Numerical modelling of the seismic behaviour of adobe buildings

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in EARTHQUAKE ENGINEERING

by

Sabino Nicola Tarque Ruiz

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ABSTRACT

In this research, the possibility to numerical describing the seismic behaviour of adobe constructions through finite element models is studied. Principally, two experimental tests were reproduced: a cyclic in-plane test on an adobe wall and a dynamic test on an adobe module, both carried out at the Pontificia Universidad Católica del Perú, Peru, where the thesis’ author have participated. The state-of-the-art for the numerical modelling of unreinforced masonry point to three main approaches: macro-modelling, simplified micro-modelling and detailed micro-modelling. The first one related to continuum models and the last two approaches are related to discrete models. In all three approaches, the use of elastic and inelastic parameters is required. For adobe masonry, the lack of knowledge concerning some of the material mechanical properties, especially in tension and shear, makes numerical modelling more difficult.

The results of tests on adobe blocks (i.e. compression strength, elasticity modulus, shear strength), as well as the results of cyclic and dynamic tests on adobe masonry components and adobe modules show that the mechanical properties of adobe masonry highly depend on the type of soil used for the production of units and mortar. Basic properties, such as elasticity modulus, can have significant variation from one soil type to another. The adobe material is characterized as a brittle material; it has acceptable compression strength but it is poor regarding tensile and shear strength.

Here, the mechanical properties of the adobe masonry used in the model for the simulation of the cyclic in-plane experimental response were calibrated to match well the global lateral strength-deformation response of the adobe wall and its crack pattern evolution. The adobe masonry studied is representative of the Peruvian adobe constructions. Macro-modelling (smeared crack and damaged plasticity models) and simplified micro-modelling (discrete model) strategies were used in finite element software with an implicit solution strategy. After verification of the results it was preliminary concluded that a macro-modelling strategy could be used for adobe masonry. The lack of accurate material properties for the mud mortar joints ends with convergence problems when dealing with the simplified micro-modelling.
Then, the dynamic test of an adobe module was reproduced with a continuum model (damaged plasticity model) following an implicit and an explicit solution strategy, and using the material properties derived in the calibration. The comparison in terms of relative displacements and crack patterns in all the adobe walls studied showed a good agreement between the numerical and experimental results. Also, it was seen that an explicit solution strategy could be beneficial for analyzing adobe constructions due to its improvement in the calculation speed.

The result of this work is a benchmark for the numerical analysis of adobe walls under seismic actions. Since the adobe masonry can be considered as a homogeneous material, the macro-modelling (continuum model) approach, based on a damaged plasticity model, is a good option for modelling adobe structures. Finally, the proposed material parameters for numerical modelling predict well the adobe walls seismic capacity and the damage evolution. Therefore, the proposed mechanical parameters and methodology for numerical analyses could be used for modelling more complex configurations of unreinforced adobe walls: historical and vernacular.

Key words: non-linear finite element analysis, adobe masonry, material properties, discrete and continuum models, seismic analysis.
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# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... v

ACKNOWLEDGEMENTS ........................................................................................................................... vii

TABLE OF CONTENTS ........................................................................................................................... ix

LIST OF FIGURES ................................................................................................................................. xv

LIST OF TABLES .................................................................................................................................... xxv

1. INTRODUCTION ................................................................................................................................ 1
   1.1 GENERAL ........................................................................................................................................ 1
   1.2 JUSTIFICATION ............................................................................................................................... 2
   1.3 ASSUMPTIONS ............................................................................................................................... 2
   1.4 OBJECTIVES .................................................................................................................................. 3
   1.5 THESIS OUTLINE ........................................................................................................................... 3

2. ADOBE HOUSES IN PERU ................................................................................................................ 7
   2.1 GENERALITIES ............................................................................................................................ 7
   2.2 EVOLUTION OF THE ADOBE CONSTRUCTION IN PERU [VARGAS ET AL. 2005] ................. 10
   2.3 SEISMIC BEHAVIOUR OF UNREINFORCED AND REINFORCED ADOBE STRUCTURES .......... 14
      2.3.1 The simple earth material, unreinforced adobe structures ............................................... 14
      2.3.2 Seismic behaviour of unreinforced adobe houses .............................................................. 14
      2.3.3 The earthquake-resistant reinforced adobe buildings ....................................................... 21
2.4 SUMMARY....................................................................................................................................... 27

3. EXPERIMENTAL TESTS ON ADOBE MATERIAL ........................................................................... 29

3.1 COMPRESSION TESTS ON ADOBE CUBES .................................................................................. 29

3.2 COMPRESSION TESTS ON ADOBE PRISMS.................................................................................. 30

3.2.1 Specimens.................................................................................................................................. 30

3.2.2 Testing......................................................................................................................................... 31

3.2.3 Results......................................................................................................................................... 31

3.3 DIAGONAL COMPRESSION TEST ON ADOBE WALLETS ............................................................... 34

3.3.1 Specimens.................................................................................................................................. 34

3.3.2 Testing......................................................................................................................................... 34

3.3.3 Results......................................................................................................................................... 35

3.4 STATIC SHEAR WALL TESTS ............................................................................................................ 37

3.4.1 Specimens.................................................................................................................................. 37

3.4.2 Tests............................................................................................................................................ 38

3.4.3 Results......................................................................................................................................... 39

3.5 CYCLIC TESTS................................................................................................................................... 39

3.5.1 Specimens.................................................................................................................................. 39

3.5.2 Tests............................................................................................................................................ 42

3.5.3 Results......................................................................................................................................... 43

3.5.4 Evaluation of the elasticity modulus......................................................................................... 45

3.6 DYNAMIC TESTS............................................................................................................................... 50

3.6.1 Specimens.................................................................................................................................. 50

3.6.2 Shake table description.............................................................................................................. 52
3.6.3 Test ........................................................................................................................... 53
3.6.4 Results. .................................................................................................................... 55
3.7 SUMMARY ................................................................................................................... 60
4. REVIEW OF NUMERICAL MODELS APPLIED TO MASONRY STRUCTURES............. 63
4.1 FROM MICRO-MODELLING TO MACRO-MODELLING............................................. 63
4.2 FINITE ELEMENT APPROACHES FOR MASONRY MODELLING ............................... 69
   4.2.1 Fracture mechanics approach: discrete model (micro-modelling) ......................... 70
   4.2.2 Continuum mechanics approach: plasticity and damage mechanics (macro
modeling) ..................................................................................................................... 71
4.3 EXAMPLES OF NUMERICAL MODELLING ON MASONRY PANELS ....................... 73
4.4 SUMMARY ................................................................................................................... 78
5. DISCRETE AND CONTINUUM MODELS FOR REPRESENTING THE SEISMIC
BEHAVIOUR OF MASONRY ......................................................................................... 79
5.1 REVIEW OF THEORY OF PLASTICITY......................................................................... 79
   5.1.1 Fundamentals .................................................................................................. 80
   5.1.2 Yield criterion........................................................................................................ 80
   5.1.3 Flow rule .............................................................................................................. 82
   5.1.4 Hardening/softening behaviour .......................................................................... 83
5.2 DISCRETE MODEL: COMPOSITE CRACKING-SHEARING-CRASHING MODEL ........ 85
   5.2.1 Two-dimensional interface model .................................................................... 87
   5.2.2 Three-dimensional interface model .................................................................. 93
5.3 SMEARED CRACK MODEL: DECOMPOSED-STRAIN MODEL ................................. 95
   5.3.1 Uncracked state material ..................................................................................... 96
   5.3.2 Cracked state material ....................................................................................... 96
5.3.3 Crack fracture parameters

5.4 SMEARED CRACK MODEL: TOTAL-STRAIN MODEL

5.4.1 Compressive behaviour with lateral cracking

5.5 DAMAGED PLASTICITY MODEL

5.5.1 Strain rate decomposition

5.5.2 Stress-strain relations

5.5.3 Hardening variables

5.5.4 Yield function

5.5.5 Damage and stiffness degradation under uniaxial condition

5.6 COMPRESSION AND TENSION CONSTITUTIVE LAWS

5.6.1 Compression models

5.6.2 Tension models

5.7 SUMMARY

6. NON-LINEAR PSEUDO-STATIC ANALYSIS OF ADOBE WALLS

6.1 IMPLICIT SOLUTION METHOD FOR SOLVING QUASI-STATIC PROBLEMS

6.2 DISCRETE MODEL: MODELLING THE PUSHOVER RESPONSE OF AN ADOBE WALL

6.2.1 Calibration of material properties

6.2.2 Results of the pushover analysis considering a discrete model

6.3 TOTAL-STRAIN MODEL: MODELLING THE PUSHOVER RESPONSE

6.3.1 Calibration of material properties

6.3.2 Results of the pushover analysis considering a total-strain model

6.4 CONCRETE DAMAGED PLASTICITY: MODELLING THE PUSHOVER RESPONSE

6.4.1 Results of the pushover response considering the concrete damaged plasticity model
6.5 CONCRETE DAMAGED PLASTICITY: MODELLING THE CYCLIC BEHAVIOUR ..........................139

