation Tests	177
4.4.6	Destructive Methods	184
4.4.6.1	Sample Removal and Transport	185
4.4.7	Load Tests	186
4.4.8	Moisture Testing	189
4.4.9	Diagnosing Corrosion	195
4.4.10	Laboratory Testing	198
4.4.10.1	Chemical and Elemental Composition	198
4.4.10.2	Material Property Testing	199
4.4.11	Dynamic Testing for Damage Identification and Health Monitoring	202
4.5	Analysis	203
4.5.1	General	203
4.5.2	Estimation of In Situ Material Properties	203
4.5.3	Evaluation of the Significance of Observed Cracks	204
4.5.4	Structural Modeling	205
4.6	Summary: Site Investigation and Analysis	208
4.7	References	208

5 RETROFIT 213

5.1	Introduction	213
5.1.1	Terminology	213
5.1.2	General Retrofit Objectives	214
5.1.2.2	Historic Preservation Philosophy	215
5.1.3	Strategy	218
5.2	Foundation Retrofit	221
5.2.1	Adding a New Footing	222
5.2.2	Soil Improvement	223
5.2.3	Underpinning	224
5.3	Techniques Related to Demand	226
5.3.1	Base Isolation	226
5.3.2	Friction Sliding Isolation (Soft Joints)	227
5.3.3	Reducing Torsional Effects	228

5.4	Techniques Related to Increasing Element Resistance	229
5.4.1	Attachments of an Additional Wythe, Conversion of Nonloadbearing Walls to Structural Walls, and Adding Elements	229
5.4.2	External Reinforcing Overlay	231
5.4.3	External Reinforcing with Steel Plates	238
5.4.4	External Steel Frames	239
5.4.5	Near-Surface Mounted (NSM) FRP Rods	241
5.4.6	Internal Reinforcing	241
5.4.7	Drill and Bond Method	247
5.4.8	Post-Tensioning	248
5.4.9	Prestressed Masonry	251
5.2.10	Grout Injection	252
5.5	Techniques related to Increasing System Stability and Structural Integrity	263
5.5.1	Post-Installed Anchors	263
5.5.2	Bracing	266
5.5.3	Connecting Floor Diaphragms to Masonry Walls	267
5.5.4	Connecting Cross and Flanged Walls	269
5.5.5	Installing Supplemental Structural Support	271
5.5.6	Blast Resistance	273
5.6	Adding an Opening to an Existing Wall	274
5.7	Techniques Related to Improving Serviceability	277
5.7.1	Repointing	277
5.7.2	Crack Repair	280
5.7.3	Creating New Movement Joints	282
5.7.4	Reducing Water Penetration	282
5.7.5	Addressing Corrosion	284
5.7.6	Installing an Air Barrier to Prevent Moisture Condensation	285
5.7.7	Salt Extraction	285
5.7.8	Application of Water-Resistant Treatments	286
5.8	Replacement	287
5.9	Organization of Retrofit Work	289
5.9.1	Preparation of Retrofit Plans and Specifications	289
5.9.2	Supervision and Inspection of Retrofit Work	290
5.9.3	Quality Assurance and Quality Control	291
5.10	Closure	291
5.11	References	291
6	MONITORING	297
6.1	Introduction	297
6.1.1	Monitoring Objectives	298
6.1.2	Motivation and Strategy	298

6.2	Monitoring Process	299
6.2.1	Static-Based Monitoring	300
6.2.1.1	Monitoring Cracking Activity	300
6.2.1.2	Monitoring Building Envelope Thermal and Moisture Response	301
6.2.2	Dynamic-Based Monitoring	303
6.2.3	Dynamic-Based Damage Identification	308
6.2.4	Structural Health Monitoring of Monuments	309
6.2.5	Structural Health Monitoring of Masonry Bridges	309
6.2.6	Monitoring of Buildings During Construction	310
6.2.7	Post-Earthquake Monitoring of Building Structures	311
6.3	Monitoring System Design	312
6.3.1	Monitoring Parameters	313
6.3.2	Period and Frequency	313
6.3.3	Sensors	314
6.3.4	Data Logging	315
6.3.5	Cabling and Communication	316
6.3.6	Protection	316
6.3.7	System removal	316
6.4	Equipment	317
6.4.1	Sensor types	317
6.4.2	Data Acquisition	322
6.4.3	Remote Sensing	322
6.5	Data Analysis and Reporting	323
6.6	Summary	327
6.7	References	327
7	MAINTENANCE	329
7.1	Introduction	329
7.2	Code Requirements	330
7.3	Maintenance Process	331
7.4	Maintenance Items and Deterioration Mechanisms	331
7.5	Inspection Intervals	332
7.6	Maintenance Activities	333
7.6.1	Mortar Repointing	334
7.6.2	Masonry Unit Replacement	334
7.6.3	Treating Rising Damp	337
7.6.4	Flashing Maintenance	339
7.6.5	Shelf Angle Replacement	341
7.6.6	Opening Weeps	341

7.7	Cleaning	341
7.7.1	Cleaning Methods	343
7.7.2	Cleaning Stains	348
7.7.3	Cleaning Precautions	349
7.7.4	Planning a Cleaning Program	353
7.8	Maintenance Plan Design	354
7.9	Maintenance and Repair Costs	355
7.10	Summary	356
7.11	References	356
8	CASE STUDIES	359
8.1	Introduction	359
8.2	Case Study 1: Brick Masonry Retrofit for High Wind	359
8.2.1	Introduction	359
8.2.2	Background	360
8.2.3	Condition Evaluation	362
8.2.4	Retrofit	366
8.2.5	Discussion and Lessons Learned	368
8.3	Case Study 2: Stone Masonry Seismic Retrofit	371
8.3.1	Introduction	371
8.3.2	Background	371
8.3.3	Condition Evaluation	371
8.3.4	Retrofit	373
8.3.5	Discussion and Lessons Learned	377
8.4	Case Study 3: Brick Veneer Maintenance and Retrofit	378
8.4.1	Introduction	378
8.4.2	Background	378
8.4.3	Condition Evaluation	380
8.4.4	Retrofit	384
8.4.5	Discussion and Lessons Learned	388
8.5	Case Study 4: Repair of Cracked Brick Veneer	389
8.5.1	Introduction	389
8.5.2	Condition Evaluation	389
8.5.3	Retrofit	390
8.5.4	Discussion and Lessons Learned	390
8.6	Case Study 5: Thermal Evaluation of a Masonry Cavity Wall System	391
8.6.1	Introduction	391
8.6.2	Problem-Solving Approach	392
8.6.3	Thermal Analysis	393
8.6.4	Condensation Analysis	393
8.6.5	Discussion and Lessons Learned	394

8.7	Case Study 6: Water Leakage of Single-Wythe Exterior Masonry Walls	397
8.7.1	Introduction	397
8.7.2	Background	397
8.7.3	Causes of Leakage	398
8.7.4	Retrofit	398
8.7.5	Discussion and Lessons Learned	399
8.8	Case Study 7: Cracking and Water Leakage of Masonry Cavity Walls	400
8.8.1	Introduction	400
8.8.2	Condition Evaluation	401
8.8.3	Distress Causes	403
8.8.4	Retrofit	406
8.8.5	Discussion and Lessons Learned	407
8.9	References	407

APPENDICES 409

Appendix A	Referenced Standards and Guidelines	409
Appendix B	Masonry Building Survey Form	415
Appendix C	Brick Masonry Evaluation Checklist	427
Appendix D	Masonry Maintenance Checklist	435
Appendix E	Masonry Cleaning Recommendations	439

INDEX 443