



National Technical University of Athens (NTUA)
Faculty of civil engineering

**DAMAGE ASSESSEMENT AND REHABILITATION OF
HISTORIC TRADITIONAL STRUCTURES**

Doctoral thesis

By

Mohamed Mostafa Mohamed Abdelmegeed

Assistant Lecturer, conservation and restoration department, Faculty of Archaeology

Under the supervisor of

Dr. Michael D., Kotsovos

Former Professor, School of Civil Engineering, Department of structural Engineering,
Reinforced Concrete Laboratory

Dr. Vougioukas E.

Lecturer, School of Civil Engineering,
Department of structural Engineering,
Reinforced Concrete Laboratory

Dr. Badogiannis E.

Lecturer, School of Civil Engineering,
Department of structural Engineering,
Reinforced Concrete Laboratory

Athens 2015

Mohamed M. Abdelmegeed

National Technical University of Athens (NTUA)
Faculty of Civil Engineering
Σχολη Πολιτικών Μηχανικών ΕΜΠ

Copyright © Mohamed Mostafa Abdelmegeed 2015
All rights reserved.

No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without indicate or mention to the author. With the exception of storage and distribution for non-profit, educational or research nature, provided to indicate the source and keep this message Questions concerning the use of labor for profit should be addressed to the author. The views and conclusions contained in this document reflect the author and should not be interpreted as representing the official views of National Technical University of Athens

List of tables

Table of contents

- List of table.....	xv
- Acknowledgement.....	xvi
- Abstract.....	xvii
- Greek abstract (Περίληψη).....	xxi
- Arabic abstract (ملخص الرسالة).....	xxiii
- Key Words.....	xxvi
- Introduction.....	xxvii
- PhD text structure.....	xxviii
- List of publications	xxx
- Importance of Historic traditional masonry and ethics of rehabilitation.....	xxxi

Chapter 1: Historic traditional masonry structures: History, Development and Structural elements..... 1

1.1-Masonry as a Construction Technique through History.....	2
1.2-Historic traditional masonry.....	4
1.3-Historic Traditional Masonry Structures developing through time.....	6
1.3.1- Historic Traditional houses" History and Development".....	8
1.4-Historic Traditional masonry in Athens-Greece.....	11
1.4.1- Structural element joints and connection techniques.....	16
1.4.1.1- Stone connection.....	18
1.4.1.2- Wood connection.....	19
1.4.1.3- Steel connection.....	23
1.4.1.4- Anchor Steel Bar Tie Technique " T shape".....	25
1.5-Historic Traditional masonry in Cairo-Egypt.....	29
1.5.1- Historic traditional masonry houses in Cairo-Egypt.....	34
1.5.2- Architectural and construction characteristics of traditional houses in Cairo.....	35
i- The Majaz (Entrance).....	37
ii-The Courtyard	39
iii- The Qa'a (sitting hall)	43
iv- The Takhtabush.....	45
v- The Malqaf (Sky open)	46
vi- The Mashrabiya (arabesque wooden window)	49
1.6-Structural Elements.....	53
1.6.1- Walls.....	54
i- Un-coursed Random Rubble Stone Masonry wall.....	56
ii- Un-coursed Semi-Dressed Stone Masonry wall.....	57
iii- Dressed Stone Masonry wall (Ashlars Masonry).....	58
1.6.2- Floor and Roof Structures.....	59
1.6.2.1- gabled roof.....	63
1.6.2.2- Gabled roof structures and materials.....	64
1.6.3- Cantilevered Stairs.....	67
1.7- Concluding remarks	69
- References.....	73

Chapter 2: Factors and Aspects Damage of Historic Traditional Masonry	76
- Introduction	77
2.1-Earthquakes	78
2.1.1- Earthquake Causes	79
2.1.2- Earthquake Effects on historic traditional masonry.....	82
2.1.3- Damage mechanism of historic traditional masonry.....	86
i- Lack of Anchorage.....	91
ii- In-plan Failures.....	92
iii- Out-of-Plane Failures.....	93
2.1.4- Damage Mechanism to Historic Traditional Masonry Walls.....	95
2.1.4.1- Free Standing Masonry Wall.....	96
2.1.4.2- Wall enclosure without roof.....	99
2.1.4.3- Roof on Wall Enclosure.....	100
2.1.4.4- Shear Wall with Openings.....	101
2.2- Change and conversion	102
2.3- Structural and construction defects	104
2.3.1- Irregularities in plane and vertical direction.....	104
2.3.2- Lack of vertical confining elements.....	105
2.3.3- Weak out-of-plane response.....	106
2.3.4- Unconfined wall corners.....	106
2.3.5- Poor building materials quality.....	107
2.4- Cracks	108
2.4.1- Crack causes and mechanism in historic traditional masonry.....	110
2.4.1.1- Cracks caused by Excessive lateral forces	112
2.4.1.2- Cracks caused by eccentric loading.....	112
2.5- Delamination of wall wythes	113
2.6- Out-of-plane movement	114
2.7- Ground Moisture	115
2.8- Roof deterioration	116
2.9- Concluding remarks	119
- References	126
Chapter 3: Structural appraisal	131
- Introduction	132
3.1-Historical, structural and architectural investigations"	136
3.1.1- Historical analysis.....	138
3.1.2- Direct observation.....	139
3.1.3- Drawings.....	140
3.2-Monitoring	140
3.2.1- The Auto plumb.....	142
3.2.2- Electronic Theodolite.....	142
3.2.3- Total stations.....	143
3.2.4- High accurate leveling devices (HLS).....	143
3.2.5- Invar-wire" Convergence measurements ".....	145
3.3-The structural scheme and damage	145
3.4-Geometric documentation methods for historic traditional masonry	146

3.5-Orientation and scaling	147
3.6-Testing methods	148
3.6.1- Flat-jack test.....	148
3.6.2- Georadar.....	151
3.6.3- Dilatometer.....	152
3.6.4- Visual inspection or endoscopy	153
3.6.5- Thermography.....	154
3.6.6- In situ vibration measurements.....	155
3.6.7- Shear Test.....	156
3.6.8- Auxiliary lattice steel structure.....	157
3.6.9- Finite Element Method (FEM).....	159
3.7-Laboratory work	160
3.7.1- Mechanical tests.....	160
3.7.2- Physical tests.....	160
3.7.3- Chemical tests.....	160
3.7.4- Optical and mineralogical analysis.....	161
3.7.5- Durability tests.....	161
3.7.6- Sonic tests.....	161
3.8-Concluding remarks	163
- References	166
Chapter 4: Historic Traditional Masonry Building Rehabilitation Methods	169
- Introduction.....	170
4.1-Strengthening of structural behavior	170
4.1.1- Strengthening of masonry wall.....	170
4.1.1.1- Injection.....	171
4.1.1.2- Transversal anchorage in walls "Stitching"	172
4.1.1.3- Reinforced cement coating" steel mesh'.....	173
4.1.1.4- The use of polypropylene mesh.....	173
4.1.1.5- Strengthening with FRP bar.....	174
4.1.1.6- Strengthening with composite materials (CFRP and GFRP).....	176
4.1.1.7- The use of horizontal tie rods.....	177
4.1.1.8- Retrofitting by post tensioning.....	178
4.2-Improving the connection between walls and floor	181
4.3-Floors repair	182
4.3.1- Floor strengthening.....	183
4.3.1.1- Concrete slab.....	184
4.3.1.2- Composite steel-Concrete slab.....	184
4.3.1.3- Metal grid.....	185
4.3.1.4- Steel ties.....	185
4.4-Seismic strengthening	187
4.4.1- Concrete walls.....	188
4.4.2- Base isolation.....	189
4.5 Remove Existing Features from Other Historic Periods.....	190
4.5-Re-use of historic traditional buildings	190
4.6-Concluding remarks	195
- References	197

Chapter 5: Case study	199
5.1-Introduction	200
5.1.1- Plaka.....	200
5.2-Aktaiou building	202
5.3-Historical description	203
5.4-Structure	207
5.4.1- General description.....	206
5.4.2- Structural walls.....	210
- Limestone.....	210
- Marble.....	210
- Volcanic stone.....	211
- Mortar.....	211
5.4.3- Partition walls.....	212
5.4.4- Floors.....	212
5.4.5- Roof.....	214
5.4.6- Other structural elements.....	215
5.5-Damage identification and mapping	218
5.5.1- General.....	218
- Abbreviations.....	218
5.5.2- Main bearing walls.....	219
- Wall 1.....	219
- Wall 2.....	220
- Wall 3.....	220
- Wall 4.....	221
- Wall 5.....	221
- Wall 6.....	221
- Wall 7.....	222
- Wall 8.....	222
5.5.3- Internal secondary walls.....	223
5.5.4- Floors – Timber beams.....	223
5.5.5- Roof	223
5.5.6- Other structural elements.....	224
5.6-Damage Assessment	225
5.6.1- Documentation	225
5.6.1.1- Sampling	225
- Stones.....	226
- Mortar.....	228
5.6.2- Testing	229
5.6.2.1- Chemical and mineralogical characterization.....	229
5.6.2.2- Mechanical characterization	235
5.6.2.3- Strain Gauges.....	236
5.6.3- Assessment of masonry mechanical characteristics.....	240
5.7-Casus of damage	242
4.7.1- Identification of the causes of damage based on visual observation.....	242
5.7.1.1- Damage at the crowing of the walls	242
5.7.1.2- Damage at the connection of intersecting walls.....	243
5.7.1.3- Damage of the lintels.....	244

5.7.1.4- Damage of the wall pessary	245
5.7.1.5- Separation between roof and bearing walls.....	246
5.7.2- Identification of the causes of damage based on numerical analysis.....	247
5.7.2.1- Damage at the crowing of the walls.....	247
5.7.2.2- Damage at the connection of intersecting walls.....	248
5.7.2.3- Damage of the lintels.....	249
5.7.2.4- Damage of the wall pessary.....	249
5.7.3- Discussion.....	250
5.8-Proposed interventions	251
5.8.1- Strengthening of structural behavior.....	252
5.8.2- Strengthening through grout injection	252
5.8.3- Strengthening through reinforced cement paste coating	253
5.8.4- Strengthening of the floor beams	254
5.9-Verification of proposed interventions.....	254
- Concluding remarks	259
- References	264
6-CONCLUSIONS	265
7- Proposals for future work.....	277

List of figures**Figure**

1.1-	Different kinds of stone masonry.....	3
1.2-	View of Parthenon and Roman masonry walls.....	4
1.3-	Beehive houses from a village in Cyprus and rectangular dwellings from a village in Iraq.....	8
1.4-	Typical stone masonry building with exterior stone masonry walls and an interior timber frame.....	9
1.5-	Types of traditional houses of Cyprus and Athens. Upper row: Single room houses. Lower row: Twin room houses with vaulted partitions.....	10
1.6-	typical rural houses.....	10
1.7-	Historic traditional houses in historic cities	11
1.8-	Historic traditional houses: two and three floor house with different elevations of first, second and third floor.....	12
1.9-	Corinth. Schematic plan of a byzantine house in the Agora area.....	13
1.10-	Historic traditional masonry buildings in "PLAKA", Athens.....	13
1.11-	Ventilation strategies: Small openings at the loft of the buildings.....	14
1.12-	Use of limestone as a connection method between walls.....	15
1.13-	Saint Filothei house in Athens (Charalambos 1983).....	18
1.14-	Poor and good connections in wall corners.....	19
1.15-	Detail of the timber tie within masonry.....	20
1.16-	Timber ties technique between floors and at floor levels in some buildings.....	21
1.17-	Timber bands used in historic traditional walls.....	21
1.18-	Masonry infill timber-framed system and Bağdadi lath system... ..	22
1.19-	Rubble Stone walls with wooden joists.....	23
1.20-	The triple header masonry bond.....	24
1.21-	Timber elements inside the brick walls.....	24
1.22-	exterior views showing the tie timber element rods.....	24
1.23-	Steel connection tie technique in historic traditional masonry.....	25
1.24-	Steel anchors tie roof with wall.....	26
1.25-	Connection between beam and masonry with single and double steel element.....	26
1.26-	Positioning of double steel ties in historic traditional building AKTIOU building and tie positioning, plan.....	27
1.27-	Three steel ties positioning, plan.....	27
1.28-	Positioning of three steel ties in historic traditional building (Alfatihia Mosque....	28
1.29-	Positioning of steel ties in connection of arches with columns (pottery art Mosque in Monostrakii).....	28
1.30-	Positions of steel ties in connection of arch with wall (Pottery art Mosque in Monostrakii).....	28
1.31-	General views to historic Cairo and some historic district	29
1.32-	Historic streets and historic traditional buildings in historic Cairo.....	30
1.33-	Typical distinct defined by the surrounding continuity of houses.....	31
1.34-	Historic Traditional houses and the effect of 20 th century modernity	32
1.35-	Deterioration phenomena of historic Traditional masonry building in Cairo.....	33
1.36-	Urban fabric of historic traditional masonry in Cairo.....	35

1.37-	Bent Entrance idea in historic traditional house in Cairo.	38
1.38-	The main entrance (Majaz) in Al-Sehaimi house.....	39
1.39-	Al-Sehaimi house: A-the main façade and B-the main entrance and courtyard.....	40
1.40-	Plan of the courtyard typologies in historic traditional houses in Cairo where A- Gamal Eddin Al Zahabi, Ottoman period, B-Zeinab Khatoun, Mamluk period, C-Alkiritlia house Mamluk period D-AlHarra wihouse Mamluk period.....	40
1.41-	Courtyard in historic traditional houses in Cairo, courtyard at Al-Sehaimy house: A-the main façade B- courtyard at Al-Sennary house, and C- plan of Al-Sehaimy house shows the two courtyards.....	42
1.42-	Drawing sections of Qa'a and of Malqaf (left) and Maq'ad (right).....	43
1.43-	The plan of <i>qa'a</i> , <i>durqa'ah</i> , and <i>Ruaq</i> or <i>'iwans</i> (Al-Sehaimi house 18 th century)....	44
1.44-	The qa'a and takhtabosh in traditional houses: A- takhtabosh in Al-Sehaimi house B- the qa'ah in Al-Sennary house and C- plan of Al-Sehaimi house shows the takhtabosh place.....	45
1.45-	Diagram of operation of Malqaf.....	47
1.46-	the malqaf idea in historic traditional houses.....	47
1.47-	The <i>malqaf</i> in historic traditional houses.....	48
1.48-	Show Malqaf from outside and inside.....	49
1.49-	<i>Mashrabiya</i> in Zeinab Khatoun House.....	50
1.50-	<i>Mashrabiya</i> from outside and inside view.....	51
1.51-	Traditional masonry wall construction details: wall un-coursed "random rubble stone masonry"; semi-dressed stone wall; wall with an exterior Wythe built using wedge shaped dressed stone.....	55
1.52-	Round stone boulders used for traditional stone masonry and semi-dressed stones ready for wall construction.....	57
1.53-	Un-coursed semi-dressed stone masonry walls.....	57
1.54-	Dressed stone masonry: an isometric view of a typical wall, and an exterior of wall.....	58
1.55-	The tree leaves wall in historic traditional masonry.....	59
1.56-	Typical floor constructions with wooden beams and planks, ballast fill, and tile flooring.....	60
1.57-	Double timber frame floor.....	62
1.58-	Terms used to describe the elements of the roof.....	64
1.59-	Some typical roof forms.....	65
2.1-	Cyclic waves of constant amplitude and period.....	79
2.2-	Common terms and factors affecting shaking intensity at a given site.....	80
2.3-	Inertia forces caused by the earthquake ground motion.....	82
2.4-	Different buildings shapes or configurations.....	83
2.5-	Total collapse of construction.....	86
2.6-	Typical wall cracking.....	86
2.7-	Stress condition in a wall element.....	87
2.8-	Out of plane corner mechanisms of masonry units located in the historical center of San San Felice sul Panaro.....	88
2.9-	Sub-units in masonry building – walls behave as discrete units during earthquake.....	88
2.10-	Earthquake response of a hipped roof masonry building.....	89

2.11-	Masonry building during earthquake shaking: a) loosely connected walls without slab at the roof level, b) a building with well connected walls and a roof slab.....	90
2.12-	Wall B properly connected to Wall A: Walls A (loaded in the strong direction) support Walls B (loaded in the weak direction)	90
2.13-	Inadequate wall-to-roof anchorages.....	91
2.14-	In-plane damage of stone masonry walls: a) typical wall with openings; b) rocking failure, and c) diagonal shear cracking.....	92
2.15-	Example of Out-of-plane collapse of a wall with tie beams, and roof hammering the masonry walls.....	93
2.16-	The effect of earthquake hazards on church of Sants Maria Maggiore.....	94
2.17-	Simplified conceptual representation of out-of-plane seismic response.....	95
2.18-	The form of X (double-diagonal shear) cracks.....	96
2.19-	In-plane failure modes of a laterally loaded URM wall: shear failure, sliding failure, and rocking failure.....	96
2.20-	Example of predictable mechanisms of collapse.....	97
2.21-	Cathedral of San Paolo during 2012 earthquake where: a- before collapsed b and c after collapsed by earthquake.....	97
2.22-	a- Perpendicular force at upper end of wall A b- Unreinforced wall B with small length to width ratio c- Wall B with moderate length to width ratio d- Wall B with long length to width ratio.....	98
2.23-	Failure Mechanism of Wall Enclosure without Roof	99
2.24-	Roof on wall enclosure where " Earthquake forces".....	100
2.25-	Deformation, cracks and stresses of a shear wall with openings.	101
2.26-	Salerno building before (left) and after (right) partial collapse.....	103
2.27-	Sant Agostino town hall.....	105
2.28-	Collapse of a corner and vertical cracks near the corner for masonry buildings.....	105
2.29-	Out of plane failure in historic masonry buildings.....	106
2.30-	Detail of wall failure caused by irregular stones.....	108
2.31-	Partial collapse in Salerno building	109
2.32-	The use of poor building materials and poor mortar bond.....	109
2.33-	typical crack patterns in masonry walls.....	111
2.34-	Cracks aspects in historic traditional masonry buildings in Greece.....	112
2.35-	Cracks aspects in historic traditional masonry buildings in Italy.....	113
2.36-	Cracks aspects in historic traditional masonry buildings in Egypt.....	113
2.37-	Delamination of stone masonry walls: a) delamination in progress and b) delamination of wall Wythes due to earthquake.....	115
2.38-	Shows water vapour in and out of masonry walls.....	117
2.39-	Representation of the effects of air movement on the critical moisture content of a porous masonry wall.....	117
2.40-	Decay aspects in timber roofs.....	119
3.1-	Steps of historic building inspections and documentation	135
3.2-	Historic building studies before restoration measurements.....	138
3.3-	Hydrostatic leveling system – measuring principle.....	144
3.4-	Building blocks of the HLS – Cross section of a HLS level sensor.....	145
3.5-	Invar wire measurements at the Church of Saint Mary at Tangerine.....	146

3.6-	Placing flat jack in masonry wall and Relation between the contact area of flat jack and the real area of realized cut.....	149
3.7-	Phases of the test for obtaining the stress level.....	149
3.8-	Phases of the flat-jack test.....	150
3.9-	Double flat jack in a regular stone.....	151
3.10-	Rectangular flat jack.....	152
3.11-	using of Georadar in the surface of deterioration walls.....	153
3.12-	Phases of the dilatometer test.....	153
3.13-	Rigid lens endoscope.....	154
3.14-	Flexoscope.....	154
3.15-	The thermovision camera.....	155
3.16-	The measurement axis of the accelerometer is aligned vertical by adjustable screws.....	156
3.17-	Diagonal shear test setup.....	157
3.18-	Auxiliary lattice steel structure for the tests: (a) general view (b) Schematic representation.....	157
3.19-	General view of the experimental set-up used to perform the tests.....	158
4.1-	Masonry wall injection techniques.....	171
4.2-	Grout injections.....	172
4.3-	Local confinement" steel anchor connector" for multi-layer walls.....	173
4.4-	Masonry walls strengthening with steel mesh inside the building.....	173
4.5-	Implementation of PP band method of retrofitting and anchorage throughout the wall.....	174
4.6-	Guns for Installation of Embedding Paste.....	175
4.7-	The application of CFRP/GFRP on historic traditional masonry wall.....	176
4.8-	The application of horizontal tie rods on masonry walls.....	178
4.9-	Utilizing of steel tie rods to absorb horizontal movement in arches.....	178
4.10-	Strengthening with Prestressed FRP: (a) prestressing (b) bonding (c) end anchorage and release and finally the stress reduction.....	179
4.11-	Strengthening with post tensioning technique.....	179
4.12-	Applying Post-Tension.....	180
4.13-	Post tension (a) Coring operations; (b) Bar post tensioning.....	180
4.14-	In plan stiffening with metallic diagonal and L shaped steel plates as connection reinforcement between walls and floor.....	181
4.15-	Strengthening with steel ties (plan view).....	186
4.16-	Maximum horizontal displacement on floors.....	187
4.17-	Strengthening using concert walls.....	188
4.18-	Tomb of Cyprus is said to be the oldest base isolated structure in the world.....	189
4.19-	Base isolation techniques.....	190
5.1-	Plaka district in Athens.....	200
5.2-	Shows historic traditional masonry building in Plaka.....	201
5.3-	Aktaiou house in Plaka district.....	202
5.4-	The Aktaiou building: façade in Aktaiou Street (left) and northern face in Lykomidon Street (right).....	203
5.5-	View of Aktaiou building house.....	204
5.6-	Building materials in Aktaiou building.....	205
5.7-	Shows ground floor rooms and decorative colors tiles.....	205
5.8-	The building wooden staircase.....	206

5.9-	Shows over painting covering original wall paintings.....	206
5.10-	Bearing masonry wall system.....	208
5.11-	Building facade – Wall 1.....	208
5.12-	plan of the main façade.....	209
5.13-	Northern face – Wall 2.....	209
5.14-	plan of Lykomidon façade.....	210
5.15-	Typical masonry structure.....	210
5.16-	Wall masonry.....	211
5.17-	Wall and window cornerstones.....	211
5.18-	Steel connector tying orthogonal walls and roof.....	211
5.19-	Partition walls.....	212
5.20-	Beams of ground level floor.....	212
5.21-	Wall recesses where the beams of ground level floor are supported.....	212
5.22-	Spacing of beams of ground level floor.....	213
5.23-	Beams of 1 st storey floor beams.....	213
5.24-	Spacing of beams of 1 st storey floor.....	213
5.25-	Central roof.....	214
5.26-	Wing roof.....	214
5.27-	Truss of central roof.....	214
5.28-	Truss of wing roof.....	214
5.29-	Steel connector.....	215
5.30-	Carpenter Connection.....	215
5.31-	Single slope truss.....	215
5.32-	Typical balcony.....	216
5.33-	Typical gallery looking in the internal open space with temporary prop.....	216
5.34-	Typical gallery in a state of collapse.....	216
5.35-	Typical lintel of internal opening.....	217
5.36-	Typical lintel of external opening.....	217
5.37-	Metal support of door lintel.....	217
5.38-	Lintel cracking (W1-in, 1 st floor) and vertical cracking at both the top (W1-ex, 1 st floor) of the building.....	220
5.39-	Wall cracking at the top of the building (W2-ex, 1 st floor).....	220
5.40-	Wall cracking (W3-in, and W3-ex of ground floor).....	221
5.41-	Vertical crack near wall connection (W6, 1 st floor).....	222
5.42-	Horizontal crack at the connection part between wall 3 and the roof in the 1 st floor.....	222
5.43-	Typical diagonal cracking of secondary wall.....	223
5.44-	Truss deviation from vertical.....	223
5.45-	Failure of truss member.....	224
5.46-	Excessive truss deflection.....	224
5.47-	Collapsed galleries.....	224
5.48-	Removal of stone D7-MS.....	226
5.49-	Drilling of core D10-LS.....	226
5.50-	Location of sampling at the ground floor.....	227
5.51-	Location of sampling at the 1 st floor.....	227
5.52-	Fragmented mortar.....	228

5.53-	XRD patterns of the three types of masonry materials (LS, MS and VS.). 1::Calcite; 2: Dolomite; 3: Quartz; 4: Muscovite; 5: Clinocllore; 6: Anorthite; 7: Alunite.....	230
5.54-	XRD patterns of limestone specimen.....	231
5.55-	XRD patterns of Marble specimen	232
5.56-	XRD patterns of volcanic stone specimen	232
5.57-	XRD pattern of mortar sample, 1: Calcite, 2: Muscovite, 3: Quartz, 4: Clinocllore.....	233
5.58-	Optical microscopy photographs of the mortar sample	234
5.59-	Stone drilling core from ground floor	234
5.60-	Core and cylindrical specimens.....	235
5.61-	Testing arrangements for (a) cubes and (b) cylinders	235
5.62-	Mean compression strength values for marble, limestone, and volcanic stone.....	237
5.63-	strain gauges test.....	238
5.64-	Typical stress-strain curves obtained from testing specimens D10 in uniaxial compression.....	238
5.65-	Typical stress-strain curves obtained from testing specimens D11 in uniaxial compression.....	239
5.66-	Typical stress-strain curves obtained from testing specimens D12 in uniaxial compression.....	239
5.67-	Cracking of the wall crowning.....	240
5.68-	Near vertical near the primary wall intersection.....	243
5.69-	Wall separation along the interface between primary and secondary walls.....	243
5.70-	Masonry cracking supported by door wooden lintel.....	244
5.71-	Masonry cracking of external wall above windows.....	245
5.72-	Detachment of non bearing walls from bearing walls at 1 st level due to lack of connection.....	245
5.73-	Isolation parts between main bearing walls and the roof.....	246
5.74-	Tensile stresses (in kN/m ²) exceeding the tensile strength of masonry developing at the wall crowning under seismic action in the direction y-y (i.e. along the building's façade in Aktaiou street).....	246
5.75-	Tensile stresses (in kN/m ²) exceeding the tensile strength of masonry developing in the region of the wall intersections under seismic action in the direction y-y (i.e. along the building's façade in Aktaiou street).....	247
5.76-	Tensile stresses (in kN/m ²) exceeding the tensile strength of masonry developing in the region of the openings of a typical internal wall in the x-x direction (i.e. parallel to the building's façade in Lykomidon Street)..	248
5.77-	Deformed shape and related tensile stresses exceeding the tensile strength of masonry (in kN/mm ²) under the combined action of the service load and seismic excitation in the x-x direction.....	249
5.78-	Process of drilling (left) and grouting (right).....	250
5.79-	Schematic representation of location of injections	253
5.80-	Steel mesh of cement paste coating	253
5.81-	Location and intensity of principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of 1 st level in the y-y direction of the building under seismic action.....	253

5.82-	Location and intensity of principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of 1 st level in the x-x direction of the building under seismic action.....	255
5.83-	Location and intensity of the principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of ground level in the y-y direction of the building under seismic action.....	256
5.84-	Location and intensity of principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of ground level in the x-x direction of the building under seismic action.....	257
5.85-	Location and intensity of principal compressive stresses (in MPa) developing in the in the x-x direction of the walls of the building under seismic action.....	257
5.86-	Location and intensity of principal compressive stresses (in MPa) developing in the in the y-y direction of the walls of the building under seismic action.....	258

List of tables

Table

2.1-	Factors influencing the seismic vulnerability of historic masonry buildings.....	85
2.2-	Conversion methods and the risks to historical traditional buildings.....	106
3.1-	The methods used in Historical, structural and architectural investigations.....	137
5.1-	Abbreviations	219
5.2-	Type of samples and location of sampling.....	226
5.3-	Petrologic description of the investigated samples composition in accordance with X-ray diffraction data.....	229
5.4-	Results of chemical analysis (% w.w) of the stones samples.....	230
5.5-	Dimensions and weight of cubic specimens.....	236
5.6-	Dimensions of and weight cylindrical specimens.....	236
5.7-	Compressive strength and specific weight of stone specimens.	237
5.8-	Empirical formulae used for assessing the masonry mechanical characteristics....	240
5.9-	Masonry mechanical characteristics.....	241

Acknowledgement

First of all, I would like to acknowledge and express the deepest gratitude and my gratefulness to my PhD supervisor professor Dr. **Michael D.Kotsovos** for his persistent and untiring advice to make me understand the way of looking into the problem and methodology of doing this bibliography research, without which it would have been practically impossible to complete the thesis timely. I also want to show him my veneration for his positive attitude in all aspects. This research was greatly improved by his expertise, and I have thoroughly enjoyed tackling these challenging problems under his mentorship. I cannot thank him enough for the opportunities he has provided me, and for truly looking out for my best interests. He has set an example which I hope to emulate in my career.

And special thanks for Dr. **Emmanuel Vougioukas** and Dr. **Efstratios Badogiannis** for their never-ending guidance and support, great contributions and their invaluable patience and kindness which I will remember with gratitude in every moment in my life. I cannot thank them enough for the opportunities they have provided me, and for truly looking out for my best interests.

My sincere thanks my deepest gratitude go to my examiner committee professor Dr. **Sowteropoulo**, Professor Dr. **Mona Fouad**, Professor Dr. **Mohamed El-Gohary** and Dr. **Georgios Pallis** for providing invaluable guidance to the work to be in its final form.

Also I thank giving to my family '*my parents, my wife, my children, my brother and my sisters*' for their endless faithful support and for their consistent mental support and advices which encourage me to overcome any difficulties that I have ever faced to pursue my goals forever. Sincere thanks to all my dear colleague and friends whom I found beside my with their kind helpful during this hard working study, many special thanks to, **Gerasimos Kotsovos, Nikos Zygoris, Kostas Chrisidis**

Finally I would like to acknowledge the financial support of **IKY** Scholarship Commission to carry on my PhD. I also deeply remember my (**NTUA**) colleagues.

Abstract

Historical traditional masonry is a form of architecture built by using local resources. It includes materials, techniques and skills of its constructors, and it is the fundamental expression of the culture of the different communities and their relation with nature and the landscape. Historic traditional masonry structures are the cultural reflections of a society; they create a strong link between the past and the present by presenting the economic, social and technical situation of the ancestors of a society.

Historic traditional masonry structures are also works of art and no matter whether they are famous monuments or so called minor or even vernacular architectures represent an important part of our cultural heritage. This patrimony which is the living memory of a country's history and development deemed to be a historic document of our past.

Traditional buildings present several structural deficiencies, such as fragility of the main walls and foundations under tensile forces, in addition to the total absence of seismic design, besides its poor capacity. It is also important to point out the contribution of the almost lack of maintenance and some poor interventions that lead to reduce building structural resistance.

From the structural risk point of view, the structural safety of historic traditional masonry seems to be very low and they may collapse under slight earthquakes without any apparent warning sign. Therefore, an appropriate use of the structural analysis could be employed in defining the eventual state of danger and in forecasting the future behavior of the structure.

The work that forms the subject (damage assessment and rehabilitation of historic traditional structures) lies on many scientific fields (civil engineering,

architecture engineering, restoration and conservation science and materials science) cooperate to identify damage cases and damage assessment to historic traditional buildings and proposed adequate intervention methods to strengthening and rehabilitation of traditional buildings to re-use it in cultural job .

The research tried to employment previous experiences and works in building restoration and conservation of historic buildings in addition to in situ survey to historic traditional masonry buildings in Athens and Cairo used all of these studies to damage assessment of historic traditional masonry houses in Athens-Greece and Cairo-Egypt which date back to 18th and 19th century. The methodology of the research has been discussed in five chapters, as follows:

1st chapter: Historic traditional masonry structures; history, development and structural elements. In this chapter we study the historical and architectural development of historic traditional masonry buildings and the development of traditional masonry residential buildings in Athens-Greece and Cairo-Egypt; attention is focused on a comparative study of the architectural components which governed the design concept of Athens and Cairo traditional house and highlighted its distinctive characteristics, building materials used for structural elements, and deterioration phenomena. Moreover, the study included the comparison of structural element joints and connection techniques.

2nd Chapter: Factors and aspects damage of historic traditional masonry. This chapter is concerned with a study of the deterioration factors and phenomena which may affect the integrity of historic traditional buildings. Such factors include earthquakes, change in uses and past conversion(s), structural (construction) defects, cracking, wall delamination, and the absence of conservation and restoration. On the

other hand the chapter discussed the deterioration mechanism to historic traditional buildings.

3rd Chapter: Structural appraisal; Registration, Documentation, and Testing methods. As for the structural appraisal of historic traditional masonry, the chapter discusses and explains the procedures adopted for structural appraisal. These procedures include registration and documentation, monitoring, testing methods and laboratory work.

4th Chapter: Rehabilitation Methods for Historic Traditional Masonry Building. In this part the work focused on studying the methods which used to improve structural behaviour of the historic traditional masonry buildings. These methods involve the strengthening of masonry walls, the improvement of the connections between walls and floors, the repair of floors, and removal of existing features from those of other historic periods. The study is concluded with a discussion on how to re-use historic traditional buildings

5thChapter: Case study. The building that forms the subject of the case study presented herein is located at the intersection of Aktaiou and Lykomidon streets and will be referred to as ‘Aktaiou’ building, thereafter. It was built in the early 19th century and it is considered to represent the structural and architectural trends prevailing in Athens this period, also it represented the structural and architectural characteristics of historic building in Egypt these buildings which located in the heart of historic Cairo (El-Kahera El-Khedeoia) and many building in Alexandria which date back to 18th, 19th and 20th century.

Aktaiou building has suffered significant deterioration phenomena. The work was divided as follows: General description of the building, history of the building,

archaeological studies, presents appraisal, deterioration phenomena and factors, present condition, damage assessment and identification of damage phenomena. The work was based on mechanical and chemical tests such as XRD, XRF, optical microscope, compression tests, strain gage measurements, study of the mechanical and physical properties and linking these properties with deterioration phenomena.

Structural analysis of the building in both its initial state and after the implementation of the proposed interventions, identification of the causes of damage based on visual observation and mapping of the deterioration phenomena., identification of the causes of damage based on numerical analysis. The identification of the causes of damage is based on the results obtained by finite element stress analysis of the building, proposed intervention methods for Aktaiou building rehabilitating, and verification of proposed intervention of Aktaiou building to resist different deterioration factors in the future

Περίληψη

Η ιστορική παραδοσιακή τοιχοποιία είναι μια μορφή αρχιτεκτονικής που αναπτύχθηκε με τη χρήση τοπικών πόρων (που περιλαμβάνουν υλικά, τεχνικές και δεξιότητες των κατασκευαστών) και αποτελεί βασική έκφραση του πολιτισμού διαφόρων κοινοτήτων και τη σχέση τους με τη φύση και το τοπίο. Οι ιστορικές παραδοσιακές κατασκευές από τοιχοποιία είναι οι πολιτιστικές αντανakλάσεις μιας κοινωνίας και δημιουργούν ένα ισχυρό δεσμό ανάμεσα στο παρελθόν και το παρόν με την παρουσίαση της οικονομικής, κοινωνικής και τεχνικής κατάστασης των προγόνων μιας κοινωνίας.

Οι ιστορικές παραδοσιακές κατασκευές από τοιχοποιία είναι επίσης έργα τέχνης και είτε είναι μεγαλοπρεπή είτε ελάσσονα μνημεία παραδοσιακής αρχιτεκτονικής αποτελούν ένα σημαντικό μέρος της πολιτιστικής μας κληρονομιάς. Αυτή η κληρονομιά, που είναι η ζωντανή μνήμη της ιστορίας και της ανάπτυξης μιας χώρας, θεωρείται ότι είναι ένα ιστορικό έγγραφο του παρελθόντος.

Τα παραδοσιακά κτίρια χαρακτηρίζονται από αρκετά ελαττώματα του φέροντος οργανισμού τους, όπως η ευθραυστότητα του σε εφελκυσμό και η παντελής απουσία αντισεισμικού σχεδιασμού. Είναι επίσης σημαντικό να επισημανθεί ότι η απουσία συντήρησης και η αναποτελεσματικότητα των επεμβάσεων οδήγησαν σε μείωση της φέρουσας ικανότητας.

Όσον αφορά τη στατική επάρκεια, οι ιστορικές κατασκευές από τοιχοποιία δεν θα μπορούσαν να χαρακτηριστούν ως ασφαλείς, δεδομένου ότι είναι υψηλός ο κίνδυνος κατάρρευσης χωρίς προειδοποίηση ακόμη και στην περίπτωση ελαφρών σεισμικών δονήσεων. Ενδεχομένως η χρήση κατάλληλων αριθμητικών μεθόδων ανάλυσης θα μπορούσε να οδηγήσει σε μια εκτίμηση της επικινδυνότητάς τους και πρόβλεψη της συμπεριφοράς τους υπό τη δράση των προβλεπόμενων από τους κανονισμούς φορτίων.

Το αντικείμενο της παρούσας εργασίας είναι η εκτίμηση των ζημιών και η αναπαλαίωση μιας ιστορικής παραδοσιακής κατασκευής από τοιχοποιία. Είναι ένα αντικείμενο κοινό σε διάφορες γνωστικές περιοχές, όπως αυτές των Πολιτικών Μηχανικών, Αρχιτεκτόνων Μηχανικών, Χημικών Μηχανικών, Ιστορικών και

Συντηρητών. Απαιτεί συνεργασίες μεταξύ επιστημόνων των παραπάνω ειδικοτήτων για τη μελέτη των ζημιών και την υιοθέτηση κατάλληλων μεθόδων παρέμβασης για την ενίσχυση και αποκατάστασή τους ώστε να είναι κατάλληλες για τη χρήση για την οποία προορίζονται.

Η παρούσα εργασία βασίστηκε στην εμπειρία του ΥΔ σε θέματα συντήρησης και αποκατάστασης ιστορικών κτιρίων και συμμετοχή σε επιτόπιες έρευνες παραδοσιακών λιθόκτιστων κτιρίων στην Αθήνα και το Κάιρο, η κατασκευή των οποίων χρονολογείται από το 18^ο μέχρι τον 19^ο αιώνα. Το εκπονηθέν έργο περιγράφεται εις τα ακόλουθα πέντε κεφάλαια:

Κεφάλαιο 1: Ιστορικές παραδοσιακές κατασκευές τοιχοποιίας: Ιστορία, Ανάπτυξη και δομικά στοιχεία

Σε αυτό το κεφάλαιο γίνεται μια ανασκόπηση της ιστορικής και αρχιτεκτονικής εξέλιξης των ιστορικών παραδοσιακών κτιρίων από φέρουσα τοιχοποιία που καταλήγει σε μια συγκριτική μελέτη των αρχιτεκτονικών στοιχείων, των κατασκευαστικών υλικών και τεχνικών δόμησης και της λογικής σχεδιασμού που χαρακτηρίζουν τις παραδοσιακές κατοικίες της Αθήνας και του Καίρου της περιόδου 18^{ου} και 19^{ου} αιώνα.

Κεφάλαιο 2: Βλάβες και αίτια βλαβών ιστορικών παραδοσιακών κατασκευών από τοιχοποιία

Αυτό το κεφάλαιο έχει ως αντικείμενο τη μελέτη των αιτίων των ζημιών και φαινομένων που ενδέχεται να επηρεάζουν τη φέρουσα ικανότητα των ιστορικών παραδοσιακών κτιρίων. Οι παράγοντες αυτοί περιλαμβάνουν νσεισμικές δονήσεις, αλλαγές χρήσης και μετατροπές, κατασκευαστικά ελαττώματα, εμφάνιση ρωγμών και αποκολλήσεις τοίχων, καθώς και την έλλειψη συντήρησης και αποκατάστασης ζημιών.

Κεφάλαιο 3: Αποτίμηση κτιρίων

Αντικείμενο του κεφαλαίου αυτού είναι η παρουσίαση των διαδικασιών αξιολόγησης της στατικής επάρκειας παραδοσιακών κατασκευών από τοιχοποιία. Η διαδικασία αυτές περιλαμβάνουν την καταγραφή της φθοράς και των ζημιών, τη

διερεύνηση των αιτίων τους και την περιγραφή των εργαστηριακών μεθόδων των οποίων γίνει χρήση για το σκοπό αυτό.

Κεφάλαιο 4: Μέθοδοι αποκατάστασης

Το κεφάλαιο αυτό επικεντρώνεται στην μελέτη των μεθόδων που χρησιμοποιούνται για τη βελτίωση της δομικής συμπεριφοράς των ιστορικών παραδοσιακών κτιρίων από φέρουσα τοιχοποιία. Αυτές οι μέθοδοι περιλαμβάνουν την ενίσχυση της τοιχοποιίας, τη βελτίωση των συνδέσεων ανάμεσα στους φέροντες τοίχους και τα δάπεδα, την επισκευή των δαπέδων και την άρση σύγχρονων χαρακτηριστικών από εκείνα άλλων ιστορικών περιόδων. Η μελέτη ολοκληρώνεται με μια συζήτηση σχετικά με το πώς να χρησιμοποιήσετε ξανά την ιστορική παραδοσιακά κτίρια

Κεφάλαιο 5: Μελέτη αποκατάστασης κτίριου

Το κεφάλαιο αυτό έχει ως αντικείμενο την παρουσίαση της μελέτης αποκατάστασης ενός τυπικού παραδοσιακού κτιρίου της Αθήνας που βρίσκεται στη διασταύρωση των οδών Ακταίου και Λυκομιδών και θα αναφέρεται ως κτίριο «Ακταίου» στη συνέχεια. Κτίστηκε στις αρχές του 19ου αιώνα και θεωρείται ότι αντιπροσωπευεί όχι μόνο τις δομικές και αρχιτεκτονικές τάσεις που επικρατούσαν στην Αθήνα αυτή την περίοδο, αλλά, επίσης, έχει δομικά και αρχιτεκτονικά χαρακτηριστικά ιστορικών κτιρίων της Αιγύπτου που βρίσκονται στην καρδιά του ιστορικού Καΐρου (Ελ -Kahera El-Khedeoia) και πολλές περιοχές της Αλεξάνδρειας και η κατασκευής τους χρονολογείται από το 18^ο έως της αρχές του 20^{ου} αιώνα.

Με την πάροδο των ετών, το κτίριο Ακταίου έχει υποστεί σημαντικές ζημιές που οφείλονται σε διάφορες αιτίες, όπως η σεισμική διέγερση, έλλειψη συντήρησης, ελαττώματα κατασκευής, κ.λπ. Η μελέτη της αποκατάστασης περιλαμβάνει τα ακόλουθα: Γενική περιγραφή του κτιρίου και του φέροντος οργανισμού του, την καταγραφή των ζημιών και τη διερεύνηση των αιτίων τους, την περιγραφή των μεθόδων διερεύνησης των ζημιών (που περιλαμβάνουν εργαστηριακές μεθόδους προσδιορισμού των φυσικών, χημικών και μηχανικών ιδιοτήτων των υλικών κατασκευής και αριθμητικές μεθόδους ανάλυσης του κτιρίου τόσο στην αρχική του κατάσταση, όσο και μετά την εφαρμογή των προτεινόμενων μέτρων αποκατάστασης).

Ο προσδιορισμός των αιτίων βλάβης βασίστηκε σε οπτικές παρατηρήσεις και εργαστηριακές μεθόδους, ενώ για την επαλήθευσή τους έχει χρήση των αριθμητικών μεθόδων, μέσω των οποίων διερευνήθηκε και η αποτελεσματικότητα των προτεινόμενων μεθόδων αποκατάστασης.

ملخص الرسالة

تعتبر المباني الأثرية التقليدية الأنعكاس الثقافي والمعماري والحضارى لأى مجتمع من المجتمعات فى فترة تاريخية معينة فهى تخلق رابط قوى ما بين الماضى والحاضر من خلال عرض للوضع الاجتماعى والأقتصادى لهذه المجتمعات داخل عناصرها المعمارية المختلفة. وتعتبر المباني التاريخية التقليدية هى عمل فنى سواء كانت هذه المباني شاهقة ذات مساحة كبيرة او مجرد مبنى صغير الحجم فكلها متساوية من الناحية او الوجة التاريخية والمعمارية لانها تمثل جزء من الموروث المعماري و الثقافى. وتعتبر المباني الأثرية التقليدية مباني فريدة من نوعها ولا تقدر بثمن وذلك لكونها تعتبر الذاكرة الحيه والمرئية لتاريخ بلد ما فى فترة ما كما أنها تعكس مدى التقدم الحضارى لهذا البلد والذى ينعكس على مدى التقدم المعماري فى هذه المنشآت.

تتعرض المباني الأثرية التقليدية للعديد من مظاهر التلف نتيجة تعرضها لعوامل تلف مختلفة لذا فهى تحتاج إلى تأهيل اكثر من غيرها من المباني الأخرى وذلك نتيجة اندماجها داخل النسيج الحضري للعديد من المدن القديمة والحديثة فى كثير من الأقطار ذات التاريخ الحضارى والمعماري على مر العصور. فالمباني الأثرية التقليدية تبدي العديد من مظاهر التلف المعماري فعلى سبيل المثال لا الحصر ضعف او عدم قدرة الجدران والأساسات على مقاومة قوى الشد الواقعة على هذه الجدران ، عدم وجود أنظمة مقاومة الحركات الزلزالية داخل هذه المباني ، هذا الى جانب عوامل التلف المختلفة مع عدم قدرة هذه المباني على مقاومتها أضف الى ذلك عدم وجود الصيانه الدوريه واعمال الترميم الخاطئه التى قد تتعرض لها هذه المباني نتيجة إجراء عمليات الترميم التى لا تستند الى الدراسات الوافيه حول الأثر وعوامل ومظاهر التلف المحيطه به .

إن منهجية ترميم وتأهيل المباني الأثرية تقوم على أتباع بعض الأسس والقواعد والنظريات التى تنظم هذه العمليه حتى يتم تأهيل المباني الأثرية بطريقة علمية ممنهجه وعليه وبناء على هذه الأسس والنظريات فإن موضوع العمل الذى تقوم عليه الرساله " تقييم التلف داخل المباني الأثرية التقليدية وطرق التأهيل Damage Assessment and Rehabilitation of Historic Traditional Masonry" يقع فى خمسة خطوات أو فصول رئيسيه وهى :

الفصل الأول: دراسة التطور التاريخي والمعماري للمباني الأثرية التقليدية Historic traditional masonry

ومعماريه " دراسة نظريه وموقعيه Literature and in-situ study" للتطور التاريخي والمعماري للمباني الأثرية التقليدية فى مدينة أثينا باليونان ومدينة القاهره التاريخيه " القاهره الإسلاميه-Islamic Cairo" فى مصر مع عمل دراسة مقارنة بين هذه المباني فى العصور المختلفه. وقد تركزت الدراسة فى هذا الفصل على دراسة التطور المعماري لمواد البناء المستخدمه فى هذه المباني إلى جانب تطور الشكل والمساحه المعماريه والشكل الداخلى والخارجى للمنزل التقليدى فى اثينا والقاهره. كما تم دراسة طرق ربط العناصر المعماريه والأنشائيه لهذه المباني و التى أستخدمت لربط العناصر المعماريه بعضها ببعض.

الفصل الثانى: دراسة عوامل ومظاهر التلف داخل المباني الأثرية التقليدية Factors and aspects damage

of historic traditional masonry : وقد تركزت الدراسة فى هذا الفصل على دراسة عوامل ومظاهر التلف

المعماري التي تتعرض لها المباني الأثرية التقليدية والتي قد تؤثر على الثبات المعماري والأنشائي لهذه المباني ، مثل هذه العوامل تشمل الحركات الأرضية (الزلازل earthquakes) ، تغيير الوظيفة والنظام الأنشائي للمبنى Structural change in uses and past conversion(s) ، العيوب الأنشائية والمعمارية ، "Construction" defects ، الشروخ والأنفصالات Cracking ، تفسخ الجدران (الجدران المزدوجة Neglect Wall delamination (Double walls ، الأهمال وغياب الصيانة الدورية للمباني الأثرية التقليدية Neglect or absence of "conservation and restoration"

الفصل الثالث: الطرق العلمية للتقييم الأنشائي والمعماري " التسجيل، التوثيق، طرق الأختبار " Structural "Registration, Documentation, and Testing methods". وتركزت الدراسة في هذا الفصل على دراسة الطرق العلمية الحديثة التي تستخدم في تقييم العناصر المعمارية والأنشائية للمباني الأثرية التقليدية ومعرفة اسباب وميكانيكية التلف داخل هذه العناصر المعمارية تلك الطرق والأجراءات التي تشتمل على التسجيل Registration ، التوثيق Documentation ، المراقبة Monitoring ، طرق الأختبار والتحليل المعملية Testing methods and Laboratory work .

الفصل الرابع: طرق ترميم وتأهيل المباني الأثرية التقليدية Historic Traditional Masonry Building Rehabilitation Methods تم دراسة ومناقشة الطرق العلمية التي تستخدم لتحسين وتقوية التصرف الأنشائي للمباني الأثرية التقليدية حتى تتمكن من مقاومة عوامل التلف المعماري التي قد تتعرض لها وهذه الطرق تشمل :

- طرق تقوية الجدران The strengthening of masonry walls methods,
- طرق تحسين او تقوية الربط بين العناصر المعمارية (بين الجدران بعضها البعض وبين الجدران والأرضيات الخشبية والأسقف) The improvement of the connections between walls and floors,
- طرق علاج الأرضيات الخشبية The repair of wooden floors
- إزالة التعديلات والأضافات من العصور المختلفة Removal of existing features from those of other historic periods.
- دراسة أسس وقواعد إعادة استخدام المباني الأثرية التقليدية Discussion on how to re-use historic traditional buildings.

الفصل الخامس : الدرسة التطبيقية Case study قامت الدراسة التطبيقية لتقييم التلف وتأهيل المباني الأثرية التقليدية على أختيار مبنى أثرى تقليدي يشترك في التفاصيل المعمارية والخواص الأنشائية ويشبه في تكوينه المعماري كلا من المباني الأثرية التقليدية اليونانية والمباني الأثرية التقليدية المصرية في الفترة من نهاية القرن الثامن عشر وبداية القرن التاسع عشر الميلادي فقد قمنا كما سبق الشرح في الفصل الأول بدراسة مقارنه بين المباني الأثرية التقليدية اليونانية في مدينة أثينا باليونان ومدينة القاهره التاريخية وكذلك المنازل التقليدية بمدينة الإسكندرية القديمه بجمهورية مصر العربيه وقد وقع الأختيار على أن يكون مبنى أكتيو

AKTAIOU building ليكون المثال التطبيقي حيث أن المبنى يشترك في خواصه المعمارية كلاً من المنزل اليوناني والقاهري في هذه الفترة (القرنين الثامن والتاسع عشر الميلادى).

يعانى مبنى AKTAIOU building من العديد من مظاهر التلف المعماري التي أثرت على ثباته الأنشائي ومن هذه المظاهر الشروخ العميقة بجميع أنواعها سواء كانت شروخ أفقيه أو رأسيه أو مائله نتيجة تأثير الزلازل ، كما يعانى المبنى من انهيارات فى بعض عناصره المعمارية ، هذا الى جانب نزيف المونه Mortar bleeding.....الخ.

وقد تركزت الدراسة حول ترميم وتأهيل المبنى على عدة محاور رئيسيه تتفرع منها خطوات أخرى هذه المحاور او الأعمال هي: وصف عام للمبنى – دراسه تاريخية ومعمارية للمبنى – توثيق ورفع معمارى للحاله الراهنه للمبنى – دراسة عوامل ومظاهر وميكانيكية التلف بالمبنى – دراسة الحالة الراهنة للمبنى- تقييم التلف المعماري للمبنى – دراسة مظاهر التلف المعماري بالمبنى دراسه موقعية ومعملية وبالأضافة إلى الطرق الرقمية Finite Element Method- ثم عمل دراسه لترميم المبنى ودراسة التصرف الأنشائي للمبنى بعد الترميم لمعرفة مدى قدرة المبنى على مقاومة عوامل التلف بعد إجراء عملية الترميم له.

وقد اعتمد العمل داخل المبنى على عمل أختبارات ميكانيكيه وكيميائيه Mechanical and Chemical tests لدراسة الخواص الكيميائية والميكانيكية لمواد البناء المستخدمه فى تشييد المبنى (الرخام- الحجر الجبرى- الحجر البركاني ومونة البوزولانا مع الجير والطين) وذلك بأستخدام طريقتى تفلور الأشعه السينية وتفلور الأشعه السينية XRD, XRF ، كذلك الأستعانة بطريقتى الميكروسكوب الضوئى Optical Microscope للتعرف على تركيب وخواص المونه المستخدمه فى المبنى . كما تم عمل أختبارات الضغط Compression Tests لعينات من مواد البناء (عينات مكعبه وأسطوانية الشكل) وكذلك أختبار جهاز تعيين الأجهاد Strain Gages Measurements لتعيين الأجهادات فى الأتجاهيين الرأسى والأفقى للأحجار المستخدمه فى تشييد المبنى.

بعد ذلك تم عمل تحليل أنشائي للمبنى على حالته الراهنة وكذلك عمل تحليل أنشائي للمبنى بعد إجراء عمليات الترميم والتأهيل المختلفه لمعرفة مدى نجاح عمليات الترميم فى تقوية العناصر المعماريه والثبات الأنشائي للمبنى حتى يتم إعادة أستخدامه فى وظيفة جديدة تناسب حالة المبنى؛ كما تم دراسة عوامل ومظاهر التلف المختلفه للمبنى عن طريق الدراسه الموقعيه وتحليل عوامل ومظاهر التلف ثم عمل خريطه معمارية لتوقيع مظاهر التلف على العناصر المعمارية المختلفه ، ثم التعرف على عوامل وميكانيكية التلف عن طريق أستخدام الطرق الرقمية الحديثه وذلك بأستخدام طريقه Finite Element Method (FEM) كما أستخدمت الطريقه نفسها كما سبق الذكر فى تقييم أعمال الترميم التى أقترح لتأهيل المبنى ومدى قدرة المبنى بعد عمليات الترميم على مقاومة الأحمال وعوامل التلف التى قد يتعرض لها سواء من الظروف البيئيه المحيطة او من استخدام المبنى فى وظيفه جديده.

Keywords:

Building materials, documentation, cracking, damage, deterioration phenomena, documentation, structural assessment, structural system, historic traditional masonry building, structural analysis, finite element method, registrations, rehabilitation, re-use.

INTRODUCTION

PhD Text Structure

The methodology adopted is comprised of four main phases:

- **Documentation:** A detailed documentation of the aspects of the historic traditional masonry structures which include the history and the structural development of historic traditional masonry houses in Athens-Greece and Cairo-Egypt in 18th -20th century , architectural documentation, building materials and structural elements. It considers factors and aspects damage phenomena of historic traditional masonry such as earthquakes, change in uses and past conversion(s), structural "construction" defects, cracking, wall delamination, neglect or absence of “conservation”. The documentation phase is very important to understand the building and its behavior.
- **Diagnoses:** by understanding the data collected in the first phase, comprehensive diagnoses is obtained to define and stand up in the main problems attacking the traditional structures on the level of architecture, structure, building materials, and the use of the buildings.
- **Remedy:** this phase includes all the treatment and restoration applications that are used to; prevent the deterioration phenomena or factors attacking the historic traditional structures, guarantee the safety needed to use them, respect for authenticity in all genre (design, materials, workmanship, etc.). Apply the principle of minimal intervention, apply the principle of recognizable intervention, and ensuring reversibility. The compatibility and retreatability should be the main criteria of any intervention applied to the historic buildings and finally planning for adaptive re-use.
- **Case study:** structure chosen was the Aktaiou building, which is a masonry building, located in the historic district of Athens, PLAKA near to Acropolis. It

included damage assessment methods, damage identification, structural assessment of bearing and architectural elements of Aktaiou building, followed by proposed interventions for strengthening and rehabilitation. Exploring recent technologies that are applied in the field of historic building rehabilitation in order to understand it and adopt them to the case study to have the resistance to resist the deteriorations factors and be able to re-use.

List of publications

1- Journals

- 1.1- Abdelmegeed M., Badogiannis E., Kotsovos G., Vougioukas E., "Assessment of physical and mechanical properties of historical and traditional masonry buildings: a case study" International Journal of conservation science (IJCS), Volume 5, Issue 3, July-September 2014.
- 1.2- Abdelmegeed M., Badogiannis E., Kotsovos G., Vougioukas E., "Structural damage assessment of historic traditional masonry buildings: a case study" International Journal of conservation science (IJCS), Volume 6, Issue 2, April-June 2015.

2-Conferences

- 2.1- Abdelmegeed M., Badogiannis E., Vougioukas E., and Kotsovos M. D. "Structural assessment and rehabilitation of an historic traditional masonry building in Athens" 6th International Congress on "Science and Technology for the Safeguard of Cultural Heritage in the Mediterranean Basin" Athens, Greece 22 – 25 October 2013.
- 2.2- Abdelmegeed M., Badogiannis E., Vougioukas E., and Kotsovos M. D. " Historic traditional masonry structures: Historical review, structural investigation and damage assessment" First international conference – Recent Trends in Archaeological Sciences – faculty of Archaeology, Fayoum University, Fayoum, Egypt, 9-11 April 2014.

Importance of Historic Traditional Masonry and Ethics of Rehabilitation

Imbued with a message from the past, the historic monuments of generations of people remain to the present day as living witnesses of their age-old traditions. It has become customary to classify as traditional buildings all buildings constructed without a formal design process. Their form, plan and method of construction simply follow a tradition developed with time at the place of their construction. Masonry is a non-homogeneous material comprising blocks, natural (stones) or manufactured (bricks), and a series of mortar joints arranged either irregularly (in stone masonry) or regularly (in brickwork).

The main distinction between historic and contemporary buildings results from the fact that labour was comparatively cheap in the past and the transportation of materials difficult and expensive when compared with current costs. Past building practices are now regarded as craftsmanship, and this difference between traditional and modern construction practice increases the value of our historic buildings, as the latter are part of our cultural heritage, and, thus an irreplaceable resource. All historic buildings, large or small, complex or simple, make a contribution to the quality of our life by informing us of our past, the lives and achievements of our predecessors.

In Athens-Greece and Cairo-Egypt, the cities' historical centers are mainly dominated by historic traditional masonry buildings, built with stone masonry walls, frequently constituted by multiple leaves having little or no connection between them, and built with various materials, and poor mortars. The common typology encountered is the double bearing walls or three-leaf masonry walls supporting timber beams and trusses. Masonry construction is the typology that presents more problems and is more in need of rehabilitation. This kind of construction presents several structural deficiencies, such as fragility of the main walls and foundations under tensile forces, in addition to the total absence of seismic design, besides its poor capacity. It is also

important to point out the contribution of the almost lack of maintenance and some interventions of poor quality to the reduction of the building's structural resistance

Most of the historic traditional buildings are works of art and the signs of true genius can be found in the innovative designs of historic buildings. For this reason, the conservation and restoration (rehabilitation) of historic monuments are different from the processes applied on ordinary buildings. Since they are unique and priceless, rehabilitation of historic monuments require a good cooperation of engineering, architecture and the science of history.

In the last decade the word (restoration) has more and more been substituted by the term (preservation). Also in the case of damage due to earthquake or other calamities the expression (adequate) was substituted by the expression (improve) by minor repair and strengthening. Rehabilitation of traditional building can be successfully accomplished only if a diagnosis of the state of damage of the building has been formulated. The history of the structure and its surroundings should be well examined. Inspection should be carried out on the construction methods, construction materials and the functions of the structure. These all constitute the very important step, which could be named "understanding the Building".

The diagnosis should result from an experimental investigation on site and in the laboratory. On the other hand the effectiveness of the repair techniques should also be controlled during and after the repair work, as well. The investigation may also require long-term monitoring of the structure.

The main objective of the restoration and conservation of historic buildings is to maintain the character of the building as much as possible. Repair is the keyword in restoration of historic structures, which principally means that replacement of

deteriorated architectural features should be avoided as much as possible. If replacement is urgent, similar materials, preferably identical, to the original one should be used. Each property should be recognized as a physical record of its time, place and use; thus, changes that create a false sense of historical development must be avoided. All of these methods should retain and preserve the historical character of the building. It is very important to conserve the original concept in order to enlighten the past correctly and carry it to the future with its original characteristics

1

Historic Traditional Masonry Structures: History, Development and Structural elements

- 1.1- Masonry as a Construction Technique through History
- 1.2- Historic Traditional masonry
- 1.3- Historic Traditional Masonry Structures developing through time
- 1.4- Historic Traditional Masonry Structures in Athens-Greece
- 1.5- Historic Traditional Masonry houses in Athens-Greece
- 1.6- Structural element joints and connection techniques
- 1.7- Historic Traditional Masonry in Cairo-Egypt
- 1.8- Historic Traditional Masonry houses in Cairo-Egypt
- 1.9- Structural Elements and Building Materials.

1.1- Masonry as a Construction Technique through History

Masonry is a non-homogeneous material with two constitutive elements: blocks and mortar. Thus, we can consider masonry as a combination of two material phases comprising blocks in natural or manufactured shape and a series of mortar joints arranged irregularly (as in stone masonry) or regularly (as in brickwork) (Lopez et al 1998). In masonry structures, mortar forms layers between blocks and permits a uniform transmission of the internal forces. It is important to know that the mechanical properties of masonry do not depend exclusively on the mechanical properties of the constitutive materials, or the arrangement of the blocks in masonry structures (Pena 2004).

So, it can be said that masonry is a heterogeneous material that consists of units and mortar. Units such as bricks, blocks, ashlar, adobes, irregular stones etc, and mortar can be clay, bitumen, chalk, lime/cement based paste. The huge number of possible combinations generated by the geometry, nature and arrangement of units, as well as the characteristics of mortars raises doubts about the term masonry (Lourenço 1998).

Masonry is the oldest building material still found in today's buildings. The most important characteristic of masonry construction is its simplicity. Laying pieces of stone, bricks or blocks on top of each other, either with or without cohesion via mortar, is a simple, though adequate, technique that has been successfully used ever since remote ages. Naturally, innumerable variations of masonry materials, techniques and applications occurred during the course of time. The influence factors were mainly the local culture and wealth, the knowledge of materials and tools, the availability of material and architectural reasons (Lourenço 1998). The use of blocks and mortar combined a construction technique is called masonry construction

technique, while the use of undressed rough stone without a pattern is called rubble masonry construction technique and generally used for the construction of walls. Smooth square or rectangular stones are used in the ashlar masonry construction techniques, coursed ashlar masonry technique requires stones of the same height within each course, but each course can vary in height as shown in Fig. 1.1.

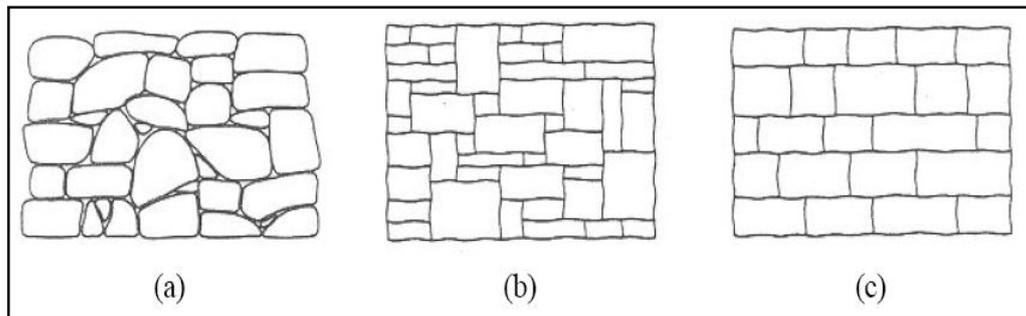


Figure 1.1: Different kinds of stone masonry: a) Rubble masonry b) Ashlar masonry, c) Coursed ashlar masonry (Lourenço 1998)

Most probably, the first masonry material was natural stone, and regular shaped stone substituted natural stone as tools and construction techniques developed. The first bricks were made from mud or clay dried by the sun; these bricks were then laid with mud or lime into walls. In the valleys of the Nile and the Mesopotamia, this process has been used to construct dwellings (Ozen 2006).

As for the evolution of the form, Greek Architecture was based on rules of proportion and symmetry. Limestone was used as the construction material. The Parthenon (5th Century BC) is one of the most famous examples of this era as shown in Fig. 1.2a. The Romans constructed not only temples, but also roads, bridges, aqueducts and introduced many innovations related to materials and structural concepts, as the quality of the bricks improved and the size of the bricks became more standardized. Fig. 1.2b shows some general types of Roman masonry walls. In the course of time, the structural shape evolved from linear to curved or arched forms that enabled to span larger distances.

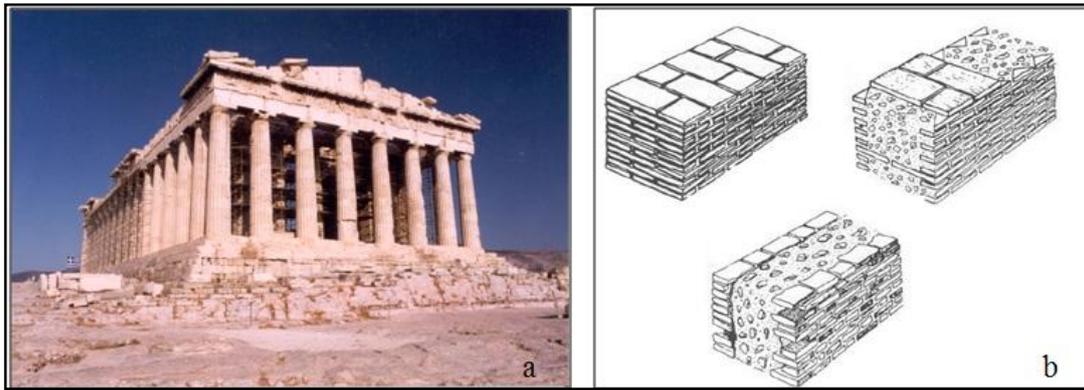


Figure 1.2: a) view of Parthenon. b) Roman masonry walls.

1.2- Historic Traditional masonry

It has become widely accepted to classify any buildings put up without a formal design process as traditional masonry. Their form, plan and method of construction simply follow tradition and the time and place of their conception. This principle is not confined to dwellings; it caters for churches, mills, barns, byres and other building uses as well.

Traditional principles have evolved over a long period of time in virtually all countries of the world. People have developed building techniques excellently adapted to the building materials available and local conditions such as climate, topography, etc. Autochthonous building is a similar principle used by “simple people” (without a specific education in building) adapting their houses to the immediate natural environment and employing locally available materials in an economically sound and resource-efficient manner, vernacular building, can be defined as a building culture adapted to the existing environment and available resources, producing houses with the help of traditional techniques which have a certain purpose and represent values, economic conditions, and the lifestyle of the builders. Adapting to local conditions and location requirements as, topography, climate, other environmental conditions, and social aspects, traditional building offers a number of advantages as well as disadvantages. The advantages include the

utilization of natural building materials, relatively low energy content of building material, excellent energy-efficiency during the phase of use, natural thermal insulation(cold and heat) through appropriate orientation of the building, utilization of thermal masses, integration of shading elements, utilization of the cooling effects of water expanses, compactness of buildings, bright colors of facades, intelligent inner structure, regional building materials, relatively high share of handwork positively affecting the local labour market, generally user-friendly and easy-to-use materials, avoidance of damage to historic buildings by using existing technologies and materials, adaptation to most adverse conditions, and value enhancement of the building (Dirlich 2004).

Traditional ways of building have evolved, one person learning from another. Changing circumstances have led to changing solutions and along the influences line from other cultures have gradually been blended in. At any given point in time, there have been shared values, shared customs, local materials and local ways to use them and the learning process has always been to build on the past (Oram and Stelfox 2004).

Finally, historic traditional buildings do not just carry their cultural significance as relics by image alone. As understanding the architectural style and decorative form of historic structures is important, the cultural meaning of many of the most significant buildings is resident within the reality of the artefact itself. A historic structure is important because it is exactly that – it is old, and thus has been a part of human lives. As the English critic John Ruskin (1901) eloquently stated: *Indeed the greatest glory of a building is not in its stones, or in its gold. Its glory is in its Age, and in that deep sense of voicefulness, of stern watching, of mysterious sympathy, nay, even of approval or condemnation, which we feel in walls that have*

long been washed by the passing waves of humanity (Randolph 2004). Buildings and structures may be classified as historic for three main reasons: They are associated with acts of historical importance, they are old and a long time has passed since their construction, and they are monumental and irreplaceable (Gülkan and Wasti 2009).

1.3- Historic Traditional Masonry Structures developing through time

Historic traditional buildings are constructed from old materials that are rarely used in the majority of buildings constructed today. The main distinction between historic buildings and new-build is stems from the fact that labour was comparatively cheap in the past and the transportation of materials difficult and expensive in comparison to today. Much of the practice of building in the past is now regarded as craftsmanship; this difference between traditional and modern construction practice puts a value on all our historic buildings in terms of our cultural heritage, and as an irreplaceable resource. All historic buildings, large or small, complex or simple, make a contribution to our quality of life by informing us of our past. Also they have historic interest because they reflect the lives and achievements of our predecessors (Urquhart 2007).

Historical traditional masonry is a form of architecture built by using local resources, it covers materials, techniques and the skills of its constructors, and it is the fundamental expression of the culture of the different communities and their relation with nature and the landscape (Casanovas 2007).

Stone traditional masonry has been used in building construction since ancient times since stone is durable and locally available. There are huge numbers of historic stone buildings in any country, ranging from rural houses to royal palaces and temples. In a typical rural stone house, there are thick stone masonry walls built using

rounded stones with mud/lime mortar. These walls are constructed with stones placed in a random manner, and hence do not have the usual layers (or courses) seen in brick walls. These un-coursed walls have two exterior vertical layers (called Wythes) of large stones, filled in between with loose stone rubble and mud mortar. In many cases, these walls support heavy roofs (for example, timber roof with thick Aramid overlay) (Lourenço 2002).

Stone masonry is a traditional form of construction that has been practiced for centuries in regions where stone is locally available. Stone masonry has been used for the construction of some of the most important monuments and structures around the world. Buildings of this type range from cultural and historical landmarks, often built by highly skilled stonemasons, to simple dwellings built by their owners. Stone masonry buildings can be found in many earthquake-prone regions and countries including Mediterranean Europe, North Africa, the Middle East, and Southeast Asia (Bothara and Brzev 2011).

Although in the 20th century masonry was displaced for many applications by steel and concrete, it remains of great importance for load bearing walls in low and medium rise buildings and for internal walls and cladding of buildings where the structural function is met by one of these newer materials. The market for masonry construction may be divided into housing and non-housing sectors (Emeritus1996). The latter is including industrial, commercial and educational buildings, in addition to a wide variety of buildings used for administrative and recreational purposes (Thomas 1996).

1.3.1- Historic Traditional houses'' History and Development''

It is about ten thousand years ago, with the earliest civilization, that the history of architecture really begins and simultaneously masonry arises as a building technique. The primitive savage efforts of mankind to secure protection against the elements and from attack included seeking shelter in rock caves, learning how to build tents of bark, skins, brushwood and huts of wattle-and-daub. Some of such types crystallized into houses of stone, clay or timber. The first masonry material to be used was probably stone. In the ancient Near East, evolution of housing was from huts, to beehive houses (as shown in Fig. 1.3a), and finally to rectangular houses (as shown in Fig. 1.3b) (Lourenço1998).

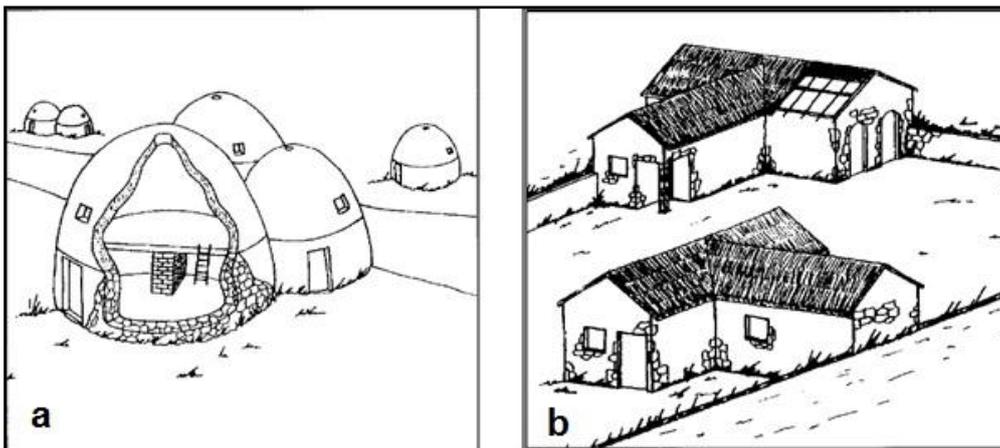


Figure 1.3- a) beehive houses from a village in Cyprus, b) rectangular dwellings from a village in Iraq (Lourenço 1998).

Historic traditional masonry houses are found in urban and rural areas around the world. There are broad variations in construction materials and technology, shape, and the number of stories. Houses in rural areas are generally smaller in size and have smaller sized openings, on the contrary, houses in urban areas are often of mixed use - with a commercial ground floor and a residential area above. In hilly Mediterranean areas the number of stories varies from two (in rural areas) to five (in urban centers). These buildings have often experienced several interior and exterior repairs and

renovations over the course of their lives. Typically, stone masonry houses are built by owners themselves or by local builders without any formal training. The quality of construction in urban areas is generally superior to that found in rural areas. In some cases, a dual gravity load-bearing system is used (see Fig. 1.4).

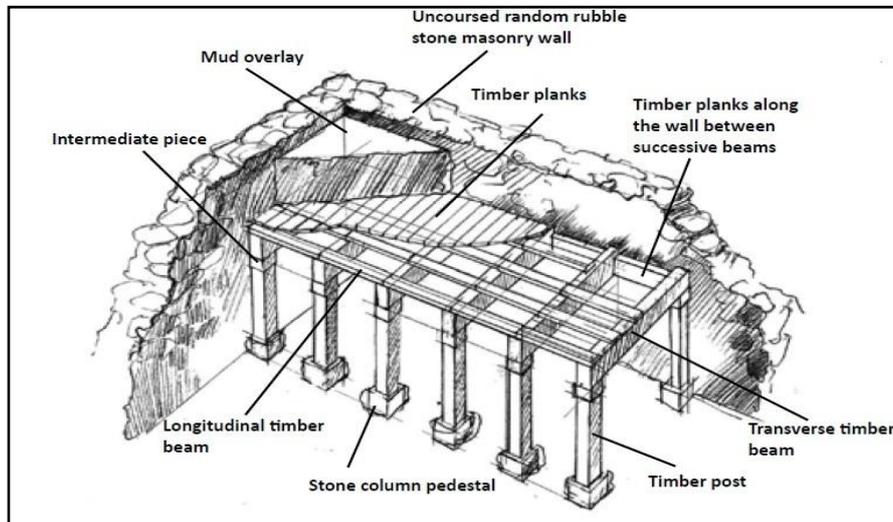


Figure 1.4: typical stone masonry building with exterior stone masonry walls and an interior timber frame (Bothara and Brzev 2011).

This system consists of a timber roof structure supported by timber columns and beams, and stone masonry walls at the exterior. In this case, the walls may not provide support to the floor/roof structure. It performed poorly in past earthquakes due to the absence of wall-to-roof connections and walls collapsing outward (Bothara and Brzev 2011).

So it can be said that the architectural typology is based on the repetition of a basic rectangular housing unit with flat roofing. As shown in Fig. 1.5, the basic unit can be used to form a long single room house (called ‘makrynari’) or it can be used to form a twin room house with a vaulted wall separating the two rooms and subsequently supporting the roof.

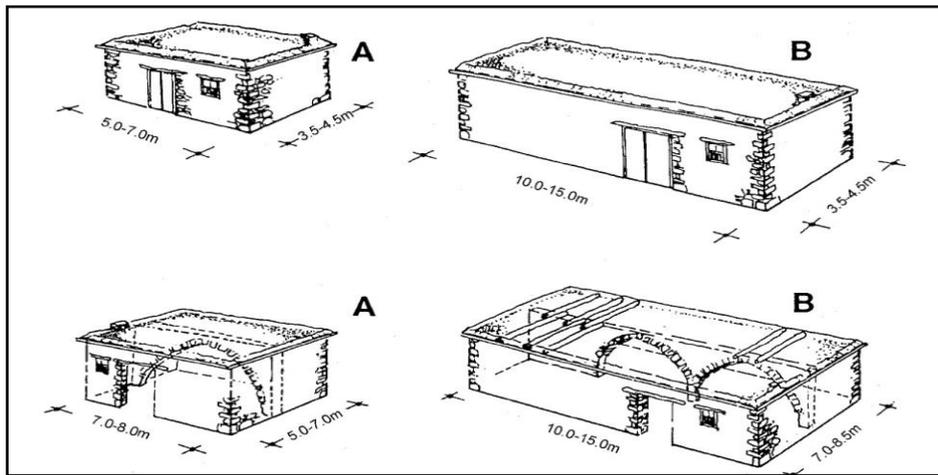


Figure 1.5: Types of traditional houses of Cyprus and Athens. Upper row: Single room houses. Lower row: Twin room houses with vaulted partitions (Bothera and Brzev 2011).

This type of the elongated structures presented in the upper row of Fig. 1.5 is a model of a structure in the village, and it is a typical example of a housing unit with a vaulted separating wall, like the one presented in the lower row of Fig. 1.5. Afterwards, the process of housing was development to the next step in the form of simple two stories house, as the building shown in Fig. 1.6, which deemed a typical example of a developed single-room house.

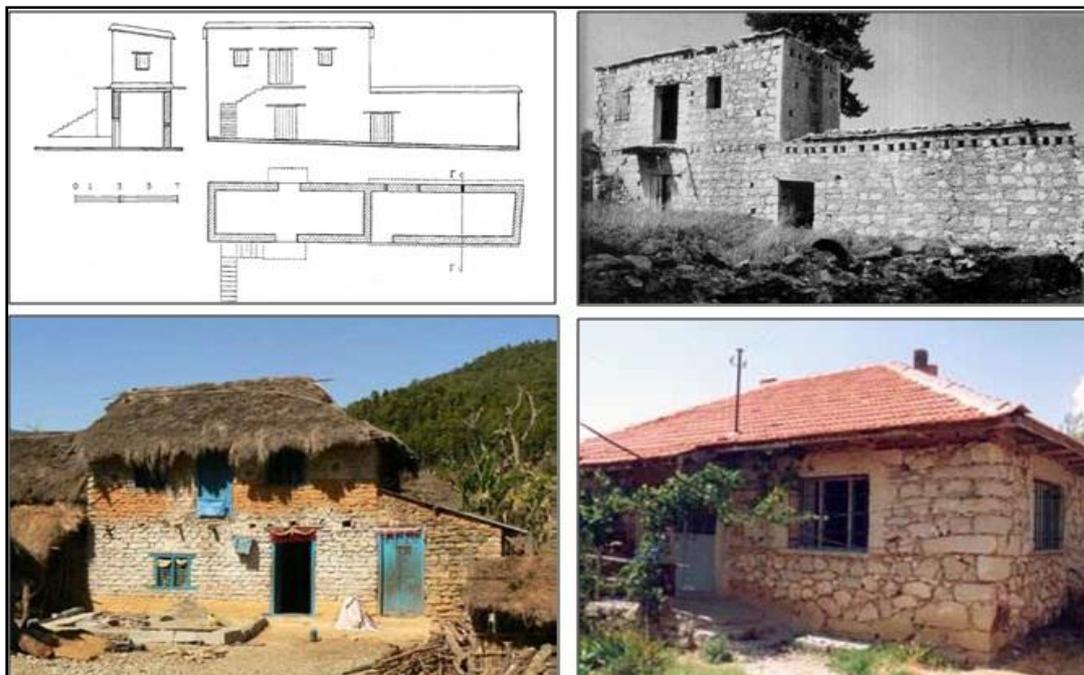


Figure 1.6 typical rural houses (Alexandris et al. 2004).

The ground floor consists of two elongated rooms with dimensions 4×10 m, and the first floor consists of a single room, which covers only half of the ground floor area. The house was built by medium strength stone masonry, with sandstone and lime-sand mortar. The roof is almost flat and was originally supported by wooden beams, spanning the short dimension of the structure, and it was covered by earth to provide insulation (Alexandris et al. 2004).

Then the process of the development began to accelerate, especially in urban areas rather than rural areas. There are broad variations in construction materials and technology, shape, and the number of stories, as shown in Fig. 1.7.



Figure 1.7 Historic traditional houses in historic cities "Greece, Italy and Egypt"

1.4- Historic Traditional Masonry Structures in Athens-Greece

Traditional Urban Residential Masonry (TURM) buildings in Greece are usually made of rubble (cobble) natural stones and a large volume of low strength lime mortars, while their floors/roofs are made of timber elements. Their load-bearing walls are of the single-leaf type (with various degrees of bonding and block interlocking) or of the so-called three-leaf type (with two discrete external leafs and an infill “material” of a large voids ratio), with thicknesses less or more than approx. 700 mm, respectively. Therefore, the basic structural elements are made of a particularly “undisciplined” material, to be finally handled or formed as a “pseudo-continuum” medium (Saatcioglu and Anderson 2004).

As general rule, when we look to the historic traditional buildings here in Athens, we will find that the level of development of the structural system depends on the use of each individual building, while the size of buildings varies depending on their use (church, palace or residential house). Thus, there are buildings with plan dimensions varying from some meters to some tenths of meters.

The survey of the historic traditional constructions in the different regions of the country shows that there are significant variations in construction methods, materials and structural elements connections. In general, the historic traditional houses in Athens have slightly square or rectangular in-plan geometry, with two or three floors at most, as shown in Fig. 1.8 and Fig.1.9. As these buildings are traditionally built by local building materials, it is usual that the first floor has high elevation; the second floor height is smaller than the first one and the third floor, if found, has the smallest height, the high elevation being intended for ventilation purposes as shown in Fig. 1.10.



Figure 1.8 Historic traditional houses: two and three floor house with different elevations of first, second and third floor

The house in 12th century has a large area with an intervening triple arcade, a "tribelon" that invested a large living-room with certain grandeur. Another oblong room, with an arch springing from columns that supported a wall of the upper storey, was found in the 12th-century house (Fig. 1.9).

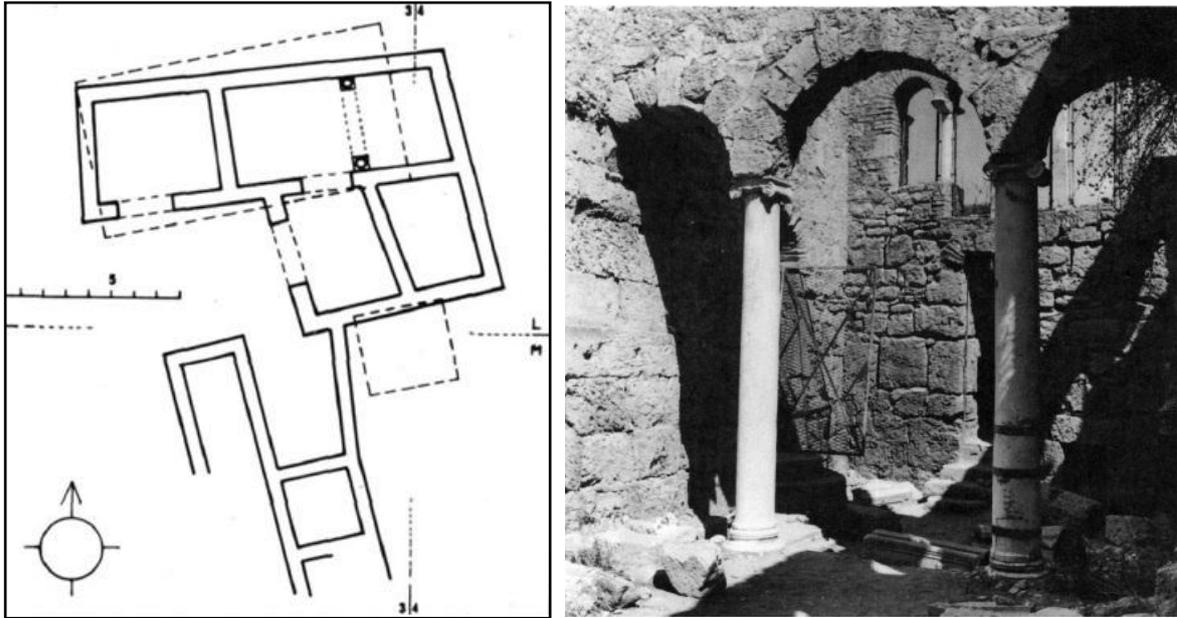


Figure 1.9 Corinth. Schematic plan of a byzantine house in the Agora area

Historic traditional masonry buildings in Athens in the 17th century and 18th century are mainly constructed from rubble and ashlar masonry stones which may have polished, drowed or broached finish because these ashlar were the cheapest local building materials available for building masonry walls, this is in addition to the stones having a significant impact on the ability of the wall to react to changes in moisture content.

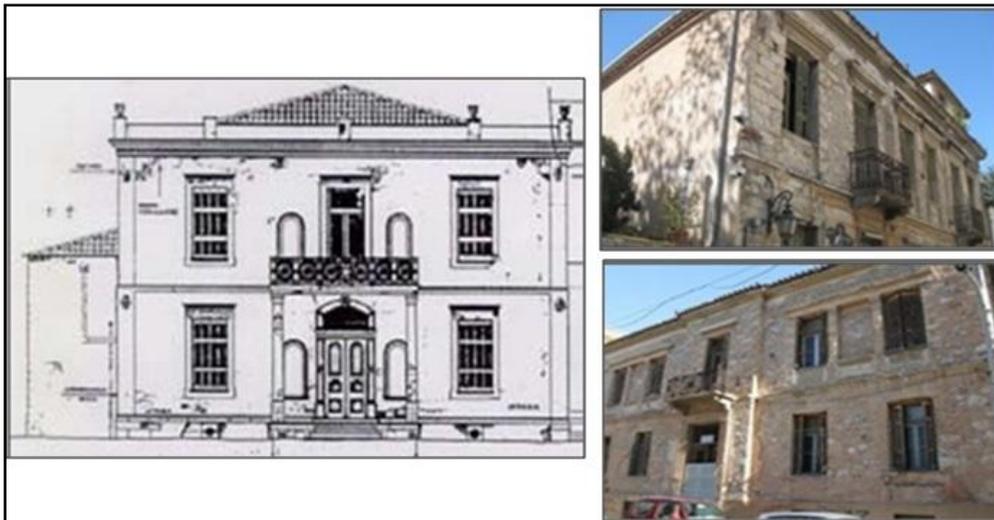


Figure 1.10 Historic traditional masonry buildings in PLAKA- Athens

Also, these dwellings have many features relevant to environmental influence:

- Wide tiles, being firmed up to a thick layer of clay, sealed the roof from both heat and cold. Moreover, thick planking of 0.04 m. prevented heat or cold from penetrating the roof.
- Each floor was particularly high, approximately 3.0 m., whereas the windows were of small dimensions. This ratio permitted the cooling of the house: warm air rose to the ceiling away from human level, as cooler air kept coming in from the windows.
- The floor was uplifted well enough, in order to create a thermal insulation gap between the floor and the ground.
- The masonry of buildings consists of stone about 0.60 m. thick; the stone, as a structural material, has very low heat conductivity and wide thickness also plays a fundamental role in the insulation of a building. This principle is particularly useful, since there is a wide variation of temperature during the day in the hot-dry climate of Athens in summer.
- Ventilation strategies: the loft or the roof can have small openings (skylights), thus the hot air of the interior will go up naturally and will slip from the skylights (Charkiolakis et al 2008) in some cases the building depends on the courtyard in the ventilation of interior as in Saint Filothei house (see Fig1.12).

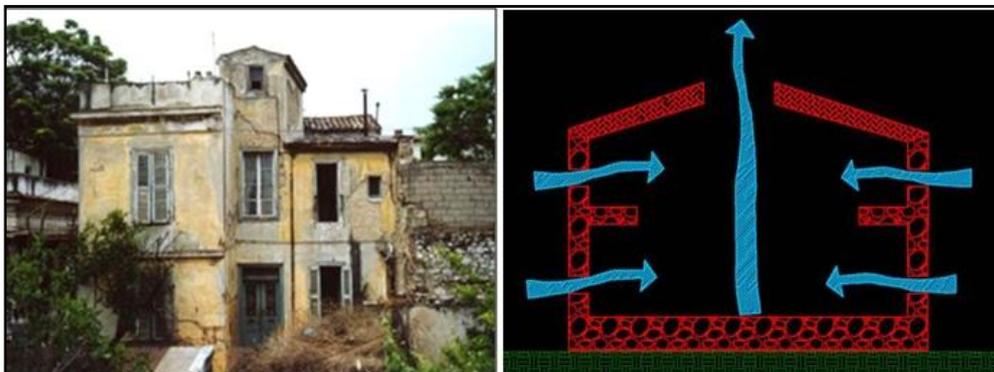


Figure 1.11 Ventilation strategies: Small openings at the loft of the buildings (Charkiolakis et al. 2008).



Figure 1.12 Saint Filothei house in Athens (Charalambos 1983)

In general historic traditional masonry houses which are found both in urban and rural areas have broad variations in their shape and the number of stories. Houses in rural areas were generally smaller in size and have smaller openings, since they are typically used by a single family. On the other hand, houses in urban areas are often of mixed use, that is, with a commercial ground floor and multifamily residential area above. Also the houses in the countryside are built as stand-alone structures, while the adjacent houses in old town centers often share a common wall (World Housing Encyclopedia No 16).

So one can say that the historic traditional masonry houses in Athens have its own architectural and construction characteristics; these buildings are typically found in flat (individually), sloped and hilly terrain. They do not share common walls with adjacent buildings. The typical separation distance between buildings is 5 meters and more as a rule when separated from adjacent buildings, the typical distance from a neighboring building is 5 meters.

Typical shape of a building plan is mainly rectangular. The building has at least eleven openings per floor, of an average size of 3.5 m² each. The estimated opening area to the total wall surface is 18%. This is relevant to the resistance of this

type of building. The main function of this building typology is single-family house. It is very common to find these historic buildings used for commercial purposes.

The vertical load-resisting system is timber frame load-bearing wall system. - Load bearing walls - Timber or metal strengthening elements. The lateral load-resisting system is un-reinforced masonry walls. The main lateral load-resisting system consists of unreinforced stone masonry bearing walls. Floors and roof are wood structures. The wall layout in plan is critical for the lateral performance of this construction type. Also, the wall connections and roof/floor-to-wall connections are the critical elements of the lateral load resistance. The materials and type of construction are the most important factors affecting the seismic performance of these buildings.

The typical plan dimensions of these buildings are: lengths between 10 and 10 meters, and widths between 15 and 15 meters. The building has 2 to 3 storey(s). The typical span of the roofing/flooring system is 5 meters. The typical storey height in such buildings is 3-4 meters. (Tassios, and Syrmakizis 2002)

1.4.1- Structural element joints and connection techniques

The connections between structural elements in unreinforced masonry buildings (URM) are critical building components that must perform adequately before the desirable seismic response of URM buildings may be achieved. These connections typically consist of wood ties and steel anchors installed either at, or, after the time of construction or post construction.

Field observations made during the initial reconnaissance and the subsequent damage surveys of numerous cases to historic traditional masonry have demonstrated the importance of anchor connections joining masonry walls or parapets with roof or

floor. It was realized that the techniques used for this purpose provided some seismic protection; they were devised by skilled workmen with a deep knowledge of the materials and the building systems of that time, which not only was maintained, but also kept developing for centuries, pass on from one generation to the next. This knowledge was developed by craftsmen with a very good perception of how the structure elements behavior as whole and in individual members or elements, the skills of which improved through observations of structural behavior during earthquakes led to the development of interesting and efficient seismic construction systems these observations also used for repairing damages (Tondre1999).

Joints play a special role during earthquakes and in the seismic response of the building. Resistance of joints against jolting and shaking due to earthquakes is beyond those usually required for gravity and wind loads and it is believed that fractures which occur during an earthquake due to stress concentrations, progressive deformations, and loosening of joints are of particular concern. (Ambrose and Vergun 1999)

The survey of historic traditional masonry buildings for studying the methods and techniques used for connecting structural elements in the building (walls-floors-roofs) show that there are three types of connection techniques developed by local craftsmen for connecting structural elements (wall-to-wall, and roof-to-wall) in order to minimize seismic hazards. These techniques involve the use of stone connections, wood connections and steel connections.

1.4.1.1- Stone connections

In traditional masonry walls, larger limestone's were used at the corners, where larger stress concentrations tend to develop, in order to provide an appropriate connection

between the wall panels as shown in Fig. 1.13. On the other hand stones of smaller dimensions are used in the remaining wall, facilitating their handling during building construction process.

The stiffness and strength of walls, as well as of their connections, depend on the quality and size of the stones used their arrangement and method of construction. An appropriate arrangement of limestone in the construction of the walls is of extreme importance, largely affecting the mechanical properties of the walls and its structural performance. Stone connectors can play a fundamental role for the monolithic behavior of the masonry walls, especially in multi-leaf walls with multi-building materials (more than two different building materials)

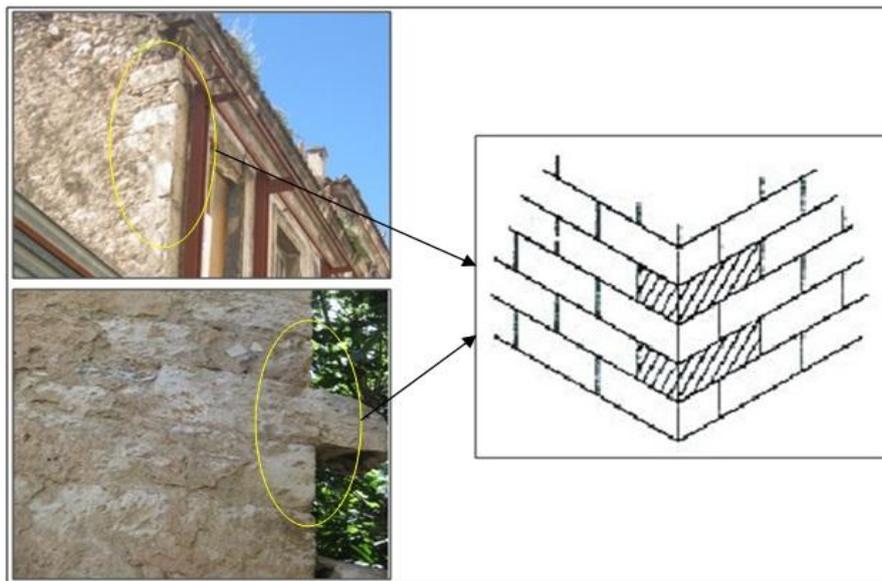


Figure 1.13 Use of limestone as a connection method between walls

Also masonry corners play an important role in the building structural performance, since they ensure the connection between perpendicular walls. However, masonry wall corners tend to attract the large forces induced by wind and earthquakes, as well as the resulting thrust from the roof structure.