6.5.1 Calibration of stiffness recovery and damage factors .............................................140

6.6 VIBRATION MODES ........................................................................................................152

6.7 ENERGY BALANCE FOR QUASI-STATIC ANALYSIS ..................................................154

6.8 SUMMARY ......................................................................................................................155

7. NON-LINEAR DYNAMIC ANALYSIS OF AN ADOBE MODULE ...............................157

7.1 SOLUTION APPROACHES FOR SOLVING DYNAMIC PROBLEMS ..........................157

7.1.1 Governing equations .............................................................................................157

7.1.2 Implicit analysis ....................................................................................................159

7.1.3 Explicit analysis .....................................................................................................160

7.2 IMPLICIT FINITE ELEMENT ANALYSIS OF THE ADOBE MODULE .............................162

7.2.1 Model 1 ..................................................................................................................164

7.2.2 Model 2 ..................................................................................................................166

7.2.3 Model 3 ..................................................................................................................167

7.2.4 Model 4 ..................................................................................................................167

7.2.5 Model 5 ..................................................................................................................169

7.2.6 Model 6 ..................................................................................................................170

7.2.7 Model 7 ..................................................................................................................172

7.2.8 Model 8 ..................................................................................................................173

7.3 EXPLICIT FINITE ELEMENT ANALYSIS .................................................................175

7.3.1 Model 9 ..................................................................................................................176

7.3.2 Model 10 ...............................................................................................................178

7.3.3 Model 11 ...............................................................................................................179
7.3.4 Model 12....................................................................................................................... 180
7.3.5 Model 13....................................................................................................................... 182
7.4 VIBRATION MODES ........................................................................................................... 186
7.5 ENERGY BALANCE ............................................................................................................ 189
7.6 SUMMARY......................................................................................................................... 190

8. SUMMARY AND CONCLUSIONS ...................................................................................... 193

REFERENCES .................................................................................................................... 199

APPENDIX A. Comparison of the experimental and numerical relative displacement response of the adobe module. Implicit analysis................................................................. 211
APPENDIX B. Comparison of the experimental and numerical total acceleration response of the adobe module. Implicit analysis............................................................................... 221
APPENDIX C. Comparison of the experimental and numerical relative displacement response of the adobe module. Explicit analysis................................................................. 231
APPENDIX D. Comparison of the experimental and numerical total acceleration response of the adobe module. Explicit analysis............................................................................... 237
LIST OF FIGURES

Figure 2.1. Map of earthen constructions around the world.................................................................8
Figure 2.2. Typical Peruvian adobe houses. ............................................................................................8
Figure 2.3. Construction process of a tapial wall [Minke 2005].................................................................9
Figure 2.4. Construction process of a quincha panel.................................................................10
Figure 2.5. Drawing of the ancient Caral city built in adobe.................................................................10
Figure 2.6. Temple of Pachacamac, ancient temple built in adobe. .........................................................11
Figure 2.7. Chan-Chan city (Trujillo, Peru). .........................................................................................11
Figure 2.8. Views of Carabayllo church ...............................................................................................12
Figure 2.9. Colonial adobe houses of two and three storeys in Lima, Peru...........................................13
Figure 2.10. A vernacular adobe house located in Cusco (Peru) with no adequate geometrical configuration [Vargas et al. 2006].................................................................13
Figure 2.11. Destruction of adobe houses due to earthquakes ............................................................15
Figure 2.12. Vertical crack at the corner of an adobe house produced during the Pisco earthquake in 2007, Peru .................................................................16
Figure 2.13. Collapse of adobe houses during the Pisco earthquake in 2007, Peru.................................16
Figure 2.14. Diagonal cracks produced in the adobe houses located at block corners, Pisco earthquake 2007 .................................................................17
Figure 2.15. Typical X-shape cracks on adobe walls due to in-plane actions .......................................17
Figure 2.16. Configuration of typical roofs of adobe houses located in Pisco, Peru...............................18
Figure 2.17. Seismic deficiencies on adobe masonry [CENAPRED 2003] ..............................................18
Figure 2.18. Typical failure damage on adobe masonry according to Dowling [2004].................20
Figure 2.19. Typical types of damage observed in historic adobe buildings after the Northridge earthquake [Webster and Tolles 2000].................................................................21
Figure 2.20. Internal cane mesh reinforcement.................................................................22
Figure 2.21. Adobe models after seismic tests at the Pontificia Universidad Católica del Perú [Ottazzi et al. 1989]......................................................................................................23
Figure 2.22. External wire mesh reinforcement.................................................................24
Figure 2.23. Existing adobe buildings with external wire mesh reinforcement.......................24
Figure 2.24. External plastic (geogrid) mesh reinforcement................................................25
Figure 2.25. Adobe model reinforced with plastic mesh.....................................................26
Figure 2.26. Sketch of the prototype model of the scaled adobe module [Tolles and Krawinkler 1990]..............................................................................................................................27
Figure 3.1. Dry process of adobe bricks.................................................................29
Figure 3.2. Compression test on an adobe prism...............................................................31
Figure 3.3. Stress-strain curves for axial compression tests on adobe prisms (modified from Blondet and Vargas [1978]). F-1 and F-2 refers to the lateral deformeters, while F-3 refers to the upper deformeters .........................................................33
Figure 3.4. Scheme of the diagonal compression test (modified from NMX-C-085-ONNCE [2002]).................................................................................................................................34
Figure 3.5. Diagonal compression tests on adobe wallets.................................................35
Figure 3.6. Scheme of the adobe walls for static shear test carried out by Blondet and Vargas [1978].................................................................................................................................38
Figure 3.7. Scheme of the adobe walls for static shear test carried out by Vargas and Ottazzi [1981].................................................................................................................................38
Figure 3.8. Adobe walls for static shear tests [Blondet and Vargas 1978]..............................39
Figure 3.9. Adobe walls subjected to the cyclic test.........................................................40
Figure 3.10. Scheme of the adobe walls for cyclic test [Blondet et al. 2005]......................40
Figure 3.11. Scheme of the reinforced concrete ring beams [Blondet et al. 2005]..................41
Figure 3.12. Detail of load application and instrumentation on the adobe walls [Blondet et al. 2005].................................................................................................................................41
Figure 3.13. Load application history for the cyclic tests.............................................................42
Figure 3.14. Hysteretic curves and crack pattern of the adobe walls subjected to the cyclic tests [Blondet et al. 2005; 2008]. All the right figures refer to the end of the cyclic tests...................................................................................................................44
Figure 3.15. Envelope of the hysteretic curves (positive and negative branch) from the cyclic tests........................................................................................................................................45
Figure 3.16. Scheme for evaluating the lateral stiffness of the adobe wall I-1..........................47
Figure 3.17. Estimation of effective flange widths in structural walls (modified from Paulay and Priestley [1992])..........................................................................................................49
Figure 3.18. Scheme of the adobe module subjected to a dynamic test [Blondet et al. 2005]....50
Figure 3.19. Views of the adobe module subjected to the dynamic test.....................................51
Figure 3.20. Position of accelerometers and LVDTs on the adobe module...............................52
Figure 3.21. Horizontal acceleration record from May 1970 Peruvian earthquake, component N08W, registered in Lima...............................................................53
Figure 3.22. Views of the adobe module during and after the dynamic test..............................54
Figure 3.23. Displacement input at the base, Phase 1.................................................................55
Figure 3.24. Relative displacement history during Phase 1..........................................................56
Figure 3.25. Total acceleration history during Phase 1.................................................................57
Figure 3.26. Displacement input at the base, Phase 2.................................................................58
Figure 3.27. Relative displacement history during Phase 2........................................................58
Figure 3.28. Total acceleration history during Phase 2...............................................................59
Figure 3.29. Rotation history between Right and Left Wall during Phase 2...............................60
Figure 4.1. Modelling strategies for masonry structures (modified from Lourenço [1996]).......64
Figure 4.2. Masonry failure mechanisms [Lourenço 1996]..........................................................65
Figure 4.3. Composite yield surface model proposed by Lourenço [1996]........................................66
Figure 4.4. Test scheme and sequence of loads of the masonry wall analyzed by Lourenço [1996]........................................................................................................................................67
Figure 4.5. Experimental crack patterns for different masonry walls analyzed by Lourenço [1996]........................................................................................................................................67
Figure 4.6. Comparison of experimental and analytical pushover curves [Lourenço 1996].................68
Figure 4.7. Analysis of Kuçuk Ayasofya Mosque (Istanbul) by Roca et al. [2010] following a macro modelling approach...............................................................................................69
Figure 4.8. Concrete crack models [Midas FEA v2.9.6 2009]. ........................................................69
Figure 4.9. Stress-displacement diagrams for quasi brittle materials [Lourenço 1996].......................70
Figure 4.10. Constitutive law for masonry composite (stress-strain curves)....................................71
Figure 4.11. Orthogonal crack models [Midas FEA v2.9.6 2009].......................................................72
Figure 4.12. Analysis of numerical results of an unreinforced masonry wall made by Lotfi and Shing [1994]..........................................................................................................................73
Figure 4.13. Finite element discretization of masonry infill [Stavridis and Shing 2010].....................74
Figure 4.14. Comparison of pushover curves analyzed by Stavridis and Shing [2010]......................74
Figure 4.15. Numerical failure pattern of the masonry infill wall analyzed by Stavridis and Shing [2010]........................................................................................................................................75
Figure 4.16. Mohr Coulomb with tension cut-off inelastic failure surface [Attard et al. 2007]........................................................................................................................................75
Figure 4.17. Modelling of masonry units by Attard et al. [2007]........................................................76
Figure 4.18. Experimental test and analytical approach of an URM building [Yi 2004]......................77
Figure 4.19. Solid spandrel-cracked pier perforated URM wall model [Yi 2004]...............................78
Figure 5.1. Representation of a general yield surface (modified from Saouma [2000])......................81
Figure 5.2. Failure criteria for biaxial stress state illustrated for plane stress state (Modified from Jirasek and Bažant [2002])..........................................................................................81
Figure 5.3. Representation of associated and non-associated flow rule [Roca et al. 2010].

