STRUCTURAL ANALYSIS OF HISTORICAL CONSTRUCTIONS
Possibilities of numerical and experimental techniques

Edited by
Paulo B. Lourenço
Pere Roca
Claudio Modena
Shailesh Agrawal
Contents
Volume 1

Invited Lectures

Technological Knowledge Systems Approach: From Little Insights to a Paradigm shift in Structural Knowledge and Application ......................... 3
N.M. Thakur

The Study and Restoration of Historical Structures: From Principles to Practice ......................... 9
P. Roca

Experimental Approach to the Analysis of Historic Timber and Masonry Structures .................. 25
M. F. Drdácký

Grouting of Three-Leaf Stone Masonry: Types of Grouts, Mechanical Properties of Masonry before and after Grouting ......................................................... 41
E. Vintzileou

Homogenisation Approaches for Structural Analysis of Masonry Buildings ............................ 59
P.B. Lourenço, A. Zucchini, G. Milani, A. Tralli

From “Opus Craticium” to the “Chicago Frame”: Earthquake Resistant Traditional Construction ................................................................................................................. 77
R. Langenbach

Safety and Use vs. Integrity of Historical Constructions: Conflict or Synergy? ......................... 93
C. Viggiani

Codes of Practice for Architectural Heritage in Seismic Zones .................................................. 107
C. Modena, F. Casarin, M.R. Valuzzi, F. da Porto

A Conceptual Model for Multi-Hazard Assessment of the Vulnerability of Historic Buildings ............................................................................................................. 121
D. D'Ayala, A. Copping, H. Wang

Conservation of Architectural Heritage in India: The Fundação Oriente Experience ............. 141
S. Mascarenhas

Historical Aspects and General Methodology

A Conservation Plan Method for Historical City Centres .............................................................. 151
F. Fraga, G. Monti, G. Scalora
Investigation of Construction Techniques and Materials in a Group of Ottoman Baths .......... 159
K. Reyhan, B. Yêkoôlu

Historical Development of Traditional Earthquake-Resistant Construction Techniques in Anatolia ............................................................................................................. 167
H. Dişkaya

Authoring and Multimedia Technologies for Management and Presentation of Information on Heritage Constructions ................................................................. 175
X. Romão, E. Paupério, J. Guedes, A. Costa

Preliminary Study and Proposal for Restoring a Jesuit College at Saragossa, Spain .......... 183
R. Bustamante, B. Lauret, J. Monjo, J.M. Valero

Design Characteristics and Contructional Techniques of a Byzantine Cistern in Istanbul ...... 191
M. Alper

Bam Citadel after the Earthquake ..................................................................................... 199
M. Hejazi

The Space-Structure Relation in Sinan’s Works .................................................................. 209
R. Günay

Strengthening for Preservation .......................................................................................... 217
S. Casiello

Comparative Analysis of an Antic Stone with Restored Stone of Restoration Project ........... 221
J.P. Tarachand, B.N. Tandon

Structural Arguments in the Analysis and Conservation of Some Romanesque Churches in Romania ............................................................................................... 227
L. Roşiu

Researches on historical constructions built in several stages .............................................. 235
I. Bucur-Horvâth, A. Paşca-Hedeş, J. Virâg, M. Bindea

Masonry Arches: Historical Rules and Modern Mechanics ................................................. 243
A. Brencich, R. Morbiducci

The Berlin AEG Turbine Fitting Shop by Peter Behrens and Karl Bernhard ......................... 251
M. Mende

The Challenges of Structural Stabilization Following the Hurricane Katrina Disaster .......... 261
S.J. Kelley, P. Sparks
Delhi Domes in Transition...................................................................................................... 269
S. Gupta

The Tecnology for the Raising of the Broken Obelisks the Cases of the San Giovanni in Laterano Obelisk (Roma 1587) and the Axum Stelae (Tigray 2006) ............................................. 277
M.G. D'Amelio