The quality of the materials and their arrangement in the corners is even more important for buildings with multi-leaf walls, considering that for these cases the quality of the masonry is lower in some cases due to the smaller dimensions and poor mechanical properties of the stone units. In some cases we find mixed use of limestone and marble in the walls' intersections and this is one of construction defects in some buildings, as shown in Fig. 1.14, leading to failure in some cases.

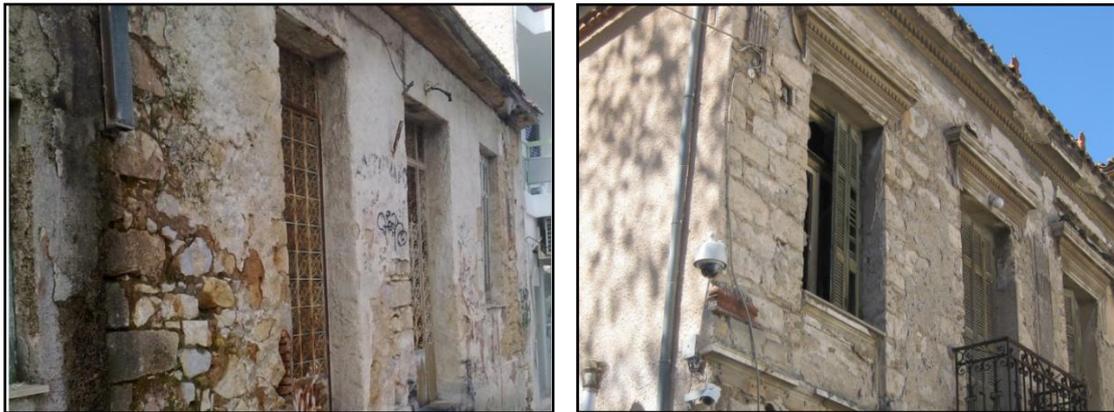


Figure 1.14 Poor and good connections in wall corners

1.4.1.2- Wood connections

The traces of the use of timber reinforcement in buildings are found in numerous structures (residential houses, churches and towers) of the Byzantine era. It is interesting to observe that timber ties are widely known under the term of 'imandosis', which is a Greek word means tying system; it ties together timber elements embedded in buildings. In this period, they always used timber as reinforcement in the form of timber ties at many levels within the height of the walls (both in longitudinal and transverse directions).

The investigation of composite or complex buildings has shown that timber ties (both visible and invisible) are used in the cells, as well as in the tower of monasteries. One may observe that (visible) timber elements are used as ties at the origins of arches and vaults, as well as within masonry along the perimeter walls in the form of timber ties (imandosis). The fact that the constructors were aware of the

importance of timber elements is also demonstrated by their care to protect them from humidity. Fig. 1.15 shows a detail of the timber tie located within the masonry of the cells (Vintzileou 2011).

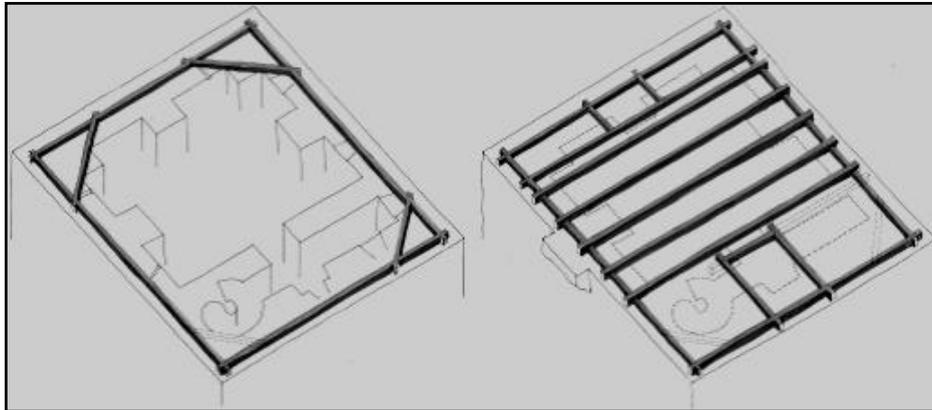


Figure 1.15 Detail of the timber tie within masonry (Vintzileou 2011)

Below timber elements, a recess was formed using stones. This recess (20 to 30 mm deep) covered with lime mortar, plays the role of drainage for the timber elements, thus keeping their humidity constantly below the biological attack level. A system of horizontal timber ties was detected at floor levels, as well as at intermediate levels (at the bottom of openings).

At intermediate levels, the connection among longitudinal timber pieces is ensured by means of diagonally placed stiffening elements. At floor levels, timber ties (located within the thickness of masonry) are connected to the timber beams of the floors. Timber pavements fixed onto the floor beams ensure a diaphragm action of the floors, thus forcing the walls to deform jointly in case of an earthquake. The concern of the constructors about the seismic behavior of the tower is also demonstrated by the fact that floor beams are positioned along the x- or along the y-direction every other floor. In this manner, a uniform behavior of the construction is sought, independently of the predominant direction of the seismic motion.

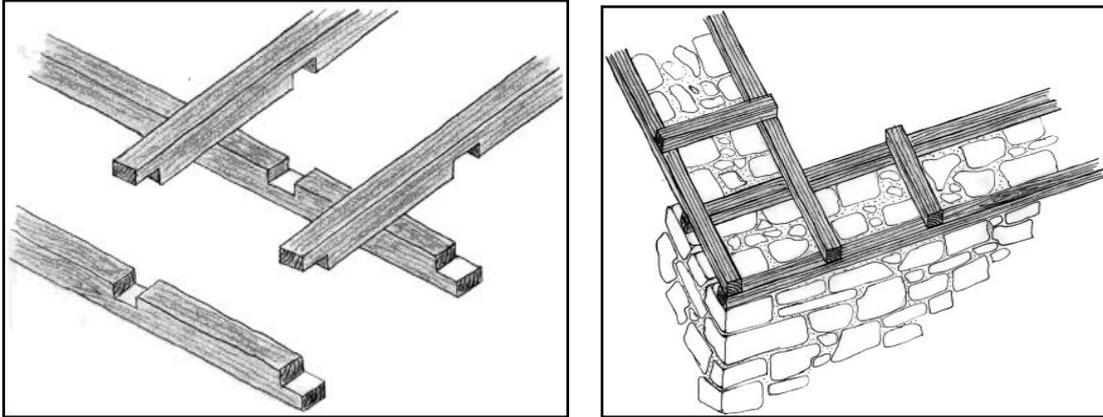


Figure 1.16 Timber ties technique between floors and at floor levels in some buildings (Vintzileou 2011)

In the next period, 17th, 18th and 19th century, the survey of historical traditional masonry structural systems has shown that, practically in all these systems, timber reinforcement (made of wood from olive or chestnut trees in many cases) is used within the thickness of masonry. The typology of timber ties (location, dimensions of wood elements, arrangement within masonry thickness and along the height of walls, splices in longitudinal timber elements, connections between longitudinal and transverse elements are shown in Fig. 1.16 (Vintzileou2011).

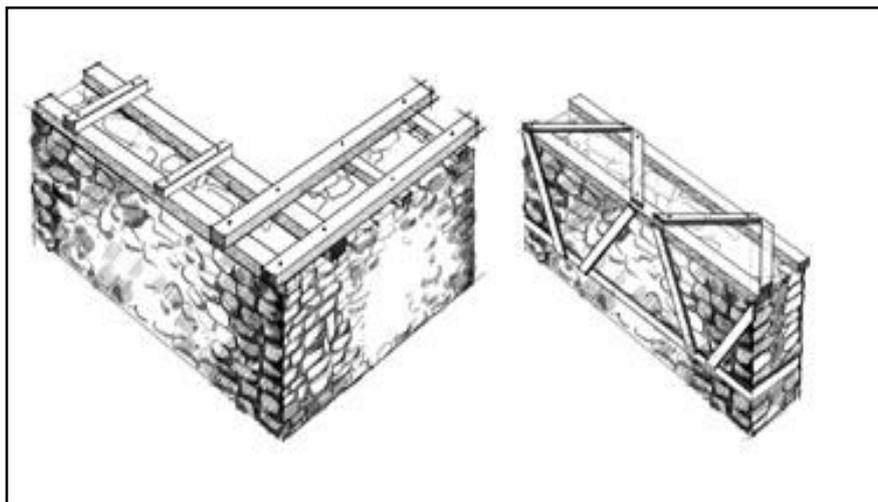


Figure 1.17 Timber bands used in historic traditional walls (Vintzileou 2011)

Also, timber framed construction with a brick filling material were used between the 15th and the 18th century. Buildings were constructed using this system, but, after the 18th century, there was a decrease in the quality of work and walls with brick filling began to be plastered over as shown in Fig. 1.18. The filling of timber skeletons with masonry material continued to the end of 18th Century.

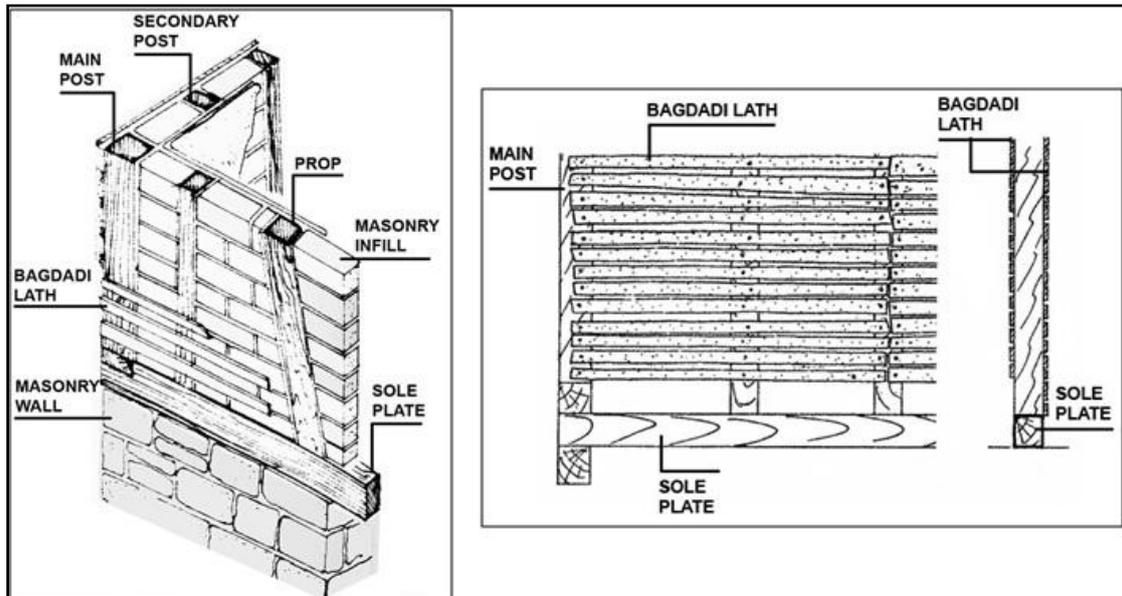


Figure 1.18 Masonry infill timber-framed system and Baġdadi lath system

In the construction of these houses, different types of trees had been used, depending on their characteristics. Generally trees which could be found easily around the region were preferred for construction. To ensure the consistency of main carrier system, posts, sole plates, props and joists, oak and yellow pine trees were generally used; ceiling and floor coverings were of yellow or red pine, and for parts, as sheathing and windows, yellow pine was used. For balustrades and carved ceilings, red pine, walnut and linden were the preferred materials.

When surviving artefacts are investigated, it is obvious that the traditional timber skeleton house is generally composed of 2 or 3 storeys, a wooden frame structure settled on a masonry foundation, as seen in Fig. 1.19, basement or first floor, from 1 to 1.5 meters above the ground.

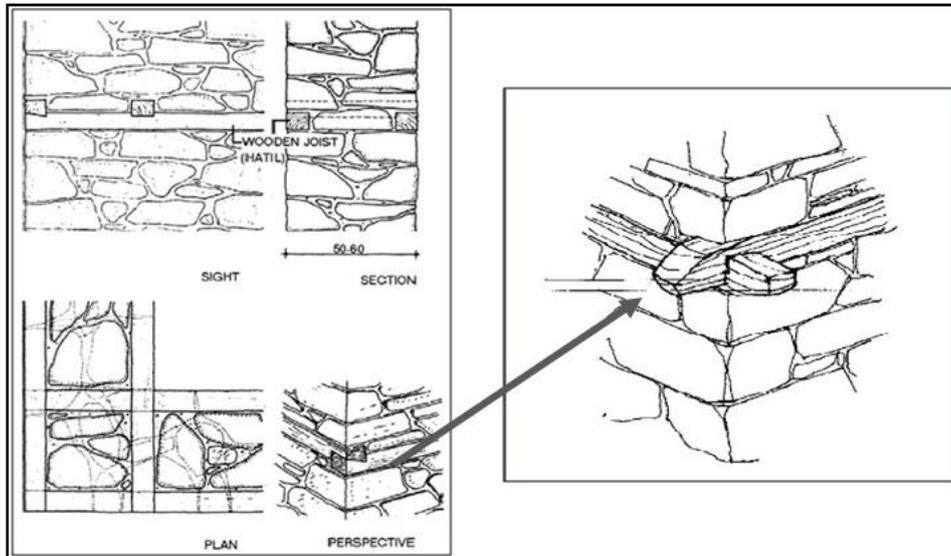


Figure 1.19 Rubble Stone walls with wooden joists

The sole plates are half-overlapped at the corners and the posts are mounted on these sole plates leaving spaces of 1 or 2 meters. The posts are generally supported by the diagonal props in the corners or at the centre. The secondary posts are placed between the main ones every 60 to 70 cm. The posts, props and the secondary posts are tied together with the lintels. The joists are placed on the soles as their sections become upright to the front of the structure (Dişkaya 2007).

In some cases of brick structures (in churches) with the triple header masonry bonding timber element was found inside the triple header masonry lateral walls in the anchorage region of the tie rods with the purpose of enhancing their efficiency as shown in [Figs. 1.120-1.22](#)

1.4.1.3- Steel connections

Steel or iron has not been used in building construction process in the main structural elements until the Industrial Revolution. Until then, it provided builders with solutions for structural details and as a local strengthening measure; it was used in masonry for securing portions that were prone for collapse, such as building corners,

and to connect roofs with walls (see Fig. 1.23). Moreover, it was mainly used for nails and straps in timber roof structures.

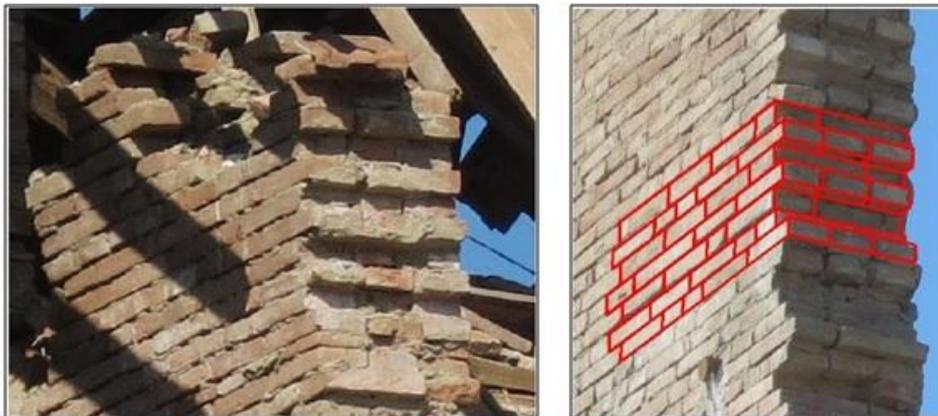


Figure 1.20 The triple header masonry bond



Figure 1.21 Timber elements inside the brick walls



Figure 1.22 exterior views showing the tie timber element rods

Steel was also used as a secondary structural element in the monuments of ancient Greece and Rome. Iron tensile connections and shear dowels were placed in the interfaces between stone blocks to enhance structural performance and prevent small relative movement. Having lost the complete understanding of this technique in later years, iron tying members were widely used, in faulty applications and often unprotected, in restoration works on ancient monuments and other masonry structures. This type of technique is divided into three types, all of them using steel bars in order to achieve good connection between walls and walls, or walls and floors/ roofs.

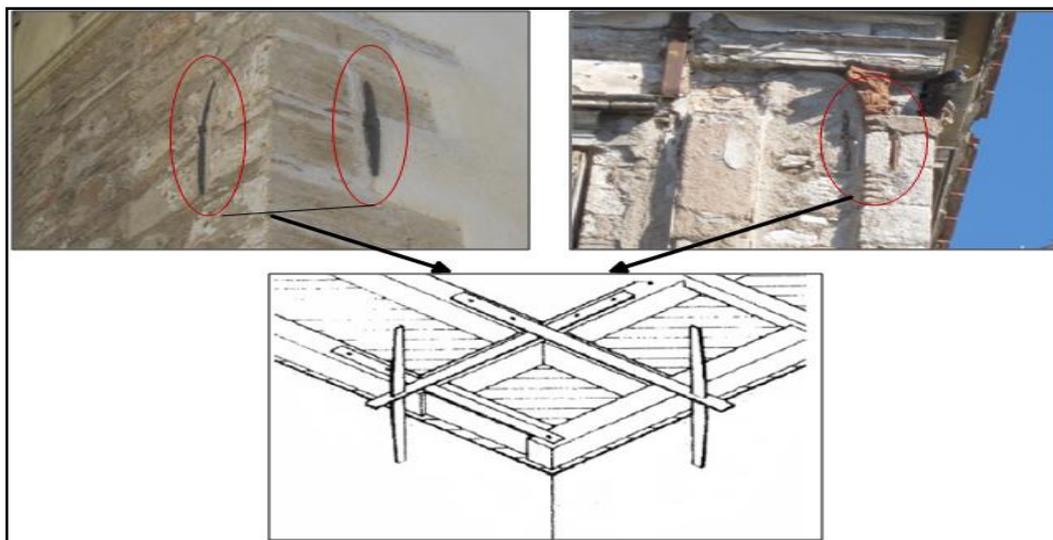


Figure 1.23 Steel connection tie technique in historic traditional masonry

1.4.1.4- Anchor Steel bar Tie Technique " T shape"

In most of the anchor systems that were used, threaded steel rods had the same shape and diameter. These rods were embedded in the masonry wall to a depth equal to the wall thickness. Although at times hard to identify, there appears to be little evidence suggesting the use of bent anchors (having an angle of at least 22.5° to the perpendicular projection from the wall surface) and the majority of observed anchors were positioned horizontally (Dizhur et al 2011).

In historic traditional masonry, steel was used to connect floors with walls in order to achieve good structural performance under seismic excitation. The builders, in this period used a steel T bar or anchor bars in order to connect the floor with walls (see Figs. 1.24 and 1.25). This connection technique was used in different types of historic buildings, such as mosques, churches, houses, etc.

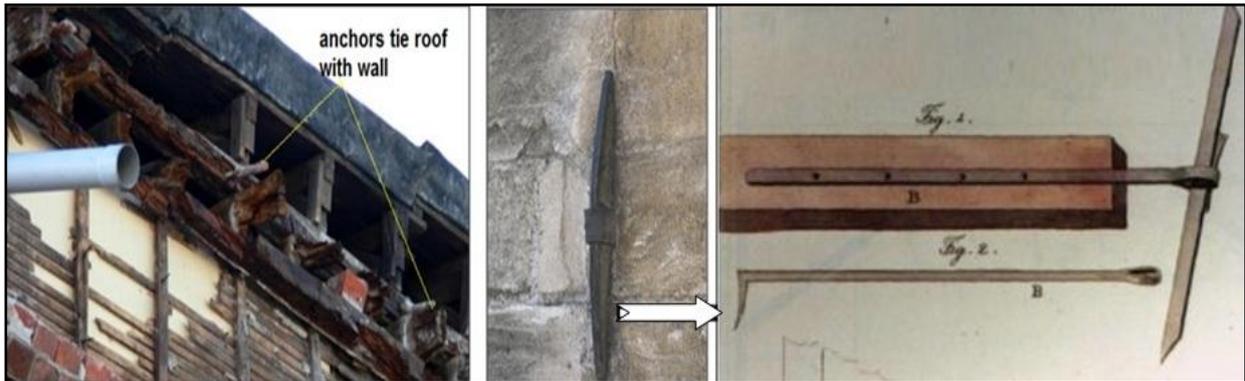


Figure 1.24 Steel anchors tie roof with wall

As shown in Fig.1.35, it was used in one side of the building, usually in parallel to the main floor wood rafters, in order to connect or tie this steel bar with one of the floor wood rafters or roof with walls as shown in Fig. 1.26: in some cases double steel ties used in the main façade, as shown in Fig. 1.26, in order to connect the roof with the main walls which were stronger, and with other walls providing resistance to the action of the loads exerted on the building

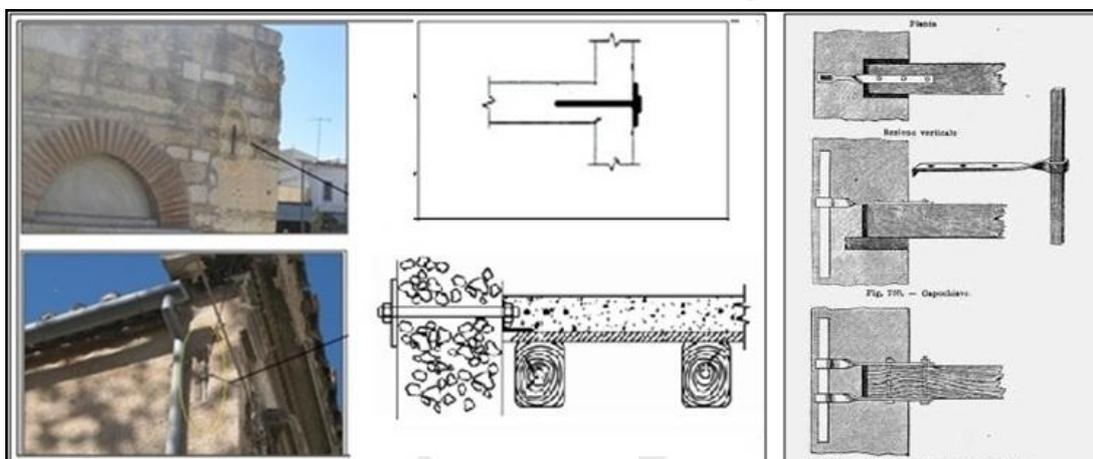


Figure 1.25 Connection between beam and masonry with single and double steel element

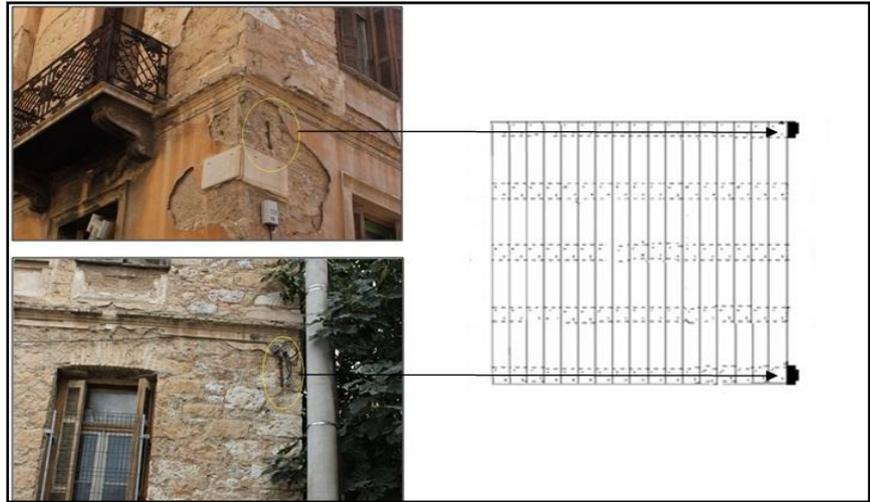


Figure 1.26 Positioning of double steel ties in historic traditional building AKTIOU building and tie positioning, plan.

On the one hand, in buildings where large numbers of people meet, such as religious buildings (mosques, churches, and governmental buildings), the builder has been found to use more than two or three steel bar ties or steel anchor bars on all sides of the building, as shown in Fig.1.27 and Fig. 1.28. On the other hand, in pottery art mosque, anchor steel bars were used for connecting the column capital which supported arches in order to sustain the thrust of arches as shown in Figs.1.29 and 1.30.

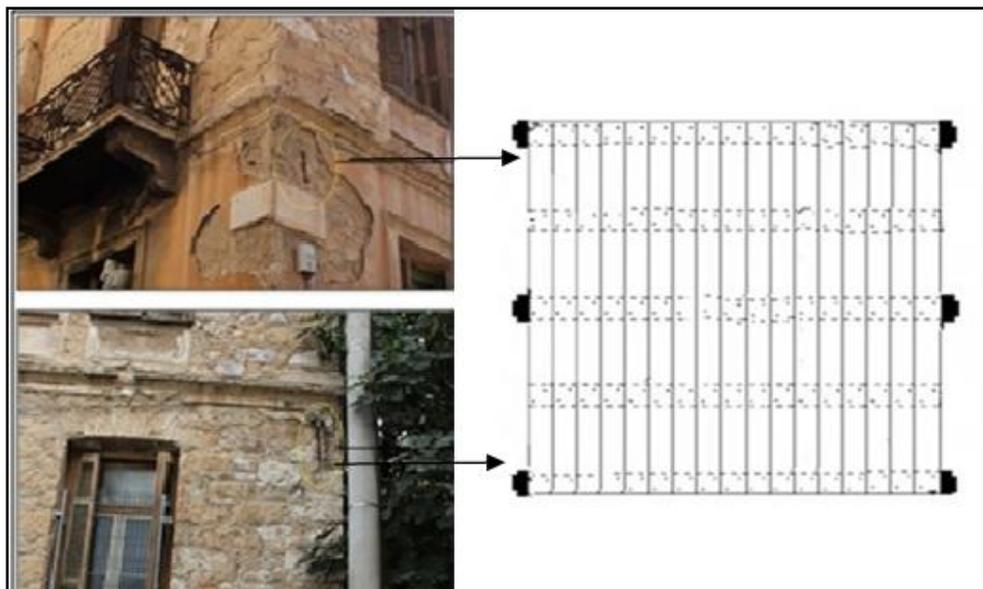


Figure1.27 Three steel ties positioning, plan



Figure 1.28 Positioning of three steel ties in historic traditional building (Alfatihia Mosque)

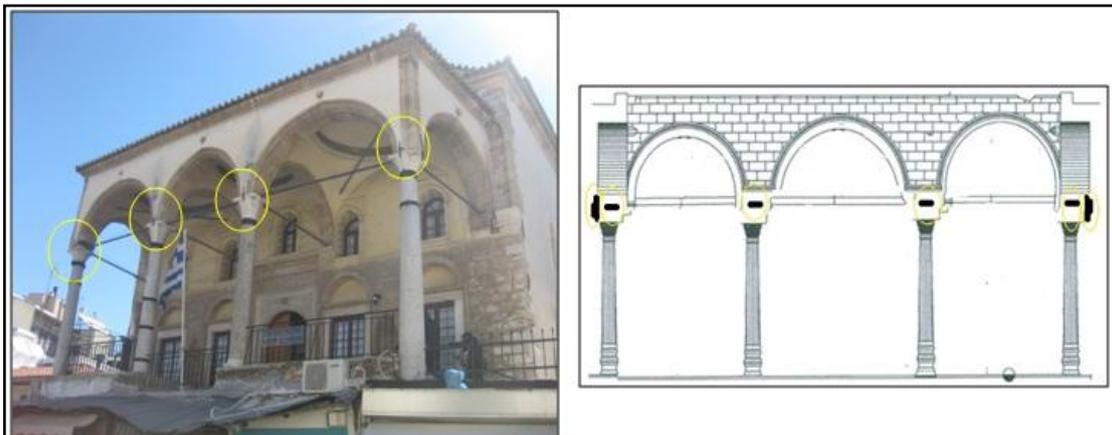


Figure 1.29 Positioning of steel ties in connection of arches with columns (pottery art Mosque in Monostrakii)

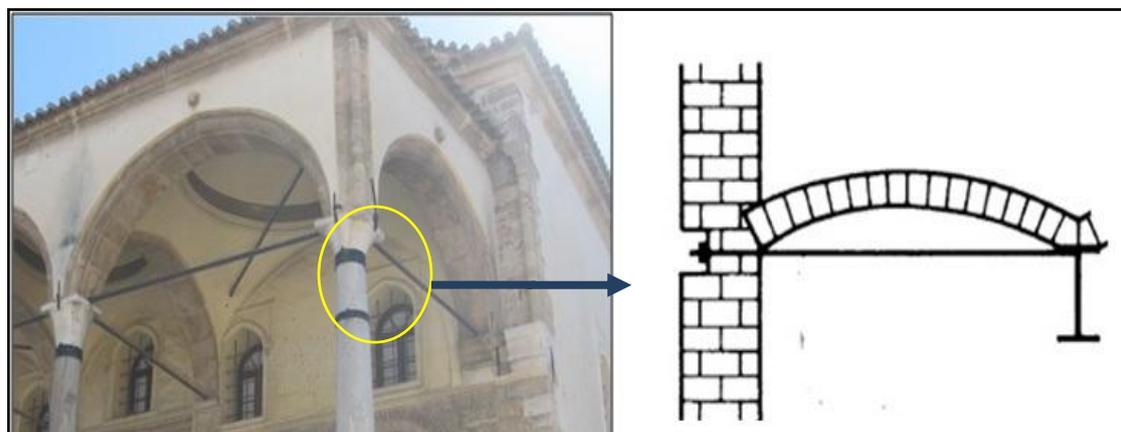


Figure 1.30 Positions of steel ties in connection of arch with wall (Pottery art Mosque in Monostrakii)

1.5- Historic Traditional Masonry in Cairo - Egypt

Historic Cairo is deemed one of the most prominent world heritage cities worldwide. Cairo is the city where history comes to life and where splendid architectural wonders abound, making it the city with the largest cluster of heritage architecture worldwide. It isn't simply the largest in the number of monuments to the glorious era, but also in the weight of their architectural, artistic, and historic value. It contains many of Pharaonic, Greek Roman, Coptic, and Islamic buildings. (Abdulmunim 2006)

Cairo is home of a number of historical districts and significant monuments that demonstrate the architectural wealth of the city, not only as a capital of the Islamic world but as a wonder of the human urban experience. As such, it was inscribed on the world heritage list in 1979 under the title of “Islamic Cairo”. In the nomination file, Cairo’s historic city was cited as covering an area of around 32 square kilometers on the eastern bank of the River Nile and the foot of the Moqattam Hills (see Fig 1.31).

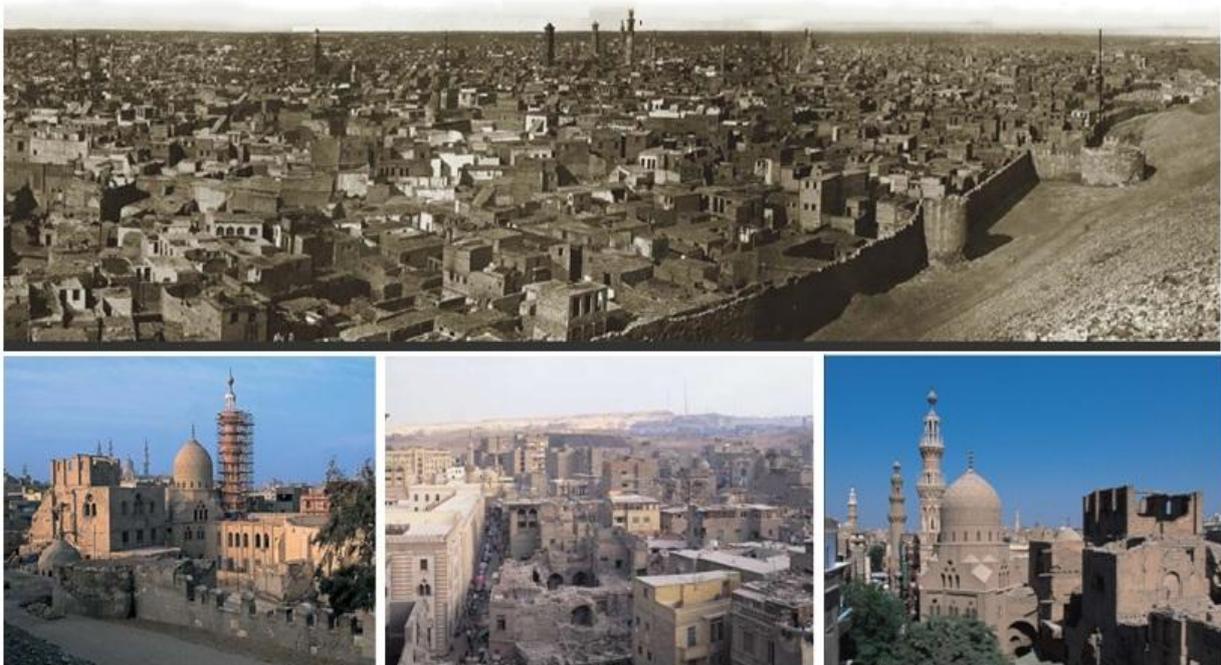


Figure 1.31 General views to Historic Cairo and some historic districts

It is clear that in the 19th century a process began that heavily transformed the structure and image of historic Cairo, particularly its residential urban fabric. Although numerous monuments were preserved, palaces and larger houses were often abandoned or divided into smaller plots. More than 10 Courtyard houses were replaced with rental flats, and changes also occurred in the architectural and typological characters of the city.

Nevertheless, the main components of historic Cairo's urban morphology show a remarkable continuity throughout the city's development stages. In historic Cairo there are some historic expressions or idiom such as, *Darb* (pathway), *Hara* (alley), *Atfa* (side alley) and *Zuqaq* (dead-end alley or cul-de-sac) (see Fig. 1.32).

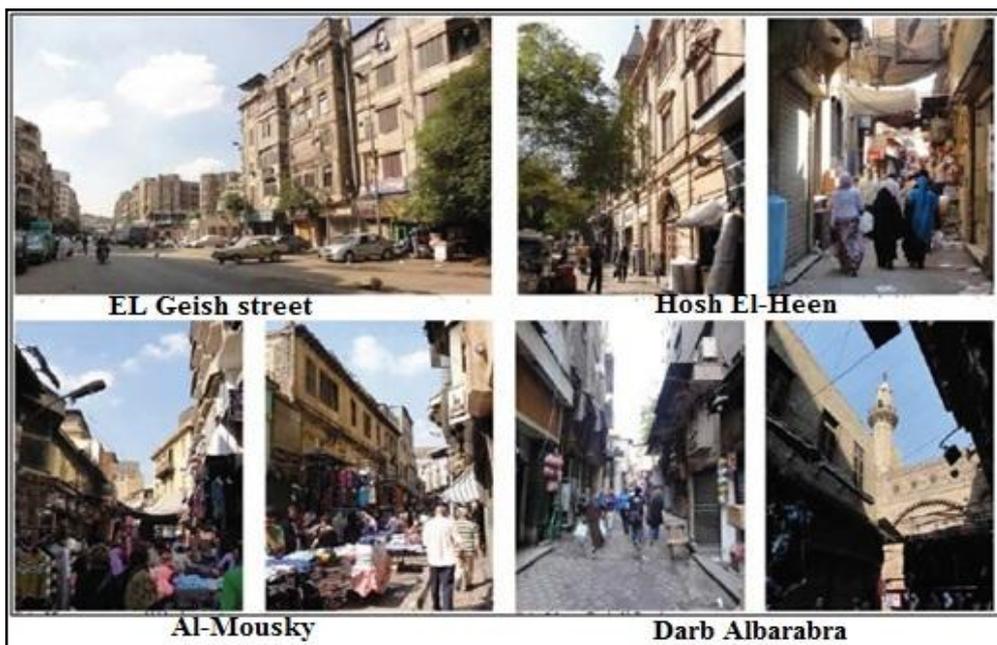


Figure 1.32 Historic streets, alleys in historic Cairo (UNESCO 2012)

Historic Cairo is an urban ensemble that extends from street to alley to lane and covers a large number of historic buildings ranging from religious structures such as mosques and churches, to service buildings such as bathes (*hammams*) and structures for the charitable dispensation of water (*sabils*) to commercial building such as shops (*khans*), caravanserais (*wikalas*) also residential structures such as

palaces and houses (*manazels*). The massive scale and density of listed monuments complemented by an even larger number of unregistered historic building dating from the 19th century inwards, also of architectural and aesthetic value and in need of preservation. The latter is a repository of architectural history of equal importance to the registered monuments as they are like the fabric that binds these listed monuments together and lends them an urban dimension.

The medieval core of historic Cairo comprises a group of destinations (*hawari*) — predominantly residential communities forming around narrow, non-straight alleyways and incorporating a limited amount of commercial activity. Each *harah* is characterized by the spatial order of its shared public space — the alleyway — bounded by its entrances/ gates and lined by attached low-rise houses. But it is also defined by a distinct social structure, and cultural identity (see Fig. 1.33).

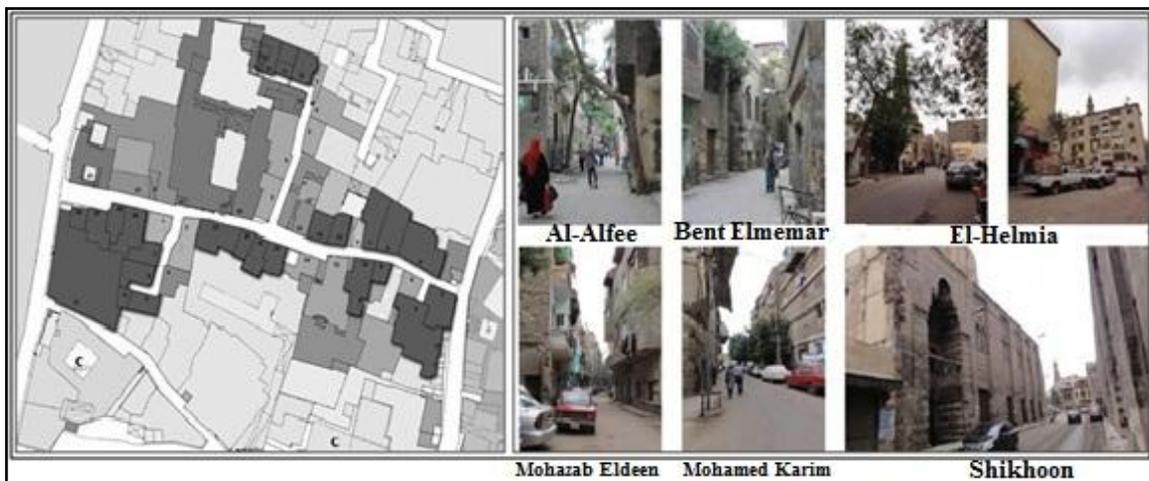


Figure 1.33 typical distinct defined by the surrounding continuity of houses (UNESCO 2012)

Yet with the advent of modernity in the nineteenth century the state of the city changed, as the aristocracy and the elite deserted it and moved westwards into the new extension to the city. Such demographic change adversely affected the social structure, as most of the deserted buildings were re-occupied by laborers and minor traders and most buildings were transformed into industrial workshops to serve the

shops and markets. All that had an adverse effect on the historic fabric and on the historic building themselves. Most of the historic building fell into disuse and many were deserted. Other historic buildings were used indiscriminately for deferent, mostly unsuitable functions. Furthermore, they suffered from a lack of necessary maintenance as shown in Fig 1.34 (UNESCO 2012)

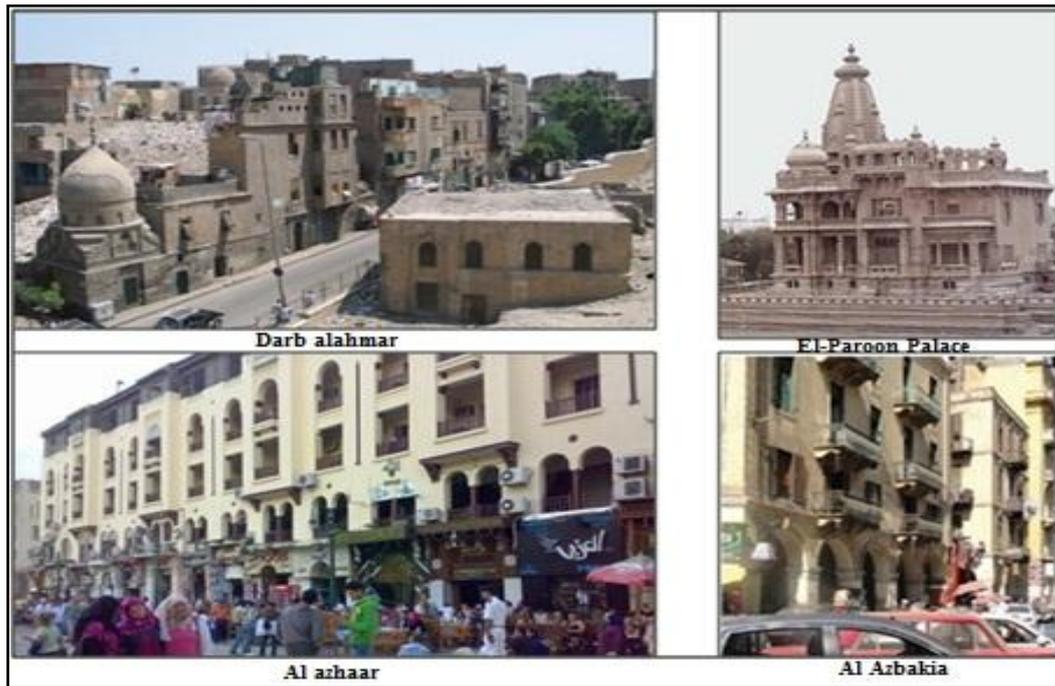


Figure 1.34 Historic Traditional houses and the effect of 20th century modernity

On the other hand all historic Traditional masonry which lies in these historic districts suffers many Deterioration phenomena commonly found through Islamic/historic Cairo (and many others historic city centers in developing countries) the combined result of a serious of social economic and physical factors:

- Low family incomes and an economic base that often lags behind development in newer parts of Cairo
- A deteriorating housing core resulting from unrealistic planning constraints, pending demolition orders, limited access to credit and widespread insecurity of tenure

- continued deterioration of monuments and historic structures especially houses due to the misuse of inhabitants in these historic traditional houses
- the consequence of 1992 earthquake and a lack of public investment and regular upkeep of city infrastructures
- the absence of essential community facilities and services (Siravo 2002)
- The hard attack of environmental factors (groundwater, humidity, etc.)

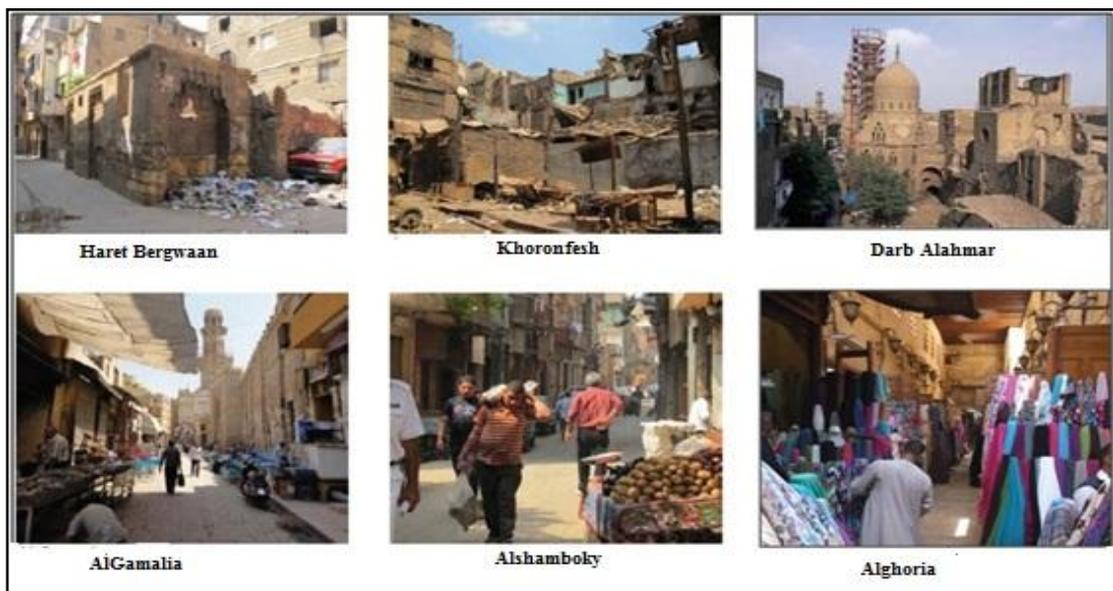


Figure 1.35 Deterioration phenomena of historic Traditional masonry building in Cairo (UNESCO 2012)

But the district has also significant strengths and opportunities that are the source of the area's vibrant character. These strengths are the result of the district's closely integrated physical and social fabric, namely:

- A traditional layout and pedestrian orientation where housing, open spaces, commerce, mosques, and places of social gathering are integrated and create a high cohesive urban environment.
- an outstanding collection of mediaeval monuments and historic buildings
- A dense residential core where neighbors help and depend upon each others

- A well-established community with a population largely employed in productive activities
- An important pool of skilled workers and small enterprises.

1.5.1- Historic traditional masonry houses in Cairo-Egypt

In many parts of the historic Cairo, one can realize many distinctive examples of traditional architecture, mainly houses. Although there were socio-cultural differences in each region, the design of houses retained a common architectural language that responded to both the common hot arid zones climate and the common religious needs. The historic traditional house in Cairo is also one of the best examples that express the *sakina* which comes from the Arabic word *sakan*, which is the Arabic name for a house and relates to dwellings in peace and purity. The heritage of traditional houses includes various forms, which were developed in response to religious, cultural, and traditional factors along with the specificity of the local built environment. The remarkable traditional houses of medieval Cairo are all evidence to the rich wealth of Islamic-Arab residential architecture. (Abdelmonem 2012)

Traditional dwellings were an integral part of the traditional urban fabric of Cairo city and it weren't towering individually alone, but the houses of rich and poor were adjacent within the neighborhood unit, without caste or social discrimination, whether in the form of a housing unit or external processors of these houses (see Fig 1.36). The difference lays in the interior thus it achieving the most important features of traditional architectures in the singularity of its appearance and difference in substance.

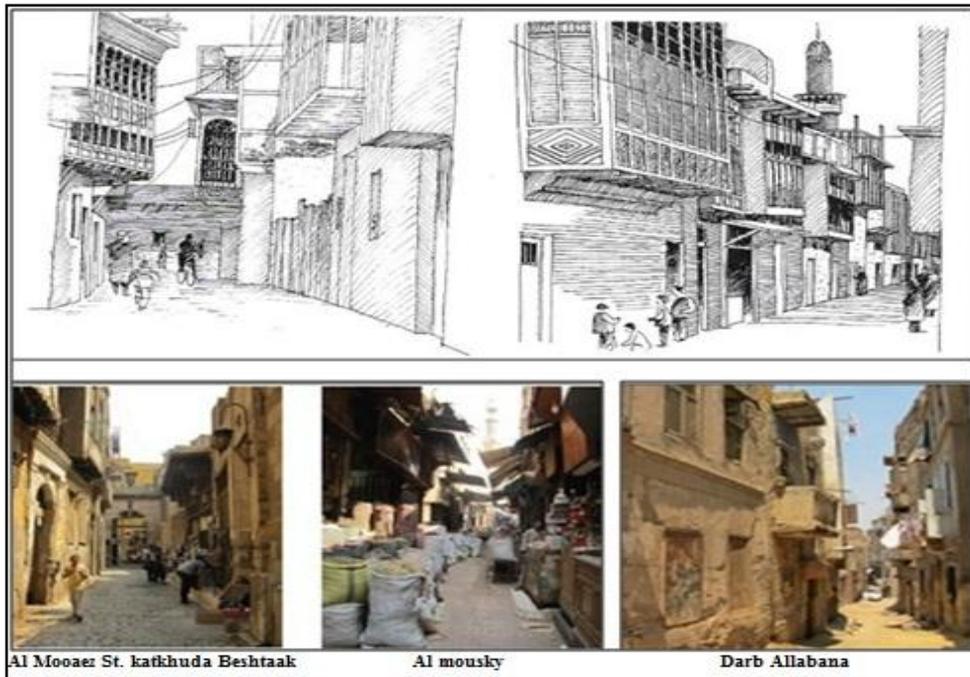


Figure 1.36 Urban fabric of historic traditional masonry in Cairo

Distinction between the rich and the poor housing was achieved through different housing sizes and the number of spaces and courtyards, thus affecting the diversity of the spatial organization, Adding some positives in environmental performance within the overall design of the urban fabric through the formation of different places in the pressure and dislocations air which helped to move the air naturally between different parts of the urban fabric and, within the housing between the multiple spaces inside the house.

1.5.2- Architectural and construction characteristics of traditional houses in Cairo

Every architectural element in the historic traditional house represented a solution or an answer to different problems that appeared according to a specific condition. They were a sequence of related problems, which were met successfully to achieve a unified and a harmonious house. In fact, the beauty of these traditional houses

represents an art form that has resulted from an understanding of a unique mode of religious and cultural human life. (Abdelmonem 2012)

The Islamic way of life has its effect on the design of traditional houses in Cairo; while the public areas in a house are the domain of men, the private and family areas are the domain of women. The privacy of the family was also an essential element which affected the shape and the plan form of all traditional houses, to be clearly defined as public, semi-public and private spaces. The cultural and religious emphasis on visual privacy in Islamic communities has also tended to produce an inward-looking plan with plain external walls to discourage strangers from looking inside. Climate also played an important role as a moderating factor and complemented the cultural and religious need for privacy. The houses of the hot arid zones such as Cairo, are introverted, and where family-life looked into a courtyard rather than looking out upon the street (Salama 2006) (Abdelmegeed 2009).

The ground floor is usually occupied by kitchens, storages for food or stalls, places of service and reception. The upper floor is occupied by bedrooms, living rooms or service; it is almost entirely closed to defend against hot and alien invasions, moreover it combines two important aspects of everyday life: the public and private sphere of family playing an antithetical but, at the same time, symbiotic role.

On the other hand the rooms in historic traditional masonry houses in Cairo enclose themselves the sphere of private: the rooms of the women separated from those of the men: beautiful places without large openings; introverted rooms reflecting the unique character of the Cairo house and where tranquility and privacy are guaranteed by the architectural complex. These concepts are well represented in the most characteristic room of the house (the qa'a).

The need for a reception and representation room is transformed across the centuries acquiring significant specializations; in the fifteenth century it becomes a new reception room reserved for men and called *maq'ad*. It opposes, in its architectural design to *qa'a* that is usually closed and not very bright, almost dark, with a large balcony overlooking the courtyard or the garden, across two or more arches to ensuring a moment of openness and breathing. As evidence of this constant and continuous development, in the seventeenth century, it adds the ancient loggia above the *maq'ad*: a new place of rest and reception, a sort of porch or *takhtabush* relating and organizing within the courtyard or garden (Ficarelli 2009)

However, the architectural components which governed the design concept of Cairo house and highlighted its distinctive characteristics were the *majaz* (entrance), the courtyard, the *The Qa'ah* (sitting hall), the *malqaf* (sky open), the *takhtabush* (terrace), and the *mashrabiyyah* (balcony).

i- The Majaz (Entrance)

Entrances in most of the Cairo traditional houses were bent. The idea of using bent entrances was to provide privacy for the house residents, preventing the street pedestrians from seeing the inside of the house. Another function of the bent entrance was to protect the interior of the house from wind, dust and noise. In all houses with varied surface areas, entrances were bent to right angles perpendicular on the street not leading directly to the courtyard. Attached to the entrance was a doorway that confirms the separation of the peaceful interior from the harshness of the outside/exterior (see Fig. 1.37).

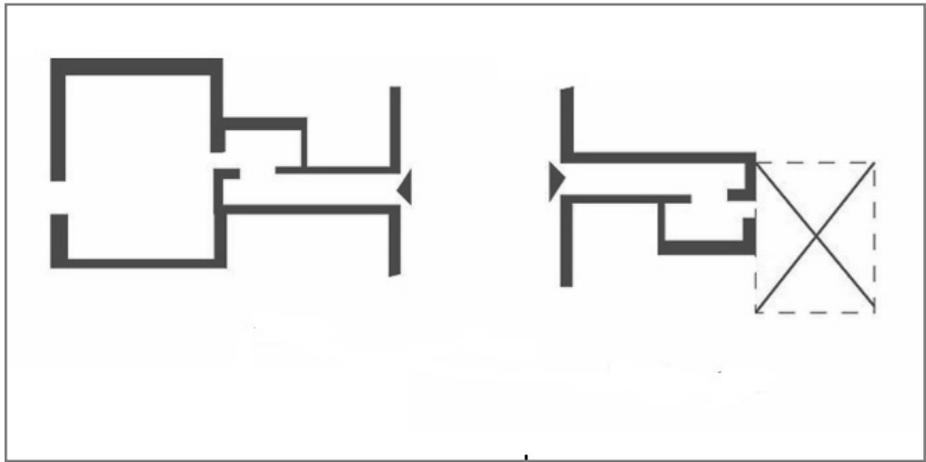


Figure 1.37 Bent Entrance idea in historic traditional house in Cairo.

Traditional houses in Cairo have two entrances; the *majaz* (the main entrance of a house), which usually opens onto a courtyard and the doorway, which is the main external feature at ground floor level (see Fig. 1.38). It was designed to open into a blank wall to obstruct views into the inside from outside in order to preserve the privacy of the family. On the other hand, the doorway is functional and modest because ostentation is discouraged according to the egalitarian basis of Islam. Al-Sehaimi house is a good example, which expresses the relationship between the main entrance and the courtyard (see Fig. 1.38).

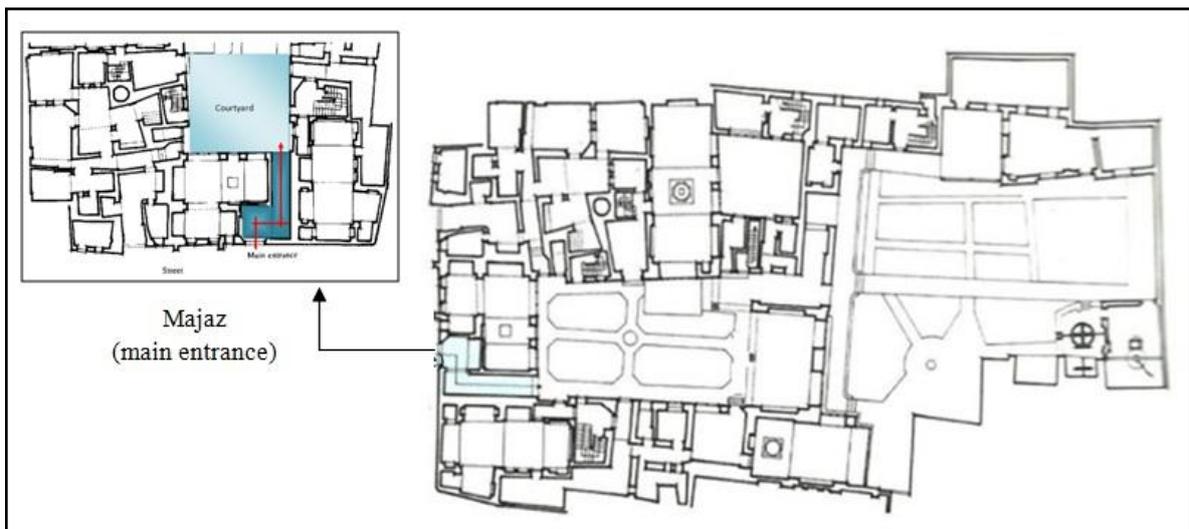


Figure 1.38 The main entrance (Majaz) in Al-Sehaimi house.

However, they preferred to have the main entrance open into this clean and holy space (courtyard), which is on the scale of the house, rather than into the public street, which is on the scale of the city (see Fig. 1.39) (Abdelmegeed 2009).

During the Ismailia period (Khediawii Ismail 1830-1895), one observes the drift towards ignoring traditional behavioral aspects, as in this model, entrances were followed by a lobby or a doorway then a hall for the purpose of the partitioning of spaces (as influence of European architecture) .

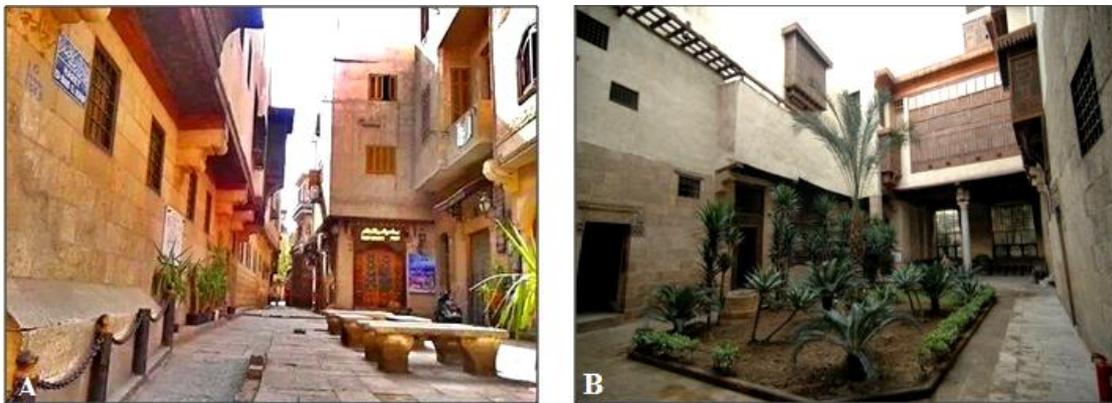


Figure 1.39 Al-Sehaimi house: A-the main façade and B-the main entrance and courtyard

ii- The Courtyard

Intellect design of the traditional dwelling was based on the use of the inside yard as a central point to achieve the principle of inside orientation The inside yard is one of the main principles of design in the architecture of various civilizations worldwide, despite the contrast in environments of cultural and natural characteristics of these civilization, and this stems from the ability of the central yard to adapt to different conditions such as privacy And whether protection from the dangers harsh environment, especially in warm climate zones (Al-Zubaidi and Shahin 2005).

The courtyard is a square or rectangular open space, usually located in the heart of the house; it performs an important function as a modifier for climate as well as for lighting purposes. The various daily activities are practiced and performed in the

courtyard especially in small houses. In some cases, the house has more than one court, where the major spaces open onto the large court and the service spaces open onto the smaller one as in Al-Sehaimi house (see Fig. 1.40). Originally, the courtyard surrounded by four unequal iwans with a fountain in the center. The form and typology of the courtyard has changed dramatically over the years. A fountain was placed in the middle with the iwan at or living spaces opened onto it as shown in Fig. 1.40. (Michelle 1995) (Salama 2006).

The concept of the courtyard is commonly used in traditional architecture, both rural and urban, of the hot arid regions; it dates back to the Greek-Roman tradition. Egyptian builders adopted the concept of the courtyard because it suited their religious and social needs, especially the degree of privacy needed. The arrangements of the courtyard also provided a satisfactory solution to their specific environmental problems. The size of the courtyard varies, according to the available space and resources.

Figure 1.40 plan of the courtyard typologies in historic traditional houses in Cairo where
 A- Gamal Eddin Al Zahabi, Ottoman period,
 B-Zeinab Khatoun, Mamluk period,
 C-Alkiritlia house Mamluk period
 D-AlHarrawi house Mamluk period



Courtyards in traditional houses in Cairo were typically three types (see Fig. 1.40). This prototype evolved from the original traditional Islamic house to the 19th century model, and was later influenced by the Turkish and European styles (see Fig. 1.40B). This type continued to exist until the transformation of the late 19th / early 20th century, when it became obsolete and was replaced by the new Western prototypes. Houses with side courtyard may be observed to be the same as those of central courtyard (see Figs 1.40A & 1.40D).

However, they differ in terms of the pattern of use of the courtyard as a living space. Adding up, the third type (see Fig. 1.41C) involved a court but has practically served as light wells or ventilation shafts for the service spaces of the house only, while the major spaces were usually opened to streets.

The courtyard is the most essential element, which represented the core of all historic traditional houses in Cairo such as the courtyard of Al-Sehaimi house (see Figs. 1.39 and 1.41), Zeinab Khaton house and Al-Sinaary house. The courtyard is an effective device to generate air movement by convection. In hot dry zones the air of the courtyard, which was heated by the sun during the day, rises and is replaced by the cooled night air coming from above. The accumulated cool air in the courtyard seeps into and cools the surrounding rooms. During the day, the courtyard is shaded by its four walls and this helps its air to heat slowly and remains cool until late in the day, moreover in some houses the courtyard contains fountain to help to accommodate the surrounding as in Al-Sennary house (see Fig. 1.41B).

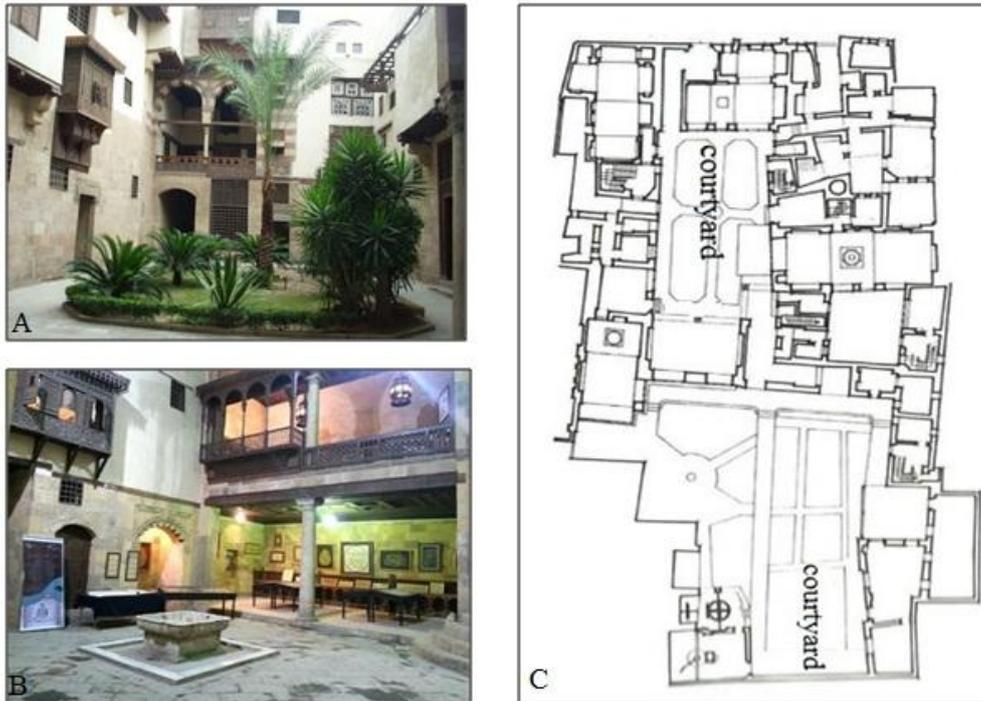


Figure 1.41. courtyard in historic traditional houses in Cairo, courtyard at Al-Sehaimy house: A-the main façade B- courtyard at Al-Sennary house, and C- plan of Al-Sehaimy house shows the two courtyards.

During the Mamluk and Ottoman periods, the courtyard was a common feature in all traditional houses in Cairo. The existence of the courtyard is also observed in the examples of the early nineteenth century. In El-Leithy house, it has been used as an open space for climatic and lighting purposes, the courtyard type continued along during the transitional period of the late 19th/early 20th centuries, and was witnessed in the early apartment buildings in the traditional districts of Cairo, Shubra, A'bdin, Helmia and others. It has played the role of directing circulation space leading to staircases of different wings of the buildings.

Regarding the example of the Ismailian (Khedawii Ismail) period, that emphasizes the openness to Europe, one observes the transformation of the traditional courtyard into a hall for the purpose of receiving short-visit guests. At the same time, this hall stood in the crossroads, playing the role of a distributing point to the interior spaces of the house. Eventually, the courtyard lost its environmental role, due to the

raise in number of floors to four and more, an aspect that led to its complete disappearance shortly afterwards (Salama 2006).

iii-The Qa'a (sitting hall)

It is a reception space overlooking the courtyard and composed of three or more open spaces. The qa'a includes a durqa'a, which –typically- is surrounded by two iwans (iwan is a space between columns row) facing each other with a central fountain in the middle of this durqa'a. The floor level of the two iwans is higher than that of the durqa'a. In some cases, the durqa'a is surrounded by three iwans, forming a T-shape. Some courtyard houses included more than one qa'a and extra reception spaces for women. Generally, the durqa'a has a square or rectangular shape with double-height; it is slightly lowered compared with iwan on the sides (see Fig.1. 42).

On the top stands a lantern, in the purpose of the ventilation and the lighting of qa'a. Often, in the centre of the durqa'a, there is a fountain that has an aesthetic role and above all it contributes to cool the air of the room mixing air and water to increase the humidity.

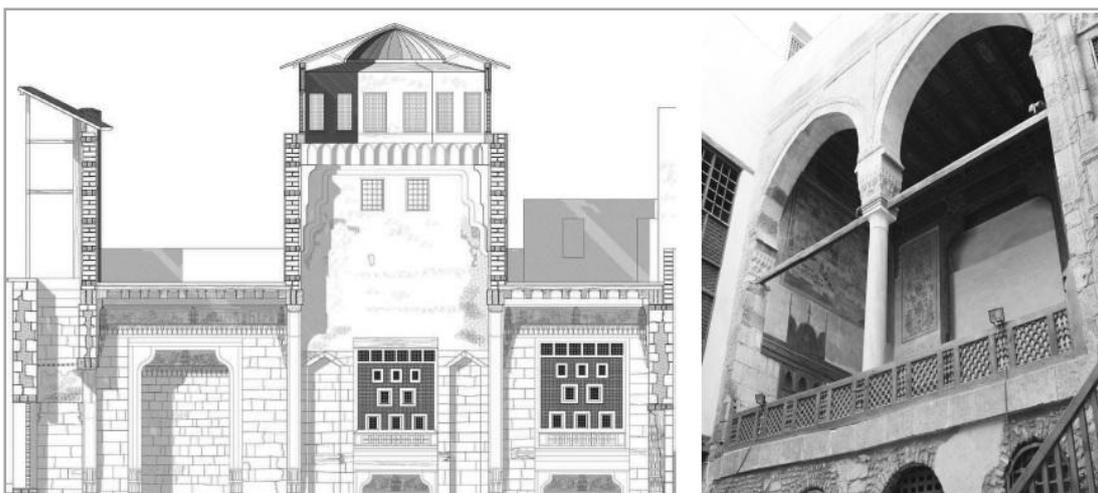


Figure 1.42: Drawing sections of Qa'a and of Malqaf (left) and Maq'ad (right); (Ficarelli 2008)

On the other hand *durqa'ah* (a central part of the *qa'a* with a high ceiling covered by the *shukhshakhah* (wooden lantern on the top), and two *'iwans* (sitting areas) at a higher level on both the north and south sides (see Fig. 1.43). The lantern is provided with openings to allow the hot air to escape. Its shape could be square, octagonal, or hexagonal. It was also flat on the top, in order to help the upper layer of air to be heated up through exposure to the sun.

Tracing the examples of the early nineteenth century, the luxurious divided *qa'a* shrank into a prestigious hall for guests designated for living and dining activities. Starting from the Ismailian period and onwards, the *qa'a* no longer existed, but transformed into several divided spaces accommodating activities of receiving guests (salon), dining and living, until the introduction of the open plan by the modern movement where one large space is left free to accommodate those activities. This clearly explains the impact of Westernization from the Ismailian period by openness to Europe up to the mid-20th century through importing modern movement trends by the Egyptian scholars who studied architecture in Europe. (Michelle 1995)

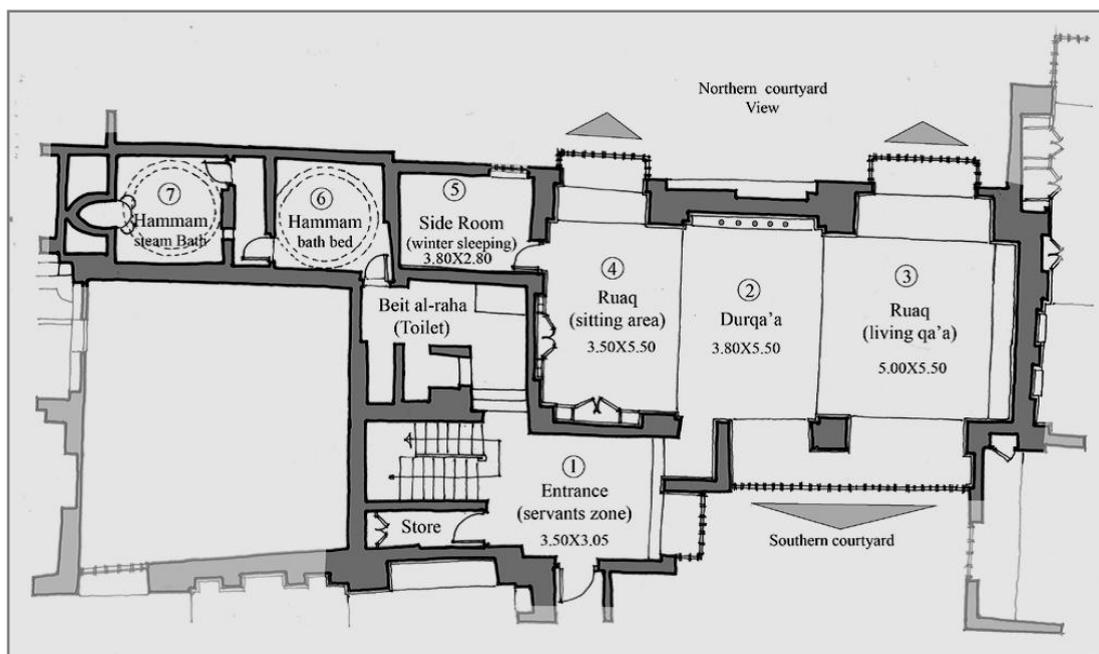


Figure 1.43: The plan of *qa'a*, *durqa'ah*, and Ruaq or *'iwans* (Al-Sehaimi house 18th century)

iv- The Takhtabush

In the early Egyptian houses the courtyard also represented an intermediary space between the entrance and the guest area. Meeting casual male visitors, who are not relatives, always took place in the *takhtabush*, the Arabic word of the room with a side open to the courtyard. On the other hand, important male visitors would enter indirectly from the courtyard to another large reception hall with a lofty central space, which was flanked by two spaces at a slightly higher level.

Takhtabush is a type of loggia – a covered outdoor sitting area - at the ground floor level, located between the courtyard and the back garden, opening completely onto the courtyard with a *mashrabiya* onto the back garden as shown in Fig. 1.44A. The *takhtabush* is generally rectangular or square in shape acting as a waiting area. It played another role in dealing with climatic factors since it allowed for air circulation via its *mashrabiya* from the courtyard (Salama 2006)

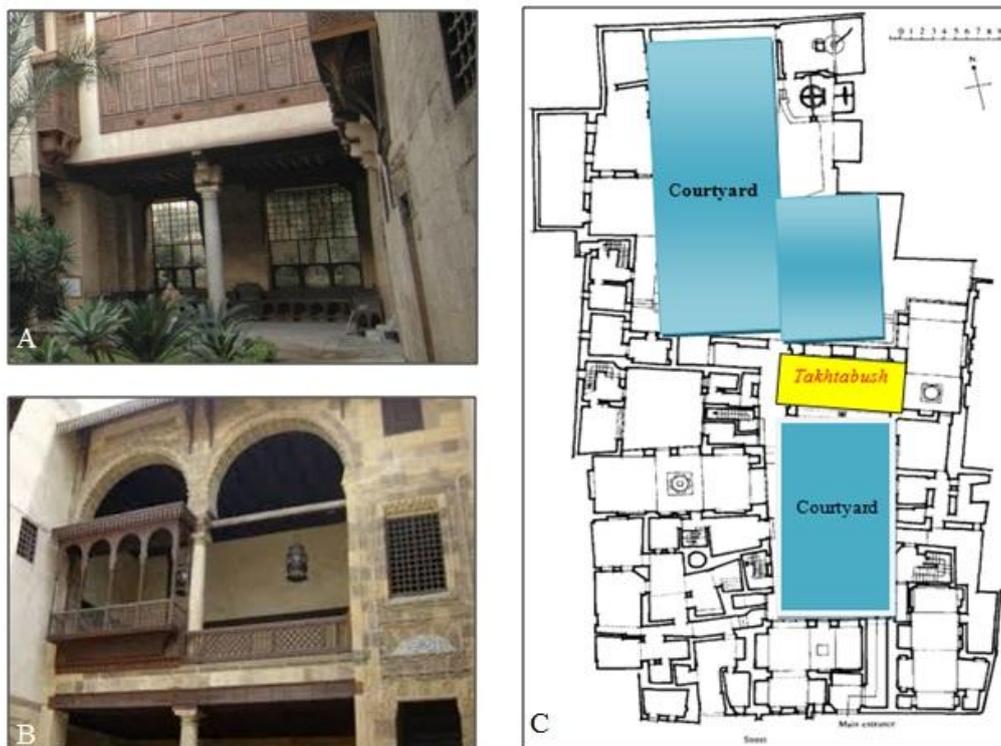


Figure.1.44 The qa'a and takhtabosh in traditional houses: A- takhtabosh in Al-Sehaimi house B- the qa'ah in Al-Sennary house and C- plan of Al-Sehaimi house (the takhtabosh place).

The *takhtabush* appears between the sixteenth and seventeenth century: it is a sort of porch with stone columns covered with wooden ceiling. It is usually placed near the entrance of the houses and it is used to welcome the guests. Its dimensions are variable; the orientation in the south ensures interior ventilation through the presence of windows (Ficarelli 2009)

Originally the *takhtabush* has one side opening completely onto the paved-courtyard and through *mashrabiya* onto the back garden. Air heats up more readily in the courtyard than in the back garden creating an area of low air pressure. However, the heated air rising in the courtyard draws cool air from the back garden of the *takhtabush*, creating a cool draft. The *takhtabush* can be found in the medieval Cairo houses, such as Al-Sehaimi house and Al-Sinnari house (see Fig. 1.41). Reviewing the examples of the traditional courtyard houses together with those of the early nineteenth century, one observes the location of the *takhtabush* open to the courtyard and directly accessible from the main entrance in a location that doesn't allow the exposure of the private spaces to the guests. From the Ismailian period and afterwards, the name of the *takhtabush* changed into *entree*. (Salama 2006).

v- The Malqaf (Sky open)

With the covered courtyard, *malqaf* is a new system of ventilation invented to achieve thermal comfort inside the *qa'a*. The *malqaf* is a shaft rising high above the building with an opening facing the prevailing wind and constructed on the north to traps the cool air “like sails capturing the wind” and channels it down into the interior of the building as shown in Fig. 1.45.

The northern malqaf channeled the north cool breeze and brings it in the qa'a to increase pressure to air caused by the wind at the entrance (see Figs. 1.45-1.48). The lantern is provided with malqaf to allow the hot air to escape. Its shape could be square, octagonal, or hexagonal. It was also flat on the top, in order to help the upper layer of air to be heated up through exposure to the sun.

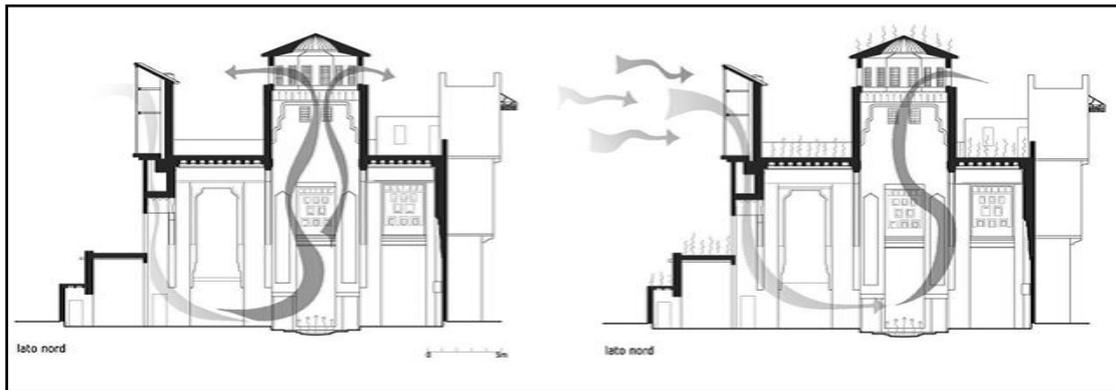


Figure 1.45: Diagram of operation of Malqaf; (Ficarelli 2008)

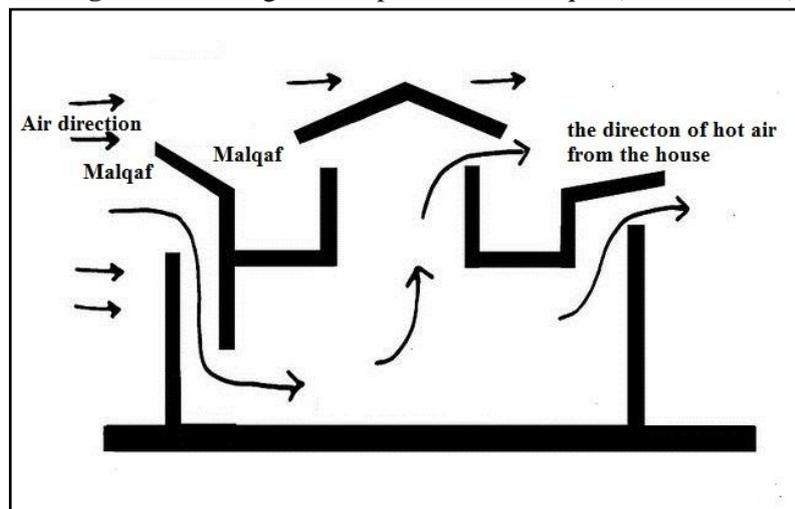


Figure1.46 The malqaf idea in historic traditional houses

The idea of the *malqaf* dates back to the early Pharaonic periods. Examples can be found in the Eighteenth Dynasty houses of Tal Al-Amarna, such as house of Neb-Amun, which was depicted on his tomb of the Nineteenth Dynasty (1300 BC.). It shows a *malqaf* with two openings, one facing windward to capture the cool air and the other facing leeward in order to evacuate the hot air by suction.

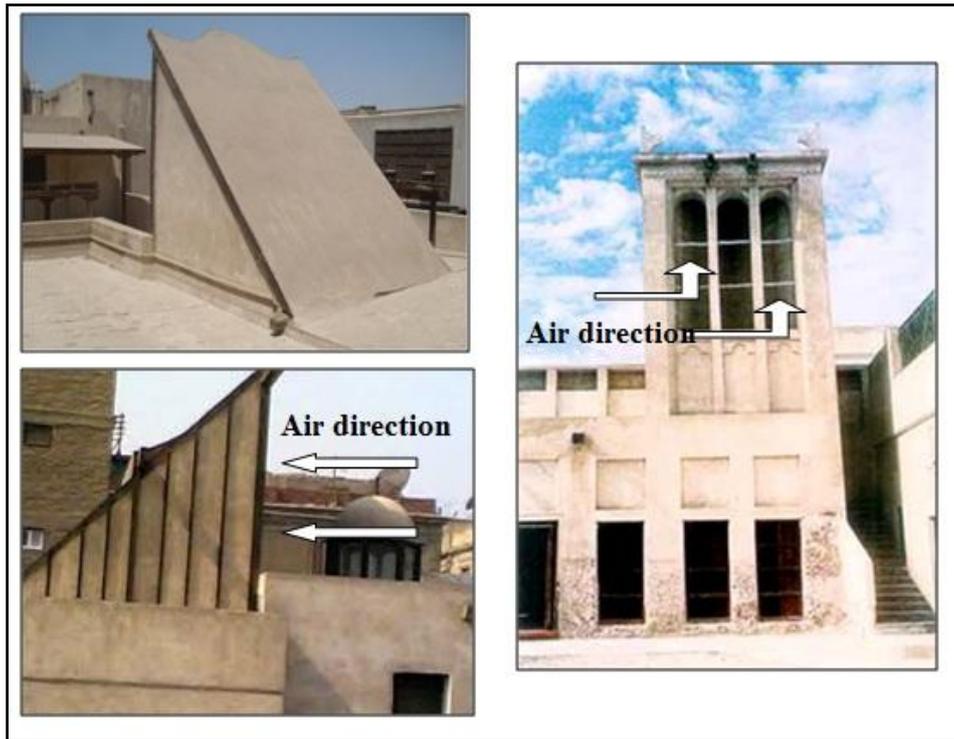


Figure1.47 The *malqaf* in historic traditional houses

To increase the humidity of the air coming from the *malqaf*, the *salsabil* was also introduced. *Salsabil* is a marble plate, decorated with wavy patterns and provided with a source of water. The *salsabil* was put against the wall of the opposite side of the *'iwan* and placed at an angle to allow the water to trickle over the surface. However, this new system of ventilation combined the *malqaf*, the *salsabil* and the lantern in one design to assure a good circulation of cool air in the *qa'a*. The *salsabil* and the lantern in one design to assure a good circulation of cool air in the *qa'a* (El-Shorbagy 2010)

For the correct functioning of this component it is necessary to have a system to close and to filter. The *malqaf* channels inside the prevailing current of air from the north to adjust the flow and the admission in *qa'a* through a series of different openings. The air directed to the central part of *qa'a* is further cooled by a fountain on the floor of *durqa'a*; when the air becomes warmer it tends to rise upward, coming out

through the high central tower of the room, the *shukhsheikha*. On the top of this one there is a lantern hexagonal, octagonal or circular with openings on the sides: this device expedites the flow of air upward and facilitates the expulsion of the hot air from the tower toward the outside (Ficarelli 2009).



Figure 1.48 Show Malqaf from outside and inside (Ficarelli 2008)

vi-The Mashrabiya (arabesque wooden window)

The *mashrabiya* is another important character element in Cairo historic traditional houses which was used to cover openings (windows) as well as to achieve thermal comfort and privacy in a house. Its name is originally derived from the Arabic word *sharab* "drink" and referred to "a drinking place".

The term "mashrabiya" literally means "place reserved for drinks" and corresponded to the small objects in half-light used as basis of support for the small jars: they needed to stay cool. This kind of balcony was composed of small wooden elements assembled to create a grid. Across the centuries the term has been extended for the large wooden panels made with this technique: the *mashrabiya*. This was a cantilevered space covered with a lattice opening, where water jars were placed to be cooled by the evaporation effect as air moved through the opening. The form and function of the *mashrabiya* has changed to become a wooden lattice screen.

It is composed of small wooden circular balusters, arranged at specific regular intervals, in a decorative and intricate geometric pattern. The *mashrabiya* has five functions and its design may fulfill some or all of these functions. These are: controlling the passage of light, controlling the air flow, reducing the temperature of the air current, increasing the humidity of the air current and ensuring privacy. To control the amount of light and air and to graduate the contrast between shade and light, the size of the interstices and the diameter of the balusters are adjusted. *Mashrabiya* is found in most of the historic traditional masonry houses in Cairo, such as Gamal Al-Din Al-Dahabi House, and Zeinab Khatoun House as shown in Figs.1.49 &1.48 (Abdelmegeed 2009)

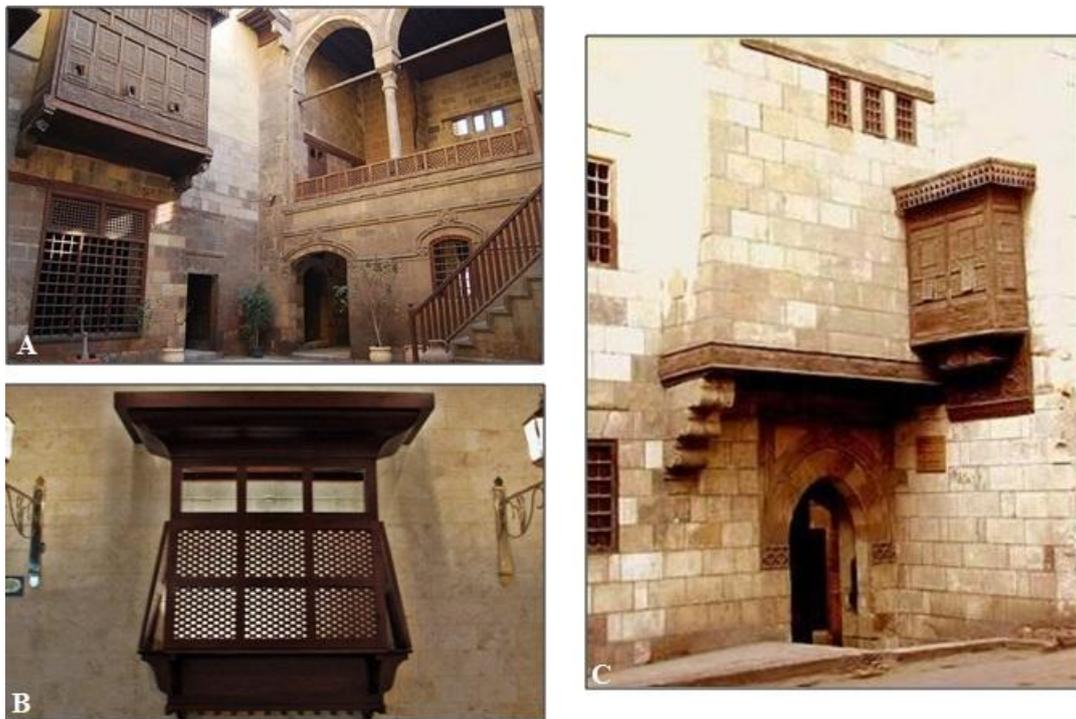


Figure 1.49 *Mashrabiya* in Zeinab Khatoun House

The mashrabiya is a window element that automatically activates a convective cycle moving air masses from the zone of high to that of low pressure. This phenomenon naturally ventilates small streets and makes incredibly fresh the courtyards of the houses. In the afternoon, when the courtyard begins to warm up, the

system works contrarily: the air comes back in courtyard from the secondary roads creating a perfect balance between the two areas, in the evening. In the seventeenth century the opening becomes the window in the wall screened by a grate in carved wood, flat or rounded, which will be called “mashrabiya” (Ficarelli 2009).



Figure 1.50 *Mashrabiya* from outside and inside view

The traditional masonry house in Cairo has its own architectural structural characteristics; it revealed an understanding of the laws of composition, which created a conscious arrangement of elements of a building in a functionally and visually satisfying whole. Hierarchies were an essential factor in the design process of the Cairo house, which highlighted the importance of the interior and exterior of a building. Scale, proportion, contrast and balance were also tools, which enhanced the character of buildings.

All the spaces in traditional houses were covered with variations of vaults, *shukhshakhah* and flat roofs, which achieved pleasant spatial and visual characteristics. The design of the Cairo traditional house also respected human reference and human scale and this had enabled people to articulate and comprehend the elements of their buildings. Harmony with the surrounding landscape was another important factor in the design process, where these houses were carefully integrated to the environment which has existed in equilibrium for a very long time.

The environmental and morphological characteristics of the site determine the shape and orientation of buildings, the characteristic of the structure, of the wrapper, of the distribution as in the case of the openings covered with panels made of wooden grids to protection of the privacy of the house from the outside world. The shield of the window is necessary to reduce the dazzle and it is used to control the humidity of the breeze passing through it

Applied colour seldom appears in Cairo traditional house, but the natural colours of materials, which identified both the origins of this architecture and its close link to the landscape. The visual impact of the homogeneous single colour emphasized the basic form of the building without the distraction of various colours, textures or materials.

Cairo traditional houses were also largely, determined by a unique vision of light and its influence on materials. The dynamic contrast of light and shade, and the dramatic use of space were also features, which can be sensed in the architecture of Cairo traditional house. The real power of light is not derived completely from its inherent character, but requires some sort of darkness to assert itself. For example, light entering through a window or *mashrabiya* evokes an expressive shadow, which accentuates the shape of the interior

The ground floor is usually occupied by kitchens, storages for food or stalls, places of service and reception. This is the most private part of the house and the organizing and administrative heart. The upper floor is occupied by bedrooms, living rooms or service. It is almost entirely closed to defend against hot and alien invasions. This part of the house combines two important aspects of everyday life: the public and private sphere of family playing an antithetical but, at the same time, symbiotic role.

The rooms enclose themselves the sphere of private: the rooms of the women separated from those of the men: beautiful places without large openings; introverted rooms reflecting the unique character of the Cairo house and where tranquility and privacy are guaranteed by the architectural complex. These concepts are well represented in the most characteristic room of the house: the qa'a. Depending on the circumstances, this space can be used for family meetings, receptions.

1.6- Structural Elements

Traditional materials and methods of construction in historic traditional buildings cover a vast range, but many materials and methods can be confined to specific geographical areas because they were sourced from their immediate locality. Distinctive buildings resulted from this diversity of methods. However, a common feature of most historic traditional buildings is that they contain soft, weak or permeable materials, such as lime mortars, plasters, renders and paints. There is a considerable diversity of materials and methods found in historic buildings. In addition to the most common forms of structures, stone walls built in lime mortar with slate covered pitched roofs are seen as the principal building method (Urquhart 2007).

The structural performance of a masonry wall structure can be understood provided the following factors are known:

- geometry;
- characteristics of its masonry texture, single or multiple-leaf walls, connection between the leaves, joints empty or filled with mortar, physical, chemical and mechanical characteristics of the components bricks, stones and mortar.
- Characteristics of masonry as a composite material (Chronopoulos et al. 2012).

1.6.1- Walls

Walls in historic traditional masonry can be classified to one of three types: one leaf solid wall, two leaf solid wall, and three leaf solid wall (Vasconcelos et al. 2006). Although traditional masonry walls can be viewed as unsuitable structures to undergo seismic actions, they, in fact, exist and frequently represent the most important structural elements of ancient buildings. In fact, unreinforced stone masonry walls were, in the past, widely used in the construction of monumental and traditional buildings (Binda et al. 2000).

Walls in historic traditional masonry are generally uniformly distributed in both orthogonal directions with a wall thickness ranging from 400 mm to 700 mm. A lot of walls in historic traditional masonry are made of rubble stone in mud/lime mortar; these walls are built by local builders or by owners themselves, most of them not having any formal training. The quality of construction in urban areas is generally superior to that found in rural areas (World Housing Encyclopedia No 16).

The building materials used in the construction of the walls depend on what is locally available. The most common walling material is undressed rubble stone and the second most common is semi fired and fired brick. The stonework is occasionally exposed, but more often it is protected, at least by layers of lime wash but, usually there is also one coat of plaster or more, as shown in Fig. 1.51. Semi fired and fired bricks were always available but, until they could be mass produced, they were not commonly used, either because they were very expensive or due to the nature of Athens land which has many mountains. Early bricks were made with local clay and usually fired on site in a purpose built clamp. These bricks were thin, very much like the bricks made by the Romans, often as little as 60 mm in depth.

Stone masonry walls can be classified into three types: un-coursed random rubble stone, un-coursed semi-dressed stone, and dressed stone as shown in Fig. 1.46. This classification is based on the type of stone, extent of shaping, and the layout, where these walls are constructed from stone boulders bonded together with mortar; and the differences in stone masonry wall construction also depend on economic factors, the availability of quality construction materials, and artisan skills and experience (Bothara and Brzev 2011).

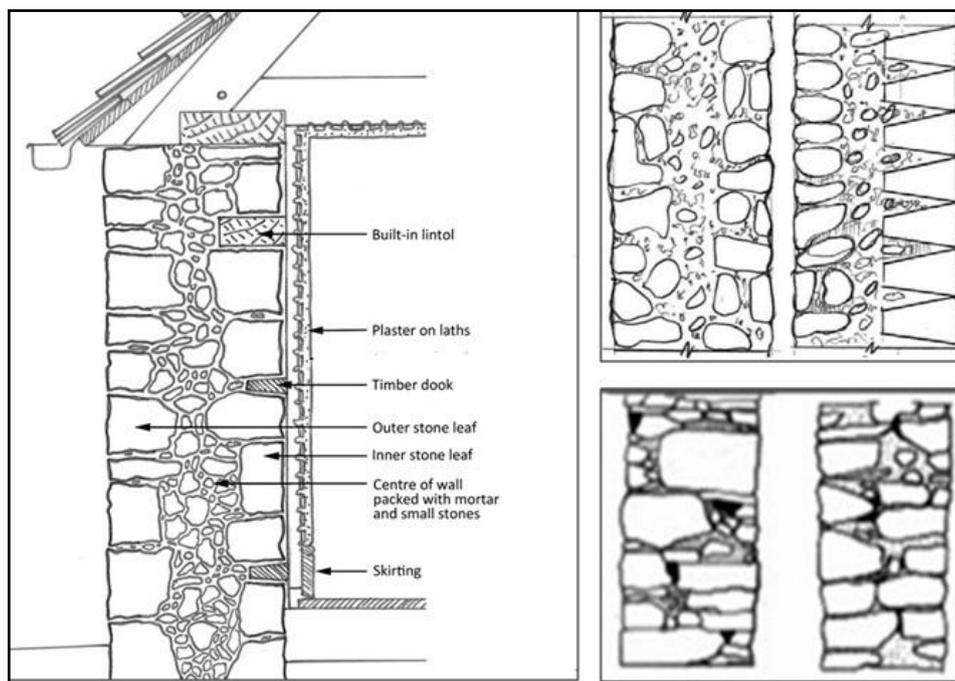


Figure 1.51 Traditional masonry wall construction details: wall un-coursed "random rubble stone masonry"; semi-dressed stone wall; wall with an exterior Wythe built using wedge-shaped dressed stone (Bothara and Brzev 2011)

In many instances, the exterior walls of the building are constructed first and the interior walls are constructed later without any connection. Rooms in these buildings are generally small and there are few small wall openings. From the architectural point of view, masonry offers advantages in terms of great flexibility of plan form, spatial composition and appearance of external walls for which materials are available in a wide variety of colours and textures. Complex wall arrangements,

including curved walls, are readily built without the need for expensive and wasteful formwork (Emeritus 2001).