Figure 5.4. Movement of the yield surfaces. $\sigma_1$ and $\sigma_2$ are the principal stresses (modified from Cruz et al. [2004]).

Figure 5.5. Normal and tangential relative traction and displacement in 2D.

Figure 5.6. Normal and tangential relative traction and displacement in 3D.

Figure 5.7. Simplified representation of bricks and mortar joints into a numerical model [Lourenço 1996].

Figure 5.8. Numerical and experimental shear behaviour of mortar joints reported by Lourenço [1996].

Figure 5.9. Numerical and experimental tensional behaviour of mortar joints reported by Lourenço [1996].

Figure 5.10. Hardening/softening compression law for masonry [Lourenço 1996].

Figure 5.11. Three-dimensional interface yield function (modified from Midas FEA v2.9.6 [2009]).

Figure 5.12. Decomposition of strains [Lotfi and Espandar 2004].

Figure 5.13. Relative displacements and tractions of the crack in the local coordinate system [Cruz et al. 2004].

Figure 5.14. Loading and unloading behaviour of the Total Strain Crack model [Midas FEA v2.9.6 2009].

Figure 5.15. Response of concrete under compression and tension loads implemented in Abaqus for the damaged plasticity model (modified from Wawrzynek and Cinco [2005]).

Figure 5.16. Yield surface for the plane stress space (modified from Wawrzynek and Cinco [2005]).

Figure 5.17. Yield surface in the deviatoric plane corresponding to different values of $K_c$ [Abaqus 6.9 SIMULIA 2009].

Figure 5.18. Uniaxial load cycle behaviour for the damaged plasticity model in Abaqus 6.9 SIMULIA [2009].
Figure 5.19. Effect of the compression recovery parameter $w_c$ [Abaqus 6.9 SIMULIA 2009].

Figure 5.20. Parabolic compression curve used for modelling masonry material.

Figure 5.21. Tension models.

Figure 6.1. Iteration process for an implicit solution.

Figure 6.2. Finite element model of the adobe wall subjected to horizontal displacement loads at the top. Discrete model, Midas FEA.

Figure 6.3. Comparison of the pushover curves in models with different penalty stiffness values. Discrete model, Midas FEA.

Figure 6.4. Variation of tensile strength $f_i$ at the interface, $G_{ij}^t = 0.0008 \text{ N/mm}, b = 15 \text{ mm}$.

Figure 6.5. Influence of the tensile strength $f_i$ on the pushover response. Discrete model, Midas FEA.

Figure 6.6. Variation of fracture energy $G_{ij}^t$ at the interface, constant $f_i = 0.01 \text{ MPa}, b = 15 \text{ mm}$.

Figure 6.7. Influence of the fracture energy in tension $G_{ij}^t$ on the pushover response. Discrete model, Midas FEA.

Figure 6.8. Variation of compression strength $f_c$ at the interface, constant $G_{ij}^c = 0.02 \text{ N/mm}, b = 115 \text{ mm}$.

Figure 6.9. Influence of compression strength $f_c$ on the pushover response. Discrete model, Midas FEA.

Figure 6.10. Variation of fracture energy $G_{ij}^c$ at the interface, constant $f_i = 0.25 \text{ MPa}, b = 115 \text{ mm}$.

Figure 6.11. Variation of $k_p$ for the compression curve, constant $f_c = 0.25 \text{ MPa}$ and $G_{ij}^c = 0.02 \text{ N/mm}, b = 115 \text{ mm}$.
Figure 6.12. Influence of the shear fracture energy $G_f^{II}$ at the interface on the pushover response. Discrete model, Midas FEA.................................................................124

Figure 6.13. Damage pattern of the adobe wall subjected to a horizontal top displacement. .................................................................125

Figure 6.14. Experimental damage pattern for wall I-1 due to cyclic displacements applied at the top. Just the adobe wall is shown here, the concrete beam and foundation are hidden, [Blondet et al. 2005]. ........................................................................126

Figure 6.15. Load-displacement diagrams, experimental and numerical. .................................................................126

Figure 6.16. Finite element model of the adobe wall subjected to horizontal displacement loads at the top. Total-strain model, Midas FEA.................................................................127

Figure 6.17. Comparison of the pushover curves in models with different $E$ Total-strain model........................................................................................................................128

Figure 6.18. Variation of tensile strength for total-strain model, constant $f_t = 0.01$ $N/mm$, $b = 141.4 mm$. ........................................................................................................128

Figure 6.19. Influence of the tensile strength $f_t$ on the pushover response. Total-strain model, Midas FEA.................................................................129

Figure 6.20. Variation of fracture energy $G_f^{I}$ for total-strain model, constant $f_t = 0.04$ $MPa$, $b = 141.4 mm$. ........................................................................................................129

Figure 6.21. Influence of the fracture energy in tension $G_f^{I}$ on the pushover response. Total-strain model, Midas FEA.................................................................130

Figure 6.22. Influence of the shear retention factor $\beta$ on the pushover response. Total-strain model, Midas FEA.................................................................131

Figure 6.23. Variation of compression strength $f_c$ for total-strain model. Relation $G_f^{C} / f_c = 0.344 \text{ mm}$ in all cases, $b = 141.4 \text{ mm.}$ ........................................................................................................131

Figure 6.24. Influence of the compression strength $f_c$ on the pushover response. Total-strain model, Midas FEA.................................................................132

Figure 6.25. Damage evolution of the wall subjected to a horizontal top load (4 displacement levels). The top and bottom concrete beam and the lintel are hidden. Total-strain model, Midas FEA.................................................................132
Figure 6.26. Evolution of maximum principal stresses in the adobe wall subjected to a horizontal top displacement. Total-strain model, Midas FEA........................................134

Figure 6.27. Deformation of the adobe wall due to a maximum horizontal top displacement of 9.34 mm. Total-strain model, Midas FEA........................................134

Figure 6.28. Finite element model of the adobe wall subjected to horizontal displacement loads at the top. Concrete Damaged Plasticity model, Abaqus/Standard...........135