Understanding Traditional Wisdom of Earthquake-Resistant Construction in the Himalayas . 285
A.M. Dixit, J.K. Bothara, S.N. Shrestha, B.K. Upadhyay, M. Gupta, A. Sharma

Conservation and Restoration of Brazilian Colonial Architecture ........................................... 291
B.T. de Oliveira, V.A. Braide

Behaviour of Masonry Vaults and Domes: Geometrical Considerations .............................. 299
G. Arun

Determination of the Mechanical Characteristics of Masonry Walls of the Traditional Housing in Seville between 1700 and 1900 ................................................................. 307
F.P. Gálvez, C.R. Liñán, P.R. de Hita

Timber Structures

The Reconstruction of the Timber Roof of the “Pieve” in Cavalese ......................................... 319
M. Piazza, M. Riggio

The Simulated Timber Structure of the Volumnis' Hypogeum in Perugia, Italy ..................... 327
D. Blersch, M. Balzani, G. Tampone

New Methodological Approaches To The Survey on Timber Historical Foundations .......... 335
C. Bertolini, L. Cestari, T. Marzi, N. Macchioni, B. Pizzo, O. Pignatelli

The Use of X-ray Images for the Assessment of the State of Preservation of Strengthening Interventions on Wooden Structures ................................................................. 343
M. Mattone

Experimental Correlations between Destructive and Non-Destructive Tests on Ancient Timber Elements .............................................................................................................. 351
B. Calderoni, C. Giubileo, F.M. Mazzolani, G. De Matteis

Strengthening Techniques of Portuguese Traditional Timber Connections .......................... 359
J. Branco, P. Cruz, M. Piazza, H. Varum

Frame Structure of Vietnam Traditional Wooden Architecture .............................................. 367
Le Thanh Vinh
Study of Strains and Stresses in Historical Carpentry Joints ................................................................. 375
J. Jasieñko, L.J. Engel, P. Rapp

Traditional Responses of Moisture Related Decay Mitigation in Timber Architecture of Travancore (kerala) - A Search into the Traditional Knowledge Base ................................................. 385
B. Tom

Italian Standardisation Activity in the Field of Diagnosis and Restoration of Ancient Timber Structures ........................................................................................................ 395
N. Macchioni, M. Piazza

Strengthening and Stiffening Ancient Wooden Floors with Flat Steel Profiles ...................... 405
N. Gattesco, L. Macorini

Restoration Of historic roof structures on Common Rafters and Tie-Beams with Collars ...... 413
B. Gy. Szabó

Timber Strengthening Systems Operated On The Vasari's Ceiling in Palazzo Vecchio .......... 421
P.P. Derinaldis, G. Tampone, G. Tempesta

Injuries, Past Repairs and Conservation Views for Stabilization of Sakyamuni Tower, China 429
B. Messeri, G. Tampone, G. Tempesta

Analysis of Pre' Failure State of Historicial Wooden Church ......................................................... 437
P. Berkowski, G. Dmochowski, M.Y. Minch, J.P. Szolomicki

Transformation of Wooden Roof Pitches into Antiseismic Shear Resistance Diaphragms ..... 445
A. Marini, E. Giuriani

Analysis, Intervention and Repair of Timber Structures ............................................................ 453
C.R. Liñán, P.R. de Hita, J.C. Gómez de Cózar, F.P. Gálvez

Historic Timber Structures in New Zealand – Restoration Works and Lessons for the Future 463
J. Chapman

Analysis of Wooden Roofing Structures in Monumental Buildings .......................................... 471
A. Marzo, B. Faggiano, F.M. Mazzolani

Kärsämäki Church in Finland – Modern Language of Form Combined with Old Techniques and Craftsmanship .................................................................................. 479
A. Soikkeli, J. Koisoo-Kanttila

Timber Coverings of Palatine Chapel in Caserta Royal Palace ..................................................... 487
C. Ceraldi, E.R. Ermolli
On Acceptable Levels of Safety in the Breeding Barn at Shelburne Farms .............................. 495
D.W. Porter, D.C. Fischetti