Stone masonry walls are constructed with the use of a variety of mortars, such as mud, lime, or cement/sand mortar. Mud and lime mortars are considered to have low strength. When cement mortar is used, the cement-to-sand ratio is 1:6 or leaner. In some areas, cement mortar has replaced other types because of its increased affordability and availability. The use of cement mortar does not necessarily imply an increase in wall strength, so it often creates a false sense of security in terms of expected superior building performance.

i) Un-coursed Random Rubble Stone Masonry wall

Stone boulders from various sources, including river stones, field stones, and quarried stones, are used for stone masonry construction, where river stones or field stones are often used in their natural round or irregular forms as shown in Fig. 1.50; this is especially the case when the materials, expertise, or labour required to shape these stones is difficult to find or excessively expensive. Alternatively, an artisan stone-cutter can shape stones to produce semi-dressed stones, which have at least one exterior flat surface (wedged stone), as shown in Fig. 1.52. In some cases, stones can be fully dressed into regular shapes to better suit construction (Bothara and Brzev 2011).

Stones used for this type of construction are irregular shape, including small or medium-size river stones, smooth stone boulders with rounded edges, or stones from quarries. Sometimes, these round stones are usually laid in mud or lime mortar. The walls consist of two Wythes and the space between the Wythes is filled with mud, small stones and pieces of rubble. Wall thickness is usually of the order of 600 mm,

but it can be excessively large up to 2 m. In many instances, the exterior walls in the building are constructed first and the interior walls are constructed later without any connection. Rooms in these buildings are generally small and there are few small wall openings (if any) (World Housing Encyclopedia No 16).



Figure 1.52 Round stone boulders used for traditional stone masonry and semi-dressed stones ready for wall construction (Bothara and Brzev 2011)

ii) Un-coursed Semi-Dressed Stone Masonry wall

This construction type is similar to random rubble stone masonry in that there are two external wall Wythes and an interior filled with rubble. However, in the case of semi-dressed stone masonry, the exterior Wythes are dressed. As a result, the construction has a better appearance, although its seismic performance may not be significantly improved.



Figure 1.53 Un-coursed semi-dressed stone masonry walls (Bothara and Brzev 2011)

Fig. 1.53 show examples of un-coursed semi-dressed stone masonry, in some regions of the world, timber or brick bands are used to enhance the wall stability in both un-coursed random rubble and semi-dressed masonry.

iii) Dressed Stone Masonry wall (Ashlars Masonry)

Dressed stone masonry is constructed during the use of stones of regular shape that look like solid blocks, as shown in Fig. 1.54. Stones with a rectangular or square face are also called ashlar. Dressed stone masonry can be found in Europe. It should be noted that some types of stone are easier to shape than others. For example, the widespread use of dressed stone masonry in Also; in this type of walls, they used tuffs (rocks formed from volcanic ash), which are relatively easy to shape. Mortar in dressed stone masonry walls is usually of poor quality. The thickness of dressed stone masonry walls is less than other types of stone walls, in the range of 300 to 600 mm.

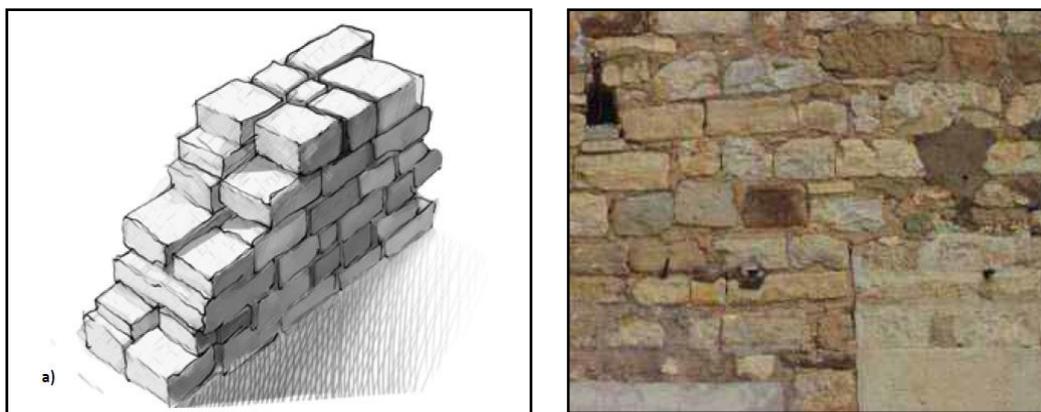


Figure 1.54 Dressed stone masonry: an isometric view of a typical wall, and an exterior of a wall

Multiple-leaf walls are frequently found in historic traditional masonry walls. They usually consist of two or three leaves made up of different materials such as limestone, brick or rubble masonry in Cairo (see Fig. 1.53) in historic traditional houses in Athens the three leaves walls were built with rubble marble, limestone, bricks, and Volcanic stone (if any), using mortar with lime, mud, and pozzolans.

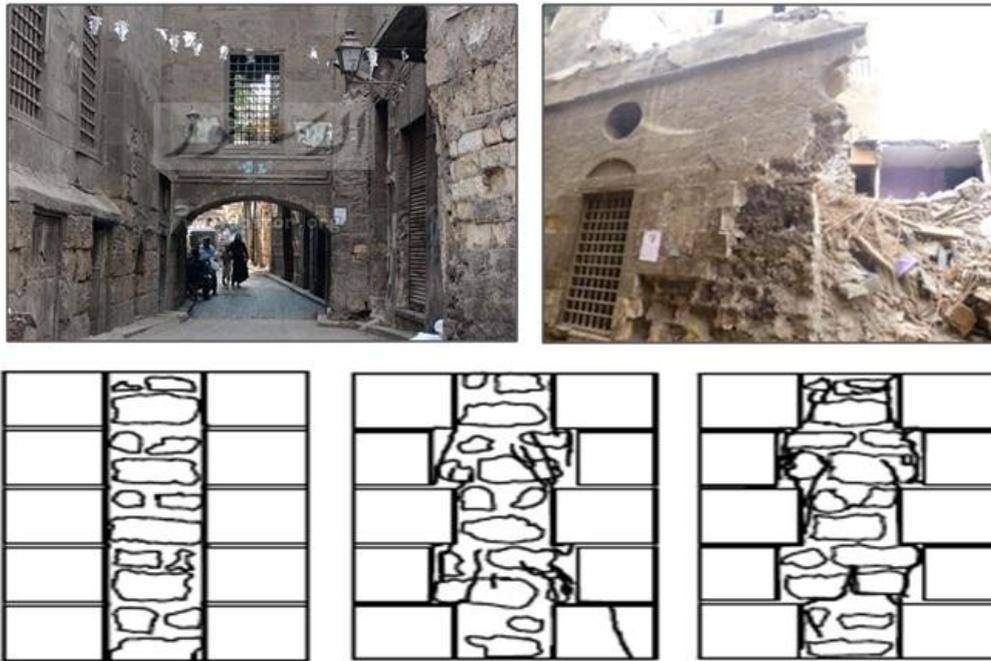


Figure 1.55 The three leaves walls in historic traditional masonry buildings

1.6.2- Floor and Roof Structures

Floor and roof structures in historic traditional masonry construction utilize a variety of construction systems and materials. The choice is often governed by the regional availability and cost of materials, and local artisan skills and experience. Floor and roof systems include masonry vaults and timber joists or trusses. Floor structures in towns and historic centers have timber joists at the upper floor levels. Timber joists are usually placed on walls without any physical connection (World Housing Encyclopedia No 16).

Timber floor construction may be in the form of wooden beams covered with wooden planks, ballast fill, and tile flooring, as shown in Fig. 1.56. A timber floor structure overlaid by planks and bamboo strips is also common, in hot climate regions, a thick mud overlay is provided on top of the roof for thermal comfort. In most cases, timber joists are placed on top of walls without any positive connection; this has a negative effect on seismic performance (Bothara and Brzev 2011).

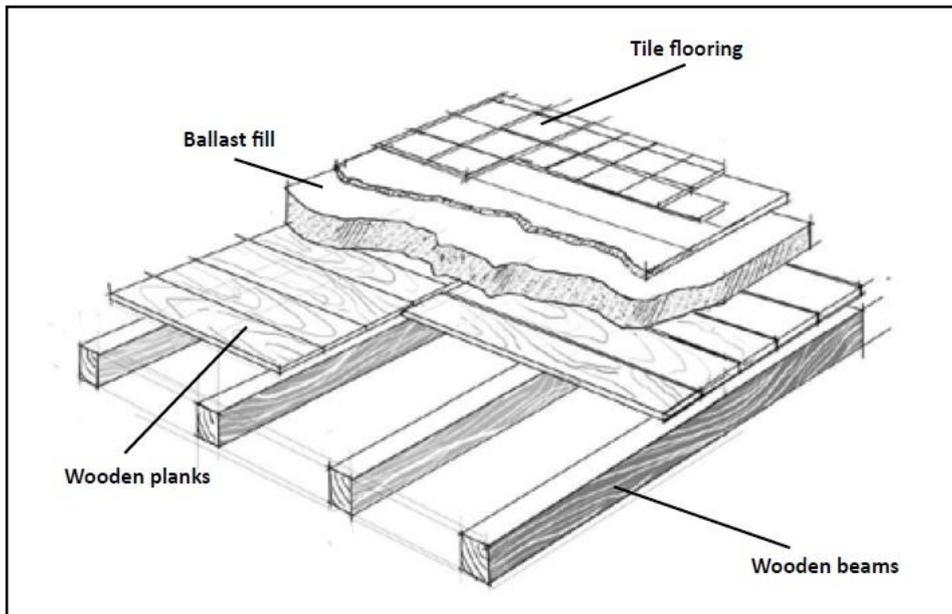


Figure 1.56 Typical floor constructions with wooden beams and planks, ballast fill, and tile flooring (Bothara and Brzev 2011)

However, in some instances, particularly in earlier roofs, timber roofs were framed, that is to say, their members were joined together and braced so as to form a rigid structure very much like a boat turned upside-down that only needed vertical support, all other forces being sustained by the frame; but some original roof members were seriously undersized, especially in the periods when timber was in particularly short supply. Framed roofs generally had numbered joints. If the numbers don't coincide, then the timber is probably re-used from an older roof. In early roofs, the timber was split, and axed with a minimum of sawing. The faces left by machine sawing are quite different in appearance from hand sawn surfaces. Early roof timber pegged together; only later roofs have nails and screw fixings. In early roofs the lower rafter ends are held in place by being built into the head of the wall, whereas in later roofs there is a timber wall plate

The suspended floors found in most domestic buildings are single floors consisting of one set of timber joists, called common joists or bridging joists. In such buildings, the joists span the full distance between the bearing walls with the ends

supported by wall plates, either bracketed off the wall or built into the supporting masonry. In floors of a wider span, one or more beams or binders run from wall to wall to carry the joists, with the beam ends supported by the bearing wall. In the largest floors heavy beams or girders run between supports and carry a series of binders which in turn carry the joists as shown in Fig. 1.57

In medieval floor construction, fairly shallow butt-jointed boards were often let into rebates running along the upper edges of large section joists. The continuous floor finish was formed of boards and the exposed parts of the joists and the floor may well have been left open to view from the underside, and decorated in higher status buildings. Later floors were simpler, with plain or square edged boards laid over the joists at right angles to provide a continuously boarded upper surface. This is the most common type of suspended floor, found in most buildings of the 18th, 19th and early 20th centuries. Floorboards were generally secured by cut nails called floor brads, usually twice the thickness of the board in length, nailed through, about 25mm from each edge of the boards. For top nailed boards, the most common method was two nails driven through each board over every joist junction, including two nails at the ends.

The character of the floorboards, including their surface finish or patina, their deflection and undulation with the movement of the structure, and their fixing and jointing pattern, will all contribute to the overall character and historic interest of a building. In historical buildings one can distinguish three types of floors: caisson, double and single frame floors. The knowledge of the structural complexes in these sources is based on the arrangement of the timber elements (dimensions and lying out) forming the structure with operations aimed at improving the structural performance at the actual state of preservation of the handwork.

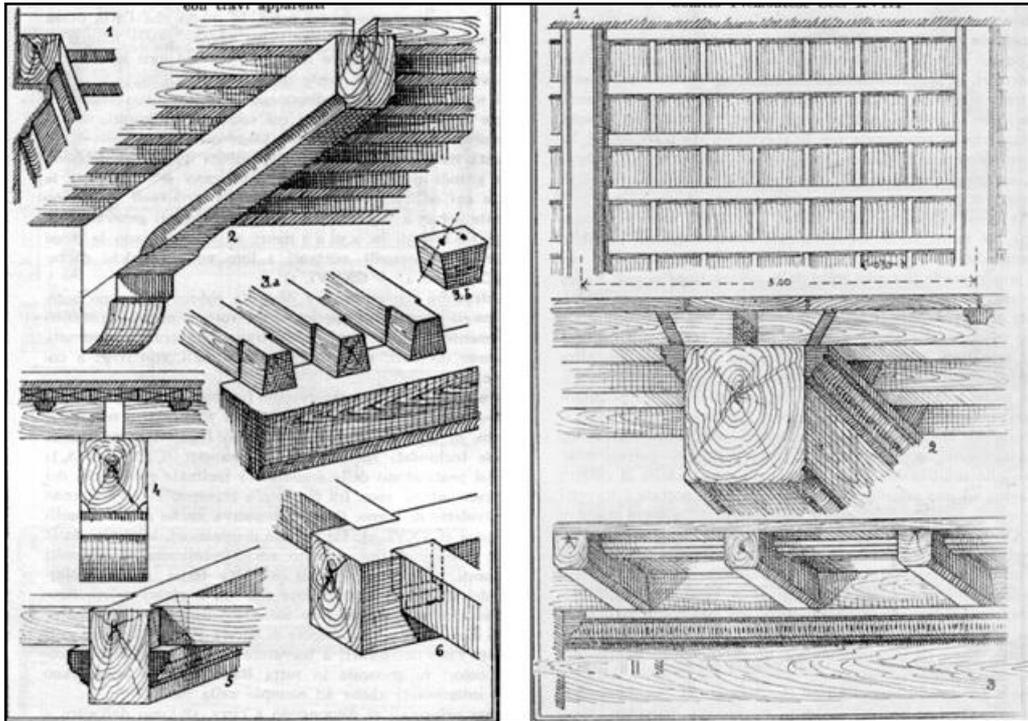


Figure 1.57 Double timber frame floor

Generally, in the historic treatises, they are defined as floor of length equal to the width of the room to be covered and it is further classified as simple floor made of beams set according to the width of the room at a close distance between centers of the roof with a superposed deck and a compound floor of main beams always placed along the short side of the room and by secondary beams laid out orthogonally with respect to the first and to the deck. In relation to the dimensioning of the simple floor beams, Scamozzi (1615) supplies indications on the basis of specific proportional ratios in function of the beams' clearance: heights equal to $1/24$ or $1/30$ of the span, bases $1/4$ or $1/3$ to the height and pitch equal to the height of the beam; furthermore, Scamozzi emphasizes two recommendations: "...use the same type of timber for all the beams used for the floor and set the beams at the correct distance, because, in case the beams are too close, their weight and the resulting excessive holes will weaken the masonry, while, on the other hand, in the case of beams too spaced, their increased deflection could provoke cracks in the floor above".

Toward the end of 1800, the practice of laying out simple floors in rooms with a width of less than 3 m and double floors in rooms with a width between 3 and 6 m appears to have been well established: for simple frame floors, the proposed distance between the floor centers ranging from 40 cm to 50 cm, while for compound floors, the main beams distance from the centre ranging between 2 m and 3 m and 40 cm to 50 cm for the secondary beams (Cestari and Di Lucchio 2001).

1.6.2.1- Gabled roof

A gabled roof is a double-pitched roof finished at each end with a gable wall. A range of materials was employed to construct and cover roofs in historic traditional houses. Archaeological evidence suggests that the earliest roofs used rough timber, even branches, covered with a variety of locally available materials such as thatch and plants branches.

The structure and form of roofs, and the materials with which they were built, changed over the centuries in response to both developing construction technology and architectural fashion. Medieval tower houses were generally constructed with thick masonry walls supporting heavy oak-beamed roofs. The roofs of tower houses were typically concealed behind stepped parapets, with wall walks, from which rainwater was thrown clear via projecting stone spouts.

Under the influence of the architectural ideas of the Renaissance, the form of the roof came to be seen as integral to the overall composition. Roof dormers became common and were designed to read as part of the fenestration pattern of the entire façade. On more substantial structures, the roof profile was enhanced by decorative corbels and pediment fronts. Seventeenth-century roof profiles tended to be steeply pitched to ensure a fast flow of water off the small slate or tile cover. Plain (flat) and

double-curved clay tiles, or ‘pantiles’, were commonly used. The use of slate at this time was limited to prestigious buildings. (Donnelly 2010)

1.6.2.2- Gabled Roof Structures and Materials

The shape and appearance of a traditional roof were determined primarily by the properties of the materials chosen to construct and to clad the roof. However, architectural fashions and styles also played a role and influenced the final roof form. Other important components of the traditional pitched roof – the ridge, the verge and the eaves – could be built and assembled in many ways, giving rise to the myriad of different forms found in traditional roofs. The capability of the chosen structural material to span between supports dictated not only the shape of the roof, but also the overall depth and dimensions of the building. Traditionally, timber was the most common structural material used in roofs and the shape and proportions of these roofs were based on the span of the timbers between supports, usually load-bearing walls (see Fig. 1.58).

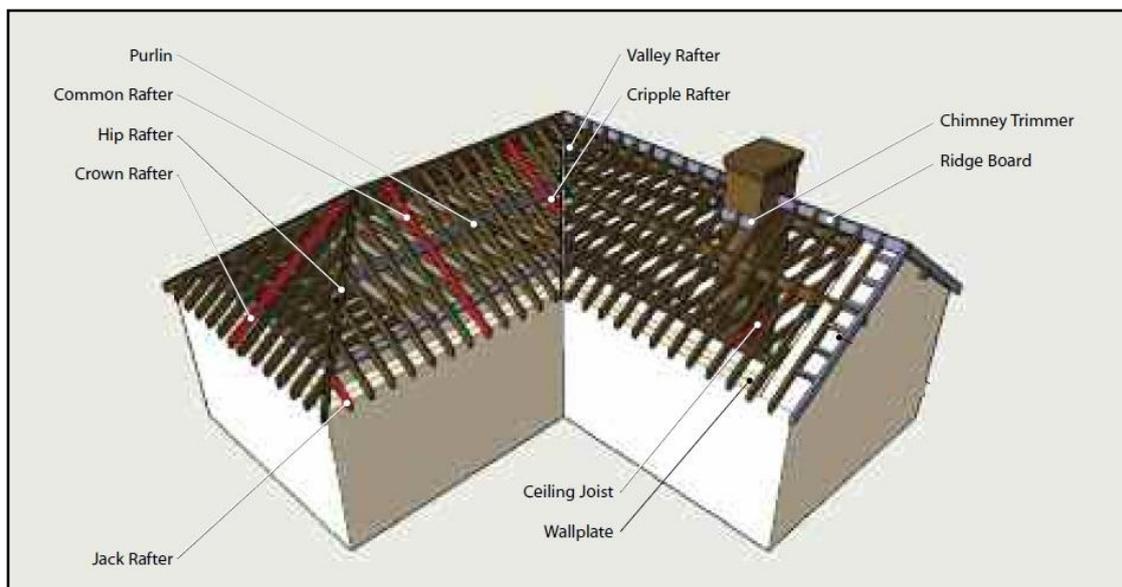


Figure 1.58 Terms used to describe the elements of the roof (Donnelly 2010)

The pitch, or slope, of a roof was determined both by the characteristics of the cladding material to be used and by architectural type. Different cladding materials are required to be laid at different pitches if they are to provide a watertight roof that will counteract wind pressure and avoid becoming saturated by rainwater.

The roof pitch may range from a steep 60 degrees on some seventeenth-century buildings to a shallow 30 degrees or less on eighteenth-century roofs designed to be concealed behind a parapet, but is commonly between 40 – 45 degrees on slate roofs. Clay tile (Aramid) can tolerate being laid at a shallower pitch, as low as 22.5 degrees for interlocking tiles and pan tiles.

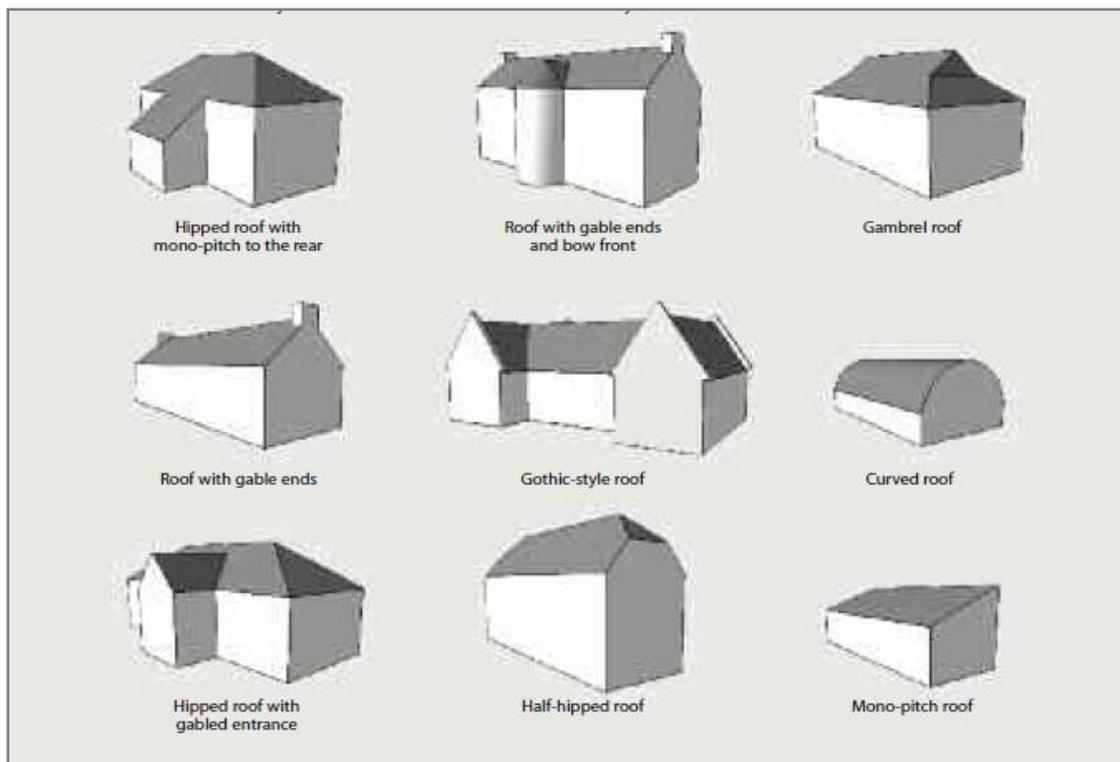


Figure 1.59 Some typical roof forms

The most common form of traditional roof is the double-pitched or ‘A-framed’ roof. The rafter pairs were usually tied with horizontal tie beams. Ceiling finishes, if applied at all, were fixed directly to the underside of the rafters and tie beams. Although a simple double pitch is the most common form of roof found, roofs may

vary from a single, or mono, pitch to more complex arrangements. In the eighteenth century, the desire to reduce the visual prominence of the roof led to the use of two double pitched roofs, each with a shallow pitch, forming a double 'A' profile with a central valley, thus reducing the overall span and the height of the roof.

Traditional roof construction evolved to commence with the laying of a sawn timber wall plate along the wall tops to provide a good horizontal bed off which to build the roof. This wall plate was usually, but not always, located at the inner face of the wall and also served to distribute the weight of the roof evenly along the wall. To achieve a continuous and secure wall plate, lengths of timber were scarf jointed and bedded in lime mortar and were frequently secured with timber ties or wrought-iron strapping.

Sawn timbers were then laid in couples connected to each other at their apex and, from the early eighteenth century onwards, to a timber ridge board. These timbers, running from wall plate to ridge to support the roof cladding, are the rafters. Purlins, running between the rafters and parallel to the ridge, helped to stabilize the roof and reduce the span of the rafters. Collar ties were installed in many roofs, usually at mid-rafter span, but sometimes higher or lower, not only to help reduce any sag in the rafters but also to limit the outward thrust of the ends of the rafters, which would otherwise tend to push out the tops of the walls. Battens were often not used in these roofs and the flags were secured by nails hammered directly into rafters or purlins. Spans were kept to a minimum and rafters placed close together.

Builders often used timber economically, developing techniques that reduced the need for large or long beams and skilled carpentry. Masonry cross walls were continued into the roof space, allowing for the use of shorter purlins supported

between the cross and gable walls. From the early-eighteenth century onwards, ceiling and floor construction was also simplified by using clear spanning joists. The advantage of this long joist form of construction was that it provided a particularly efficient and continuous tie between structural walls. The downside of these long spans coupled with the rather small sizes of joist chosen by many builders is that they tend to result in larger-than-satisfactory ceiling deflections. The structural timbers of a historic roof are frequently older than the roof covering, which may have been replaced, sometimes several times, in the course of the building's existence.

1.6.3- Cantilevered Stairs

There are many situations in the conversion of a historic building where existing stone or timber cantilevered stairs have to be retained and required to support increased loadings. Such stairs formed the principal staircase in many town and country houses and are thus important in defining the character of the building. While these stairs have passed the test of time and are structurally sound, engineers have been unable to provide detailed structural calculations to prove the ability of a stair to support increased imposed loads (Binda et al. 2000).

There are therefore concerns about their real strength. While the ends of the steps are built into a masonry wall and the stone then cantilevered out, the stair does not act as a true cantilever as the load is transferred down through the steps to the lowest step and then to the supporting floor. Each tread carries the weight from above on its back edge and is supported under its front edge by the tread below. The bearing capacity of the wall (which is also subjected to out-of-plane moments), the condition of the masonry around the built-in end of each step (or landing), the bearing of one tread upon another and the strength of the supporting floor all contribute to the stability of the stair.

When assessing the strength of an existing staircase, the unknowns may include:

- The strength of the stones of the staircase
- The quality of the material of the supporting wall
- The quality of the mortar between the treads
- The way the staircase was built (i.e. tread on tread, or the whole flight on centering),
- The vertical and horizontal support provided at the top and bottom of the flights,
- The way landing slabs have been jointed.
- The strength and stiffness of the handrail

As a result, the only practical means of determining whether the stair has the ability to support the actual loads to be imposed, as a result of change in use, is to subject the stair to a load test (Urquhart 2007).

Concluding Remarks

- A multi-disciplinary approach is obviously to damage assessment and rehabilitation of historic traditional masonry buildings requires the organization of studies and analysis in steps that are similar to those used in medicine, anamnesis, diagnosis, thereby and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of efficiency of the interventions.
- Historic traditional masonry structures are the cultural reflections of a society; they create a strong link between the past and the present by describing the economic, social and technical situation of the ancestors of a society.
- Historic traditional masonry are a form of architecture which makes use of local resources, both materials and construction techniques, skills and expresses the fundamental culture of different communities and their relation with nature and the landscape; it represents an important part of our cultural heritage.
- It has become widely accepted to classify any buildings put up without a formal design process as traditional masonry, Their form, plan and method of construction simply follows tradition aspects. The most important characteristic of masonry construction is its simplicity, laying pieces of stone, bricks or blocks on top of each other, either with or without cohesion via mortar.
- Traditional ways of building have evolved, one person learning from another. Changing circumstances have led to changing solutions whereas influences from other cultures have gradually been blended in. At any given point in

time, there have been shared values, shared customs, local materials and local ways to use them and the learning process has always been to build on the past.

- Historic traditional masonry houses are found in urban and rural areas around the world. There are broad variations in construction materials and technology, shape, and the number of stories. Houses in rural areas are generally smaller in size and have smaller sized openings, on the contrary, houses in urban areas are often of mixed use - with a commercial ground floor and a residential area above.
- Architectural typology is based on the repetition of a basic rectangular housing unit with flat roofing. The basic unit can be used to form a long single room house or it can be used to form a twin room house with a vaulted wall separating the two rooms and subsequently supporting the roof.
- The process of housing development to form simple two stories house, the ground floor consists of two elongated rooms and the first floor consists of a single room, which covers only half of the ground-floor area. It was built by medium strength stone masonry. The roof is almost flat and was originally supported by wooden beams covered by earth to provide insulation.
- Historic traditional houses includes various forms, which were developed in response to religious, cultural, and traditional factors along with the specificity of the local built environment.
- Traditional urban residential masonry buildings in Greece are usually made of rubble (cobble) natural stones and a large volume of low strength lime mortars, while their floors/roofs are made of timber elements.

- Historic traditional houses in Athens are typically found in flat (individually), sloped and hilly terrain. They do not share common walls with adjacent buildings. The typical separation distance between buildings is 5 meters and more as a rule when separated from adjacent buildings, the typical distance from a neighboring building is 5 meters.
- Historic traditional house in Athens has at least eleven openings per floor, of an average size of 3.5 m² each. The estimated opening area to the total wall surface is 18%. This is relevant to the resistance of this type of building. The main function of this building typology is single-family house. It is very common to find these historic buildings used for commercial purposes.
- In traditional buildings in Athens, large limestone were used at the corners, where larger stress concentrations tend to develop, in order to provide an appropriate connection between wall panels. On the other hand timber ties are widely used, builders always used timber as reinforcement in the form of timber ties at many levels within the height of the walls.
- in addition to stone and timber steel connections used in traditional masonry in Athens to connect roofs with walls, this type of technique use steel bars in order to achieve good connection between walls and walls, or between walls and floors or roofs
- Historic Cairo is an urban ensemble that extends from street to alley to lane and covers a large number of historic buildings range from religious structures such as mosques and churches, to residential structures such as palaces and houses (*manazels*).
- Traditional dwellings were an integral part of the traditional urban fabric of Cairo city. The houses of rich and poor were adjacent within the neighborhood

unit, without caste or social discrimination, whether in the form of a housing unit or external processors of these houses. However, a common feature of most historic traditional buildings is that they contain soft, weak or permeable materials, such as lime mortars, plasters, renders and paints.

- The environmental and morphological characteristics of the site determine the shape and orientation of historic traditional houses in Cairo, the characteristic of the structure, of the wrapper, of the distribution as in the case of the openings covered with panels made of wooden grids to protection of the privacy of the house from the outside.
- Walls in historic traditional masonry are generally uniformly distributed in both orthogonal directions with thickness ranging from 400 mm to 700 mm, made of undressed rubble stone and semi fired and fired brick in mud/lime mortar and most of them have not any formal training.
- Stone masonry walls can be classified into three types: un-coursed random rubble stone, un-coursed semi-dressed stone, and dressed stone
- Floor and roof structures in historic traditional masonry construction utilize a variety of construction systems and materials. The choice is often governed by the regional availability and cost of materials, and local artisan skills and experience. Floor and roof systems include masonry vaults and timber joists or trusses. Timber joists are usually placed on walls without any physical connection

After that and according to the methodology of rehabilitation of historic building it must be study and identify the deterioration phenomena and deterioration factors in historic traditional masonry buildings.

References

- 1- Abdelmegeed M., 2009 " study of the causes of cracking and collapsing of archaeological Islamic buildings and the proposed methods treatment to the selected buildings "Master degree, restoration and conservation department, Faculty of archaeology, Cairo University, Cairo, Egypt.
- 2- Abdelmonem M. 2012 " The Practice of Home in Old Cairo: Towards Socio-Spatial Models of Sustainable Living" Traditional Dwellings and settlement Review (TDSR) volume xxiii Portland, Oregon.
- 3- Abdel-moniem E., 2010 " Traditional Islamic-Arab House: Vocabulary And Syntax" International Journal of Civil & Environmental Engineering IJCEE-IJENS Vol:10 No:04
- 4- Abdulmunim A., 2006 "Historic Cairo conservation project" 1st international conference on restoration of heritage masonry structures, Cairo, Egypt, April 24-27.
- 5- Alexandris A. Protopapa E., and Psycharis I., 2004 "Collapse mechanism of masonry buildings derived by the distinct element method" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6,
- 6- Al-Zubaidi M., and Dr. Shahin B., 2005 " Sustainability Principals of Traditional Architecture in the Islamic Perception" Architectural Engineering Department Faculty of Engineering-University of Baghdad, Iraq
- 7- Ambrose, J., Vergun, D.1999 "Design for Earthquakes". John Wiley & Sons, Inc. New York.
- 8- Binda L., Saisi A., Tiraboschi C. 2000 "Investigation procedures for the diagnosis of historic masonries "Construction and Building Materials.
- 9- Bothara J. and Brzev S. 2011 "Improving the Seismic Performance of Stone Masonry Buildings" first published, Earthquake Engineering Research Institute, Oakland, California.
- 10- Casanovas X. 2007 "Traditional Mediterranean Architecture II. Rehabilitation Buildings" Barcelona, 30 June 2007.
- 11- Cestari C. B., and Di Lucchio A., 2001 " Interventions on historical building timber floors: Retractable – visible? Invasive – not visible A case study" Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães.
- 12- Charkiolakis N. , Aggeliki Koumna A., Leni M, Manos Mikelakis, Maria Psallida 2008 "Traditional Environmental Architecture in re-use: The "Courtyard of Miracles" in Athens, Greece" WSEAS Transactions on environment and development Issue 11, Volume 4, November
- 13- Chronopoulos P, Chronopoulos, Nikos, Zigouris, Panagiotis Asteris 2012 "Investigation/Documentation and Aspects of Seismic Assessment and Redesign of Traditional Masonry Buildings in Greece" EACS 2012 – 5th European Conference on Structural Control Genoa, Italy – 18-20 June 2012 Paper No. # 238
- 14- Dirlich S. 2004 "The Building Stock and Traditional Building Principles: Sustainability Assessment for Historic Buildings" Leibniz-Institute of Ecological Urban and Regional Development, Dresden, Germany.
- 15- Dişkaya H., 2007" Damage Assessment of 19th Century Traditional Timber Framed Structures in Istanbul" From Material to Structure - Mechanical Behaviour and Failures of the Timber Structures ICOMOS IWC - XVI International Symposium – Florence, Venice and Vicenza 11th -16th November 2007.

- 16- Dmytro D., 2011 " performance of masonry buildings and churches in the 22 February 2011 Christchurch earthquake" Bulletin of the new Zealand society for earthquake engineering, Vol. 44, No. 4, December 2011
- 17- Donnelly J., 2010" Roofs: a guide to repair historic roofs " first published the stationary office, sun alliance house, Dublin2
- 18- Emeritus A.W. 1996 "Masonry walls materials and construction" Construction and Building Materials, Elsevier Science Ltd. All rights reserved.
- 19- Ficarella L., 2009 " The Domestic Architecture in Egypt between Past and Present: The Passive Cooling in Traditional Construction" Proceedings of the Third International Congress on Construction History, May 2009, Cottbus.
- 20- GARİP Ö. Ö. 2006 "Comparison of elastic and inelastic behavior of historic masonry structures at the low load levels" a thesis, the graduate school of natural and applied sciences of Middle East technical university.
- 21- Gülkan P. and Wasti1 S. T. 2009 "Seismic Assessment and Rehabilitation of Historic Structures" Copyright © 2009 Tech Science Press SL, vol.1, no.2.
- 22- Lopez J. Oller S., Oñate E., Lubliner J. 1998 "An Homogeneous constitutive model for masonry" Computational mechanics New Trends and Applications S. Idelsohn, E. Oñate and E. Dvorkin (Eds.) © CIMNE, Barcelona, Spain.
- 23- Lourenço P. B. 1998 " Experimental and numerical issues in the modeling of the mechanical behavior of masonry" structural analysis of historical constructions II P. Roca, J.L. González, E. Oñate and P.B. Lourenço (Eds.) CIMNE, Barcelona.
- 24- Lourenço P. B. 2002 " Structural behavior of civil engineering structures: highlight in historical and masonry structures" Structural Engineering and Materials.
- 25- Michelle G., 1995 "Architecture of the Islamic World, Its History and Social Meaning" Thames and Hudson, London
- 26- Oram R., and Stelfox D. 2004 "Traditional Buildings in Ireland" First published, Mourne Heritage Trust.
- 27- Ozen G. Ö. 2006 "Comparison of elastic and inelastic behavior of historic masonry structures at the low load levels" a thesis, the graduate school of natural and applied sciences of Middle East technical university.
- 28- Pena F. 2004 " the role of the tension strength in the collapse mechanism of unreinforced brick masonry constructions" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 1080
- 29- Randolph L. 2004 'Architectural issues in the seismic rehabilitation of masonry buildings', in Disaster Management Programs for Historic Sites, Association for Preservation Technology (Western Chapter) and the Johnstone Centre, Charles Sturt University.
- 30- Saatcioglu, M., and Anderson, D., 2004" World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 548
- 31- Salama A., 2006 " A typology perspective; the impact of cultural paradigmatic shifts on the evolution of courtyard houses in Cairo" Middle East technical University JOURNAL (METU JFA) (23: 1) 41-58
- 32- Siravo F.," Reversing the decline of a historic district" Historic cities support program, historic Cairo conservation, Cairo, Egypt.
- 33- Tassios T. P., Syrmakizis K., 2002 " Housing report- Load-bearing stone masonry building" World Housing Encyclopedia an Encyclopedia of Housing, Construction in Seismically Active Areas of the World, report 16, Greece.
- 34- Thomas K 1996 "Masonry walls" Butterworth, Heinemann, Oxford.

- 35- Tondre F. 1999 "EUR-OPA major hazards agreement of the council of Europe" in the Conference "Advances on Natural Hazards Mitigation- Experiences from Europe and Japan", held in Athens, 3-7 November 1999).
- 36- UNESCO World Heritage Centre - Management of World Heritage Sites in Egypt Urban Regeneration Project for Historic Cairo FIRST REPORT OF ACTIVITIES July 2010-June 2012
- 37- Urquhart D., 2007 "Conversion of Traditional Buildings Application of the Scottish Building Standards part 1 Principles and Practice" Guide for Practitioners Technical conservation research and education group, Published by Historic Scotland @ Crown copyright.
- 38- Urquhart D., 2007 " Guide for practitioners Conversion of Traditional Buildings Application of the Building Standards" Commissioned by Guide for Practitioners Technical conservation research and education group Published by Historic Scotland © Crown copyright Edinburgh .
- 39- Vasconcelos G.; and others 2006" Experimental Investigations on Dry Stone Masonry Walls" 1st International Conference on Restoration of Heritage Masonry Structures Cairo, Egypt April 24-27, 2006.
- 40- Vintzileou E. 2011 "Timber-reinforced structures in Greece: 2500 BC–1900 AD" Proceedings of the Institution of Civil Engineers Structures and Buildings 164.
- 41- World Housing Encyclopedia No 16 an Encyclopedia of Housing Construction in Seismically Active Areas of the World no 16.

2

Damage Factors and Aspects in Historic Traditional Masonry

- Introduction
- 2.1- Earthquakes
- 2.2- Change and conversion
- 2.3- Structural and construction defects
- 2.4- Cracks
- 2.5- Delamination of wall wythes
- 2.6- Out-of-plane movement
- 2.7- Ground Moisture
- 2.8- Roof deterioration

INTRODUCTION

Before starting work on the conservation and restoration (rehabilitation) of historic masonry buildings, we must first stand on the damage phenomena and its causes in these buildings (Mills 1998). Thus understanding the causes of damage is deemed to be the first step in the conservation and restoration processes adopted for historic masonry buildings (Honeyborn 1998).

When dealing with a historic building, it is important to think of the building as an integral part of environmental system, not as an amalgam of separate elements that function independently of each other (Urquhart 2007). When thinking of the damage processes or damage mechanisms, the essence of it is the interaction between the building and the surrounding environment; in fact, it has been confirmed that the continuous changes of the surrounding environment plays an important role in the historic masonry buildings deterioration (Sharma and Maitis 1995).

In historic traditional masonry buildings, structural and architectural damage occurs when the stresses due to the action or effect of external forces exceed the strength of the materials at locations of the structural elements parts significant for structural integrity, either because the actions/forces themselves increase beyond expected limits or because of building materials deterioration. Substantial changes in the structure, including partial demolition, occur due to the acting forces and the type of construction materials used. Brittle material failure occurs in the form of cracking without any warning due to their low deformability, while ductile materials exhibit considerable deformation before failure, thus providing ample warning of the impending collapse (ICOMOS 2003)

Historic massive masonry structures frequently exhibit very typical mechanical deterioration phenomena such as the formation of vertical cracking and the local detachment of the outer wythes or layers in the case of multiple-leaf walls. Such types of damage may occur due to various causes such as, seismic action, foundation settlement, overloading due to structural modifications (e.g. added storey or change in the use of the building) chemical, physical and mechanical degradation of building materials.

It has also been found that high dead loads can activate time dependent phenomena (creep), which result in overloading the load bearing elements due to internal stress redistribution, which may lead to sudden failures without any warning in the form of crack extension and widening (Valluzzi et al 2005).

To this end, the investigation of the causes of damage of historic traditional masonry is important for reducing damage rates or for minimizing damage. Moreover, it is a prerequisite in restoration to develop data bases with suitable alternative materials for avoiding past mistakes (Honeyborn 1998). Dov (2004) has classified the deterioration of historic buildings in terms of unpredictable actions, such as, earthquakes, fires, etc, design faults, change and conversion, building materials, workmanship, and inspection/maintenance.

2.1 Earthquakes

Earthquake is one of the nature's greatest hazards to human life and property. It poses a unique engineering design problem. An intense earthquake constitutes a severe loading to which most civil engineering structures are likely to be subjected during their service life. (Shrestha 2008)

2.1.1 Earthquake Causes

Most earthquakes are caused by rock movement along rupturing faults located in the earth's crust. On a global scale, the earth's crust is divided into separate sections known as plates. Major faults are typically located at plate boundaries. However faults move or "slip" when shear stresses deep underground exceed the ability of the compressed faulted rock to resist those stresses.

Fault slip can move the nearest ground surface vertically, laterally, or in some combination. When this slip occurs suddenly, it causes seismic shock waves to travel through the ground, similar to the effect seen when tossing a pebble onto the surface of still water. These seismic waves cause ground shaking that is felt during an earthquake. Ground motion contains a mix of seismic waves having two primary characteristics as shown in Fig. 2.1; one is the wave amplitude, which is a measure of the size of the wave.

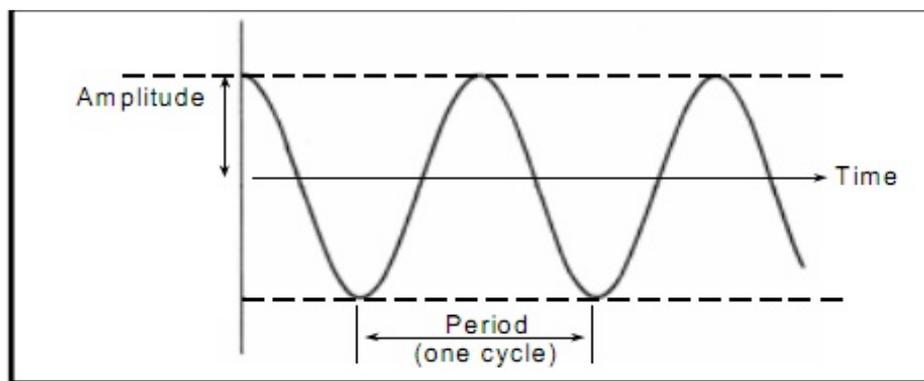


Figure 2.1 Cyclic waves of constant amplitude and period (Arya et.al, 2012)

The other is its period, which is measure of the time interval between the arrival of successive peaks or valleys, known as one cycle. This concept of time measurement can also be expressed as frequency, which refers to the period, i.e. one period, and it describes the number of cycles occurring per second, everything in the path of a seismic wave will be shaken.

However, the amount of ground motion at any given location depends on three primary factors; the first factor is the distance between the site and the source location of the earthquake, known as the focus or hypocenter. The shallower the focus, the stronger the waves will be when they reach the surface. The second factor is the total energy released from the earthquake. The last of the three primary factors is the nature of the soil or rock at the site: generally, sites with deep soft soils or loosely compacted fill will be more strongly shaken than sites with stiff soils, soft rock, or hard rock (Atc 1997)

Earthquake studies have almost invariably shown that the intensity of a shock is directly related to the type of soil layers supporting a building. Structures built on solid rock and firm soil frequently perform far better than buildings on soft ground. Also, buildings on sites with flat and even topography are usually less damaged during an earthquake than buildings on ridges, in narrow valleys, and on steep slopes as shown in Fig. 2.2 (Arya et al 2012).

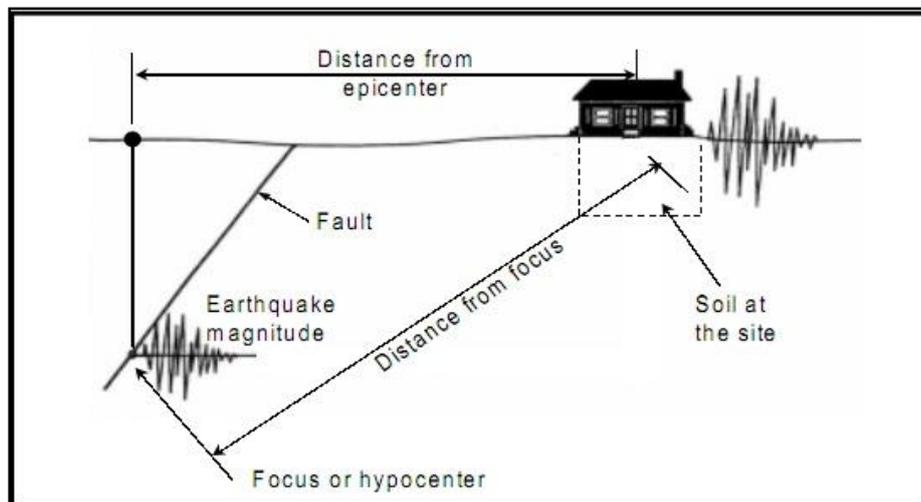


Figure 2.2 Common terms and factors affecting shaking intensity at a given site (Arya et al 2012).

Besides the above factors, there are other factors affecting damage, such as the following:

- **Building configuration:** An important feature is regularity and symmetry in the overall shape of the building. A building shaped like box, rectangular both in plan and elevation, is inherently stronger than a L or a U-shaped, such as a building with wings. An irregularly shaped building will twist as it shakes, thus suffering more damage.
- **Opening size:** In general, openings in walls of the building tend to weaken the walls, and the fewer the openings the less the damage suffered during an earthquake.
- **Stiffness distribution:** The horizontal stiffness of a building along its height should be uniform. Changes in the structural system of a building from one floor to the other will increase the potential for damage, and should be avoided. Columns or shear walls should run continuously from foundation to the roof, without interruptions or changes in material.

The horizontal ground motion is similar to the effect of horizontal force acting on the building; hence the term “seismic load” or “lateral load” is used. As the base of the building moves in an extremely complicated manner, inertia forces are created throughout the mass of the building and its contents as shown in Fig. 2.3. These reversible forces cause the building to move and sustain damage or collapse.

An additional and uplift effect is caused on slabs, beams, cantilevers and columns due to vertical vibrations, which may cause damage. Being reversible, at certain instants of time, the effective load increases, at others, it decreases. Earthquake loads are dynamic and impossible to predict precisely in advance since every earthquake exhibits different characteristics. The following equivalent lateral force F is used for seismic design as the product of the mass of the structure m and the acceleration

a , - $F = ma = eW$ - where e is the seismic coefficient and W is the weight of a building including its contents.

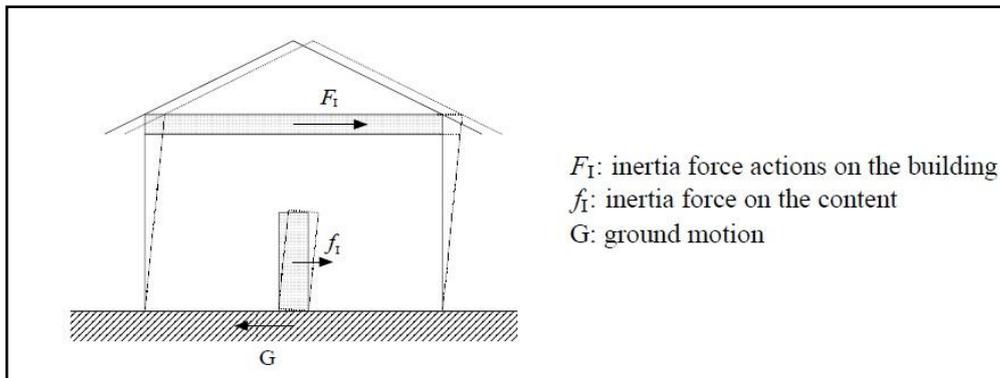


Figure 2.3 Inertia forces caused by the earthquake ground motion (Arya et.al, 2012)

The inertia forces are proportional to the mass (or weight) of the building and only building elements or contents that possess mass will give rise to seismic force on the building. Therefore, the lighter the material, the smaller will be the seismic force (Arya et al 2012).

2.1.2- Earthquake Effects on historic traditional masonry

It is said that "Earthquake damage is the mother of earthquake engineering" and that provides a good opportunity for learning from the observation of damage (Boen. 2001). Observation of structural performance of buildings during and after earthquake shaking can clearly identify the strong and weak aspects of the design, as well as the desirable qualities of materials, techniques of construction and site selection: the study of damage provides an important step in the evolution of strengthening measures for different types of buildings (Boen 2001).

The Mediterranean and Balkan area is greatly exposed to seismic hazards. Consequently, its cultural building heritage is strongly susceptible to undergo severe damage or even collapse due to earthquake. The constructions mostly exposed to seismic risk are the historical and monumental ones, since in many cases they are not

endowed with basic anti-seismic features and/or no seismic retrofit has been applied to them (Mazzolani 2008)

Ground shaking is the principal cause of earthquake-induced damage; as the earth vibrates, all buildings on the ground surface respond to that vibration in varying degrees. Earthquake induced accelerations, velocities and displacements can damage or destroy a building. Seismic design loads are extremely difficult to determine due to the random nature of earthquake motions (Arya et al 2012).

Shape or configuration is another important characteristic that affects building response, Earthquake shaking of simple rectangular buildings results in a fairly uniform distribution of the forces throughout the building, whereas in T- or L -shaped buildings, forces concentrate at the inside corners to those shapes. Similar problems arise when building floor or roof levels offset vertically (split levels), or when the first storey is taller or “softer” than the others. Irregularly shaped buildings, shown in Fig. 2.4 are subject to special design rules because otherwise they can suffer greater damage than regularly shaped buildings (ATC 1997)

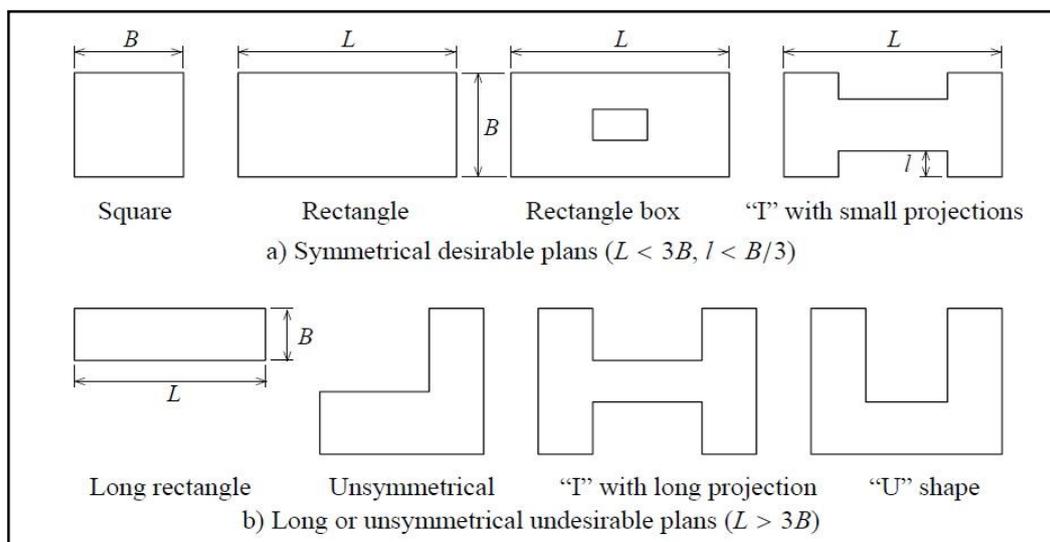


Figure 2.4 Different buildings shapes or configurations (ATC 1997)

Relative poor seismic performance of some traditional building systems is the main reason of failure to many masonry structures in seismic zones. In addition to the poor physical properties of building materials. As a consequence of this, masonry is widely thought to be unsuitable to comply with performance-based requirements in seismically prone regions (Toranzo et al 2001).

Most of the structural failures in traditional building masonry which was observed in past earthquakes were associated with deficiencies in the structure as built, whether caused by design, by lack of supervision, or poor physical properties of materials, poor workmanship (Boen 2001), so the extremely unsatisfactory degree of seismic protection is clearly apparent. Degradation in material, lack of appropriate maintenance and absence of elementary anti-seismic provisions are the clear reasons of the very large number of the collapses, particularly in old masonry structures, that occurred during earthquakes (Mazzolani 2008).

It has been proven that all of the old historic traditional stone masonry buildings tend to be at greater seismic risk than comparable new buildings, not only because they have been designed with minor or no seismic loading requirements, but also because they are not capable of dissipating energy through large inelastic deformations during an earthquake (Bruneau1994). Table 2.1 shows the factors influencing the seismic vulnerability of historic masonry buildings. Damages, which are frequently attributed to earthquake, have different causes and may have occurred due to excessive dead load or soil settlements, or simply due to lack of maintenance (Binda et al2006).

The structural damage assessment of historic traditional masonry due to earthquake indicates the following types of failures:

- 1- Total collapse of the traditional building as shown in Fig. 2.5
- 2- The destruction and collapse of load bearing walls
- 3- The deep fissuring in the load bearing walls
- 4- Vertical or shear cracks to the walls as shown in Fig. 2.6
- 5- The collapse of internal walls
- 6- The destruction of floors
- 7- The destruction of roofs as well as stairs

Table 2.1 Factors influencing the seismic vulnerability of historic masonry buildings (Magenes 2006).

	Higher vulnerability	Lower vulnerability
i)	Insufficient quality of materials (poor mortar, weak/brittle units), poor “internal connection” of masonry (uncoursed irregular rubble stones, multi-leaf masonry with no transverse connection...).	Regular and robust units, good bond and interlocking of units, masonry behaves monolithically through the whole thickness of the wall.
ii)	Very slender walls (out-of-plane instability)	Limited slenderness of walls; restraints to out-of-plane failure
iii)	Lack of efficient connections among walls and between walls and horizontal structures, lack of structural redundancy	Good interlocking at wall intersections, presence of tie rods and ring beams at each floor (and roof) level to favor “box action”, efficient floor-to-wall connections which reduce stress Concentration.
iv)	Floors do not provide diaphragm action	Sufficiently stiff and resistant diaphragms to provide restraint to out-of-plane vibration of walls, to increase structural redundancy and favor internal force redistribution.
v)	Presence of horizontal thrusts (e.g. from roof or arched or vaulted structures) equilibrated only by out-of-plane resistance of structural walls	Horizontal thrusts are reacted by in-plane action of strong walls/buttresses or by suitable structural elements (ties, floor diaphragms...) to form a “closed” self equilibrating system
vi)	Excessive unsupported floor spans, widely and irregularly spaced walls	Limited floor spans, regularly spaced shear walls in at least two orthogonal directions
vii)	High structural and non structural masses and low material strength	Masses and weights produce a low stress/strength ratio
viii)	Structural irregularity in plan (torsion effects, stress concentrations) and in elevation (inefficient load path, stress concentrations)	Regular structure, sufficient torsion resistance, Regular path of forces from upper structure to foundation.

Table 2.2: Earthquake intensity and the typical observed effects

Earthquake intensity	Vibration intensity	Definition (Description of typical observed effects (abstracted))
I	Not felt	Not felt (Recorded by seismographs)
II	Micro (Scarcely felt)	Micro earthquakes. Felt only by very few sensitive individual people at rest in houses. Recorded by seismographs
III	Weak	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	Largely observed	Felt indoors by many people, outdoors by very few. A few people are awakened. Windows, doors and dishes rattle.
V	Strong	Felt indoors by most, outdoors by few. Many sleeping people awake. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	Slightly damaging	Many people are frightened and run outdoors. Some objects fall. Some houses suffer slight non-structural damage like hair-line cracks and fall of small pieces of plaster.
VII	Damaging	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many well built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls.
VIII	Heavily damaging	Many people find it difficult to stand. Many houses have large cracks in walls. A few well built ordinary buildings show serious failure of walls, while weak older structures may collapse
IX	Destructive	General panic. Many weak constructions collapse. Even well built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	Very destructive	Many ordinary well built buildings collapse.
XI	Devastating	Most ordinary well built buildings collapse, even some with good earthquake resistant design are destroyed.
XII	Completely devastating	Almost all buildings are destroyed.



Figure 2.5 Total collapse of construction



Figure 2.6 Typical wall cracking (Abdessemed 2003)

2.1.3- Damage mechanism of historic traditional masonry

Existing historic traditional masonry buildings, often do not satisfy basic construction design rules or requirements, for example, well-connected walls and floors and a proper horizontal stiffness of floors, the construction methods of common buildings in historic areas are often realized by following traditional codes/rules of practice and according to typologies (multi-material masonry, multi-leaf walls) and construction details (poor connection between intersecting walls, between walls and floors and even differences in the wall thickness layers). Such traditional practices, in some cases, lead to serious deficiencies for the stability and the safety under seismic actions (Abdessemed-Foufa 2003). Thus, such types of buildings/masonry often have insufficient strength to resist earthquake forces in high and moderate seismic zones and lack the ability to dissipate energy (Dizhur et al 2010).

Historic traditional masonry buildings frequently have unsatisfactory behavior under seismic activity, due to the poor resistance of the masonry walls to tensile stresses and the presence of flexible wooden floors (Branco and Guerreiro 2011). Horizontal seismic forces are reversible in direction and structural elements such as walls, beams, and columns that bear only vertical loads before the earthquake have

now to carry horizontal, bending and shearing forces as well. When the bending tension due to an earthquake exceeds the vertical compression, net tensile stress will occur. If the building material is weak in tension such as brick or stone masonry, cracking occurs which reduces the effective area for resisting bending moment, as shown in Fig. 2.7, it follows that the building material strength in tension and shear is important for earthquake resistance.

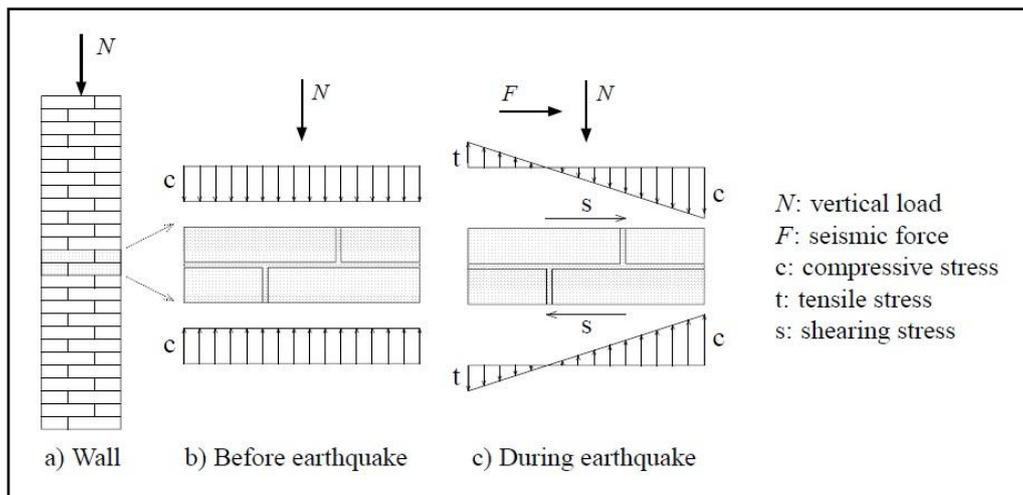


Figure 2.7 Stress condition in a wall element (Bothara and Brzev 2011)

The excessive thickness of stone walls, often compounded by heavy floors or roof, account for the heavy weight of these buildings, thus resulting in significant inertia forces being developed during an earthquake. As a building material, stone usually has a significant strength when subjected to compression, and it is stronger than most other conventional masonry units (bricks and concrete blocks). However, when round, unshaped stones and low-strength mortar are used and artisan skills are at a low level, the resulting structures are extremely vulnerable (Bothara and Brzev 2011).

Therefore, in some historic traditional masonry, it has been observed that the collapse of the façade occurred due to the lack of connection between floors and walls or between walls themselves or detachment of the external layer of the wall due to

the absence of good multi-layer connection and the collapse of the corner due to the excessive nearness of corner to the openings (see Fig. 2.8) (Abdessemed-Foufa 2003).



Figure 2.8 Out-of-plane corner mechanisms of masonry building units located in the historical center of San Felice sul Panaro and Salerno building (Branco M., 2011, Augenti, N. 2007)

Also horizontal bands are provided in the form of masonry lintel band and roof band, even if horizontal bands are provided, masonry buildings are weakened by openings in walls (as shown in Fig. 2.9). From past observations, it can be said that during the earthquake shaking all the elements of the building tend to move in the same and opposite or contrary direction, the roof tends to separate from the supports, the roof covering tends to be dislodged, the walls tends to tear apart and, if unable to do so, tends to shear off diagonally in the direction of motion, but arches and columns tend to tear and collapse' (Magenes 2006)

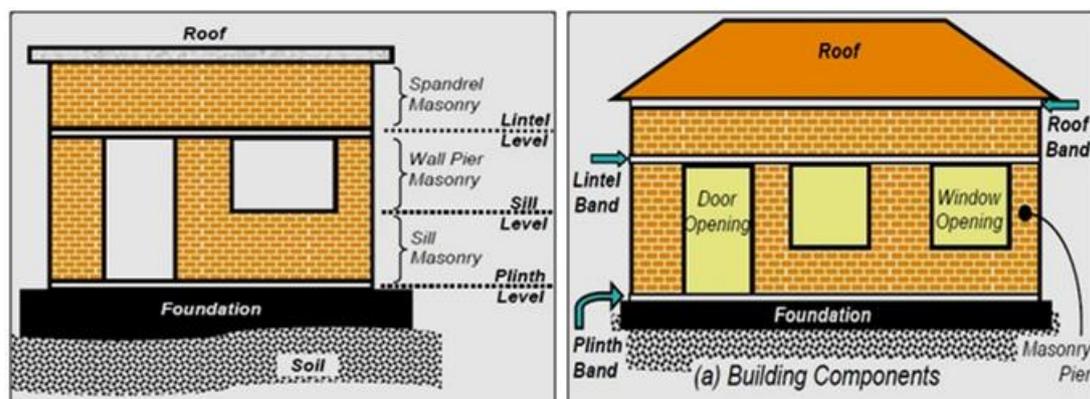


Figure 2.9 Sub-units in masonry building – walls behave as discrete units during earthquakes (Boen 2011)

The shaking of a masonry pier can crush the masonry at the corners. Shaking is possible when masonry piers are slender, and when weight/load of the structure

above is small; otherwise, the piers are more likely to develop diagonal (X-type) shear cracking (as shown in Fig. 2.10) this being the most common type of failure in masonry buildings. During strong earthquake shaking, the building may slide just under the roof, below the lintel band, or at the sill level. Sometimes, the building may also slide at the plinth level (Boen 2001).

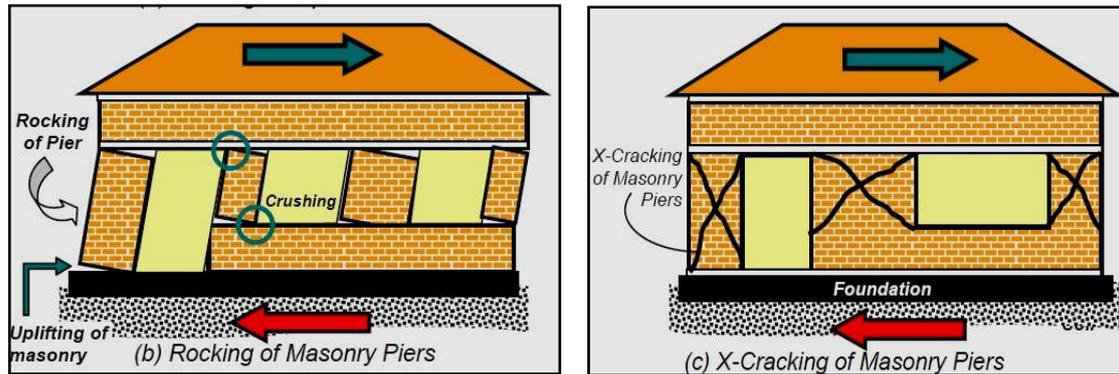


Figure 2.10 Earthquake response of a hipped roof masonry building (Boen 2011)

The seismic performance of an unreinforced masonry building depends on how well the walls are tied together and anchored to the floor and the roof; consider a simple building as shown in Fig. 2.11. When the walls are not connected at the intersections, each wall is expected to vibrate on its own when subjected to earthquake ground shaking (see Fig. 2.11a). In this situation, the walls perpendicular to the direction of the shaking (transverse walls) are going to experience out-of plane vibrations and are prone to instability, and possibly collapse when anchorage to the roof and transverse walls is not adequate. Walls parallel to the direction of the shaking (shear walls) are also susceptible to damage. When the walls are well connected, there is a rigid roof, and a horizontal ring beam (band) at the lintel level acts like a belt, the building is expected to vibrate as a monolithic box; that is a satisfactory seismic performance (see Fig. 2.11b).

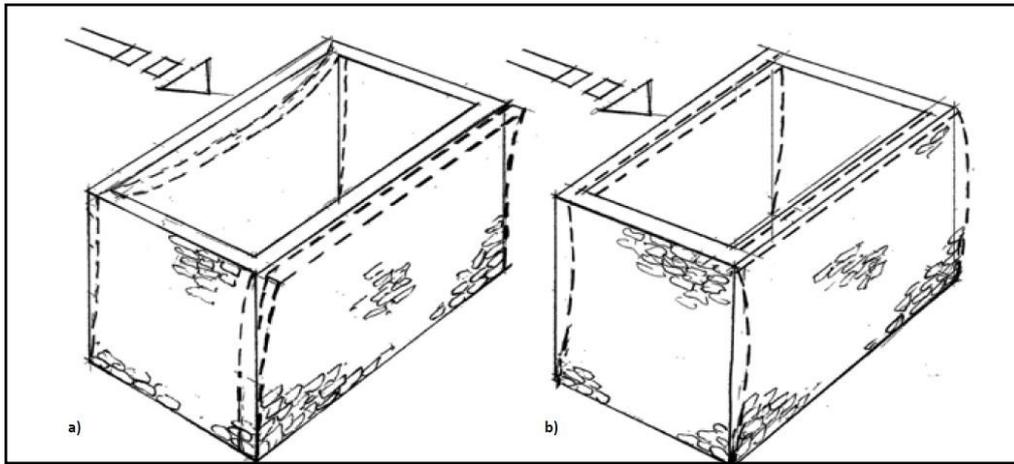


Figure 2.11 Masonry building during earthquake shaking: a) loosely connected walls without slab at the roof level, b) a building with well connected walls and a roof slab (Bruneau 1994)

It should be noted that a stone masonry building with a flexible roof may show good seismic performance provided that the walls are well connected and the roof maintains its integrity. During earthquake shaking, a band undergoes bending and pulling actions. A portion of the band perpendicular to the direction of earthquake shaking is subjected to bending, while the remaining portion is in tension. Wall intersections are particularly vulnerable to earthquake effects due to significant tensile and shear stresses developing when seismic forces are transferred from walls B (transverse walls) to walls A (shear walls). As a result, vertical cracks develop or separation may take place at wall intersections as illustrated in Fig. 2.12. The most failure causes of historic masonry buildings failure are the following:

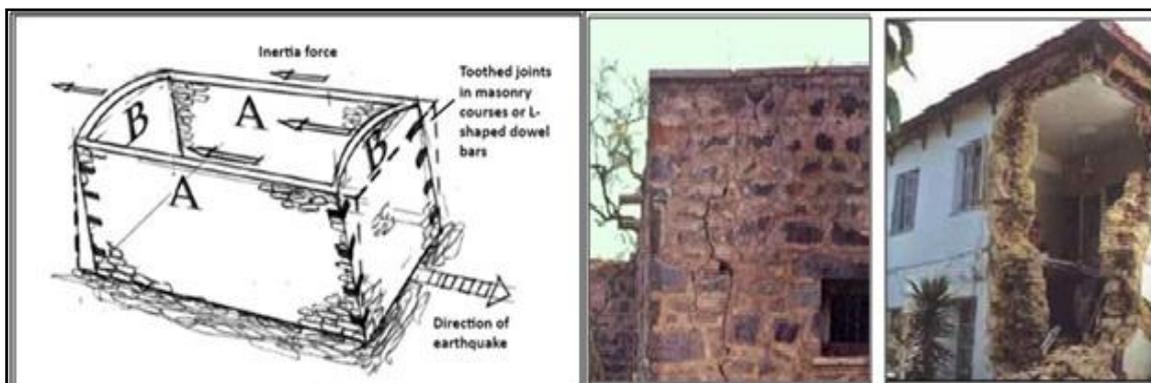


Figure 2.12 Wall B properly connected to Wall A: Walls A (loaded in the strong direction) support Walls B (loaded in the weak direction)

i) Lack of Anchorage:

In many unreinforced masonry (URM) buildings, there is a total absence of anchorage of the floor and roof to walls, the end of joists and beams, where the gravity system rest on the walls, being simply supported and, in most of these buildings, the walls are constructed around the supported beams, using a weak grout, so the exterior walls behave as cantilevers over the total building height. The risk of wall out-of-plane failure due to excessive flexural stresses at the base of the wall obviously increases with its height (Bruneau 1994).

When an anchorage is not adequate, the walls perpendicular to the direction of the earthquake shaking move away from the floors and roof, and might topple outward; this is known as “out-of plane” collapse, (see Fig. 2.13). On the other hand, some traditional buildings have timber roofs with rafters spanning two walls in a room, instead of spanning the full length of the building. As a result, the floor in each room behaves as an independent system, and it has a tendency to pull apart from the other floors during the strong ground shaking. This causes a partial or total collapse (Bothara and Brzev 2011)

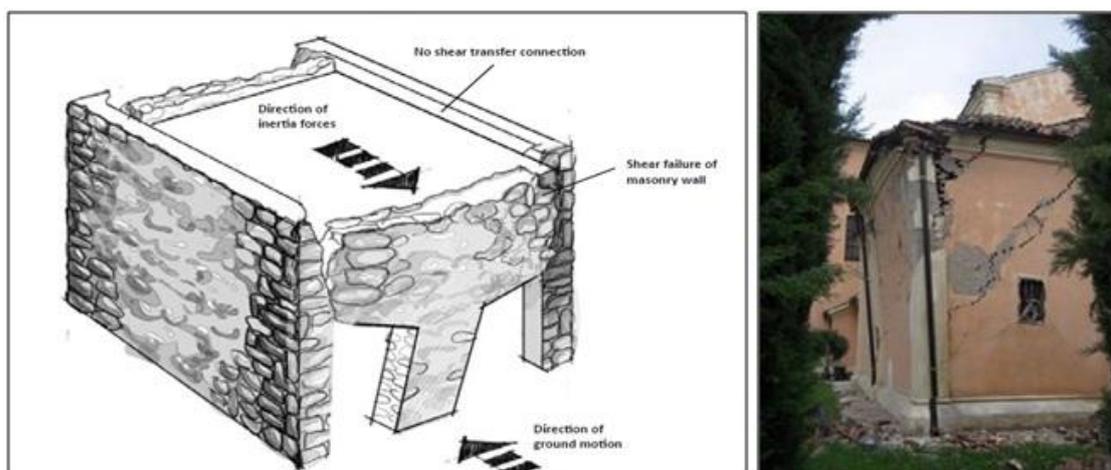


Figure 2.13 Inadequate wall-to-roof anchorages (Bothara and Brzev 2013)

ii) In-plan Failures:

Excessive bending or shear may produce in-plane failure depending on the aspect ratio of the URM elements. For URM walls, shear in-plane failures are more common, as expressed by double-diagonal (x) cracking. Masonry facades with numerous window openings, spandrels and the short piers between spandrels may also fail in shear (Bothara and Brzev 2011).

A typical masonry wall consists of piers between openings, plus a portion below openings (sill masonry) and above openings (spandrel masonry), as shown in Fig. 2.14a. When subjected to in-plane earthquake shaking, masonry walls demonstrate either rocking or diagonal cracking. Rocking is illustrated in Fig. 2.14b. It is characterized by the rotation of an entire pier, which results in the crushing of the pier end zones. Alternatively, masonry piers subjected to shear forces can experience diagonal shear cracking (X-cracking), as shown in Fig. 2.14c.

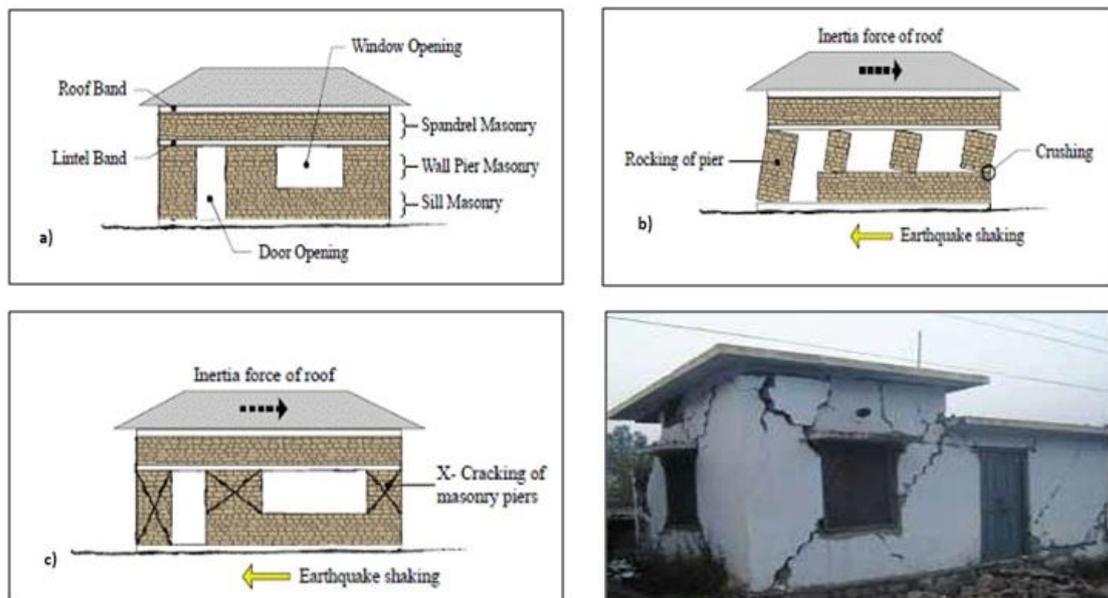


Figure 2.14 In-plane damage of stone masonry walls: a) typical wall with openings; b) rocking failure, and c) diagonal shear cracking (Bothara. and Brzev 2011)

Diagonal cracks develop when tensile stresses in the pier exceed the masonry tensile strength, which is inherently very low. This type of damage is typically observed in

the bottom story of a building. Several factors influence the in-plane failure mechanism of stone masonry buildings, including pier dimensions, wall thickness, building height, and masonry shear strength. (Bothara and Brzev 2011).

iii) Out-of-Plane Failures:

Joist-to-wall anchors provide out-of-plane support to the walls, if present in sufficient numbers and strength; these anchors will transform the out-of-plane behavior of the URM walls, from tall unrestrained cantilevers to shorter one-story-high panels dynamically excited at each end by the floor diaphragms. URM buildings are most vulnerable to flexural out-of-plane failure as shown in Fig. 2.15 (Binda et al 2006).

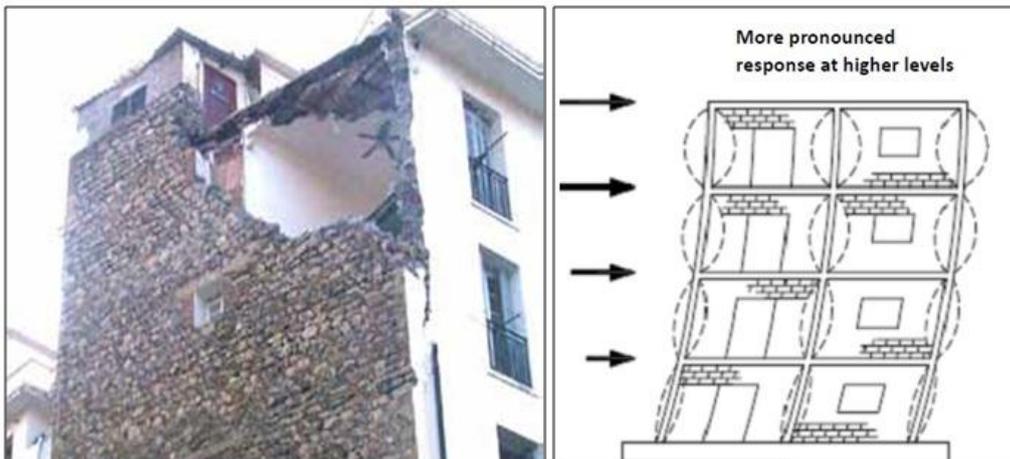


Figure 2.15 Example of Out-of-plane collapse of a wall with tie beams, and roof hammering the masonry walls (Binda et al 2006)

Out-of-plane wall collapse is one of the major causes of destruction in historic stone masonry buildings, particularly in buildings with flexible floors and roofs; overall building integrity is critical for the satisfactory seismic performance of stone masonry buildings. The connections between structural components are important for maintaining building integrity. Integrity is absent or inadequate when the walls are not connected at their intersections and there are no ties or ring beams at the floor and roof levels (see Fig. 2.16).

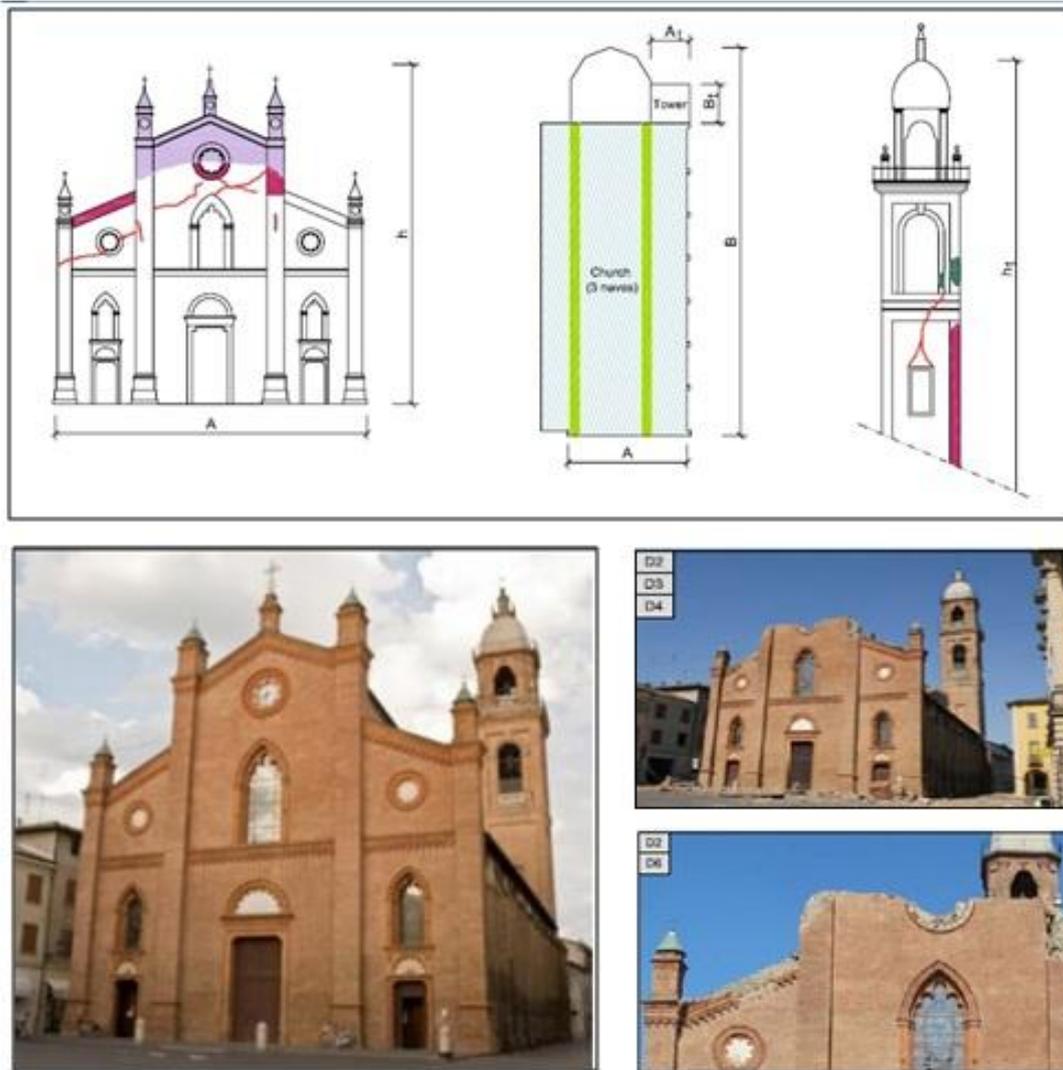


Figure 2.16 The effect of earthquake hazards on church of Santa Maria Maggiore (Pauperio E., et al 2012)

In multi-story buildings, this type of collapse usually takes place at the top floor level due to the significant earthquake accelerations there, as shown in Fig. 2.17. When the walls are oriented orthogonally to the direction of earthquake shaking, the central areas of long walls are subjected to significant out-of-plane vibrations and may collapse. The inadequacy of connections between the cross walls and long walls is one of the key factors influencing out-of-plane wall collapse. Depending on the intensity of earthquake ground shaking, this failure mechanism is characterized either by vertical cracks developing at the wall intersections, or by tilting and collapse of an entire wall, (see Fig. 2.17) (Bothara and Brzev 2011).

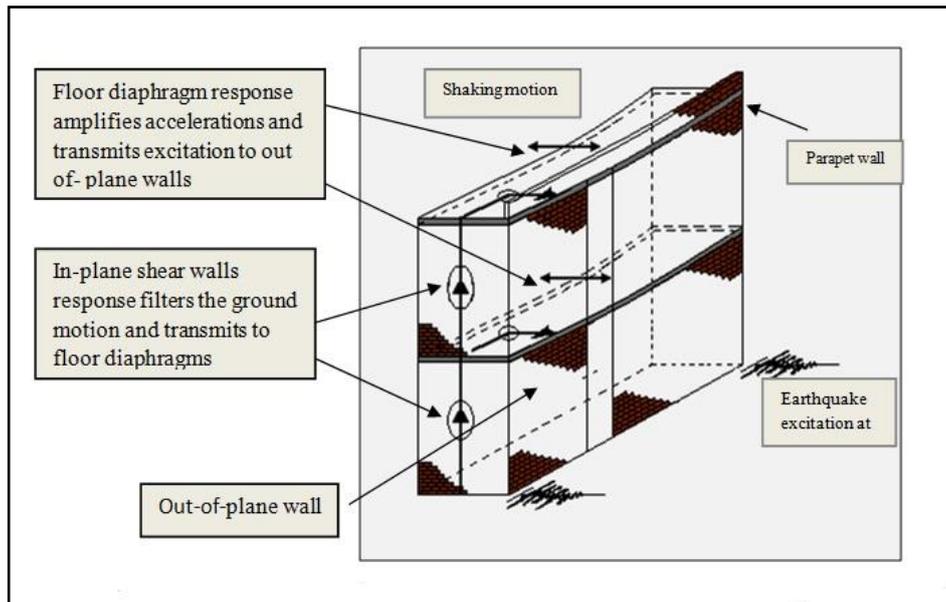


Figure 2.17 Simplified conceptual representation of out-of-plane seismic response

2.1.4- Damage Mechanism to Historic Traditional Masonry Walls

Load-bearing walls in historic traditional masonry suffered the greatest damage by earthquakes, because they have not any connection between the walls. Nevertheless, certain houses resisted the effect of horizontal earthquake forces; it is probably due to the good quality of construction techniques applied (Abdessemed-Foufa 2003). During earthquakes, walls vibrate laterally and tend to separate from the floors, the latter usually slipping off their support, leading to dramatic collapses, and this often occurred after major earthquakes, because they had insufficient strength to resist lateral earthquake forces in high and moderate seismic zones (see Fig. 2.17) (Dizhur et al 2010).

The length of the load-bearing walls is the most important factor for masonry building damage occurring during earthquakes. Excessive bending and shear may produce in-plane failures, depending on the aspect ratio of the unreinforced masonry elements. Many masonry buildings have suffered very significant wall damage in the form of double-diagonal shear cracks (X cracks), as shown in Fig. 2.18 (Boen 2001).



Figure 2.18 The form of double-diagonal shear cracks (Boen 2001)

Although, this cracking seldom causes total collapse, it may become unstable leading to collapse when a full X crack occurs during an earthquake (Doğangün 2008). On the other hand, the accurate assessment of lateral load capacity of URM walls is difficult because of the complex in stone/brick-mortar interaction. Also during an earthquake different modes of failure of load bearing walls in masonry buildings are possible as shown in Fig.2.19 (Decanini et al 2004).

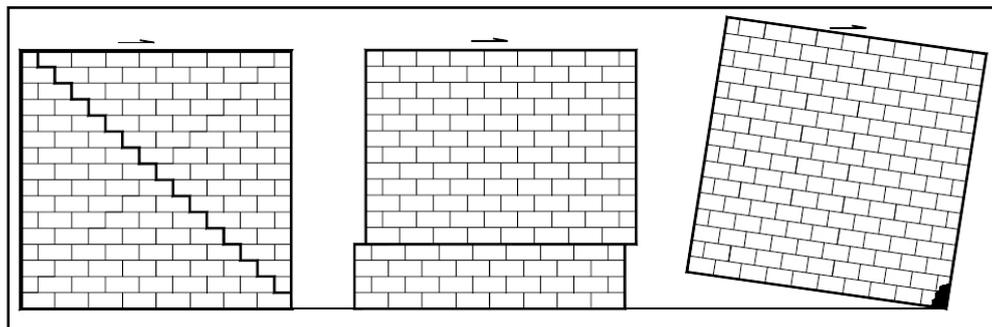


Figure 2.19 In-plane failure modes of a laterally loaded URM wall: shear failure, sliding failure, and rocking failure (Decanini et al 2004)

The worst defect of masonry wall is to be not monolithic in the lateral direction; this can happen, for instance, when the wall is made by small pebbles or by two external layers well ordered but not mutually connected and containing a rubble infill. This makes the wall to become more brittle, particularly when external forces act in the horizontal direction, the same problem can happen under vertical eccentric loads act (Bruneau 1994).

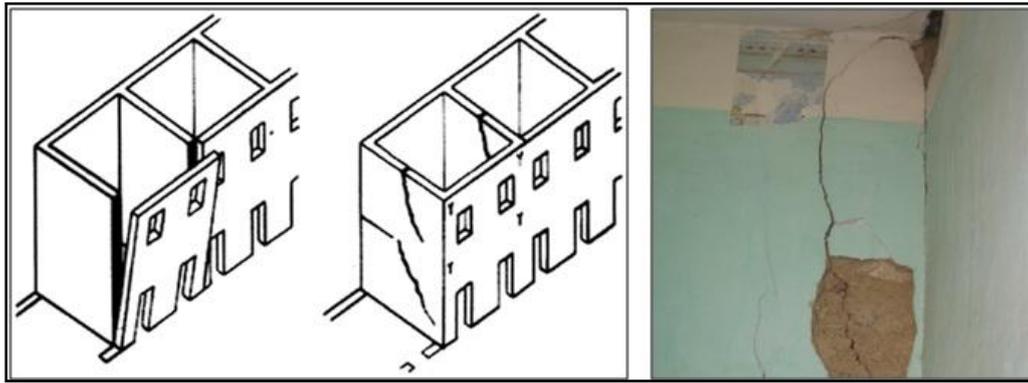


Figure 2.20 Example of predictable mechanisms of collapse

So it may be concluded that the disorders observed on the walls have their origins in the previous four-mentioned main causes: the bad quality of materials; the aging and the absence of maintenance; the bad implementation of masonry (quality of the code of practice); the absence of vertical and horizontal links to the connections of the load-bearing walls, between the load-bearing and partition walls and the heavy and insufficiently braced roofs and the result is partial or total collapsing to historic traditional buildings (see Fig. 2.21). (Badoux et al 2003, Pauperio E., et al 2012).

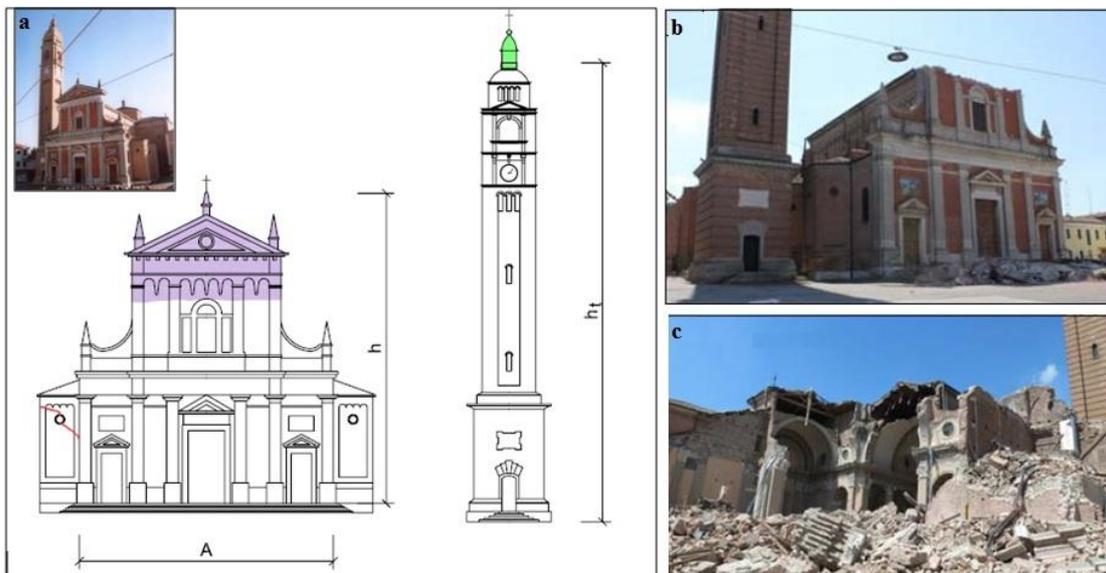


Figure 2.21 Cathedral of San Paolo during 2012 earthquake where: a- before collapse, b and c after collapsed by the earthquake (Pauperio E., et al 2012)

In the following, we will discuss the effect of earthquake on the different kinds of historic traditional masonry walls

2.1.4.1- Free Standing Masonry Wall

Consider the free standing masonry walls shown in Fig.2.22. We will see in Fig. 2.22a, the ground motion acts transversely to a free standing wall A and the force acting on the mass of the wall tends to overturn it; seismic resistance of the wall is by virtue of its weight and tensile strength of mortar and it is obviously very small. This wall will collapse by overturning under the ground motion, the free standing wall "B" fixed on the ground in Fig. 2.22b is subjected to ground motion in its own plane; such a wall is termed a shear wall.

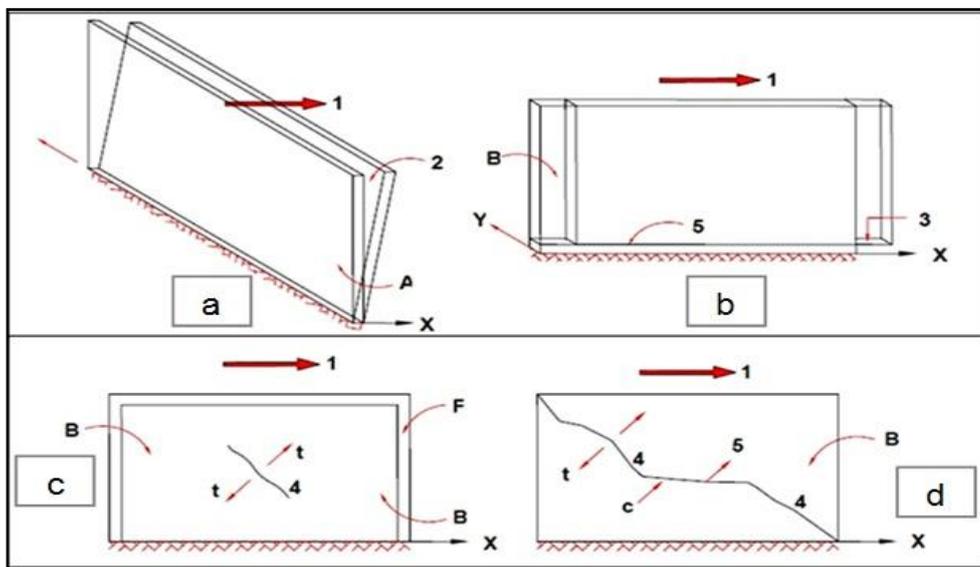


Figure 2.22 (a) Perpendicular force at upper end of wall A (b) Unreinforced wall B with small length to width ratio (c) Wall B with moderate length to width ratio (d) Wall B with long length to width ratio (Boen 2001)

In this case, the wall will offer much greater resistance because of its large depth in the plane of bending. The damage modes of an unreinforced shear wall depend on the length-to-width ratio of the wall or aspect ratio of the wall. (Jack et al 1984, Binda et al 2000). Wall A with small length-to-width ratio will generally develop a horizontal crack due to bending tension and then slide due to shearing. A wall with moderate length-to-width ratio and bounding frame will suffer diagonal cracking due to shearing as shown in Fig. 2.22c. A wall with large length-to-width

ratio, on the other hand, may develop diagonal tension cracks at its edges and horizontal cracks at its middle part as shown in Fig. 2.22d (Binda et al 2000).

2.1.4.2- Wall enclosure without roof

Now consider the combination of walls A and B as an enclosure shown in Fig. 2.23. For a force acting in direction x as shown in the figure, walls B act as shear walls and, besides resisting the action of the applied force, they offer resistance against the collapse of wall A as well. As a result, walls A now act as vertical slabs supported on two vertical sides and the bottom plinth. Walls A are subjected to the inertia force of their own mass.