Figure 6.29. Influence of tensile strength $f_t$ on the pushover response. Concrete damaged plasticity model, Abaqus/Standard.................................................................136

Figure 6.30. Influence of compression strength $f_c$ on the pushover response. Concrete damaged plasticity model, Abaqus/Standard.................................................................137

Figure 6.31. Deformation of the adobe wall due to a maximum horizontal top displacement of 10 mm. Concrete damaged plasticity model, Abaqus/Standard.................................................................137

Figure 6.32. Evolution of maximum in-plane plastic strain in the adobe wall subjected to a horizontal top displacement. Concrete damaged plasticity model, Abaqus/Standard.................................................................138

Figure 6.33. Evolution of maximum principal stresses in the adobe wall subjected to a horizontal top displacement. Concrete damaged plasticity model, Abaqus/Standard.................................................................139

Figure 6.34. History of static horizontal displacement load applied to the numerical model. ......140

Figure 6.35. Comparison of the experimental and numerical cyclic behaviour of the adobe wall taking into account variability in the recovery stiffness and damage factors, in tension and compression. Horizontal load applied on the left part of the top concrete beam. ......................................................................................................145

Figure 6.36 Finite element model of the adobe wall considering both ends of the top concrete beam for application of the cyclic horizontal displacement. Concrete Damaged Plasticity model, Abaqus/Standard.................................................................148

Figure 6.37. Comparison of the experimental and numerical cyclic behaviour of the adobe wall taking into account variability in the recovery stiffness and damage factors, in tension and compression. Horizontal load applied at both ends of the top concrete beam. ......................................................................................................149

Figure 6.38. Formation process of the tensile plastic strain on the adobe wall under cyclic loads. A non unique legend in placed each to each figure to visualize better the plastic strain. Concrete damaged plasticity model, Abaqus/Standard...........150
Figure 6.39. Tensile damage factor for Model 28 at the end of the history of cyclic horizontal displacement load. .................................................................151

Figure 6.40. Contribution of the modes of vibration in the X-X direction until reaches the 90% of the total mass of the model. .................................................................152

Figure 6.41. Modes of vibration in the X-X direction. .................................................................153

Figure 6.42. Energy balance for Model 28, non-linear static analysis with concrete damaged plasticity model in Abaqus/Standard. ............................................................155

Figure 7.1. Views of the right and left wall of the adobe module. ...............................................163

Figure 7.2. Views of the roof of the adobe module. .................................................................163

Figure 7.3. Input acceleration at the base for dynamic analysis. This acceleration belongs to the Phase 2 of the experimental test. .................................................................164

Figure 7.4. Finite element model for dynamic analysis: Model 1. ..............................................164

Figure 7.5. Results of Model 1 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 14.53 \( s \). .................................................................165

Figure 7.6. Displacement history of the right and rear wall of Model 1. The analysis stops at 14.53 \( s \). ......................................................................................165

Figure 7.7. Results of Model 2 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 10.44 \( s \). .................................................................166

Figure 7.8. Results of Model 3 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 10.60 \( s \). .................................................................167

Figure 7.9. Finite element model for dynamic analysis: Model 1. ..............................................168

Figure 7.10. Results of Model 4 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 8.59 \( s \). .................................................................168

Figure 7.11. Finite element model for dynamic analysis: Model 5. ............................................169

Figure 7.12. Results of Model 5 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 8.62 \( s \). .................................................................170

Figure 7.13. Finite element model for dynamic analysis: Model 1. ............................................171

Figure 7.14. Results of Model 6 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 5.86 \( s \). .................................................................171
Figure 7.15. Finite element model for dynamic analysis: Model 7.................................172

Figure 7.16. Results of Model 7 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 9.11 s.................................................................172

Figure 7.17. Finite element model for dynamic analysis: Model 8.................................173

Figure 7.18. Displacement history of the left and rear wall of Model 8. The analysis stops at 10.46 s..................................................................................174

Figure 7.19. Results of Model 8 with concrete damaged plasticity in Abaqus/Standard. The analysis stops at 10.46 s.................................................................174

Figure 7.20. Displacement history of the walls of the Model 9........................................177

Figure 7.21. Results of Model 9 with concrete damaged plasticity in Abaqus/Explicit........178

Figure 7.22. Results of Model 10 with concrete damaged plasticity in Abaqus/Explicit........179

Figure 7.23. Displacement history of the walls of the Model 11.........................................180

Figure 7.24. Results of Model 11 with concrete damaged plasticity in Abaqus/Explicit........180

Figure 7.25. Results of Model 12 with concrete damaged plasticity in Abaqus/Explicit........181

Figure 7.26. Displacement history of the walls of the Model 12.........................................181

Figure 7.27. Results of Model 13 with concrete damaged plasticity in Abaqus/Explicit........183

Figure 7.28. Tensile damage factor for Model 13 at the end of the analysis in Abaqus/Explicit.................................................................183

Figure 7.29. Displacement history of the walls of the Model 13.........................................184

Figure 7.30. Progressive of the tensile plastic strain of the numerical model, (1) Cracking due to bending, (2) Cracking due to in-plane forces, (3) Vertical cracking, (4) Crushing.................................................................185

Figure 7.31. Contribution of the modes of vibration for reaching the 90% of the total mass in the X-X and Z-Z horizontal direction.........................................................187

Figure 7.32. Modes of vibration in the horizontal direction for the numerical model........188

Figure 7.33. Energy balance for Model 13, non-linear dynamic analysis with concrete damaged plasticity model in Abaqus/Explicit.........................................................190
# LIST OF TABLES

Table 3.1. Results of compression tests on adobe cubes. .................................................................30  
Table 3.2. Results of compression tests on adobe prisms carried out by Blondet and Vargas [1978]..................................................................................................................32  
Table 3.3. Results of compression tests on adobe prisms carried out by Vargas and Ottazzi [1981]..................................................................................................................32  
Table 3.4. Results of diagonal compression tests on adobe wallets carried out by Vargas and Ottazzi [1981]. ..................................................................................................35  
Table 3.5. Characteristics of adobe walls for static shear test [Blondet and Vargas 1978]..........................................................................................................................37  
Table 3.6. Description of damage on the walls subjected to the cyclic tests. .................................42  
Table 6.1. Elastic material properties of the adobe blocks, concrete and timber materials. ......................................................................................................................117  
Table 6.2. Variation of elasticity of module of the mortar joints for evaluating the penalty stiffness $k_s$ and $k_t$. ............................................................118  
Table 6.3. Preliminary material properties for the interface model (mortar joints). ...............................119  
Table 6.4. Material properties for the adobe masonry within total-strain model. ............................127  
Table 6.5. Material properties for the adobe masonry within concrete damaged plasticity model. ..............................................................................................................135  
Table 6.6. Proposed compression damage factor: $D_{c-1}$. .................................................................140  
Table 6.7. Proposed tensile damage factor: $D_{t-1}$. ...........................................................................141  
Table 6.8. Proposed tensile damage factor: $D_{t-2}$. ...........................................................................141  
Table 6.9. Proposed tensile damage factor: $D_{t-3}$. ...........................................................................141
Table 6.10. Proposed tensile damage factor: Dt-4................................................................. 141
Table 6.11. Proposed tensile damage factor: Dt-5................................................................. 142
Table 6.12. Proposed tensile damage factor: Dt-6................................................................. 142
Table 6.13. Proposed tensile damage factor: Dt-7................................................................. 142
Table 6.14. Proposed tensile damage factor: Dt-8................................................................. 142
Table 6.15. Proposed tensile damage factor: Dt-9................................................................. 143
Table 6.16. Proposed tensile damage factor: Dt-10............................................................... 143
Table 6.17. Values of the frequency and period of vibrations of the numerical model in the X-X direction.......................................................... 154
Table 7.1. Values of the frequency and period of vibrations of the numerical model in the horizontal direction.......................................................... 187
1. INTRODUCTION

1.1 GENERAL

Adobe is a Spanish word derived from the Arabic atob, which literally means sun-dried brick, and it is one of the oldest and most widely used natural building materials, especially in developing countries (Latin America, Middle East, north and south of Africa, etc) where there is also a moderate to high seismic hazard. The use of sun-dried blocks dates back to 8000 B.C. and till the last century was estimated that around 30% of the world’s population lives in earth-made construction [Houben and Guillard 1994]. Adobe and adobe construction have some attractive characteristics, such as low cost, local availability, self/owner-made or the need for only unskilled labour (hence the term “non-engineered constructions”), good thermal insulation and acoustic properties [Memari and Kauffman 2005].