Gothic Roof Structures Modelling ............................................................................................. 503
I. Kirizsán

An Evaluation on Post Disaster and Timber Framed Houses by
Macro Approach Based Assessment.......................................................................................... 511
S. Akarsu, N.Ş. Güçhan

Acousto-Ultrasonic Non-Destructive Evaluation of Historical Wooden Structures ............ 519
J.-L. Sandoz, Y. Benoit

Non-Destructive Testing, Inspection and Monitoring

Hydrostatic Levelling System: Monitoring of Historical Structures ..................................... 529
L. Schueremans, K. Van Balen, P. Smars, V. Peeters, D. Van Gemert

Application of Structural Dynamic Methods in Diagnosis of Historic Buildings ............. 537
C. Szymczak, H. Walukiewicz, A. Tomaszewska

AE Structural Assessment of a XVIIth Century Masonry Vault ........................................... 545
A. Carpinteri, S. Invernizzi, G. Lacidogna

NDT-Control of Injection of an Appropriate Grout Mixture for the Consolidation
of the Columns Foundations of Our Lady's Basilica at Tongeren (B) .................................. 553

Dynamic Identification of Detachment Conditions on Prehispanic
Mural Paintings in Central Mexico ....................................................................................... 561
J.C.A. Garaygordóbil, H.R. Escalante, A.O. Bustamante

Reinforcement and In Situ Testing of the Upper-Choir of Pópulo Church in Braga, Portugal . 569
J. Guedes, A. Costa, E. Paupério

Moisture and Salt Mapping by TRD in the Historical Stonework of the
Finca Marina-Manresa in Mallorca ...................................................................................... 577
R. Plagge

NMR Techniques for Non-Destructive Investigations of Historical Stone Artefacts .......... 585
M. Camaiti, P. Fantazzini, M. Gombia
Medieval Towers as Sensitive Earthquake Receptors ............................................................... 593
A. Carpinteri, G. Lacidogna, G. Niccolini

G. Martínez, P. Roca, O. Caselles, J. Clapés

Numerical and Experimental Study of the Dynamic Behavior of San Nicolás Belltower
(Valencia, Spain) ....................................................................................................................... 609
S. Ivorra, F.J. Pallarés, M.L. Romero

Iterative System Identification for the Assessment and Retrofitting of a
Historical Pre-Stressed Concrete Bridge in Berlin ................................................................. 617
W. Lorenz

Monitoring Historic Buildings Using Distributed Technologies ........................................ 625
D. Zonta, M. Pozzi, P. Zanon

Investigation Techniques Carried out on the Qutb Minar, New Delhi, India ....................... 633
L.F. Ramos, F. Casarin, C. Algeri, P.B. Lourenço, C. Modena

Vibration Based Damage Identification of Masonry Structures ......................................... 641
L.F. Ramos, G. de Roeck, P.B. Lourenço, A. Campos-Costa

Integrated Methods for the Assessment of the Structural Vulnerability of Historic Towers ... 651
E. Speranza, A. Viskovic, V. Sepe

Dynamic Monitoring and Model Updating of a Masonry Bell Tower in Pisa ..................... 659
M.L. Beconcini, P. Croce, M. Mengozzi

Solar Radiation Measurements and Modelling at the Humayun’s Tomb, New Delhi .......... 667
C. Finkenstein, H. Petzold, P. Häupl, B. Bhattacharjee

Combined Author Index, Volumes 1,2 and 3 .................................................................... 675
Experimental Results and Laboratory Tests

Chemical Anchoring Systems for Strengthening and Structural Restoration Purposes .......... 683
G. Ferrari

Mechanical Properties of Masonry Reinforced with Timber Ties........................................... 691
E.N. Vintzileou, D.A. Papadopoulou, V.A. Palieraki

Study on Historic Mortars Produced from Artificial Hydraulic Lime................................. 699
M. Kosior-Kazberuk, M. Gawlicki, A. Rakowska