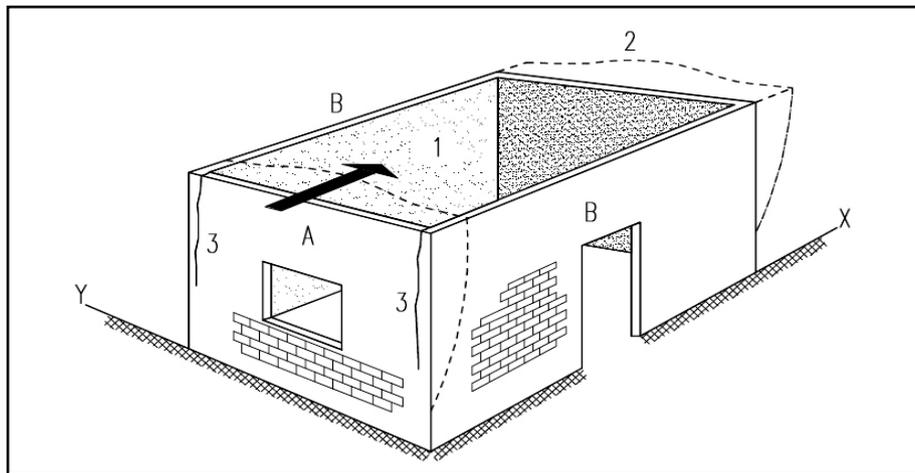


Figure 2.23 Failure Mechanism of Wall Enclosure without Roof where: 1) Earthquake force
2) Bending of Wall A 3) Bending cracks at ends of wall A (Boen 2001)

Near the vertical edges, the wall will carry reversible bending moments in the horizontal plane where the masonry has little strength; consequently; cracking and separation of the walls may occur along these edges as shown in Fig. 2.23. It can be seen that walls B act as shear walls, walls A acting as flanges connected to the walls B forming a T shaped cross section. Thus, if there is good connection between walls A and B, the building will tend to act as a box and its resistance to horizontal loads will be much larger than that of walls B acting separately.

Most unreinforced masonry enclosures have very weak vertical joints between walls meeting at right angles due to the construction procedure involving toothed joint which is generally not properly filled with mortar. Consequently the corners fall and lead to collapse of the walls. It may also be easily imagined that the longer the walls in plan, the smaller will be the support to them from the cross walls and the lesser will be the box effect (Boen 2001, Jack et al 1984).

2.1.4.3- Roof on Wall Enclosure

Now consider a complete wall enclosure with roof on the top subjected to an earthquake force acting along x-direction as shown in Fig. 2.24. If the roof is rigid and acts as a horizontal diaphragm, its inertia will be distributed to the four walls in proportion to their stiffness.

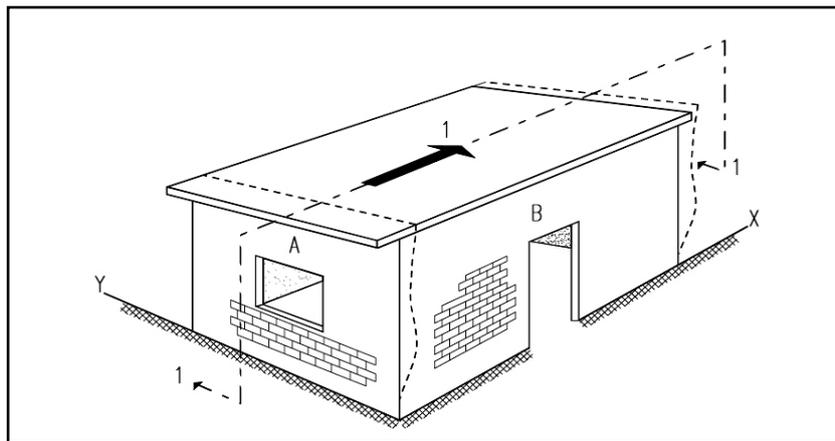


Figure 2.24 Roof on wall enclosure where 1- Earthquake forces (Boen 2001)

The inertia of roof will almost entirely go to walls B since the stiffness of walls B is much greater than that at walls A in the x direction. In this case, the plate action of walls A will be restrained by the roof at the top and horizontal bending of wall A will reduce. On the other hand, if the roof is flexible, the roof inertia will go to the wall on which it is supported and the support provided to plate action of walls A will also be little or zero. (Boen 2001).

2.1.4.4 Shear Wall with Openings

Shear walls are the main lateral earthquake resistant elements in many buildings. For understanding their behavior, let us consider a shear wall with three openings as shown in Fig. 2.25. Obviously, the piers between the openings are more flexible than the portion of wall below (sill masonry) or above (spandrel masonry) the openings. The internal actions or forces which developed the horizontal seismic force are also sketched in Fig. 2.25.

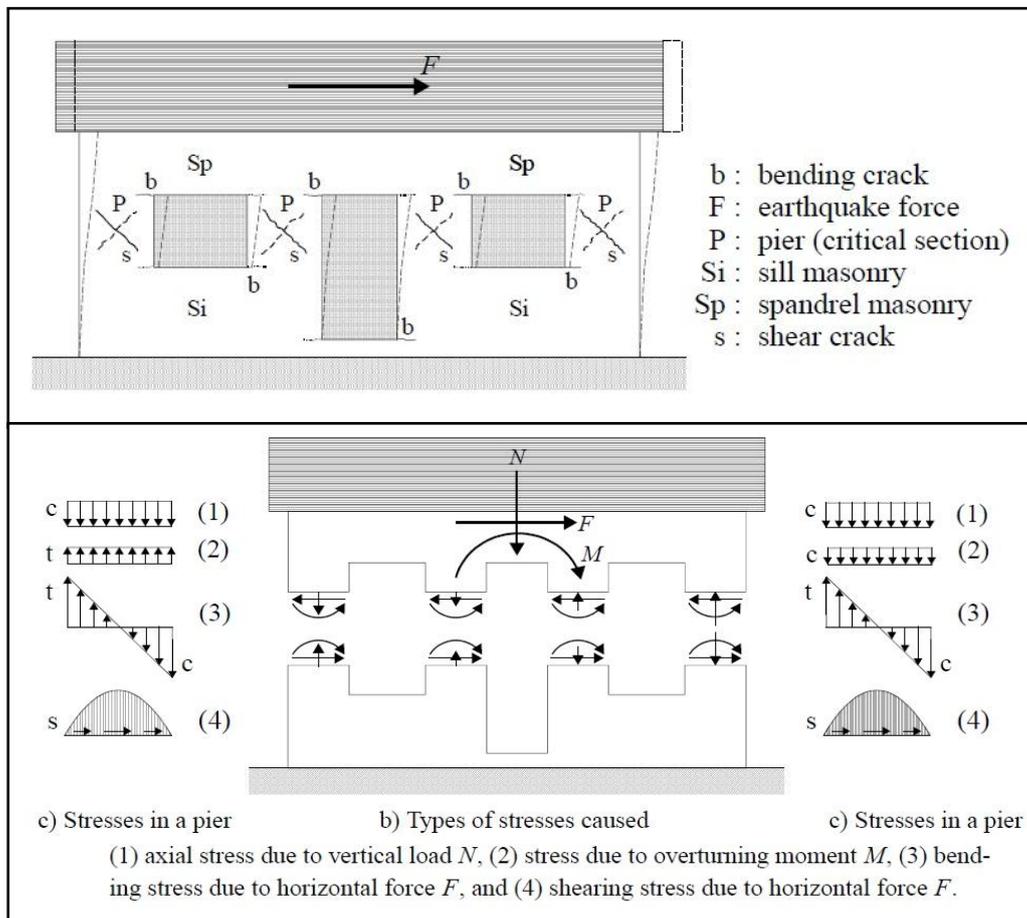


Figure 2.25- Deformation, cracks and stresses of a shear wall with openings (Boen 2001)

The sections at the level of the top and bottom of opening are found to be the worst stressed in tension as well as in compression and those near the mid-height of piers carry the maximum shear. Under reversed horizontal loading, the sections carrying tensile and compressive stresses also reverse. Thus, it is seen that tension occurs in the piers of openings and at the corners of the walls (Boen 2001) (Jack et a 1984).

2.2- Change and conversion

In a conversion, one of the key structural issues that are most likely to occur is an increase or change in loading conditions due to change of use. The fact that a building is historic does not remove the overriding requirement for public safety. However, this does not mean that the conversion should be carried out in a manner that will diminish the value and appearance of the building

Typical changes that may affect the structural system as a result of conversion, some of which may result in collapse, include increased floor loads due to change in occupation, inadequate tying-in of floors and roofs to walls which may become more critical with increased loads, and increased loads on escape routes including stairs and landings.

Few historic buildings, apart from those built for industrial purposes such as mills and warehouses, are capable of carrying large imposed floor loadings. It has often been the case that quite drastic structural strengthening has been designed into historic building conversions to accommodate design floor loads for change of use to offices. Existing historic stairs are another contentious structural issue, the structural capacity of many historic stairs, some constructed of stone steps and landings, ostensibly 'cantilevered' out from supporting walls, cannot be confirmed by normal design calculation but are likely to be well capable of withstanding the superimposed loads likely to be encountered in a change of use conversion.

Also, large walls which constructed from different kinds of material (such walls include cavity walls, rubble filled masonry walls and veneered brick walls) which have a poor quality core, not only may the core material be less capable of carrying load but it can also produce thrusts on the faces. In this type of masonry, the

external layers can separate from the core; so thus, it is necessary to determine whether the layers and the core are acting together or separately. The case of wall layers separating is usually dangerous because the layers may become unstable. In-plane lateral loads can cause diagonal cracks or sliding. Out-of-plane loads may cause separation of the leaves in a multi-leaf wall or rotation of an entire wall about its base, when the latter occurs; horizontal cracks at the base might be seen before overturning occurs (Urquhart 2007).

On the other hand, historic traditional buildings usually undergo to many types of conversion such as making new openings for ventilation or removing a column or pillar or even a wall from the building (Barry 2001). As a result of such modifications the buildings are susceptible to serious damage to architectural aspects such as sweeping and bulging of facades resulting from the removal of orthogonal walls or large openings in these walls see Fig. 2.26 (Mills 1998).



Figure 2.26 Salerno building before (left) and after (right) the partial collapse

Table 2.2 summarizes the conversion methods and the risks to historical traditional buildings.

Table 2.3 Conversion methods and the risks to historical traditional buildings

Issue	Issue Risks to historic/traditional buildings
1. Poor understanding of traditional building materials and structures	<ul style="list-style-type: none"> • Inappropriate structural intervention, which may be unnecessary and adversely affect historic character. Cracking may also result due to lack of understanding of load paths in traditional materials.
2. Increased floor loading	<ul style="list-style-type: none"> • Excessive deflections causing damage to historic ceilings or collapse of the floor. • Insensitive floor strengthening can be destructive to fabric and architectural value of spaces. • Detachment of inner and outer faces of walls with a rubble core. • Introduction of new supporting columns and beams could be damaging to historic spaces.
4. Improving stability of rubble-cored walls	<ul style="list-style-type: none"> • The use of exposed plates, as part of the stabilizing process, may be aesthetically unacceptable for a converted building. • Gravity grouting of voids in the wall may cause further damage if poorly or if too strong grouting mortar is used.
5. Removal of internal walls	<ul style="list-style-type: none"> • The load paths and load transfer mechanisms in historic buildings are often difficult to determine, so removal of apparently non-structural walls can cause structural distress.
6. Temporary removal of floorboards	<ul style="list-style-type: none"> • In some situations the floorboards act as a horizontal bracing membrane and the complete removal of the boards (even temporarily) may cause movement in walls or buckling of the floor.
7. New openings in floors	<ul style="list-style-type: none"> • Forming a new opening in a timber floor may change loading conditions on other parts of the floor and on supporting walls and beams.
8. New door and window openings	<ul style="list-style-type: none"> • Any new or altered penetrations in walls will change the pattern of load distribution in the wall, and new lintels or cells can affect wall stability if they are not properly built in. • Poorly built-in replacement safe lintels may promote settlement of the wall above.
9. Slender internal load bearing masonry walls	<ul style="list-style-type: none"> • Historic buildings may have half-brick thick load bearing partitions associated with high floor to ceiling heights. The walls may extend the full height of the building without being effectively tied to floors – any increased loads may result in buckling or collapse of the wall.
10. Use of inappropriate materials	<ul style="list-style-type: none"> • The use of hard, dense and shrinkable cement mortar and concrete in traditional structures may change the moisture distribution pattern and promote shrinkage stresses within the existing materials.
11. Shallow foundations	<ul style="list-style-type: none"> • Historic walls often have shallow foundations with very little cover, built from large stones placed on the ground. Uncontrolled excavations for new drainage, services and landscaping etc, can undermine or reduce the stability of such foundations

2.3- Structural and construction defects

One of the most famous deterioration factors of historic traditional masonry is the construction defects which may lead to wall cracks or collapse of a building over time (Fitzsiman and James 1998). Structural defects include faults in the choice of building soil/site, irregular distribution of the structure's loads on the foundations, and faults in the choice of proper building materials and joists between bearing walls (Urquhart 2007).

2.3.1- Irregularities in plane and vertical direction

Load-bearing walls of masonry buildings must be arranged in plan, as much as possible, regularly and symmetrically in respect of the two main axes. Some masonry buildings were built with different kinds of masonry units (stone, solid brick and hollow clay tiles) at the different storeys; in these cases, the lateral rigidities of each storey differ, and such differences in stiffness and loads increase the risk of failure (ICOMOS 2003). Figs 2.27 on the right side, the cracks have induced the collapse of the façade wall corresponding to a large hall having openings taller than those on the parallel opposite side (Fig. 27b).



Figure 2.27 Sant Agostino, Town hall (Decanini L et al 2012)

2.3.2- Lack of vertical confining elements

Vertical confining elements should be located at the end of the load-bearing walls, at both sides of the doors and windows opening. Fig. 2.28 shows two damaged masonry buildings due to the lack of vertical confining elements, the side of load-bearing wall next to joint space failed and the door opening was extremely narrowed around the middle of the door height as shown in Fig. 2.28, as a result or due to the lack of vertical confining element there is X cracking in this wall (Doğangün et al 2008).



Figure 2.28- Collapse of a corner and vertical cracks near the corner for masonry buildings (Doğangün A. et al., 2008)

2.3.3- Weak out-of-plane response

Unreinforced masonry buildings are the most vulnerable to flexural out-of-plane failure. If the connection between walls and floors is not adequately restrained, the whole wall panel, or a significant portion of it, will overturn due to seismic excitation in the perpendicular direction to the wall plane (see Fig. 2.29).

On the other hand gable walls located at the top of the buildings are subjected to the greatest amplification of the ground motions, and are consequently prone to flexural failures under the roofs. In masonry buildings, when the height at the end of a wall resting on the horizontal bond beam at the top storey exceeds 2m, vertical and inclined bond beams are required to be constructed. But almost all the buildings

which have large gable walls in earthquake region did not satisfy this requirement (Doğangün et al 2008).



Figure 2.29 Out of plane failure in historic masonry buildings (Decanini L et al 2012, Parisi, F.; Augenti, N.2012, and Doğangün et al 2008)

2.3.4- Unconfined wall corners

Failure can be the formation of vertical cracks at the corners of an unconfined masonry building in which the wall begins to form a hinge from the swaying. Failures and cracks at the corners occurred because of the insufficient connections between the walls and floors, as shown in Fig. 2.28. As seen in Fig. 2.28a, failure occurred in the bearing wall between the window and the corner (Doğangün et al 2008).

Fig. 2.28b shows separation of adjacent walls due to vertical cracks at the building corners and poor connection between walls. Likewise, for all types of masonry buildings, this has been playing significant role in the damage. The length of the load-bearing wall segment between the corner of a building and the nearest window or door opening to the corner shall not be less than 1.5 m in the first and second seismic zones. So, vertical confining elements are recommended for confined masonry buildings to prevent this type of failure to occur in the corner. Corners acting

as rotational restraints to horizontal diaphragm deflections can attract torsion forces that can lead to diagonal cracking (Doğangün et al2008).

2.3.5- Poor building materials quality

The use of low quality building materials and poor construction practices often result in significant earthquake damage or destruction. For example, semi dressed/dressed stone masonry in lime generally suffered less damage than random rubble stone in mud mortar. During earthquake shaking, irregularly placed stones tend to move out (displace) from the wall and cause localized damage or even collapse in extreme cases. When the stone surface is not clean, or smooth river boulders are used, the bond between stones and mortar can be weak. Poor bond strength is generally not a problem, except under earthquake conditions, during lateral movement in the structure the mortar crumbles as the stones move and the walls lose integrity and may suffer damage or collapse (see Figs 1.30-1.32).

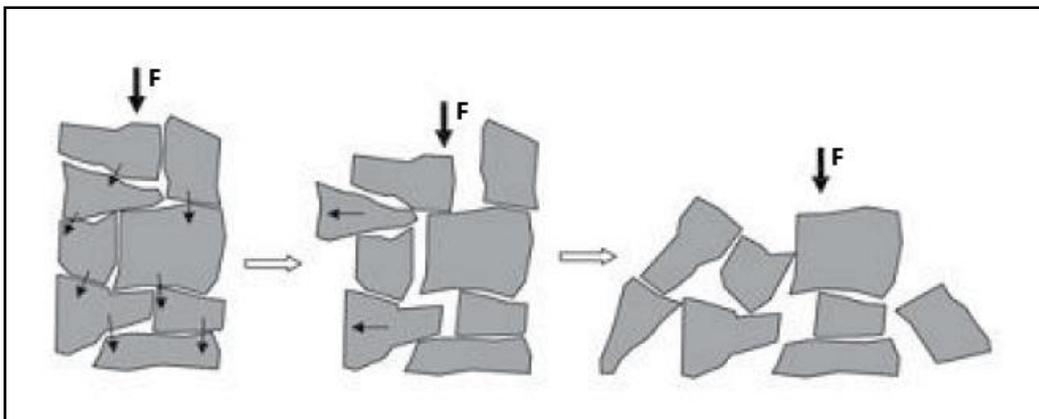


Figure 2.30- Detail of wall failure caused by irregular stones (Bothara and Brzev 2011)

When the mortar used for construction is made of mud instead of lime, the mortar becomes the weak link and prevents a proper bond between mortar and stones as shown in Fig. 2.30. Another problematic construction practice is the use of more than one kind of material for wall construction; for example, stones and brick. Because of the differences in size and shape of materials, the bond between

orthogonal walls reduces. The use of mixed structural materials and systems results in dissimilar strength and stiffness in the different parts of a building. It is acceptable to mix materials provided only one material is used for each story and the stronger building materials should be used for ground floor wall construction (Bothara and Brzev 2011) .



Figure 2.31 Partial collapse in Salerno building (Augenti, N. 2008)



Figure 2.32 The use of poor building materials and poor mortar bond (Augenti, N. 2008)

2.4- Cracks

Masonry is generally relatively strong in compression, has a moderate resistance to sliding along the bed-joints and is weak in tension. Masonry structures are therefore generally designed to work in compression and sometimes in horizontal shear.

Damage to masonry structures usually takes the form of tension and /or shear cracks as a result of imposed deformation due to differential settlement or excessive lateral forces (arch thrust); alternatively, it may occurred from incipient bursting due to buckling of ashlar or expansion of rubble fill in structures that consist of two ashlar faces/wythes with a core of rubble and mortar (all unintended gaps in masonry are usually referred to as cracks) (Abrams 2004).

Cracking can be a very dangerous; however not all cracks are evidence of a serious problem. For example wall painting can suffer hairline cracking between the sheets. Similarly, cracks at the junction of new joinery timbers are a natural consequence of drying shrinkage and can be filled and over-painted; such cracks are not evidence of structure distress. On the other hand, cracking can also indicate serious problems, particularly when monitoring indicates that it is active, i.e. continuing beyond the normal variations to be expected from daily or seasonal changes in temperature and moisture content or from any movement, (see Fig. 2.33) (Bussell 2007). Cracking occurs when the total imposed tensile strain on a material exceeds its tensile strain capacity; materials such as unreinforced masonry and concrete are brittle and have low tensile strain capacity (Miliston and Domone 2001).

The pattern of cracks is a very important pointer to the cause of movement Fig. 2.33 shows common patterns of overall cracking in a masonry building, indicating the most probable causes. It is may also indicate if the movements are

structurally significant, but it must be stressed that this is dependent on the circumstances of specific cases and it should not be taken as hard and fast advice. In particular, if movement continues, cracking is likely to become structurally significant.

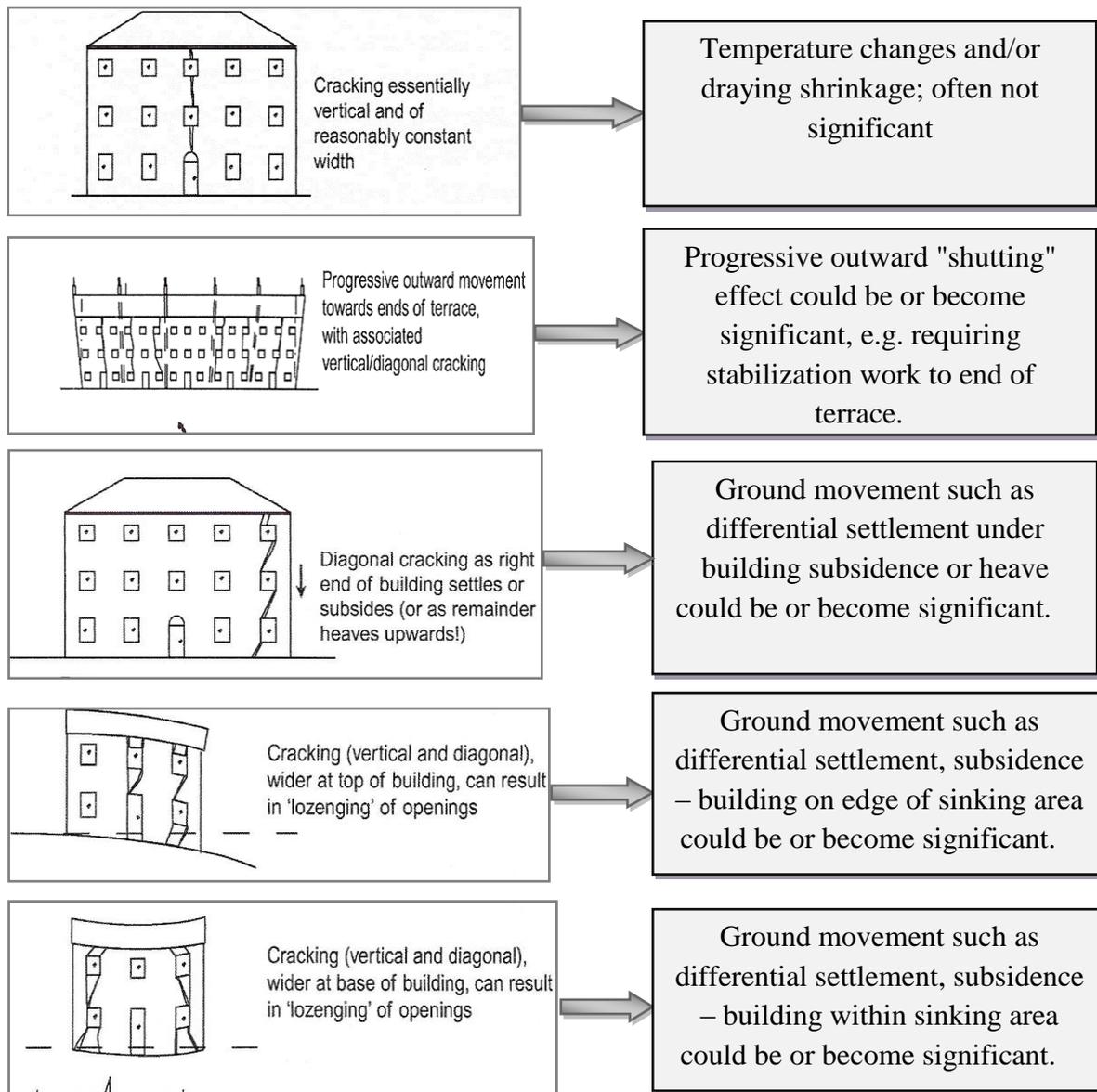


Figure 2.33- typical crack patterns in masonry walls

Another valuable pointer is the state of the crack faces. If they are clean and bright, this suggests recent movement, whereas dirty faces with dead spiders and so on indicate that cracks occurred some time ago, but this of course does not mean that the movement responsible for cracking has necessarily stabilized. Structural cracks

can be divided to many types - according to size, to cracks, micro-cracks, macro-cracks, - according to direction in the building to vertical cracks, horizontal cracks, diagonal cracks - and according to effectiveness, to active cracks, passive or dead cracks (Bussell 2007).

2.4.1- Crack causes and mechanism in historic traditional masonry

There are many causes for cracking to occur in historic traditional masonry elements (foundations, bearing walls, roofs). The following are the most important causes

- 1- Overloading.
- 2- Ground water under the building foundations.
- 3- Digging and installation piles.
- 4- Sometimes bearing walls consist of many different materials which differ in physical and mechanical properties (see Fig. 2.34)
- 5- Irregularity in the distribution of vertical loads
- 6- Cracks due to earthquake (see Fig. 2.35).
- 7- Low tensile strength of building materials
- 8- Cracks due to differential settlement (see Fig 2.36) (Beckmann and Bowles 2004, Barry 2001).



Figure 2.34 Cracks aspects in historic traditional masonry buildings in Greece (Abdelmegeed M. 2014)



Figure 2.35 Cracks aspects in historic traditional masonry buildings in Italy (Pauperio E. et al 2012)

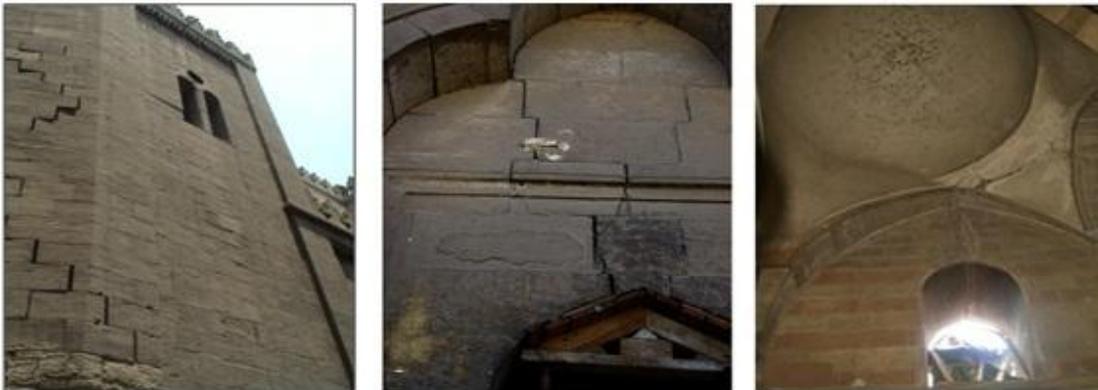


Figure 2.36 Cracks aspects in historic traditional masonry buildings in Egypt (Abdelmegeed M. 2010)

2.4.1.1 Cracks caused by excessive lateral forces

The cracks caused by excessive lateral forces, in the plane of the wall or pier, are usually accompanied by significant deformations and are a symptom of structural deficiency, unless the cause is eliminated, cracking is likely to progress until such time that instability results. Cracks due to pressure from rubble filling in multi layer walls are also a sign of a continuing process, and unless this process is stopped, the structure will eventually burst and collapse.

2.4.1.2 Cracks caused by eccentric loading

One type of cracking that sometimes causes unnecessary structural concern is that due to eccentric loading. If the load in a wall or pier is not acting along the central plan, it will subject it to bending and the stress will vary across the thickness of the wall. If the load acts one-sixth of the thickness from the central plane, the stress will vary

linearly from zero at the face furthest from the load to a maximum at the other face. If the load moves outside the middle third of the wall thickness the conventional theory of bending stresses indicates that tensile stress should develop near the face away from the load

In coursed masonry, particularly in some building built with ordinary lime mortar, there is negligible tensile capacity across bed-joints, so tensile stresses cannot develop. Instead, the stress drops to zero over part of the section and this may be accompanied by a slight opening of the bed-joints. It is sometimes thought that this indicates failure of the wall or pier. This is not so; what is overlooked in this argument is the fact that equilibrium is possible between the load and a triangular stress distribution across the uncracked part of thickness of the wall (Almeida et al 2012).

2.5- Delamination of wall wythes

Delamination takes place when vertical wall layers (Wythes) bulge and collapse outward due to earthquake ground shaking, as shown in Fig. 2.37. One of the causes of delamination is the absence of through-stones (i.e. long stones) which tie the Wythes together. Other factors influencing delamination include intensity of ground shaking, shape of stone (round, irregular, or regular), and the magnitude of the gravity load. Also delamination is triggered by high-frequency vibrations that cause inter-stone vibrations. This results in a reduction of frictional forces that hold the stones together, particularly when wedge-shaped stones are used.

Another possible cause of delamination is an increase in internal lateral pressure from the soil or rubble core of the wall, which pushes the wall Wythes outward. Delamination is usually initiated in the upper portion of the wall, and the appearance of the damaged wall is as if the exterior Wythe has been peeled off.

Spreading (delamination) damage in stone masonry walls begins at the top of the building, where the lack of overburden weight allows the masonry to vibrate apart. The stability of the wall can be most at risk when the masonry units vary in size and are laid with a minimum of horizontal bedding.

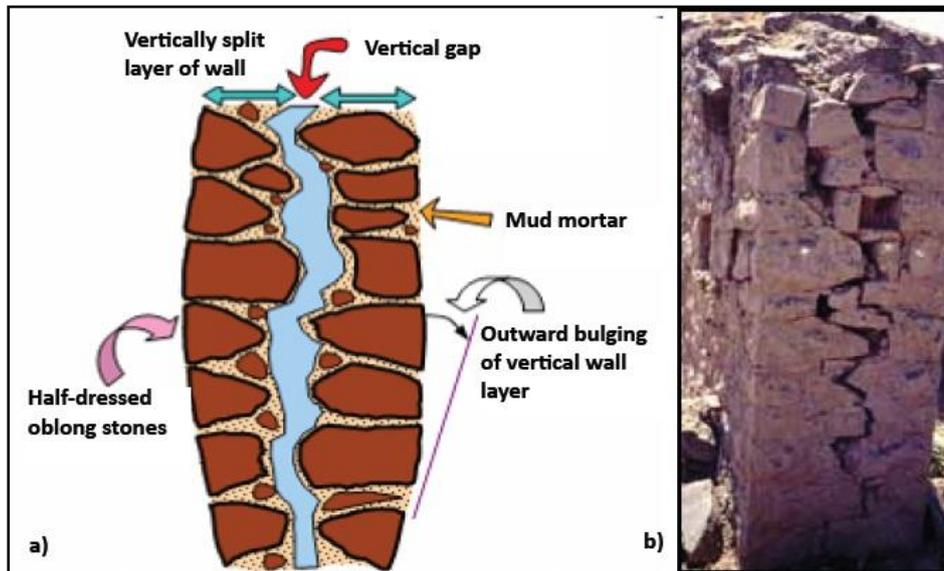


Figure 2.37- Delamination of stone masonry walls: a) delamination in progress and b) delamination of wall wythes due to earthquake

2.6- Out-of-plane movement

Out-of-plane movement is one of the out of plumb kinds with or without tilt. Out-of-plane movement is a characteristic of columns or walls rather than the structure overall. The principal types of out-of-plane movement are bowing and bulging: Bowing curvature of the member with no change in thickness and bulging unmatched curvature of the member on one or both faces. Both can threaten the stability of the building overall or the individual column or wall. Whether or not tilt occurs in addition depends on the absence or presence of lateral restraint, together with a triggering cause for the tilt such as foundation rotation or eccentric loading. A wall in the absence of lateral head restraint results in both tilt and bowing owing to foundation rotation, (overall tilt is prevented by the vertical restraint provided by the bonded –in cross-walls at either end of the wall panel); a wall where lateral head

restraint complements vertical restraint from the cross-walls to confine the form of movement to bowing.

Bowing can arise from a variety of causes, the commonest of which are: Foundation movement, eccentric loading on the member or its foundation, inadequate lateral restraint, and decay of bonding timbers. Bulging involves distortion of the wall or column cross section. The commonest causes are: slumping of rubble fills in stone walls due to deterioration or absence of building mortar, and failure of wall ties in cavity wall construction, rendering both individual leaves more slender and hence vulnerable to bowing (Alexandris et al 2004).

2.7- Ground Moisture

Most historic buildings of masonry construction rely on the combination of mass of masonry and air movement to counteract the effects of moisture transfer from the ground. This transfer of moisture can be both vertical and horizontal. The ability of a wall to transport moisture depends on the pore size and structure of the material, which influences the capillary forces acting to draw moisture into the wall. Capillary forces drawing moisture upwards, gravitational forces acting downwards and the rate of evaporation from the wall govern the height of moisture movement.

Equilibrium is reached when the transfer from the ground (and downward flow of rain water within the wall) is balanced by evaporation losses. Therefore, maintaining a flow of air across the surface will help to reduce the moisture content of the pores adjacent to the exposed surface. This is the principle underlying the need to provide ventilation of air spaces. [Figs. 2.38 and 2.39](#) represent the effects of air movement on the critical moisture content of a porous masonry wall. Historic traditional masonry buildings are not generally constructed with damp-proof courses in walls or damp

proof membranes below ground floors; they rely on the mass of porous masonry to absorb moisture, control rising damp and disperse salts from the ground, together with adequate air movement to prevent deteriorating effects on construction materials.

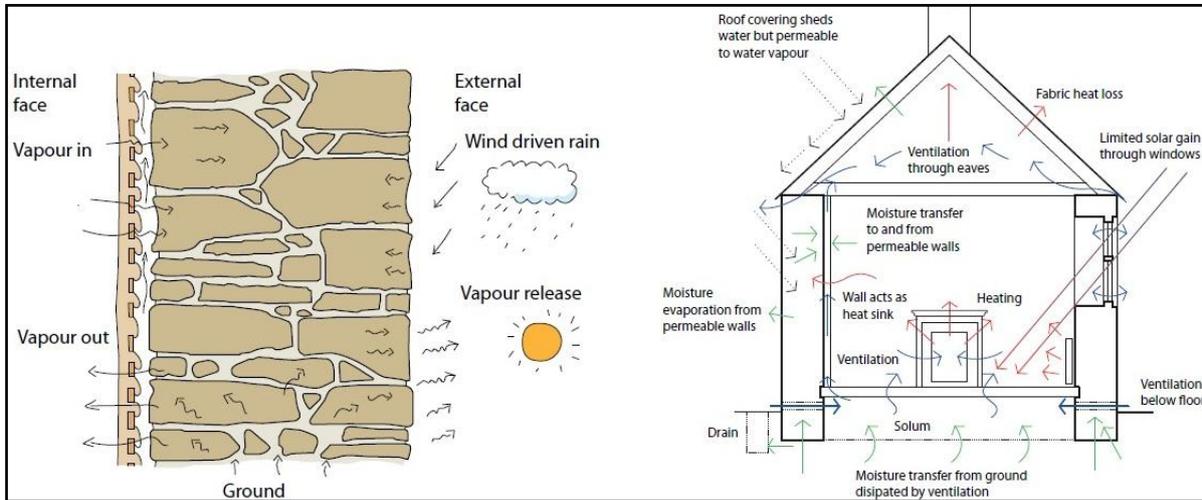


Figure 2.38 Shows water vapour in and out of masonry walls

When a breathable stone-flag floor is lifted and re-laid, it can actually increase levels of moisture within a wall. The new impermeable membrane below the floor allows moisture to accumulate below the slab, and encourages the migration of moisture to the sides of the slab and into the base of the wall (Urquhart 2007).

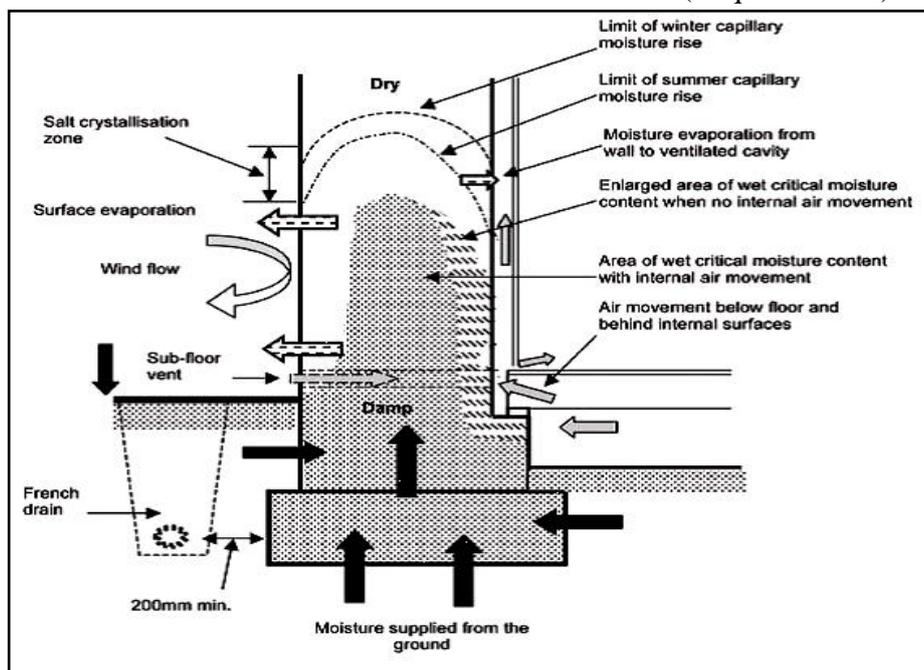


Figure 2.39- Representation of the effects of air movement on the critical moisture content of a porous masonry wall (Urquhart 2007)

Groundwater is considered the major factor contributing to the deterioration of the archaeological buildings through rising damp followed by salt weathering phenomenon. This phenomenon that leads to one outcome type before the effect (*alternative hydration and crystallization cycles*) and another type after it (*full disintegration mechanisms and forms*). The sources of ground waters are divided into two main types (*Dispersed water and Ground water*).

Table 2.4 comparative between dispersed water and ground water

Characteristics	Dispersed water	Ground water
Definition	Spin-off or incidental water that hasn't any continuously effect and it can be control and dray	Underground water which cannot be dray or control
Sources	Rainwater, lakes, wells, seas, drainage water.etc	All flowing water sources within the aquifer which fed by the other water sources like rivers and seas
The deterioration phenomena in historic buildings	Topicality deterioration phenomena in building structural elements (walls, foundations.etc). And its effect is noticeable in one building among all the surrounded historical buildings. It can be an undulating up and down during the year.	It effects on all the building structural elements. And its effect is noticeable in all the surrounded historical buildings. It cannot be an undulating up and down during the year.

2.8- Roof deterioration

Wood has been used in both load-bearing and framed structures, in composite structures of wood and masonry and to form major elements of load-bearing masonry structures. Its structural performance is affected by species growth characteristics, and by decay.

Preliminary operations should be identification of the species, which are differently susceptible to biological attack, and the evaluation of the strength of individual members which is related to the size and distribution of knots and other growth characteristics. Longitudinal cracks parallel to the fibers due to drying shrinkage are not dangerous when their dimensions are small. Durability may be

affected by the methods of harvesting, seasoning and conversion, which may have been different at different times.

Fungal and insect attack is the main sources of damage. These are linked to a high moisture content and temperature. The in-service moisture content should be measured as an indication of vulnerability to attack. Poor maintenance of buildings or radical changes in the internal conditions is the most common causes of timber decay.

Because decay and insect attack may not be visible at the surface, methods, such as micro-drilling, are available for the examination of the interior of the timber. Chemical products can protect the wood against biological attack. For example, in floors or roofs the ends of the beams inserted into masonry walls may need to be protected. Where either reinforcing materials or consolidants are introduced, their compatibility with the timber structure must be verified. For example steel fasteners may be susceptible to corrosion in association with some species and so stainless steels should be used. Interventions should not restrict the evaporation of moisture from the timber. To dismantle and reassemble timber structures is a delicate operation because of the risk of damage.

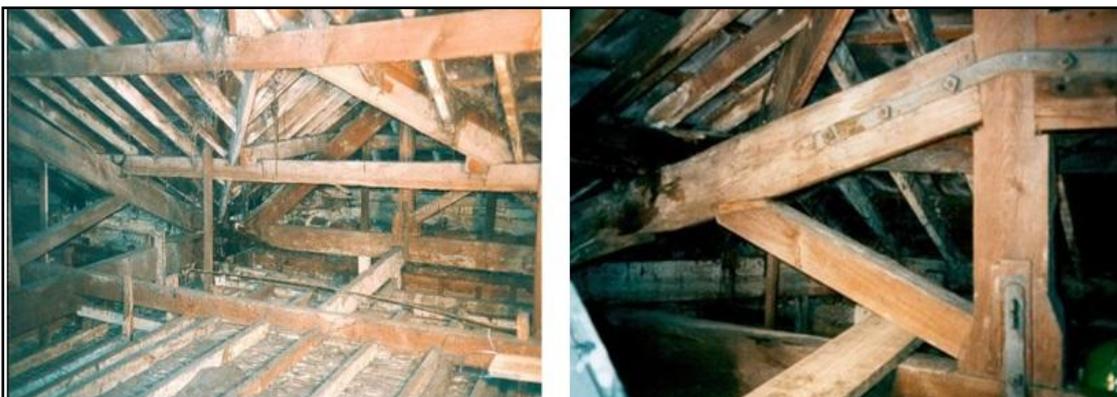


Figure 2.40 Decay aspects in roof timber

There is also the possible loss of associated materials that are of historical significance. However, because many timber structures were originally prefabricated, there are circumstances where either partial or complete dismantling may facilitate an effective repair. Timber is often used to form framed and trussed structures where the main problems are related to local failure at the nodes. Common remedial measures involve the reinforcement of the nodes or the addition of supplementary diagonal elements when it is necessary to improve the stability against lateral forces (ICOMOS 2003).

Concluding Remarks

- Before starting work on the conservation and restoration (rehabilitation) of historic masonry buildings, we must first stand on the damage phenomena and its causes in these buildings.
- The essence of the damage processes or damage mechanism is the interaction between the building and the surrounding environment; the continuous changes of the surrounding environment play an important role in the historic masonry buildings deterioration.
- Structural and architectural damage occurs when the stresses due to the action or effect of external forces exceed the strength of the materials at locations of the significant for structural integrity, either because the actions/forces themselves increase beyond expected limits or because of building materials deterioration.
- Building configuration affects the building resistance to earthquake damage. A building shaped like box, rectangular both in plan and elevation, is inherently stronger than a L or a U-shaped, such as a building with wings. An irregularly shaped building will twist as it shakes, thus suffering more damage. Otherwise openings in walls of the building tend to weaken the walls, and the fewer the openings the less the damage suffered during an earthquake
- Observation of the structural performance of the buildings during and after earthquake shaking can clearly identify the strong and weak aspects of the building design, as well as the desirable qualities of materials, techniques of construction and site selection.
- Relative poor seismic performance of some traditional building systems is the main reason of failure, in addition to the poor physical properties of building

materials. As a consequence of this, masonry is widely thought to be unsuitable to comply with performance-based requirements in seismically prone regions.

- The structural damage assessment of historic traditional masonry due to earthquake indicates many types of failures such as total collapse of the traditional building, the destruction and collapse of load bearing walls, vertical or shear cracks to the walls, the collapse of internal walls, the destruction of floors, and the destruction of roofs as well as stairs.
- Historic traditional masonry buildings frequently have unsatisfactory behavior under seismic activity, due to the poor tensile strength of the masonry walls and the mobility of flexible wooden floors to act as diaphragms. Horizontal seismic forces are reversible and the columns are capable of bearing primarily vertical loads their ability to carry horizontal forces as well.
- When the tension due to bending exceeds the vertical compression, masonry suffer cracking which reduces the effective area for resisting bending moment.
- Out-of-plane wall collapse is one of the major causes of destruction in historic stone masonry buildings, particularly in buildings with flexible floors and roofs; overall building integrity is critical for the satisfactory seismic performance of stone masonry buildings.
- The connection between structural components is important for maintaining building integrity. Integrity is absent or inadequate when the walls are not connected at their intersections and there are no ties or ring beams at the floor and roof levels.
- The length of the load-bearing walls is the most important factor for masonry building damage occurring during earthquakes. Excessive bending and shear

may produce in-plane failures, depending on the aspect ratio of the unreinforced masonry elements. Many masonry buildings have suffered very significant wall damage in the form of double-diagonal cracks (X cracks).

- The causes of damage in double bearing walls in historic traditional masonry under earthquake excitation are linked with poor quality of materials, poor construction practices, the absence of vertical and horizontal links to the connections between load-bearing walls and partition walls and the heavy and insufficiently braced roofs.
- Historic traditional buildings usually undergo many types of conversion such as making new openings for ventilation or removing a column or pillar or even a wall from the building. As a result of such modifications the buildings are susceptible to serious damage to architectural aspects such as sweeping and bulging of facades resulting from the removal of orthogonal walls or large openings in these walls.
- Construction defects are deemed to be one of the most usual deterioration factors of historic traditional masonry; they may lead to wall cracks or collapse of a building over time. Structural defects include faults in the choice of building soil/site, irregular distribution of the structure's loads on the foundations, and faults in the choice of proper building materials and joists between bearing walls etc.
- Failures and cracks at the wall corners in historic traditional masonry occurred because of the insufficient connections between the walls and floors. Failure can be caused by the formation of vertical cracks at the corners of an unconfined masonry building in which the wall begins to form a hinge from the swaying.

- Damage to masonry structures usually takes the form of tension and /or shear cracks as a result of imposed deformation due to excessive lateral forces; alternatively, it may occur from incipient bursting due to buckling of ashlar or expansion of rubble fill in structures that consist of two ashlar faces/wythes with a core of rubble and mortar (all unintended gaps in masonry are usually referred to as cracks).
- Cracking occurs when the total imposed tensile strain on a material exceeds its tensile strain capacity; materials such as unreinforced masonry and concrete are brittle and have low tensile strain capacity.
- Cracking may occur due to various causes such as, overloading, irregularity in the distribution of vertical loads, earthquake excitations, differential settlement etc.
- Wall delamination in historic traditional masonry takes place when vertical wall layers (wythes) bulge and collapse outward due to earthquake ground shaking, or due to the absence of through-stones (i.e. long stones) which tie the wythes together. Other factors influencing delamination include intensity of ground shaking, shape of stone (round, irregular, or regular), and the magnitude of the gravity load.
- Fungal and insect attack is the main sources of wooden roof and floor damage in historic traditional masonry buildings; these are linked to a high moisture content and temperature (radical changes).

After studying the history and development stages of historic traditional masonry building, and discussed deterioration phenomena and factors, the next step is to study registration, documentation, and testing methods used to identify and monitoring the deterioration phenomena in historic traditional masonry buildings.

References

- 1- Abdessemed Amina F (2003) " Damage survey of the old nuclei of the Casbah of Dellys (Algeria) and performance of preventive traditional measures in the wake of the Boumerdes earthquake "Performance of preventive traditional measures after the Boumerdes's earthquake of May 21, 2003 in Algeria's Casbah
- 2- Alexandris Argiris, Eleni Protopapa, and Ioannis Psycharis (2004) " Collapse mechanism of masonry buildings derived by the distinct element method" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 548
- 3- Almeida, C., Paulo Guedes J., Arêde A., Costa C.Q., Costa A. (2012) " Physical characterization and compression tests of one leaf stone masonry walls" *Construction and Building Materials* , Contents lists available at SciVerse ScienceDirect,30 (2012) 188–197
- 4- Anand S. Arya, Teddy Boen and Yuji Ishiyama (2012) " Guidelines for Earthquake resistant non-Engineered construction" International Association for Earthquake Engineering (IAEE), United Nations Educational, Scientific and Cultural Organization (UNESCO) and International Institute of Seismology and Earthquake Engineering (IISEE) , February 2012.
- 5- Arsalan Kalali, Mohammad Zaman Kabir "Experimental response of double-wythe masonry panels strengthened with glass fiber reinforced polymers subjected to diagonal compression tests" *Engineering Structures* 39 (2012) 24–37
- 6- Augenti N, Antonio N. and Fulvio P. (Construction Failures and Innovative Retrofitting) *Journal of buildings*, www.mdpi.com/journal/buildings. 2013 3, 100-121
- 7- Badoux M., Elgwady M. A., Lestuzzi P. (2003) "earthquake simulator test on unreinforced masonry walls before and after upgrading with composites "Published by Elsevier science Ltd. All rights reserved 12th European conference on earthquake engineering paper reference 862
- 8- Barry, A., (2001) "Defects and deterioration in buildings" second edition, spon press, London and New York.
- 9- Beckmann Poul and Robert Bowles (2004) "structural aspects of building conservation" second edition, McGraw-Hill international (UK).
- 10- Betti M. and Galanol. 2012 "Seismic Analysis of Historic Masonry Buildings: The Vicarious Palace in Pescia (Italy)" *Buildings* 2012, 2, 63-82
- 11- Belén Riveiro, Pedro Arias, Julia Armesto, and Celestino Ordóñez 2011 "A methodology for the inventory of historical infrastructures: Documentation, current state and influencing factors" *International Journal of Architectural Heritage*, 5: 629–646, 2011
- 12- Binda L., Cardani G., Saisi A. and Valluzzi M.R. 2006 " Vulnerability analysis of the historical buildings in seismic area by a multilevel approach " *Asian Journal of Civil Engineering (BUILDING AND HOUSING)* Vol. 7, No. 4 .
- 13- Binda L., Saisi A., C. Tiraboschi (2000) "Investigation procedures for the diagnosis of historic masonries " *Construction and Building Materials*.
- 14- Binda L., Modena C., Baronio G., Abbaneo S., 1997 "Repair and investigation techniques for stone masonry walls, in *Construction and Building Materials*, Vol. 11, N.3,
- 15- Binda L. and Saisi A. 2001 "Non destructive testing applied to historic buildings: The case of some Sicilian Churches" *Historical Constructions*, P.B. Lourenço, P. Roca (Eds.), Guimarães.

- 16- Boen Teddy (2001) "Earthquake Resistant Design of Non-Engineered Buildings In Indonesia" Presented during EQTAP Workshop IV, Kamakura Dec 3-4, 2001.
- 17- Bothara Jitendra and Svetlana Brzev (2011) "Improving the Seismic Performance of Stone Masonry Buildings" first published, Earthquake Engineering Research Institute, Oakland, California.
- 18- Branco Miguel, Guerreiro Luis Manuel (2011) "Seismic rehabilitation of historical masonry buildings" *Engineering Structures* 33 (2011) 1626–1634, Contents lists available at Science Direct
- 19- Bruneau Michel (1994) "state of the art report on seismic performance of unreinforced masonry buildings" *journal of structural engineering* vol 120 No 1 January 1994.
- 20- Branco M., and Guerreiro M. 2011 "Seismic rehabilitation of historical masonry buildings" *Engineering Structures* 33 (2011) 1626–1634
- 21- Building Safety and Earthquakes Part A (1997) "Earthquake Shaking and Building Response" ATC/SEAOC Joint Venture c/o Applied Technology Council 555 Twin Dolphin Drive, Suite 550 Redwood City, California 9406.
- 22- Bussell Michael (2007) "effects of induced movement" in structures and construction in historic building conservation, first edition, Blackwell publishing Ltd, Britain.
- 23- Cardoso R, Lopes M, Bento R. "Seismic evaluation of old masonry buildings". Part I: method description and application to a case-study. *Eng Struct* 2005; 27:2024–35.
- 24- Ceroni F., Pecce M., Stefania S., and Garofano A. 2012 "Assessment of Seismic Vulnerability of a Historical Masonry Building" *Buildings* 2012, 2, 332-358.
- 25- Daniel P., Abrams (2004) "Seismic assessment and rehabilitation of unreinforced masonry buildings in the USA" *SÍSMICA - 6º Congresso Nacional de Sismologia e Engenharia Sísmica*.
- 26- Decanini,L., Sortis, AD., Goretti,A., Langenbach,R., Mollaioli, F. and Rasulo, A. (2004) " Masonry Building Performance in the 2002 Molise Earthquake" . *Earthquake Spectra*, forthcoming-spring.
- 27- Decanini L. D. Domenico L. Luigi S. "Preliminary report on the 2012, May 20th Emilia earthquake" *May 2012, v.1*Sapienza University of Rome Department of Structural Engineering and Geotechnics via Antonio Gramsci 53, 00197 Roma Italy
- 28- Dellys, (2006) "Proceedings of the International Conference on World Heritage Cities at Luxor (Egypt)". 28 November to 02 December 2006.
- 29- Dizhur D., Derakhshan H., Lumantarna R., & Ingham J.M. (2010) " In-situ out-of-plane testing of unreinforced masonry wall segment in Wintec Block F building" NZSEE Conference, New Zealand Society for Earthquake Engineering Inc.
- 30- Dizhur Dmytro, Hossein Derakhshan, Ronald Lumantarna, and Jason Ingham. (2010) " Earthquake – damage unreinforced masonry building tested in-situ " *Journal of the Structural Engineering Society New Zealand Inc "SESOC Journal"*
- 31- Doğangün, A. Ural, and R. Livaoğlu (2008) "Seismic performance of masonry buildings during recent earthquakes in Turkey "The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China.
- 32- Dov, M., S., 2004 "Design and construction failures lessons from forensic investigation" Galgotia publication, New Delhi, India and New York, USA.
- 33- Emeritus A.W. Hendry (2001) "Masonry walls materials and construction" *Construction and Building Materials*, Elsevier Science Ltd. All rights reserved. 15 .
- 34- Fitzsiman, N, and James, C., (1998) "Diagnosis and prognosis of structural integrity" in conservation of historic stone building and monuments, Washington, D, C.

- 35- Guido Magnes (2006) "Masonry building design in seismic areas: recent experiences and prospects from a European standpoint" First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC) Geneva, Switzerland, 3-8 September 2006 .
- 36- Hak S., Morandi P. and Magenes G. 2013 "Local effects in the seismic design of RC frame structures with masonry infills" COMPDYN 2013- 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Kos Island, Greece, 12–14 June 2013
- 37- Hessin, M., Gomaa (1997) "Cracks and restorations" third edition Cairo, Egypt.
- 38- Honeyborn David B., (1998) "weathering and decay of masonry" in conservation of building and decorative stone, Butterworth, London, Britain.
- 39- Hume Ian (2007) "the philosophy of conservation engineering" in structures and construction in historic building conservation, first edition, Blackwell publishing Ltd, Britain.
- 40- ICOMOS (2003) "Recommendation for the analysis, conservation and structural restoration of architectural heritage" International scientific committee for analysis and restoration of structures of architectural heritage 22/5/2003.
- 41- Jack G, miha tomazevic Emanuel Csorba (1984) "Design and construction of stone and brick – masonry buildings" in building construction under seismic conditions in the Balkan region volume 3 Vienna.
- 42- Jitendra Bothara and Svetlana Brzev (2011) "Improving the Seismic Performance of Stone Masonry Buildings" first published, Earthquake Engineering Research Institute, Oakland, California.
- 43- Karakosta, C., Lekidis V., Makarios T., Salonikios T., Sous I., Demosthenous M., 2013 "Seismic response of structures and infrastructure facilities during the Lefkada, Greece earthquake of 14/8/2003" Engineering Structures 27 (2005) 213–227
- 44- Kui Zhao, William L., Tilson, Dan Zhu, 2013 " Architectural Features of Stilted Buildings of the Tujia People: A Case Study of Ancient Buildings in the Peng Family Village in Western Hubei Province, China" Journal of Building Construction and Planning Research, 2013, 1, 131-140 Published Online December 2013
- 45- Lourenço P.B. (1998) " Experimental and numerical issues in the modeling of the mechanical behavior of masonry" Structural analysis of historical constructions II P. Roca, J.L. González, E. Oñate and P.B. Lourenço (Eds.) CIMNE, Barcelona .
- 46- Lourenço PB. "Recommendations for restoration of ancient buildings and the survival of a masonry chimney". Constr Build Mater 2006;20:239–51.
- 47- Luis A. Toranzo1 , and others (2001) " Improvement of traditional masonry wall construction for use in low-rise / low-wall-density buildings in seismically prone regions" Dept. of Civil Engineering, University of Canterbury, Christchurch p 2.NZSEE Conference.
- 48- Magenes G. 2006 " Masonry building design in seismic areas: recent experiences and prospect from a European standpoint " First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC) Geneva, Switzerland, 3-8 September 2006
- 49- Mazzolani F.M. (2008) "The Prohitech research project" Structural Analysis of Historic Construction – D’Ayala & Fodde (eds) © 2008 Taylor & Francis Group, London.
- 50- Miliston, J., M., and Domone, J., (2001) "construction materials, their nature and behavior" third edition U.S.A, New York.
- 51- Mills, R.," structural failure and repair (1998) "in conservation of building and decorative stone, Butterworth, London, Britain.

- 52- Moxon E. "Masonry restoration of the old civil engineering building Fredericton Campus, university of new Brunswick Dana " UNB- 9th Canadian masonry symposium
- 53- Murty C.V.R." Why is Vertical Reinforcement required in Masonry Buildings?" Building Materials and Technology Promotion Council, Indian Institute of Technology Kanpur Kanpur, New Delhi, India.
- 54- Nicola Augenti , Antonio Nanni , and Fulvio Parisi " Construction Failures and Innovative Retrofitting" *Buildings* 2013, 3, 100-121; doi:10.3390/buildings3010100 [www.mdpi.com/ journal/buildings](http://www.mdpi.com/journal/buildings).
- 55- Pakari, A., A., (1994) "structure and collapse" first edition, scientific books house for publication, Cairo, Egypt.
- 56- Parisi, F. Augenti, G. "Seismic capacity of irregular unreinforced masonry walls with openings" *Earthq. Eng. Struct. Dyn.* **2012**, 42, 101–121.
- 57- Parisi F., Augenti G. 2012 "Uncertainty in Seismic Capacity of Masonry Buildings" *Buildings* 2012, 2, 218-230.
- 58- Pauperio E., Romao X., Tavares A., "Survey of churches damage by the May 2012 Emilia-Romagna earthquake sequence" faculty of Engineering, University of Porto and university of Aveiro, Portuga.
- 59- Penazi D., Valluzzi M.R., Saisi A., Binda L., Modena C. "Repair and strengthening of historical masonry buildings in seismic areas " SSN (National Seismic Service), and CNR-GNDT
- 60- Pere Roca, Miguel Cervera, Giuseppe Gariup, Luca Pela 2010 "Structural Analysis of Masonry Historical Constructions. Classical and Advanced Approaches" *Arch Comput Methods Eng* (2010) 17: 299–325
- 61- Pineda P., Robador M.D. and Gil-Martí M.A. 2011"Seismic Damage Propagation Prediction in Ancient Masonry Structures: an Application in the Non-Linear Range via Numerical Models" *The Open Construction and Building Technology Journal*, 2011, 5, (Suppl 1-M4) 71-79 71
- 62- Poul Beckmann and Robert Bowles (2004) "structural aspects of building conservation" second edition, McGraw-Hill international (UK).
- 63- Sharma, R., and Maitis, (1995) " Conservation of ashlar monuments challenges and need for new strategies" the restoration and conservation of Islamic monuments in Egypt, the American university in Cairo press, Egypt, Cairo.
- 64- Shrestha Meena (2008) "Effects of openings in shear wall on seismic response of frame –shear wall structures" master thesis, Master of Engineering (Civil Engineering) Graduate school, Kasetsart University.
- 65- Syrmakizis C. A. 1998 "Report of the EAEE Working group 7: Preservation of historical structures and historical centres" 11th European Conference on Earthquake Engineering © 1998 Balkema, Rotterdam.
- 66- Urquhart Dennis (2007) "Conversion of Traditional Buildings Application of the Scottish Building Standards part 1 Principles and Practice" Guide for Practitioners Technical conservation research and education group, Published by Historic Scotland @ Crown copyright.
- 67- Valluzzi Maria Rosa, Binda Luigia, Modena Claudio (2005) "Mechanical behavior of historic masonry structures strengthened by bed joints structural repointing" *Construction and Building Materials*.
- 68- Valluzzi M., Porto F. and Modena C. 2001 "Behaviour of multi-leaf stone masonry walls strengthened by different intervention techniques" *Historical Constructions*, P.B. Lourenço, P. Roca (Eds.), Guimarães.
- 69- Valluzzi M., Cardani G., Binda L., Modena C 2004 " Seismic vulnerability methods for masonry buildings in historical centers: validation and application for prediction

- analysis and intervention proposals" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 .
- 70- Webster F. and Tolles E. 2000 "Earthquake damage to historic and older adobe buildings during the 1994 Northridge, California, earthquake " 12 WCEE 2000
- 71- Zhou F. "Retrofit for existing buildings with seismic control of structures".In: Post-earthquake rehabilitation and reconstruction. 1996. p. 378–96.

3

Structural appraisal

- Introduction
- 3.1- Registration and documentation "Historical, structural and architectural investigations"
- 3.2- Monitoring
- 3.3- The structural scheme and damage
- 3.4- Geometric documentation methods
- 3.5- Orientation and scaling
- 3.6- Testing methods
- 3.7- Laboratory work

Introduction

Structural appraisal is a process which usually encompasses the following: document search, inspection, measurements and recording, and structural analysis; sometimes it includes testing of materials and occasionally load testing of entire structures is involved (see Fig 3.1) (Beckmann and Bowles 2004)

Structural appraisal is a different activity to structural design insofar as it is aimed at assessing the real condition of an existing structure; there is a parallel in the field of medicine: any treatment must be preceded by a correct diagnosis. In appraisal, the restorer is left face to face with an existing structure of definable qualities and must determine its condition and suitability of use (Sullivan and Keane 2004), in the same time the structures of architectural heritage, by their very nature and history (material and assembly), present a number of challenges in diagnosis and restoration that limit the application of modern legal codes and building standards. Recommendations are desirable and necessary to both ensure rational methods of analysis and repair methods appropriate to the cultural context (ICOMOS 2003).

In fact, when neither the real state of damage nor the effectiveness of repairs is known, the effectiveness of any intervention is also unknown; prevention and rehabilitation can be successfully accomplished only if diagnosis of the state of damage of the building has been carefully carried out (Binda et al 2000). So historical masonry buildings should be understood very well in order to performing successful assessments and interventions. In fact the behavior of masonry is influenced by three main factors: the shape and the connections of the structures, the structure materials and its behavior under the imposed forces, accelerations and deformations.

But in the same time we should know the fact that structural analysis of historic masonry structures is a difficult task because of various reasons: the first one is the large variability of mechanical properties, due to inconsistent workmanship and use of natural materials. Secondly, significant changes in the core and constitution of structural elements, associated with long construction periods. In the course of time, structures might have undergone various changes which lead to different behavior than that expected from recently constructed masonry buildings (Kishali et al. 2009)

Next reason is that construction sequence of historic structures is unknown, especially of huge structures such as mosques, churches, palace etc. Finally, the inconvenience of restoration of old buildings is that new regulations and codes cannot be applied to them. These codes were written for new buildings and thus the performance requirements can be satisfied by old buildings (Urquhart 2007).

However, safety evaluation is also a difficult task because the methods of structural analysis used for new construction may be neither accurate nor reliable for historic structures and may result in inappropriate decisions. This is due to such factors as the difficulty in fully understanding the complexity of an ancient building or monument, uncertainties regarding material characteristics, the unknown influence of previous phenomena (for example soil settlements) (Valluzzi et al 2004). Also the continuous changes in materials and construction techniques that swiftly moved away from traditional practice, and the challenging technical and scientific developments, which make new possibilities available for all the agents involved in the preservation of the architectural heritage, are key aspects in the division between the science of construction and the art of conservation and restoration (Sullivan and Keane 2004). In another way we can say that the historic buildings appraisal process has the following steps:-

- 1- Structural appraisal is based on historical information and qualitative and quantitative approaches. The qualitative approach is based on direct observation of the structural damage and material decay as well as historical and archaeological research, while the quantitative approach requires material and structural tests, monitoring and structural analysis (Silman and Ennis 1993.)
- 2- The level of the investigation should always be defined by careful design; investigation should be performed to choose more detailed and specific investigation in order to: check the reliability of hypothesis on damage causes and evolution, control the structure before, during and after the intervention, control the effectiveness of the repair and strengthening.
- 3- Existing conditions assessment.
- 4- Determination of structural condition.
- 5- Analysis of structural threats and causes of deterioration.
- 6- identification of "character-defining features"
- 7- Development of rehabilitation guidelines and cost estimate.
- 8- Projection of long-term maintenance needs and costs (Schueremans and Van 2001).

Finally, we must remind that the peculiarity of heritage structures, with their complex history, requires the organization of studies and analysis in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions, to be both cost effective and ensure minimum impact on the architectural heritage it is often appropriate to repeat these steps in an iterative process (Hume 2007)

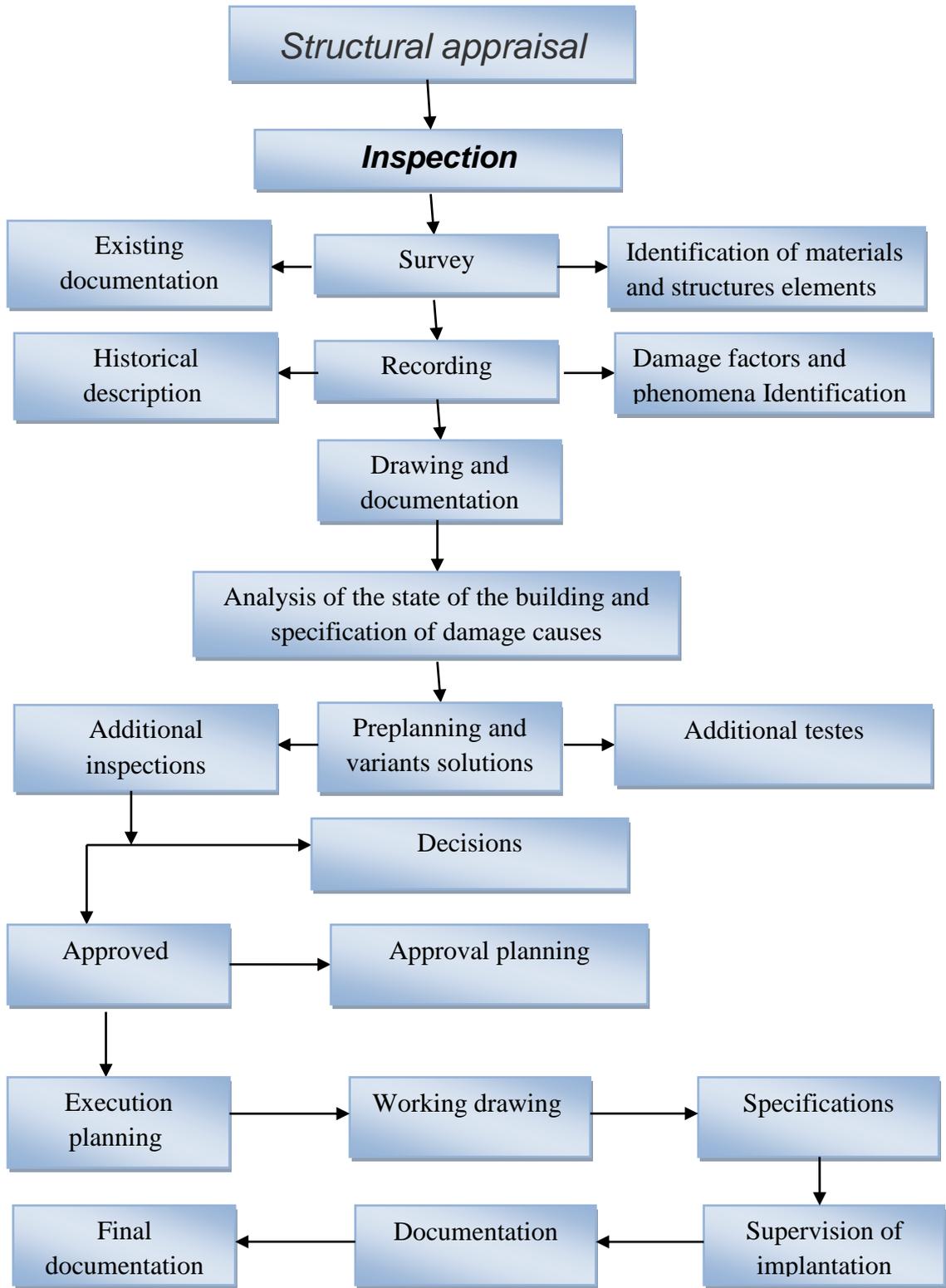


Figure "3.1" Steps of historic buildings inspection and documentation

3.1- Historical, structural and architectural investigations''

The purpose of the historical survey is to understand the conception and the significance of the building, the techniques and the skills used in its construction, the subsequent changes in both the structure and its environment and any events that may have caused damage. Documents used for this should be noted (Binda et al. 2000). The purpose of all studies, research and interventions is to safeguard the cultural and historical value of the building as a whole and structural engineering is the scientific support necessary to obtain this result. The investigation of the structure requires an interdisciplinary approach that goes beyond simple technical considerations because historical research can discover phenomena involving structural issues while historical questions may be answered from the process of understanding the structural behavior.

Knowledge of the structure requires information on its conception, on its constructional techniques, on the processes of decay and damage, on changes that have been made and finally on its present state. If these stages are performed incorrectly, the resulting decisions will be arbitrary: poor judgment may result in either conservative or therefore heavy handed conservation measures or inadequate safety levels. Evaluation of the safety of the building should be based on both qualitative (as documentation, observation, etc.) and quantitative (as experimental, mathematical, etc.) methods that take into account the effect of the phenomena on structural behavior (Henry and Smith 2004). Thus assumptions made in the interpretation of historical material should be made clear. Particular attention should be paid to any damage, failures, reconstructions, additions, changes, restoration work, structural modifications, and changes of use that lead to the present condition (see

Table 3.1 and Fig. 3.2) where the methods of historical, structural and architectural investigations are presented (Schueremans et al. 2006, Meier et al 2004)

Table: 3.1 the methods used in Historical, structural and architectural investigations (After (Schueremans et al. 2006, Meier et. al 2004).

Technique	place	Principle and application,
Historic research	ND IS+ IL	Information about the geometry of the structure, used materials, loads, Strengthening, structural events...
Visual inspection	ND IS	Is being used in all cases. This still is the cheapest and often also the most efficient, non-destructive test method. Use of additional guidance, e.g.: Damage Atlas and expert system
Fotogrammetry	ND IS	Evolution of large cracks en relative displacements. Is often used for measuring and documenting of damage of structural elements and materials
Electric resistivity	ND IS	Qualitative interpretation of the global condition of masonry (cavities, layering of material,...) Very valuable to check the effectiveness of executed consolidation injection
Radiography	ND IS	By radiation of the element by gamma-rays discontinuities that are located deep in the masonry (reinforcement, cavities, trusses,...) can be identified and located. Both sides of the element have to be admissible. Only very powerful apparatus can be used for masonry. Safety precautions have to be taken into consideration
Infra-red thermo-graphic	ND	Identification of the layering of the structure (e.g.: hidden behind stucco), traces of hidden cavities and discontinuities
Magnetic methods	ND IS	Locating of iron elements in thick masonry walls (e.g.: reinforcement bars, connection clamps...)
Radar	ND	Receiving of transmitted or reflected electric energy allows to identify different layers, hidden cavities, old foundations,
Mechanical pulse velocity	ND IS	By the impact, waves of 0.3-5.0 kHz are sent into the material. The wave velocity is a measure for the density and integrity of the material
Ultra sonic	ND IS	Only useful for homogeneous materials, like natural stones. In case of heterogeneous materials (masonry) the penetration depth is too small.
Vibration tests	ND IS	Relative stiffness, control of possible progressive damage of the structure in time
Endoscopy	ND/ D IS	Check out of the inner structure of the masonry. Use in drilling holes. Can be combined with photographs or video images
Flat jack	(S)D IS	Quantitative determination of the stress-strain relation of masonry (SD) and possibly also compressive strength (D)
Proof loading	ND IS	Check of the resistance of the structure for the expected loading. Is ND when the loading remains in the elastic area
Monitoring	IS	Permanent (automatic) data-acquisition of parameters that are of importance for the structural behavior, such as: high accurate leveling devices (HLS), Invar-wire measurements...
Abbreviations :- D:Destructive; SD: Semi-Destructive; ND: Non-Destructive IS: In Situ; IL: In Lab		

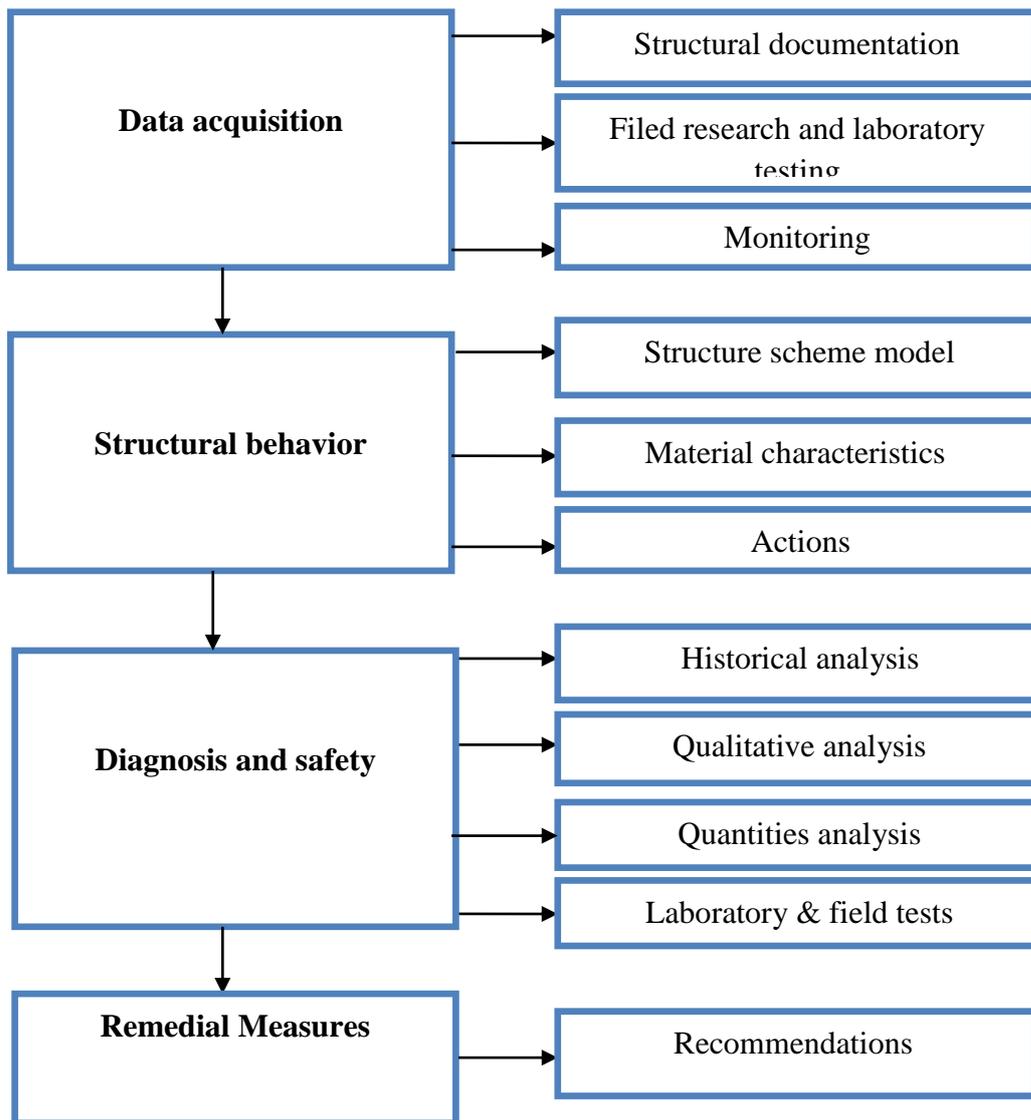


Figure 3.2 Historic building study steps before restoration measurements (Schueremans et. al. 2006)

3.1.1- Historical analysis

Knowledge of what has occurred in the past can help to foresee future behavior and can be a useful indication of the level of safety provided by the present state of the structure. History is the most complete, life-size, experimental laboratory. It shows how the type of structure, building materials, connections, joints, additions and human alterations have interacted with different actions, such as overloads, earthquakes, landslides, etc., perhaps altering the structure's original behavior by causing cracks,

fissures, crushing, movement out-of plumb, decay, collapse, etc. The structural task is to discard superfluous information and correctly interpret the data relevant to describing the static and dynamic behavior of the structure (Wei et al. 2004).

Although satisfactory behavior shown in the past is an important factor for predicting the survival of the building in the future, it is not always a reliable guide. This is particularly true where the structure is working at the limit of its bearing capacity and brittle behavior is involved (such as high compression in columns), when there are significant changes in the structure or when repeated actions are possible (such as earthquakes) that progressively weaken the structure (Schueremans et al. 2006).

3.1.2- Direct observation

Direct observation of the structure is an essential phase of the study, usually carried out by a qualified team to provide an initial understanding of the structure and to give an appropriate direction to the subsequent investigations. The main objectives include, identifying decay and damage, determining whether or not the phenomena have stabilized, deciding whether or not there are immediate risks and therefore urgent measures to be undertaken, and identifying any ongoing environmental effects on the building

Direct observation of structural faults begins by mapping visible damage, during this process interpretation of the findings should be used to guide the survey, Survey drawings should map different kinds of materials, noting any decay and any structural irregularities and damage, paying particular attention to crack patterns and crushing phenomena (Hui Gao et al. 2001)

3.1.3- Drawings

Drawings are therefore essential for the purpose of structural appraisal; drawings should show sections and elevations, generally of small enough scale that the whole of the building can be shown on one sheet. These sections and elevations should include all significant structural features, and any observed defects should be superimposed after the inspection. As wall cracks do not always show up on photographs, their positions, widths, and directions should be recorded on sketches (Schueremans et al. 2006).

Drawings of the construction of all or part of the structure and records of any work carried out to the structure, if available, examined. Records of former works will give indications of past problem and will indicate where apparent problems have already been dealt with (Carpinteri and Lacidogna 2003).

3.2. Monitoring

Structural observation over a period of time may be necessary, not only to acquire useful information when progressive phenomena are suspected, but also during a step by- step procedure of structural renovation. A monitoring system usually aims to record changes in deformations, cracks, temperatures, etc. Dynamic monitoring is used to record accelerations. Some cases require the use of computerized monitoring systems to record the data in real time (ICOMOS 2003). Monitoring technique can be divided to:-

Static monitoring; Where an important crack pattern is detected and its progressive growth is suspected due to soil settlements, temperature variations or excessive loads, the measurements of displacements in the structure as function of time has to be collected. Monitoring systems can be installed in the structure in order to follow this

evolution; in some cases the knowledge of the crack pattern evolution can help preventing the collapse of the structure. This system may stay in place for years before a decision can be taken for repair or strengthening. Also, the monitoring should be long-term, not less than 1.5 years, in order to rule out the influence of temperature variation at every reading of the eventual displacements.

Dynamic monitoring; In-situ testing using dynamic methods can be considered a reliable non-destructive procedure to verify the structural behavior and integrity of a building. The principal objective of the dynamic tests is to monitor the behavior of the structure may subject to vibration. Finite element method (FEM) in this manner it is possible to verify the effectiveness of the computational methods used for the analysis and control of the structure (Scherer 2002).

Accurate monitoring has a number of advantages. First, it can help in the correct diagnosis of structural deteriorations; this means that an effective and sympathetic treatment is more likely to be implemented. Before remedial works are commenced a careful survey of cracks and other damage should be made and accurate monitoring commenced to learn more about the building problems. Secondly it can be a source of reassurance and an invaluable aid in convincing others that the decision to take no action to remedy an apparent problem was correct because the structure having once moved is now stable.

Thirdly monitoring is deemed the most effective, indeed often the only way of proving satisfactorily and without doubt that apparently distressed structures are in fact stable and therefore no major remedial works need be undertaken; it is very rare for structures to collapse without warning (Nickerson 1994).

3.2.1- The Auto plumb

The Auto plumb is an optical device which acts like a plumb bob, but without the problems of bob swing and wind effects on the line (Ariasa and Ordóñez 2006). The Auto plumb is a sophisticated optical form of plumb bob that can be used over heights of between 2 and 150 meters. Because it is an optical instrument, it doesn't have the problems of bob swing and wind drag on the line. This instrument can read down to better than 0.5mm in 10 meters.

At some high point on the structures a target must be attached, and a small reference point is also necessary at ground level. This instrument is used at ground level and thus only in high level "visit" need be made. It is often possible to use a brass screw or a small bracket as the high level target (ICOMOS 2003).

3.2.2- Electronic Theodolite.

Over the last two decades, the technological progress in angle measurements has been mainly in the automation of the readout systems of the horizontal and vertical circles of the theodolite. The optical readout systems have been replaced by various, mainly photo-electronic, scanning systems of coded circles with an automatic digital display and transfer of the readout to electronic data collectors or computers.

As far as accuracy is concerned, electronic theodolites have not brought any drastic improvements in comparison with the precision optical theodolites. Some of the precision electronic theodolites can sense the inclination (misleveling) of the theodolite to accuracy better than 0.5 inch and automatically correct not only vertical but also horizontal direction readouts (Paweł and Lourenço 2003).

A theodolite can be used to check the out of vertical movements of structures to a degree of accuracy similar to that of the Auto plumb but without the need to gain

access at high level. The modern electronic distance reading theodolite is capable of measuring distances (and therefore can measure stretching and shortening of structures) to an accuracy of 1 mm, and this is a much more useful instrument for monitoring than the older type of manually operated theodolite. For structural monitoring purposes, a target has to be attached to the structure under observation and a base station for the theodolite set-up, the target can be a small white reflector, 24 mm in diameter (Lombillo et al. 2009).

3.2.3- Total stations.

Any electronic theodolite linked to an Electronic Dimension Measurement (EDM) instrument and to a computer creates a total surveying station which allows for a simultaneous measurement of the three basic positioning parameters, distance, horizontal direction, and vertical angle, from which relative horizontal and vertical positions of the observed points can be determined directly in the field. Several manufacturers of survey equipment produce integrated total stations in which the EDM and electronic angle measurement systems are incorporated into one compact instrument with common pointing optics (Acito et al. 2008).

3.2.4- High accurate leveling devices (HLS)

This monitoring system is based on the principle of communicating vessels. The instrument is composed of vessels (see Fig. 3.3 and Fig. 3.4), linked to a double circuit: one to let the measuring liquid circulate and another one, an air circuit, to set an identical pressure in all the vessels (Lombillo et al. 2009). The liquid used is water (normal water, non-distilled so that it can conduct electricity, treated with anti-algae and antifreeze,) with a coloring to be able to control the presence of bubbles. In each vessel, the height is measured with a capacitive sensor which measures the distance between the water level and the sensor, the readings range from 5000 μm to 10000 μm .

The advantages of hydrostatic measuring systems are their high accuracy and resolution. Due to their simple and robust configuration, hydrostatic measuring systems are furthermore well suited for permanent, all-season monitoring, combined with remote control systems and automated data acquisition (Binda and Tiraboschi 1997).

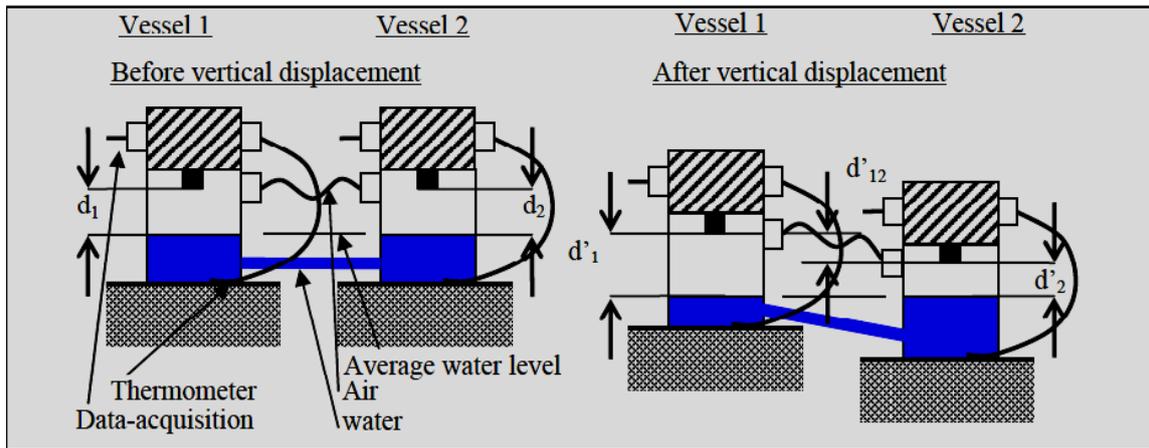


Figure 3.3: Hydrostatic leveling system – measuring principle (After Lombillo et al. 2009)

Hydrostatic measuring systems work all on the fundamental principle which says that water surface which is under the influence of a gravitational field and free to move, orients towards a certain level surface. Measuring pots, which are connected to each other, obey the law of the communicating vessels and therefore the water surface represents a stable, reliable and very accurate reference for leveling purposes (Binda et al. 2000)

Measurements are taken with the system frequency (about 33 Hz) and the results are directly visible on the computer screen. The data are stored with an adjustable frequency. The tubes of the water circuit are placed as horizontally as possible in order to remove the effects of a temperature gradient. The tubes of the air circuit lead upwards from the vessels to prevent the condensation water from staying in the air circuit (see Fig 3.4) (Lombillo et al. 2009)

HLS is a dedicated synchrotron radiation facility. The monitoring software is running on a PC. The PC communicates with the monitor through RS232/RS485 to form a whole voltage monitoring system (Binda et al 2000)

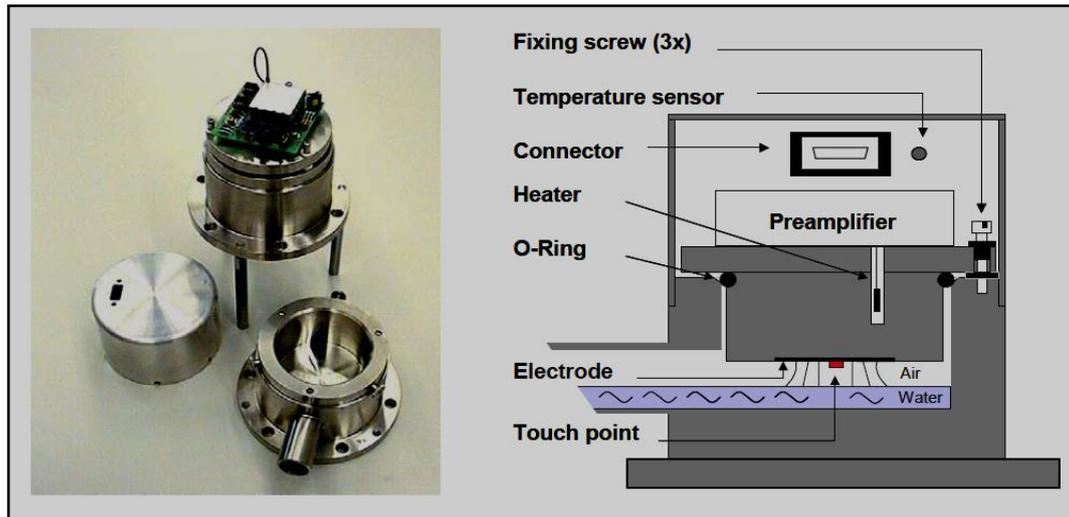


Figure 3.4: Building blocks of the HLS – cross section of a HLS level sensor (Lombillo et al 2009)

3.2.5- Convergence measurements (invar-wire)

Convergence measurements using invar wire as shown in Fig. 3.5 are used for an accurate measurement of the distance between two materialized fixed points on a structure. The accuracy that can be reached in practice is about 0.05 mm. Recently, it is used in several practical applications, such as in the Church of Saint Mary at Tangerine, to check the stability of the pillars during archeological excavation in the different naves of the church. (Brownjohn et al. 1992)

3.3. The structural scheme and damage

The structural system shows how the building transforms actions into stresses and ensures stability. The original structural system may have changed as a result of damage (cracking), reinforcement, or other modifications of the building. The system used has to take into account any alterations and weakening, such as cracking,

disconnections, crushing, leanings, etc., whose effect may significantly influence the structural behavior.

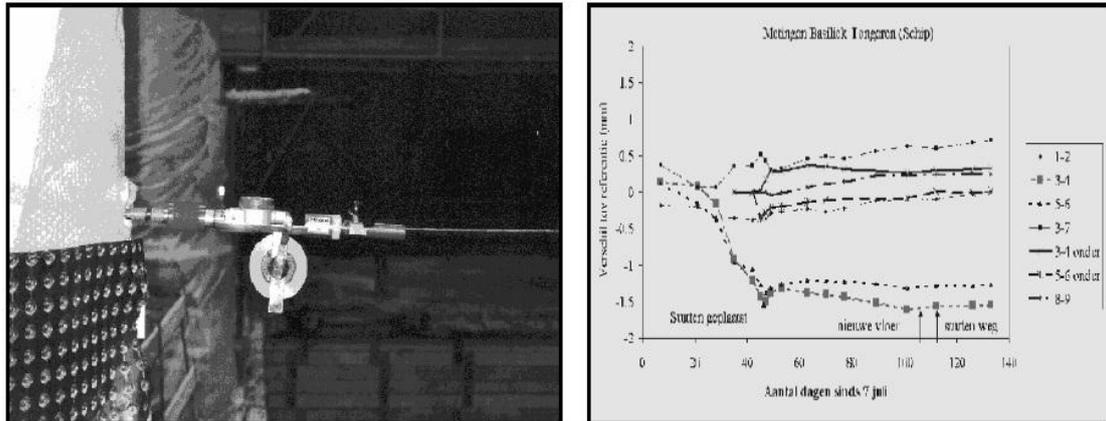


Figure 3.5 Invar wire measurements at the Church of Saint Mary at Tangerine (Brownjohn et al. 1992)

These alterations may have been caused either by natural phenomena or by human interventions. The latter includes the making of openings, niches, etc; the elimination of arches, slabs, walls, etc., which can create unbalanced forces; increases in height of the structure, which can increase weights; excavations, galleries, nearby buildings, etc., which can reduce the soil bearing capacity (Xia and Brownjohn 2004).

3.4. Geometric documentation methods for historic traditional masonry

According to Scherer 2007 there are four principal methods for compiling data: traditional manual, topography, photogrammetric, and scanning methods. The choice of one method or another will depend on several factors: end use, accuracy required, budget available, the characteristics of the structure to be documented, etc. Knowledge of the exact geometrical shape is of fundamental importance for the stability assessment of thin masonry vaults. All the irregularities of the geometry are detected in detail and can be given as input data to a structural analysis model (Valluzzi et al 2004).

Traditional manual methods determine dimensions by measuring angles and distances. The equipment used is very simple (flex meters, plumb lines, poles, squares, measuring tapes, manual laser distance meters) and little training is needed to carry out the work (Frunzio et al 2001)

Topographical methods, which require specialist equipment, are based on determining the three-dimensional (X, Y, Z) coordinates of specific points of an object in order to establish its geometry. The device traditionally used is the tachometer, although by now electronic total stations are very frequent (Dizhur et al 2010)

Photogrammetric methods apply the classical techniques and methods of close-range photogrammetry. One of the great advantages of photogrammetry compared to other techniques is the short period of time spent measuring the object. Also it reproduces true position and scale.

Scanning methods have become popular recently due to the commercial availability of laser scanners, which automatically and very rapidly (1000 points/second) measure the angles and distances from point to point. The result is a cloud of thousands of points on the object's surface (Taiab and Edres 2010).

3.5. Orientation and scaling

True position in space (orientation) and the scale of the models are performed by means of plumb lines. Plumb lines are used to define the direction of the Z axis in the absolute orientation process, during the laboratory work, and thus stabilize and level the shape of the model. The plumb lines must drop in a perfect vertical line and should be suspended from any projecting element on the walls of the building. The length of the plumb lines will depend on the height of the construction to be surveyed,

but should be as long as possible. Marks are made in the plumb lines at known distances. These should be sufficiently visible when photographing the building. The precise distance between marks should be known, as this is essential to obtaining the scale of the model in the absolute orientation phase. Lengths should be proportional to the size of the construction. (Sturgis 2003).

3.6. Testing methods

The schedule of tests should be based on a clear preliminary view of which phenomena are the most important to understand. Tests usually aim to identify the mechanical (strength, deformability, etc.), physical (porosity) and chemical (composition) characteristics of the materials, the stresses and deformations of the structure and the presence of any discontinuities within the structure (Binda et al. 1999).

3.6.1- Flat-jack test

Flat-jack testing is a direct and in-situ testing method that requires only the removal of a portion of mortar from the bed joints. Therefore, it can be considered as nondestructive because the damage is temporary and is easily repaired after testing (Lourenço 1998). In general, a flat jack consists of two stainless steel plates welded along the edges with one or two entry and exit ports, which are connected to a hydraulic circuit with a pump, through which an internal pressure is induced. It can be found in different forms and sizes.

The method was originally applied to determine the in-situ stress level of the masonry and it has been extended to the detection of its deformability characteristics. It appears to be the only way to achieve reliable information on the main mechanical characteristics of a masonry structure (deformability, strength, state of stress). The

single flat-jack test is carried out by introducing a thin flat-jack into the mortar layer. After the test is completed, the flat-jack can easily be removed and the mortar layer restored to its original condition (Timchenko 2000).



Figure 3.6 Placing the flat jack in the masonry wall and Relation between the contact area of the flat jack and the real area of the realized cut (Timchenko 2000).

The thickness of the flat-jack is determined by its specific function: An ideal flat-jack will completely fill the slot in the mortar joint (see Figs. 3.6 & 3.7). The reference field of displacements is first determined by measuring distances between gauge points fixed to the surface of the masonry (distances d_i in Fig. 3.8b). Then, a slot is cut in a plane normal to the direction of measured stresses. This allows deformations in a direction normal to the slot.

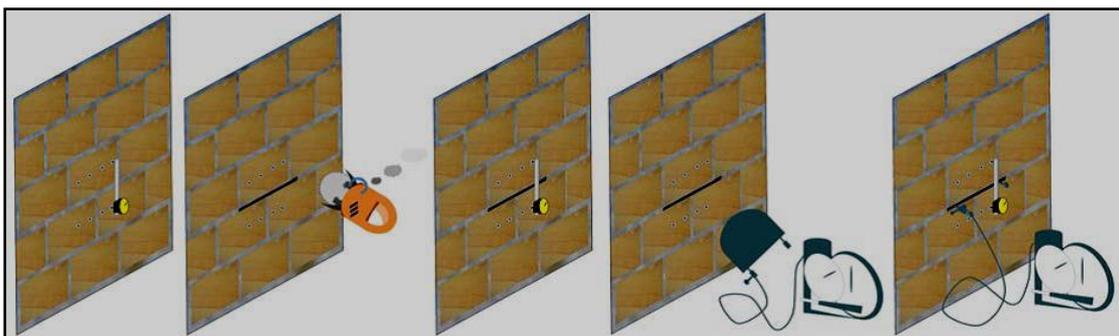


Figure 3.7 Phases of the test for obtaining the stress level (Teddy 2001).