Adobe buildings have high seismic vulnerability due to the low tension strength of the material, which ends in an undesirable combination of mechanical properties for these constructions, namely: 1) earthen structures are massive and thus attract large inertia forces; 2) they are weak and cannot resist these forces; and, 3) they are brittle and collapse without warning [Blondet et al. 2006]. The seismic capacity of an adobe house depends on the individual block mechanical characteristics, building location and design, and on the quality of the construction and maintenance [Dowling 2004]. Each time an earthquake occurs in a region with abundant earth-construction, enormous social and economical losses are recorded, as has been the case in El Salvador (2001), Iran (2003), Peru (1970, 1996, 2001 and 2007), Pakistan (2005), China (2008 and 2009).

Around the world only few universities and laboratories have been studied the seismic behaviour of adobe constructions (e.g Pontificia Universidad Católica del Perú, University of Aveiro in Portugal, University of Basilicata in Italy, The Getty Conservation Institute in USA, Stanford University in USA, Institute of Earthquake Engineering and Engineering Seismology in Republic of Macedonia, Saitama University in Japan). The author of this thesis was involved into the dynamic experimental campaign for analyzing the seismic behaviour of unreinforced and reinforced adobe dwellings at the Pontificia Universidad Católica del Perú [Blondet et al. 2006] with partial support from the Getty Conservation Institute (GCI).
The tests for material characterization of adobe blocks as well as cyclic and dynamic tests reveal that the adobe mechanical properties (i.e. compression strength, elasticity modulus, shear strength, etc.) and the seismic performance of adobe constructions highly depend on the type of soil used for the production of units and mortar (i.e. Vargas et al. [2005], Yamin et al. [2004], Liberatore et al. [2006], Silveira et al. [2007]).

The analysis of the mechanical behaviour of adobe constructions still represents a true challenge. In this sense, researchers have been modelling the seismic behaviour of unreinforced masonry structures (URM), where adobe buildings can be included. However, little works for specific numerical modelling of adobe constructions (such as monuments or dwellings) has been done and the approach can focus to the micro-modelling of the individual components (bricks and mortar) or to the macro-modelling of masonry as a composite.

One of the major difficulties for numerical modelling of adobe constructions is the lack of information about material properties (especially the inelastic ones) and, in some cases, the geometric and structural complexity of the buildings. However, some calibration of the material properties and some simplifications for the geometry can be done (by using a finite element or discrete element method) in order to have good approximation of the seismic behaviour of adobe constructions, as presented in this work.

1.2 JUSTIFICATION

In some countries, especially those located in South-America and the Middle East, there exist many adobe constructions, from monuments until dwellings. The seismic behaviour of these buildings is not adequate. In order to reduce the inherent high seismic risk of these buildings, it is important to implement an adequate methodology to study their seismic behaviour through experimental and numerical modelling. Since dynamic tests are costly, a good alternative for analyzing the seismic vulnerability of adobe buildings -and therefore the justification of this work- is through numerical modelling.

1.3 ASSUMPTIONS

The main assumption of this research is that it is possible to generate numerical models to represent the dynamic behaviour of adobe buildings, serving as a tool for vulnerability assessment of constructions and risk analysis of sites.

Another assumption concerns the finite element approaches developed for the analysis of concrete and masonry panels; these models can be used for representing the behaviour of the adobe masonry, treated as an isotropic material.
1.4 Objectives

The general objective of this work is to calibrate the material properties of the adobe masonry for assessing the seismic vulnerability of adobe constructions through non-linear dynamic analyses.

The specific objectives of this research are:

1) To gather information about the material properties of adobe bricks, and pseudo-static and dynamic tests carried out on adobe constructions;
2) To better understand the seismic behaviour of adobe dwellings subjected to earthquakes;
3) To numerically represent the failure pattern and seismic capacity of cyclic and dynamic tests carried out on adobe masonry.

1.5 Thesis Outline

The thesis is organized as follows: Chapter 2 presents a summary of the evolution of adobe construction in Peru, initiating from Caral city, which is considered the oldest American city funded around 3000 BC, until the present time. The poor geometrical configuration of vernacular adobe dwellings is discussed too, especially the ones located at the coastal sub-urban areas which typically host families with low income. Peru is a country with tradition in constructing with adobe. Nowadays, the total adobe construction represents about 43% of the total number of buildings. Based on a survey of damage carried out after the last big Peruvian earthquake (2007), the seismic behaviour of unreinforced and reinforced adobe dwellings is also discussed. Different materials for seismic reinforcement of adobe building are presented based on researches carried out mainly at the Pontificia Universidad Católica del Perú (PUCP).

The principal input data in any numerical analysis are the properties of the studied material, in this case the adobe masonry. Chapter 3 summarizes the experimental tests carried out at the Pontificia Universidad Católica del Perú, which started in the early 80’s with compression and diagonal tests on adobe masonry and shear tests on full adobe walls. Besides, the results of cyclic and dynamic tests carried out on adobe walls and adobe modules, respectively, are analyzed in terms of failure pattern and seismic capacity. These last tests were carried out in 2004 and 2005 with the participation of the thesis’s author. The analyzed data from the static tests allows to compute the elasticity modulus, shear modulus, compression and tension strength of the adobe masonry; while the pseudo-static and dynamic results allow the calibration of the principal material properties (especially in the inelastic part) for matching the failure pattern of the numerical models developed in the following chapters.
The numerical analysis of unreinforced masonry structures (URM) has been studied by many authors and a summary of these analyses is presented in Chapter 4. Generally, the modelling analyses are based on a micro or macro modelling. The first assumes discontinuities between the masonry components (mortar and bricks), while the second assumes a distributed damage all over the masonry panel without distinction between mortar and bricks. In this thesis the finite element models used for analysis of cracking and damage on masonry and concrete panels are used for the evaluation of the seismic capacity of the adobe masonry.

Chapter 5 presents the theory of the finite element approaches for modelling the cracking and damage of concrete and masonry panels. These approaches are used in this thesis for the analysis of the adobe walls. Besides, a review of the theory of plasticity is presented with emphasis on the concepts of yield criterion, flow rule and softening/hardening law. As previously states, two main approaches exist for masonry analysis: the micro and macro modelling. For micro modelling a review of the composite model developed by Lourenço [1996] is presented. The finite element programme Midas FEA makes uses of this composite model. For macro-modelling a smeared crack model and a damaged plasticity model are discussed and used in this thesis with two programmes: Midas FEA and Abaqus (Standard and Explicit). At the end, constitutive laws for tension and compression behaviour of material such as adobe, masonry or concrete are described.

Taking advantage of the cyclic tests carried out by Blondet et al. [2005] and using the preliminary properties shown before, the material parameters both elastic and inelastic of the adobe masonry for loading and unloading are calibrated in Chapter 6. These material parameters -which are the input data for finite element models- should represent the failure pattern and seismic capacity of the tested adobe wall. Two finite element programmes are used here: Midas FEA and Abaqus/Standard, in both cases especial attention is given for the solution method and for the control parameters in order to avoid convergence problems. The first programme includes the composite model developed by Lourenço [1996] and a discrete analysis is performed. The adobe wall is also modelled using a smeared crack approach in Midas FEA and a concrete damaged plasticity model in Abaqus/Standard.

In Chapter 7 the dynamic analysis carried out by Blondet et al. [2006] on an adobe module is modelled using Abaqus/Standard and Abaqus/Explicit. The principal difference between these two methods is the way how the nodal accelerations, nodal velocities and nodal displacements are computed. The material properties used are the ones calibrated in Chapter 6. The experimental model was subjected to three levels of displacement records at the base, in this thesis just the second level is reproduced since it was related to the initiation of damage on the adobe walls. This chapter ends with the comparison
between the displacements records of the best numerical model and the experimental results.