Dynamical Behaviour of Rigid Block Structures Subjected to Earthquake Motion.............. 707
F. Peña, F. Prieto, P.B. Lourenço, A. Campos-Costa

Experimental Study of the Synthetic Mesh Reinforcement of Historical Adobe Buildings ..... 715
M. Blondet, J. Vargas, J. Velasquez, N. Tarque

Investigation of the Bond Mechanism between Stones or Bricks and Grouts......................... 723
C.-E. Adami, E. Vintzileou, E.-E. Toumbakari

Conservation of a Sandstone Monument at Kanchipuram, Tamilnadu, India...................... 731
R. Vedamuthu, D. Jayanthi

Study of Mortars for Repair by Anastylosis of Ruins of Our Lady of Nazareth Church (Almagre ruins), Cabedelo, Paraíba, Brazil................................................................. 739
T.M.A. Bonilla, A.M.P. Carneiro

Water Retention Transfer Functions of Old Ceramic Bricks............................................... 747
R. Plagge, J. Grunewald, P. Häupl

Compressive Strength of Solid Clay Brick Masonry: Calibration of Experimental Tests and Theoretical Issues................................................................. 757
A. Brencich, E. Sterpi

Experimental Results of Shear Strength and Stiffness of Existing Masonry Walls ............. 767
A. Brignola, S. Podestà, S. Lagomarsino

Tests on Gothic Sandstone Pinnacles Subjected to a Combined Climatic Load................... 775
M.F. Drdácký, J. Lesák, S. Pospíšil, Z. Sli_ková
Mechanical Properties of Three-leaf Stone Masonry ................................................................. 783
E. Vintzileou, A. Miltiadou-Fezans, A. Vrouva, S. Anagnostopoulou

Mechanical Properties of Three-leaf Stone Masonry after Grouting............................................ 791
A. Miltiadou-Fezans, E. Vintzileou, E. Papadopoulou, A. Kalagri

Structural Behaviour of Damaged Venetian Buildings: Experimental Evaluation..................... 799
P. Faccio, D. Chiffi, A. Vanin

Experimental Investigation on Historic Brickwork Subjected to Eccentric Axial Loads............. 809
G. de Felice

Experimental Investigation on the Structural Behaviour and Strengthening of Three-leaf Stone Masonry Walls................................................................................................................. 817
D.V. Oliveira, P.B. Lourenço, E. Garbin, M.R. Valuzzi, C. Modena

Testing for Assessment of Load Carrying Capacity of Masonry Arch Bridges......................... 827
K. Pardeep, N.M. Bhandari

Experimental and Analytical Out-of-plane Behaviour of Calcarenite Masonry Walls................. 835
L. Cavaleri, M. Fossetti, L. La Mendola, M. Papia

Assessment of the In-plane Shear Strength of Stone Masonry Walls by Simplified Models...... 843
G. Vasconcelos, P.B. Lourenço

Typological and Experimental Investigation on the Adobe Buildings of Aliano (Basilicata, Italy) ................................................................................................................................. 851
D. Liberatore, G. Spera, M. Mucciarelli, M.R. Gallipoli, N. Masini, V. Racina,
C. Tancredi, A. Capriuoli, A. Cividini, C. Tedeschi, D. Santarsiero

Quasi-Non-destructive Testing of Historical Structural Materials using Micro-Cores ............... 859
M. Sklodowski

Construction and Structural Behaviour of Lead Joints in Gothic Stone Structures................. 867
R. Barthel, M. Beckh

Effects of Pozzolanas on Mechanical Properties of Mortars in Historical Buildings............. 875
D.E. Akbulut, F. Aköz

Analytical and Numerical Approaches

Structural Characterization of Rakanji Stone Arch Bridge by Numerical Model Updating .... 887
T. Aoki, D. Sabia, D. Rivella, T. Komiyama
Structural Identification and Seismic Vulnerability of the Tower of Matilde in Italy

T. Aoki, H. Muto, E. Murdolo

Structural Behaviour of the Corbelled Vaults of Ta Prohm

S. Chandran, A.M. Prasad, D. Menon

Creep Behaviour of Masonry Structures - Failure Prediction Based on Archeological Model and Laboratory Tests


Probability Density Functions for Masonry Material Parameters - A Way to Go?