Distances between gauge points decrease (i.e. distance d in Fig. 3.8c is smaller than reference distance d_i). Cutting the slot causes partial stress relief in masonry above and below. It is not necessary, and often it is not possible, to apply load in all

the thickness of the wall, taking into account the big thickness that can reach the ancient masonry walls. Nevertheless, in all the cases one of the masonry leaves (or sheets) have to be tested at least. In such a case, the obtained results refer only to the leaf that has been tested (Ariasa and Ordóñez 2006)

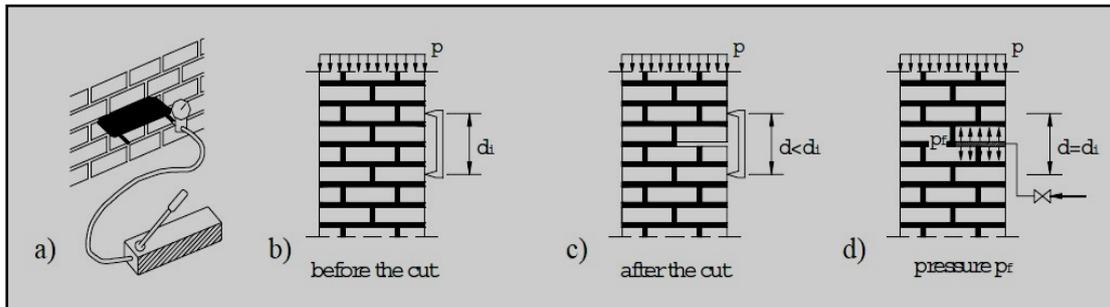


Figure 3.8 Phases of the flat-jack test ($p=p_f$ when $d=d_i$) (Ariasa and Ordóñez 2006).

The test is based on the following assumptions: the stress in place of the test is compressive; the masonry surrounding the slot is homogenous; the masonry deforms symmetrically around the slot; the state of stresses in the place of the measurement is uniform; the stress applied to masonry by the flat-jack is uniform. The value of stresses (compared to compressive strength) allows the masonry to work in an elastic regime. The determination of the state of stress is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is determined by a partial closing of the cutting, i.e. the distance between two points after the cutting is lower than before (Acito et al. 2008)

The test described can also be used to determine the deformability characteristics of masonry. A second cutting is made; parallel to the first one and a second jack is inserted, at a distance of approximately 40-50 cm from the other. The two jacks delimit a masonry sample of appreciable size to which a uniaxial compression stress can be applied. Measurement bases for removable strain-gauge on the sample face provide information on vertical and lateral displacements. In this

manner, a compression test is carried out on an undisturbed sample of large area (Binda et al. 2000).

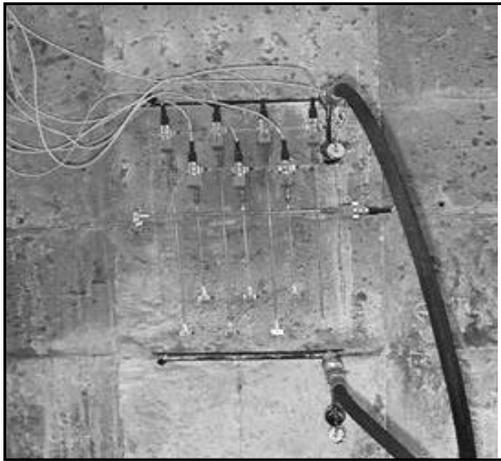


Figure 3.9- Double flat jack in a regular stone

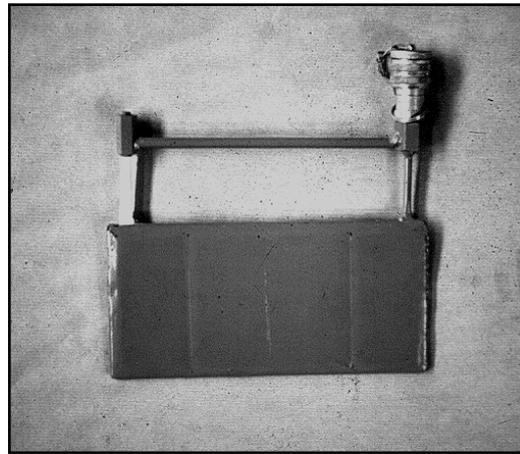


Figure 3.10- Rectangular flat jack (Binda et al. 2000).

3.6.2- Georadar

Impulse radar is based on the emission, reflection/transmission and detection of very short electromagnetic impulses by an antenna system. Reflection of the emitted impulses occurs at interfaces between materials with different permittivity or conductivity, e.g., at the surface of the structure, at interfaces of layered materials, at voids, inclusions and other inhomogeneities inside the material and at the backside of the structure (depending on the thickness) (Bam 2004). The propagation velocity and the signal penetration depend on the electric and dielectric properties of the materials.

Radar testing is carried out in order to:

- locate the position of large voids and inclusions of different materials, like steel, wood, etc
- qualify the state of conservation or damage of the walls.
- define the presence and the level of moisture;
- control the effectiveness of repair by injection techniques; and

- detect the morphology of the wall section in multiple-leaf stone and brick masonry structures (Binda et al. 2000).

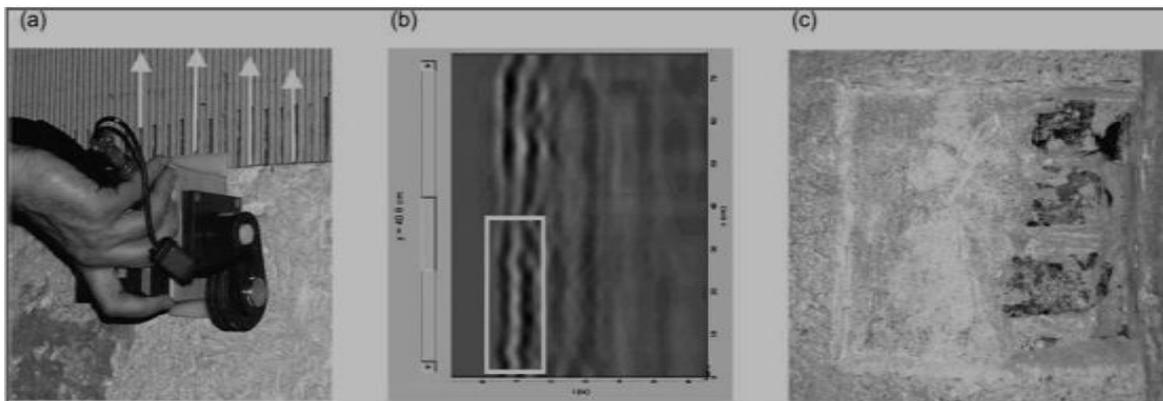


Figure 3.11- using of Georadar in the surface of deterioration walls (Bam 2004 and Binda et al. 2000)

When the transmitting and receiving antennas, which are often contained in the same housing, are moved along the surface of the object under investigation, radar grams (color or grey scale intensity charts giving the position of the antenna against the travel time) are produced. Measuring the time range between the emission of the wave and the echo, and knowing the velocity of propagation in the media it would be possible to know the depth of the obstacle in the wall.

In the real cases, the velocity is unknown because it changes from one material to the other or in the presence of voids. Furthermore, the velocity is higher in dry walls, and lower in wet walls (Binda et al. 2007).

3.6.3- Dilatometer

The dilatometer technique is an in situ load test carried out on a wall in which a stress level is introduced by means of a cylindrical tube that can expand radially and while is lodged in a perforation practiced in the wall (see Fig. 3.12).

The procedure of the test consists of drilling a perforation, being careful to reduce to the minimum the disturbance in the wall, with a diameter compatible with the size of the tube to be introduced. From the readings of the test, the curve pressure

given by the tube and increase of volume can be obtained, of which can be estimated the module of deformation of the masonry. (Lombillo et al. 2009)

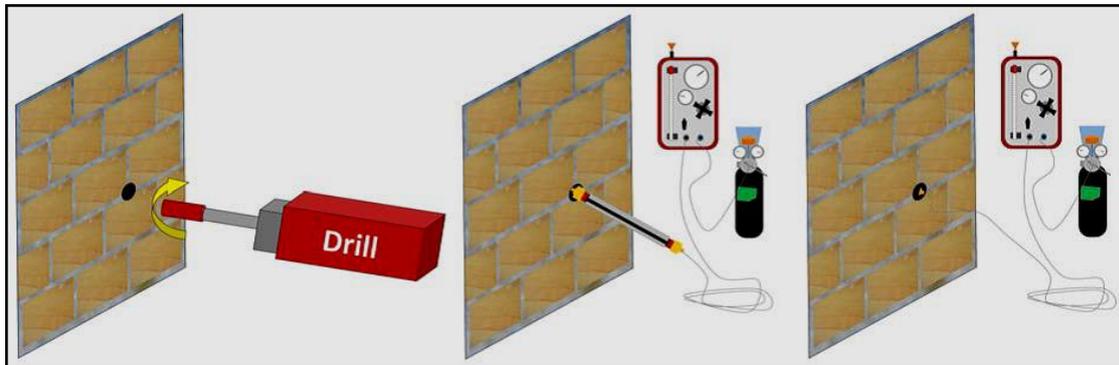


Figure 3.12- Phases of the dilatometer test (Lombillo et al. 2009)

3.6.4- Visual inspection or endoscopy

Endoscopy is the indirect observation of the interior of something, through an existing perforation or an elaborated one, that enables visual inspecting. Currently these devices allow measurements in inaccessible points using a mobile head composed of two lenses that can estimate distances with accuracy thanks to the stereoscopic effect.

Endoscopies provide images of non recognizable areas by sight. Show caves with difficult access in a simple and precise way, with a degree of sharpness, fidelity in the reproduction of colors and brightness that are crucial. For all that, the endoscopy provides excellent opportunities for a non aggressive examination designed like a complement of the normal exploration methods. The main advantage of endoscopy is that it allows access to not visible points in a natural way and provides visual and diagnostic targets (see Fig. 3.13).

Inside this flexible pipe, obviously cannot install a lens system, so that this type of endoscopes is based on a system of image transmission through thin glass fibers (beam transmitter of images, Fig. 3.14), through which the image is transmitted to the eye

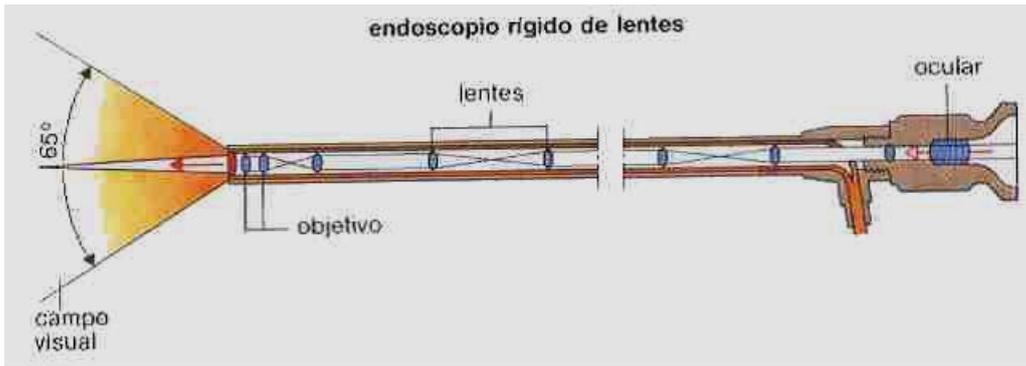


Figure 3.13- Rigid lens endoscope (Lombillo et al. 2009)

The image resolution of a flexible endoscope and the appreciation degree of the details of the examined area depends on the number, density and quality of the fibers that make up the beam transmitter of images. Since each fiber transmits only one point of the image, the beam transmitter consists of a bundle of fibres. The precise cluster beam transmitter imaging is the key for getting an image of quality and valid information (Lombillo et al. 2009)

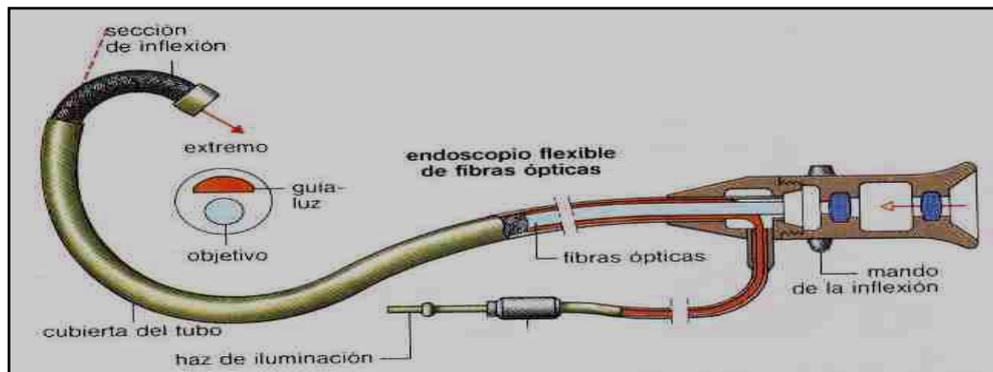


Figure 3.14- Flexoscope (Lombillo et. al. 2009)

3.6.5- Thermography.

The thermographic survey has the advantage of being applicable to wide surfaces of walls; it is a telemetric method and has high thermal and spatial resolution. The thermographic analysis is based on the thermal conductivity of a material and may be passive or active. The passive application analyses the radiation of a surface during thermal cycles due to natural phenomena insulation and subsequent cooling. If the survey is active, forced heating to the surfaces analyzed are applied.

The thermal radiation is collected by a camera sensitive to infrared radiation (see Fig. 3.15). In fact, each material emits energy (electromagnetic radiation); this radiation is characterized by a thermal conductivity, i.e. the capacity of the material itself of transmitting heat, and its own specific heat. Each component of an inhomogeneous material like masonry shows different temperatures. The thermo vision detects the infrared radiation emitted by the wall. The result is a thermographic image in a colored or black and white scale (Binda et al. 2007).

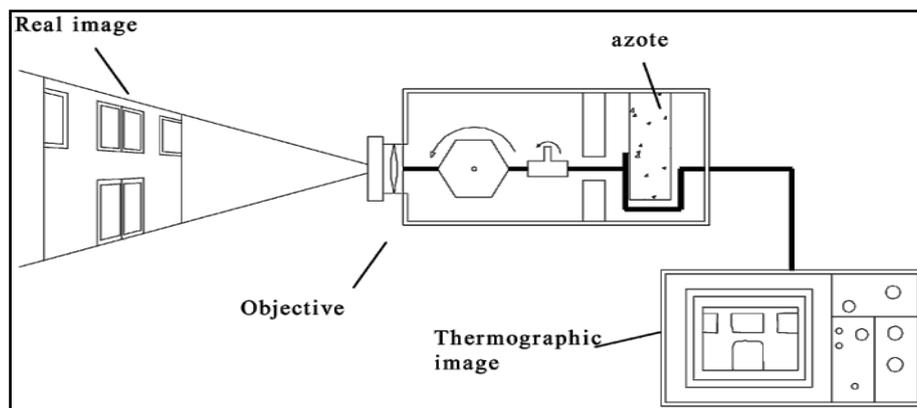


Figure 3.15- The thermovision camera

3.6.6- In situ vibration measurements

The use of in situ vibration measurements has become an actively pursued research topic. In civil engineering, vibration data can be used for several purposes. One common purpose of vibration data is in the updating of uncertain features and parameters of finite element (FE) models. Also to predict the performance of the structural system under loading conditions that is impractical to test. Another purpose of the vibration data is in detecting damage in civil structures from changes in their vibration characteristics (Pavic et al 2002).

Recently, the research on vibration testing of historic masonry systems has started to increase. Such an investigation is only possible if the undamaged and damaged states of the same structure can be tested separately. But in such testes we

observe that there are two things we must take in our attention: the first is in earlier studies, both ambient and forced excitation techniques have been successfully performed on historic masonry monuments. The second is when testing historic monuments, difficulty in transportation, positioning, and alignment of the shaker device at the top of historic element is prohibitive. Transient hammer impact excitation provides a practical and convenient alternative (Atamturktur et al. 2007). Impulse hammer is used to excite the structure. To broaden the impact duration and induce low frequency vibration the softest hammer tip is preferred. The hammer operator excites the structure consistently in the vertical direction. To reduce the degrading effects of ambient noise, 5 impact data sets are measured and averaged for each excitation location (Frunzio et al. 2004).



Figure 3.16 The measurement axis of the accelerometer (Q-Flex QA 750 model force balance accelerometers) is aligned vertically by adjustable screws (Pavic et al. 2002).

3.6.7- Shear Test

The wall panels are tested in diagonal shear. The testing procedure involves rotation of the URM wall panel by 45° and loading along one of the wall's diagonals. For the testing of the wall panels extracted from the any building, the standard method is modified such that the wall remained in its original orientation and the loading mechanism was rotated. The test setup is shown in Fig. 3.17 (Dizhur et al. 2004).

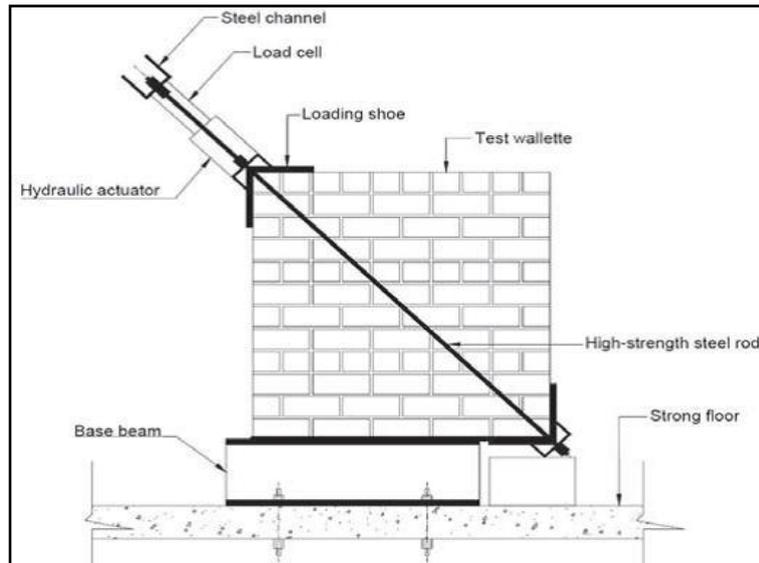


Figure 3.16 - Diagonal shear test setup (Dizhur et al. 2004).

3.6.8- Auxiliary lattice steel structure

Auxiliary steel lattice structures are prepared to allow performing the panel tests, as shown in Fig. 3.18. By applying vertical loads on the lattice the panel became horizontally loaded in the transverse direction near to its top end. Under oscillation, the load produces forced movement that amplifies and induces vibrating horizontal action on the wall.

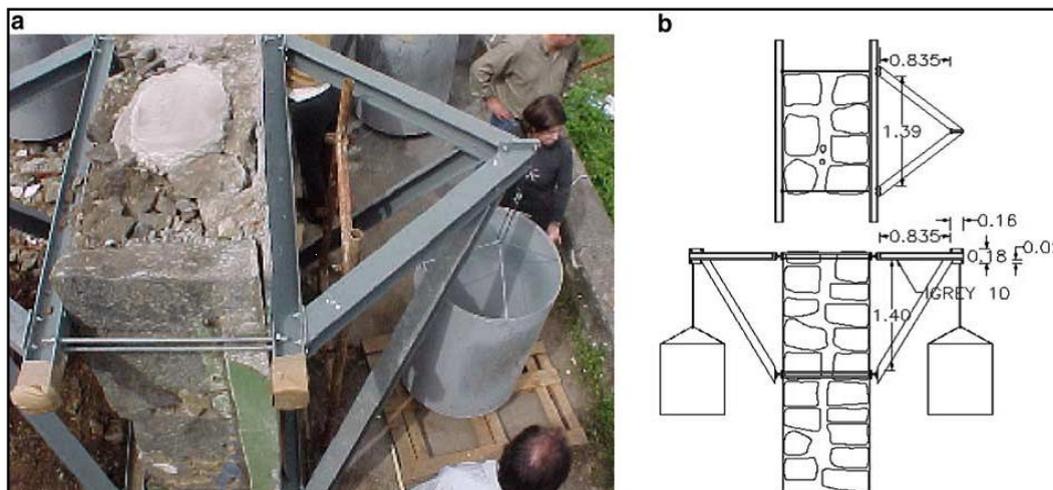


Figure 3.18- Auxiliary lattice steel structure for the tests: (a) general view; (b) Schematic representation (Costa and Arede 2006).

The auxiliary structure is made of HEB100 steel bars in a way that allow an eccentricity of 1.0 m for the vertical load. Loads were created by means of a metal

bucket suspended from a steel cable and filled with sand, whose weight is placed in several stages and always monitored. The metal bucket is provided with a bottom closure to allow discharging the sand, also in various stages. Instruments are used to evaluate the static and dynamic response of the wall, from which the mechanical characteristics of the masonry were derived

These instruments include mechanical dial gauges, suitable for the static loading stages and an accelerograph to obtain records of the dynamic response. Dial gauges are placed at the wall top-end, one pair and at the wall mid-height (also one pair). Note that the buckets are filled with sand and subjected to forced oscillation. The vibration recordings and the respective analyses are an indirect technique of estimating the mechanical elasticity properties of a given structure.

Therefore, several acceleration plots are obtained for each panel and for different load stages in the buckets upon the application of an impact on the panel. That signal is processed to estimate the predominant frequencies and damping, respectively, by selecting amplitude peaks of the signal (Costa and Arede 2006).



Figure 3.19 - General view of the experimental set-up used to perform the tests (after Costa and Arede 2006)

3.6.9 Finite Element Method (FEM)

The analysis methods proposed for masonry elements up to the second half of last century were essentially based on the techniques of graphic statics and on the principles of structural mechanics available at that time, (Valluzzi et al. 2000). The finite element method is deemed one of numerical analysis methods that are used to find approximate solutions to many of the problems for which it is difficult to find exact solutions when using traditional solution methods. ANSYS/11.0 is one of the numerical packages adopted for this purpose; it is equipped with a library containing a variety of elements for modeling a structure and can be applied to a wide range of engineering problems. (Binda et al 1999)

The finite element method is usually adopted to achieve sophisticated simulations of structural behavior. A mathematical description of the material behavior, i.e. the relation between the stresses and strains at any point with the structure is necessary for this purpose. The application of this method for the analysis of masonry structures is based on the assumption of quasi-brittle material behavior.

Masonry is a material that exhibits distinct directional properties due to the mortar joints which are considered to represent planes of weakness. In general, the approach towards its numerical representation can focus on the micro-modeling of the individual components, or the macro modeling of masonry as a composite

The availability of software makes it practical for engineers to perform static and dynamic analysis of structures quickly and efficiently. The purpose of the analysis is not to simulate the actual behavior, but to get reliable information on the correlation between the observed damages and the results of the analysis. The

correlation is not perfect, but is sufficiently good to draw conclusion regarding the ability of historical buildings to withstand earthquakes (Valluzzi et al 2004).

3.7. Laboratory work

When masonry is damaged by aggressive agents, the decay is never uniform; if maintenance is needed and only some bricks or stones or decorations are affected by the damage, the best remedy is frequently the substitution of the most decayed elements. In this case, laboratory tests can give useful information for the choice of the appropriate material for substitution. So laboratory tests are needed for the right choice of the treatment. The tests have to be carried out on both deteriorated existing bricks and stones, and on undamaged and new ones. The following tests are suggested:

3.7.1- *Mechanical tests*: compressive and indirect tensile tests, hardness tests at different points of the brick or stone sections in order to determine the depth of the decay.

3.7.2- *Physical tests*: the volumetric mass, the water absorption by total immersion, the water absorption by capillary rise are important characteristics needed to determine the durability of the materials and the effects of surface treatments; the initial rate of suction of bricks and stones and X-ray diffraction measurements can detect the type of salts found inside or on the surface of a decayed masonry; thermal and water expansion coefficients must also be measured on new bricks and stones.

3.7.3- *Chemical tests*: tests for alkaline sulfate can be conducted on material samples taken at different depth of the masonry in order to detect the presence and quantity of these very aggressive salts.

3.7.4- *Optical and mineralogical analysis:* optical observations stereomicroscopy, Scanning Electron Microscope (SEM), defines the deterioration, its causes and the presence of salts. Petrographic observations on thin sections determine the pore size distribution of the material, the size and distribution of the aggregates, the geographical origin of clays and stones, the firing temperature of bricks and the decay and its causes.

3.7.5- *Durability tests:* freezing / thawing cycles and salt crystallization tests are needed for new bricks and stones in order to determine their performance under aggressive agents (Ariasa and Ordóñez 2006).

3.7.6- *Sonic tests.* Testing methodology is based on the generation of sonic or ultrasonic impulses at a point of the structure. A signal is generated by percussion or by an electrodynamic or pneumatic device (transmitter), and collected by a receiver which can be placed in various positions (Ariasa and Ordóñez 2006). The use of sonic tests for the evaluation of masonry structures has the following aims: to qualify masonry through the morphology of the wall section, to detect the presence of voids and flaws and to find crack and damage patterns; and to control the effectiveness of repair by injection technique in others which can change the physical characteristics of materials (Binda et al 2000)

Finally all previous documentation and tests must provide information on three types of phenomena; continuous processes (for example decay process, slow soil settlements, etc.) which will eventually reduce safety levels below acceptable limits, and measures must be taken before this occurs; Phenomena of cyclical nature (variation in temperature, moisture content, etc.) which produce increasing deterioration (Padaratz and Forde 1995), and phenomena that can occur suddenly

(such as earthquakes, hurricanes, etc.). The probability of the latter occurring at any defined level increases with the passage of time, so that the degree of safety to be provided can theoretically be linked to the life expectancy of the structure (for example, it is well known that to protect a building against earthquakes for five centuries it is necessary to assume highest actions than those assumed to protect the same building for one century) (Mariana 2007).

Concluding Remarks

- a correct structural analysis of an historic building requires a deep knowledge of: (a) the building history and its evolution; (b) the geometry; (c) the structural details; (d) the cracking pattern and the damage map; and (e) the masonry construction techniques
- A preliminary in-situ survey of historic traditional masonry is useful in order to provide details of the geometry of the structure and the visible damage (cracks, out of plumb, material decay) and also, in order to identify the points where more accurate observations have to be concentrated.
- Historical analysis and direct observation of the structure are an essential phase of the study, usually carried out by a qualified team to provide an initial understanding of the structure and to give an appropriate direction to the subsequent investigations. The main objectives include, identifying decay and damage, determining whether or not the phenomena have stabilized, and deciding whether or not there are immediate risks.
- In-situ and laboratory investigation is the base for the knowledge of the structural behavior and of the effectiveness of intervention. The goal of these operations should always be clear before performing them in order to avoid high expenses with low benefits.
- The level of the investigation should always be defined by a careful design; investigation should be performed to choose more detailed and specific investigation in order to: check the reliability of hypothesis on damage causes and evolution, control the structure before, during and after the intervention, control the effectiveness of the repair and strengthening.

- Non-destructive Methods (NDM) can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests such as flat jack test, sonic test, Georadar, etc.
- The flat-jack tests give local measurements and are slightly destructive: nevertheless they can give directly the values of mechanical parameters. In the case of ND tests an overall qualitative response of the masonry can be obtained.
- At present the most common ND techniques are the sonic (or ultrasonic), radar and Thermography techniques.
- ND techniques can be used for several purposes: (i) detection of hidden structural elements, like floor structures, arches, pillars, etc., (ii) qualification of masonry materials, mapping of non-homogeneity of the materials used in the walls (e.g. use of different bricks in the history of the building), (iii) evaluation of the extent of mechanical damage in cracked structures, (iv) detection of the presence of voids and flaws, (v) evaluation of moisture content and capillary rise, (vi) detection of surface decay, and (vii) evaluation of mortar and brick or stone mechanical and physical properties.
- In-situ testing using dynamic methods can be considered a reliable non-destructive procedure to verify the structural behaviour and integrity of a building. The principal objective of the dynamic tests is to assess the behaviour of the structure to vibration. A simple example of dynamic test is to induce tensile stresses in tie rods. The forced vibrations could be produced by local hammering systems. An accelerometer net is installed in chosen significant parts of the structure.

- When masonry is damaged by aggressive agents the decay is never uniform; maintenance is needed if only some bricks or stones or decorations are affected by the damage. In this case, laboratory tests can give useful information for the choice of the appropriate material for substitution, thus laboratory tests are needed for the right choice of the treatment. Laboratory tests include mechanical and physical tests, chemical tests, optical and mineralogical analyse.

Following the discusses Of the historic traditional masonry buildings in chapter 1, the deterioration aspects and deterioration factors and mechanisms in historic traditional masonry in chapter 2, and the structural appraisal methods in chapter 3, the next step is to discuss the methods used to restore and rehabilitate the historic traditional masonry buildings.

References

- (1) Acito M., L. Binda & G. Cardani 2008 " Experimental and numerical study on the application of the flat-jack tests to masonry walls" *Structural Analysis of Historic Construction – D’Ayala & Fodde (eds) © Taylor & Francis Group, London.*
- (2) Ariasa P., Ordóñez C. 2006 "Methods for documenting historical agro-industrial buildings: a comparative study and a simple photogrammetric method" <http://france.elsevier.com/direct/CULHER/> *Journal of Cultural Heritage* 7
- (3) Arron J. Sturgis 2003 "Historic Structures Report Benson’s Property Town of Hudson, New Hampshire" investigate in New Hampshire's Heritage, land and community heritage investment program.
- (4) Atamturktur, S., Fanning, P., Boothby, T., 2007 “Traditional & Operational Modal Testing of Monumental Masonry Structures,” *International Operational Modal Analysis Conference, Copenhagen, Denmark.*
- (5) Beckmann Poul, and Bowles Robert 2004 "structural aspects of building conservation" second edition, McGraw-Hill international (UK) .
- (6) Belén Riveiro, Pedro Arias, Julia Armesto, and Celestino Ordóñez 2011 "A methodology for the inventory of historical infrastructures: Documentation, current state and influencing factors" *International Journal of Architectural Heritage*, 5: 629–646, 2011
- (7) Binda L, Gambarotta L, Lagomarsino S, Modena C. 1999 “A multilevel approach to the damage assessment and seismic improvement of masonry buildings in Italy.” *On: Seismic Damage to Masonry Buildings, Bernardini Ed., Rotterdam: Balkema.*
- (8) Binda L, Gatti G, Mangano G, Poggi C, Sacchi Landriani G. 1992 " The collapse of the Civic Tower of Pavia" a survey of the materials and structure. *Masonry Int*
- (9) Binda L, Lualdi M, and Saisi A 2007 "Non-Destructive testing techniques applied for diagnostic investigation: Syracuse cathedral in Sicily, Italy " *International Journal of Architectural Heritage, London.*
- (10) Binda L. and Saisi A. 2001 "Non destructive testing applied to historic buildings: The case of some Sicilian Churches" *Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães.*
- (11) Binda L, Tiraboschi C., 1997" Flat-jack test: a slightly destructive technique for the diagnosis of brick and stone masonry structures "11th International Brick/ Block Masonry Conference, Shanghai, China, 1.
- (12) Binda L., Saisi A., Tiraboschi C. 2000 "Investigation procedures for the diagnosis of historic masonries " *Construction and Building Materials.*
- (13) Binda L., Lualdi M., and Saisi A. 2007" Non-destructive testing techniques applied for diagnostic investigation: Syracuse Cathederal in Sicily, Italy" *International Journal of Architectural Heritage*, 1: 380–402, 2007
- (14) Boen T., 2001 "Earthquake Resistant Design of Non-Engineered Buildings In Indonesia" Presented during EQTAP Workshop IV, Kamakura.
- (15) Brownjohn, J., Dumanoglu, A., Severn R., 1992 “Ambient vibration survey of the Faith Sultan Mehmet (Second Bosphorus) suspension bridge,” *Earthquake Engineering and Structural Dynamics*, vol. 21.
- (16) Carpinteri A., Lacidogna G. 2003" Damage diagnostic in concrete and masonry structures by acoustic emission technique " *Mechanics, Automatic Control and Robotics Vol.3, No 13.*
- (17) Costa A., and Arede A., 2006" Strengthening of structures damaged by the Azores earthquake of 1998" *Construction and Building Materials.*

- (18) Dizhur D., Derakhshan H., Lumantarna L., and Ingham J., 2010" Earthquake damaged unreinforced building tested in-situ "Journal of the Structural Engineering Society New Zealand Inc "SESOC Journal.
- (19) Frunzio, M., and Gesualdo A., 2001 " 3D F.E.M. analysis of a Roman arch bridge" Historical Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães.
- (20) Gao H, WeibinW., Wentong C., and Weiming L., 2001" The design of HLS voltage network monitoring system based on AD7756" proceeding of the second Asian particle accelerator conference, Beijing, China.
- (21) Gregorczyk P., Lourenço P., "A Review on Flat-Jack Testing "Universidade do Minho, Departamento de Engenharia Civil Azurém, Guimarães, Portugal.
- (22) Groza Othilia Mariana 2007 "Rehabilitation of the historical buildings with masonry structure" PhD thesis The Faculty of Architecture and Constructions, University of Oradea.
- (23) Henry J. and Smith R. 2004 "Dictionary of architecture and building " Fourth edition, by Spon Press 11 New Fetter Lane, London EC4P 4EE.
- (24) Hossain K., M. and Lachemi M., 2006 " NDE for assessment and rehabilitation of ancient masonry structures- a state of the art" 1st international conference on restoration of heritage masonry structures Cairo, Egypt, April 24-27, 2006.
- (25) Hume Ian 2007" investigating, monitoring, and load testing historic structures" structures & construction in historic building conservation, Blackwell publishing Ltd.
- (26) ICOMOS 2003" Recommendations for the analysis, conservation, and structural restoration of architectural heritage " International Scientific Committee for Analysis and Restoration of Structural of Architectural Heritage 22/5/2003
- (27)IAE 2002 "A Guidebook on non-destructive testing of concrete structures" INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA, VIENNA, 2002.
- (28) kishali E. and others 2009 " traditional techniques and district rehabilitation sustainable rehabilitation and preservation strategies in historic quarters "sustainable building conference " SB10mad" .
- (29) Lombillo, I; Villegas, L; Elices, J. 2009 " Non "minor" destructive methodologies applied to the study and diagnosis of masonry structures of the building heritage: a state of the art "Building Technology, the Department of Publication Service of the University of Cantabria. Spain.
- (30) Lourenço B 2002" Structural behavior of civil engineering structures: highlight in historical and masonry structures" Structural Engineering and Materials.
- (31) Lourenço P., 1998 " Experimental and numerical issues in the modeling of the mechanical behavior of masonry" Structural analysis of historical constructions II P. Roca, J.L. González, E. Oñate and P.B. Lourenço (Eds.) CIMNE, Barcelona.
- (32) Nickerson S.,1994" Comparison of hand measurement techniques, Available at: <http://www.nickerson.icomos.org/steve/papers/mea-c.html> .
- (33) Padaratz J., Forde MC., 1995 " Influence of antenna frequency on impulse radar surveys of concrete structures". Proceedings of the 6th International Conference on Structural Faults and Repair.
- (34) Pavic, A., Armitage, T., Reynolds, P. and Wright, J. 2002 (Methodology for Modal Testing of the Millennium Bridge, London," Proceedings of the Institution of Civil Engineers: Structures and Buildings, vol. 152.
- (35) Paweł G., and Lourenço B. 2003 " A Review on Flat-Jack Testing " Universidade do Minho, Departamento de Engenharia Civil Azurém, Guimarães, Portugal

- (36) Polimi Bam and Zag Slig 2004" Technical guidelines for an appropriate use of the suggested equipment Radar" On-site investigation techniques for the structural evaluation of historic masonry buildings Germany.
- (37) Scherer M., 2002 "About the synthesis of different methods in surveying", Proceedings of XVIII International Symposium of CIPA, Potsdam, Germany.
- (38) Schroedel J., 2002 " Structural Deformation Surveying" EM 1110-2-1009 .
- (39) Schueremans L., and Koenraad Van Balen 2006" Hydrostatic Levelling System: Monitoring of Historical Structures" Structural Analysis of Historical Constructions, New Delhi 2006 P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)
- (40) Schueremans L., Van Rickstal F. " Continuous Assessment of Historic Structures – A State of the Art of applied Research and Practice in Belgium" Department of Civil Engineering, Kasteelpark Arenberg 40, 3001Heverlee, Belgium, Luc.Schueremans @bwk.kuleuven.ac.be .
- (41) Silman R. and Ennis, M., 1993 “Non-Destructive Evaluation to Document historic Structures”, Zurich, International Association for Bridge and Structural Engineering (IABSE).
- (42) Sturgis A., 2003 "Historic Structures Report Benson’s Property Town of Hudson, New Hampshire" investigates in New Hampshire's Heritage, land and community heritage investment program.
- (43) Sullivan Dominic and Keane Marcus M. 2004' The specification of a web based multimedia information system for building appraisal "EENUI Department of Civil & Environmental Engineering National University of Ireland, Cork, .
- (44) Taiab M., and Edres S.," Stability of Al-Hadba minaret a-parametric study 2010 " engineering and Technology journal, Volume 28.
- (45) Teddy B., 2001" Earthquake Resistant Design of Non-Engineered Buildings In Indonesia" Presented during EQTAP Workshop IV, Kamakura.
- (46) Timchenko I., 2000 "Experience of reconstruction and rehabilitation of historical buildings in the downtown of Tbilisi "Institute of Structural Mechanics & Earthquake Engineering (SMEE); Center AGESAS, Tbilisi 12WCEE.
- (47) Urquhart Dennis 2007" Guide for practitioners Conversion of Traditional Buildings Application of the Building Standards" Commissioned by Guide for Practitioners Technical conservation research and education group Published by Historic Scotland © Crown copyright Edinburgh .
- (48) Valluzzi M, Cardani G, Binda L, Modena C.2004 “Analysis of the seismic vulnerability of masonry buildings in historical centers and intervention proposals”, Proceedings of the 6th Int. Symp. On the Conservation of Monuments in the Mediterranean Basin, Lisbon, Portugal, 7-10 April 2004..
- (49) Valluzzi M., Cardani G., Binda L., Modena C 2004 " Seismic vulnerability methods for masonry buildings in historical centers: validation and application for prediction analysis and intervention proposals" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 2765
- (50) Wei F.Q., Rivkin L., Wrulich A. 2004, " Experiences with the hydrostatic leveling system at the SLS" Paul Scherrer Institute, Villigen, Switzerland Proceedings of EPAC 2004, Lucerne, Switzerland .
- (51) Xia, P., Brownjohn, M., 2004 “Bridge Condition Assessment Using Systematically Validated Finite- Element Model,” Journal of Bridge Engineering, vol. 9.

4

Rehabilitation Methods for Historic Traditional Masonry Buildings

- INTRODUCTION
- 4.1- Strengthening of structural behavior
- 4.1.1- Strengthening of masonry wall
- 4.2- Improving the connection between walls and floor
- 4.3- Floors repair
- 4.4- Remove Existing Features from Other Historic Periods
- 4.5- Re-use of historic traditional buildings

INTRODUCTION

The basic principle of the proposed interventions is to improve the static and seismic behavior of the building without changing its historic and aesthetic fabric (where possible). So, the goal is the proposed interventions not to change the historic and architectural character of a historic building, but also given the opportunity to prepare it for new use, if possible. The main principle of restoration and conservation of historic buildings is to keep the building as original as possible. If replacement is urgent, materials similar, preferably identical, to the original ones should be used. Each property should be recognized as a physical record of its time, place and use. All rehabilitation work should retain and preserve the historical character of the building. It is very important to conserve the original concept in order to enlighten the past correctly and carry it to the future with its original characteristics.

4.1- Strengthening of structural behavior

A wide variety of intervention techniques can be considered for strengthening and repair of masonry structures that have undergone damages due to overload, ground settlement, temperature variation, natural calamities like wind, earthquake etc. A rough distinction can be made among the traditional and the modern ones. Traditional techniques employ the materials and building processes used originally for the construction of ancient structures. Modern techniques aim at more efficient solutions using innovative materials and technologies. (Rashadul 2008).

4.1.1 Strengthening of masonry wall

In order to increase the seismic resistance of structural walls, the basic building material has to be strengthened. Stone masonry can be strengthened by means of deep repointing and/or by systematically filling the voids with injected cement-based grout,

the installation of through-stones, the pointing of exterior walls with cement mortar and the strengthening of wall corners using wire mesh and cement overlay (Marjana 2010).

Therefore, we must improve the structural behavior of wall masonry in historic traditional masonry in order to improve or strengthen the structural behavior of the whole building. There are a lot of methods as mentioned before used in strengthening of historic masonry walls as injection, reinforced cement coating, steel mesh, polypropylene mesh, the use of composite materials CFRP and GFRP, and improving the connection between walls and floors .

4.1.1.1- Injection

It is particularly indicated for the rehabilitation of the masonry that has internal cracks connected between them. This solution is based on the injection (in holes previously made with injection tubes and spread throughout the wall), of grout to the internal cracks. For the external cracks the coating should be removed previously and the injection tubes may also be used. Figs. 4.1 and 4.2 show the techniques of the grouting process.



Figure 4.1 masonry wall injection techniques (Meireles and Bento 2013).

This technique shows improves in the mechanical characteristics of masonry. It is more suited for stone masonry. To deliver a specific injection grout one must carry on in situ and laboratory tests to refine the grout (Meireles and Bento 2013).

Also, injection is used to repair walls presenting a diffuse presence of voids in the inner part of the walls, incoherence of the rubble filling material, visible cracks in the external parameters. Injection increases the continuity of the masonry and hence improves its mechanical properties (Rashadul 2008).

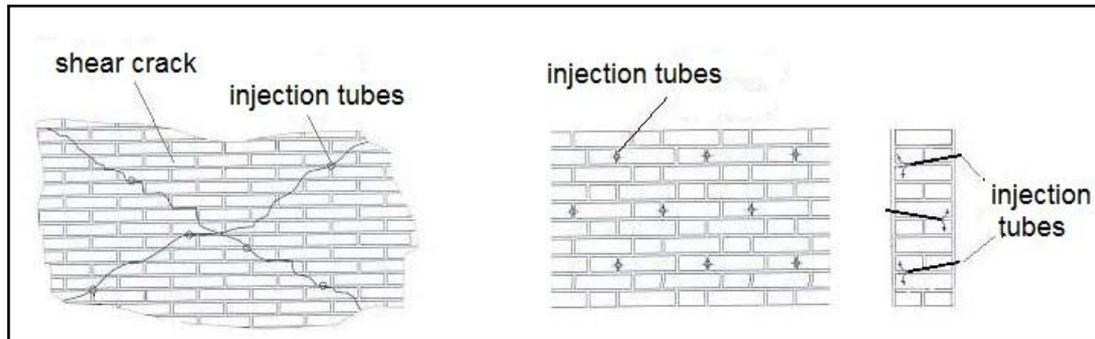


Figure 4.2: Grout injections (Meireles and Bento 2013)

4.1.1.2- Transversal anchorage in walls "Stitching"

This technique is used in the case of any masonry elements needing higher cohesion and improved mechanical characteristics without visible modification. Application of confinement to the wall can be achieved either with transversal steel bars, anchored to plates or other steel devices at both sides of the wall, or with reinforced concrete elements cast in transversal holes drilled through the whole thickness of the wall. Fig. 4.3 shows how steel anchor connectors are used in masonry vaults. The main target in this technique is to improve the mechanical properties and the ductility of the element. (Rashadul 2008).

The application of transversal anchorage in walls aims also to improve the connection of the two layers of the wall preventing their separation from the interior core, as can be seen in Fig. 4.3. The interior core usually comprises low quality rubble (Meireles and Bento 2013).

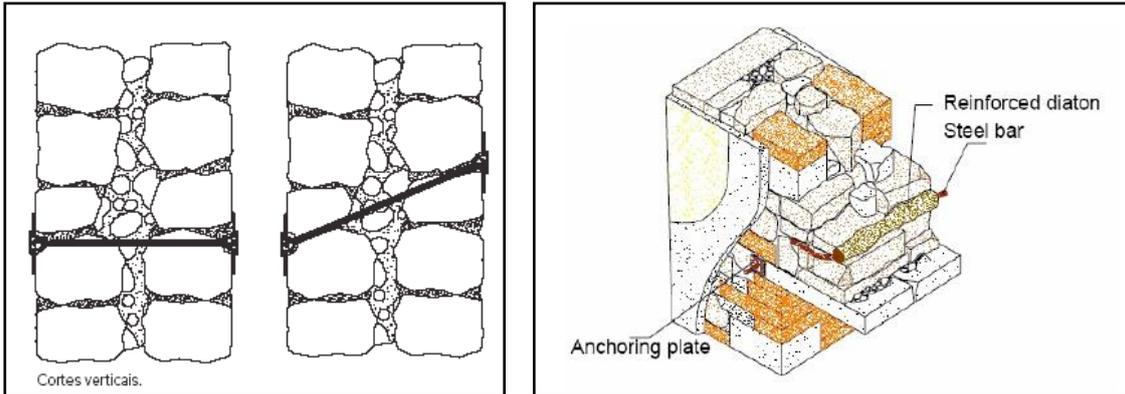


Figure 4.3 Local confinement through steel anchor connector for multi-layer walls (Rashadul 2008).

4.1.1.3- Reinforced cement coating' steel mesh'

This comprises thin layers of cement coatings less than 10 mm with a mesh of steel or glass fibre or plastic meshes, on masonry walls. The coating increases the wall strength and ductility. It can be placed outside or inside or both, depending on the most accessible areas. To enable the behavior of both elements (existing and new) to work together one places steel connectors on the wall.



Figure 4.4 Masonry walls strengthening with steel mesh inside the building (Rashadul 2008).

4.1.1.4- The use of polypropylene mesh

Polypropylene meshing uses common polypropylene packaging straps (PP bands) to form a mesh, which is used to encase masonry walls (see Fig. 4.5), preventing collapse during earthquakes. PP bands are used for packaging all over the world and are therefore cheap and readily available while the retrofitting technique itself is

simple enough to be suitable for local builders. This method is most readily applicable in terms of low cost upgrading of traditional structures to limit damage caused by normal earthquakes. (Mayorka and Meguro 2008)

A PP band mesh provides enough seismic resistance to safeguard limited and controlled cracking of the retrofitted structures. Under extremely strong ground motions, they are expected to prevent or delay the collapse, thus, increasing the rates of survival. This method is good for one storey buildings and can be used for a maximum of two storeys. To protect the polypropylene from ultra violet rays, mud plaster is used on the outside, providing adequate cover to ensure the durability of the material (Shrestha et al 2012).



Figure 4.5 Implementation of PP band method of retrofitting and anchorage throughout the wall (Mayorka and Meguro 2008)

4.1.1.5- Strengthening with FRP bar

Fiber-reinforced polymer (FRP) is used as a strengthening material to increase the flexural capacity of URM walls. The use of FRP bars is attractive since their application does not require any surface preparation work and requires minimal installation time. Another advantage is the feasibility of anchoring these bars into members adjacent to the one to be strengthened (i.e., columns and beams).

The technique consists of the installation of FRP reinforcing bars in slots grooved in the masonry surface. An advantageous aspect of this method is that it does not require sand blasting and puttying. The strengthening procedure can be summarized as

- 1- Grooving of slots having a width of approximately one half times the bar diameter and cleaning of surface,
- 2- Application of embedding paste (epoxy-based or cementitious-based paste) the groove is first half filled with a paste, a bar is then placed into the groove and lightly pressed to force the paste to flow around the bar.
- 3- Encapsulation of the bars in the joint, the groove is then filled with more paste and the surface is leveled.
- 4- Finishing and coating for environmental action.



a) Air Powered Gun



b) Electric Powered Gun

Figure 4.6 Guns for Installation of Embedding Paste (Rashadul 2008)

Depending on the kind of embedding material, cementitious-based or epoxy-based, a mortar gun can be used for tuck pointing or an epoxy gun can be used. The guns can be hand, air or electric powered, being the latter two, the most efficient in terms of efficiency. Fig. 4.6a illustrates the application of an epoxy-based paste using an air powered gun. Fig. 4.6b shows the application of a cementitious-based paste with an electric powered gun (Rashadul 2008)

4.1.1.6- Strengthening with composite materials (CFRP and GFRP)

It is possible to strengthen with composite materials such as carbon or glass fibres reinforced polymers, piers and spandrels within walls and/or columns of masonry. Carbon Fiber Reinforced Polymer (CFRP) or Glass Fiber Reinforced Polymer (GFRP) layers of material are glued with epoxy resin to the cleaned surface of masonry. The weak element is the masonry or the glued surface if the bonding is not well done. There can be placed also connectors, especially on walls, so that the material is well bonded to the masonry. Fig. 4.7 showed the application of CFRP/GFRP on a building wall.

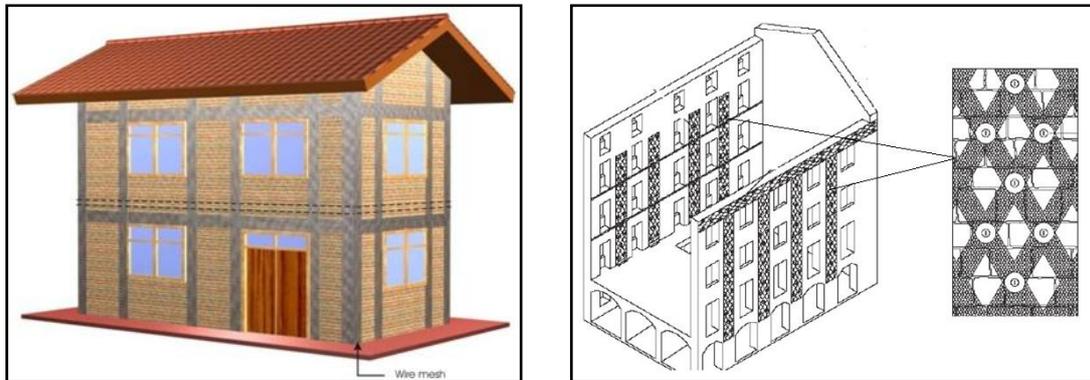


Figure 4.7 The application of CFRP/GFRP on historic traditional masonry wall. (Rashadul 2008)

CFRP sheets are applied on one side of the wall, while the other side remained with exposed block masonry. CFRP was applied using the wet layup procedure. The wall surface was first prepared prior to the application of CFRP. The preparation involved;

- i- Surface cleaning by wire brush, followed by air pressure to remove loose mortar,
- ii- Application of putty consisting of two component epoxy and silica fume to cover head and bed joints and to smoothen the wall surface, then removal of any extra putty by a plastic putty knife

- iii- After curing for a day inspection of the surface and covering any noticeable air bubbles with putty using the same plastic knife then sanding the surface by sand paper after two days of curing.

When the wall surface is ready to apply of CFRP sheets, the sheets are cut to the required sizes and applied on the wall surface, this application involved the following steps:

- i) Apply a layer of two epoxy components on the wall surface.
- ii) Apply of the first layer of CFRP sheets whose fibers are parallel to the bed joint, saturated in epoxy
- iii) Removal of extra epoxy and air pockets by ribbed steel roller
- iv) Apply another layer of epoxy prior to the placement of the next layer.
- v) Apply the second layer of CFRP sheets whose fibers are perpendicular to the bed joint and Remove of extra epoxy and air pockets by ribbed steel roller

4.1.1.7- The use of horizontal tie rods

One of the best techniques for protecting arches is inserting the tie between Springer's. It reduces the lateral thrust to the piers. Tie steel rods can be used in several applications of old masonry buildings. For instance, they can prevent or at least reduce the probability of out- of-plane failure. Fig. 4.8 shows the application of horizontal tie rods to connect parallel walls at the level of the floors. (Rashadul 2008) Tie rods can be also used in arches to absorb horizontal movement as shown in Fig. 4.9 .



Figure 4.8: the application of horizontal tie rods on masonry walls (Rashadul 2008)



Figure 4.9: Utilizing of steel tie rods to absorb horizontal movement in arches (Rashadul 2008)

4.1.1.8- Retrofitting by post tensioning

Post-tensioning can be used to close or control cracking in masonry structures or to increase the cracking moment resistance in new construction. Post-tensioning has been applied successfully to a variety of masonry structural forms. The advent of advanced composite materials provided an alternative to the corrosion protection measures adopted previously. In particular, Fiber Reinforced Polymers (FRP's) have properties that are attractive for post-tensioning applications (Sayed Ahmed and Shrive, 1998).

Post-tensioning enhances cracking loads, improves the cracking behavior and results in an increased flexural resistance of masonry walls. The glass in some GFRP's is sensitive to alkaline solutions. CFRP is better because of the high strength

and durability. CFRP tendons have a propensity to rupture under shear or lateral loading. Figs. 4.10, 4.11 and 4.12 show the mechanical system of applying post tension. (Rashadul 2008).

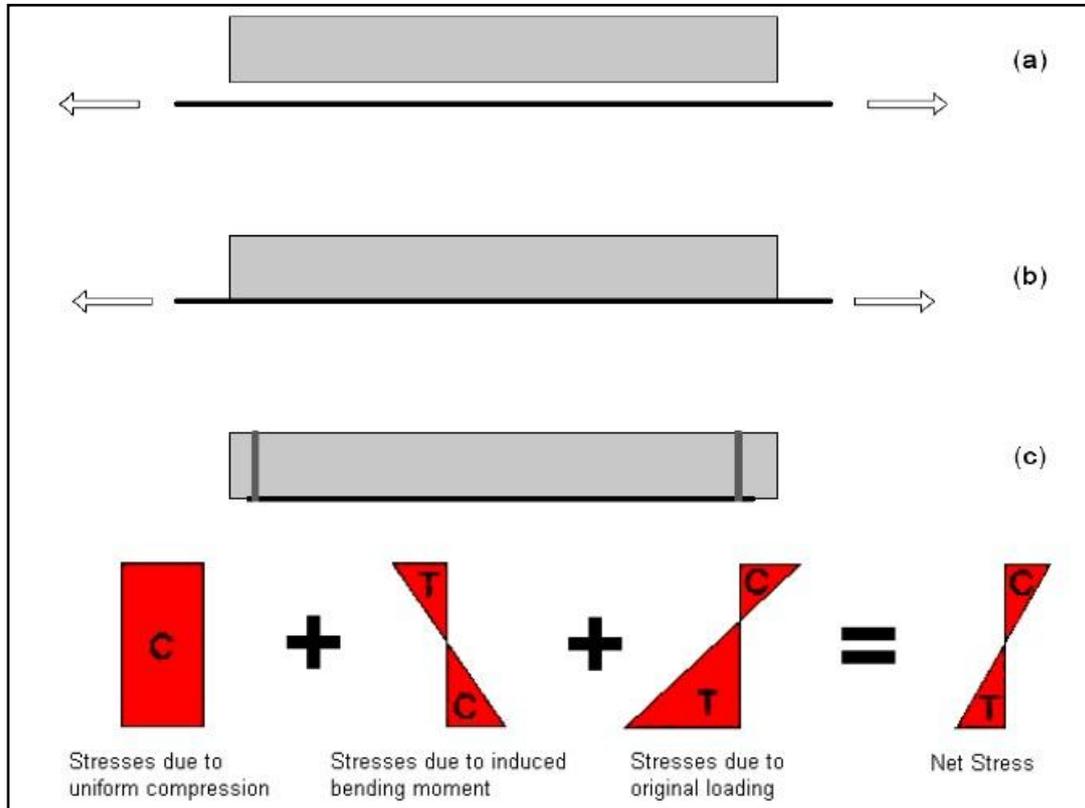


Figure 4.10: Strengthening with Prestressed FRP: (a) prestressing (b) bonding (c) end anchorage and release and finally the stress reduction (Rashadul 2008).

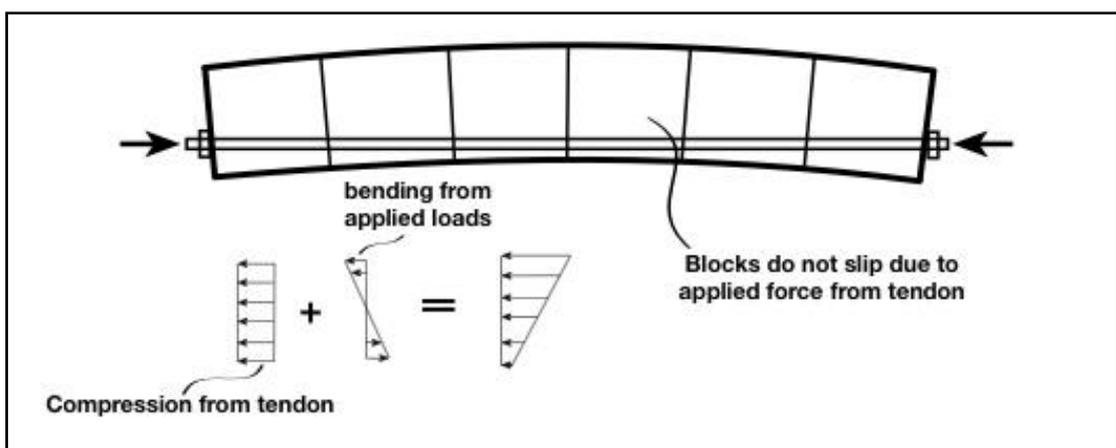


Figure 4.11: Strengthening with post-tensioning technique

The performance of post tensioned URM walls depends upon the initial post tensioning force, tendon type and spacing, restraint conditions and the level of confinement. Post tensioning can either be bonded when tendons are fully restrained by grouting the cavity or left unbounded by leaving the cavities unfilled.

4. 2- Improving the connection between walls and floor

Increasing of in plane stiffness of floors is an evident and most effective method to improve the seismic behavior of traditional masonry structures. This is mainly because increase of in plane stiffness of floors enables the structure to behave like a box, i.e. enables the horizontal forces to be redistributed between the different vertical structural elements, and then the horizontal forces of failing walls can be redistributed to the adjacent remaining walls.

The technique involves the inclusion on the floor of the horizontal bracing composed of steel ties arranged in crosses (Fig. 4.14) and has been developed for many decades. Care is taken to improve the connection between the floor and the masonry wall with L-shaped steel plates. In contrast with the previous techniques this one does not increase significantly the mass of the floors and is reversible.



Figure 4.14 In plan stiffening with metallic diagonal and L shaped steel plates as connection reinforcement between walls and floor.

4.3- Floors repair

Best practice in old buildings is to conserve the old floor boards and patch repair them locally as necessary. Floorboards should only be replaced where repair is impossible. Replacement timber should match the existing timber both in species and in manner of conversion, which will allow the quality and grain also to match. Considerable care may need to be taken when relaying old floorboards. Boards should generally be re-fixed in their original positions with nails, taking great care not to puncture underlying cables or pipe-work.

However in certain situations, for example over a decorative plaster ceiling, a valuable ceiling painting, or a lath and plaster ceiling where the plaster key is suspect and might be disturbed by the vibration from nailing above, it is advisable to use screws instead. Brass screws are often preferred, and can be lightly greased before fitting to aid later removal for maintenance. Where a board is likely to be frequently lifted and re-laid, use brass cups to protect the board from damage caused by the screw head. (Ogley et al 2012).

When selecting the most appropriate insulation material for each building, it is important to ensure that the material will continue to perform at a suitable level for many years. If the insulation is likely to suffer physical degradation a more robust material may be appropriate. Similarly, insulation which tolerates vapour movement will be required if high moisture levels are anticipated.

Most types of foamed plastic insulation, such as closed cell polyisocyanurate, polyurethane or polystyrene are inappropriate for general use in historic and traditional buildings as their inability to absorb and release moisture may increase the risk of condensation. They are often also difficult to form and fit accurately to

irregular historic construction. They are therefore not usually appropriate for the insulation of suspended timber floors. Perhaps the most common materials used for insulating existing buildings are fibre glass and mineral wool, primarily because they are cheap, easy to handle and convenient to install. However, they are not necessarily the best materials for the job, even though they are air permeable and thus able also to the passage of moisture vapour.

The most appropriate materials for older buildings currently available are those based on natural fibres, such as sheep's wool, hemp fibre, cellulose (fibres derived from recycled newsprint) and wood fibre board. 'Natural' insulation materials have the ability to 'breathe', allowing them to pass both air and moisture vapour slowly through, thus minimizing and diffusing the danger of condensation. An additional benefit of natural insulation materials is their good acoustic performance. They are also non-hazardous and unlikely to be irritants (Ogley et al 2012).

4.3.1- Floor strengthening

In old diaphragm properties is essential to impose a global behavior of the structure. Its main advantage is to assume compatible horizontal displacements in every point of each floor and therefore to allow the distribution of the seismic forces in accordance to the stiffness of the resistant vertical elements. This property also allows a reduction in the analysis model's number of degrees of freedom, therefore reducing the amount of calculation required.

One of the main collapsing mechanisms in masonry buildings is the fall of the exterior walls by excessive deformation in the floor plane. With the increase of the floor stiffness, it is possible to control the horizontal displacements, which minimizes the risk of this kind of collapse.

To enhance the floor properties (floor diaphragm stiffness) recently there are four different solutions: using reinforced concrete slabs, using composite steel–concrete slabs, using a metallic grid supported by steel beams, and strengthening of the original floor with crossed steel ties. One should be aware that each of these solutions alters the dynamic characteristics of the original structure to different extents. For example, the reduction in mass or the increase in stiffness will lead to an increase in the frequencies of vibration, which has a direct effect on the seismic loads.

4.3.1.1- Concrete Slab

The first stiffening technique is the substitution of the original floor by a concrete slab 0.20 m thick. This solution has the benefit of guaranteeing the stiff diaphragm property and therefore of distributing the forces in an effective way to the resistant walls. Nevertheless, it is an intervention which produces a small number of problems that should be accounted for. The original floor has a weight of about 1.1kN/m², while this solution has a weight of 5kN/m². This excessive increase in mass has two direct consequences: on the one hand, the larger mass produces the increase of the inertial forces during an earthquake; on the other hand, it overloads the masonry walls, which might already be in poor condition. This solution normally implies the need to strengthen the foundations and to build concrete columns in the exterior walls to bear the increase of loads. This additional work makes this solution less viable, due to the complexity of execution.

4.3.1.2- Composite Steel–Concrete slab

Another solution is the replacement of the wooden pavement by a composite steel–concrete slab placed over a grid of steel beams which are pinned to the masonry walls. A slab with a total thickness of 0.10 m of concrete was considered over steel sheeting

0.75 mm thick. The composite slab is supported by HEA200 steel beams placed 2 m apart, which are supported by HEA300 beams. This solution has the advantage of being lighter than the previous one, with a weight of 2 kN/m². The functional demands related to fire resistance, acoustic, and thermal insulation are accomplished with the use of special paints and foams, which may increase its cost. Another issue is the need to remove the original pavement, which makes this technique impossible to execute in inhabited buildings.

4.3.1.3- Metal grid

The solution of replacing the pavement by a metal grid placed over steel beams is not adequate to use in buildings for residential use. Even so, it can be interesting to consider its use for offices or industrial purposes. In comparison with the previous techniques, it has the advantage of being lighter (1 kN/m²). Nevertheless, it has several functional problems, since it is not able to guarantee an efficient separation between floors, and neither thermal nor acoustic insulation is achieved.

4.3.1.4- Steel Ties

This strengthening technique consisted of the application of steel ties through wooden beams of the existing pavement. It was intended to strengthen each room separately and to connect to each other along the interior walls. The steel rods were anchored in each corner of the room, forming a cross. The connection between rooms was assured through steel plates and beams connected by bolts. UNP beams were used in the direction parallel to the primary wooden beams, while in the other direction LNP beams were used. These beams were interrupted by the wooden beams to preserve integrity (see [Fig. 4.15](#)).

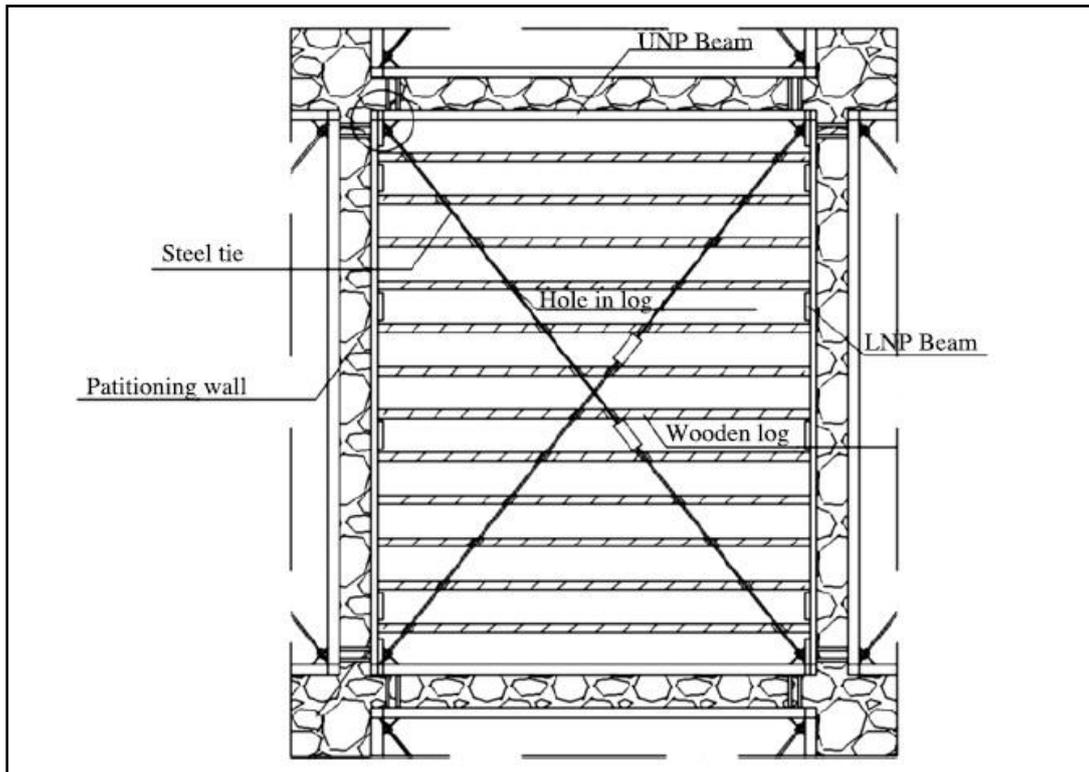


Figure 4.15: Strengthening with steel ties (plan view).

This solution has several advantages, such as being reversible. It minimizes the interruption of the normal function of the building and it does not contribute to an excessive increase of the structure's weight. In contrast to the other techniques presented, which would need relocation of the residents during the entire rehabilitation, this solution could be executed with the displacement of people for a shorter period of time and from local zones (Branco M., Guerreiro L.M. 2011)

The performance of each technique was evaluated according to the horizontal displacements on each floor for seismic load according to the code. The evaluation of the displacements has two different objectives: first, to compare the displacements on each floor, and second, to compare the displacements at different points of the top floor. The comparison of the displacements on each floor revealed which technique minimizes the seismic deformations. The resulting horizontal displacements along the smaller dimension of the building are presented in [Fig. 4.16](#).

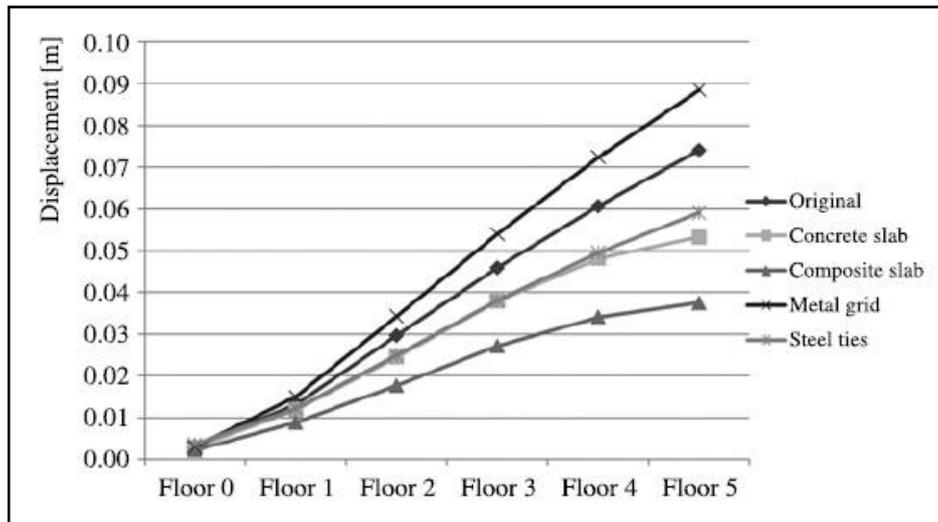


Figure 4.16: Maximum horizontal displacement on floors

The best results were achieved by the composite slab. The strengthening technique with steel ties presented results similar to the concrete slab. The concrete slab did not perform as well when compared with the previous solutions. This is due to the larger inertial loads generated by the larger amount of mass vibrating. The technique with the worst results was the steel pavement, which was even worse than the original configuration.

4.4- Seismic strengthening

In an unreinforced masonry building, resistance to horizontal actions is only accomplished by the stone masonry walls. This material has good behavior for compression (generated by vertical loads, such as the gravity loads); nevertheless, under horizontal actions, bending moments are generated which produce tensile stresses in the masonry. The tensile strength is only achieved by the compression state associated to gravity loads and mortar strength. The latter may have already lost part of its bonding properties through the years, due to aging and lack of preservation. The consolidation of the masonry walls with a reinforced concrete layer, the use of a base

isolation system, and the installation of viscous dampers (Lourenço P 2006) (Cardoso R. et al 2005)

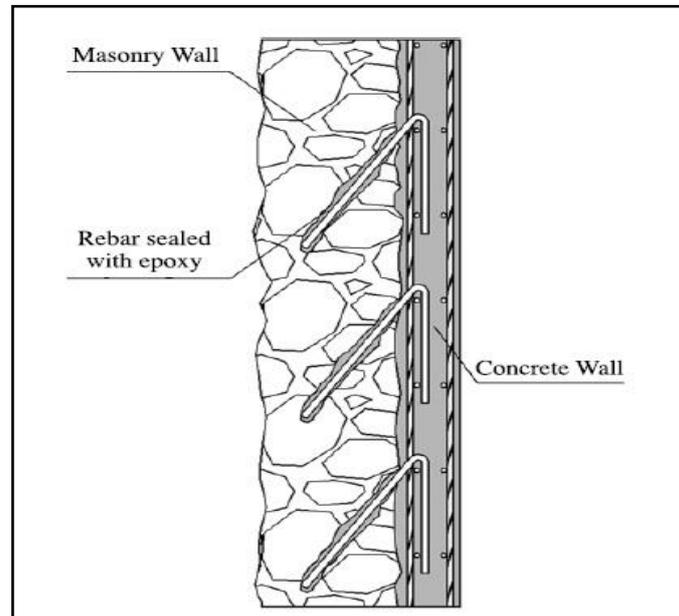


Figure 4.17 strengthening using concert walls

4.4.1- Concrete walls

The use of concrete walls was intended to control inter-story drifts through an increase in the global stiffness of the structure. Nevertheless, this may cause an increase in floor acceleration due to the changes in the dynamic properties of the building. This may cause an increase in internal forces due to seismic loading. It was intended to create reinforced concrete cores coupled with the interior patio walls, stiffening the structure. To be effective, this strengthening technique must ensure that the reinforced concrete elements will work together with the existing structure. Therefore, steel elements are sealed in the masonry and anchored in the concrete walls (see Fig. 4.17). A mortar could be used between these two materials to accommodate the different behaviors.

4.4.2- Base isolation

Base isolation is one of the most powerful tools of earthquake engineering pertaining to the passive structural vibration control technologies. It is meant to enable a building or non-building structure to survive a potentially devastating seismic impact through a proper initial design or subsequent modifications (Wikipedia, 2014)



Figure 4.18 Tomb of Cyprus is said to be the oldest base isolated structure in the world (Wikipedia, 2014)

The base isolation system consists of separating the building from the ground through the use of a bearing system with low horizontal stiffness separating the structure movement from the ground displacements. Currently, there are several kinds of device that are suitable to isolate a structure according to the forces and displacements that are generated. A common type of base isolation system is the elastomeric high-damping rubber bearing (Zhou F 1996) (Guerreiro L. et al 2006)

This solution created a more flexible building which allowed the reduction of the seismic dynamic response by reducing its frequency. Another characteristic of this technique is to make the building behave as a stiff body, concentrating the major displacements at ground level, reducing the displacements between the elevated stories.

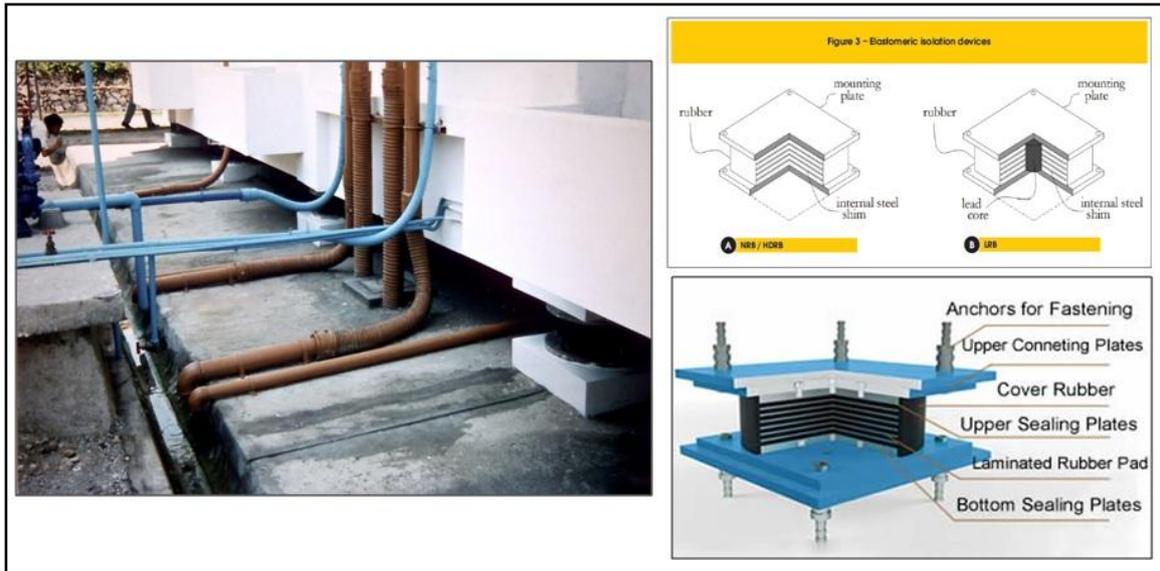


Figure 4.19 Base isolation techniques

4.5- Remove Existing Features from Other Historic Periods

Most buildings represent continuing occupancies and change over time, but in restoration, the goal is to depict the building as it appeared at the most significant time in its history. Thus, work is included to remove or alter existing historic features that do not represent the restoration period. This could include features such as windows, entrances and doors, roof dormers, or landscape features. Prior to altering or removing materials, features, spaces, and finishes that characterize other historical periods, they should be documented to guide future research and treatment. (Weeks et al 1995).

4.6- Re-use of historic traditional buildings

Most buildings do not go through their life without alteration at some time. The quality of these alterations may not be of the standard set by the original building, or changes may not have recognized the original structural configuration. When assessing a historic building's suitability for a new use, the structural form, the structural elements (walls, foundations, framework, beams, lintels, floors, access stairs and roof structure) and the condition and suitability of materials must be assessed against the structural needs of the converted building. As part of the decision

about the suitability for a new use for a building, a structural assessment will have a major influence on the project brief. The structural appraisal should highlight the limits of additional loadings (or changes in loading conditions) that can be imposed on a historic building before major structural intervention becomes necessary. A significantly increased loading, particularly to floors, will inevitably require structural enhancement, which may be both expensive and destructive to historic fabric.

When major structural intervention is necessary to produce a building capable of accommodating its new use, the whole viability of the project and the suitability of the projected use for that historic building must be questioned. The fact that many structural elements may be hidden does not mean that they are not important to the special character and historic importance of the building. When 'opening-up' of historic fabric, to inspect floors and other elements, is required for structural assessment purposes.

When considering structural interventions, it is necessary to ensure that any new openings or bearings introduced recognize the presence of existing voids and whether there is a need for viable flues. Failure to recognize the presence of flues can lead to instability of the walls. Another cause of instability is when floors have not been properly tied into walls, a structural concept that was not always properly addressed at the time of construction, and has sometimes been overlooked in the insertion of new stairs etc across floors that tie the building together.

The structural issue that creates the greatest difficulty and has most potential to influence the viability of use of a historic building, is when a change of use imposes greater floor loadings; for example, where there is a change from domestic to office floor loadings. While the British Standard, BS 6399 Part 1: 1996, *Loading for*

buildings – Code of Practice for dead and imposed loads provides recommended floor loads for various categories of occupation, very careful thought has to be given to how the spaces *actually* will be used. English Heritage (1994) has produced a useful guidance note on office loadings in Historic Buildings. For example, in the case of an office building, the recommended design floor loading of 5.0kN/m² for filing and storage spaces will represent the maximum loading in these areas. Should storage be required for heavy files and the like, the design of the conversion may be able to accommodate file storage at ground or basement level, where such a loading may be more easily dealt with without the need for structural strengthening of upper floors.

However, it is not simply the timber strengths, sizes, and spans that should be assessed, because a major weakness in an old floor may be the joints and connections between the timber members, and between other structural elements. It should also be noted that servicing requirements may have changed greatly since the building was originally constructed, and it is all too easy to notch and cut timbers to accommodate services, thereby introducing isolated weaknesses into the structural elements. So the following information should be collected:

- identification of the species and quality of the timber (including the extent of any infestation or decay),
- determination of member sizes, and their overall geometrical relationship,
- Examination of joints and connections.
- Existing deformations.

There are other structural elements where it is almost impossible to determine their structural strength using design calculations. A particular example is when

cantilevered or pen check stairs are encountered. This particular form of stair, which is often circular, relies on its strength through stone, or sometimes timber, treads being built into a masonry wall and detailed to interact to form a series of cantilever or torsional beams. Alternatively, stair flights can be supported on projecting cantilevered landings. The quality and condition of the stone needs to be assessed, and a load test may be required to provide the necessary proof of structural strength for the proposed loads.

The installation of modern services into a historic building can be very intrusive and can have an adverse effect on the structural stability of the building. Frequently, little attention is paid to how services will be incorporated, and services drawings may show only a diagrammatic services layout of pipe work, cables and ducts. Important decisions on the exact positions and how they will be installed within structural elements, such as floors, is often left to the discretion of the tradesperson on site. Usually the most serious impact on structural stability is when services are required to run within and across the joists in a timber floor.

The increase in loading on the floor must be considered. The ill-considered cutting of notches for cables and pipes in joists and beams can significantly affect the performance of the floor. There is a tendency for holes and notches to be oversized to make installation easier. When dealing with the design of a conversion, it is recommended that detailed drawings are available that show clearly the location and maximum dimensions of all holes and notches that have to be formed to accommodate services, and to design them to run parallel to joists. (Urquhart 2007). Designing and constructing new additions to historic buildings when required by the new use. New work should be compatible with the historic character of the setting in terms of size, scale design, material, color, and texture.

When we decide to choose a new job for a historic building the following points are not recommended

- Creating a false historical appearance because the replaced feature is based on insufficient documentary or physical evidence.
- Introducing a new building or landscape feature that is out of scale or otherwise inappropriate to the setting's historic character, e.g., replacing pickets fencing with chain link fencing.
- Placing parking facilities directly adjacent to historic buildings which result in damage to historic landscape features, such as the removal of plant material, relocation of paths and walkways, or blocking of alleys.
- Introducing new construction into historic districts that is visually incompatible or that destroys historic relationships within the setting. (Kay and Grimmer 1995)

Concluding Remarks

- The main principle for the restoration and conservation of historic buildings is to keep the building as original as possible. A wide variety of intervention techniques can be considered for strengthening and repairing masonry structures that have undergone damage due to overload, ground settlement, temperature variation, natural calamities like wind, earthquake etc. A rough distinction can be made between the traditional and the modern ones.
- In order to increase the seismic resistance of structural walls, the basic building material has to be strengthened. Stone masonry can be strengthened by means of deep repointing and/or by systematically filling the voids with injected grout.
- There are a lot of methods used for strengthening of historic masonry walls, the chapter discussed some of them which are suitable for strengthening historic traditional masonry houses in Athens and Cairo. These methods include: injection, reinforced cement coating (steel mesh), polypropylene mesh, the use of composite materials (CFRP and GFRP), and strengthening by improving the connection between walls and floors.
- The structural behavior of an existing masonry building subjected to seismic action, is strongly affected by the in-plane stiffness of the floors, and by the connections between the horizontal diaphragms and the masonry walls. The aim of the proposed interventions is to improve the behavior of timber floor refurbished using different techniques, with special regard to the in-plane stiffness, and historical fabric and value of the floor.
- To enhance the floor properties (floor diaphragm stiffness) recently there are four different solutions: using reinforced concrete slabs, using composite

steel–concrete slabs, using a metallic grid supported by steel beams, and strengthening of the original floor with crossed steel ties

- The floor strengthening, to obtain stiff diaphragm properties, allows the reduction of the floor displacements and a more effective distribution of forces to the resistant elements. It is important to consider a solution with a composite slab (concrete-steel slab) and with steel ties. The first allows compatible horizontal displacements along the pavement's perimeter in the same way as a reinforced concrete slab, with the advantage of being lighter. The second technique, despite being less effective, has the advantage of being less intrusive, since it does not require removing the original pavement
- The most historic traditional buildings represent continuing occupancies and change over time, but in restoration, the goal is to depict the building as it appeared at the most significant time in its history, by removing existing features from other historic periods
- When assessing a historic building's suitability for a new use, the structural form, the structural elements (walls, foundations, framework, beams, lintels, floors, access stairs and roof structure) and suitability of materials must be assessed against the structural needs of the converted building.

In accordance with and by considering different levels of the study (damage assessment and rehabilitation of historic traditional masonry buildings) now we will explore and use all of the knowledge and experience obtained from the previous chapters to apply the chosen suitable steps on a case study to study the history and architectural and construction elements, damage assessment masonry studies, damage phenomena and factors, the mechanisms of damage, methods used to damage identification, proposed intervention methods, and re-use of the building.

References

- 1- Arsalan Kalali, Mohammad Zaman Kabir "Experimental response of double-wythe masonry panels strengthened with glass fiber reinforced polymers subjected to diagonal compression tests" *Engineering Structures* 39 (2012) .
- 2- Augenti N., Nanni A., and Parisi F. 2013 "Construction Failures and Innovative Retrofitting" *Buildings* 2013, 3, 100-121.
- 3- Betti M., and Galano L., 2012 "Seismic Analysis of Historic Masonry Buildings: The Vicarious Palace in Pescia (Italy)" *Buildings Journal* ,2012, 2.
- 4- Betti, M., and Vignoli A. "Modelling and analysis of a Romanesque church under earthquake loading: Assessment of seismic resistance" *Eng. Struct.* 2008, 30.
- 5- Binda L., Modena C., Baronio G., Abbaneo S., 1997 "Repair and investigation techniques for stone masonry walls, in *Construction and Building Materials*, Vol. 11, N.3, pp. 133- 142.
- 6- Branco M., Guerreiro L.M. 2011 "Seismic rehabilitation of historical masonry buildings" *journal of Engineering Structures* 33(2011) 1626–1634.
- 7- Cardoso R, Lopes M, Bento R. 2005 "Seismic evaluation of old masonry buildings. Part I: method description and application to a case-study. *Engineering Structure* 27.
- 8- Dennis Urquhart 2007" *Conversion of Traditional Buildings Part 1: Principles and Practice Commissioned by" Guide for Practitioners technical conservation research and education group* Edinburgh.
- 9- Guerreiro L, Craveiro A, Branco M. 2006 "The use of passive seismic protection in structural rehabilitation." *Structure Material Engineering* 4
- 10- Kay. D. and Grimmer A. E. 1995" *The Secretary of the Interior's Standards for the Treatment of Historic Properties with Guidelines for Preserving, Rehabilitating, Restoring & Reconstructing Historic Buildings" Department of the Interior National Park Service Cultural Resource Stewardship and Partnerships Heritage Preservation Services* Washington.
- 11- Lourenço PB. 2006 "Recommendations for restoration of ancient buildings and the survival of a masonry chimney. *Constr Build Mater.*
- 12- Magenes G. 2006 " *Masonry building design in seismic areas: recent experiences and prospect from a European standpoint " First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC) Geneva, Switzerland, 3-8 September 2006*
- 13- Marjana Lutman, 2010" *stone masonry construction" Slovenian National Building and Civil Engineering Institute, Slovenia.*
- 14- Mayorka P. and Meguro K, 2008, "A step towards the formulation of a simple method to design PP Band mesh retrofitting for Adobe/Masonry houses", 14th World Conference on Earthquake Engineering, Beijing, October 2008.
- 15- Meireles, HA, 2012, "Seismic vulnerability of Pombalino buildings, PhD Thesis, IST, Portugal
- 16- Meireles; H. R. Bento 2013 "Rehabilitation and strengthening of old masonry buildings" *Relatório ICIST, DTC.*
- 17- Moxon E. "Masonry restoration of the old civil engineering building Fredericton Campus, university of new Brunswick Dana " UNB- 9th Canadian masonry symposium
- 18- Phil Ogle, David Pickles, Ian Brocklebank, Chris Wood 2012 " *Energy Efficiency and Historic Buildings Insulation of suspended timber floors" Application of Part L of the Building Regulations to historic and traditionally constructed buildings* English Heritage.

- 19- Rashadul Md. Islam 2008 "Inventory of FRP strengthening methods in masonry structures" master thesis department of construction technical university of Catalonia, Barcelona, Spain, 2008.
- 20- Sayed Ahmed, E.Y., and Shrive, N.G. 1998. 'A new steel anchorage system for post tensioning applications using carbon fibre reinforced plastic tendons', Canadian Journal of Civil Engineering,
- 21- Shrestha H., Pradhan S., Guragain R., 2012 " Experiences on Retrofitting of Low Strength Masonry Buildings by Different Retrofitting Techniques in Nepal, Proc. of the 15th World conference on Earthquake Engineering, pp 2012, Lisbon, Portugal
- 22- (Wikipedia- structural engineering- May 2014).
- 23- Syrmakezis C. A. 1998 "Report of the EAEE Working group 7: Preservation of historical structures and historical centres" 11th European Conference on Earthquake Engineering © 1998 Balkema, Rotterdam.
- 24- Valluzzi M., Cardani G., Binda L., Modena C 2004 " Seismic vulnerability methods for masonry buildings in historical centers: validation and application for prediction analysis and intervention proposals" 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 2765
- 25- Zhou F. 1996 "Retrofit for existing buildings with seismic control of structures". In: Post-earthquake rehabilitation and reconstruction. 1996.

5

Case study

- 5.1- INTRODUCTION
- 5.2- AKTAIOU BUILDING
- 5.3- HISTORICAL DESCRIBTION
- 5.4- STRUCTURE
- 5.5- DAMAGE IDENTIFICATION AND MAPPING
- 5.4.1- DOCUMENTATION
- 5.6- DAMAGE ASSESSMENT.
- 5.7- THE PROPOSED INTERVENTIONS
- 5.8- VERIFICATION OF PROPOSED INTERVENTIONS

5.1- INTRODUCTION

Athens is one of the most famous heritage cities of the world; it contains many historic buildings of different ages. The heritage of the classical era is still evident in the city, represented by ancient monuments and works of art, the most famous of all being Parthenon considered a key landmark of early Western civilization. The city also retains Roman and Byzantine monuments, as well as a smaller number of Ottoman monuments. *Plaka* is the oldest region of modern Athens located at the feet of the Acropolis' rock.

5.1.1- PLAKA (Πλάκα)

Plaka (Greek: Πλάκα) is the old historical neighborhood of Athens, clustered around the northern and eastern slopes of the Acropolis, and incorporating labyrinthine streets and neoclassical architecture. Plaka is built on top of the residential areas of the ancient town of Athens. The origin of its name is meaning "Old Athens". Plaka is on the northeast slope of Acropolis, between *Syntagma* and *Monastiraki* square (see Fig. 5.1).

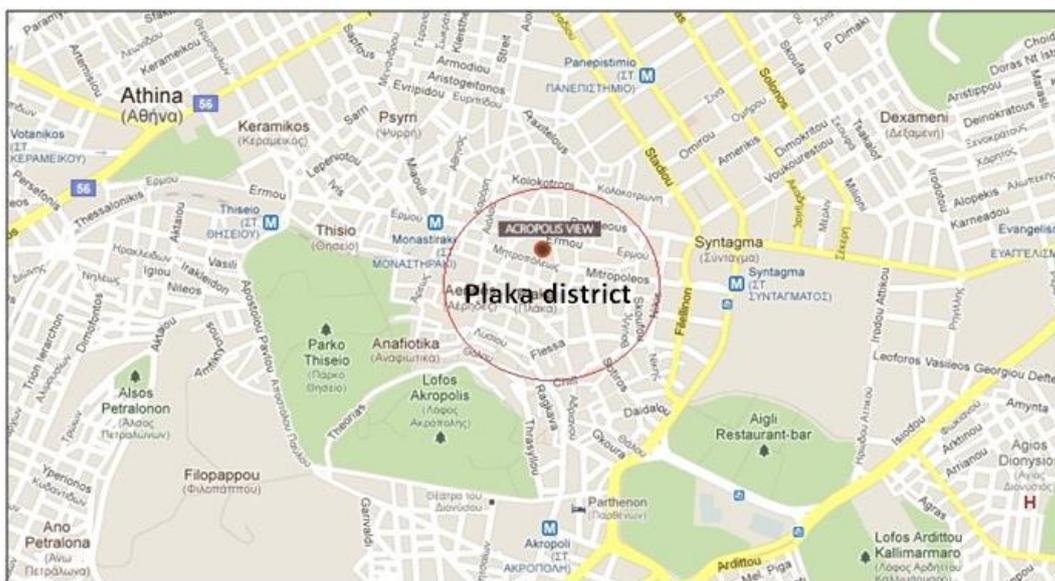


Figure 5.1 Plaka district in Athens

Plaka was developed mostly around the ruins of ancient Agora of Athens in an area that has been continuously inhabited since antiquity. The area was repopulated during the first years of King Otto's rule. Plaka had a sizable *Arvanite* community till the late 19th century, which led some to refer to it as the *Arvanite* quarter of Athens. At the same period the traditional masonry buildings, was built by settlers from the Aegean island of *Anafi* (see Fig. 5.2).



Figure 5.2 Shows historic traditional masonry building in Plaka district

Plaka, the Athenian historical centre, contains a large number of historical, economical, architectural and traditional masonry buildings. The oldest parts of the city of Athens remnants of the Late-Roman city wall are embodied in 20th century buildings at Plaka, while the Ancient Agora of Athens is found in buildings of the 18th until 20th century. Remnants of Byzantine and post Byzantine churches (Saint Thomas and Saint Elissaios), and wealthy mansions of the late Ottoman domination (Chomatianou-Logothetis' mansion), are visible at the district.

In Plaka stand important historical monuments. At the west side there is the fully restored Hellenistic Stoa of Attalos and at the east side the reconstructed church

of Saint Elissaios of Plaka. In completion of these monumental and symbolic borders of the Ancient Greek and Byzantine heritage comes the well known as "the Athenian historical centre". (Wikipedia 2015, Charkiolakis et al 2008)

Near this region (Plaka) at Theseion, to the west of Acropolis, in a neighborhood that was created in the late 19th-early 20th c. where the building that forms the subject of the present chapter is located, at the crossing of Aktaiou and Lykomidon streets and will be referred to as ‘Aktaiou’ building, thereafter (see Fig.5.3) .



Figure 5.3 shows Aktaiou house in Theseion (Plaka district neighborhood)

5.2- Aktaiou building

The Aktaiou building, which was built in the early 1900’s, is considered to represent the structural and architectural trends prevailing in Athens this period. Over the years, this house (see Fig. 5.4) has suffered significant damage due to various causes, such as seismic excitation, lack of maintenance, construction defects, neglect, environmental surrounding factors etc.; it is now being in the process of being rehabilitated and converted into a cultural centre.



Figure 5.4: The Aktaiou building: façade in Aktaiou Street (left) and northern face in Lykomidon Street (right)

The present chapter presents the work carried out to date in order to achieve this aim. This work includes the following stages: Description of the structural system, mapping of the damage, documentation of the materials used, structural assessment for the building, the proposed intervention, rehabilitation methods that can be used to restore or strengthening the building, and verification of proposed interventions. The above discussion is preceded by a concise description of the history of the building

5.3 Historical description

Before considering rehabilitation of the Aktaiou building, it is essential to study its history and the evolution of its construction. Historical description or historical evolution of the structure has to be known in order to identify the changes in the structural system of the building with time.

Over the years, the building was used as a shelter for the accommodation of refugees. Henceforth the building remained completely forlorn and derelict. As a result of the long period of neglect and lack of maintenance it has sustained damages to a considerable extent.



Figure 5.5: View of Aktaiou building house

Aktaiou building, which is a two-storey building with U shape in-plan geometry, is a typical urban Athenian house of its period. It was constructed with local materials, rubble (cobble) and ashlar natural masonry stones which may have had a polished, dressed or broached finish, the ashlar being the cheapest local material with good insulation properties for masonry structures. The building can be considered as a historic load-bearing masonry structure. It is an excellent example of residential architecture initially influenced by the urban architecture of the late 18th and early 19th century. It comprises basement, ground floor, and first floor. The building has a gable roof formed by wooden trusses and covered by terracotta tiles.

Limestone, marble, and volcanic stone, in addition to semi-fired bricks are the main building materials used for the construction of the Aktaiou building structural and architectural elements; the semi-fired bricks were used in between the main building materials and under the windows (see Fig. 5.6). The mortar used is a mud-lime-pozzolan mortar which is a commonly used mortar in most houses built in Athens in the early 19th century. Steel only appears in certain architectural elements of

the building such as that used in the courtyard entrance and the steel connecting the first floor to the wall (see section 5.4).