Finally, Chapter 8 contains a summary of the work and explains the conclusions of the thesis. It also discusses and points to further research on modelling of adobe structures with different configurations but using the proposed material properties and modelling.
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2. ADOBE HOUSES IN PERU

Adobe is one of the oldest materials used for civil and monumental constructions. It dates back to 8000 B.C. [Houben and Guillard 1994]. Archeological evidence shows entire cities built of raw earth, such as Jericho, history’s earliest city; Catal Hunyuk in Turkey; Harappa and Mohenjo-Daro in Pakistan; Akhlet-Aton in Egypt; Chan-Chan in Peru; Babylon in Iraq; Dueros near Cordoba in Spain and Khirouqta in Cyprus [Easton 2007]. The adobe brick is composed mainly of mud (clay, sand and silt), straw and water, and can be cast into a desired form. The straw is added to the bricks in order to reduce the cracking due to drying. The adobe constructions are relatively easy and fast to build; generally bricks are placed on top at each other with mud mortar.

Adobe was mostly used in areas with sparse water and vast open space but has been used effectively in cooler locations as well. When temperatures are low, adobe walls absorb and radiate heat throughout the house when the sun goes down. In the summer, the temperature in the house remains comfortable. In deserts, for example, where the climate is characterized by hot days and cool nights, the high thermal mass of adobe levels out the heat transfer through the wall to the living space.

In Peru, the adobe material is considered a traditional material. The majority of adobe dwellings can be found in the highlands cities, such as Cusco where more than 75% of the total buildings are made of adobe. Cusco is located at 3400 m altitude. However, unreinforced adobe constructions have a low seismic strength; they are considered brittle and use to collapse mainly by wall disconnection (out-of-plane actions). In this chapter, a brief review of the evolution of Peruvian adobe constructions and the analysis of the seismic behaviour of unreinforced and reinforced adobe houses is presented. Seismic reinforcement studied by professionals and researchers is also presented.

2.1 GENERALITIES

According to Houben and Guillard [1994] 30% of the world’s population lives in earth-made constructions, with approximately 50% of them located to developing countries. Adobe constructions are very common in some of the world’s most hazard-prone regions, such as Latin America, Africa, The Indian subcontinent and other parts of Asia, The Middle East and Southern Europe [Blondet et al. 2003]. Figure 2.1 compares the distribution of earthen constructions with the seismic hazard in the world.
In Peru, the percentage of the country’s population living in earth dwellings has gone down from 54% to 43% in the last 15 years [INEI 2008] with most of the concentration in urban and coastline areas. Figure 2.2 shows some typical Peruvian adobe dwellings located at the countryside. In other countries, such as in India, there is a vast concentration of adobe houses. According to the 1971 Indian Census, 73% of the total building population is made with earth.

Similar to adobe, there exist other techniques for building with earth, such as tapial and quincha. The term tapial or tapia is derived from Arabic, tabiya, which indicates a mould for the realization of a packed earth wall. The origin of the word “quincha” goes far back in time and derives from “quichu”, in ancient Quechua language.

Jurina and Righetti [2008] reports that the tapial, as it is called in Latin America, or pise in Europe or rammed earth in the USA, stands for a building technique in packed earth with
rather thick walls (a minimum of 40 cm) made by compressing earth into lateral shapes (mobile moulds) which are progressively shifted upwards, as work proceeds (Figure 2.3). In this way parts of walls take shape. These parts are about 2-3 m long, about 0.80 m high, and of a thickness which usually tapers off upwards.

Jurina and Righetti [2008] define the quincha as follows: “The *Quincha* is a technique in which the earth and cane are utilized as a secondary filling element (Figure 2.4). The mixture, to which straw – or plaster – cement/lime are sometimes added to, is useful in covering up a structure, in another material, made up of wooden supporting elements and by a plugging feature in vertical or horizontal rushes fixed to such a structure and united to one another. The earth here fulfils the function of customary plaster. Round or square wood is utilized indistinctly, in order to create the supporting external frame which is then plugged with matting of rushes joined to one another by means of nails, iron wire, cord, vegetable fibre or slender strips of cow or sheep”.

Figure 2.3. Construction process of a tapial wall [Minke 2005].
2.2 Evolution of the Adobe Construction in Peru [Vargas et al. 2005]

Peru is located in a high seismic hazard zone where three cultures used the soil for construction: the pre-Inca, the Inca and the Spanish culture. The main used technologies included the adobe, the rammed earth and the quincha (wooden frame infilled with cane and soil).

Caral city, the oldest city in America (3000 B.C.) located 200 km at the north of Lima, shows the use of the three mention methodologies plus some stone masonry, which are still visible today [Vargas et al. 2005], (Figure 2.5). The Caral constructors used bags to carry the stones that were used for the construction of the pyramids. The complex of Caral—which was considered metropolis—included houses, an amphitheatre, temples and 19 pyramids.
Numerical modelling of the seismic behaviour of adobe buildings

Near Lima there are more than 300 important archeological sites, where the most important is the Temple of Pachacamac (Figure 2.6). The old part of this temple was built around 200 B.C. It was made in adobe and was used by the Incas till the arrival of the Spanish in XVI century.

![Figure 2.6. Temple of Pachacamac, ancient temple built in adobe.](http://www.latinotravel.com.pe/images/fotosp/pachacamac.jpg)

The Mochica civilization (100-800 A.D.) centered in Trujillo (in northern Peru) bequeathed posterity with the grand remains of two main huge temples built with adobes called Huaca del Sol (342 m long, 159 m wide and 45 m high, today largely degraded) and Huaca de la Luna, evidence of a work method concerning various and independent groups of producers. Another example of adobe construction is the citadel of Chan-Chan, located in Trujillo, which was built between 600 to 700 A.D. This citadel has an area around 20 km². It is estimated that this citadel was a shelter for more than 100 000 people during its apogee as capital of the Chimú’s kingdom. The Chan-Chan walls have high archeological value due to their shapes and high relief decorated walls (Figure 2.7).

![Figure 2.7. Chan-Chan city (Trujillo, Peru).](http://www.thetrip.net/the%20north/Chan_Chan_La_Libertad.jpg)
During the Chimu’s culture, another important construction was the Paramonga shrine. It was built between 1200 and 1400 A.C. The shrine is also called Fortress because of its dimensions and because it was built on a hill. Puruchuco palace is an archeological monument partially restaurated and placed to the east of Lima. The adobe walls are around 4 m tall and 0.60 m thick. This Inca construction has many lounges, corridors and yards, and it was probably the house of an important local authority.

During the colonial period (1540 to 1821), earth was still used for construction. The colonizers built many houses in adobe, tapial and quincha, or mix of them. Many of the churches in important urban and rural cities were built in adobe (e.g. the Descalzos’ convent in Lima, San Pedro de Carabayllo church -Figure 2.8- etc). The roof of the churches is made of wooden trusses which are covered by rod canes (following the longitudinal axes of the vault) and a mud mortar is placed above them. Below the wooden trusses a wooden ceiling was added.

The colonial houses of the Spanish conquerers were also built with earth, having 2 or 3-storey (Figure 2.9). The history books report of many earthquakes, mainly at Lima, during this period of time. The 1687 earthquake (beginning of the devotion for El Señor de Los Milagros, a religious Peruvian festival) and the 1746 earthquake (followed by a tsunami at Callao harbour) destroyed the majority of earthen constructions in Lima and in Callao [Gascón and Fernández 2001]. Due to the 1746 earthquake the authorities limited the earth constructions to 1-storey, allowing other storeys in quincha. As mentioned before, the quincha is composed of wooden frames infilled with mud and cane. The Figure 2.9 shows a typical colonial house, with the first floor built in adobe and the second one in quincha, as specified by the old building code. The technique of the quincha has rather ancient traditions which date back many centuries before the arrival of the Spaniards.
The earthen dwellings from the Colony and first years of the Republic that still exist now have many thicker walls placed in the two principal directions of each house. Therefore, the walls have low slenderness ratio (high/thick ratio lower than 6). The rooms have similar dimensions in both directions and are symmetrical distributed. The walls have few and centred small openings. The roof is typically made with wooden beams, covered with a mud layer.

The construction of Peruvian earthen dwellings has increased since the Republic period. Nowadays, there are more than two and a half million earthen dwellings, more than 40% of the total Peruvian houses [INEI 2008]. The majority of adobe houses are located at the Peruvian highlands. Unfortunately, because of economical reasons, the good building practices have been lost through time. The new buildings present for example few walls, large room dimensions, large openings, consequently the new adobe houses are less earthquake-resistant (Figure 2.10) when compared with the traditional ones.
2.3 Seismic behaviour of unreinforced and reinforced adobe structures

2.3.1 The simple earth material, unreinforced adobe structures

The beginning of earth, as a construction material, has its origins with the discovery that wet earth gets harder when it gets dry, and has important compression strength. Earth construction is widely used at the Peruvian highlands because of the accessibility to the material and due to its thermal properties. Adobe houses are considered ecological constructions because they are compatible with nature and do not show any hazard to the environment. The combination of economic necessity, deep cultural and social traditions, the need for little or no experience to build adobe structures, and material availability make the use of adobe materials inevitable [Gavrilovic et al. 1998].