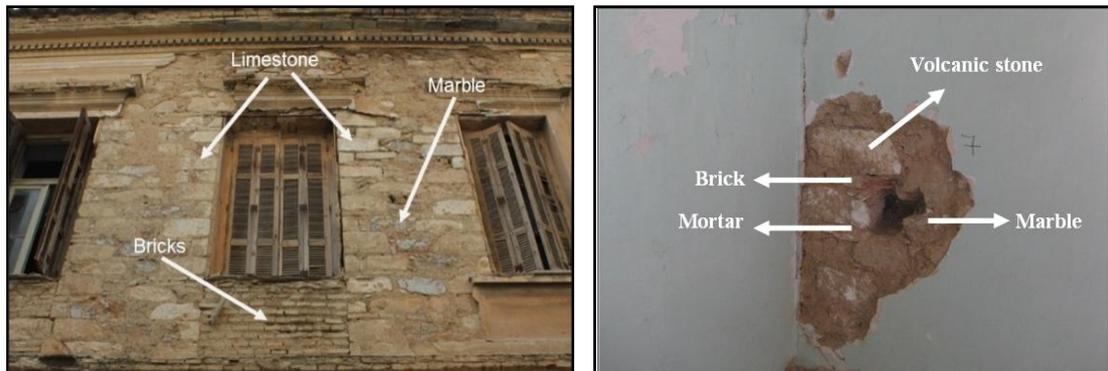


Figure 5.6 Building materials in Aktaiou building

Their load-bearing walls (with various degrees of bonding and interlocking of the blocks) comprise two discrete external leaves and an infill material. The floors are made of timber boards and the roof has a gable shape made from wooden trusses. The first floor has high elevation; the second floor’s height is smaller than that of the first floor, the high elevation being intended for ventilation purposes. The ground floor has 12 rooms with varying shapes, and dimensions, the walls are covered with multi-coloured paintings. The floor of the ground and first floor rooms are covered with wooden planks; whereas the corridors between rooms are paved with colour tiles as shown in Fig. 5.7.



Figure 5.7 shows ground floor rooms and decorative colours tiles

One can reach the first floor by the wooden staircase shown in Fig. 5.8. The first floor comprises ten main rooms and some smaller rooms used as rest rooms and storage areas. Some of the rooms overlook Aktaiou Street and the remainder Lykomidon Street. All the first floor rooms are almost equal in size with wooden floors and walls covered with frescoes as shown in Fig. 5.9. The first floor can also be reached by secondary staircase when entering the building from the entrance in Lykomidon Street.



Figure 5.8 The building wooden staircase



Figure 5.9: shows over painting covering original wall paintings

The Aktaiou building has many features introduced for insulation purposes which are typical to most dwellings in Athens (Charkiolakis et. al., 2008):

- Wide tiles, being firmed up to a thick layer of clay, sealed the roof from both heat and cold. Moreover, thick planking of 0.04 m. prevented warm or cold from penetrating the roof.
- Each floor was particularly high, approximately 3.0 m., whereas the windows were of small dimensions. This ratio permitted the cooling of the house: warm air rose to the ceiling away from human level, as cooler air kept coming in from the windows.
- The floor was uplifted well enough, in order to create a thermal insulation gap between the floor and the ground.
- Wide thickness also plays a fundamental role in the insulation of a building. This principle is particularly useful, since there is a wide variation of temperature during the day in the hot-dry climate of Athens in summer.

5.4- STRUCTURE

Aktaiou building is one of the best examples of historic traditional masonry buildings in Athens, and it is considered to represent the structural and architectural trends prevailing in this period (late 18th century/ early 19th century)

5.4.1- General description

The Aktaiou building is a two-storey masonry building with basement; the bearing walls forming part of its structural system are shown in Fig. 5.10, which also shows the wall names adopted for the work.

The facade of the building lay in Aktaiou Street (wall 1), has a length of 18.40 m (see Figs 5.11 and 5.12); its left-hand side face (wall 2), which lies in Lykomidon street, has a length of 18.00 m (see Figs. 5.13 and 5.14), whereas its right-hand side face (wall 3) sees in an internal open space and has a length of 17.00 m. Wall 4 essentially forms the fence separating the building from the adjacent property.

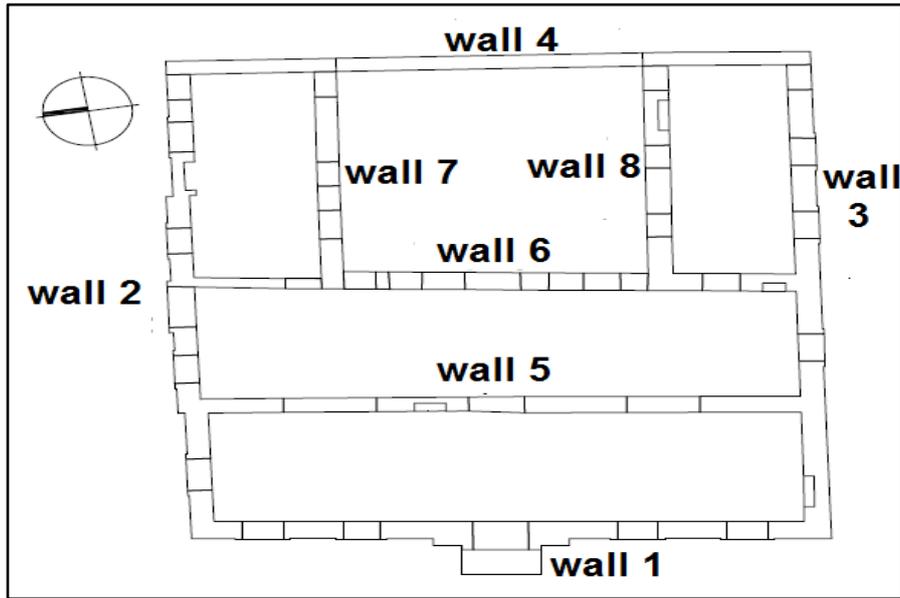


Figure 5.10: Bearing masonry wall system

The basement extends within the part of the plan enclosed by walls 1, 5 and parts of walls 2 and 3. The in-plan geometry of the building has a U shape with a central part (CB) extending between walls 1, 6, 2, and 3 and two wings extending between walls 6, 4, 2, and 7 (W1) and walls 8, 3, 6, and 4 (W2), respectively. An open space forms between walls 7, 8, 6 and 4.



Figure 5.11: Aktaiou building facade (main façade) – Wall 1

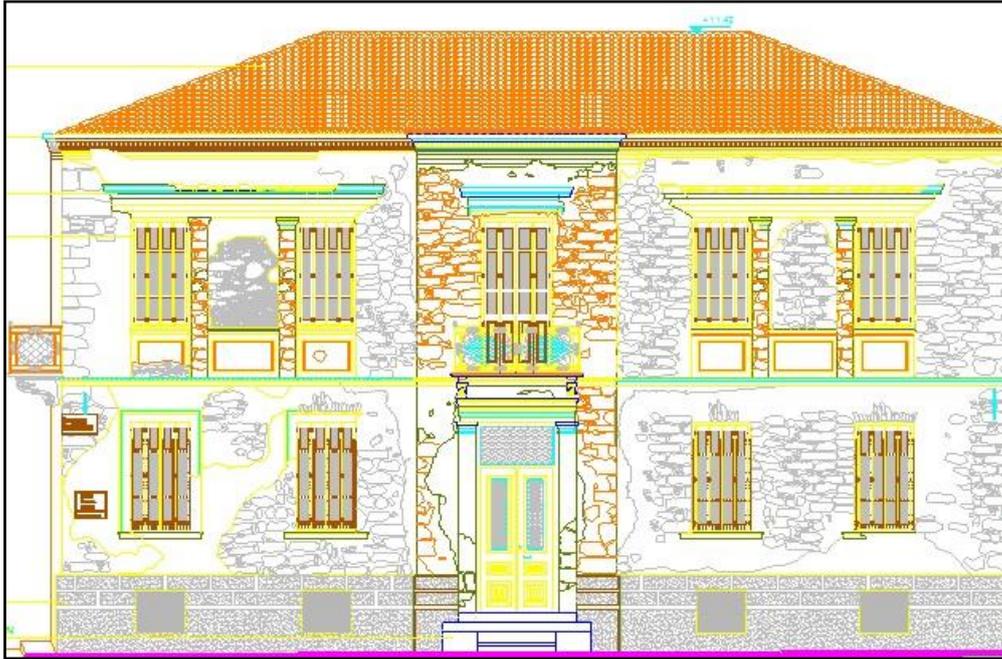


Figure 5.12: Plan of the main facade

There are a number of internal walls which, as discussed later, are classified as bearing or partition walls depending on the wall width. The timber floors are supported by wooden beams simply-supported at the opposite walls, whereas the roof is supported by a simply-supported truss system.



Figure 5.13: Northern face – Wall 2



Figure 5.14: Plan of Lykomidon facade

5.4.2- Structural walls

The structural walls have a width that varies from 0.5 m up to approximately 0.7 m. They were built with inert semi-chiselled stones, bound together with mortar "ashlars masonry", in two interlocking layers. The masonry structure is shown in Fig. 5.15. More specifically, the materials used for building the masonry walls were as follows:

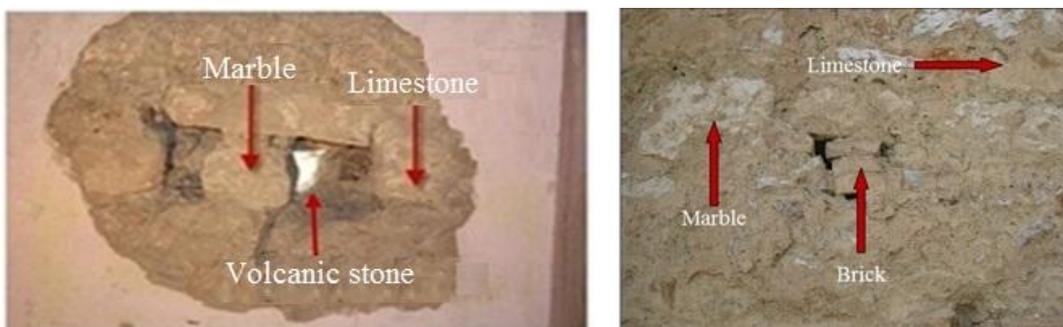


Figure 5.15: Typical masonry structure

- **Limestone** – semi-chiselled or chiselled stones used as corner stones or for strengthening the sides of wall openings (doors or windows) (see Figs 5.16 and 5.17)
- **Marble** – of irregular shape and varying sizes being one of the constituents of the parts of the masonry between wall openings and wall corners (see also Figs 5.16 and 5.17)

- **Volcanic stone** (lightweight stone) – encountered in the walls of the 1st floor in between limestone and marble stones , and
- **Mortar** (binding material) – containing a large quantity of sand and a significantly smaller quantity of lime



Figure 5.16: Wall masonry



Figure 5.17: Wall and window cornerstones

The connection between the main bearing walls was effected not only through the use of large pieces of limestone (corner stone's), but also through the use of steel connectors (short anchor elements) which improve the connection of walls orthogonal to each other (see Fig. 5.18).



Figure 5.18: Steel connector tying orthogonal walls and roof

5.4.3-Partition walls

The partition walls (secondary walls) were made of 8 cm wide bricks as indicated in Fig. 5.19. The partition walls and room walls were built in one-leaf brick masonry, connected by a low-resistance mortar, and presented low structural properties.



Figure 5.19: Partition walls

5.4.4 - Floors

Both the ground level and the 1st storey floors were made of 17 cm high x 11 cm wide timber beams arranged in parallel at distances of 50 cm (see Figs 5.20 and 5.21), covered with 21 cm wide x 2.5 cm thick planks. The beams are simply supported within recesses formed in opposite walls (see Figs 5.22 to 5.23).



Figure 5.20: Beams of ground level floor



Figure 5.21: Wall recesses where the beams of ground level floor are supported



Figure 5.22: Spacing of beams of ground level floor



Figure 5.23: Beams of 1st storey floor beams



Figure 5.24: Spacing of beams of 1st storey floor

5.4.5- Roof

The roof of the central part of the building (CB) is two-way supported and comprises single and double slope trusses, whereas the roof of the wing parts (W1 and W2) of the building are one-way supported and comprise double slope trusses (see Figs 5.25 and 5.26). The latter comprise one vertical and two inclined struts, a horizontal tie and two diagonal struts as indicated in Fig. 5.27. The inclined struts of the trusses support 2 cm thick purlins extending in parallel to the supporting walls, with the purlins being covered by planking which underlies the byzantine tiles.



Figure 5.25: Central roof



Figure 5.26: Wing roof

The trusses of the wing roofs comprise inclined struts and horizontal tie only (see Fig. 5.28). Although carpenter connections were formed for the truss members, steel connectors were also used in certain cases (see Figs 5.29 and 5.30).



Figure 5.27: Truss of central roof



Figure 5.28: Truss of wing roof



Figure 5.29: Steel connector



Figure 5.30: Carpenter Connection

The single-slope trusses comprise inclined and vertical struts supported either on the horizontal tie or on the upper side of wall 5 (see Fig. 5.31). The roof trusses have timber supports encased within the upper side of the walls forming the perimeter of the building' plan. It is interesting to note that the building walls are not braced.



Figure 5.31: Single slope truss

5.4.6- Other structural elements

The stair steps of the main entrance to the building are made of marble stones, whereas the internal staircase is made of timber (see Fig. 5.8). The balconies on the faces on the Aktaiou and Lykomidon streets are made of marble plates supported on sculptured marble cantilevers (see Fig. 5.32). The galleries looking in the open space forming between the building's central and wing parts essentially form extensions of

the 1st floor and roof beams (see Fig. 5.33) and they are currently in a state of collapse (see Fig. 5.34).



Figure 5.32: Typical balcony



Figure 5.33: Typical gallery looking in the internal open space with temporary prop



Figure 5.34: Typical gallery in a state of collapse.

For the internal openings timber beams are used as lintels (see Fig. 5.35), whereas the lintels of the external openings are made of rubble and brickwork (see Fig. 5.36) and have an arch shape. The lintel of the main door to the internal open space has been provided with metal supports (see Fig. 5.37).



Figure 5.35: Typical lintel of internal opening



Figure 5.36: Typical lintel of external opening



Figure 5.37: Metal support of door lintel

5.5- Damage identification and mapping

5.5.1- General

From visual observation, it has been established that the building does not suffer any significant structural damage in the perimeter masonry walls, such as crushing or sliding, swelling, out-of-plane displacements, loss of mass, deep cracking, collapse of corner wall connections, etc.

The damage suffered as a result of aging, construction faults/ defects, lack of maintenance, seismic and environmental actions may be broadly described as follows:

- Inclined and vertical cracking with a relatively small width not extending throughout the wall thickness.
- Fragmentation of masonry mortar.
- Extensive detachment and loss of wall plaster.
- Failure in localized regions and large deflections of the bearing members of the roof structure
- Collapse of timber galleries
- Active deep cracks between wall and roof.
- Separation of roof and bearing walls

Abbreviations

The abbreviations used for the description of the locations of damage, and the description of the masonry pathology (deterioration phenomena and deterioration factors effected on the Aktaiou building), are provided in the following [Table 5.1](#).

Table 5.1: Abbreviations

Abbreviations	Description
W1-ex	Wall 1- external face
W1-in	Wall 1- internal face
W2-ex	Wall 2- external face
W2-in	Wall 2- internal face
W3-ex	Wall 3- external face
W3-in	Wall 3- internal face
W4-ex	Wall 4- external face
W4-in	Wall 4- internal face
W5-ex	Wall 5- external face
W5-in	Wall 5- internal face
W6-b	Wall 6- western face
W6-f	Wall 6- eastern face
W7-in	Wall 7- external face
W7-in	Wall 7- internal face
W8-ex	Wall 8- external face
W8-in	Wall 8- internal face

5.5.2- Main bearing walls

- Wall 1

The damage of the external face of the wall (wall 1-ex) is characterized, on the one hand, by vertical cracking at both the top of the building and the lintels of the 1st floor openings and, on the other hand, by loss of plaster in localized regions of the wall. The damage of the internal face of the wall (wall 1-in) is characterized by both vertical and inclined cracking of both the wall and the lintels of the 1st floor openings (see Fig. 5.38). Vertical cracking also exists between the wall openings of the ground floor, as well as at the connection of the wall with walls in the orthogonal direction (bearing and secondary walls).



Figure 5.38: Lintel cracking (W1-in, 1st floor) and vertical cracking at both the top (W1-ex, 1st floor) of the building

- Wall 2

As for the case of wall 1, the external face of wall 2 (wall 2-ex) is characterized by the presence of small width vertical cracks at the top of the building (see Fig. 5.39), whereas the internal face of the wall (wall 2-in) is characterized by the presence of vertical cracking of the lintels of the openings and local dislocation of the stones of a part of it between openings. The cracking, both vertical and inclined, of the lintels of the openings of the 1st floor is more pronounced than that of the ground floor, with significant cracking also existing at the corner wall connections.



Figure 5.39: Wall cracking at the top of the building (W2-ex, 1st floor)

- Wall 3

Vertical cracking is visible at the external face of the wall at the top of the building and the lintels of the 1st floor, whereas vertical and inclined cracks are also visible at

the internal face of the part of the wall between openings (see Fig. 5.40) and at the lintels of the openings.



Figure 5.40: Wall cracking (W3-in, and W3-ex of ground floor)

- Wall 4

The wall is only characterized by local stone dislocations.

- Wall 5

Vertical and inclined cracking of the lintels and the some of the wall parts between successive openings exist both at the ground floor and 1st floor, with cracking being more pronounced at the 1st floor, where vertical cracking also exist at the corner wall connections with walls 2 and 3.

- Wall 6

At the ground floor, small width inclined cracks are visible in some of the lintels and at the wall connection with wall 3. Cracking, both vertical and slightly inclined, is more pronounced at the lintels of the 1st floor and, particularly, at the wall corners with wall 3 (see Fig. 5.41).

- *Wall 7*

Cracking is visible only at the 1st floor: inclined cracking of some of the lintels and vertical cracking at the wall connection with wall 4.



Figure 5.41: Vertical crack near wall connection (W6-in, 1st floor)

- *Wall 8*

As for wall 7, there is inclined cracking of the lintels and vertical cracking of the wall connections with walls 4 and 6. As modeled in Fig. 5.42, there has also been separation of the roof and wall 3, probably due to horizontal movement of the roof caused by seismic excitation; this movement was allowed by the lack of any means for connecting the roof to the wall, the direction of the seismic excitation is also indicated in Fig. 3.42.



Figure 5.42 Horizontal cracks at the connection part between wall 3 and the roof in the 1st floor

5.5.3- Internal secondary walls

The damage characterizing these walls is mainly cracking at the wall connections and inclined cracking of the lintels of the openings (see Fig. 5.43).



Figure 5.43: Typical diagonal cracking of secondary wall

5.5.4- Floors – Timber beams

The floors of both the ground- and the 1st- levels, do not appear to have suffered any failure or excessive deflection. Also, the timber does not appear to have suffered any damage due to environmental causes apart from some limited wear of the planking.

5.5.5 -Roof

The roof of the central building is significantly damaged. Although the structural members of the trusses do not appear to have suffered failure, some of the trusses exhibit a significant deviation from the vertical (see Fig. 5.44).



Figure 5.44: Truss deviation from vertical

Large deflections and failure has been suffered by the single-slope diagonal trusses (both members (see Fig. 5.45) and connections (Fig. 5.46)); significant deflections have also been suffered by the roof perlin.

The roof of the ‘wings’ do not exhibit visible deflections; however, there have been failures of the trusses, whereas only the perlin have deflected excessively. It should also be noted that many of the truss members have been arbitrarily replaced. Also, the large deflection of the roof trusses has caused dislocation of the wall corner joints at the region of the truss supports.



Figure 5.45: failure of truss member



Figure 5.46: Excessive truss deflection

5.5.6- Other structural elements

In contrast with the collapsed timber beams supporting the galleries overlooking the interior open space (see Fig. 5.47), the marble balconies of the street facades suffered no damage.



Figure 5.47: Collapsed galleries

5.6- Damage Assessment

Damage assessment is aimed at assessing the real condition of an existing structure; there is a parallel in the field of medicine: any treatment must be preceded by a correct diagnosis (Sullivan and Keane 2004). In appraisal, the restorer is left face to face with an existing structure of definable qualities and must determine its condition and suitability of use (ICOMOS 2003).

5.6.1- Documentation

The assessment of the mechanical characteristics of the masonry materials usually aim to identify the mechanical (strength, deformability, etc.), physical (porosity, etc.) and chemical (composition, etc.) characteristics of the materials and the presence of any discontinuities within the structure. The assessment of the mechanical characteristics of the masonry materials is based on visual observation and sampling of the construction materials and the laboratory testing of the samples (X Ray Diffraction (XRD), X Ray Florescence (XRF) uniaxial compression test).

5.6.1.1- Sampling

As already discussed, the main materials used are limestone, marble and volcanic stones in addition to mortar.

- Stones

The sampling included all types of stones. It was carried out either by carefully removing relatively small stones through the use of chisel or by drilling cores out of larger stones (see Figs. 5.48 and 5.49). The material and specimen types and the locations of sampling are provided in Table 5.2, whereas the precise location of sampling is shown in Figs 5.50 and 5.52.



Figure 5.48: Removal of stone D7-MS



Figure 5.49: Drilling of core D10-LS

Table 5.2: Type of samples and location of sampling

Specimen name	Material type	Specimen type	Sampling location
D1-MS	Marble	Cube	Ground floor
D3-MS	Marble	Cube	Ground floor
D4-MS	Marble	Cube	Ground floor
D5-VS	Volcanic stone	Cube	1 st floor
D6-VS	Volcanic stone	Cube	1 st floor
D7-MS	Marble	Cube	Ground floor
D8-LS	Limestone	Cylinder	Ground floor
D2-LS	Limestone	Cylinder	Ground floor
D9-LS	Limestone	Cylinder	Ground floor
D10-LS	Limestone	Cylinder	Ground floor
D11-LS	Limestone	Cylinder	Ground floor
D12-MS	Marble	Cylinder	Ground floor
D13-VS	Volcanic stone	Cube	1 st floor

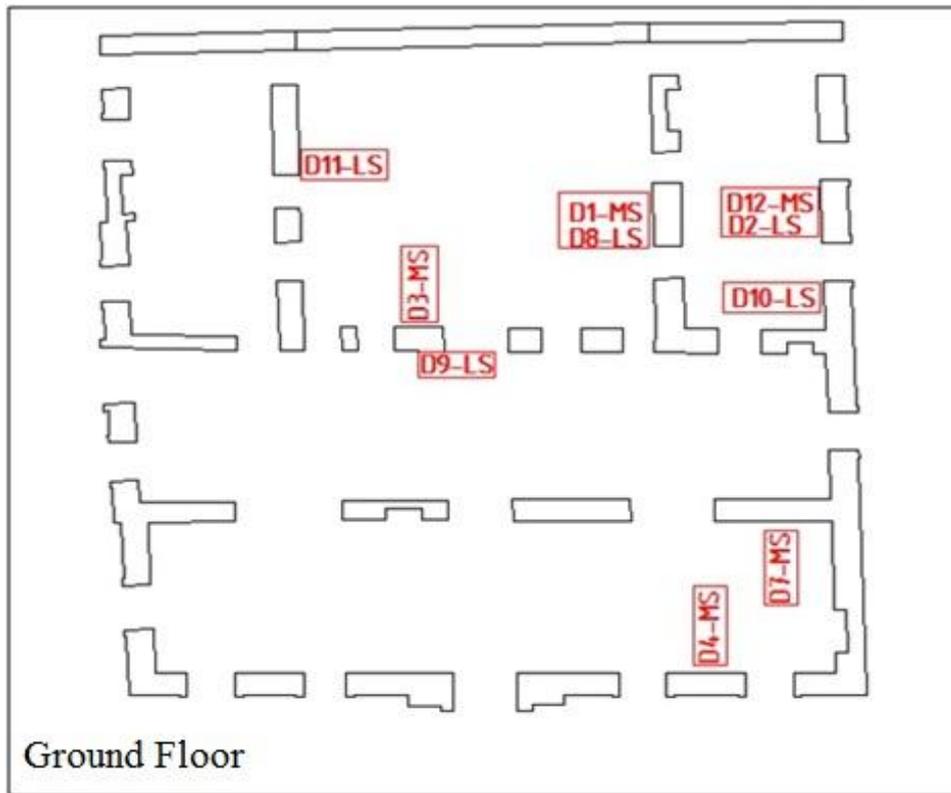


Figure 5.50: Location of sampling at the ground floor

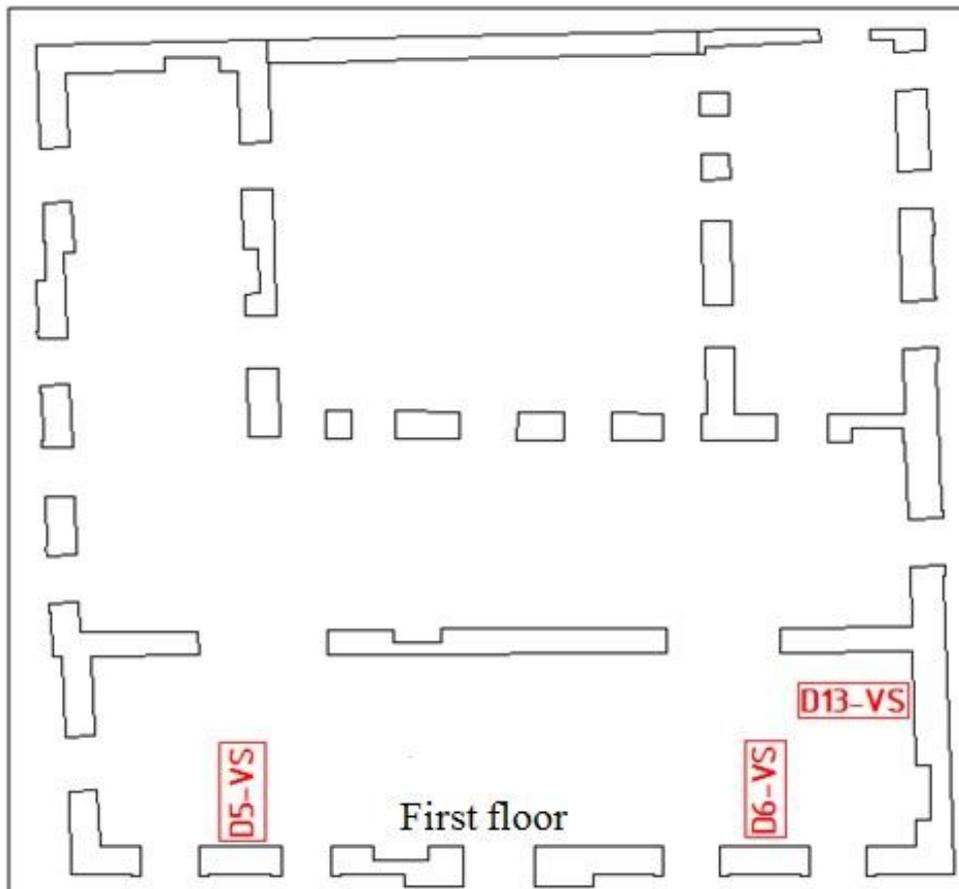


Figure 5.51: Location of sampling at the 1st floor

- Mortar

From in situ examination the mortar was found weak and friable (see Fig. 5.52) and, as a result, it has not been possible to obtain any suitable samples to estimate its mechanical properties.



Figure 5.52: Fragmented mortar

5.6.2- Testing

5.6.2.1- Chemical and Mineralogical characterization

Marbles represents granular natural limestone or dolomite of organic nature that have been re-crystallized under the influence of external agents such as heat, pressure or the presence of aqueous solutions. Marbles consist of a mosaic of various proportion of calcite and dolomite grains often inter-bedded with other minerals such as quartz, mica, graphite, iron oxides, pyrite, etc., minerals representing impurities in the original organic limestone, which reacted during metamorphism to form new compounds (Octavian 2008)

X-ray diffraction (XRD), method currently used in mineralogy and petrology of marble and limestone that makes possible identification of the minerals that compose the investigated sample. Natural marbles in Greece often contain, often together with major constituents, such as calcite or dolomite, other minor components such as quartz, magnesite, iron oxides (see Table 5.3)

Table 5.3 Petrologic description of the investigated samples composition in accordance with X-ray diffraction data (Octavian 2008)

Place	type	colour	texture	composition
Kerkira	intraclastic limestone	white-yellowish	compact, brecciate	calcite, traces of dolomite
Nauplio	precipitation limestone	white-yellowish	fine banded	Calcite, dolomite
Drama	dolomitic marble	white-yellowish	fine banded	dolomite, traces of calcite
Kavalla	calcitic marble	white-yellowish	massive, medium granular	calcite, traces of quartz
Thasos	dolomite marble	white	massive, micro - granular	dolomite, traces of calcite and magnesite,
Didimon	dolomite marble	cream-grayish	mezzo to mono-crystalline	dolomite, small amount of calcite
Trizina	sparry calcite	red-brownish	Micro crystalline to mezzo- crystalline	calcite + iron oxides
Dionysos	crystalline limestone	white	massive, micro - granular	calcite
Aliveri	calcite marble	bicolor white	massive, banded	calcite, traces of dolomite
Gramatiko	calcite marble	White-brownish	massive, micro - granular	calcite, traces of dolomite
Kozani	calcite marble	White	massive, medium granular	calcite
Naxos	calcite marble	White	massive, micro - granular	calcite

From the three types of masonry materials limestone, marble stone and volcanic stone (LS, MS, and VS) chiselled out at the locations shown in Figs. 5.50, 5.51 and 5.52, samples (limestone, marble, volcanic stone and mortar) were taken and appropriately prepared for the chemical and mineralogical characterization.

The chemical composition of the natural stones was established by through X-ray Fluorescence (XRF) analysis, while mineralogical characteristics were determined by XRD analysis, using a Siemens D-5000 X-Ray Diffractometer (XRD), with nickel-filtered Cu K α 1 radiation ($\lambda=1.5405 \text{ \AA}$, 40 kV and 30 mA). The results of the chemical analysis of the natural stones are presented in Table 5.4.

Table 5.4: Results of chemical analysis (% w.w) of the stones samples

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	L.O.I
VS	65,87	12,86	0,93	2,21	0,13	2,90	1,27	0,41	13,19
LS	0,83	0,14	0,10	30,50	21,12	-	0,11	-	46,61
MS	0,62	0,21	0,20	55,21	-	0,52	0,10	-	42,60

In Figs 5.53, 5.54, 5.55, and 5.56 the XRD patterns of the examined stones samples are presented. According to XRF and XRD analysis, sample VS is a stone of volcanic origin, while samples LS and MS, come from carbonate rocks (crystalline to microcrystalline limestone). In sample VS, a large proportion of amorphous phase is recorded by the XRD analysis, while the main detected mineralogical phases were quartz, alunite, dolomite, and calcite. Stone MS coming from metamorphic carbonate rocks microcrystalline and grainy. The main mineral phase is that of calcite. Other recorded phases are those of quartz, muscovite, clinochlore, and anorthite, but it is estimated that they exist at a low quantity level. Stone LS is a limestone mineral with main mineralogical phase the dolomite and secondary the calcite.



Figure 5.53 The fragmentation and bad mineralogical components of marble

From the chemical and mineralogical characterization of the main building materials in Aktaiou building, is expected that limestone, which contains dolomite and calcite to have better mechanical performance compared to marble (so the builder use it in the walls corner as a connection technique). The marble used in the building contains calcite and iron oxides which effect on its mechanical properties. According to these observations lime stone used in the Aktaiou building in wall corners acting as connection stone technique. On the other hand marbles which probably coming from the cutting process of the marbles were used as ashlar

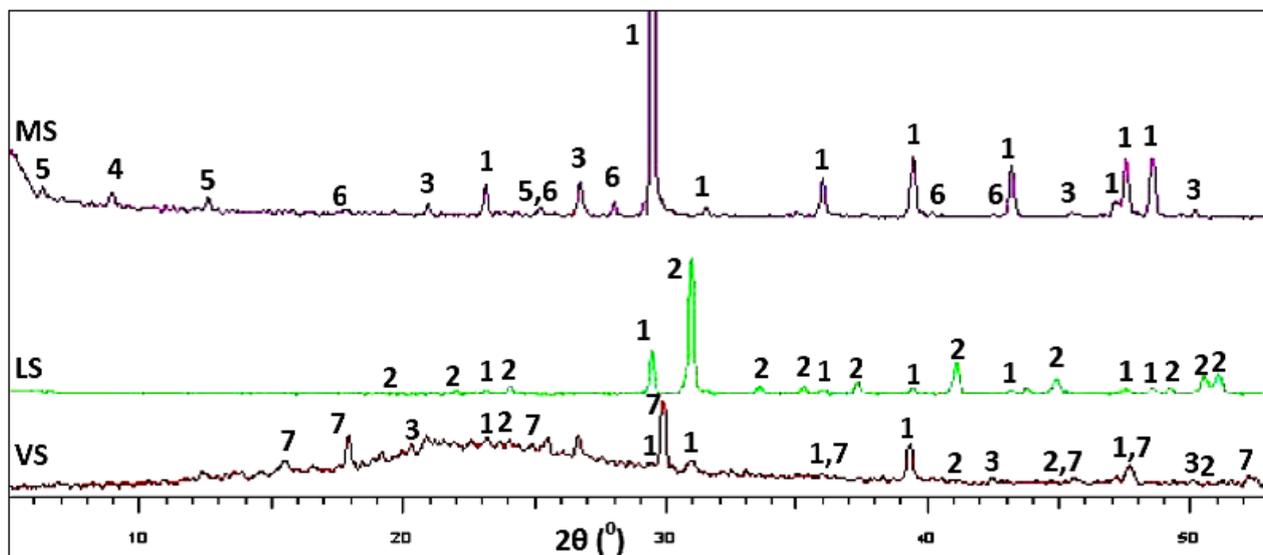


Figure 5.54: XRD patterns of the three types of masonry materials (LS, MS and VS.).
 1::Calcite; 2: Dolomite; 3: Quartz; 4: Muscovite; 5: Clinocllore; 6:
 Anorthite; 7: Alunite

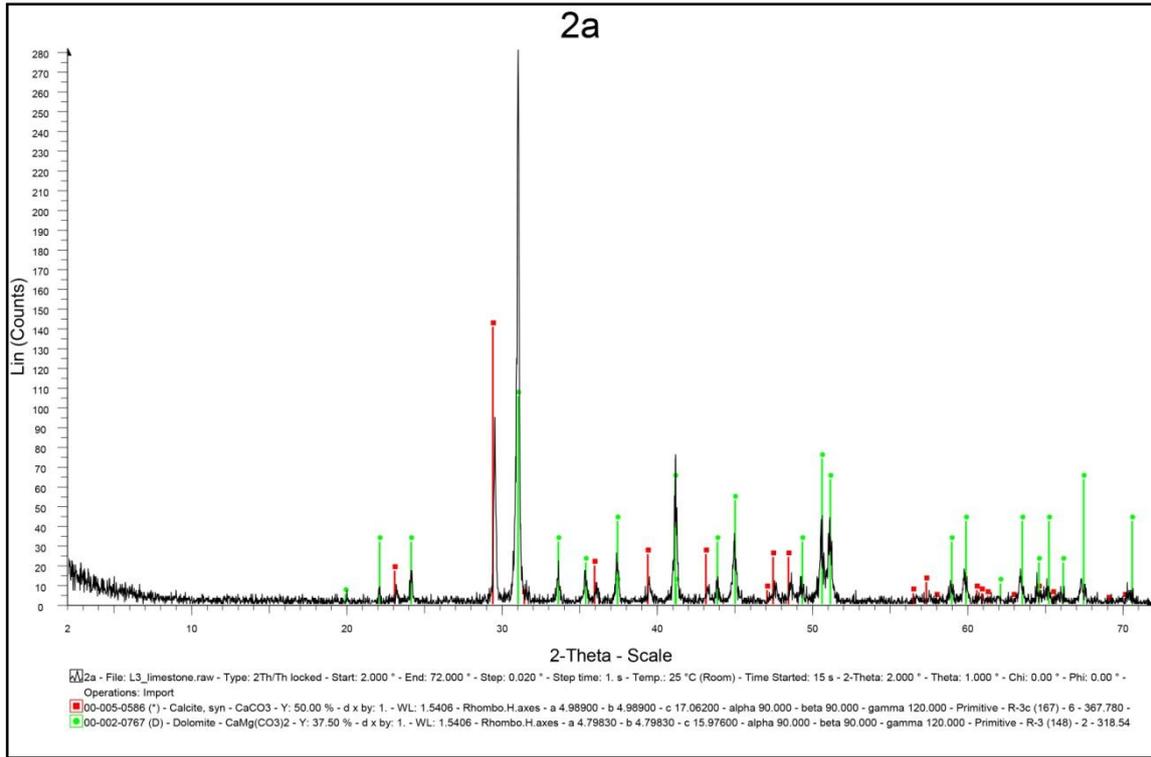


Figure 5.55: XRD patterns of limestone specimen

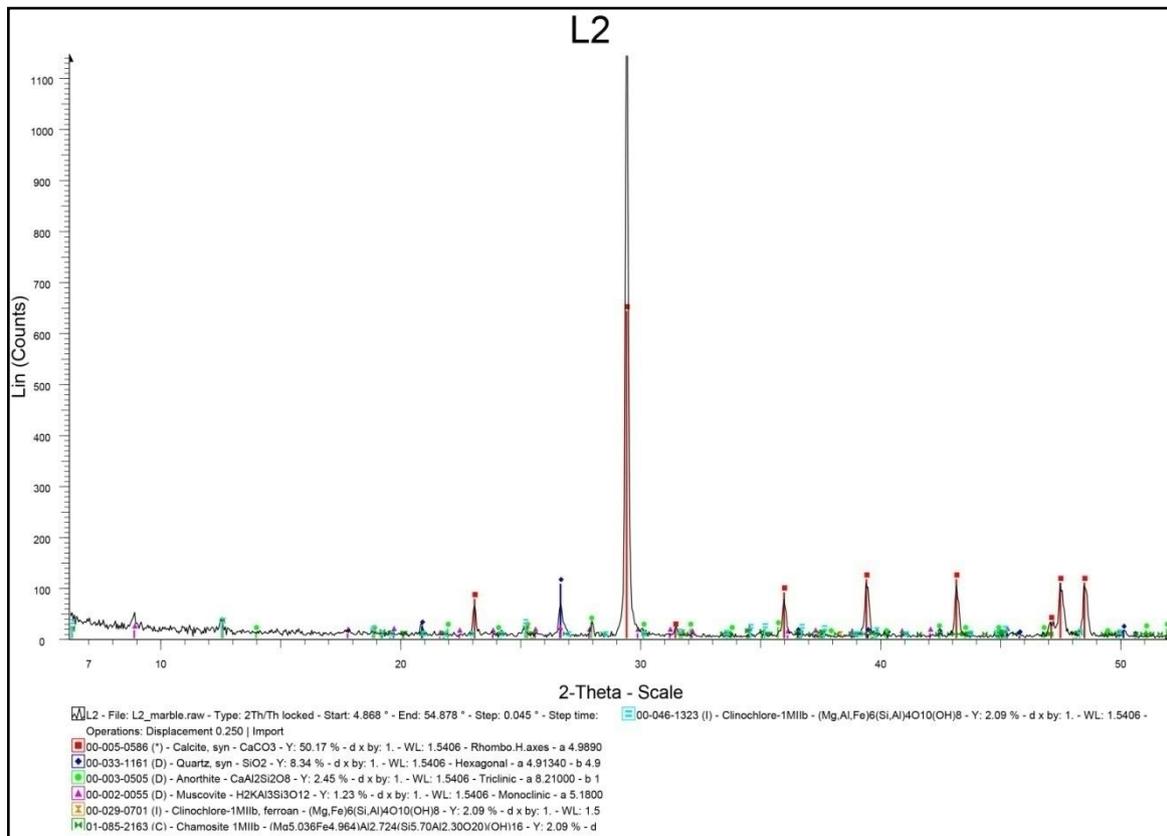


Figure 5.56 XRD patterns of Marble specimen

As far as the masonry mortar is concerned, XRD and optical microscopy were used in order to mineralogically characterize the sample and to assume whether or not a lime-pozzolan mortar was used for the masonry construction. The segregation of the mixed aggregates was achieved using ambient grinding and sieving in a 0.63 mm sieve. XRD analysis was carried out to the passing fraction of the mortar and calcite, quartz, muscovite, and clinochlore were the main detected mineralogical phases (Fig. 5.57).

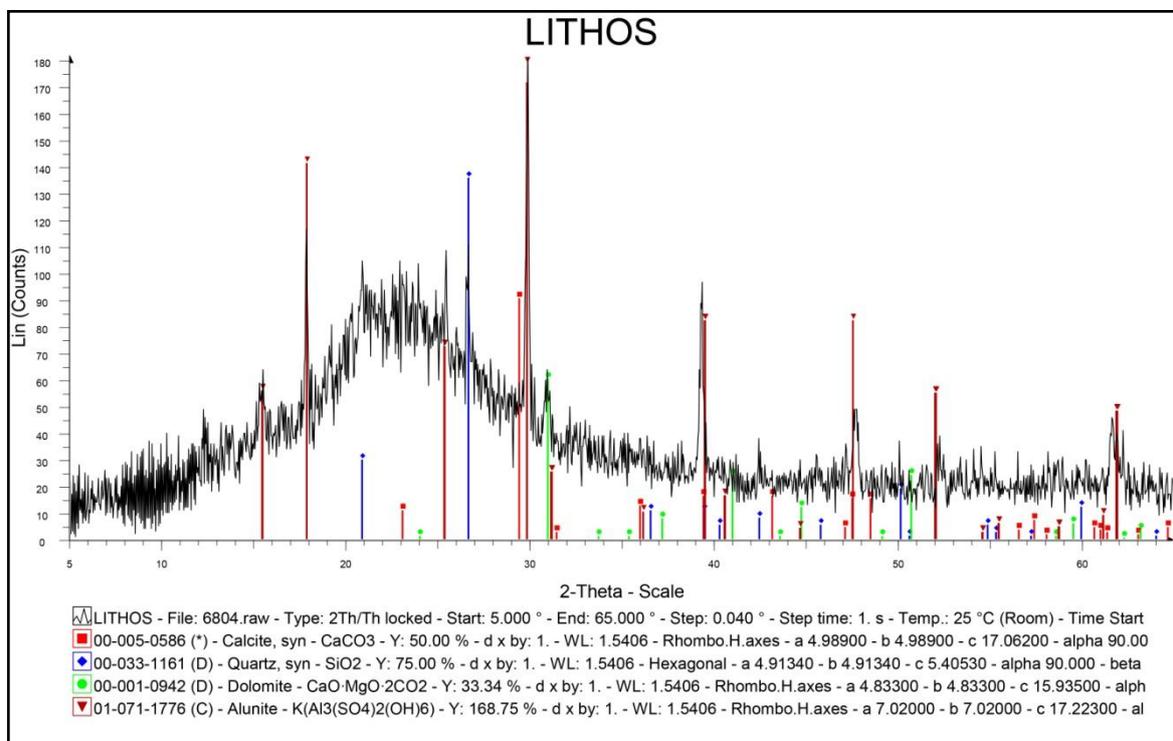


Figure 5.57: XRD patterns of volcanic stone specimen

Following the XRD analysis of building materials, an appropriate specimen was prepared for optical microscopy. The same sample, passing the 0.63 mm sieve, was treated by a 10% w/w 0.1N HCl acid, in order to dissolve calcite.

The filtered residual was dried at 105 °C and examined by optical microscopy. It was found that a finely ground glassy phase exists in the sample (Fig. 5.59), which mostly is attributed to a pozzolanic material.

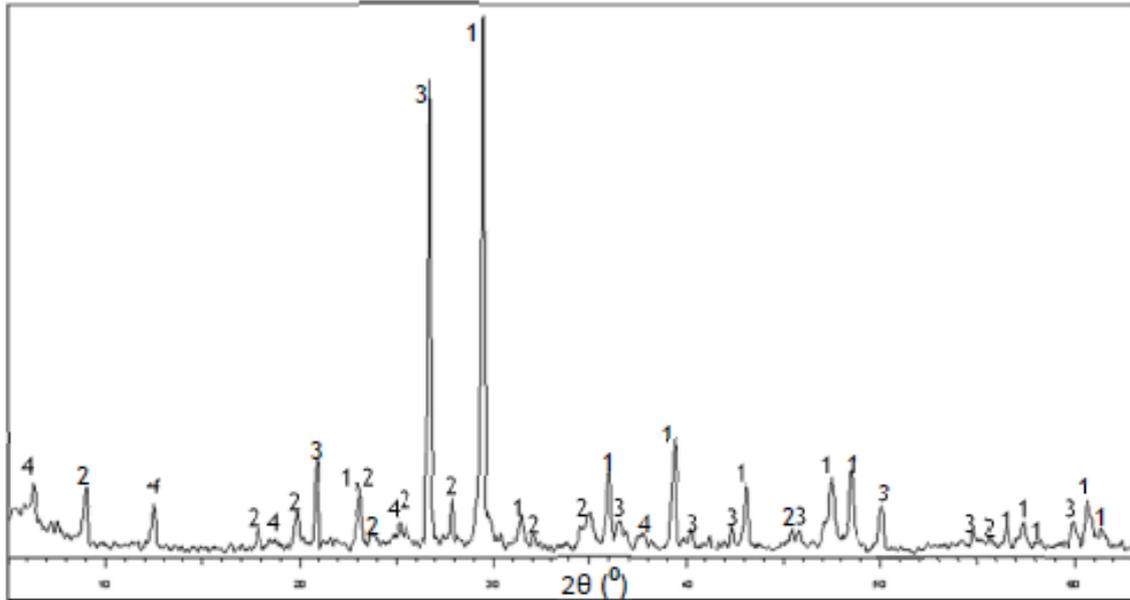


Figure 5.58: XRD pattern of mortar sample, 1: Calcite, 2: Muscovite, 3: Quartz, 4: Clinocllore



Figure 5.59: Optical microscopy photographs of the mortar sample.

5.6.2.2- Mechanical characterization

The mechanical characteristics of the samples were established from uniaxial compression tests. The samples chiselled out of the walls were machined to form cubes, whereas those cored out from larger stones (see Figs. 5.60 and 5.61) had their end faces abraded so as become cylinders with a height-to-diameter ratio of 2.



Figure 5.60: Drilling core from a ground floor stone



Figure 5.61 Cubic and cylindrical specimens

All specimens were weighted before testing. The specimens' dimensions and weight are shown in Tables 5.5 and 5.6. The cubes were used to assess strength only. The axial and transverse strains were measured by placing electrical resistance strain gauges within the middle zone of the cylinders at diametrically opposite each other in the axial and circumferential directions. The testing arrangement for the cubes and cylinders are shown in Fig.5.62. The values of the compressive strength obtained

from the tests are given in Table 5.7, whereas the stress-strain curves obtained from the tests on the cylinders samples are shown in Figs. 5.65, 5.66, 5.67.

Table 5.5: Dimensions and weight of cubic specimens

Specimen name	Material type	Dimensions (cm)			Weight (Kg)
		Side a	Side b	Height	
D1-MS	Marble	5.6	5.4	6.5	0.508
D3-MS	Marble	7.9	7.7	10.5	1.636
D4-MS	Marble	7.9	8.00	8.00	1.364
D5-VS	Volcanic stone	8.2	7.2	8.5	0.556
D6-VS	Volcanic stone	8.2	8.00	7.00	0.490
D7-MS	Marble	5.5	4.5	4.5	0.306
D13-VS	Volcanic stone	8.2	8.0	8.00	0.532

Table 5.6: Dimensions of and weight cylindrical specimens

Specimen name	Material type	Dimensions (cm)		Weight (Kg)
		Diameter	Height	
D8-LS	Limestone	4.5	11.00	0.318
D2-LS	Limestone	4.5	4.5	0.142
D9-LS	Limestone	4.5	11.3	0.438
D10-LS	Limestone	4.5	9.5	0.480
D11-LS	Limestone	4.5	11.00	0.428
D12-MS	Marble	4.5	9.4	0.402



Figure 5.62: Testing arrangements for (a) cubes and (b) cylinders

Table 5.7: Compressive strength and specific weight of stone specimens

Marble			
Specimen name	Material type	Compressive strength f_{bc}(MPa)	Specific weight (kN/m³)
D1-MS	Cube	15.76	25.84
D3-MS	Cube	24.31	25.61
D4-MS	Cube	24.10	32.31
D7-MS	Cube	32.90	27.47
D12-MS	Cylinder	29.01	26.91
Mean value		25.21	27.63
Limestone			
D8-LS	Cylinder	18.53	18.19
D2-LS	Cylinder	43.62	16.48
D9-LS	Cylinder	54.10	24.38
D10-LS	Cylinder	18.00	31.79
D11-LS	Cylinder	33.17	10.04
Mean value		33.48	20.18
Volcanic stone			
D5-VS	Cube	4.87	11.10
D6-VS	Cube	5.84	10.67
D13-VS	Cube	5.23	10.13
Mean value		5.31	10.63

The average compressive strength established from the tests was 25.2 MPa for the marble specimens, 33.5 MPa for the limestone specimens, and 5.3 MPa for the volcanic stone specimens see Fig. 5.63.

For specimens D10, D11, D12, The axial and transverse strain was measured using strain gauges (see Fig. 5.64) and the stress-strain curves obtained from testing specimens in linear uniaxial compression are shown in Fig. 5.65, 5.66, and 5.67.

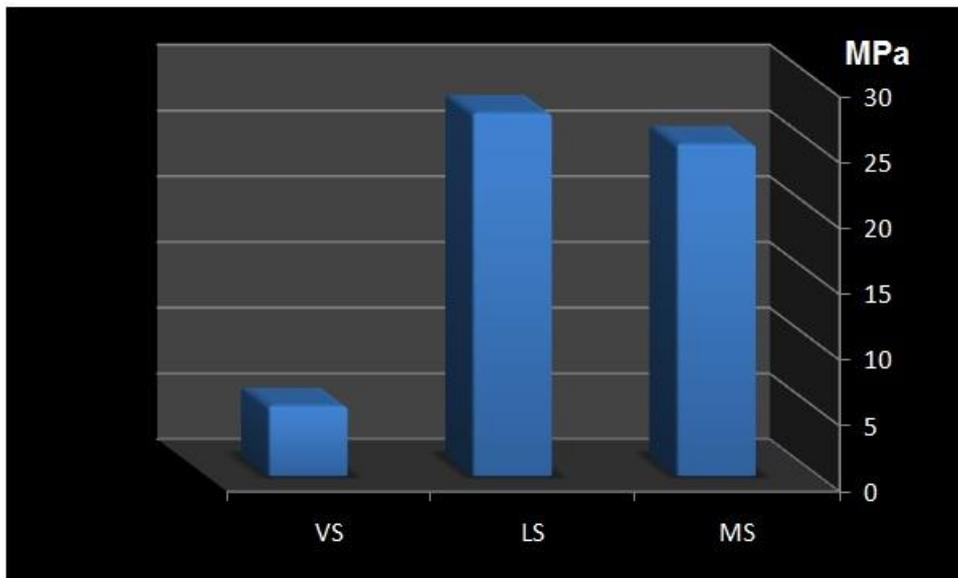


Figure 5.63: Mean compression strength values for marble, limestone, and volcanic



Figure 5.64: strain gauges test

For each curve, only the branch corresponding to low deformation level is presented, as for larger deformations strain gauges do not perform reliably, due to their local detachment from the specimens.

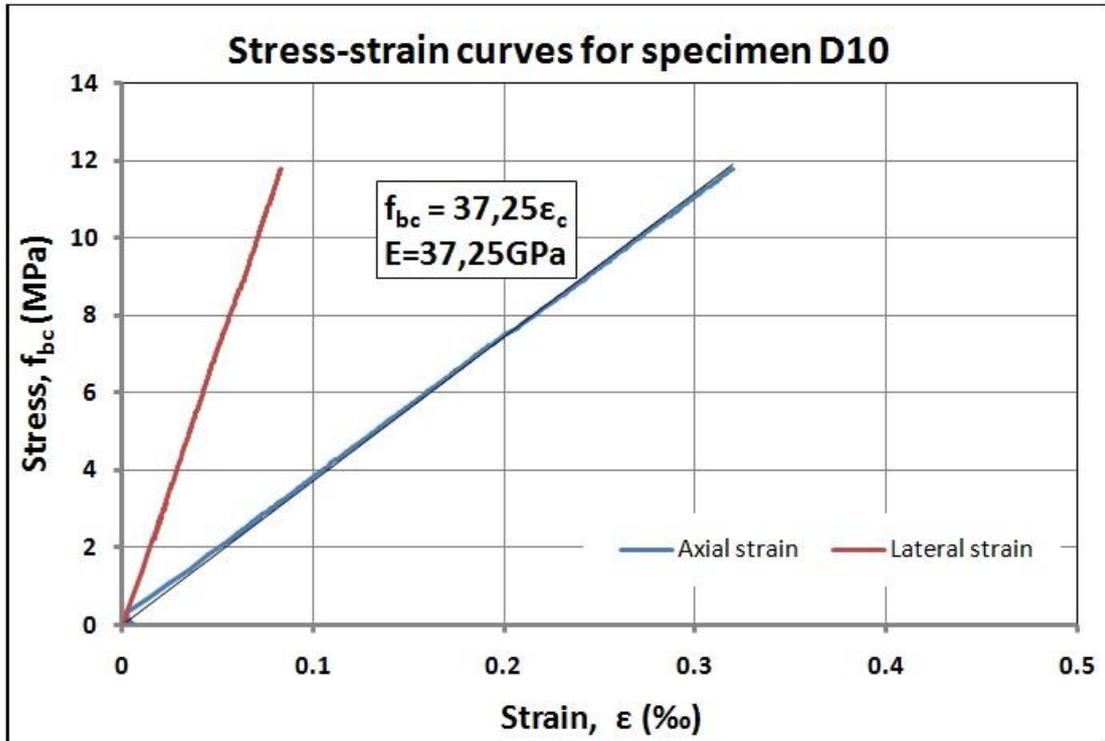


Figure 5.65: Typical stress-strain curves obtained from testing specimens D10 in uniaxial compression

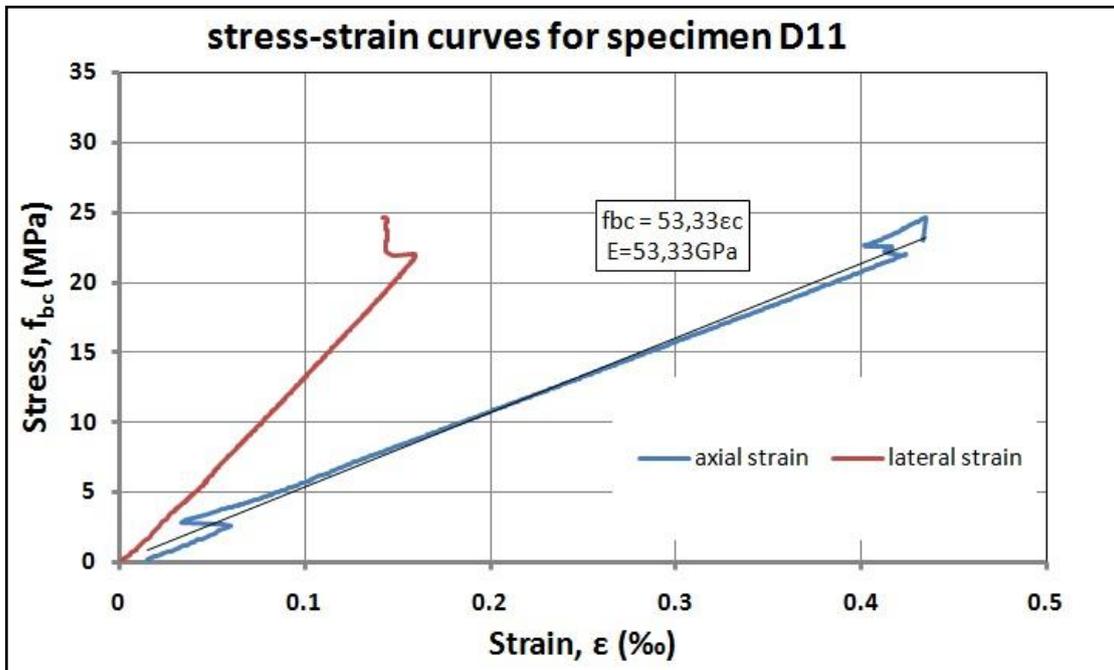


Figure 5.66: Typical stress-strain curves obtained from testing specimens D11 in uniaxial compression

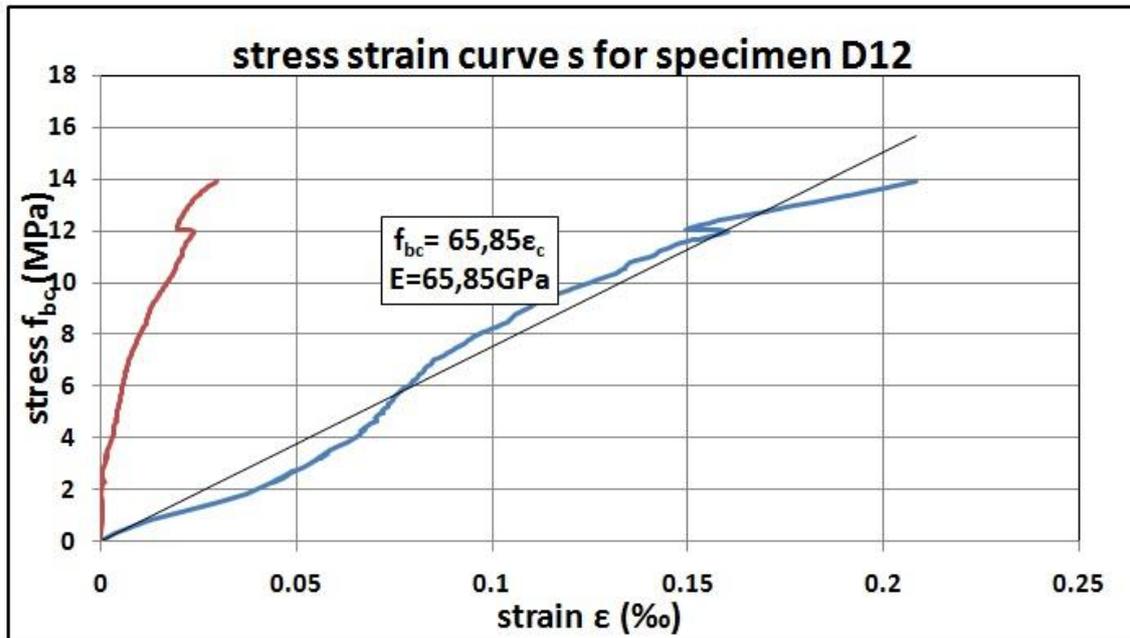


Figure 5.67: Typical stress-strain curves obtained from testing specimens D12 in uniaxial compression

5.6.3 Assessment of Masonry Mechanical characteristics

For the assessment of the masonry mechanical characteristics it was assumed that the compressive strength of the mortar was $f_{mc}=0.4$ MPa. The assessment of the mechanical characteristics of the masonry materials was based on the experimentally established strength values of the samples (see Table 5.7). These values were introduced in the empirical formulae proposed by Tassios and Chronopoulos (1987) (see Table 5.8) and the resulting characteristics are given in Table 5.9. The assessment of stone compressive strength f_{bc} was based on the mean value of the constituent materials.

Table 5.8: Empirical formulae used for assessing the masonry mechanical characteristics

	formulae
Horizontal mortar layers – Volume of mortar	25-30mm, $V_{mortar} \approx 0.30/0.40$
Material safety factor γ_m	2.00
Wall compressive strength normal (\perp) to horizontal masonry layers ($f_{wc, \perp}$)	$\left(\frac{2}{3}\sqrt{f_{bc}} - a\right) + 0.5 \cdot f_{mc}$

Wall compressive strength parallel (//) to horizontal masonry layers $f_{wc, //}$	For incomplete mortar filling $f_{wc, //} = (0.50 - 0.65) \cdot f_{wc, \perp}$
Wall tensile strength normal (\perp) to horizontal masonry layers ($f_{wt, \perp}$)	$f_{wt, \perp} = f_{mt}$
Wall tensile strength normal (//) to horizontal masonry layers ($f_{wt, //}$)	$f_{wt, //} = 2 \cdot f_{mt}$
Shear strength(horizontal sliding)	$f_{wv,0} = 0.05 + 0.25 \cdot \left(\frac{3}{4} \cdot \sigma_o\right) \approx 0.05 + 0.20 \cdot \sigma_o$
Shear strength(diagonal cracking)	$f_{wv,d} = \frac{2}{3} \cdot f_{wt,d} \cdot \sqrt{1 + \frac{0.85 \cdot \sigma_o}{f_{wt,d}}} = f_{mt} \cdot \sqrt{1 + 0.5 \cdot \frac{\sigma_o}{f_{mt}}}$
Modulus of elasticity	$E = 800 \cdot f_{wc, \perp}$
Shear modulus	G=0.40E
Poisson's ratio	0.25

Table 5.9: Masonry mechanical characteristics

Ground floor					
material	Stone compressive strength, f_{bc} (MPa)	Wall compressive strength, f_{wc} (MPa)	Modulus of Elasticity, E (MPa)	Poisson's ratio, ν	Shear modulus, G (MPa)
Marble	25,21	1,81	1448	0,25	296
Limestone	33,48				
Mean value	29,35				
1st floor					
Marble	25,21	1,25	1000	0,25	400
Limestone	33,48				
Volcanic stone	5,31				
Mean value	21,33				

5.7- Causes of damage

The bearing system of the building is vulnerable to earthquake actions mainly due to the following reasons:

- 1- The elongated shape of plan view of the central part of the building which consists of two bearing walls (W1 and W5) with a length of approximately 18.00 m without transverse walls that would reduce the likelihood of out-of-plane displacements
- 2- Lack of floor and roof diaphragms
- 3- Lack of bracing that would ensure monolithic response of the building

On the basis of the above characteristics, the identification of the causes of the damage suffered was based on visual observation and on the results obtained by numerical analysis of the building.

5.7.1- Identification of the causes of damage based on visual observation

The damage of the bearing walls described in Section 4.4.2 may be classified as follows:

- Damage at the wall crowning supporting the timber roof
- Damage at the connection of intersecting walls
- Damage of the lintels
- Damage of the wall pessary

5.7.1.1- Damage at the crowing of the walls

The timber roof is supported on the peripheral walls on short isolated wooden planks not tied together so as to create a bracing system capable of preventing the horizontal

displacement of the roof support, which is restrained entirely by friction across the wall width, the latter eventually leading to failure in the form of cracking as indicated in Fig.5.68



Figure 5.68: Cracking of the wall crowning

5.7.1.2- Damage at the connection of intersecting walls

As indicated in Fig. 5.69, the near vertical cracking suffered in the region of the connection of intersecting bearing walls occurred at some distance from the connection itself and this is indicative of tensile failure of the wall masonry rather than failure of the connection.



Figure 5.69: Near vertical near the primary wall intersection

This type of cracking is more pronounced (larger crack widths) at the 1st floor due to the lack of a bracing of the wall crowning. The presence of blind anchors across the wall width (see Fig. 5.18) may have contributed to this type of cracking.

On the other hand, there is practically no connection between primary and secondary walls. This may be the masons or the builder in this period built the double bearing walls at first and then they began to built the inside secondary walls. Therefore there is not any connection or tying between the main bearing walls and the secondary walls and, as a result, the walls appear to have separated along their interface as indicated in Fig. 5.70.



Figure 5.70: Wall separation along the interface between primary and secondary walls

5.7.1.3- Damage of the lintels

From the cracking suffered by internal walls above doors, it appears that the wooden lintels of the wider doors have given in under the weight of the overhead masonry (see Fig. 5.71). In contrast with the masonry above wide doors, the masonry above relatively narrow openings (e.g. windows) appears to have suffered crisscrossing inclined cracking due to earthquake action (see Fig. 5.72).

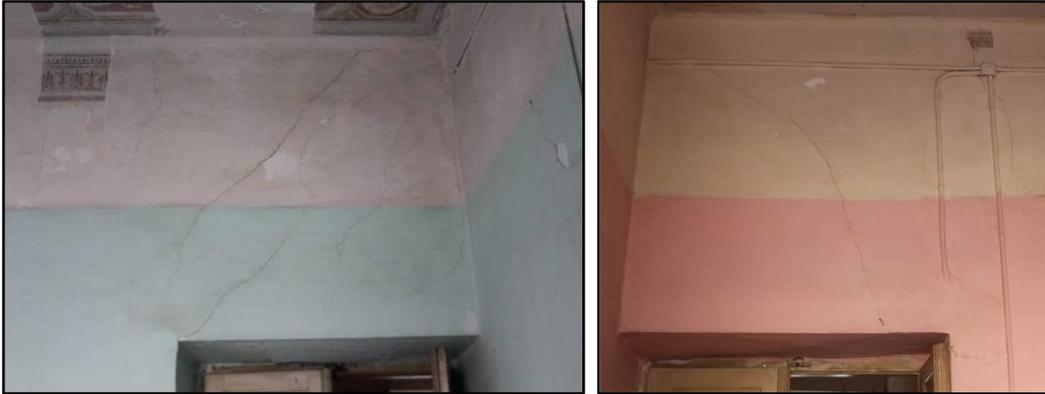


Figure 5.71: Masonry cracking supported by door wooden lintel

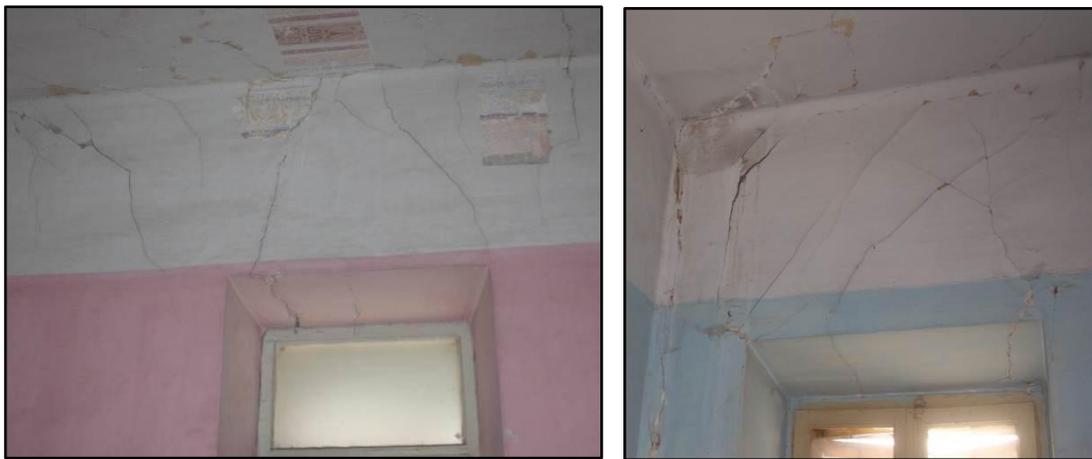


Figure 5.72: Masonry cracking of external wall above windows

5.6.1.4- Damage of the wall pessary

Wall 1, i.e. the wall of the façade of the building in Aktaiou Street, and wall 5, i.e. the internal wall adjacent to W1, have suffered near vertical, small width cracking. It is considered that these walls are vulnerable to out-of-plane actions due to their large length (18.4 m) combined with the lack of bearing walls across their direction and the absence of any bracing at both the floor and roof levels. Indicative of this vulnerability is the in-plane failure suffered by the non bearing walls across walls 1 and 5 and their detachment from the latter (see Fig. 5.73).



Figure 5.73: Detachment of non bearing walls from bearing walls at 1st level due to lack of connection

5.7.1.5- Separation of roof and bearing walls

It appears there is separation of the roof from bearing wall (see Fig 5.74). The opening caused in the separation allowed rain water to leak from the roof inside the building, the earthquake movement and the separation may have been caused by relative movements under seismic excitation allowed by the leak of connection between wall and roof.



Figure 5.74 Isolation parts between main bearing walls and the roof

5.7.2- Identification of the causes of damage based on numerical analysis

The identification of the causes of damage is based on the results obtained by finite element analysis of the building, in its initial state, under the service loading and seismic actions specified by the Greek version of EC8. Details of the analysis are provided in Kotsovos 2013. The analysis results are expressed in the form of diagrams indicating the development of internal stresses.

5.7.2.1 Damage at the crowing of the walls

The tensile stresses developing at the wall crowing under the design loading conditions were found to exceed the tensile strength of the masonry (see Fig. 5.75).

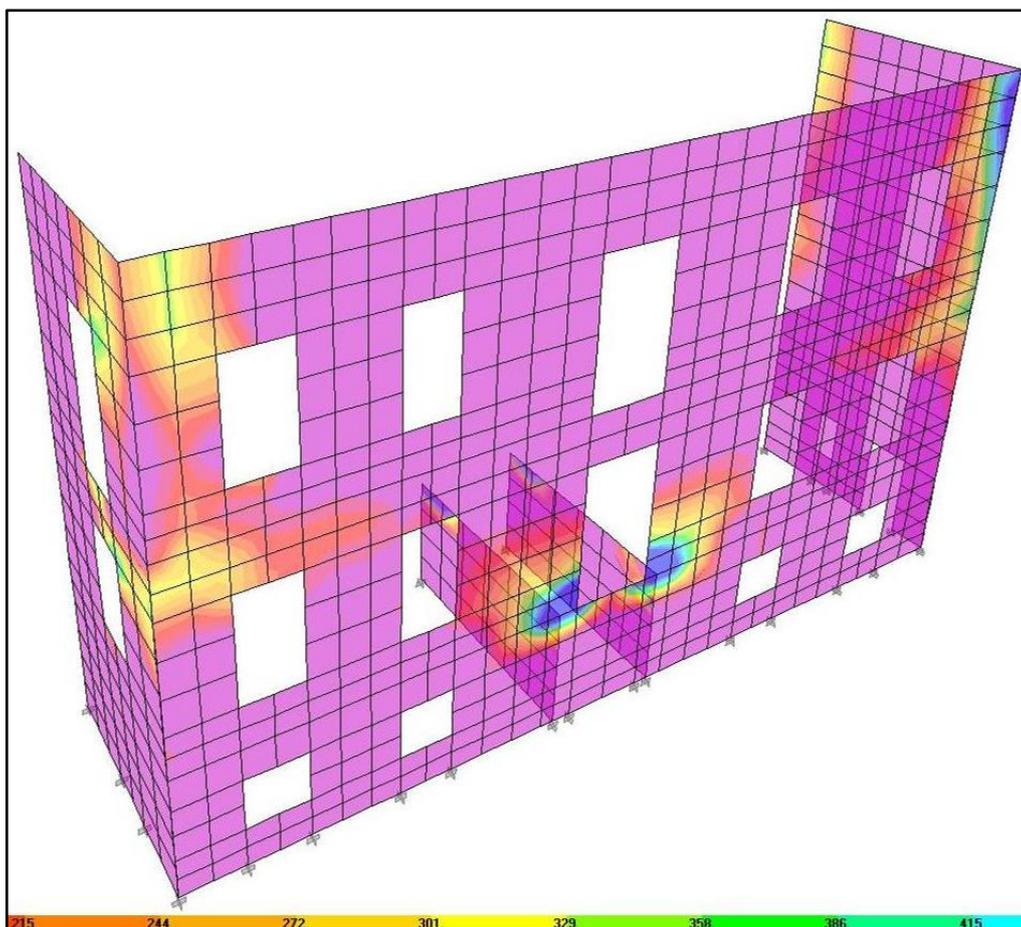


Figure 5.75: Tensile stresses (in kN/m^2) exceeding the tensile strength of masonry developing at the wall crowing under seismic action in the direction y-y (i.e. along the building's façade in Aktaiou street)

This explains the causes of the cracking observed in the building attributed to the lack of a bracing system capable of preventing the horizontal displacement of the roof support, which is entirely restrained by friction across the wall width.

5.7.2.2- Damage at the connection of intersecting walls

Fig. 5.76 shows the tensile stresses exceeding the tensile strength of the masonry developing in the region of the intersecting walls. It should be noted that it has been assumed that the walls are monolithically connected and this has led to the development of the critical tensile stresses to develop at a small distance from wall connection.

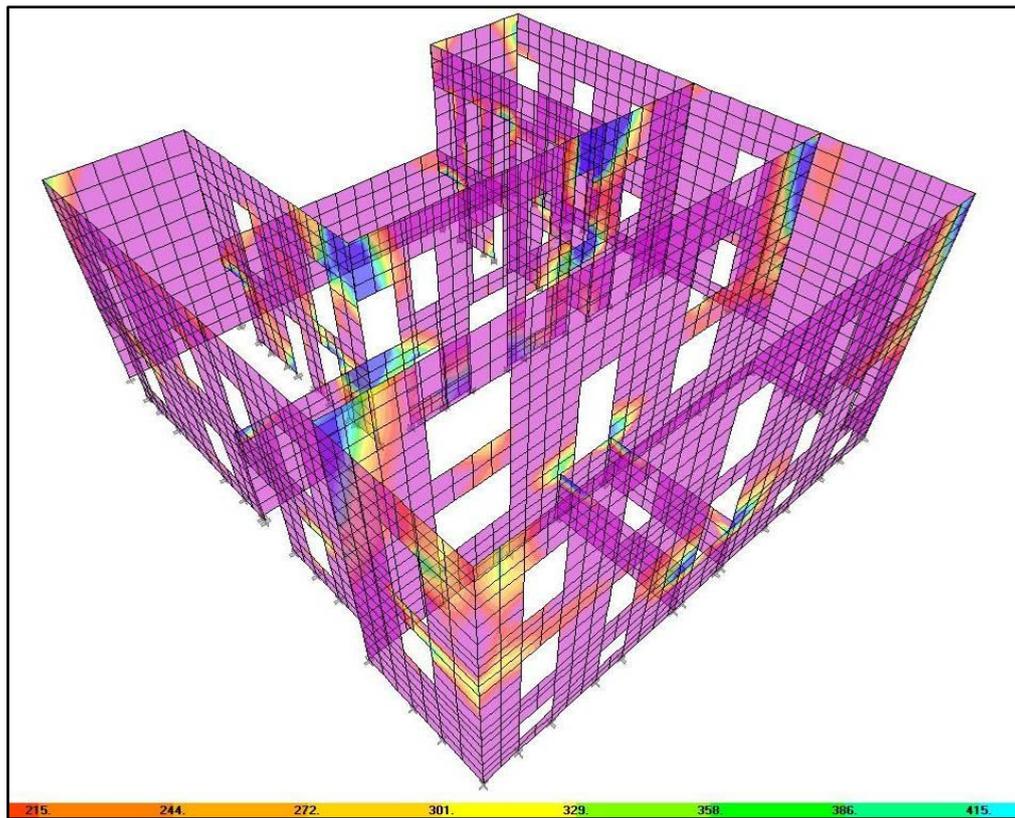


Figure 5.76: Tensile stresses (in kN/m²) exceeding the tensile strength of masonry developing in the region of the wall intersections under seismic action in the direction y-y (i.e. along the building's façade in Aktaiou street)

5.7.2.3- Damage of the lintels

The causes of cracking identified by visual observation are confirmed by the stress analysis results. The stresses exceeding the tensile strength of the masonry in the region of the openings of a typical internal wall in the x-x direction (i.e. parallel to the building's façade in Lykomidon Street) are shown in Fig. 5.77. In fact, cracking occurred in the direction orthogonal to that of the tensile stresses effect.

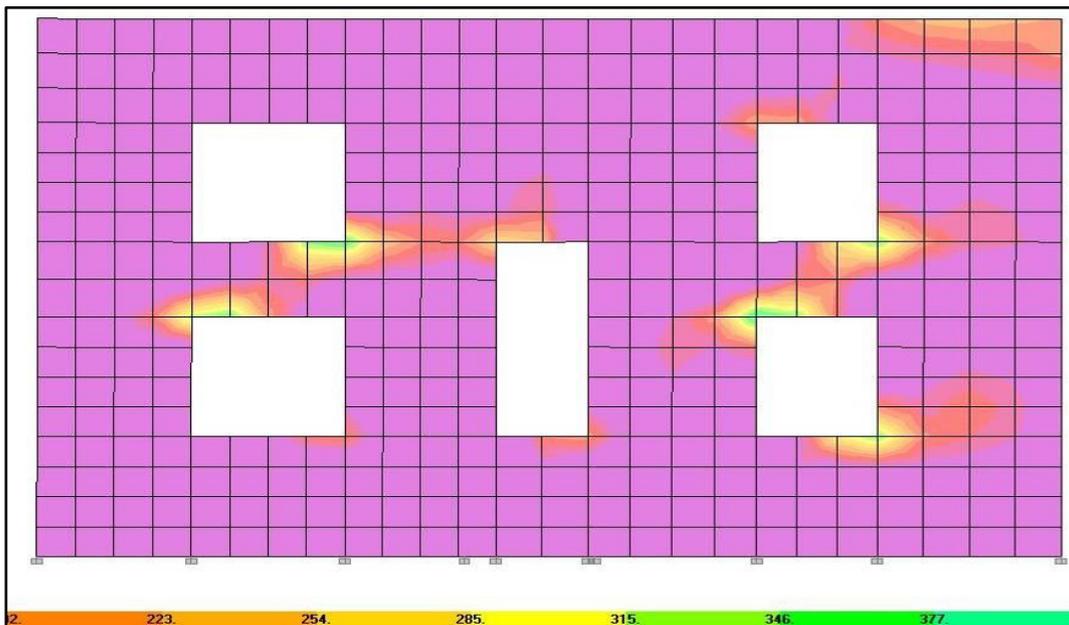


Figure 5.77: Tensile stresses (in kN/m²) exceeding the tensile strength of masonry developing in the region of the openings of a typical internal wall in the x-x direction (i.e. parallel to the building's façade in Lykomidon Street)

5.6.2.4 Damage of the wall pessary

Fig. 5.78 shows the deformed shape of the wall predicted by analysis. The figure shows that the lack of diaphragms led to out-of-plane deflection of walls 1 and 5 under seismic action in the x-x direction. The figure also shows that such out-of-plane displacements gave rise to tensile stresses in excess of those that can be sustained by masonry. Although the development of such stresses is sufficient to cause the observed cracking of the pessary, it is recognized that the causes of such cracking may be due to other causes which affect the integrity of the building structural elements

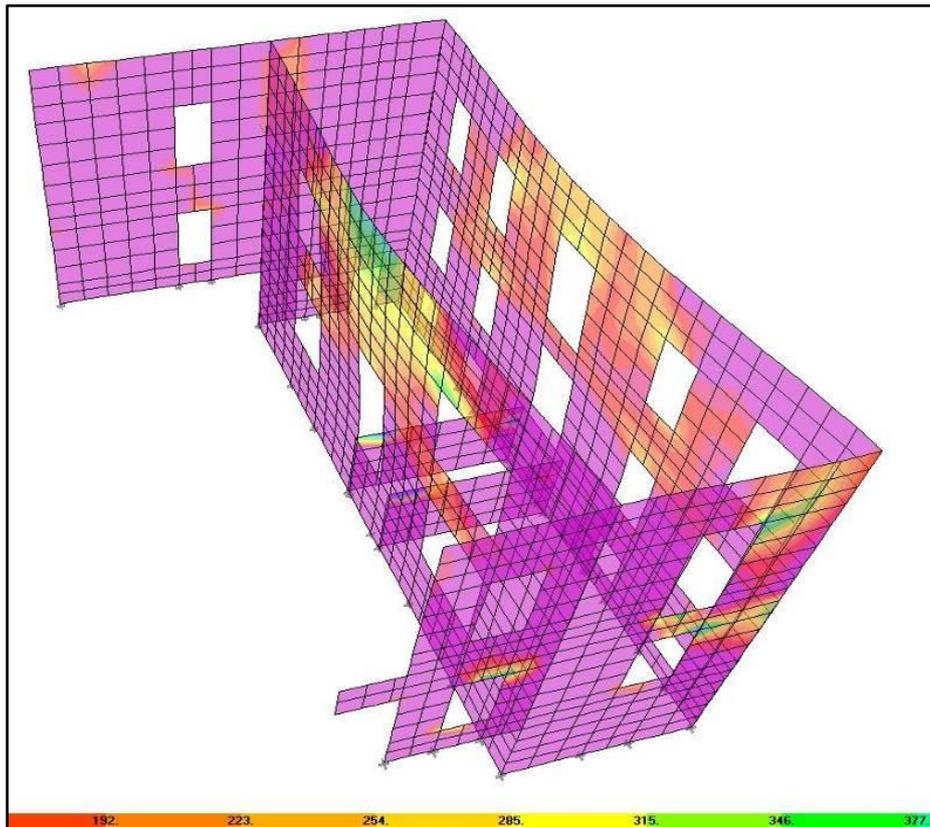


Figure 5.78: Deformed shape and related tensile stresses exceeding the tensile strength of masonry (in kN/mm^2) under the combined action of the service load and seismic excitation in the x-x direction

5.7.3- Discussion

From the observed damage of the building and its causes identified both visually and from the results of stress analysis, it appears that although the bearing system of the building has some positive structural features, these are combined with significant shortcomings. The positive features include openings (both doors and windows) with a relatively small width arranged nearly symmetrically.

Also, the width of the bearing walls is at least 0.50 m, whereas their height is approximately 4.00 m; thus, assuming diaphragmatic action of the floor and roof levels, the wall slenderness $\lambda = 8$ is rather small. Moreover, the connection of intersecting walls is found sufficiently monolithic.

On the other hand, a significant shortcoming of the building is the lack of diaphragmatic action at the levels of floors and roof that would contribute to the monolithic response of the building under seismic excitation. Another shortcoming is the lack of transverse walls connecting the two parallel long bearing walls (walls 1 and 5) along the façade of the building in Aktaiou Street; the lack of such walls increases the likelihood of out-of-plane displacements of the bearing walls. Finally, the lack of bracing at the wall crowning has a negative effect at the bearing wall-roof interaction.

5.8- Proposed Interventions

The interventions suggested in the following are intended to overcome the above shortcomings in order to upgrade the earthquake resistance of the building in a manner that would allow its reuse in accordance with its structural characteristics. However, as the building is considered to form part of the architectural heritage of Athens, the proposed interventions are also intended to satisfy the code performance structural requirements without affecting the architectural character of the building. The proposed interventions include:

- Improvement of the mechanical properties of the masonry through mortar grouting.
- Internal and external bracing at the level of the ground floor and construction of new 0.25 m thick concrete slab
- Strengthening of the floor beams of the 1st level with side blades/plates and reconstruction of the floor through the use of two crisscrossing layers of plywood so as to form a strong diaphragm connected to the supporting peripheral walls with diagonal metal blades

- Replacement of the existing roof with a roof of the same morphology, bracing of the supporting wall crowning with a layer of reinforced concrete, and development of diaphragmatic action through the use of metal rods in crisscrossing arrangement.

In what follows, the methods proposed for materializing the above interventions are provided.

5.8.1 Strengthening of structural behaviour

A wide variety of intervention techniques can be considered for repairing and/or strengthening masonry structures that have suffered damages due to overload, ground settlement, temperature variation, earthquake etc. A rough distinction can be made among the traditional and the modern ones. Traditional techniques employ the materials and building processes used originally for the construction of the structure. Modern techniques aim at more efficient solutions using innovative materials and technologies.

5.8.2- Strengthening through grout injection

This is particularly suited for the rehabilitation of the masonry that has internal interconnected cracks. The injection of the grout is made through tubes placed in holes drilled throughout the wall surface. For the external cracks the coating should be previously removed. Fig. 5.79 shows processes of drilling and grouting, whereas Fig. 5.80 shows a schematic representation of the location of the injection tubes.



Figure 5.79: Process of drilling (left) and grouting (right)

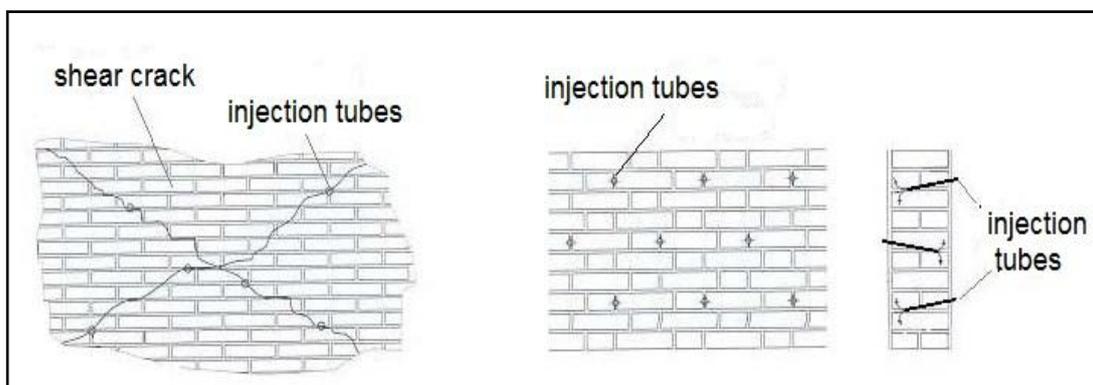


Figure 5.80: Schematic representation of location of injections

5.8.3. Strengthening through reinforced cement paste coating

Thin layers of cement paste coating 10 mm thick reinforced with a steel mesh connected to the walls with transverse anchoring rods will be placed on either side of the walls as indicated in Fig. 5.81



Figure 5.81: Steel mesh of cement paste coating

5.8.4- Strengthening of the floor beams

Best practice in old buildings is to conserve the old floor boards and patch repair them locally as necessary. Floorboards should only be replaced where repair is impossible. Replacement timber should match the existing timber both in species and in manner of conversion, which will allow the quality and grain also to match. Considerable care may need to be taken when relaying old floorboards. Boards should generally be re-fixed in their original positions with nails.

A composite steel–concrete slab placed over a grid of steel beams which are pinned to the masonry walls. A slab with a total thickness of 0.10 m of concrete was considered over steel sheeting 0.75 mm thick. The composite slab is supported by HEA200 steel beams placed 2 m apart, which are supported by HEA300 beams. This solution has the advantage of being lighter than the previous one, with a weight of 2 kN/m².

5.9-Verification of proposed interventions

The structural assessment of the building after the implementation of the proposed interventions was based on linear finite-element analysis through the use of the commercial package ETABS. The masonry was modelled by using three- and four-node shell elements with six degrees of freedom per node, beam elements were used to model the linear elements of the proposed diaphragm system, and truss elements for modelling the roof structure. More details regarding the modelling of the building are provided in Kotsovos 2013 where the full results obtained are also presented.

In what follows it is only intended to demonstrate the effectiveness of the proposed interventions in preventing damage such as that described in the preceding sections. In order to achieve this objective it is considered sufficient to present a

graphical representation of the intensity of the internal stresses developing in the masonry under the code specified loading conditions.

Figs. 5.82 and 5.83 present the values and locations of the principal tensile stresses, in excess of those that can be sustained by the masonry, developing in the walls of the 1st level of the building in the two perpendicular directions y-y and x-x, respectively.

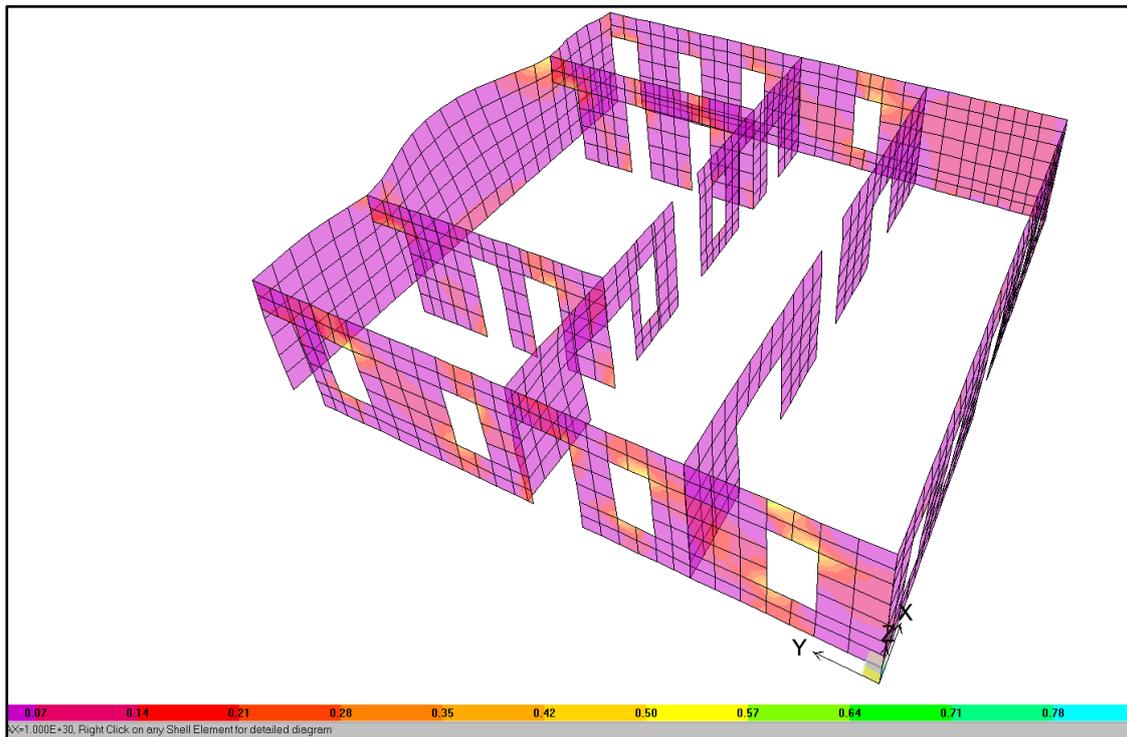
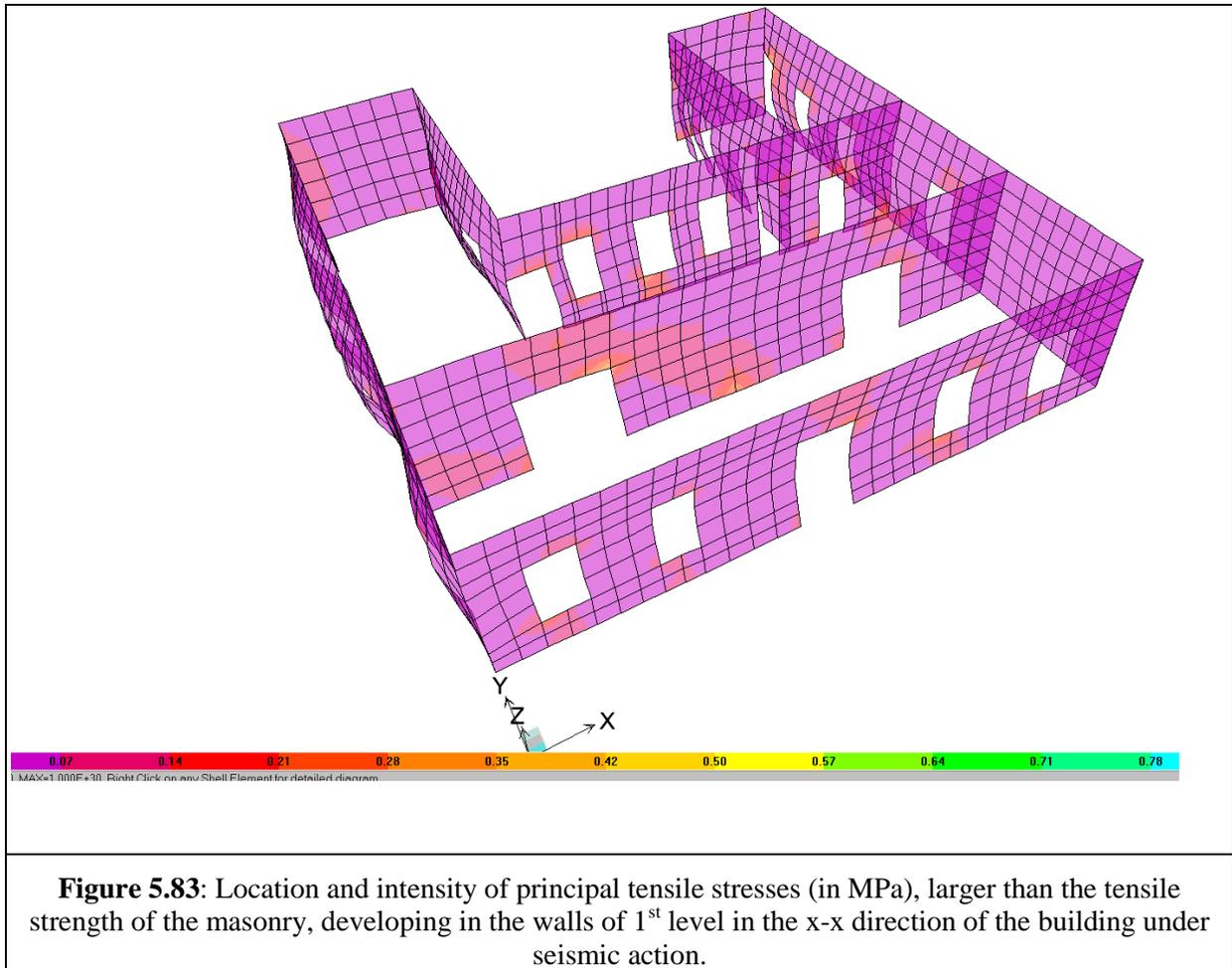


Figure 5.82: Location and intensity of principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of 1st level in the y-y direction of the building under seismic action.

On the other hand the values and locations of the principal tensile stresses, in excess of those that can be sustained by the masonry, developing in the walls of the ground floor are shown in Figs. 5.84 and 5.85. Comparing the results of Figs. 5.75 to 5.78 with those which shown in Figs. 5.82 to 5.85 shows that the intensity of the tensile stresses developing in the rehabilitated building is significantly reduced.

These stresses in excess of those that can be sustained by the masonry are sustained by the mild reinforcement of the coating which is provided in an amount sufficient for this purpose.



Figs. 5.86 and 5.87 show the location and intensity of the principal compressive stresses developing in y-y and x-x directions, respectively of the walls of the building under seismic action. The figures indicate that in all cases the intensity of the compressive stresses is small than the compressive strength of the masonry

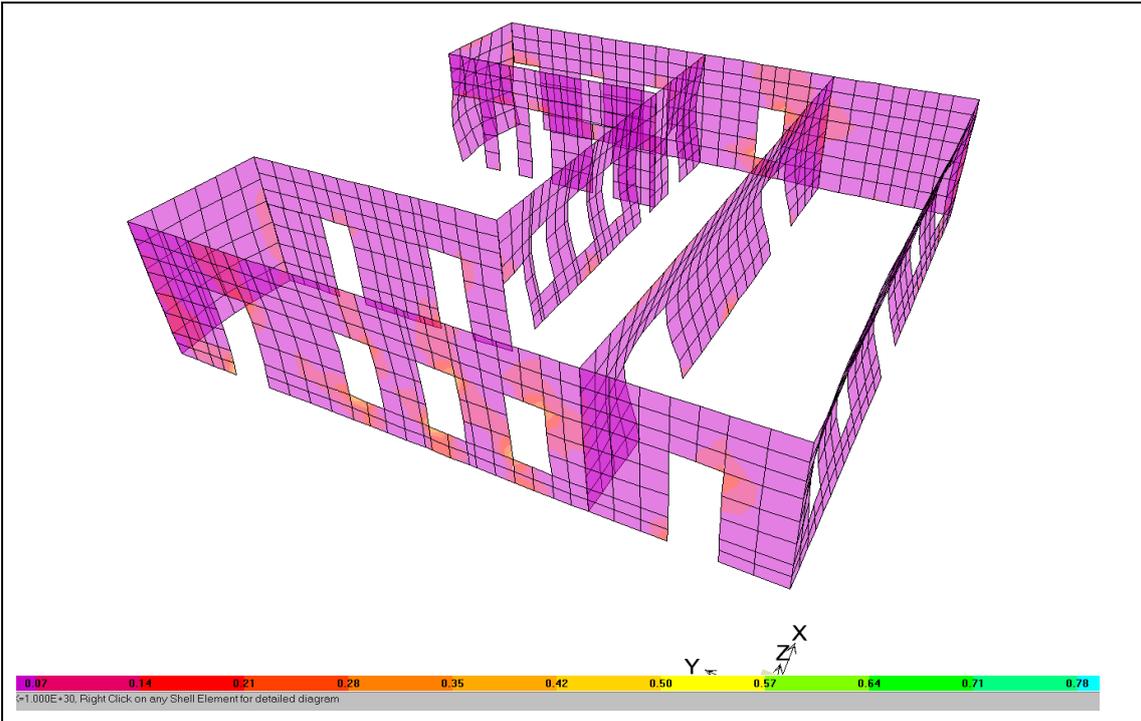


Figure 5.84: Location and intensity of the principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of ground level in the y-y direction of the building under seismic action.

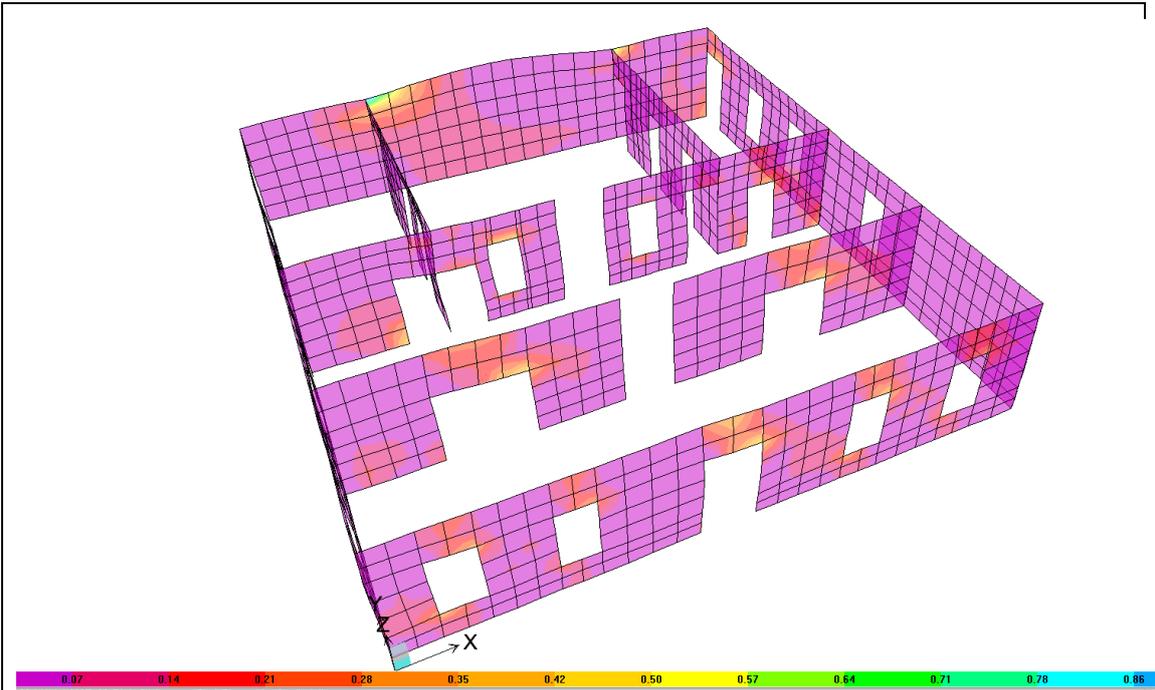
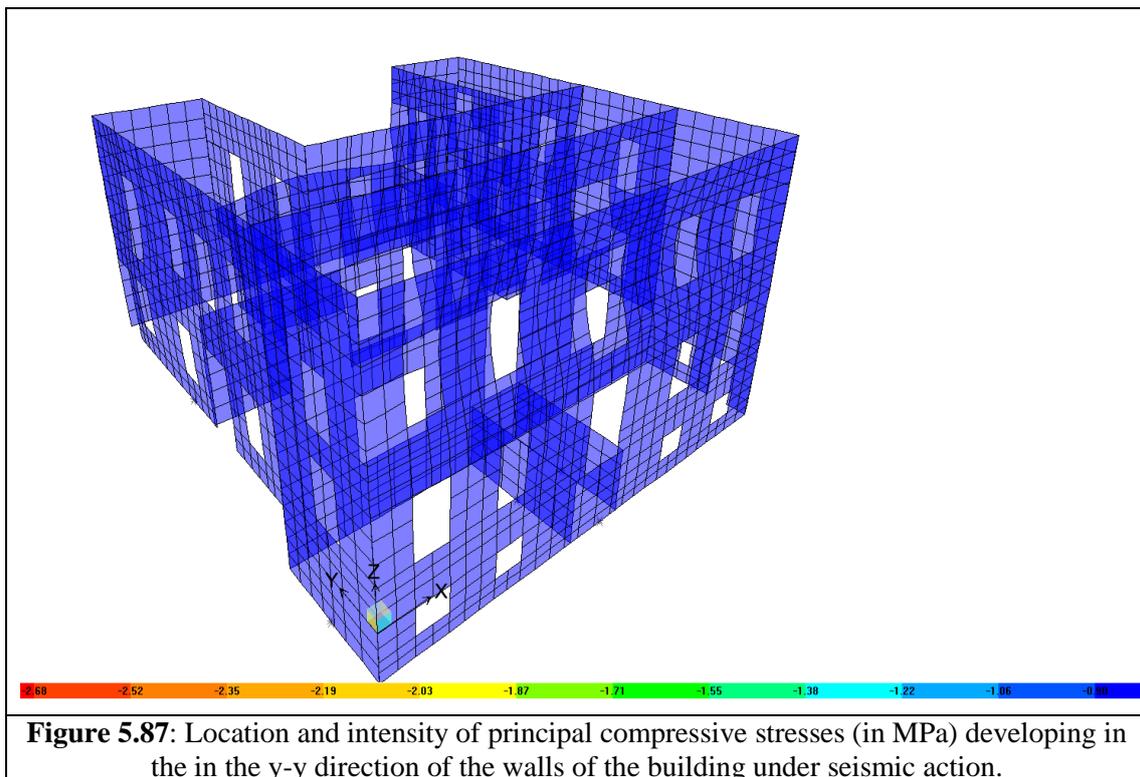
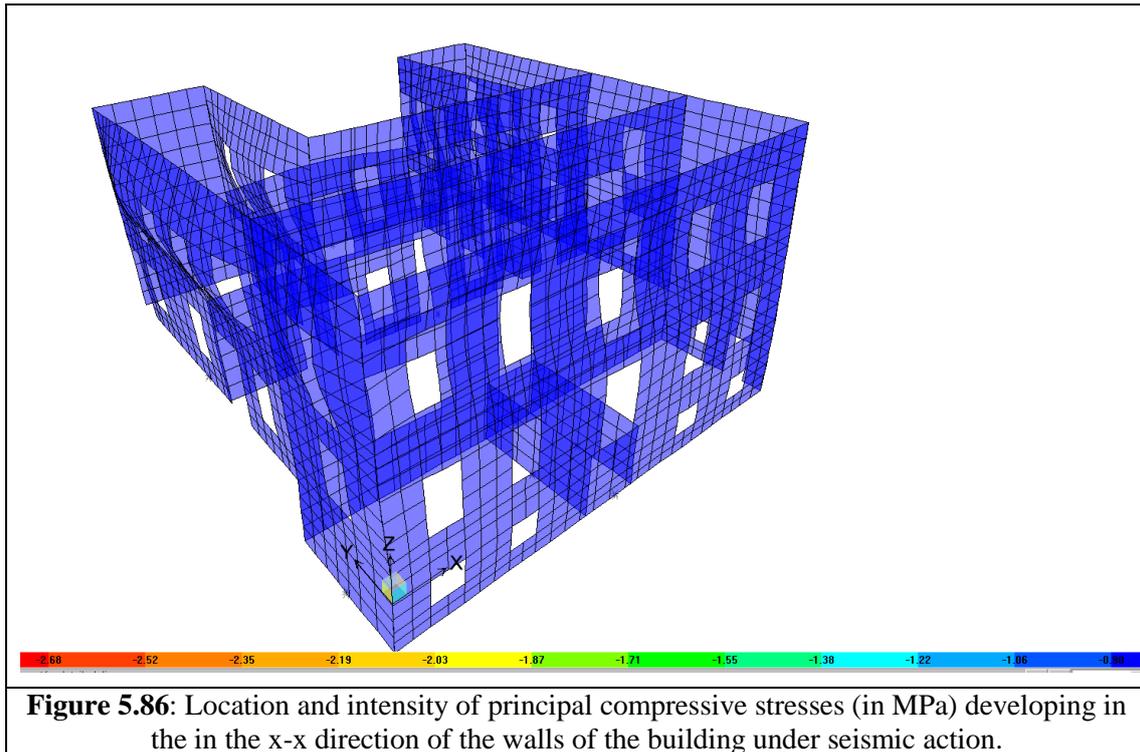


Figure 5.85: Location and intensity of principal tensile stresses (in MPa), larger than the tensile strength of the masonry, developing in the walls of ground level in the x-x direction of the building under seismic action.



Concluding Remarks

- Aktaiou building was built in the late 18th/early 19th century and it is considered to represent the structural and architectural trends prevailing in Athens this period.
- Aktaiou building is a two-storey masonry building with basement. The bearing walls forming part of its structural system were built with inert semi-chiseled stones (limestone, marble, and volcanic stone) bound together with mortar in two interlocking layers.
- The damage suffered in Aktaiou house as a result of aging, construction faults, lack of maintenance, seismic and environmental actions was mainly inclined and vertical cracking with a relatively small width not extending throughout the wall thickness, fragmentation of masonry mortar, extensive detachment and loss of wall plaster, large deflections of the bearing members of the roof structure, and collapse of timber balconies.
- From the observed damage of the building and the identified it appears that the significant shortcoming of Aktaiou building is the lack of diaphragmatic action at the levels of floors and roof that would contribute to the monolithic response of the building under seismic excitation. Another shortcoming is the lack of transverse walls connecting the two parallel long bearing walls along the façade of the building in Aktaiou Street; the lack of such walls increases the likelihood of out-of-plane displacements of the bearing walls. Finally, the lack of bracing at the wall crowning has a negative effect at the bearing wall-roof interaction.

- Limestone, marble and volcanic stone are the main building materials of the Aktaiou building, whereas lime-mud-pozzolanic mortar was used as binding material.
- Timber floors construction by wooden beams simply-supported at the opposite walls, whereas the roof is supported by a simply-supported truss system. The roof of the central part is two-way supported and comprises single and double slope trusses
- The structural walls have a width varies from 0.5 m up to approximately 0.7 m. They were built with inert semi-chiselled stones "marble, limestone, and volcanic stone" bound together with mortar, in two interlocking layers.
- The connection between the main bearing walls was effected not only through the use of large lime-stones (corner stone's), but also through the use of steel connectors.
- A large proportion of amorphous phase is recorded by the XRD analysis in volcanic stone samples, while the main detected mineralogical phases were quartz, alunite, dolomite, and calcite. The main mineral phase characterized by XRD to marble is that of calcite. Other recorded phases are those of quartz, muscovite, clinocllore, and anorthite, but it is estimated that they exist at a low quantity level. The main mineralogical phase in limestone is dolomite and the secondary is calcite. As far as the masonry mortar is concerned, XRD and optical microscopy were used in order to mineralogical characterize the sample and to assume whether or not a lime-pozzolan mortar was used for the masonry construction.

- The average compressive strength established from compression tests on marble, limestone and volcanic stone samples was 23.2 MPa, 31.7 MPa, and 5.3 MPa, respectively
- the most critical locations of the cracking are expected to be on either of the side regions of the top edge of wall 1 (façade in Aktaiou Street); in fact, at the right-hand side region cracking is predicted to occur at the joint of wall 1 with wall 3.
- Cracking is also predicted to occur at the bottom corners of the main entrance in Aktaiou Street. Cracking similar to that of wall 1 is predicted to be suffered by walls 5 and 6 (walls parallel to wall 1). As for the case of wall 1, they are predicted to occur on either side of the top edge of the walls, as well as at the bottom corners of the doors.
- Under seismic excitation in the x-direction, the internal walls are found likely to suffer cracking in the region of the diametrically opposite corners of door and windows; in fact that the largest tensile stresses develop at such locations of the doors and windows to the backyard of the building enclosed by walls 6, 4, 7 and 8.
- The seismic excitation orthogonal to walls 1, 5 and 6 causes out-of-plane displacement of the walls in the form of bending of their top edge (due to insufficient roof diaphragm) and, therefore, tensile stresses at mid-length which are likely to cause flexural cracking.
- It can be seen that allowing for diaphragmatic action at the levels of the floors and roof leads to a significant reduction of not only the values of the principal tensile stresses developing in the masonry walls, but also of the locations at which these values are larger than the tensile strength of masonry. In fact,

diaphragmatic action is found to reduce the out-of-plane displacements of the walls to such an extent that cracking as a result of such displacement seems unlikely. Moreover, since allowing for diaphragm action also causes conditions of bracing at the levels of the floors and roof, the values of the tensile stresses developing at these locations due to the lack of bracing reduce well below the tensile strength of masonry.

- Tensile stresses exceeding the masonry strength are found to develop at the diametrically opposite corners of the openings (doors and windows). Smaller tensile stresses are also found to develop diagonally within the walls under the action of in-plane horizontal loading.
- It is possible to minimize the structural deficiencies in Aktaiou house; though modifications intended to combine bracing with diaphragm action at the levels of the floors and roof. Moreover, the timber beams of the 1st level floor will be strengthened (or replaced wherever necessary) and anchored with metal rods penetrating the walls and forming anchors at their external side.
- As regards safeguarding diaphragm action at the level of the roof support, this is achieved through the use of diagonally arranged steel elements, whereas at the 1st level it is considered sufficient to stiffen the timber floor with two layers of criss-crossing plywood.
- However, as discussed in 4.3.2, in spite of the above modifications, the development of tensile stresses larger than the tensile strength of concrete cannot be prevented in localised regions of the walls. In such locations cracking may be minimised, or even prevented, if the tensile strength of the masonry is improved. The latter can be achieved through grouting that will also restore the continuity of the masonry which was disrupted by the

formation of cracking. Alternatively (or concurrently), the walls may be covered both internally and/or externally with a suitable reinforced coating (steel mesh).

References

- 1- Charkiolakis N. , Aggeliki Koumna A., Leni M, Manos Mikelakis, Maria Psallida 2008 "Traditional Environmental Architecture in re-use: The "Courtyard of Miracles" in Athens, Greece" WSEAS Transactions on environment and development Issue 11, Volume 4, November
- 2- Octavian G. Dului, Maria Nicoleta Grecu, and Corina Cristea 2009 "EPR and X-RAY Diffraction investigation of some Greek marbles and limestones" Romanian Reports in Physics, Vol. 61, No. 3.
- 3- Tassios T, Chronopoulos V., 1987"Retrofit-Strengthening/Calculation Examples, Technical Chamber of Greece, Athens (in Greek) 1987.
- 4- wikipedia.org/wiki/Plaka

6

CONCLUSIONS

Conclusions

- Historic masonry buildings, whatever use is made of them at present or in the future may belong to the following categories, depending on the use of the building (i) isolated and non accessible buildings, (ii) buildings belonging to the urban area, (iii) buildings open to the public, and (iv) buildings open to large assemblies of people (cathedrals, theatres, etc.).
- Historic traditional masonry is a form of architecture built using local resources, which covers materials, techniques and the skills of its constructors.
- Traditional ways of building have evolved, one person learning from another. Changing circumstances have led to changing solutions with influences from other cultures having gradually been blended in.
- Traditional masonry houses are found in urban and rural areas around the world. There are broad variations in construction materials and technology, shape, and the number of stories. In hilly Mediterranean areas the number of stories varies from two (in rural areas) to five (in urban centers).
- Historic traditional urban residential masonry buildings in Greece are usually made of rubble (cobble) natural stones and a large volume of low strength lime mortars, while their floors/roofs are made of timber elements.
- Traditional houses in Athens are typically found in flat, sloped and hilly terrain. They do not share common walls with adjacent buildings. The typical separation distance between buildings is 5 meters.
- Historic traditional houses in Athens have at least eleven openings per floor, of an average size of 3.5 m² each. The estimated opening area to the total wall surface is 18%. This is relevant to the resistance of this type of building. The

main function of this building typology is single-family house. It is very common to find these historic buildings used for commercial purposes.

- Field observations made during the initial reconnaissance and the subsequent damage surveys of numerous cases to historic traditional masonry buildings in Athens have demonstrated the importance of anchor connections joining masonry walls or parapets with roof or floor elements. It was realized that the techniques used for this purpose provided some seismic protection; the builder used three types of connection techniques developed by local craftsmen for connecting structural elements (wall-to-wall, and roof-to-wall).
- Historic Cairo is an urban ensemble that extends from street to alley to lane and covers a large number of historic buildings range from religious structures such as mosques and churches, to residential structures such as palaces and houses (*manazels*).
- Traditional dwellings were an integral part of the traditional urban fabric of Cairo city. The houses of rich and poor were adjacent within the neighborhood unit, without caste or social discrimination. However, a common feature of most historic traditional buildings is that they contain soft, weak or permeable materials, such as lime mortars, plasters, renders and paints.
- The environmental and morphological characteristics of the site determine the shape and orientation of historic traditional houses in Cairo.
- The architectural components which governed the design concept of Cairo houses and highlighted its distinctive characteristics were the *majaz* (entrance), the courtyard, the *The Qa'ah* (sitting hall), the *malqaf* (sky open), the *takhtabush* (terrace), and the *mashrabiyyah* (balcony).

- The results of this study found that there is mutual or common construction and structural characteristics in historic traditional masonry houses in Athens and historic traditional masonry houses in Cairo. this mutual characteristics including, the inside courtyard, the use of large limestone, the huge number of living rooms in every floor, they usually design the first floor as the high elevation more than other floors (second floor and third floor if found), the use of first floor as commercial shops.etc.
- On the other hand there are some differences between the historic traditional houses in Athens and Cairo for example in Athens the main entrance of the house is direct entrance but in Cairo house the entrance is bent entrance, in Athens house they uses a lot of large windows overlooking the outside streets but in Cairo house they used mashrabiya, also in Athens house they didn't separated the men rooms from women rooms but in Cairo houses they separated the women rooms far away the men or visitors rooms, etc.
- Walls in historic traditional masonry are generally uniformly distributed in both orthogonal directions with thickness ranging from 400 mm to 700 mm, made of undressed rubble stone and semi fired and fired brick in mud/lime mortar and most of them have not any formal training.
- Stone masonry walls can be classified into three types: un-coursed random rubble stone, un-coursed semi-dressed stone, and dressed stone
- Floor and roof structures in historic traditional masonry construction utilize a variety of construction systems and materials. The choice is often governed by the regional availability and cost of materials, and local artisan skills and experience.

- Most of historic cities are facing problems with a high number of masonry buildings in deteriorated conditions, some of them presenting a severe risk of collapse, not only because of neglect in care but also due to damage by recent earthquakes.
- Structural and architectural damage occurs when the stresses due to the action or effect of external forces exceed the strength of the materials at locations of significance for structural integrity, either because the actions/forces themselves increase beyond expected limits or because of building materials deterioration.
- In an unreinforced masonry building, resistance to horizontal actions is only accomplished by the stone masonry walls. This material has good behavior for compression (generated by vertical loads, such as the gravity loads); nevertheless, under horizontal actions, bending moments are generated which produce tensile stresses in the masonry.
- The tensile strength is only achieved by the compression state associated to gravity loads and mortar strength. The latter may have already lost part of its bonding properties through the years, due to lack of preservation.
- When tension due to bending exceeds the vertical compression, net tensile stress will occur, if the building material is weak in tension such as brick or stone masonry, cracking occurs which reduces the effective area for resisting bending moment.
- The connection between structural components is important for maintaining building integrity. Integrity is absent or inadequate when the walls are not connected at their intersections and there are no ties or ring beams at the floor and roof levels.

- Historic traditional buildings usually undergo many types of conversion such as making new openings for ventilation or removing a column or pillar or even a wall from the building. As a result of such modifications the buildings are susceptible to serious damage to architectural aspects such as sweeping and bulging of facades resulting from the removal of orthogonal walls or large openings in these walls.
- Damage to masonry structures usually takes the form of tension and /or shear cracks as a result of imposed deformation due to excessive lateral forces; alternatively, it may occur from incipient bursting due to buckling of ashlar or expansion of rubble fill in structures that consist of two ashlar faces/wythes with a core of rubble and mortar (all unintended gaps in masonry are usually referred to as cracks).
- Cracking occurs when the total imposed tensile strain on a material exceeds its tensile strain capacity; materials such as unreinforced masonry and concrete are brittle and have low tensile strain capacity.
- A preliminary in-situ survey to historic traditional masonry is useful in order to provide details on the geometry of the structure and the visible damages (cracks, out of plumb, material decay) also in order to identify the points where more accurate observations have to be concentrated.
- The analysis of ancient masonry buildings poses important challenges because of complexity of their geometry, the variability of the properties of traditional materials, the different building techniques, the absence of knowledge on the existing damage from the action which affected the masonry structures throughout their life, and the lack of codes.

- The level of the investigation should always be defined by careful design; investigation should be performed to choose more detailed and specific investigation in order to: check the reliability of hypothesis on damage causes and evolution, control the structure before, during and after the intervention, control the effectiveness of the repair and strengthening.
- Non-destructive Methods (NDM) can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests such as flat jack test, sonic test, Georadar etc.
- When masonry is damaged by aggressive agents the decay is never uniform; if maintenance is needed and only some bricks or stones or decorations are affected by the damage. In this case, laboratory tests can give useful information for the choice of the appropriate material for substitution.
- The main principle of restoration and conservation of historic buildings is to keep the building as original as possible, A wide variety of intervention techniques can be considered for strengthening and repairing of masonry structures that have undergone damages due to overload, ground settlement, temperature variation, natural calamities like wind, earthquake etc.
- There are a lot of methods used for strengthening historic masonry walls of houses in Athens and Cairo. These methods include: injection, reinforced cement coating (steel mesh), polypropylene mesh, the use of composite materials (CFRP and GFRP) etc.
- To perform an efficient seismic strengthening, it is necessary to guarantee the resistance of the existing structural elements, including walls and foundations.

It is also necessary to improve the floor characteristics so that they behave as stiff diaphragms, and therefore enable a better distribution of forces.

- The floor strengthening, to obtain stiff diaphragm properties, allows the reduction of the floor displacements and a more effective distribution of forces to the resistant elements. Among the proposed techniques, it is important to consider a solution with a composite slab and with steel ties.
- An earthquake-resistant URM building should have masonry interlocking between orthogonal walls, an effective connection between floors and walls through RC tie beams or steel ties, and floor systems with sufficient in-plane stiffness able to distribute horizontal seismic actions among walls.
- The distribution of horizontal seismic actions among walls induces the in-plane lateral loading of individual masonry walls, which typically suffer a concentration of damage. When pier and spandrel panels subjected to in-plane lateral loading, shear or flexural cracking can occur.
- In old diaphragm properties is essential to impose a global behavior of the structure. Its main advantage is to assume compatible horizontal displacements in every point of each floor and therefore to allow the distribution of the seismic forces in accordance to the stiffness of the resistant vertical elements.
- A common feature of traditional buildings is the large number of fireplaces, and resultant flues, in gable and cross-walls. When considering structural interventions it is necessary to ensure that any new openings or bearings introduced recognize the presence of existing voids and whether there is a need for viable flues. Failure to recognize the presence of flues can lead to instability of the walls. Another cause of instability is when floors have not

been properly tied into walls, a structural concept that was not always properly addressed at the time of construction.

- When assessing a historic building's suitability for a new use, the structural form, the structural elements (walls, foundations, framework, beams, lintels, floors, access stairs and roof structure) and the condition and suitability of materials must be assessed against the structural needs of the converted building.
- Changing the use of a building will require a thorough assessment of its structural configuration and condition in order to assess its ability to support the changes in loading that are likely to be imposed as a result of the proposed change of use.
- Aktaiou building was built in the late 18th early 19th century and it is considered to represent the structural and architectural trends prevailing in Athens this period.
- Aktaiou building is a two-storey masonry building with basement. The bearing walls forming part of its structural system were built with inert semi-chiseled stones (limestone, marble, and volcanic lightweight stone) bound together with mortar in two interlocking layers.
- The structural walls have a width that varies from 0.5 m up to approximately 0.7 m. They were built with inert semi-chiselled marble, limestone, and volcanic stone bound together with mortar, in two interlocking layers.
- Limestone, marble and volcanic lightweight stone are the main building materials of the Aktaiou building, whereas lime-mud-pozzolanic mortar was used as binding material.

- Timber floors are constructed on wooden beams simply-supported at the opposite walls, whereas the roof is supported by a simply-supported truss system. The roof of the central part is two-way supported and comprises single and double slope trusses
- The connection between the main bearing walls was effected not only through the use of large limestones (corner stones), but also through the use of steel connectors.
- The damage suffered in Aktaiou house as a result of aging, construction faults, lack of maintenance, seismic and environmental actions was mainly inclined and vertical cracking with a relatively small width not extending throughout the wall thickness, fragmentation of masonry mortar, extensive detachment and loss of wall plaster, large deflections of the bearing members of the roof structure, and collapse of timber balconies.
- From the observed damage of the building it appears that the significant shortcoming of Aktaiou building is the lack of diaphragmatic action at the levels of floors and roof. Another shortcoming is the lack of transverse walls connecting the two parallel long bearing walls along the façade of the building; the lack of such walls increases the likelihood of out-of-plane displacements of the bearing walls.
- A large proportion of amorphous phase is recorded by the XRD analysis in volcanic stone samples, while the main detected mineralogical phases were quartz, alunite, dolomite, and calcite. The main mineral phase characterized by XRD to marble is that of calcite. Other recorded phases are those of quartz, muscovite, clinocllore, and anorthite, but it is estimated that they exist at a low quantity level. The main mineralogical phase in limestone is dolomite and

the secondary is calcite. As far as the masonry mortar is concerned, XRD and optical microscopy were used and it proven that mud-lime-pozzolan mortar was used for the masonry construction.

- The average compressive strength established from compression tests on marble, limestone and volcanic stone samples was 23.2 MPa, 31.7 MPa, and 5.3 MPa, respectively
- the most critical locations of the cracking are expected to be on either of the side regions of the top edge of wall 1 (façade in Aktaiou Street); in fact, at the right-hand side region cracking is predicted to occur at the joint of wall 1 with wall 3.
- Cracking is also predicted to occur at the bottom corners of the main entrance in Aktaiou Street. Cracking similar to that of wall 1 is predicted to be suffered by walls 5 and 6 (walls parallel to wall 1).
- Under seismic excitation in the x-direction, the internal walls are found likely to suffer cracking in the region of the diametrically opposite corners of door and windows; in fact that the largest tensile stresses develop at such locations of the doors and windows to the backyard of the building enclosed by walls 6, 4, 7 and 8.
- The seismic excitation orthogonal to walls 1, 5 and 6 causes out-of-plane displacement of the walls in the form of bending of their top edge (due to insufficient roof diaphragm) and, therefore, tensile stresses at mid-length which are likely to cause flexural cracking.
- It can be seen that allowing for diaphragmatic action at the levels of the floors and roof leads to a significant reduction of not only the values of the principal tensile stresses developing in the masonry walls, but also of the locations at

which these values are larger than the tensile strength of masonry. In fact, diaphragmatic action is found to reduce the out-of-plane displacements of the walls to such an extent that cracking as a result of such displacement seems unlikely.

- Tensile stresses exceeding the masonry strength are found to develop at the diametrically opposite corners of the openings (doors and windows). Smaller tensile stresses are also found to develop diagonally within the walls under the action of in-plane horizontal loading.
- It is possible to minimize the structural deficiencies in Aktaiou house through modifications intended to combine bracing with diaphragm action at the levels of the floors and roof. Moreover, the timber beams of the 1st level floor will be strengthened (or replaced wherever necessary) and anchored with metal rods penetrating the walls and forming anchors at their external side.
- As regards safeguarding diaphragm action at the level of the roof support, this is achieved through the use of diagonally arranged steel elements, whereas at the 1st level it is considered sufficient to stiffen the timber floor with two layers of cross-crossing plywood.
- In spite of the above modifications, the development of tensile stresses larger than the tensile strength of concrete cannot be prevented in localised regions of the walls. In such locations cracking may be minimised, or even prevented, if the tensile strength of the masonry is improved. The latter can be achieved through grouting that will also restore the continuity of the masonry which was disrupted by the formation of cracking. Alternatively (or concurrently), the walls may be covered both internally and/or externally with a suitable reinforced coating (steel mesh).

7

Proposals for future work

PROPOSAL FOR FUTURE WORK

The research highlights on the importance of historic traditional masonry buildings in Athens-Greece and Cairo-Egypt in an attempt to make a comparative study to 17th, 18th and 19th historic traditional masonry houses in Athens-Greece and Cairo-Egypt. The comparative includes: history, structural development and architectural characteristics, building materials, and deterioration factors and phenomena; in addition, to propose some intervention methods for the rehabilitation of the historic traditional houses in order to restore and re-use them for cultural purposes.

Historic traditional masonry structures, as discussed in chapter 1, comprise many different buildings types ranging from traditional houses to palaces, and from shops to religious buildings etc. Thus, future work in the field of historic building restorations should involve the study of such buildings placing emphasis on damage assessment methods.

On the other hand, the present work concentrated on structural and architectural defects of historic traditional masonry structures which are usually exposed by seismic excitation, but there are many deterioration phenomena, besides those studied herein, which threaten structural integrity such as, for example, foundation failures, differential settlement and various urban factors (digging for Metro, Skyscrapers construction adjacent to historic traditional structures, in addition to the hazards of immigrants whom take the historic traditional houses as alternative home etc). Moreover, there are building material deterioration factors which include: underground water, salt florescence, bio-deterioration factors, damping rise, etc.

Also, other researches in the traditional masonry buildings restoration and conservation field should study the history, structural development, damage

assessment of traditional buildings older than that of the building investigated in the present work.

Finally, during our site visits to historic traditional masonry houses in Athens, Greece and in Cairo, Egypt, we observed that there is a huge number of collapsed traditional houses (partial or total collapse), and it is thought that future researches on the subject should focus on a comprehensive plan of rehabilitation aiming at the re-use of such building for cultural purposes.



Εθνικό Μετσόβιο Πολυτεχνείο (ΕΜΠ), Σχολή Πολιτικών Μηχανικών

ΑΠΟΤΙΜΗΣΗ ΒΛΑΒΩΝ ΚΑΙ ΑΠΟΚΑΤΑΣΤΑΣΗ ΙΣΤΟΡΙΚΩΝ ΠΑΡΑΔΟΣΙΑΚΩΝ ΚΑΤΑΣΚΕΥΩΝ

Εκτενής Περίληψη της Διδακτορικής Διατριβής στα Ελληνικά

Mohamed Mostafa Mohamed Abdelmegeed

Βοηθού Λέκτορα, Τμήμα Συντήρησης και Αποκατάστασης, Σχολή Αρχαιολογίας,
Πανεπιστήμιο Φαγιούμ, Αίγυπτος

Τριμελής Συμβουλευτική Επιτροπή

Μιχαήλ Δ. Κωτσοβός (επιβλέπων)

τέως Καθηγητής και Διευθυντής Εργαστηρίου Οπλισμένου Σκυροδέματος, Τομέας
Δομοστατικής, Σχολή Πολιτικών Μηχανικών, ΕΜΠ

Εμμανουήλ Βουγιούκας

Λέκτορας, Τομέας Δομοστατικής, Σχολή
Πολιτικών Μηχανικών, ΕΜΠ

Ευστράτιος Μπαδογιάννης

Λέκτορας, Τομέας Δομοστατικής, Σχολή
Πολιτικών Μηχανικών, ΕΜΠ

Αθήνα 2015

Σημασία Ιστορικής Παραδοσιακής Τοιχοποιίας και Λογική Αποκατάστασης

Διαποτισμένα με μηνύματα από το παρελθόν, τα ιστορικά μνημεία γενεών ανθρώπων παραμένουν μέχρι σήμερα ζωντανοί μάρτυρες των αιωνόβιων παραδόσεών τους. Έχει γίνει συνήθεια να χαρακτηρίζονται ως παραδοσιακά κτίρια όλα τα κτίρια που κατασκευάστηκαν χωρίς επίσημη διαδικασία σχεδιασμού. Η μορφή, το σχέδιο και η μέθοδος της κατασκευής τους απλά ακολουθούν μια παράδοση που αναπτύχθηκε με το χρόνο στον τόπο της κατασκευής τους. Η τοιχοποιία είναι μια ανομοιογενής κατασκευή που αποτελείται από φυσικούς ή τεχνητούς λίθους που συνδέονται μεταξύ τους με διάφορους τύπους κονιάματος και διατάσσονται είτε ακανόνιστα (λιθοδομή) είτε τακτικά (τοιχος).

Στα ιστορικά κέντρα της Αθήνας και του Καΐρου κυριαρχούν τα κτίρια τοιχοποιίας με τοίχους από λιθοδομή που αποτελούνται από πολλαπλά φύλλα, με ελάχιστη ή καμία σχέση μεταξύ τους, κτισμένα με διάφορα υλικά και κακής ποιότητας κονιάματα. Κονό χαρακτηριστικό των κτιρίων είναι η δίφυλλη ή τρίφυλλη φέρουσα τοιχοποιία στην οποία στηρίζονται ξύλινα πατώματα και οροφή.

Οι κατασκευές τοιχοποιίας είναι αυτές με τη μεγαλύτερη τρωτότητα και τη μεγαλύτερη ανάγκη για αποκατάσταση. Η τρωτότητά τους οφείλεται κυρίως στην μικρή εφελκυστική αντοχή τους και στην παντελή απουσία αντισεισμικού σχεδιασμού. Όμως, πολλά από τα ιστορικά παραδοσιακά κτίρια είναι έργα τέχνης και αποτελούν δείγματα της αληθινής ιδιοφυΐας των κατασκευαστών τους που αντανakλάται στα καινοτόμα αρχιτεκτονικά σχέδιά τους. Για το λόγο αυτό, η διατήρηση και η αποκατάσταση των ιστορικών κτιρίων απαιτεί μια καλή συνεργασία δομοστατικών, αρχιτεκτόνων και αρχαιολόγων/ιστορικών.

Αποκατάσταση παραδοσιακού κτιρίου μπορεί να επιτευχθεί με επιτυχία μόνο εάν η διάγνωση της κατάστασης των ζημιών του κτιρίου έχει προηγηθεί. Η ιστορία του κτιρίου και του περιβάλλοντος χώρου πρέπει να μελετηθεί διεξοδικά και να διερευνηθούν η αρχιτεκτονική του, οι μέθοδοι δόμησης και τα υλικά κατασκευής. Όλα αυτά αποτελούν το πρώτο, πολύ σημαντικό βήμα της διαδικασίας αποκατάστασης, το οποίο θα μπορούσε να οριστεί ως «κατανόηση του κτιρίου». Η διάγνωση ή δομική αξιολόγηση θα πρέπει να συμπεριλαμβάνει έρευνα τόσο στο χώρο του κτιρίου όσο και στο εργαστήριο. Επίσης, η αποτελεσματικότητα των τεχνικών επέμβασης θα πρέπει επίσης να ελέγχεται κατά τη διάρκεια και μετά το περας των εργασιών επισκευής.

Ο κύριος στόχος της αποκατάστασης των ιστορικών κτιρίων είναι να διατηρηθεί ο χαρακτήρας τους όσο το δυνατόν περισσότερο. Σε σημαντικό βαθμό, ο στόχος αυτός επιτυγχάνεται με την όσο το δυνατόν περιορισμένη αντικατάσταση των αρχιτεκτονικών χαρακτηριστικών τους με βλάβες. Εάν η αντικατάσταση είναι αναπόφευκτη, παρόμοια υλικά, κατά προτίμηση ταυτόσημα, με το αρχικά θα πρέπει να χρησιμοποιούνται. Κάθε κτίριο θα πρέπει να θεωρείται ότι αποτελεί ένα φυσικό αρχείο του χρόνου, του τόπου και της χρήσης του. Ως εκ τούτου, πρέπει να

αποφευχθούν αλλαγές που δημιουργούν μια ψευδή αίσθηση της ιστορικής εξέλιξης. Όλες οι μέθοδοι αποκατάσης που θα χρησιμοποιηθούν θα πρέπει να διαφυλάσσουν και να διατηρούν τον ιστορικό χαρακτήρα του κτιρίου και να τον μεταφέρουν στο μέλλον με τα αρχικά του χαρακτηριστικά.

Κεφάλαιο 1: Ιστορικές παραδοσιακές κατασκευές τοιχοποιίας: Ιστορία, Ανάπτυξη και δομικά στοιχεία

1.1 Τοιχοποιία ως κατασκευαστική τεχνική μέσα από την ιστορία

Η τοιχοποιία είναι ένα ανομοιογενές υλικό με δύο συστατικά στοιχεία: τα λιθοσώματα και το κονίαμα. Τα λιθοσώματα μπορεί να είναι φυσικά ή τεχνητά, συνδέονται μεταξύ τους με κονίαμα στους αρμούς με σχήμα ακανόνιστο, στη λιθοδομή, ή ευθύγραμμο, στους τοίχους με τεχνητούς λίθους (πλίνθους) (Lopez et al 1998, Pena 2004). Η τοιχοποιία είναι το παλαιότερο δομικό υλικό και εξακολουθεί να χρησιμοποιείται σε σύγχρονα κτίρια. Το πιο σημαντικό χαρακτηριστικό της τοιχοποιίας είναι η απλότητά της. Οι παράγοντες που επέβαλαν τη χρήση της ήταν κυρίως η τοπική κουλτούρα και η γνώση των υλικών και εργαλείων, καθώς και η διαθεσιμότητα των υλικών κατασκευής (Lourenço 1998).

1.2 Ιστορική παραδοσιακή τοιχοποιία

Έχει γίνει ευρέως αποδεκτό ένα κτίριο που κατασκευάστηκε χωρίς επίσημη διαδικασία σχεδιασμού να αναφέρεται ως παραδοσιακή κατασκευή τοιχοποιίας. Η μορφή, το σχέδιο και η μέθοδος κατασκευής του απλά ακολουθεί την παράδοση, το χρόνο και τον τόπο της σύλληψής του. Οι παραδοσιακοί μέθοδοι κατασκευής έχουν εξελιχθεί, με κάθε γενιά κατασκευαστών να μαθαίνει από την προηγούμενη. Μεταβαλλόμενες συνθήκες έχουν οδηγήσει σε εξέλιξη της μορφής των κατασκευών. Σε κάθε δεδομένη χρονική στιγμή, υπήρξαν κοινές αξίες, έθιμα, τοπικά υλικά και τοπική τεχνοτροπία (Oram και Stelfox 2004).

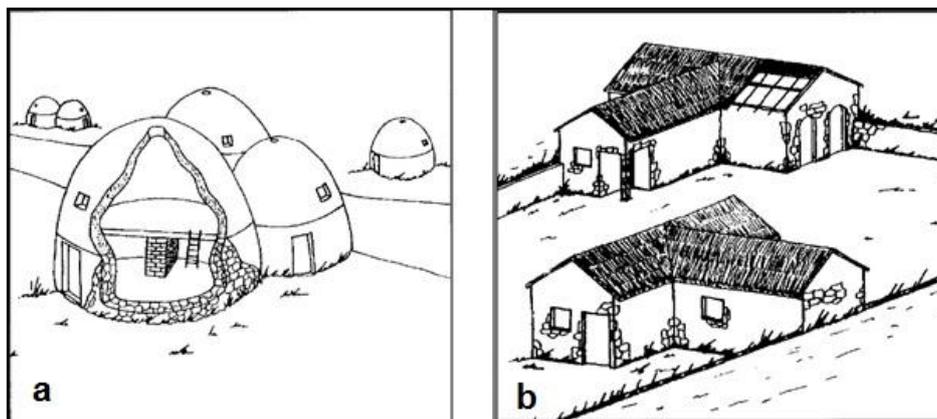
Οι άνθρωποι έχουν αναπτύξει τεχνικές οικοδόμησης άριστα προσαρμοσμένη στα διαθέσιμα οικοδομικά υλικά και τις τοπικές συνθήκες. Με την προσαρμογή στις τοπικές και κοινωνικές συνθήκες και τις απαιτήσεις θέσης, όπως, η τοπογραφία, το κλίμα, και άλλες περιβαλλοντικές συνθήκες, το, παραδοσιακό κτίριο, προσφέρει μια σειρά από πλεονεκτήματα καθώς και τα μειονεκτήματα (Dirlich 2004).

1.3 Εξέλιξη παραδοσιακής τοιχοποιίας στο χρόνο

Σε κάθε χώρα υπάρχει ένας μεγάλος αριθμός των ιστορικών κτιρίων από τοιχοποιία, που καλύπτουν όλο το εύρος των τύπων κτιρίων από αγροτικές κατοικίες μέχρι βασιλικά παλάτια και ναούς. Σε ένα τυπικό αγροτικό σπίτι από τοιχοποιία, υπάρχουν φέροντες τοίχοι από λιθοδομή χτισμένοι με στρογγυλές πέτρες και κονίαμα από λάσπη και ασβέστη. Οι τοίχοι είναι κτισμένοι με πέτρες τοποθετημένες με τυχαίο τρόπο, και ως εκ τούτου δεν έχουν τις συνήθεις στρώσεις (πατήματα) που παρατηρείται σε τοίχους από πλίνθους. Οι τοίχοι υποστηρίζουν βαριές στέγες (για παράδειγμα, ξύλινη στέγη με παχειά στρώση κεραμιδιών) (Lourenço 2002,

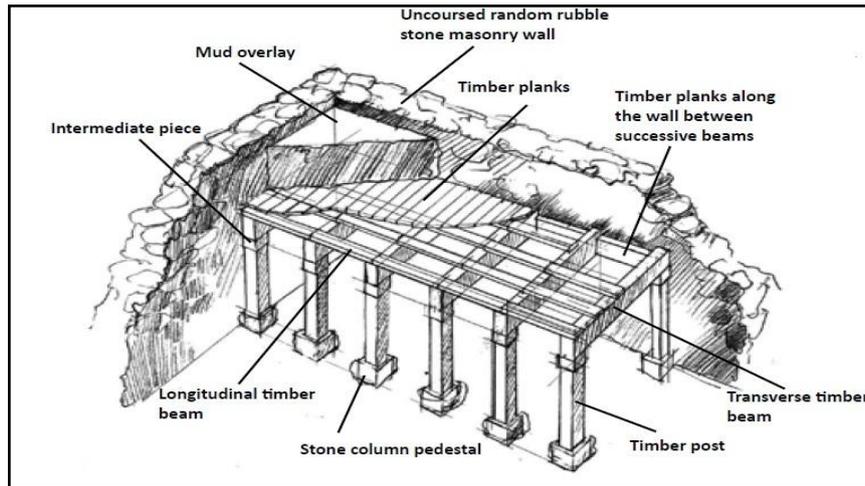
Casanovas 2007). Κτίρια από τοιχοποιία κτίρια μπορεί να βρεθούν σε πολλές σειсмоγενείς περιοχές και χώρες όπως η μεσογειακή Ευρώπη, η Βόρεια Αφρική, η Μέση Ανατολή και η Νοτιοανατολική Ασία (Bothara και Brzev 2011). Οι κατασκευές τοιχοποιίας μπορεί να διαιρεθούν σε δύο κατηγορίες που ικανοποιούν οικιακές και μη- οικιακές ανάγκες (Ομότιμος 1996, Thomas 1996).

Οι προσπάθειες της πρωτόγονης ανθρωπότητας να εξασφαλίσει προστασία ενάντι επιθέσεων περιλαμβάνουν αναζήτηση καταφύγιου σε σπηλιές, την εκμάθηση τρόπων κατασκευής σκηνών από φλοιούς, δέρματα, φρύγανα και καλυβιών από καλαμωτή μελάσπη. Μερικοί από αυτούς τους τύπους στέγασης εξελίχθηκαν σε σπίτια. Στην αρχαία Εγγύς Ανατολή, η εξέλιξη των κατοικιών ήταν από καλύβες σε σπίτια, αρχικά σχήματος «μελισσιού» (όπως φαίνεται στο Σχ. 1.1α) και, στη συνέχεια, ορθογώνια (όπως φαίνεται στο Σχ. 1.1β) (Lourenço 1998, Urquhart 2007). Τα ιστορικά παραδοσιακά σπίτια από τοιχοποιία βρίσκονται σε αστικές και αγροτικές περιοχές σε όλο τον κόσμο. Υπάρχουν ευρείες διακυμάνσεις σε δομικά υλικά και τεχνολογία, σχήμα και αριθμός ορόφων.



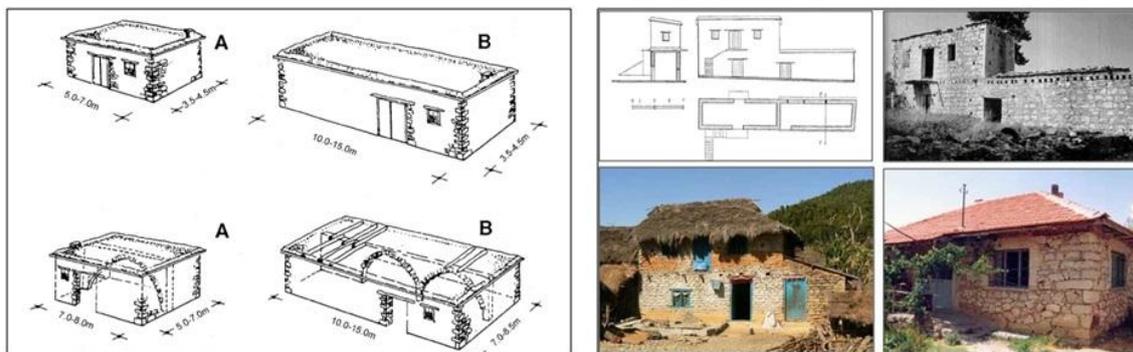
Σχήμα 1.1: α) Σπίτια σχήματος κυψέλης σε περιοχή της Κύπρου. β) Ορθογώνια κτίσματα από ένα χωριό στο Ιράκ (Lourenço 1998)

Τα σπίτια σε αγροτικές περιοχές είναι γενικά μικρότερα σε μέγεθος και έχουν μικρότερου μεγέθους ανοίγματα από τα σπίτια σε αστικές περιοχές που είναι συχνά μικτής χρήσης - εμπορική στο ισόγειο και κατοικία στους υπερκείμενους ορόφους. Σε λοφώδεις περιοχές της Μεσογείου, ο αριθμός των ορόφων κυμαίνεται από δύο (σε αγροτικές περιοχές) έως πέντε (στα αστικά κέντρα). Τα σπίτια από λιθοδομή χτίζονταν από τους ίδιους τους ιδιοκτήτες ή από τοπικούς κατασκευαστές, χωρίς καμία επίσημη κατάρτιση. Το σύστημα κατασκευής αποτελείται από μια δομή ξύλινη στέγη που υποστηρίζεται από ξύλινους στύλους και δοκούς και τοίχους από λιθοδομή στο εξωτερικό (βλ. Σχήμα 1.2) (Botharaka και Brzev 2011). Ο αρχιτεκτονική του κτιρίου βασίζεται στην επανάληψη μιας βασικής ορθογωνικής οικιστικής μονάδας με επίπεδη στέγη. Όπως φαίνεται στο Σχ. 1.3, η βασική μονάδα μπορεί να χρησιμοποιηθεί για να σχηματισθεί ένα μεγάλο μήκους δωμάτιο (το «μακρυνάρι») ή ένα σπιτιδίον συνεχών δωματίων που χωρίζονται από ένα θολωτό τοίχο που υποβαστάζει τη στέγη (Bothara και Brzev 2011).



Σχήμα1.2: Τυπικό κτίριο από λιθοδομή με εξωτερική πέτρινη τοιχοποιία και ένα εσωτερικό ξύλινο πλαίσιο (Bothera και Brzev 2011)

Στη συνέχεια, η διαδικασία της ανάπτυξης κατοικιών προχώρησε στο επόμενο στάδιο με τη μορφή απλών διώροφων κτιρίων, όπως το κτίριο που φαίνεται στο Σχ. 1.3. Το ισόγειο αποτελείται από δύο επιμήκεις αίθουσες με διαστάσεις 4×10m, και ο πρώτος όροφος αποτελείται από έναν ενιαίο χώρο, ο οποίος καλύπτει μόνο το ήμισυ του ισόγειου. Το σπίτι χτίστηκε από λιθοδομή και ασβεστοκονίαμα με άμμο. Η οροφή είναι σχεδόν επίπεδη, και καλύφθηκε με χώμα που παρέχει μόνωση (Αλεξανδρής et al., 2004).



Σχήμα1.3: Τύποι παραδοσιακών σπιτιών στην Κύπρο και Αθήνα. (Bothera και Brzev 2011, Αλεξανδρής et al., 2004)

Ακολούθησε επιτάχυνση της διαδικασίας ανάπτυξης, ιδιαίτερα στις αστικές παρά σε αγροτικές περιοχές. Υπάρχουν ευρείες διακυμάνσεις στη χρήση υλικών και τεχνολογίας, το σχήμα και τον αριθμό των ορόφων, όπως φαίνεται στο Σχ. 1.4

1.4 Ιστορικές παραδοσιακές κατασκευές τοιχοποιίας στην Αθήνα

Η φέρουσα τοιχοποιία των παραδοσιακών αστικών κτισμάτων/κατοικιών στην Ελλάδα είναι συνήθως κατασκευασμένη από φυσικούς λίθους – που ήταν το φθηνότερο υλικό που διατίθετο για την κατασκευή τοιχοποιίας κατά τον 17^ο και 18^ο αιώνα – και ένα μεγάλο σε όγκο, χαμηλής αντοχής ασβεστοκονίαμα, ενώ πατώματα και οι στέγες τους είναι ξύλινες. Τα τοιχώματα μπορεί να είναι «μονόφυλλα» ή «τρίφυλλα», στη δεύτερη περίπτωση με δύο διακριτά εξωτερικά φύλλα και υλικό

πλήρωσης με μεγάλο όγκο κενών. Το πάχος της τοιχοποιίας είναι μικρότερο ή μεγαλύτερο από περίπου 700 χιλιοστά για τα μονόφυλλα και τρίφυλλα, αντίστοιχα, τοιχώματα (Saatcioglu και Anderson 2004).

Σχήμα 1.4: Ιστορικά παραδοσιακά σπίτια σε ιστορικές πόλεις της Ελλάδας, Ιταλίας και Αιγύπτου



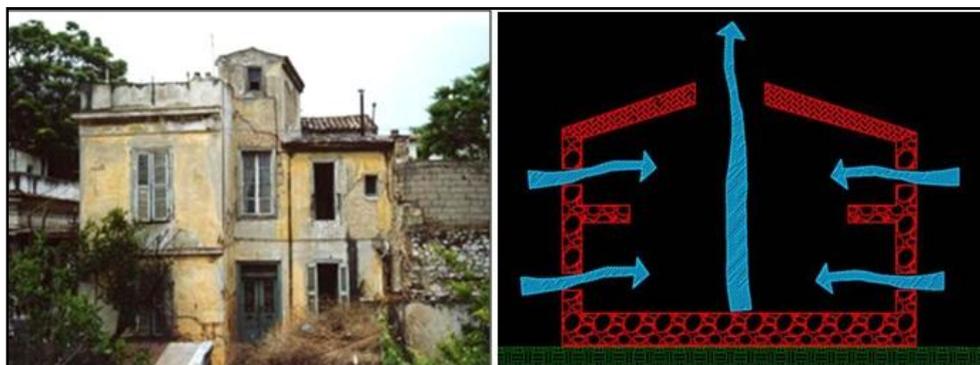
Επίσης, οικαιτικές έχουν πολλά χαρακτηριστικά που σχετίζονται με την επίδραση του περιβάλλοντος:

- Πλατιά κεραμίδια στερεομένα σε ένα παχύ στρώμα πηλού που εξασφαλίζει καλή μόνωση μαζί με το σανίδωμα της στέγης πάχους 0,04 μ.
- Κάθε όροφος είναι ιδιαίτερα υψηλός, περίπου 3,0 μ., ενώ τα παράθυρα είναι μικρών διαστάσεων. Η αναλογία αυτή επιτρέπει την ψύξη του σπιτιού το καλοκαίρι: θερμός αέρας ανεβαίνει στην οροφή, καθώς ψυχρός αέρας συνεχίζει να εισέρχεται από τα παράθυρα.
- Το δάπεδο είναι ανυψωμένο αρκετά, ώστε να δημιουργεί ένα κενό θερμικής μόνωσης μεταξύ δαπέδου και εδάφους (Χαρκιολάκης et al 2008).
- Η τοιχοποιία των κτιρίων αποτελείται από λίθους πάχους 0,60 μ περίπου. Το πάχος των τοιχωμάτων συμβάλλει σημαντικά στη μόνωση του κτιρίου. Η σοφίτα ή οροφή μπορεί να έχει μικρά ανοίγματα (φεγγίτες), ώστε ζεστός αέρας των εσωτερικών χώρων να ανεβαίνει φυσικά και να διαφεύγει από τους φεγγίτες (βλ. Fig. 1.6).



Σχήμα 1.5: Ιστορικά παραδοσιακά σπίτια. Διώροφες και τριώροφες κατοικίες με διαφορετικά υψόμετρα του πρώτου, δεύτερου και τρίτου ορόφου

- Τα κτίρια βρίσκονται ισυνήθως σε επίπεδη, επικλινή και λοφοβή εδάφη. Δεν μοιράζονται κοινούς τοίχους με τα γειτονικά κτίρια. Η τυπική απόσταση διαχωρισμού μεταξύ των κτιρίων είναι, κατά κανόνα, 5.



Σχήμα 1.6: Στρατηγικές εξαερισμού: μικρά ανοίγματα στη σοφίτα των κτιρίων (Χαρκιολάκης et al 2008)

1.4.1 Κόμβοι δομικών στοιχείων και τεχνικές σύνδεσης

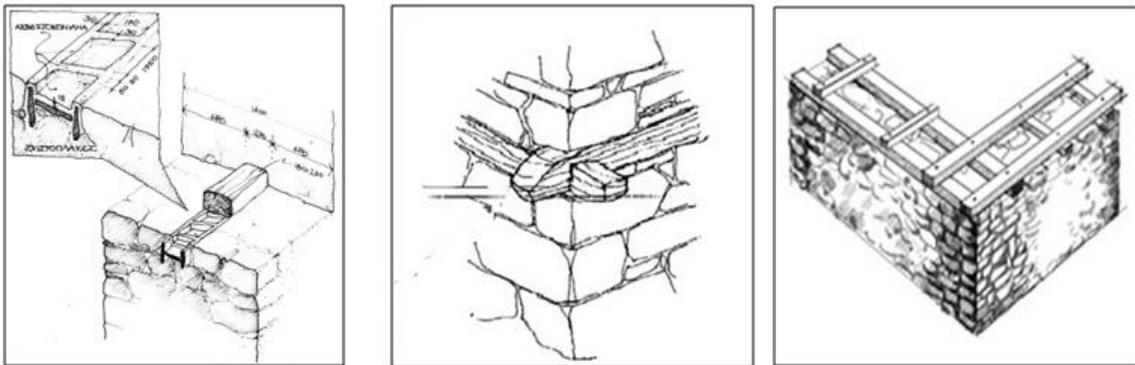
Επιτόπιες παρατηρήσεις κατά την αρχική αναγνώριση και μεταγενέστερες έρευνες ζημιών πολλών περιπτώσεων ιστορικών παραδοσιακών κατασκευών τοιχοποιίας κατέδειξαν τη σημασία των συνδέσεων του συστήματος που ενώνει τοίχους ή στηθαία με την οροφή ή τα δάπεδα. Έχει γίνει αντιληπτό ότι οι τεχνικές που έχουν χρησιμοποιηθεί για το σκοπό αυτό προσφέρουν κάποια αντισεισμική προστασία (Tondre 1999, Ambrose και Vergun 1999). Υπάρχουν τρεις τύποι τεχνικών σύνδεσης που αναπτύχθηκαν από ντόπιους τεχνίτες για τη σύνδεση δομικών στοιχείων (τοίχο με τοίχο και οροφή με τοίχο). Αυτές οι τεχνικές περιλαμβάνουν τη χρήση λίθινων συνδέσεων, ξύλινων συνδέσεων ξύλου και μεταλλικών συνδέσεων.

1.4.1.1 Λίθινες συνδέσεις

Στις παραδοσιακές τοιχοποιίες, μεγάλες λαξεμένες πέτρες από ασβεστόλιθο χρησιμοποιήθηκαν στις γωνίες, όπου μεγάλες συγκεντρώσεις τάσεων τείνουν να αναπτυχθούν, προκειμένου επιτευχθεί η κατάλληλη σύνδεση μεταξύ των τοιχωμάτων. Οι λίθινες συνδέσεις είναι θεμελιώδους σημασίας για τη μονολιθική συμπεριφορά της λιθοδομής, ειδικά σε περιπτώσεις τοιχοποιίας πολλαπλών φύλλων.

1.4.1.2 Ξύλινες συνδέσεις

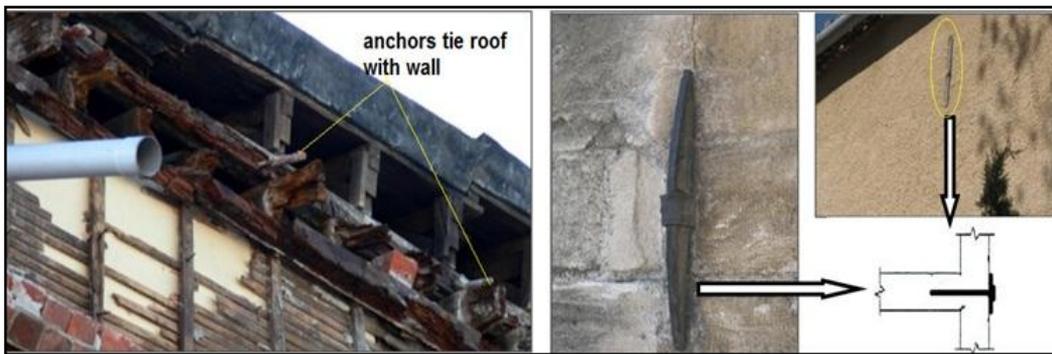
Τα ίχνη της χρήσης οπλισμού από ξυλεία σε κτίρια βρίσκονται σε πολυάριθμες κατασκευές (κατοικίες, εκκλησίες και πύργους). Ξυλεία χρησιμοποιείται ως ενίσχυση σε πολλά επίπεδα εντός του ύψους των τοιχωμάτων (τόσο σε διαμήκη όσο και εγκάρσια κατεύθυνση). Τα ορατά στοιχεία της ξυλείας χρησιμοποιούνται ως ελκυστήρες στα άκρα τόξων και θόλων, καθώς και στην τοιχοποιία κατά μήκος των περιμετρικών τοίχων με τη μορφή ξύλινων ελκυστήρων (βλ. Σχ. 1.7). Η αποτίμηση παραδοσιακών κτιρίων τοιχοποιίας που κατασκευάστηκαν μεταξύ 17^{ου} και 19^{ου} αιώνα έδειξε ότι έχει γίνει χρήση ξύλινου οπλισμού για την ενίσχυση της τοιχοποιίας με τον τρόπο που φαίνεται στο Σχ. 1.7 (Βιντζηλαίου 2011).



Σχήμα 1.7: Χαρακτηριστικά παραδείγματα χρήσης ξυλείας για την ενίσχυση τοιχοποιίας

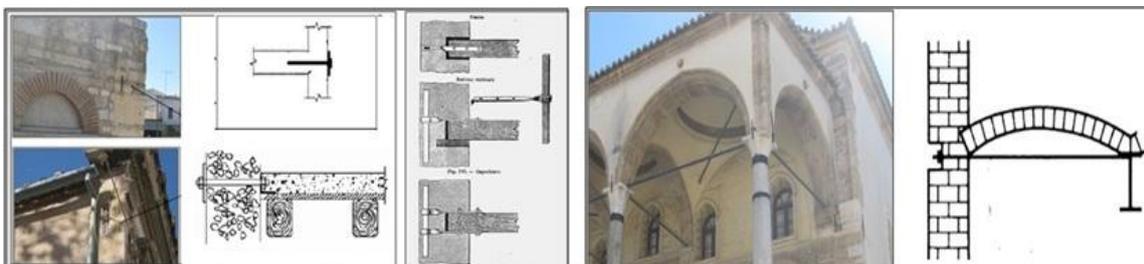
1.4.1.3 Μεταλλικές συνδέσεις

Μεταλλικές συνδέσεις χρησιμοποιήθηκαν για την εξασφάλιση έναντι αστοχίας κρίσιμων περιοχών της τοιχοποιίας, όπως γωνίες και συνδέσεις τοίχων-στέγης. Επιπλέον, χρησιμοποιήθηκαν κυρίως με τη μορφή καρφιού και ιμάντασε ξύλινες στέγες. Μεταλλικά άγκιστρα είναι ενσωματωμένα οριζοντίως στην τοιχοποιία σε βάθος ίσο με το πάχος τοιχώματος όπως φαίνεται στο Σχ. 1.8 (Dizhur et al 2011)..



Σχήμα 1.8: Μεταλλικοί σύνδεσμοι τοίχων-στέγης

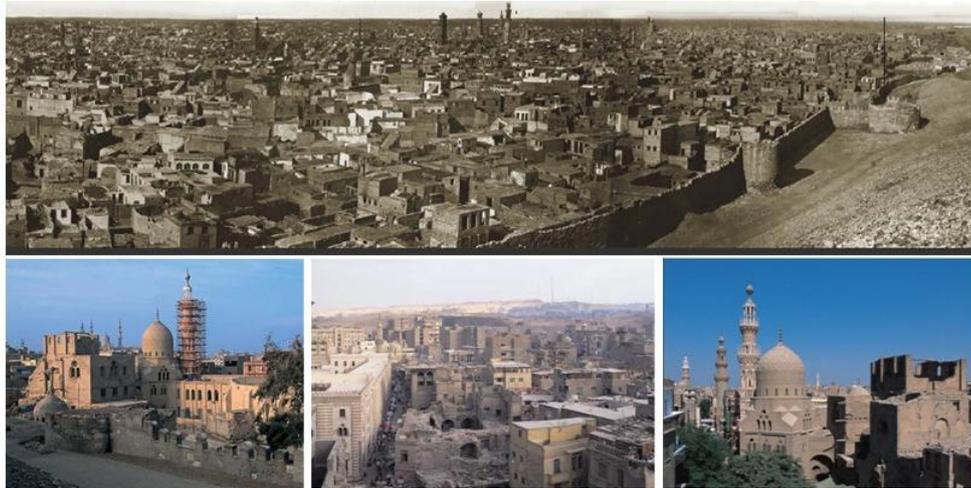
Στην παραδοσιακή τοιχοποιία, μεταλλικοί σύνδεσμοι χρησιμοποιήθηκαν επίσης για τη σύνδεση δαπέδων με τοίχους, ώστε να επιτευχθεί καλή συμπεριφορά υπό σεισμικές συνθήκες. Χαρακτηριστικοί τύποι μεταλλικών συνδέσμων φαίνονται στο Σχ. 1.9



Σχήμα 1.9: Μεταλλικοί σύνδεσμοι τοίχου δοκού και ελκυστήρες τόξων

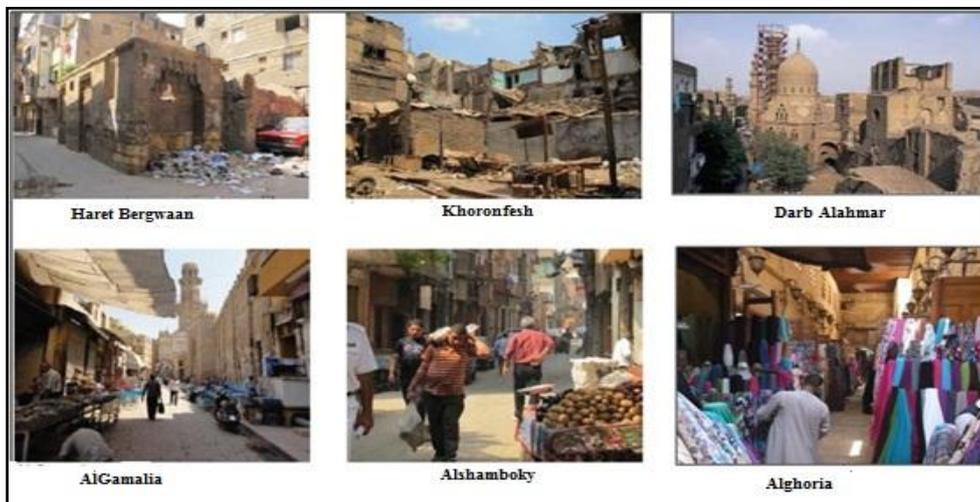
1.5 Ιστορική παραδοσιακή τοιχοποιία στο Κάιρο

Το Κάιρο θεωρείται μία από τις σημαντικότερες πόλεις παγκόσμιας πολιτισμικής κληρονομιάς στον κόσμο. Είναι η πόλη όπου η ιστορία έρχεται στη ζωή και όπου μαγευτικά αρχιτεκτονικά θαύματα αφθονούν, καθιστώντας την πόλη με το μεγαλύτερο σύμπλεγμα αρχιτεκτονικής κληρονομιάς στον κόσμο (βλέπει Σχ. 1.10) (Abdulmunim 2006).



Σχήμα 1.10: Χαρακτηριστικές ιστορικές του Κάιρου

Στο ιστορικό Κάιρο υπάρχουν ορισμένες ιστορικές εκφράσεις ή ιδιώματα, όπως, Darb (οδός), Hara (σοκάκι), Atfa (πλευρά σοκάκι) και Zuqaq (αδιέξοδο δρομάκι ή Cul- de-sac) (βλ. Σχήμα 1.11).



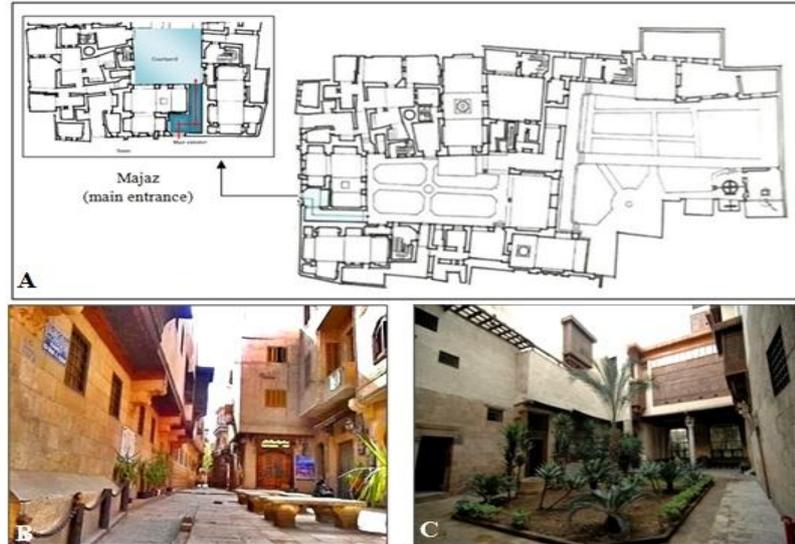
Σχήμα 1.11: Ιστορικοί δρόμοι και σοκάκια στο Κάιρο (UNESCO 2012)

1.5.1 Ιστορικές παραδοσιακές κατοικίες

Η κληρονομιά των παραδοσιακών σπιτιών περιλαμβάνει διάφορες μορφές, οι οποίες αναπτύχθηκαν σε απάντηση προς θρησκευτικούς, πολιτιστικούς και παραδοσιακούς παράγοντες μαζί με την ιδιαιτερότητα του τοπικού δομημένου περιβάλλοντος (Abdelmonem 2012). Ο ισλαμικός τρόπος ζωής επιδρά στο σχεδιασμό των

παραδοσιακών σπιτιών στο Κάιρο. Οι κοινόχρηστοι χώροι σε ένα σπίτι είναι ο τομέας των ανδρών, ενώ η προσωπική και οικογενειακή τομείς είναι τομείς γυναικών. Το κλίμα έπαιξε επίσης σημαντικό ρόλο ως εξισοροπιστικός παράγοντας και συμπλήρωσε την πολιτιστική και θρησκευτική ανάγκη για προστασία της ιδιωτικής ζωής (Salama 2006) (Abdelmegeed 2009).

Σχήμα 1.12: Κατοικία Al-Sehaimi: A – Κάτοψη και είσοδος (Majaz). B – Κύρια πρόσοψη. C - Αυλή

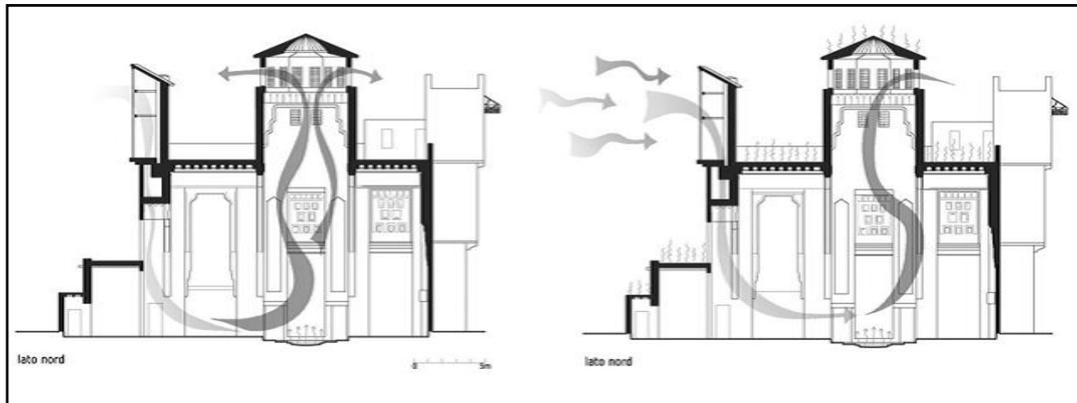


Το ισόγειο καταλαμβάνεται συνήθως από κουζίνες, αποθήκες τροφίμων ή πάγκους, σημεία εξυπηρέτησης και υποδοχής. Ο πάνω όροφος καταλαμβάνεται από κρεβατοκάμαρες, σαλόνια ή την υπηρεσία. Είναι σχεδόν εξ ολοκλήρου κλειστός για την υπεράσπιση από την εισοδο ξένων. Τα δωμάτια αυτά περιλαμβάνουν τα δωμάτια των γυναικών που διαχωρίζονται από εκείνα των ανδρών. Ο σχεδιασμός των δωματίων αντικατοπτρίζει το μοναδικό χαρακτήρα του σπιτιού του Καΐρου όπου η ηρεμία και η προστασία της ιδιωτικής ζωής είναι εγγυημένη από το αρχιτεκτονικό συγκρότημα.

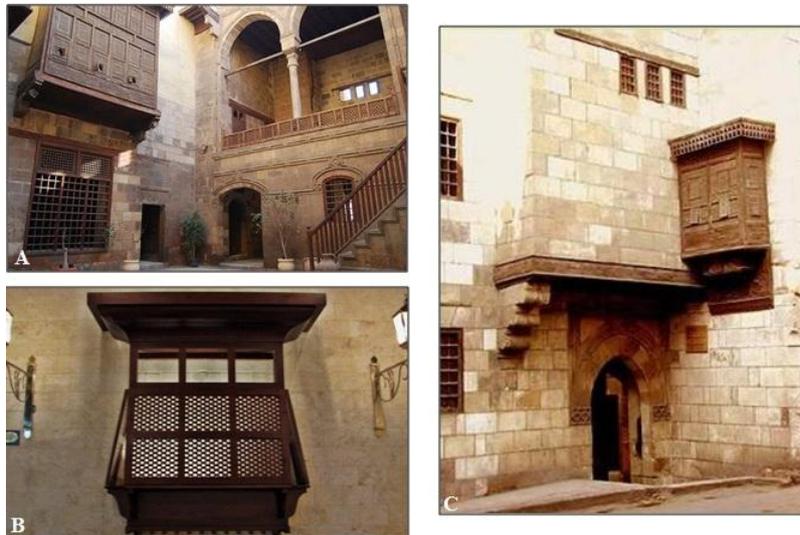
Σχήμα 1.13: A – Κατοικία Al-Sehaimi. B – Σαλόνι (qa'ah) στην κατοικία Al-Sennary. C– Κάτοψη της κατοικίας Al-Sehaimi που δείχνει την τράτασα (Takhtabosh)



Ωστόσο, τα αρχιτεκτονικά στοιχεία που χαρακτηρίζουν τη λογική σχεδιασμού του σπιτιού του Καΐρου είναι η είσοδος (Majaz), η αυλή, το σαλόνι(Qa'ah), τοαίθριο(malqaf), ηταράτσα (takhtabush) και τομπαλκόνι(mashrabiyyah) (βλ. 1.12. 1.13, 1.14, 1.15) (El-Shorbagy 2010)



Σχήμα 1.14: Διάγραμμα εξαερισμού (Malqaf) (Ficarelli 2008)



Σχήμα 1.15: Mashrabiya στην κατοικία Zeinab Khatoun

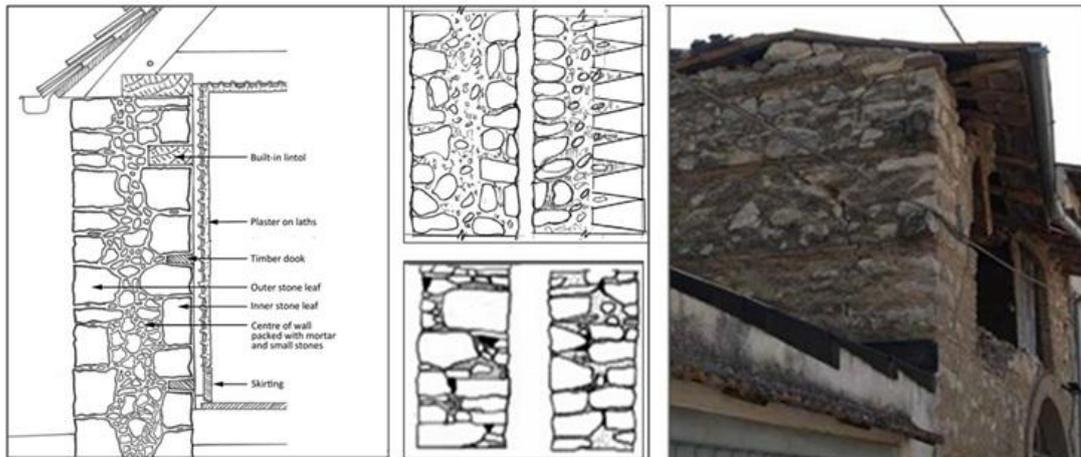
1.6 Δομικά στοιχεία

Υπάρχει μια μεγάλη ποικιλία υλικών και μεθόδων δόμησης των οποίων έγινε χρήση σε ιστορικά κτήρια. Εκτός από τις πιο κοινές μορφές κατασκευών, στους λίθινους τοίχους γλινεται χρήση ασβεστοκονιαμάτων, ενώ οι στέγες είναι κατασκευασμένες με σχιστόλιθο (Urquhart 2007).

1.6.1 Τοίχοι

Στην παραδοσιακή τοιχοποιία, οι τοίχοι μπορούν να ταξινομηθούν σε έναν από τους ακόλουθους τύπους: μονό-φυλλος, δύο-φυλλος ή τρί-φύλλος συμπαγής τοίχος (Vasconcelos et al 2006), τοίχος από un-coursed αργολιθοδομή, τοίχος από un-coursed ημι-λαξευτή και λαξευτή λιθοδομή (βλ. Σχήμα 1.16) (Bothara και Brzev 2011). Παρά το γεγονός ότι η παραδοσιακή τοιχοποιία μπορεί να θεωρηθεί ως ακατάλληλη για

κατασκευές που υπόκεινται σε σεισμικές δράσεις, συχνά αποτελούν τα πιο σημαντικά δομικά στοιχεία των αρχαίων κτιρίων (Bindaetal 2000).

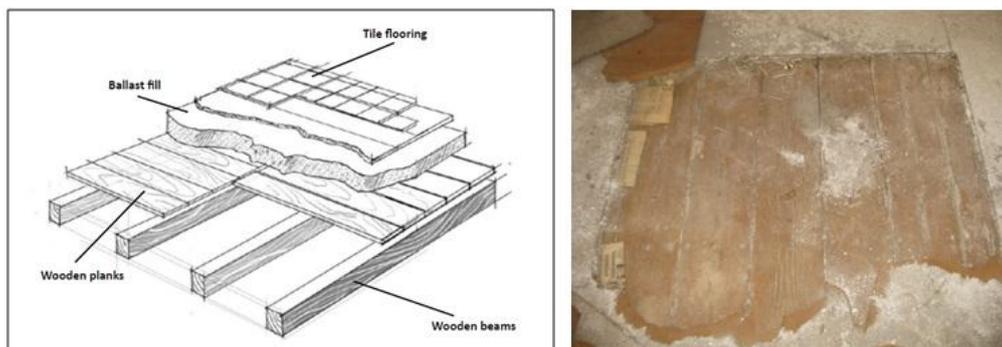


Σχήμα 1.16: Χαρακτηριστικοί τύποι τοιχοποιίας (BotharaandBrzev 2011)

Τοίχοι από ιστορική παραδοσιακή τοιχοποιία είναι γενικά ομοιόμορφοι και κατανομημένοι στις δύο ορθογώνιες κατευθύνσεις με πάχος τοιχώματος που κυμαίνεται μεταξύ 400 mm έως 700 mm. Πολλοί από τους τοίχους στην ιστορική παραδοσιακή τοιχοποιία είναι από αργολιθοδομή με λάσπη ή ασβεστοκονίαμα. Τέτοιοι τοίχοι χτίστηκαν από ντόπιους τεχνίτες ή από τους ίδιους τους ιδιοκτήτες, οι περισσότεροι από τους οποίους δεν είχαν καμία ιδιαίτερη κατάρτιση (World Housing Encyclopedia No 16).

1.6.2 Δάπεδα και Στέγες

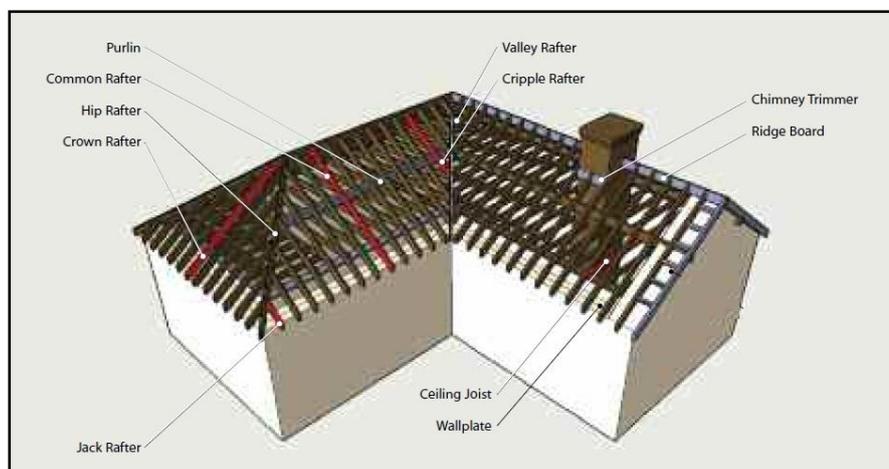
Για την κατασκευή δαπέδων και στεγών γίνεται χρήση ποικιλία μεθόδων και υλικών. Η επιλογή συχνά διέπεται από την τοπική διαθεσιμότητα και το κόστος των υλικών, και την εμπειρία και δεξιότητες των τεχνιτών. Οι φορείς δαπέδων και στεγών περιλαμβάνουν θόλους από τοιχοποιία και ξύλινες δοκούς ή δικτυώματα. Οι δοκοί συνήθως εδράζονται στους τοίχους, χωρίς οποιαδήποτε φυσική σύνδεση (World Housing Encyclopedia No 16). Χαρακτηριστικές λεπτομέρειες δαπέδων φαίνονται στο Σχ.1.17 (Bothara και Brzev2011).



Σχήμα 1.17: Κατασκευαστικές λεπτομέρειες δαπέδων

Η δομή και η μορφή των στεγών, καθώς και τα υλικά με τα οποία κτίστηκαν αλλάζει με την πάροδο των αιώνων ως αποτέλεσμα της εξέλιξης της τεχνολογίας και της

αρχιτεκτονικής με τη δίριχτη στέγη να είναι η συνηθέστερη (βλ. Σχήμα 1.18). Η κλίση της στέγης προσδιορίζεται από τα χαρακτηριστικά του υλικού επένδυσης και από την αρχιτεκτονική της κατασκευής. Διαφορετικά υλικά επένδυσης απαιτούνται για διαφορετικές κλίσεις ώστε να διασφαλίζεται η στεγανότητα και να μειώνεται η φορτία από την ανεμοπίεση (Donnelly, 2010).



Σχήμα 1.18: Περιγραφή στοιχείων του φορέα στέγης

Κεφάλαιο 2: Βλάβες και αίτια βλαβών ιστορικών παραδοσιακών κατασκευών από τοιχοποιία

Πριν από την έναρξη των εργασιών για τη συντήρηση και αναπαλαίωση των ιστορικών κτιρίων από φέρουσα τοιχοποιία, πρέπει πρώτα να αποτιμηθούν οι βλάβες και να μελετηθούν τα αίτιά τους (Mills 1998). Έτσι, η κατανόηση των αιτίων των βλαβών θεωρείται ότι είναι το πρώτο βήμα στη επιλεγθείσα διαδικασία συντήρησης και αποκατάστασης ενός ιστορικού κτιρίου από τοιχοποιία (Honeyborn 1998).

Σε ιστορικά παραδοσιακά κτίρια από τοιχοποιία, δομικές και αρχιτεκτονικές βλάβες συμβαίνουν όταν οι καταπονήσεις λόγω της δράσης εξωτερικών δυνάμεων υπερβαίνουν την αντοχή δομικών στοιχείων κρίσιμων για τη φέρουσα ικανότητα της κατασκευής ή όταν οι εξωτερικές δυνάμεις αυξάνουν πέραν αναμενόμενων ορίων ή λόγω φθοράς των δομικών υλικών. Οι βλάβες, που μπορεί να οδηγήσουν σε σημαντικές αλλαγές της λειτουργίας του φορέα, μέχρι και κατάρρευση (ICOMOS 2003), θεωρούνται ότι συνδέονται με τυχατικές δράσεις, όπως οι σεισμοί και οι πυρκαγιές, τα κατασκευαστικά σφάλματα, η αλλαγή χρήσης, η φθορά των οικοδομικών υλικών και η έλλειψη συντήρησης (Don 2004).

2.1 Επίδραση σεισμικών δονήσεων

Λέγεται ότι «η ζημιάλωγος σεισμού είναι η μητέρα της σεισμικής μηχανικής» και ότι αποτελεί μια καλή ευκαιρία για την απόκτηση γνώσης από την παρατήρηση των ζημιών. Η παρατήρηση της φυσικής κατάστασης κτιρίων μετά από σεισμική δόνηση μπορεί να οδηγήσει στον εντοπισμό των αδυναμιών του σχεδιασμού, τις επιθυμητές ιδιότητες των υλικών, την επιλογή κατασκευαστικών μεθόδων και περιοχών κατάλληλων για δόμηση (Boen 2001). Η περιοχή της Μεσογείου και των Βαλκανίων

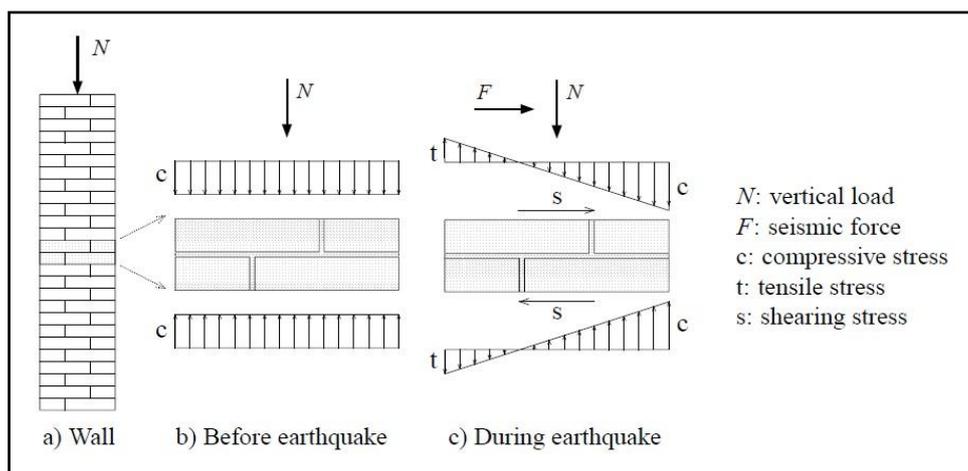
είναι σε μεγάλο βαθμό εκτεθειμένη στο σεισμικό κίνδυνο. Οι ιστορικές κατασκευές είναι ιδιαίτερα εκτεθειμένες στο σεισμικό κίνδυνο, δεδομένου ότι σε πολλές περιπτώσεις δεν διαθέτουν βασικά αντι-σεισμικά χαρακτηριστικά ή δεν έχουν αναβαθμισθεί έναντι σεισμικού κινδύνου (Mazzolani 2008, Arya et al 2012).

Οι περισσότερες από τις αστοχίες σε παραδοσιακά κτίρια από τοιχοποιία που παρατηρήθηκαν στο παρελθόν μετά από σεισμική δόνηση συνδέονται με κατασκευαστικά ελαττώματα είτε λόγω αδυναμιών του σχεδιασμού είτε από ανεπαρκή επίβλεψη ή χρήση ακατάλληλων υλικών σε συνδυασμό με κακοτεχνίες (Boen 2001, Mazzolani 2008, Toranzo et al 2001). Λεπτομερής περιγραφή των αιτιών της τρωτότητας των ιστορικών παραδοσιακών κτιρίων από τοιχοποιία δίδεται αλλού (Magenes 2006).

2.1.1 Αίτιααστοχίας

Οι μέθοδοι κατασκευής κοινών κτιρίων σε ιστορικές περιοχές συχνά εφαρμόζονται ακολουθώντας παραδοσιακούς κανόνες ορθής πρακτικής για την κατασκευή καθιερωμένων τύπων δομικών στοιχείων (τοίχοι πολλαπλών φύλλων) με υλικά (πολυσυστατικά υλικά τοιχοποιίας) και κατασκευαστικές λεπτομέρειες που δεν εξασφαλίζουν καλή σύνδεση μεταξύ τεμνόμενων τοίχων και τοίχων και δαπέδων και, ακόμη, με διαφορές στο πάχος των φύλλων του τοιχώματος. Αυτές οι παραδοσιακές πρακτικές, σε ορισμένες περιπτώσεις, δεν εξασφαλίζουν έναντι σημαντικών βλαβών σε ζώνες μέτριας και υψηλής σεισμικότητας (Abdessemed-Φούφα 2003) (Dizhur κ.ά. 2010).

Η αδυναμία των υλικών τοιχοποιίας να αναλάβουν εφελκυστικές τάσεις μειώνει την αντίσταση σε κάμψη λόγω σεισμού των τοιχωμάτων από τοιχοποιία, όπως φαίνεται στο Σχ. 2.1 (Bothara και Brzev 2011) (Branco και Guerreiro 2011).

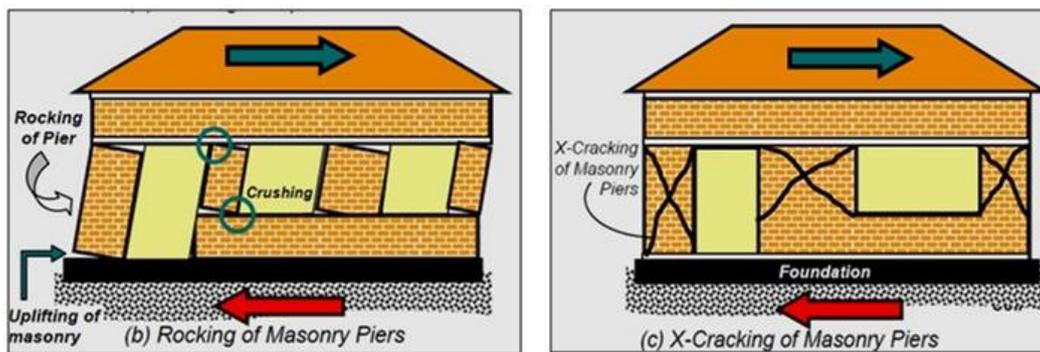


Σχήμα 2.1: Εντατική κατάσταση στοιχείου τοιχώματος (Bothara and Brzev 2011)

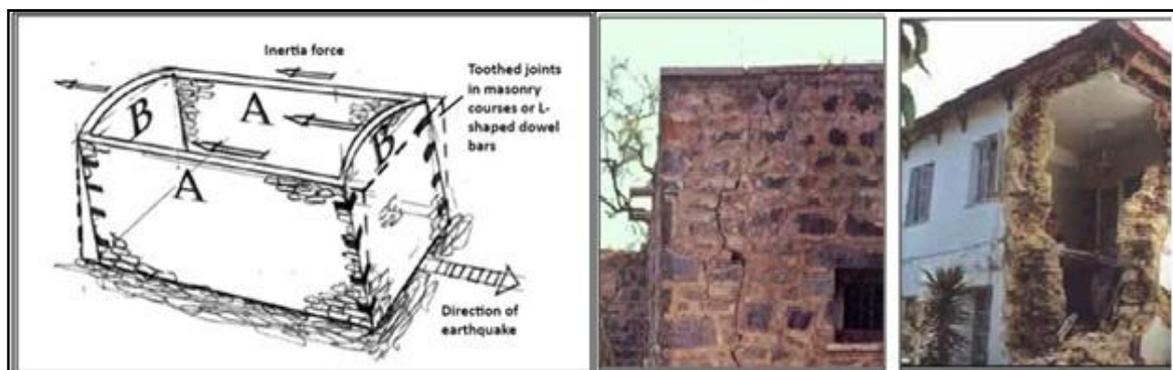
Το υπερβολικό πάχος της τοιχοποιίας σε συνδυασμό με το βάρος των δαπέδων και της οροφής έχει ως αποτέλεσμα την ανάπτυξη σημαντικών δυνάμεων αδράνειας κατά τη διάρκεια ενός σεισμού (Bothara και Brzev 2011). Έχει παρατηρηθεί ότι η κατάρρευση της πρόσοψης των ιστορικών παραδοσιακών κτιρίων από τοιχοποιία

συμβαίνει λόγω της έλλειψης σύνδεσης μεταξύ δαπέδων και τοίχων ή μεταξύ των τοίχων ή της απόσπασης του εξωτερικού στρώματος του τοιχώματος λόγω απουσίας καλής σύνδεσης μεταξύ των πολλαπλών φύλλων της τοιχοποιίας (Abdessemed-Φούφα 2003).

Κατά τη διάρκεια του σεισμού, όλα τα στοιχεία του κτιρίου κινούνται προς την ίδια κατεύθυνση. Η οροφή τείνει να διαχωριστεί από τα στηρίγματα και οι τοίχοι οι στύλοι τείνουν να ρηγματωθούν είτε στα άκρα τους είτε διαγώνια, όπως φαίνεται στο Σχ.2.2 (Magenes 2006). Οι συνδέσεις τοίχων είναι ιδιαίτερα ευάλωτες σε σεισμικές δονήσεις λόγω των σημαντικών εφελκυστικών δυνάμεων που αναπτύσσονται στην περιοχή σύνδεσης και προκαλούν καταφύρφες ρωγμές ή διαχωρισμό των τοίχων όπως φαίνεται στο Σχ. 2.3 (Bruneau 1994).