In many developing countries soil is still a widely used construction material because it is readily available at little or no cost. Most underprivileged people in these countries, therefore, have no alternative but to build with soil, because the cost of manufactured or industrial materials such as wood, fired clay bricks, cement, or reinforcing steel is completely beyond their economic means. Because building with earth is relatively simple, it is usually performed by the residents themselves, without technical assistance or quality control. Inhabitants use to organize themselves in work-festivals in order to build houses without any labour cost.

In summary, Peruvian constructions are made without any reinforcement system and are mainly used in the highlands (rural areas) and in suburban areas around large coastal cities.

2.3.2 Seismic behaviour of unreinforced adobe houses

The capacity of an adobe house to resist earthquakes depends on the individual adobe block characteristics, building location and building design, as well as the quality of construction and maintenance [Dowling 2004]. The extent of damage to an adobe structure depends on the severity of the ground motion, on the geometry of the structure, on the overall integrity of the adobe masonry, on the existence and effectiveness of various seismic retrofit measures and on the condition of the building at the time of the earthquake.

The high seismic vulnerability of earthen buildings is due to a perverse combination of the mechanical properties of their walls: earthen walls are dense and heavy, have extremely low tensile strength and they fail in a brittle fashion, without any warning. As a consequence, every significant earthquake that has occurred in regions where earthen
construction is common has produced tragic life losses and considerable material damage (Figure 2.11).

During a damage survey carried after a Peruvian earthquake in 2007 the most common failure observed in earthen buildings, especially in those with slender walls, was the overturning of the façade walls and their collapse onto the street [Blondet et al. 2008a]. This was caused because the wall strength in the intersection between the façade wall and the other house walls was too low to withstand the earthquake’s movement. The walls usually collapsed as follows: first vertical cracks appeared at the wall’s corners causing the adobe blocks in that area to start to break and fall (Figure 2.12). This triggered the walls to disconnect until finally the façade wall flipped over. The observations made after the earthquake have shown that the magnitude of damage that the buildings suffered when their walls collapsed, was directly related to whether the roof’s wooden joists were connected to the top of the façade wall or not. If they were supported by the façade, the wall’s collapse caused them to come off balance, causing the roof to collapse as well (Figure 2.13a). If, on the other hand, the joists were supported by the walls that were perpendicular to the façade wall, the roof didn’t fall apart (Figure 2.13b).
Figure 2.12. Vertical crack at the corner of an adobe house produced during the Pisco earthquake in 2007, Peru.

Figure 2.13. Collapse of adobe houses during the Pisco earthquake in 2007, Peru.

Many adobe buildings located on street corners suffered from heavy structural damage due to the collapse of their two façade walls and roof. The cracks produced on the corner between these two walls are both vertical and diagonal. The diagonal cracks extend from the top of each wall’s corner down to the house base, forming a ‘v’ such as crack pattern (Figure 2.14).
Lateral seismic forces acting within the plane of the walls generate shear forces that produce diagonal cracks, which usually follow stepped patterns along the mortar joints. The diagonal cracks often start at the corners of opening doors and windows, due to the stress concentration at these locations (Figure 2.15). If the seismic movement continues after the adobe walls have cracked, the wall breaks in separate pieces, which may collapse independently in an out-of-plane fashion.

According to Webster and Tolles [2000], vertical cracks at the wall intersections and diagonal cracks at door and window corners seem to begin for seismic intensities between PGA 0.1 to 0.2g. The damage increases when the seismic intensity increases.

The vulnerability of adobe construction is not just limited to older dwellings. In Peru, new adobe constructions are being built with thinner walls and therefore with smaller shear strength. According to Blondet et al. [2008a], some more recent buildings located in developing areas near Pisco (a Peruvian city located at the central coast area) have been
constructed without taking seismic design guidelines into consideration and are, therefore, more susceptible to suffer damage due to seismic activity than the older constructions in the area.

The walls on the modern buildings are more susceptible to collapse due to out of plane loads as they are narrower (with a 0.25m thickness) and more slender than older walls. Many of the houses in those areas only have 1 or 2 enclosed rooms, and many of them have enclosure walls constructed using adobe. The roofs are built using wood and covered with crushed cane, straw mats, cardboards or sandbags, used as insulation to keep the house inhabitants warm (Figure 2.16). The floor of the houses is usually moistened soil that has been compacted.

Memari and Kauffman [2005] and CENAPRED [2003] summarize the typical failure modes for adobe dwellings, based on the performance of these houses in past earthquakes and experimental studies, as follows (Figure 2.17):
Extensive cracking (vertical at corners, at openings, and diagonal) due to the low tension strength of the adobe material. Vertical cracks are the most typical cracks in earthen buildings.

Disintegration of walls at upper regions.

Separation of walls at corners due to vertical cracking.

Out-of-plane damage, collapse of long walls

Wall mid-height flexural damage

Dowling [2004] makes a brief description of the damage pattern of adobe dwellings based on a damage survey carried out after El Salvador earthquake (Mw 7.7, 825 fatalities) in 2001, where more than 200 000 adobe houses were severely damaged or collapsed. The damage pattern can be summarized as follows (Figure 2.18):

- Vertical cracking at corners due to large relative displacement between orthogonal walls. This type of failure is very common because relative response is largest at the wall-wall interface. Cracking occurs when the material strength is exceeded in either shear or tearing.

- Vertical cracking and overturning of upper part of wall panel. Bending about the vertical axis causes a splitting-crushing cycle generating vertical cracks in the upper part of the wall.

- Overturning of wall panel due to vertical cracks at the wall intersections. Here the wall foundation interface behaves as pin connection, which has little strength to overturning when an out-of-plane force is applied. This type of failure has been seen in long walls without intermediate lateral restraints.

- Inclined cracking in walls due to large in-plane forces, which generates tensile stresses at around 45 degrees.

- Dislocation of corner. Initial failure is due to vertical corner cracking induced by shear or tearing stresses. The lack of connection at wall corners allows greater out-of-plane displacement of the wall panels, which generates a pounding impact with the orthogonal wall. The top of the wall is subjected to greater displacements, which causes a greater pounding impact, thus inducing greater stresses that lead to failure.

- Horizontal cracking in upper section of wall panels and displacement of roof structure.

- Failing of roof tiles.
Memari and Kauffman [2005] made a damage survey on 20 historic and 9 older adobe buildings in California after the Northridge earthquake (Mw 6.7, 60 fatalities), in 1994. They concluded that ground shaking levels between 0.1 to 0.2g PGA are necessary to initiate damage in well-maintained, but otherwise unreinforced, adobes. The most typical failure is due to out-of-plane flexural damage (Figure 2.19). These cracks initiates as vertical cracks at the intersection of the perpendicular walls, extending vertically or
diagonally and running horizontally along the base between the transverse walls. Then, the wall rocks out-of-plane, back and forth, rotating about the horizontal cracks at the base. The gable-wall collapse is more specific for historic buildings. For long walls, the separation of these walls with the perpendicular ones results in out-of-plane moving of the wall. Diagonal cracks (X-shape) results from shear forces in the plane of the wall, these cracks are not particularly serious unless the relative displacement across them becomes large. When the building is located at the corner, some diagonal cracks use to appear at exterior walls since they form wedges that can easily move sideways and downward as the building shakes, and also vertical cracks at the intersection of walls due to the out-of-plane movement.

Figure 2.19. Typical types of damage observed in historic adobe buildings after the Northridge earthquake [Webster and Tolles 2000].

2.3.3 The earthquake-resistant reinforced adobe buildings

Regarding the previous section, it seems necessary to improve the seismic resistant of adobe constructions and this can be done with the addition of compatible reinforcement that can resist tension forces to complement the low tension strength of earthen materials. A compatible reinforcement means a reinforcement that can be integrated to an adobe wall and can work together up to the total collapse; it should control also the relative displacements and deformations of the wall to avoid the sudden collapse, so the compatible reinforcement should resist big deformations without failure.

The earthquake-resistant earth or reinforced earth is the union of the earthen material and a compatible reinforcement. The mix should resist compression, tension and bending actions, these two last actions are given mainly by the reinforcement. The reinforcement starts to work when fissures appear in the earth material. The *quincha*, a mix of wooden frames with mud infilled, is related to the reinforced earth but is not considered as such because the structural elements are the wooden frames and not the earth. In reinforced
earth, the structural elements are given by the earthen walls and the reinforcement are complements to improve the seismic resistant [Vargas et al. 2005].

It seems that there are three major difficulties to overcome for improving adobe buildings:

- Development of new earthen constructions with economical seismic reinforcement systems.
- Education and diffusion of new technologies amongst builders. Manuals and booklets for people should be a good idea for this issue.
- Implementation of strategies to get collaboration for the constructions of safety houses from governmental and non-governmental institutes.

The principal alternatives of seismic reinforcement for these vulnerable buildings are described below.

2.3.3.1  **Internal cane mesh reinforcement**

The reinforcement consists of vertical cane rods anchored to a concrete foundation and placed inside the adobe walls. The adobe block layout defines the distance between the vertical cane rods at 1.5 times the thickness of the wall. Horizontal layers of crushed canes are placed every few adobe rows and tied to the vertical cane reinforcement (Figure 2.20a). Finally, this internal cane mesh reinforcement is tied to a wooden crown beam (Figure 2.20b). This reinforcement increases the out-of-plane flexural and in-plane shear strength with respect to a non-reinforced adobe building.

![a) Scheme of the internal cane reinforcement  b) Wooden crown beam at the top of walls](image)

Figure 2.20. Internal cane mesh reinforcement.
This reinforcement system has demonstrated excellent response in full-scale shake table tests [Blondet et al. 1988]. Figure 2.21a shows the collapse of a full scale adobe house model subjected to simulated seismic motion without reinforcement. During a similar test (Figure 2.21b), the model reinforced with an internal cane mesh suffered significant damage, but did not collapse.

The main limitation of this reinforcement system is that cane is not available in all seismic regions. Moreover, also in areas where cane is produced, it is practically impossible to obtain the required quantity for a massive construction or reconstruction program. The use of cane, as seismic reinforcement, requires more effort from builders; therefore, inhabitants prefer to build without reinforcement.

### 2.3.3.2 External wire mesh reinforcement

This technique consists of nailing wire mesh bands against the adobe walls and then covering them with cement mortar. The mesh is placed in horizontal and vertical strips (Figure 2.22a), following a layout similar to that of beams and columns, (Figure 2.22b). Five full-scale adobe modules were tested on the shake table at the PUCP to prove the effect of the reinforcement [Zegarra et al. 1997].

This reinforcement system provided significant additional strength to adobe models under earthquake simulation tests. The performance of the model was adequate during moderate and severe shaking. However, the mode of failure was brittle during a strong test. During the Arequipa earthquake (Mw 8.4, 138 fatalities) in 2001 and Pisco earthquake in 2007 (Mw 8, 514 fatalities) in Peru, while surrounding houses were severely...
damaged or destroyed, houses reinforced with this system did not suffer any damage and were used as shelters [Zegarra et al. 1997, 2001] as shown in Figure 2.23.

Wire mesh and cement are prohibitively expensive for the inhabitants of earthen houses in developing countries. External reinforcement with welded mesh can cost up to US $200 for a typical one floor, two-room adobe house, which exceeds the economic capacity of most Peruvian adobe users [Blondet et al. 2008b]. Furthermore, the compatibility between the adobe and the basically water-proof cement mortar may cause severe humid damage to the walls. The adobe material needs to breath and the cement mortar may not allowed it.
2.3.3.3 External polymer mesh reinforcement

Since 2005 the possibility of using polymer mesh to reinforce earthen buildings has been studied at the PUCP [Blondet et al. 2006]. Several full-scale adobe housing models with different amounts and types of polymer mesh were tested on the PUCP unidirectional shake table. The reinforcement provided consisted of bands of polymer mesh tied to both sides of the walls with plastic string, threaded through the walls (Figure 2.24). Flexible lintels made with rod cane were used instead of the typical wooden lintel. The use of lintels more rigid than adobe bricks produce stress concentration at the contact zones and therefore help the initiation of thicker cracks.

The first models were reinforced with different amounts of geomesh and they showed good dynamic response during the earthquake simulation tests: although the adobe walls suffered some damage, collapse was avoided also during very strong shaking. As expected, however, the amount and spread of damage on the adobe walls increased as the quantity of polymer mesh reinforcement decreased. The greater the surface area covered by the mesh, the greater the seismic strength.

Since geogrid polymer mesh is quite expensive in Peru, it was decided to consider the use of a cheaper plastic mesh, usually employed as a soft safety fence in construction sites. The adobe model shown in Figure 2.25 was reinforced with bands of plastic mesh located in the regions where most damage was expected on the adobe walls. The plastic mesh bands were tied to the walls with plastic strings placed across the walls during construction. After a strong shaking test, the adobe walls were broken into several large pieces, which were held together by the plastic mesh. The mesh was deformed and broken in several places, indicating that the amount provided was barely adequate. It is clear, however, that although the building suffered significant damage, collapse was averted.
Moderate amounts of strategically placed polymer mesh reinforcement can therefore be used to prevent the collapse of adobe buildings, also during severe earthquakes. However, further research is needed to determine the optimal amount and placement of the mesh, and to develop simple reinforcement design procedures and construction recommendations, in order to provide the professional community with tools to design and build economical and safe earthen houses in seismic areas.

In Mexico, Meli et al. [1980] and Hernández et al. [1981] studied three strengthening methods for adobe modules to avoid or lower the level of separation between perpendicular walls and to avoid the overturning of walls. Five 1:2.5 scale adobe modules were tested on a shake table using ground motions from three earthquakes. The three strengthening methods were: a reinforced concrete beam at the top of walls, welded wire mesh nailed to both faces of the walls and covered by mortar, and steel rods tied to both faces in the upper part of the walls. The best results were obtained from the use of the welded wire mesh.

According to Webster and Tolles [2000], the most widely used strengthening method for improving adobe seismic behaviour is the bond beam (wooden or concrete) placed at the upper perimeter of the walls. However, adobe walls tend to separate from those beams due to volume changes due to shrinkage in the adobe and lose the tightening effect of the bond beam.

Tolles and Krawinkler [1990] studied the problems of dynamic similitude and material simulation in small-scale models, the dynamic response characteristics of simple adobe house configurations and the assessment of several simple improvement techniques. Six reduced-scale adobe modules were dynamically tested at the John A. Blume Stanford University. Elastic finite element models were also performed in order to correlate the
results at different phases of the testing programs. Figure 2.26 shows the geometrical characteristics of the prototype model. The tests provided information about the extent of damage and the typical failure mechanisms on these kinds of structures; wall overturning was the most often observed mode of failure. The reinforcement system was given by bond wooden beams in addition to anchored roof beams.

Figure 2.26. Sketch of the prototype model of the scaled adobe module [Tolles and Krawinkler 1990].

2.4 SUMMARY

Peru, as other countries in the Middle East or the North Africa, has an old tradition of construction with adobe, normally without considering seismic reinforcement. The adobe is a brittle material, it can resist relatively higher compression strength but almost negligible tension and bending strengths. Everytime a strong earthquake occurs in cities with adobe construction, these buildings suffered widespread damage and sometimes even collapse resulting in human casualties.

It seems that new adobe buildings, especially the ones located at the suburban areas in Peru, are more vulnerable to collapse due to seismic actions than the older ones. This is due to the new typology of adobe buildings being built in Peru, with thinner and more slender walls with large openings, trying to imitate constructions in another type of material such as confining masonry or reinforced concrete structures.

Nowadays, different techniques and materials than can be used to improve the seismic resistant of adobe constructions exist; however, since this type of buildings are related to families with low economical incomings especially in developing countries, many times the economic investment for reinforcement can not be assumed by the owner. Cheap reinforcement has been studied by the research institutes for many years in order to find an economical, resistant, easily applied and ecological reinforcement system.
In this chapter, the inclusion of a minimum reinforcement (e.g. wooden crown beam, internal cane mesh, wire welded mesh or plastic mesh) into an adobe building is discussed and it is shown that it improves the seismic performance of adobe structures; therefore, avoiding casualties.