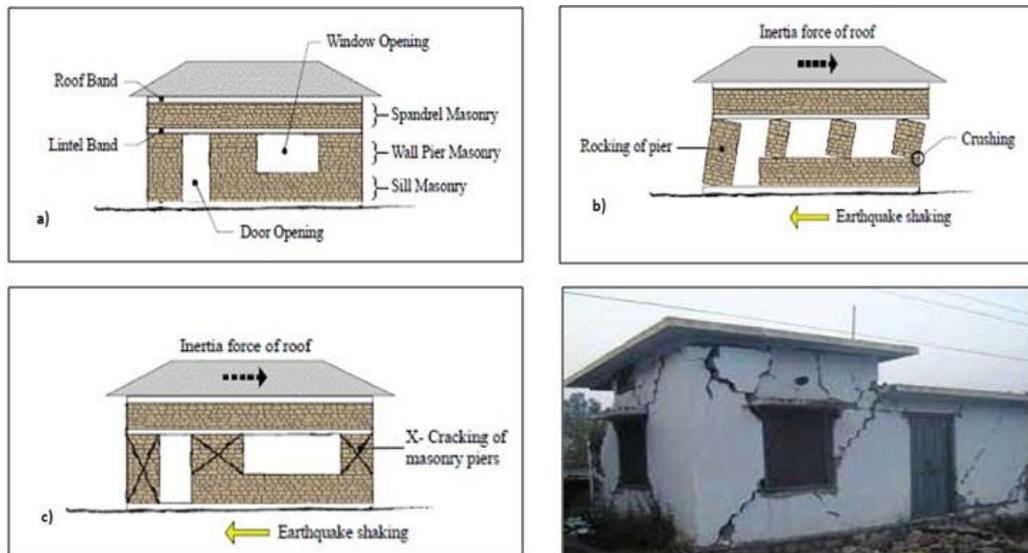
Σχήμα 2.2: Κτίριο τοιχοποιίας σε σεισμική δόνηση (Boen 2011)



Σχήμα 2.3: Τοίχοι Α αποτελεσματικά συνδεδεμένοι στους τοίχο Β: Οι τοίχοι Α υποστηρίζουν τους τοίχους Β

Υπερβολική κάμψη ή διάτμηση μπορεί να προκαλέσει συνεπίπεδη βλάβη, ανάλογα με την αναλογία διαστάσεων των στοιχείων. Σε τοίχους, συνεπίπεδες αστοχίες σε τέμνουσα είναι πιο συχνές και έχουν τη μορφή δισδιαγώνιων ρωγμών. Σε προσόψεις τοιχοποιίας με πολλά ανοίγματα (παράθυρα, πόρτες), τα υπέρθυρα και οι πεσσοί μπορεί επίσης να αστοχήσουν σε τέμνουσα (βλ. Σχ. 2.4). Οι παράμετροι που συνδέονται με το μηχανισμό αστοχίας λιθοδομών σε επίπεδη ένταση περιλαμβάνουν τις διαστάσεις του τοιχώματος, το ύψος κτιρίου, καθώς και την αντοχή τοιχοποιίας σε τέμνουσα (Bothara και Brzev 2011). Τα αγκύρια των πάτερων του δαπέδου στον τοίχο παρέχουν εκτός επιπέδου στήριξη στους τοίχους, εφόσον υπάρχουν σε επαρκή αριθμό και έχουν επαρκή αντοχή. Τα αγκύρια αυτά μεταβάλλουν

τη συμπεριφορά των τοίχων από υψίκορμους ελεύθερους πρόβολους σε κοντύτερα μονόρωφα φατνώματα υπό οριζόντια ταλάντωση επιβαλλόμενη από τη διαφραγματική λειτουργία των δαπέδων. Τα κτίρια τοιχοποιίας είναι γενικώς εύαλота σε εκτός επιπέδου καμπτική καταπόνηση (Binda et al 2006).



Σχήμα 2.4: Βλάβες λιθοδομής σε επίπεδη ένταση:(α) χαρακτηριστικοί τοίχοι με ανοίγματα, (β) αστοχία σε κλυδωνισμό και (γ) δισδιαγώνια ρηγμάτωση (Bothara. andBrzev 2011)

2.2. Μετατροπές

Τα ιστορικά παραδοσιακά κτίρια συνήθως υποβάλλονται σε πολλούς τύπους μετατροπών, όπως η κατασκευή νέων ανοιγμάτων για αερισμό ή η αφαίρεση ενός πεσσού ή ακόμα και ενός τοίχου (Barry 2001, Urquhart 2007). Ως αποτέλεσμα των τροποποιήσεων αυτών, τα κτίρια είναι ευπαθή σε σοβαρές βλάβες των αρχιτεκτονικών στοιχείων τους, όπως το φούσκωμα των προσόψεων που προκύπτει από την αφαίρεση εγκάρσιων τοίχων ή την κατασκευήμεγάλων ανοιγμάτων (Mills 1998). Ο Πίνακας 2.2 συνοψίζει τις μεθόδους μετατροπής και τους κινδύνους για τα ιστορικά παραδοσιακά κτίρια.



Σχήμα 2.5: Βλάβητοιχώματοςλόγωαπουσίαςεγκάρσιας υποστήριξης (Doğangünetal 2008)

2.3 Δομικά και κατασκευαστικά ελαττώματα

Ένα απότα πιο συχνά αίτια φθοράς των παραδοσιακών κτιρίων από τοιχοποιία είναι οι κατασκευαστικές ατέλειες που μπορεί να οδηγήσουν σερωγμές τοίχων ή ακόμα κατάρρευση με την πάροδο του χρόνου (Fitzsiman και James 1998). Τα δομικά ελαττώματα περιλαμβάνουν σφάλματα στην επιλογή της θέσης της

κατασκευής, η ανομοιομορφή κατανομή των φορτίων της κατασκευής στα θεμέλια, σφάλματα στην επιλογή κατάλληλων δομικών υλικών και μαδεριών δαπέδων, κλπ (Urquhart 2007) (Doğangün et al 2008).



Σχήμα 2.6: Κατάρρευση γωνίας και κατακόρυφη ρηγμάτωση κοντά στη γωνία κτιρίου από τοιχοποιία (Doğangün A. et al., 2008)

2.4 Ρηγμάτωση

Η τοιχοποιία είναι γενικά υψηλή αντοχή σε θλίψη, μέτρια αντίσταση σε ολίσθηση κατά μήκος των συνδέσεων με άλλα δομικά στοιχεία και μικρή αντοχή σε εφελκυσμό. Ως εκ τούτου οι κατασκευές τοιχοποιίας είναι συνήθως σχεδιασμένες για να λειτουργούν σε θλίψη και μερικές φορές σε οριζόντια τέμνουσα.

Οι βλάβες της τοιχοποιίας εκδηλώνονται συνήθως με τη μορφή της ρωγμών ως αποτέλεσμα επιβαλλόμενης παραμόρφωσης λόγω διαφορικής καθίζησης ή οριζόντιων δυνάμεων. Ρηγμάτωση μπορεί επίσης να προκληθεί λόγω κάμψης των λιθοσωμάτων ή διόγκωσης του μεσαίου φύλλου τρίφυλλων τοιχωμάτων (Abrams 2004, Bussell 2007). Γενικώς, ρηγμάτωση συμβαίνει όταν ο συνολικός επιβαλλόμενος εφελκυσμός υπερβεί την εφελκυστική αντοχή της τοιχοποιίας (Miliston and Domone 2001).

2.5 Υγρασία εδάφους

Τα περισσότερα ιστορικά κτίρια από τοιχοποιία βασίζονται στον συνδυασμό της μάζας της τοιχοποιίας και της κίνησης του αέρα για το αντιστάθμισμα των επιπτώσεων της μεταφοράς υγρασίας από το έδαφος. Αυτή η μεταφορά μπορεί να είναι τόσο κάθετη όσο και οριζόντια. Η ικανότητα ενός τοίχου να μεταφέρει την υγρασία εξαρτάται από το μέγεθος των πόρων και τη δομή του υλικού, τα οποία επηρεάζουν τις τριχοειδείς δυνάμεις που έλκουν την υγρασία από το έδαφος στον τοίχο. Οι τριχοειδείς δυνάμεις που έλκουν την υγρασία προς τα πάνω, οι βαρυτικές δυνάμεις που δρουν προς τα κάτω και ο ρυθμός εξάτμισης από τον τοίχο ρυθμίζουν το ύψος της κίνησης της υγρασίας.

Η ισορροπία επιτυγχάνεται όταν η μεταφορά από το έδαφος (και η προς τα κάτω ροή του νερού της βροχής μέσα στον τοίχο) εξισορροπείται από απώλειες λόγω εξάτμισης. Γενικώς, τα ιστορικά παραδοσιακά λιθόχτιστα κτίρια δεν έχουν

κατασκευασθεί έτσι ώστε να εμποδίζεται η άνοδος της υγρασίας μέσω των τοίχων από το έδαφος προς τους ορόφους. Η ελαχιστοποίηση της επίδρασης της υγρασίας στη φθορά των στοιχείων της κατασκευής βασίζεται στον έλεγχο της ανόδου της υγρασίας μέσω του πορώδους των υλικών της τοιχοποιίας και της επαρκούς κυκλοφορίας του αέρα στο εσωτερικό του κτιρίου (Utquhart 2007).

Κεφάλαιο 3: Αποτίμηση κτιρίων

Η αποτίμηση κτιρίων είναι μια διαδικασία που συνήθως περιλαμβάνεται εξής: αναζήτηση εγγράφων, επιθεώρηση, μετρήσεις και καταγραφές και δομική ανάλυση. Μερικές φορές περιλαμβάνει έλεγχο των υλικών και περιστασιακά δοκιμές φορτίου δομικών στοιχείων (Beckmann και Bowles 2004). Διαφέρει από το δομοστατικό σχεδιασμό ως προς το ότι αποσκοπεί στην αξιολόγηση της πραγματικής κατάστασης της υφιστάμενης κατασκευής. Όπως και στην ιατρική, όπου η διάγνωση πρέπει να προηγηθεί της θεραπείας, ο συντηρητής αφήνεται πρόσωπο με πρόσωπο με μια υπάρχουσα κατασκευή και πρέπει να εκτιμήσει την κατάσταση και την καταλληλότητα της χρήσης της (Sullivan και Keane 2004). Η εκτίμηση βασίζεται σε ιστορικές πληροφορίες και ποιοτικές και ποσοτικές προσεγγίσεις. Η ποιοτική προσέγγιση βασίζεται στην άμεση παρατήρηση των βλαβών και της φθοράς των υλικών, καθώς και την ιστορική και αρχαιολογική έρευνα, ενώ η ποσοτική προσέγγιση απαιτεί δοκιμές των υλικών και των δομικών στοιχείων, παρακολούθηση και καταγραφές και δομική ανάλυση (Silman και Ένις 1993).

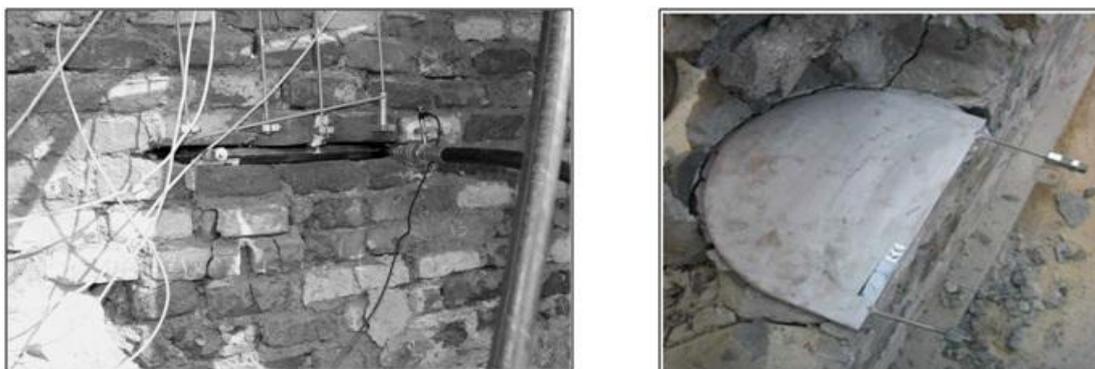
Μια προκαταρκτική επιτόπια έρευνα είναι χρήσιμη προκειμένου να παράσχει λεπτομέρειες σχετικά με τη γεωμετρία της κατασκευής και των ορατών ζημιών (ρωγμές, αποκλίσεις από την κατακόρυφο, φθορά υλικών) και προκειμένου να εντοπιστούν τα σημεία όπου οι πιο ακριβείς παρατηρήσεις πρέπει να επικεντρωθούν (Binda et al. 2000, HuiGao et al., 2001).

Η ιστορική ανάλυση και η άμεση παρατήρηση της κατασκευής είναι ένα ουσιαστικό στάδιο της μελέτης, που πραγματοποιούνται συνήθως από μια ειδική ομάδα για να παράσχει αρχική κατανόηση της κατασκευής και να δώσει την κατάλληλη κατεύθυνση για τις επόμενες έρευνες. Οι κύριοι στόχοι περιλαμβάνουν, προσδιορισμό της φθοράς και των ζημιών, καθορισμός του εσφαλμένα φαινόμενα απομείωσης έχουν σταθεροποιηθεί, απόφαση σχετικά με την επικινδυνότητα της κατασκευής (Schueremans et al. 2006, HuiGao et al. 2001).

Η επιτόπια και εργαστηριακή διερεύνηση είναι η βάση για τη κατανόηση της δομικής συμπεριφοράς της κατασκευής και της αποτελεσματικότητας της παρέμβασης. Ο στόχος αυτών των ενεργειών θα πρέπει πάντοτε να είναι σαφής πριν από την εκτέλεση τους, προκειμένου να αποφευχθούν οι υψηλές δαπάνες με αμφίβολα αποτελέσματα (Binda et al. 1999). Το επίπεδο της έρευνας θα πρέπει πάντα να αποφασίζεται μετά από προσεκτικό σχεδιασμό. Η έρευνα πρέπει να γίνει πιο λεπτομερής και συγκεκριμένη προκειμένου να ελεγχθεί η αξιοπιστία της σχετικά με τα αίτια των βλαβών και την εξέλιξή τους, τον έλεγχο της κατασκευής πριν, κατά τη

διάρκεια και μετά την παρέμβαση και τον έλεγχο της αποτελεσματικότητας της επισκευής και ενίσχυσης.

Οι μη καταστροφικές μέθοδοι μπορεί να είναι χρήσιμες για την εύρεση κρυφών χαρακτηριστικών (εσωτερικά κενά και αδυναμίες και χαρακτηριστικά μέρους των στοιχείων), τα οποία δεν μπορεί να αποκαλυφθούν παρά μόνο μέσω τέτοιων δοκιμών, όπως η τοπική φόρτιση με flat-jack, ηχητική δοκιμή, δοκιμές με γεωραντάρ, κλπ. Η δοκιμή με τοπική φόρτιση, που θα πρέπει να επισημανθεί ότι είναι ελαφρώς καταστροφική, να δώσει άμεσα τιμές των μηχανικών παραμέτρων. Γενικώς, οι μη καταστροφικές μέθοδοι μπορεί να δώσουν μια συνολική ποιοτική περιγραφή της συμπεριφοράς της τοιχοποιίας (Lourenço 1998, Timchenko 2000, Binda et al. 2000, Ariasa και Ordóñez 2006).

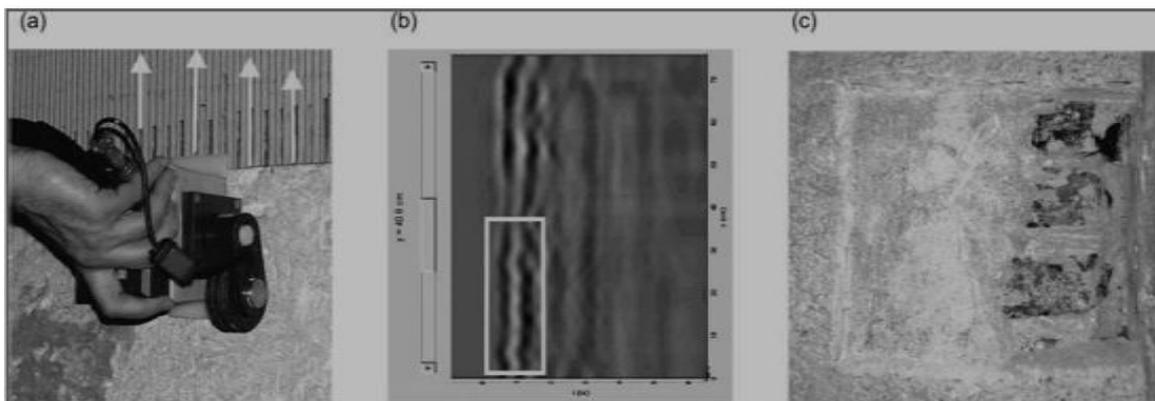


Σχήμα 3.1: Τοποθέτηση οργάνου φόρτισης (flatjack) σε λιθόκτιστο τοίχωμα και σχέση μεταξύ διεπιφάνειας οργάνου-τοιχώματος (Timchenko 2000).

Οι πλέον διαδεδομένες μη καταστροφικές μέθοδοι είναι οι μέθοδοι των υπερήχων, του ραντάρ και της θερμογραφίας. Η χρήση των μεθόδων αυτών έχει τους ακόλουθους στόχους: (i) την ανίχνευση κρυφών δομικών στοιχείων, όπως στοιχείων δαπέδων, αψίδων, στύλων, κλπ, (ii) τη διακρίβωση υλικών τοιχοποιίας και χαρτογράφηση της ανομοιογένειάς τους (π.χ. χρήση διαφορετικών πλίνθων στην ιστορία του κτιρίου), (iii) την αξιολόγηση του βαθμού της μηχανικής βλάβης ρηγματωμένων δομικών στοιχείων, (iv) την ανίχνευση κενών και ρωγμών, (v) την αξιολόγηση της περιεχόμενης υγρασίας και τριχοειδούς ανύψωσης, (vi) την ανίχνευση της επιφανειακής φθοράς και (vii) την αξιολόγηση των μηχανικών και φυσικών ιδιοτήτων των κονιαμάτων και λιθοσωμάτων (Binda et al. 2007).

Οι επιτόπιες δοκιμές με χρήση δυναμικών μεθόδων θεωρούνται ως αξιόπιστες μη καταστρεπτικές μέθοδοι για την αξιολόγηση της δομικής συμπεριφοράς και ακεραιότητας ενός κτιρίου. Ο κύριος στόχος των δυναμικών δοκιμών είναι να ελέγξει την απόκριση της κατασκευής σε κραδασμούς. Ένα απλό παράδειγμα της δυναμικής δοκιμής είναι η καταπόνηση ελκυστήρων σε εφελκυσμό. Εξαναγκασμένες ταλαντώσεις θα μπορούσαν να παραχθούν από τοπικά συστήματα σφυροκοπήματος. Ένα δίκτυο επιταχυνσιομέτρων εγκαθίσταται σε επιλεγμένες κρίσιμες περιοχές της κατασκευής. Με αυτόν τον τρόπο είναι δυνατόν να διερευνηθεί η αποτελεσματικότητα υπολογιστικών μεθόδων, όπως η μέθοδος των πεπερασμένων στοιχείων, που

χρησιμοποιούνται για την ανάλυση της κατασκευής (Nickerson 1994, Scherer 2002, Binda et al. 2007).



Σχήμα 3.2 Χρήση Georadar για την ανίχνευση επιφανειακής φθοράς (Bam 2004 and Binda et al. 2000)

Όταν η τοιχοποιία υποστεί βλάβη από επιθετικούς παράγοντες η φθορά δεν είναι ποτέ ομοιόμορφη. Συντήρηση απαιτείται όταν η βλάβη περιορίζεται μόνο σε μερικούς πλίνθους, λίθους ή διακοσμητικά στοιχεία. Στην περίπτωση αυτή, εργαστηριακές εξετάσεις μπορούν να δώσουν χρήσιμες πληροφορίες για την επιλογή του κατάλληλου υλικού για υποκατάσταση. Οι εργαστηριακές εξετάσεις συμπεριλαμβάνουν δοκιμές για τη διακρίβωση των μηχανικών και φυσικών ιδιοτήτων, και οπτικές και ορυκτολογικές αναλύσεις για τον προσδιορισμό της χημικής σύστασης (Binda et al 2000, Ariasa και Ordóñez 2006).

Κεφάλαιο 4: Μέθοδοι αποκατάστασης

Σε περιπτώσεις που εξετάζεται η αλλαγή χρήσης, η βασική αρχή των προτεινόμενων παρεμβάσεων είναι να βελτιωθεί η στατική και αντισεισμική συμπεριφορά του κτιρίου, χωρίς να αλλάξει η ιστορική και αισθητική μορφή του. Η βασική αρχή της αναστήλωσης και συντήρησης των ιστορικών κτηρίων είναι να διατηρήσει το κτίριο τα πρωτότυπα χαρακτηριστικά του όσο το δυνατόν περισσότερο. Αν η αντικατάσταση είναι αναπόφευκτη, υλικά παρόμοια, κατά προτίμηση ταυτόσημα με τα αρχικά, θα πρέπει να χρησιμοποιούνται. Είναι πολύ σημαντικό να διατηρηθεί αρχική ιδέα που οδήγησε στην κατασκευή, προκειμένου να διαφωτισθεί το παρελθόν σωστά και να μεταφερθούν τα κύρια χαρακτηριστικά του στο μέλλον (Rashadul 2008).

4.1 Ενίσχυση της κατασκευής

Προκειμένου να αυξηθεί η αντισεισμικότητα της φέρουσας τοιχοποιίας, το βασικό δομικό υλικό πρέπει να ενισχυθεί. Η τοιχοποιία μπορεί να ενισχυθεί με βαθιά αρμολόγηση των εξωτερικών τοίχων και με συστηματική πλήρωση των κενών με τσιμεντένια, με τοποθέτηση νέων λιθοσωμάτων, και με ενίσχυση των γωνιών τοίχων με συρμάτινο πλέγμα και τσιμέντο κονίαμα επικάλυψης (Marjana 2010).

4.1.1 Έγχυση

Η λύση αυτή βασίζεται στην έγχυση (μέσω σωλήνων έγχυσης τοποθετημένων σε οπές που έγιναν για το σκοπό αυτό σε πολλά σημεία του τοίχου) ρευστού τσιμεντοκονιάματος σε εσωτερικά κενά και ρωγμές (βλέπε Σχ. 4.1) Αυτή η τεχνική δείχνει βελτιώνει τα μηχανικά χαρακτηριστικά της τοιχοποιίας. Είναι πιο κατάλληλη για λιθοδομή (Meireles και Bento 2013).



Σχήμα 4.1: Τεχνικές έγχυσης ρευστού τσιμεντοκονιάματος (Meireles and Bento 2013).

4.1.2 Εγκάρσιο δέσιμο τοίχων

Αυτή η τεχνική χρησιμοποιείται στην περίπτωση στοιχείων τοιχοποιίας που χρειάζονται υψηλότερη συνοχή και βελτιώνει τα μηχανικά χαρακτηριστικά, χωρίς εμφανή τροποποίηση. Περίσφυξη στον τοίχο μπορεί να ασκηθεί είτε με εγκάρσιες ράβδους χάλυβα που αγκυρώνονται σε πλάκες ή άλλες διατάξεις χάλυβα και στις δύο πλευρές του τοίχου ή με στοιχεία οπλισμένου σκυροδέματος στοιχεία που χυτεύονται σε εγκάρσιες οπές σε όλο το πάχος του τοιχώματος (Rashadul 2008).

4.1.3 Τριμέντοκονίαμα επίστρωσης ενισχυμένο με πλέγμα

Αποτελείται από λεπτές στρώσεις επιχρισμάτων τσιμέντου πάχους μικρότερου από 10 mm που είναι ενισχυμένες με ένα πλέγμα από χάλυβα ή ίνες γυαλιού ή πλαστικό πλέγμα. Η επικάλυψη αυξάνει την αντοχή και πλαστιμότητα της τοιχοποιίας. Μπορεί να τοποθετηθεί εξωτερικά ή εσωτερικά ή και στις δύο πλευρές, ανάλογα με την προσβασιμότητα. Η συνεργασία της επίστρωσης με την τοιχοποιία ενισχύεται με την τοποθέτηση εγκάρσιων μεταλλικών συνδέσμων (Rashadul 2008).

4.1.4 Ενίσχυση με πλέγμα πολυπροπυλενίου

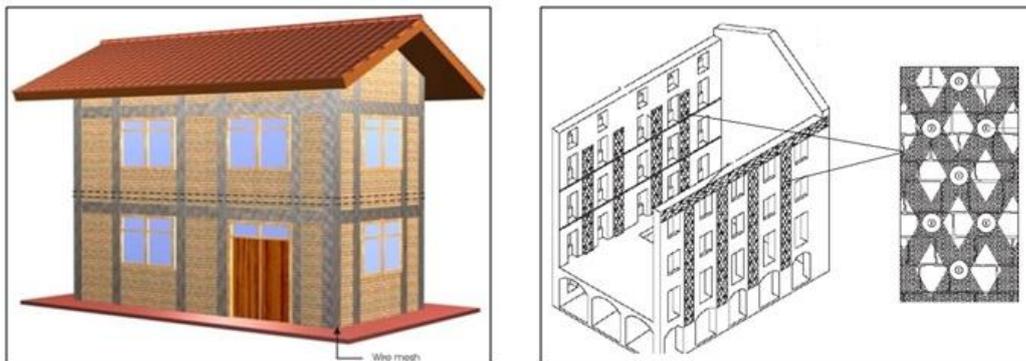
Το πλέγμα πολυπροπυλένιο αποτελείται από κοινούς μάντες συσκευασίας που σχηματίζουν ένα πλέγμα, το οποίο περιβάλλει την τοιχοποιία αποτρέποντας την κατάρρευση κατά τη διάρκεια σεισμών (Mayorka και Meguro 2008). Το πλέγμα αυτό αυξάνει σημαντικά τη σεισμική αντοχή και εξασφαλίζει περιορισμένη και ελεγχόμενη ρηγμάτωση της μετασκευασμένης κατασκευής, αναμένεται δε να αποτρέψει ή να καθυστερήσει την κατάρρευση κατά τη διάρκεια ισχυρών εδαφικών κινήσεων. Η μέθοδος αυτή δίνει καλά αποτελέσματα μονόροφα κτίρια και μπορεί η χρήση της να επεκταθεί και σε κτίρια δύο ορόφων (Shrestha et al 2012).



Σχήμα 4.2: Τοιχοποιία ενισχυμένη με μεταλλικό πλέγμα στο εσωτερικό του κτιρίου (Rashadul 2008)

4.1.5 Ενίσχυση με σύνθετα υλικά

Πεσσοί και υπέρθυρα είναι δυνατόν να ενισχυθούν με σύνθετα υλικά, όπως είναι τα πολυμερή υφάσματα ενισχυμένα με ίνες άνθρακα ή γυαλιού. Πολυμερή «υφάσματα» με ίνες άνθρακα ή γυαλιού προσκολλώνται στην τοιχοποιία με εποξειδική ρυτίνη .



Σχήμα 4.3: Ενίσχυση τοιχοποιίας με σύνθετα υλικά

4.1.6 Ενίσχυση με χρήση οριζόντιων ελκυστήρων

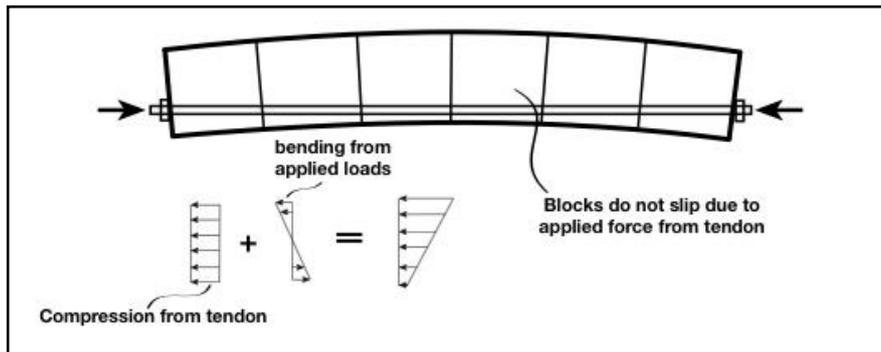
Μια από τις καλύτερες τεχνικές για την προστασία των τόξων είναι η εισαγωγή του δεσμού μεταξύ των λίθινων βάσεων στα άκρα των τόξων (Σχ. 4.4). Μειώνει την πλευρική ώθηση στις στύλες στήριξης. Ελκυστήρες από ράβδους χάλυβα μπορεί να χρησιμοποιηθούν για το λόγο αυτό σε παλαιά κτίρια από φέρουσα τοιχοποιία. Για παράδειγμα, μπορούν να εμποδίσουν ή τουλάχιστον να μειώσουν την πιθανότητα άστοχίας λόγω εκτός επιπέδου κάμψης (Rashadul 2008).

4.1.7 Μετασκευή με επιβολή θλίψης με χρήση προέντασης

Η προένταση μπορεί να επιβληθεί για το κλείσιμο ή τον έλεγχο ρωγμών σε στοιχεία τοιχοποιίας ή για την αύξηση της καμπτικής ροπής ρηγμάτωσης σε νέες κατασκευές. Προένταση έχει εφαρμοστεί με επιτυχία σε ποικιλία κατασκευών από τοιχοποιία. Η έλευση προηγμένων σύνθετων υλικών παρέχει μια εναλλακτική λύση για μέτρα προστασίας από διάβρωση που είχαν υιοθετηθεί παλαιότερα. Ειδικότερα, τα ινοπλισμένα πολυμερή έχουν ελκυστικές ιδιότητες για εφαρμογές προέντασης (Rashadul 2008).



Σχήμα 4.4: Χρήσηελκυστήρωναπόμεταλλικέςράβδους σε τόξα (Rashdul 2008)



Σχήμα 4.5: Ενίσχυση με επιβολή προέντασης

4.1.8 Χρήσητοιχωμάτωνσκυροδέματος

Η χρήση των συγκεκριμένων τοιχωμάτων προορίζεται για τον έλεγχο μετατοπίσεων μεταξύ ορόφων μέσω της αύξησης της συνολικής δυσκαμψίας της κατασκευής. Παρά ταύτα, αυτό μπορεί να προκαλέσει αύξηση της επιτάχυνσης στη στάθμη ορόφων, λόγω αλλαγών στις δυναμικές ιδιότητες του κτιρίου, και κατ' επέκταση αύξηση των εσωτερικών δυνάμεων που οφείλονται σε σεισμική φόρτιση.



Σχήμα 4.6:Συστήματα σεισμικής μόνωσης

4.1.9 Σεισμική μόνωση

Η σεισμική μόνωση επιτυγχάνεται με το διαχωρισμό του κτιρίου από το έδαφος μέσω της χρήσης ενός συστήματος έδρασης με χαμηλή οριζόντια δυσκαμψία που διαχωρίζει την κίνηση της κατασκευής από τις μετατοπίσεις του εδάφους. Επί του

παρόντος, υπάρχουν διάφορα είδη διατάξεων που είναι κατάλληλες για τη σεισμική μόνωση της κατασκευής ανάλογα με τις δυνάμεις και τις μετατοπίσεις που δημιουργούνται. Ένας κοινός τύπος συστήματος σεισμικής μόνωσης είναι μια βάση από ελαστομερές υψηλής απόσβεσης (Zhou F 1996) (Guerreiro L. et al 2006).

4.2 Βελτίωση σύνδεσης τοιχωμάτων-δαπέδων

Η αύξηση της δυσκαμψίας των δαπέδων επιτρέπει την ανακατανομή των οριζόντιων δυνάμεων μεταξύ των διαφόρων κατακόρυφα δομικά στοιχεία, και, στη συνέχεια, όταν υπάρξει αδυναμία περαιτέρω ανάληψης φορτίου από ορισμένα στοιχεία, οι οριζόντιες δυνάμεις μπορούν να αναδιανεμηθούν στα γειτονικά υπόλοιπα στοιχεία. Η αύξηση της δυσκαμψίας των δαπέδων επιτυγχάνεται με την προσθήκη στο δάπεδο μιας οριζόντιας κατασκευής αποτελούμενης από ράβδους χάλυβα τοποθετημένες χιαστί όπως φαίνεται στο Σχ. 4.7 και έχει αναπτυχθεί εδώ και πολλές δεκαετίες.



Σχήμα 4.7: Αύξηση δυσκαμψίας δαπέδου μέσω Προσθήκης κατασκευής από χιαστί τοποθετημένες ράβδους χάλυβα διατομής L .

4.3 Ενίσχυση δαπέδων

Η διαφραγματική λειτουργία των δαπέδων επιβάλλει την κατανομή των οριζόντιων σεισμικών δυνάμεων σύμφωνα με τη δυσκαμψία των κατακόρυφων στοιχείων. Υπάρχουν τέσσερις διαφορετικοί τρόποι για τη δημιουργία διαφραγματικής λειτουργίας:

4.3.1 Ενίσχυση δαπέδων

Ο πρώτος τρόπος δημιουργίας διαφραγματικής λειτουργίας είναι η υποκατάσταση του αρχικού δαπέδου από πλάκα σκυροδέματος πάχους 0.20μ. Η λύση αυτή έχει το πλεονέκτημα ότι εξασφαλίζει τη δυσκαμψία του διαφράγματος και συνεπώς την κατανομή των δυνάμεων με αποτελεσματικό τρόπο στα τοιχώματα. Το αρχικό δάπεδο έχει βάρος περίπου 1.1 kN/m^2 , ενώ η λύση αυτή προκαλεί ένα βάρος 5 kN/m^2 . Αυτή η υπερβολική αύξηση της μάζας έχει δύο αρνητικές συνέπειες: (α) η μεγαλύτερη μάζα οδηγεί σε αύξηση των αδρανειακών δυνάμεων κατά τη διάρκεια ενός σεισμού και (β) επιβάρυνση των τοιχωμάτων, τα οποία μπορεί ήδη να είναι σε κακή κατάσταση.

4.3.2 Σύμμικτη πλάκα σκυροδέματος-χάλυβα

Μία σύμμικτη πλάκα σκυροδέματος-χάλυβα τοποθετείται πάνω σε ένα πλέγμα δοκών χάλυβα, που εδράζεται αρθρωτά στα τοιχώματα. Η πλάκα αποτελείται από σκυροδέμα με συνολικό πάχος των 0,10 μπου τοποθετείται σε μια μεταλλική λαμαρίνα πάχους 0,75 χιλιοστών. Η σύνθετη πλάκα υποστηρίζεται από δοκούς από χάλυβα HEA200 τοποθετημένων σε απόσταση 2 m μεταξύ τους, οι οποίες υποστηρίζονται από δοκούς HEA300. Αυτή η λύση έχει το πλεονέκτημα ότι οδηγεί σε μικρότερο βάρος (2kN/m^2) από την προηγούμενη. Ένα άλλο ζήτημα είναι η ανάγκη να αφαιρεθεί το αρχικό πεζοδρόμιο, το οποίο κάνει αυτή η τεχνική είναι αδύνατον να εκτελεστούν σε κατοικημένα κτίρια.

4.3.3 Μεταλλικό πλέγμα

Η λύση της αντικατάστασης του δαπέδου με ένα μεταλλικό πλέγμα τοποθετημένο πάνω σε δοκούς από χάλυβα δεν είναι εφαρμοστέα σε κτίρια για οικιακή χρήση. Μπορεί, όμως, η λύση αυτή να έχει χρήση σε κτίρια για γραφεία ή βιομηχανικούς χώρους. Σε σύγκριση με τις προηγούμενες τεχνικές, έχει το πλεονέκτημα ότι το δάπεδο είναι ελαφρύτερο (1 kN/m^2). Έχει όμως διάφορα λειτουργικά προβλήματα, δεδομένου ότι δεν εξασφαλίζει ούτε αποτελεσματικό διαχωρισμό μεταξύ των ορόφων, ούτε θερμική και ακουστική μόνωση.

4.3.4 Μεταλλικοί ελκυστήρες

Αυτή η τεχνική ενίσχυσης συνίσταται στην τοποθέτηση ελκυστήρων χάλυβα μέσω των ξύλινων δοκών του υπάρχοντος δαπέδου. Η πρόθεση ήταν να ενισχυθεί κάθε δωμάτιο χωριστά και να γίνει σύνδεση μεταξύ τους κατά μήκος των εσωτερικών τοιχωμάτων. Οι ράβδοι χάλυβα αγκυρώνονται σε κάθε γωνία του δωματίου, σχηματίζοντας έναν σταυρό. Η σύνδεση μεταξύ των δωματίων εξασφαλίζεται μέσω πλακών χάλυβα και δοκών που συνδέονται με κοχλίες. Αυτή η λύση έχει ορισμένα πλεονεκτήματα, όπως ότι είναι αναστρέψιμη. Ελαχιστοποιεί την διακοπή της κανονικής λειτουργίας του κτιρίου και δεν συμβάλλει σε υπερβολική αύξηση του βάρους της κατασκευής (Branco και Guerreiro 2011).

Κεφάλαιο 5: Μελέτη αποκατάστασης κτιρίου

Η Αθήνα είναι μία από τις πιο διάσημες πόλεις της πολιτιστικής κληρονομιάς του κόσμου. Η Πλάκα είναι η παλαιότερη περιοχή της σύγχρονης Αθήνας. Είναι η περιοχή όπου το κτίριο που αποτελεί το αντικείμενο του παρόντος κεφαλαίου βρίσκεται, στη διασταύρωση των οδών Ακταίου και Λυκομιδών και θα αναφέρεται ως κτίριο «Ακταίου» στη συνέχεια. Το κτίριο Ακταίου, που χτίστηκε στις αρχές της δεκαετίας του 1900, θεωρείται ότι αντιπροσωπεύει τις οδομικές και αρχιτεκτονικές τάσεις που επικρατούσαν στην Αθήνα αυτή την περίοδο. Με την πάροδο των ετών, αυτό το κτίριο (βλ. 5.1) έχει υποστεί σημαντικές ζημιές που οφείλονται σε διάφορες αιτίες, όπως η σεισμική διέγερση, έλλειψη συντήρησης, ελαττώματα κατασκευής, κ.λπ.

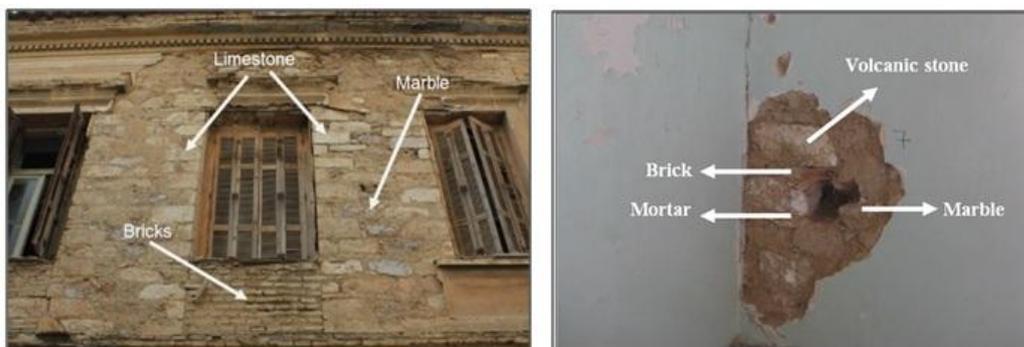


Σχήμα 5.1: Το κτίριο Ακταίου: πρόσοψη επί της οδού Ακταίου (αριστερά) και βόρεια όψη επί της οδού Λυκομιδών (δεξιά)

Το παρόν κεφάλαιο παρουσιάζει τη δουλειά που έγινε και περιλαμβάνει τα ακόλουθα στάδια: Περιγραφή του δομικού συστήματος, χαρτογράφηση των βλαβών, τεκμηρίωση των υλικών που χρησιμοποιήθηκαν, εκτίμηση της φέρουσας ικανότητας του κτιρίου, προτεινόμενη επέμβαση, περιγραφή μεθόδων αποκατάστασης και η επαλήθευση επάρκειας των προτεινόμενων παρεμβάσεων.

5.1 Ιστορική περιγραφή

Το κτίριο Ακταίου, το οποίο είναι ένα διώροφο κτίριο με σχήμα κάτοψης U, είναι ένα τυπικό αστικό αθηναϊκό κτίριο της περιόδου. Κατασκευάστηκε με τοπικά φυσικά υλικά τοιχοποιίας. Πρόκειται για ένα εξαιρετικό παράδειγμα της αρχιτεκτονικής κατοικιών των αρχών του 19^{ου} αιώνα. Αποτελείται από υπόγειο, ισόγειο και πρώτο όροφο. Το κτίριο έχει μια διόριστη στέγη που σχηματίζεται από ξύλινα ζευκτά που καλύπτονται από κεραμίδια.



Σχήμα 5.2 Υλικά τοιχοποιίας

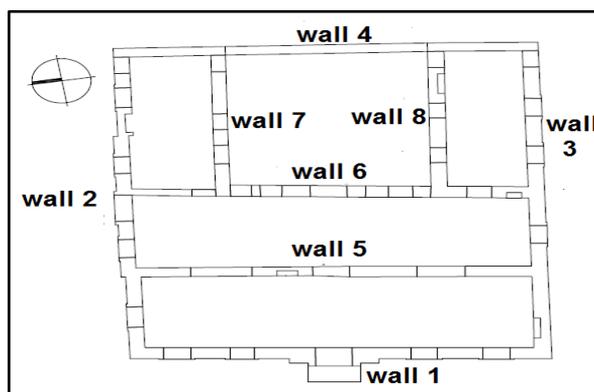
Ασβεστόλιθος, μάρμαρο, ηφαιστειακή πέτρα, και οπτόπλινθοι είναι τα κύρια οικοδομικά υλικά που χρησιμοποιήθηκαν για την κατασκευή του κτιρίου και των αρχιτεκτονικών στοιχείων του. Οι οπτόπλινθοι χρησιμοποιήθηκαν για να καλύψουν κενά μεταξύ των κύριων δομικών υλικών και κάτω από τα παράθυρα (βλ. Σχ.5.2). Το κονίαμα που χρησιμοποιήθηκε είναι ένα κονίαμα άσβεστο-ποζολάνης. Χάλυβας εμφανίζεται μόνο σε ορισμένα αρχιτεκτονικά στοιχεία και για τη σύνδεση του δαπέδου του 1^{ου} πρώτου ορόφου στον τοίχο. Το δάπεδο των δωματίων του ισόγειου και του 1^{ου} ορόφου καλύπτονται με ξύλινες σανίδες, ενώ οι διάδρομοι μεταξύ των δωματίων είναι στρωμένοι με διακοσμητικά πλακίδια όπως αυτά που φαίνονται στο Σχ.5.3



Σχήμα 5.3: Δωμάτια ισογείου και διακοσμητικά πλακάκια

5.2 Φορέας

Το κτίριο Ακταίου είναι ένα διώροφο κτίριο με υπόγειο. Τα φέροντα τοιχώματα αποτελούν τμήμα του δομικού συστήματος που φαίνεται στο Σχ. 5.4. Η πρόσοψη του κτιρίου βρίσκεται στην οδό Ακταίου (τοιίχος 1) και έχει μήκος 18,40 μ. Η αριστερή πρόσοψη (τοιίχος 2), η οποία βρίσκεται στην οδό Λυκομιδών, έχει μήκος 18,00 μ, ενώ δεξιά πρόσοψη (τοιίχος 3) βλέπει σε ένα εσωτερικό ανοιχτό χώρο και έχει μήκος 17,00 μ. Ο τοίχος 4 αποτελεί ουσιαστικά τον φράχτη που χωρίζει το κτίριο από το γειτονικό ακίνητο. Το υπόγειο εκτείνεται μέσα στο τμήμα της κάτοψης που περικλείεται από τα τοιχώματα 1, 5 και τμήματα των τοιχωμάτων 2 και 3.



Σχήμα 5.4: Σύστημα φέρουσας τοιχοποιίας

Η κάτοψη του κτιρίου έχει σχήμα U με ένα κεντρικό τμήμα (CB) που εκτείνεται μεταξύ των τοιχωμάτων 1, 6, 2 και 3 και δύο πτέρυγες που εκτείνονται μεταξύ των τοιχωμάτων 6, 4, 2 και 7 (W1) και τα τοιχώματα 8, 3, 6, και 4 (W2), αντίστοιχα. Τα δάπεδα τόσο του ισογείου όσο και του 1^{ου} ορόφου δάπεδα είναι κατασκευασμένα από ξύλινες δοκούσψους 17 εκ. και πλάτους 11 εκ. σε παράλληλη διάταξη με αποστάσεις 50 cm και καλύπτεται από σανίδες πλάτους 21 εκ. και πάχους 2.5 εκ. Οι δοκοί εδράζονται σε εσοχές που σχηματίζονται στους απέναντι τοίχους. Η οροφή του κεντρικού τμήματος (CB) του κτιρίου (βλ. Σχ. 5.5) είναι τετραέριστη και αποτελείται από δικτυώματα μονής και διπλής κλίσης (βλέπε Σχ. 5.6 αριστερά και δεξιά), ενώ η οροφή των πτερύγων (W1 και W2) του κτιρίου είναι διέριστη και αποτελείται από δικτυώματα με διπλή κλίση (βλέπε Fig.5.6).

5.3 Χαρτογράφηση βλαβών

Οι βλάβες που οφείλονται σε γήρανση, κατασκευαστικά σφάλματα/ ελαττώματα, έλλειψη συντήρησης, σεισμικές και περιβαλλοντικές δράσεις μπορούν να περιγραφούν σε γενικές γραμμές ως εξής:



Σχήμα 5.5: Κεντρική στέγη



Σχήμα 5.6: Πλευρική στέγη



Σχήμα 5.7: Δικτύωμα κεντρικής στέγης



Σχήμα 5.8: Δικτύωμα πλευρικών στεγών

- Κεκλιμένες και κατακόρυφες ρωγμές με μικρό σχετικά πλάτος που δεν εκτείνονται σε όλο το πάχος του τοιχώματος (βλέπε Σχ. 5.9).
- Κατακερματισμός του κονιάματος τοιχοποιίας.
- Εκτεταμένη απόσπαση και απώλεια του σοβά του τοίχου.
- Ενεργές βαθιές ρωγμές ανάμεσα στον τοίχο και την οροφή (βλ. Σχ. 5.10).
- Διαγώνιες ρωγμές στους τοίχους (βλ. Σχ. 5.11).
- Τοπικές αστοχίες και νεγάλα βέλη των φερόντων μελών της στέγης και κατάρρευση των ξύλινων χαγιατιών (βλ. Σχ. 5.12).



Σχήμα 5.9: Ρηγμάτωση υπέρυθρου στο εσωτερικό (W1-in, 1^{ος} όροφος) και εξωτερικό (W1-ex, 1^{ος} όροφος) του κτιρίου



Σχήμα 5.10: Κατακόρυφη ρηγμάτωση στη σύνδεση τοίχων(W6-in, 1^{ος} όροφος)



Σχήμα 5.11: Χαρακτηριστική διαγώνια ρηγμάτωση δευτερεύοντος τοίχου



Σχήμα 5.12: Χαγιάτια σε κατάρρευση

5.4 Εκτίμηση βλαβών

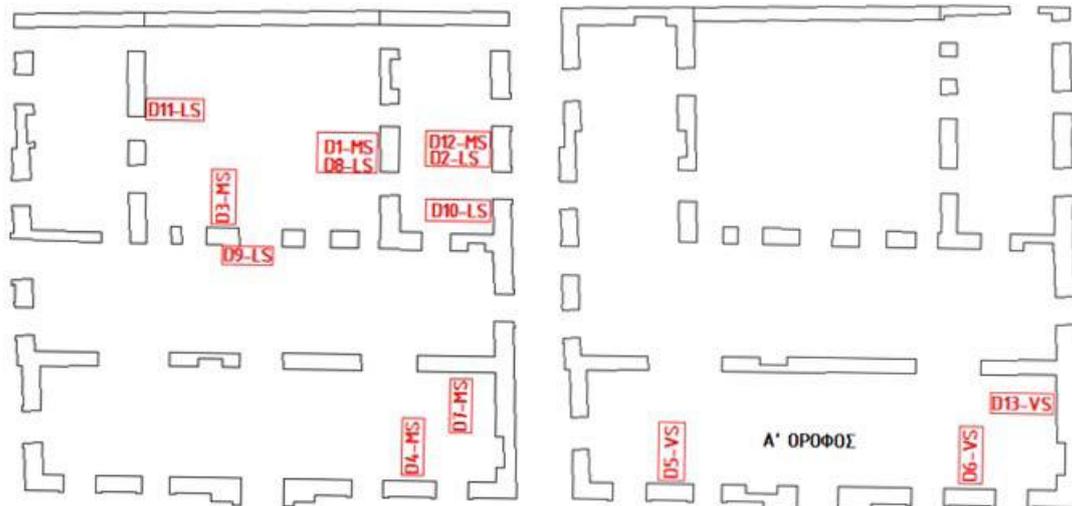
Η εκτίμηση ζημιών αποσκοπεί στην αξιολόγηση της πραγματικής κατάστασης της υφιστάμενης κατασκευής. Όπως στην ιατρική, η διάγνωση προηγείται της θεραπείας (Sullivan και Keane 2004)

5.4.1 Τεκμηρίωση

Η εκτίμηση των χαρακτηριστικών των υλικών τοιχοποιίας συνήθως στοχεύει στον προσδιορισμό των μηχανικών, φυσικών και χημικών ιδιοτήτων και την ανίχνευση ασυνεχειών εντός της κατασκευής. Η εκτίμηση αυτή βασίζεται στην οπτική παρατήρηση, τη δειγματοληψία υλικών και εργαστηριακές δοκιμές των δειγμάτων (διασκεδασμός ακτίνων X (XRD), φθορισμός ακτίνων X (XRF), δοκιμή μονοαξονικής θλίψης)

Δειγματοληψία

Τα κύρια υλικά που χρησιμοποιήθηκαν για την κατασκευή του κτιρίου είναι ασβεστόλιθος, μάρμαρο, ηφαιστειακές πέτρες και κονίαμα. Η δειγματοληψία περιλαμβάνονται όλα τα είδη των λίθων. Πραγματοποιήθηκε είτε με προσεκτική απομάκρυνση σχετικώς μικρού μεγέθους λίθων με χρήση σμίλης είτε με πυρηνοληψία από μεγαλύτερα λιθοσώματα. Τα υλικά και οι τύποι δειγμάτων περιγράφονται στον πίνακα 5.1, ενώ οι θέσεις δειγματοληψίας δίδονται στο ΣΧ. 5.13.



Σχήμα 5.13: Θέσεις δειγματοληψίας στο ισόγειο και 1^ο όροφο του κτιρίου

Πίνακας 5.1: Τύπος δείγματος και θέση δειγματοληψίας

Specimen name	Material type	Specimen type	Sampling location
D1-MS	Marble	Cube	Ground floor
D3-MS	Marble	Cube	Ground floor
D4-MS	Marble	Cube	Ground floor
D5-VS	Volcanic stone	Cube	1 st floor
D6-VS	Volcanic stone	Cube	1 st floor
D7-MS	Marble	Cube	Ground floor
D8-LS	Limestone	Cylinder	Ground floor
D2-LS	Limestone	Cylinder	Ground floor
D9-LS	Limestone	Cylinder	Ground floor
D10-LS	Limestone	Cylinder	Ground floor
D11-LS	Limestone	Cylinder	Ground floor
D12-MS	Marble	Cylinder	Ground floor
D13-VS	Volcanic stone	Cube	1 st floor

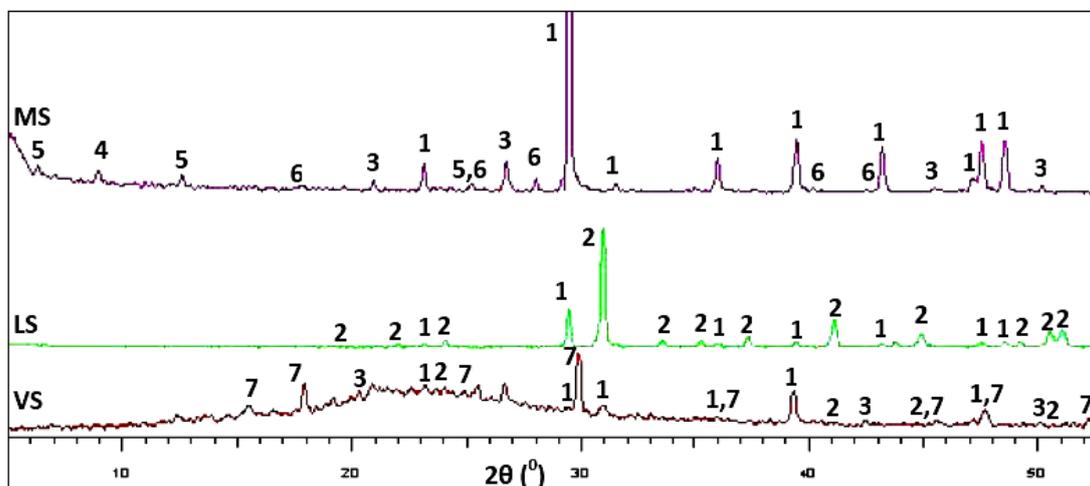
5.4.2 Χημικός και ορυκτολογικός χαρακτηρισμός

Τα αποτελέσματα της χημικής ανάλυσης των φυσικών λίθων παρουσιάζονται στον Πίνακα 5.2

Πίνακας 5.2: Αποτελέσματα χημικής ανάλυσης (% w.w) των λίθινων δοκιμίων

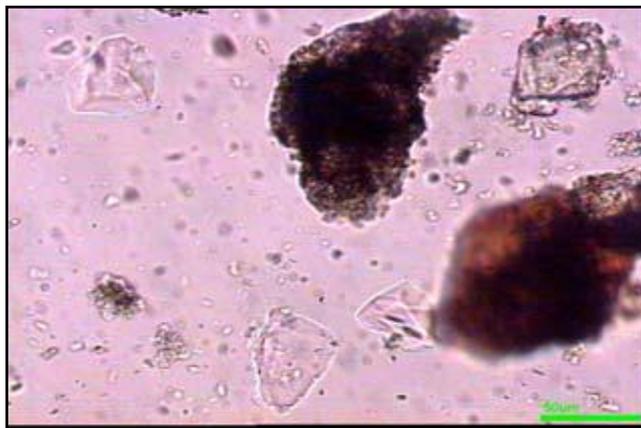
Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	L.O.I
VS	65,87	12,86	0,93	2,21	0,13	2,90	1,27	0,41	13,19
LS	0,83	0,14	0,10	30,50	21,12	-	0,11	-	46,61
MS	0,62	0,21	0,20	55,21	-	0,52	0,10	-	42,60

Τα πρότυπα XRD των εξετασθέντων δειγμάτων παρουσιάζονται στο Σχ. 5.14. Στο δείγμα VS, ένα μεγάλο ποσοστό της άμορφης φάσης καταγράφεται από την ανάλυση XRD, ενώ οι κύριες ορυκτολογικές φάσεις που ανιχνευθήσαν ήταν χαλαζίας, αλουνίτης, δολομίτης, και ασβεστίτης. Το δείγμα MS προέρχεται από μεταμορφωμένα ανθρακικά πετρώματα με μικροκρυσταλλική και κοκκώδη δομή. Η κύρια ορυκτή φάση είναι αυτή του ασβεστίτη. Άλλες φάσεις που καταγράφηκαν είναι αυτές του χαλαζία, μοσχοβίτη, clinochlore, και anorthite. Το δείγμα LS είναι ένα ασβεστολιθικό ορυκτό με κύρια ορυκτολογική φάση το δολομίτη και δευτερεύουσα τον ασβεστίτη.



Σχήμα 5.14: XRD πρότυπα των τριών τύπων υλικών της τοιχοποιίας (LS, MS and VS); 1. Ασβεστίτης, 2. Δολομίτης, 3. Χαλαζίας, 4. Μοσχοβίτης, 5. Clinochlore, 6. anorthite, 7. Αλουνίτη.

Μετά τη χημική ανάλυση, έγινε οπτική μικροσκοπική εξέταση ενός κατάλληλου. Το ίδιο δείγμα, με μέγεθος κόκκου 0,63 χιλι., υποβλήθηκε σε επεξεργασία με 10% w/w 0,1 N HCl οξύ, προκειμένου να διαλυθεί ο ασβεστίτης. Το διηθημένο υπόλοιπο ξηράνθηκε στους 105° C και εξετάστηκε οπτικά στο μικροσκόπιο. Διαπιστώθηκε ότι υπάρχει μια λεπτοθρυμματισμένη υαλώδης φάση στο δείγμα (Σχ. 5.15), η οποία ως επί το πλείστον οφείλεται σε πουζολανικό υλικό.



Σχήμα 5.15. Φωτογραφία από Οπτική μικροσκοπική εξέταση δείγματος

5.4.3 Μηχανικές ιδιότητες

Τα μηχανικά χαρακτηριστικά των δειγμάτων καθορίστηκαν από δοκιμές μοαξονικής θλίψης. Τα δείγματα που λαξεύτηκαν από τους τοίχους χρησιμοποιήθηκαν για την κατασκευή κύβων, ενώ από τα δείγματα της πυρηνοληωίας κατασκευάστηκαν κύλινδροι με αναλογία ύψους-προς-διάμετρο 2. Όλα τα δείγματα ζυγίστηκαν πριν από τη δοκιμή. Οι διαστάσεις και το βάρος των δοκιμίων παρουσιάζονται στους Πίνακες 5.3 και 5.4. Οι κύβοι χρησιμοποιήθηκαν μόνο γιατηνεκτίμηση της αντοχής.

Η αξονική και εγκάρσια ανηγμένη παραμόρφωση μετρήθηκαν τοποθετώντας ηλεκτρομηκυνσιόμετρα στη μεσαία ζώνη των κυλίνδρων σε διαμετρικά απέναντι θέσεις αξονικώς και περιμετρικώς. Ουδιατάξειστων δοκιμών των κύβων και των κυλίνδρων φαίνονται στο Σχ. 5.16. Οι τιμές της αντοχής σε θλίψη δίνονται στον Πίνακα 5.5, ενώ οι τυπικές καμπύλες τάσης-παραμόρφωσης δίδονται στα Σχ. 5.17,5.18 και 5,19.

Πίνακας 5.3: Διαστάσεις και βάρος των κύβων

Specimen name	Material type	Dimensions (cm)			Weight (Kg)
		Side a	Side b	Height	
D1-MS	Marble	5.6	5.4	6.5	0.508
D3-MS	Marble	7.9	7.7	10.5	1.636
D4-MS	Marble	7.9	8.00	8.00	1.364
D5-VS	Volcanic stone	8.2	7.2	8.5	0.556
D6-VS	Volcanic stone	8.2	8.00	7.00	0.490
D7-MS	Marble	5.5	4.5	4.5	0.306
D13-VS	Volcanic stone	8.2	8.0	8.00	0.532

Πίνακας 5.4: Διαστάσεις και βάρος των κυλίνδρων

Specimen name	Material type	Dimensions (cm)		Weight (Kg)
		Diameter	Height	

D8-LS	Limestone	4.5	11.00	0.318
D2-LS	Limestone	4.5	4.5	0.142
D9-LS	Limestone	4.5	11.3	0.438
D10-LS	Limestone	4.5	9.5	0.480
D11-LS	Limestone	4.5	11.00	0.428
D12-MS	Marble	4.5	9.4	0.402



(b)



(b)

Σχήμα 5.15: Διάταξηδοκιμής (α) κύβωνκαι (β) κυλίνδρων

Πίνακας 5.5: Αντοχή σε θλίψη και ειδικό βάρος δοκιμίων

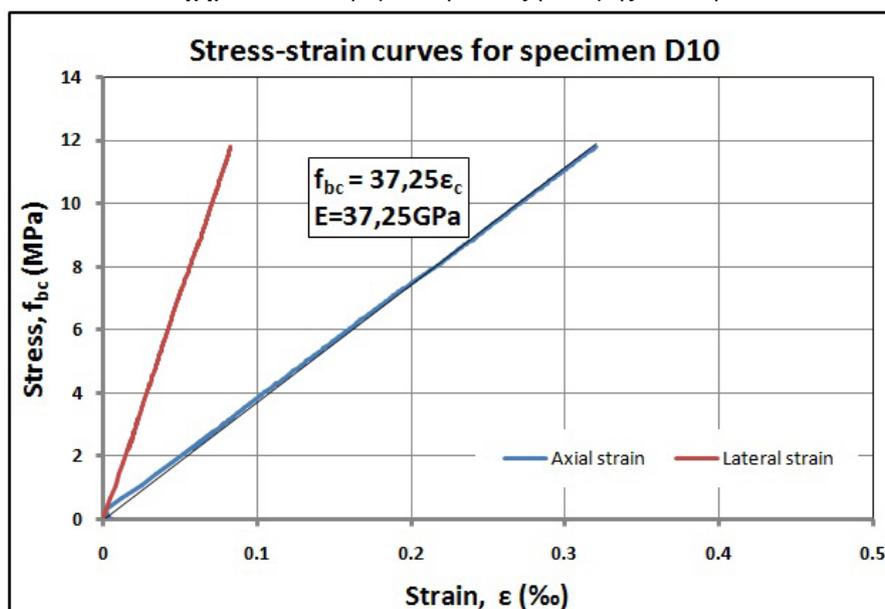
Marble			
Specimen name	Material type	Compressive strength f_{bc} (MPa)	Specific weight (kN/m^3)
D1-MS	Cube	15.76	25.84
D3-MS	Cube	24.31	25.61
D4-MS	Cube	24.10	32.31
D7-MS	Cube	32.90	27.47
D12-MS	Cylinder	29.01	26.91
Mean value		25.21	27.63
Limestone			
D8-LS	Cylinder	18.53	18.19
D2-LS	Cylinder	43.62	16.48
D9-LS	Cylinder	54.10	24.38
D10-LS	Cylinder	18.00	31.79
D11-LS	Cylinder	33.17	10.04

Mean value		33.48	20.18
Volcanic stone			
D5-VS	Cube	4.87	11.10
D6-VS	Cube	5.84	10.67
D13-VS	Cube	5.23	10.13
Mean value		5.31	10.63

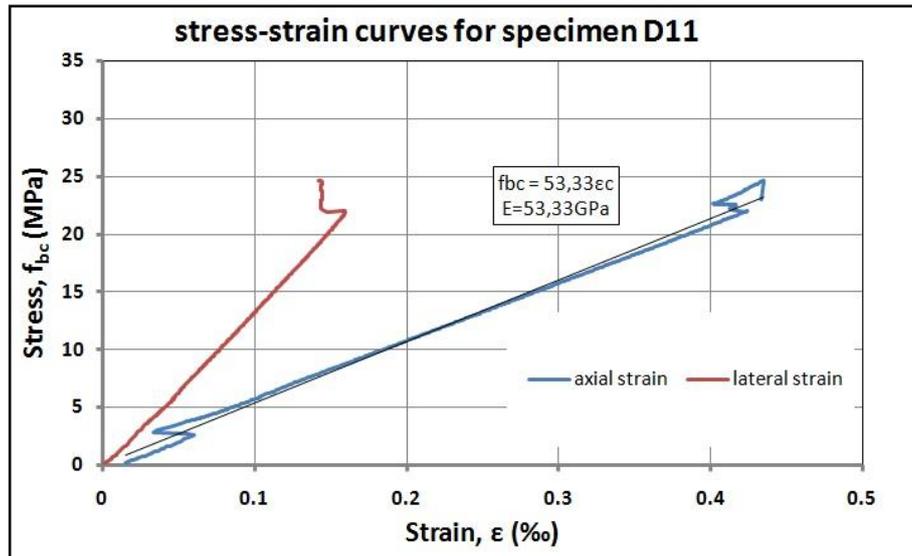
Η μέση θλιπτική αντοχή που προέκυψε από τα πειράματα ήταν 25,2 MPa για το μάρμαρο, 33,5 MPa για τον ασβεστόλιθο και 5,3 MPa για την ελαφρόπετρα. Για κάθε καμπύλη, μόνο ο κλάδος που αντιστοιχεί σε χαμηλό επίπεδο παραμόρφωσης παρουσιάζεται, καθώς για μεγαλύτερες παραμορφώσεις τα ηλεκτρομηκυσιόμετρα δεν αποδίδουν αξιόπιστα, λόγω της τοπικής αποκόλλησής τους από τα δείγματα.



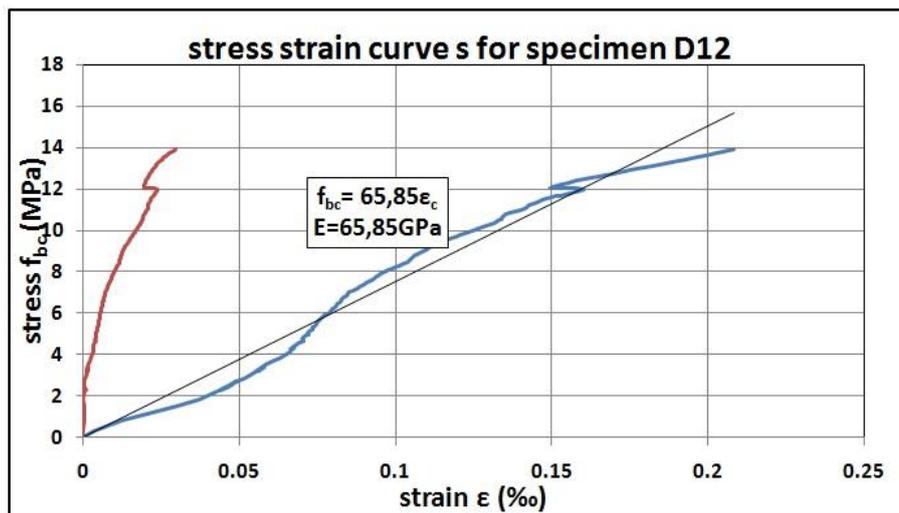
Σχήμα 5.16: Πειραματική διάταξη δοκιμής κυλίνδρων



Σχήμα 5.17: Χαρακτηριστικές καμπύλες τάσεων-ανηγμένων παραμορφώσεων για το δοκίμιο D10 σε μονοαξονική θλίψη



Σχήμα 5.18: Χαρακτηριστικές καμπύλες τάσεων-ανηγμένων παραμορφώσεων για το δοκίμιο D11 σε μονοαξονική θλίψη



Σχήμα 5.19: Χαρακτηριστικές καμπύλες τάσεων-ανηγμένων παραμορφώσεων για το δοκίμιο D12 σε μονοαξονική θλίψη

5.5 Προσδιορισμός των μηχανικών χαρακτηριστικών της τοιχοποιίας

Για την εκτίμηση των μηχανικών χαρακτηριστικών της τοιχοποιίας θεωρήθηκε ότι η θλιπτική αντοχή του κονιάματος ήταν 0,4 MPa. Η αξιολόγηση των μηχανικών χαρακτηριστικών των υλικών τοιχοποιίας βασίστηκε στις πειραματικές τιμές της αντοχής των των δειγμάτων. Οι τιμές αυτές εισήχθησαν στις εμπειρικές σχέσεις που προτάθηκαν από τους Τάσιο και Χρονόπουλο (1987) (βλέπε πίνακα 5.6) και τα χαρακτηριστικά που προέκυψαν δίνονται στον Πίνακα 5.7.

Πίνακας 5.6: Εμπειρικές σχέσεις μέσω των οποίων προσδιορίστηκαν τα μηχανικά χαρακτηριστικά της τοιχοποιίας

	formulae
Horizontal mortar layers – Volume of mortar	25-30mm, V mortar≈0.30/0.40
Material safety factor γ_m	2.00
Wall compressive strength normal (\perp) to horizontal masonry layers ($f_{wc, \perp}$)	$\left(\frac{2}{3}\sqrt{f_{bc}} - a\right) + 0.5 \cdot f_{mc}$
Wall compressive strength parallel (//) to horizontal masonry layers ($f_{wc, //}$)	For incomplete mortar filling $f_{wc, //} = (0.50 - 0.65) \cdot f_{wc, \perp}$
Wall tensile strength normal (\perp) to horizontal masonry layers ($f_{wt, \perp}$)	$f_{wt, \perp} = f_{mt}$
Wall tensile strength normal (//) to horizontal masonry layers ($f_{wt, //}$)	$f_{wt, //} = 2 \cdot f_{mt}$
Shear strength(horizontal sliding)	$f_{wv,0} = 0.05 + 0.25 \cdot \left(\frac{3}{4} \cdot \sigma_o\right) \approx 0.05 + 0.20 \cdot \sigma_o$
Shear strength(diagonal cracking)	$f_{wv,d} = \frac{2}{3} \cdot f_{wt,d} \cdot \sqrt{1 + \frac{0.85 \cdot \sigma_o}{f_{wt,d}}} = f_{mt} \cdot \sqrt{1 + 0.5 \frac{\sigma_o}{f_{mt}}}$
Modulus of elasticity	$E = 800 \cdot f_{wc, \perp}$
Shear modulus	G=0.40E
Poisson's ratio	0.25

Πίνακας 5.7: Μηχανικά χαρακτηριστικά τοιχοποιίας

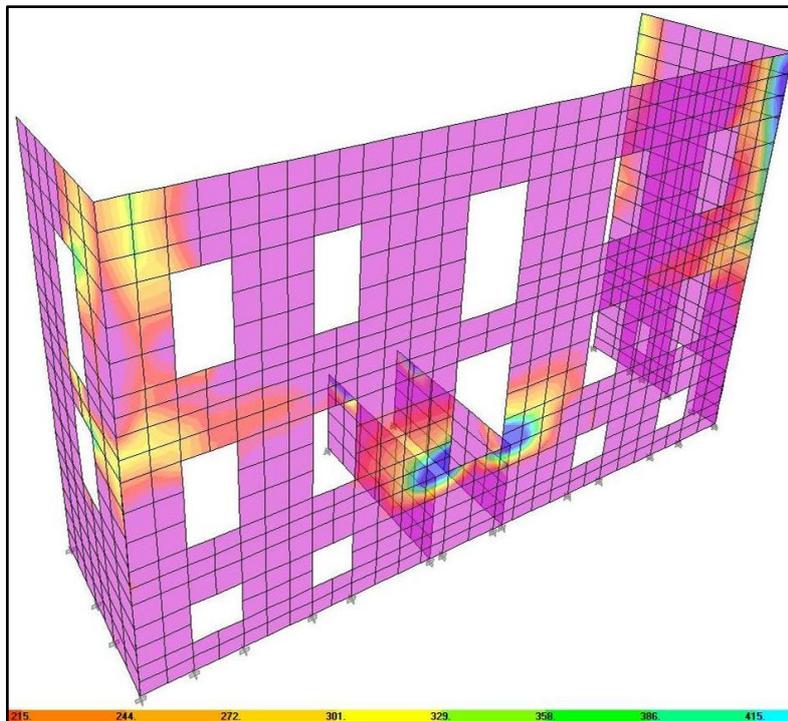
Ground floor					
material	Stone compressive strength, f_{bc} (MPa)	Wall compressive strength, f_{wc} (MPa)	Modulus of Elasticity, E (MPa)	Poisson's ratio, ν	Shear modulus, G (MPa)
Marble	25,21	1,81	1448	0,25	296
Limestone	33,48				
Mean value	29,35				
1 st floor					
Marble	25,21	1,25	1000	0,25	400
Limestone	33,48				
Volcanic stone	5,31				
Mean value	21,33				

5.6 Αριθμητική έρευνα

Ο στόχος της αριθμητικής έρευνας που περιγράφεται ακόλουθα είναι διπλός: (α) να διαπιστωθεί κατά πόσονοι ελλείψεις στα δομικά χαρακτηριστικά του κτιρίου που περιγράφηκαν στα προηγούμενα είναι πράγματι βασική αιτία των ζημιών που έχει υποστεί και (β) αναυτόπράγματι ισχύει, να δειχθεί ότι μια σημαντική βελτίωση της δομικής συμπεριφοράς μπορεί να επιτευχθεί με την εξάλειψη των ελλείψεων. Ο στόχος επιτυγχάνεται με τη σύγκριση των αποτελεσμάτων που προκύπτουν από την αριθμητική ανάλυση του κτιρίου (υποθέτοντας ότι δεν έχει υποστεί βλάβες), πριν και μετά την εξάλειψη των προβλημάτων του δομικού συστήματος υπό δράση των φορτίων που προβλέπονται από τους ισχύοντες κανονισμούς για το σχεδιασμό των κατασκευών ανθεκτικών σε σεισμούς.

5.6.1 Βλάβες στη στέγη του κτιρίου

Οι τάσεις εφελκυσμού που αναπτύσσονται στη στέγη του κτιρίου υπό τις συνθήκες της φόρτωσης σχεδιασμού βρέθηκαν να υπερβαίνουν την αντοχή εφελκυσμού της τοιχοποιίας (βλέπε Σχ. 5.20). Τα αποτελέσματα αυτά είναι σύμφωνα με την εκτίμηση ότι η ρηγμάτωση οφείλεται στις δυνάμεις τριβής που αναπτύσσονται στη στέγη του κτιρίου λόγω της οριζόντιας μετατόπισης της στέγης υπό τη δράση σεισμικών δονήσεων. Η μονολιθική σύνδεση της στέγης με τη φέρουσα τοιχοποιία αναμένεται να οδηγήσει σε σημαντική βελτίωση της συμπεριφοράς.



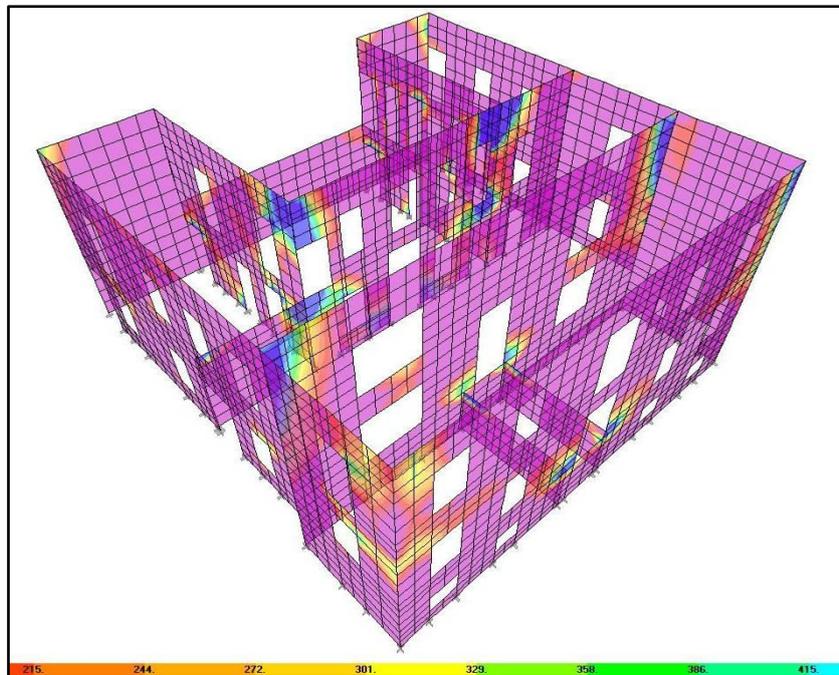
Σχήμα 5.20: Εφελκυστικές τάσεις (σε MPa) μεγαλύτερες της εφελκυστικής αντοχής της τοιχοποιίας που αναπτύσσονται στη στέγη του κτιρίου υπό σεισμικό φορτίο κατά τη διεύθυνση y-y (κατά μήκος της πρόσοψης του κτιρίου επί της οδού Ακταίου)

5.6.2 Ρηγμάτωση στη σύνδεση τοιχωμάτων

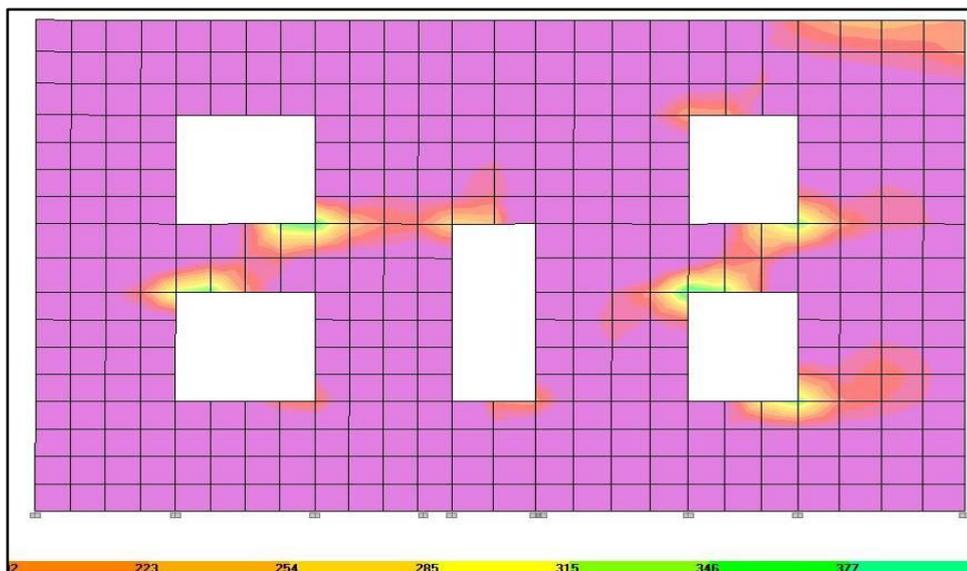
Το Σχ. 5.21 δείχνει τις τάσεις εφελκυσμού στην περιοχή των τεμνόμενων τοιχωμάτων που υπερβαίνουν την αντοχή σε εφελκυσμό της τοιχοποιίας. Θα πρέπει να σημειωθεί ότι έχει υποθεθεί ότι τοιχώματα είναι μονολιθικά συνδεδεμένα και αυτό οδήγησε στην ανάπτυξη των κρίσιμων τάσεων εφελκυσμού αναπτυσθών σε μία μικρή απόσταση από τη σύνδεση του τοίχου

5.6.3 Ρηγμάτωση των υπέρθυρων

Το Σχ. 5.22 δείχνει τις τάσεις που υπερβαίνουν την αντοχή σε εφελκυσμό της τοιχοποιίας στην περιοχή των ανοιγμάτων ενός τυπικού εσωτερικού τοιχώματος στην κατεύθυνση X-X (δηλαδή παράλληλα προς την πρόσοψη του κτιρίου επί της οδού Λυκομιδών). Όπως και στην περίπτωση της ρηγμάτωσης της στέγης, η ρηγμάτωση αυτή αποδίδεται στην έλλειψη μονολιθικής σύνδεσης της στέγης στη φέρουσα τοιχοποιία που οδήγησε στην ανάπτυξη δυνάμεων τριβής στη στέγη λόγω της οριζόντιας μετατόπισης της στέγης υπό σεισμικό φορτίο.



Σχήμα 5.21: Εφελκυστικές τάσεις (σε MPa) μεγαλύτερες της εφελκυστικής αντοχής της τοιχοποιίας που αναπτύσσονται στην περιοχή σύνδεσης τοιχωμάτων υπό σεισμικό φορτίο κατά τη διεύθυνση y-y (κατά μήκος της πρόσοψης του κτιρίου επί της οδού Ακταίου)



Σχήμα 5.22: Εφελκυστικές τάσεις (σε MPa) μεγαλύτερες της εφελκυστικής αντοχής της τοιχοποιίας που αναπτύσσονται στην περιοχή των ανοιγμάτων ενός τυπικού εσωτερικού τοιχώματος στην διεύθυνση x-x (κατά μήκος της πρόσοψης του κτιρίου επί της οδού Λυκομιδών)

5.6.4 Βλάβες πεσσών

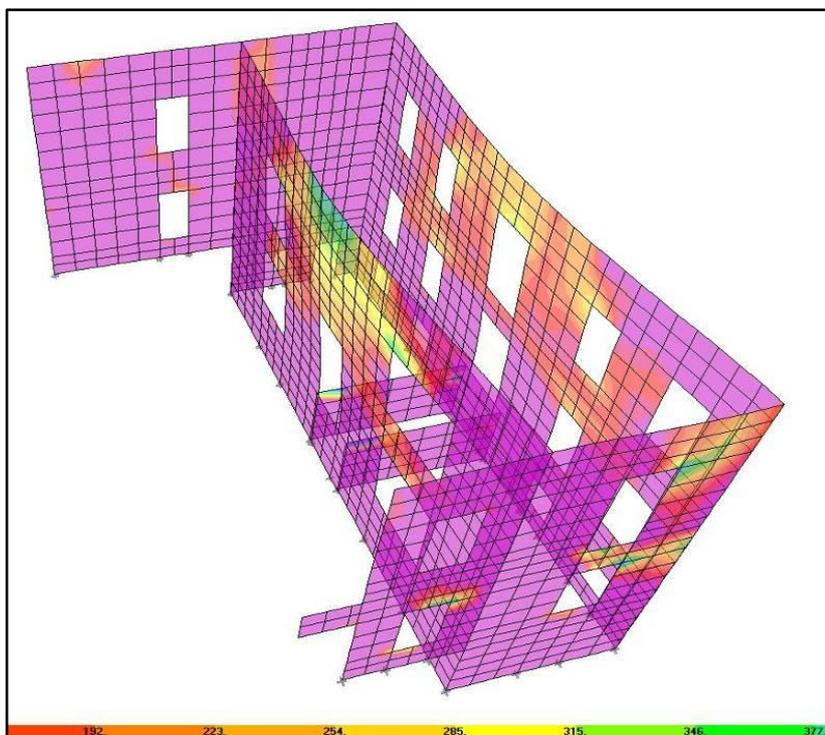
Στο Σχ. 5.23 φαίνεται το παραμορφωμένο σχήμα του τοιχώματος που προβλέπεται από την ανάλυση. Το σχήμα δείχνει ότι η έλλειψη διαφραγμάτων οδήγησε σε εκτός-επιπέδου παραμόρφωση των τοιχωμάτων 1 και 5 υπό σεισμική δράση στην διεύθυνση X-X. Το σχήμα δείχνει επίσης ότι μια τέτοια εκτός επιπέδου μετατόπιση προκάλεσε εφελκυστικές τάσεις μεγαλύτερες αυτών που μπορεί να αναληφθούν από την τοιχοποιία. Η ανάπτυξη τέτοιων τάσεων είναι επαρκής για να προκαλέσει ρηγμάτωση που υπέστησαν οι πεσσοί.

5.6.5 Σχολιασμός

Από τις παρατηρηθείσες βλάβες του κτιρίου και τον εντοπισμό των αιτίων τους τόσο οπτικά όσο και από τα αποτελέσματα της ανάλυσης, φαίνεται ότι αν και ο φέρων οργανισμός του κτιρίου έχει ορισμένα θετικά δομικά χαρακτηριστικά, αυτά συνδυάζονται με σημαντικές ελλείψεις. Τα θετικά χαρακτηριστικά περιλαμβάνουν ανοίγματα (δύο πόρτες και παράθυρα) με ένα σχετικά μικρό πλάτος τοποθετημένα σχεδόν συμμετρικά. Επίσης, το πλάτος της φέρουσας τοιχοποιίας είναι τουλάχιστον 0,50 μ, ενώ το ύψος των ορόφων είναι περίπου 4,00 μ. Έτσι, υποθέτοντας διαφραγματική δράση των επιπέδων δαπέδου και οροφής, η λυγνότητα του τοιχώματος $\lambda = 8$ είναι μάλλον μικρή. Επιπλέον, η σύνδεση τεμνόμενων τοιχωμάτων βρίσκεται να είναι αρκετά μονολιθική.

Από την άλλη πλευρά, ένα σημαντικό μειονέκτημα του κτιρίου είναι η έλλειψη της διαφραγματικής λειτουργίας στα επίπεδα των δαπέδων και της οροφής που θα συνέβαλε στην μονολιθική απόκριση του κτιρίου υπό σεισμική διέγερση. Ένα άλλο μειονέκτημα είναι η έλλειψη των εγκάρσιων τοιχωμάτων που να συνδέουν τους δύο παράλληλους μεγάλους μήκους φέροντες τοίχους (τοιχώματα 1 και 5) κατά μήκος της πρόσοψης του κτιρίου στην οδό Ακταίου. Η έλλειψη τέτοιων τοιχωμάτων

αυξάνει την πιθανότητα εκτός-επιπέδου μετατοπίσεων των τοιχωμάτων. Τέλος, η απουσία μονολιθικής σύνδεσης της στέγης στην φέρουσα τοιχοποιία έχει αρνητική επίδραση στη αλληλεπίδραση φέρουσας τοιχοποιίας-στέγης.



Σχήμα 5.23: Παραμορφωμένο σχήμα και εφελκυστικές τάσεις μεγαλύτερες από τηνεφελκυστική αντοχή της τοιχοποιίας (σε MPa) που αναπτύσσονται στους στους υπό τη συνδυασμένη δράση του φορτίου λειτουργίας και σεισμικής δόνησης κατά την διεύθυνση x-x

5.7 Προτεινόμενες επεμβάσεις

Οι επεμβάσεις που προτείνονται παρακάτω στοχεύουν στο να ξεπεραστούν τα παραπάνω μειονεκτήματα ώστε να βελτιωθεί η αντισεισμικότητα του κτιρίου με τρόπο που θα επιτρέπει την επαναχρησιμοποίηση του, σύμφωνα με τις προθέσεις του ιδιοκτήτη. Οι προτεινόμενες επεμβάσεις περιλαμβάνουν:

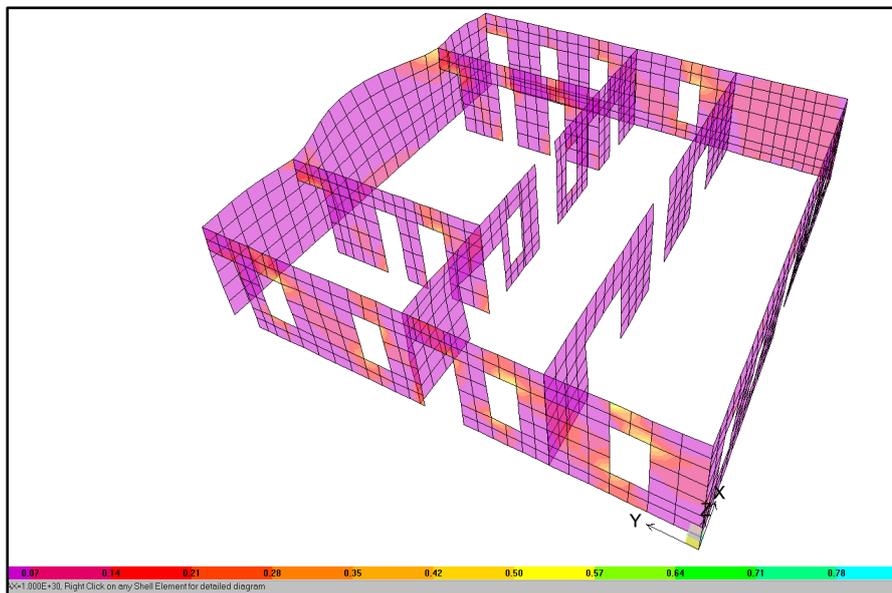
- Βελτίωση των μηχανικών ιδιοτήτων της τοιχοποιίας με κονίαμα αρμολόγησης.
- Εσωτερική και εξωτερική βελτίωση της μονολιθικότητας στο επίπεδο του ισογείου με την κατασκευή μιας πλάκας οπλισμένου σκυροδέματος πάχους 0,25 μ .
- Ενίσχυση των δοκών του δαπέδου του 1^{ου} ορόφου με πλευρικές λάμες/πλάκες και ανακατασκευή του δαπέδου με χρήση των δύο διασταυρούμενων στρωμάτων κόντρα πλακέ, έτσι ώστε να σχηματισθεί ένα ισχυρό διάφραγμα συνδεδεμένο με τα περιμετρικάφέροντα τοιχώματα με διαγώνιες μεταλλικές λάμες.
- Αντικατάσταση της υπάρχουσας οροφής με οροφή της ίδιας μορφολογίας, μονολιθικά συνδεδεμένη με τη στέγη του κτιρίου με μια στρώση από

οπλισμένο σκυρόδεμα, και ανάπτυξη διαφραγματικής λειτουργίας μέσω της χρήσης μεταλλικών ράβδων σε δισδιαγώνια διάταξη.

5.8 Έλεγχος της αποτελεσματικότητας των προτεινόμενων επεμβάσεων

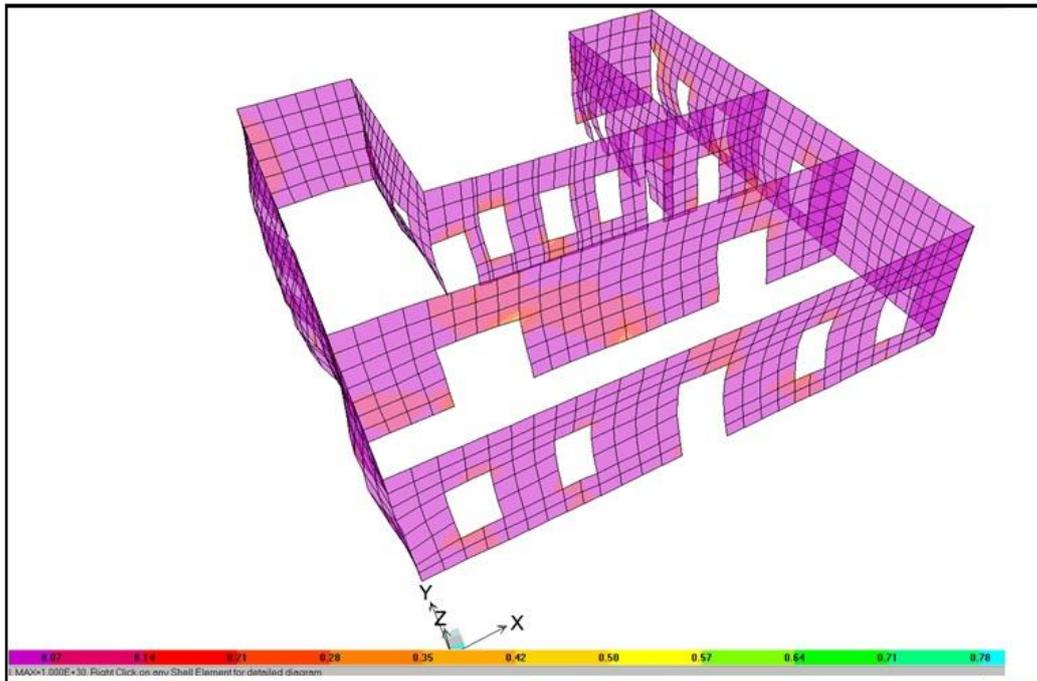
Εις τα επόμενα αποδεικνύεται η αποτελεσματικότητα των προτεινόμενων παρεμβάσεων για την αποφυγή βλαβών όπως αυτές που περιγράφονται στις προηγούμενες ενότητες. Η αποτελεσματικότητα των επεμβάσεων γίνεται φανερή από την εντατική κατάσταση της τοιχοποιίας, μετά τις επεμβάσεις, υπό τη δράση του επιβαλλόμενου φορτίου που σύμφωνα με τις ισχύουσες κανονιστικές διατάξεις.

Τα Σχ. 5.24 και 5.25 παρουσιάζουν τις τιμές και τις περιοχές των κύριων τάσεων εφελκυσμού, πέραν εκείνων που μπορούν να αναληφθούν από την τοιχοποιία, που αναπτύσσονται στα τοιχώματα του 1^{ου} ορόφου κατά τις διευθύνσεις y-y και x-x, αντίστοιχα. Οι τιμές και οι περιοχές των κύριων τάσεων εφελκυσμού, πέραν εκείνων που μπορούν να αναληφθούν από την τοιχοποιία, που αναπτύσσονται στα τοιχώματα του ισογείου παρουσιάζονται στα Σχ. 5.25 και 5.26. Συγκρίνοντας την εντατική κατάσταση που απεικονίζεται στα Σχ. 5.20 - 5.23 με αυτή που απεικονίζεται στα Σχ. 5.24 - 5.27 φαίνεται ότι οι τιμές των εφελκυστικών τάσεων που αναπτύσσονται μετά τις προτεινόμενες επεμβάσεις μειώνονται σημαντικά. Οι παραμένουσες τάσεις με τιμές μεγαλύτερες από την αντοχή της τοιχοποιίας προτείνεται να αναληφθούν από ελαφρώς οπλισμένο επίχρισμα.

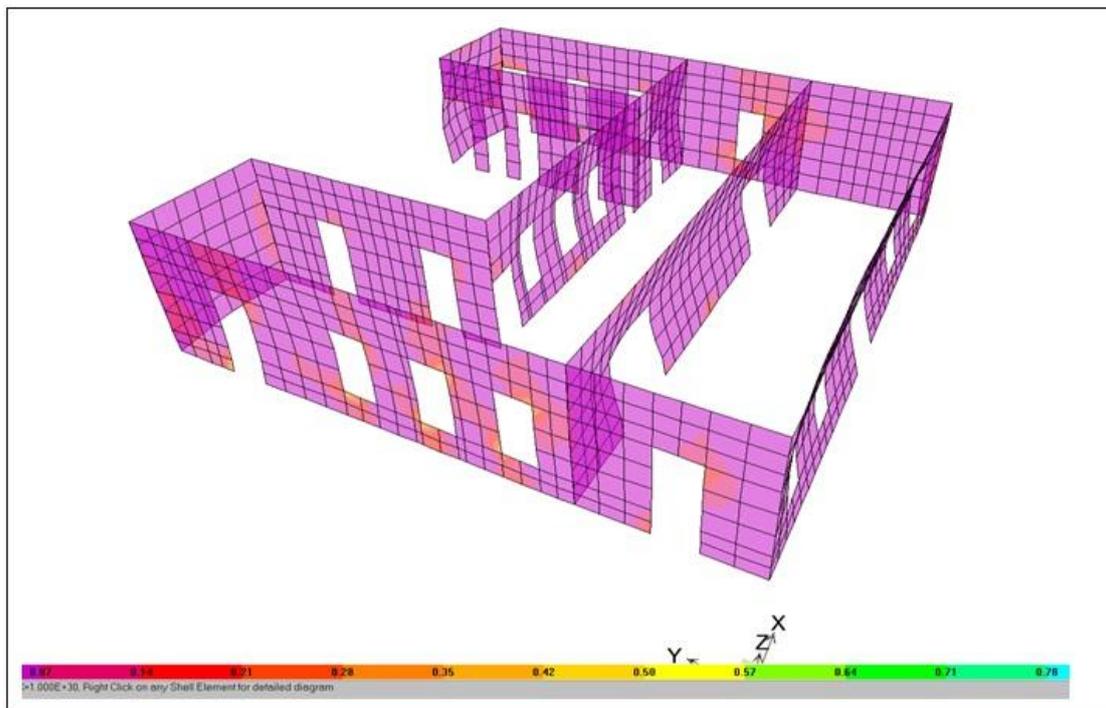


Σχήμα 5.24: Περιοχές κυρίων τάσεων με τιμές (σε MPa) μεγαλύτερες από την αντοχή της τοιχοποιίας σε εφελκυσμό που αναπτύσσονται από σεισμική δράση στα τοιχία του 1^{ου} ορόφου κατά τη διεύθυνση y-y

Τα Σχ. 5.28 και 5.29 δείχνουν τις περιοχές και τις τιμές θλιπτικών τάσεων που αναπτύσσονται στα τοιχία υπό σεισμική δράση στις διευθύνσεις y-y και x-x, αντίστοιχα. Από τα σχήματα φαίνεται ότι σε όλες τις περιπτώσεις οι τιμές των θλιπτικών τάσεων είναι μικρότερες από την θλιπτική αντοχή της τοιχοποιίας.



Σχήμα 5.25: Περιοχές και τιμές εφελκυστικών τάσεων (σε MPa) μεγαλύτερες από την αντοχή της τοιχοποιίας σε εφελκυσμό που αναπτύσσονται στα τοιχεία του 1^{ου} ορόφου υπό σεισμική δράση κατά τη διεύθυνση x-x.



Σχήμα 5.26: Περιοχές και τιμές εφελκυστικών τάσεων (σε MPa) μεγαλύτερες από την αντοχή της τοιχοποιίας σε εφελκυσμό που αναπτύσσονται στα τοιχεία του υπογείου υπό σεισμική δράση κατά τη διεύθυνση y-y.