L. Schueremans, D. Van Gemert

An “Innovative” Procedure for Assessing the Seismic Capacity of Historical Tall Buildings: The “Torre Grossa” Masonry Tower

G. Bartoli, M. Betti, P. Spinelli, B. Tordini

A Specific Rigid Element Model for Macro-Scale Dynamics of Monumental Masonry considering Damage and Micro-Structure Effects

S. Casolo

Numerical Analysis by FEM for the Assessment and the Strengthening of the Masonry Vaults of the “Pieve” in Cavalese

M. Piazza, M. Riggio

Numerical Simulation of Rigid Blocks Subjected to Rocking Motion

F. Prieto, F. Peña, P.B. Lourenço, J.V. Lemos

On the Stability of Stone Arches

M.R. Migliore, F.S. Letizia, E. Ruocco

Analysis of Vaulted Masonry Structures Subjected to Horizontal Ground Motion

M. DeJong, J.A. Ochsendorf

The Rankine-Type Criterion Aimed at Describing Masonry Orthotropy

L. Malyszko

Numerical and Experimental Tests on Three-leaves Stone Masonry Specimens

A. Drei, A. Fontana

Effect of Dome Formation in Force Flow

Z.C. Girgin, S.E. Pusat, G. Arun
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Modeling of Dry Stone Masonry Wall under Monotonic and Cyclic Reversed Loading</td>
<td>1005</td>
</tr>
<tr>
<td>R. Senthivel, P.B. Lourenço, G. Vasconcelos</td>
<td></td>
</tr>
<tr>
<td>Displacement Capacity of Ancient Structures through Non-linear Kinematic and Dynamic Analyses</td>
<td>1013</td>
</tr>
<tr>
<td>S. Giovinazzi, S. Lagomarsino, S. Resemini</td>
<td></td>
</tr>
<tr>
<td>The Discrete Element Method with 2D Rigid Polygonal and Circular Elements</td>
<td>1023</td>
</tr>
<tr>
<td>G.A.F. Rouxino, P. Providência, J.V. Lemos</td>
<td></td>
</tr>
<tr>
<td>Assessing Historical Bridge Bearings: The Development of approaches to the “Tangential Problem”</td>
<td>1031</td>
</tr>
<tr>
<td>V. Wetzk</td>
<td></td>
</tr>
<tr>
<td>In-Plane Behaviour of Unreinforced Brick Masonry - A Literature Review</td>
<td>1041</td>
</tr>
<tr>
<td>S.R. Balasubramanian, C.V. Vaidyanathan, N. Lakshmanan, M.B. Anoop, K.B. Rao</td>
<td></td>
</tr>
<tr>
<td>Durability Prognosis Model of Historical Natural Stone Masonry Regarding Joint Repairing Measures</td>
<td>1051</td>
</tr>
<tr>
<td>H. Twelmeier, S. Sperbeck, H. Budelmann</td>
<td></td>
</tr>
<tr>
<td>Limit Analysis of Multiple Span Masonry Portal Frames</td>
<td>1059</td>
</tr>
<tr>
<td>A. Giordano, A. De Luca, G. Cuomo, E. Mele, A. Romano</td>
<td></td>
</tr>
<tr>
<td>Dynamic Models for the Seismic Analysis of Ancient Bell Towers</td>
<td>1067</td>
</tr>
<tr>
<td>E. Curti, S. Lagomarsino, S. Podestà</td>
<td></td>
</tr>
<tr>
<td>Development of Macro-block Models for Masonry Walls Subject to Lateral Loading</td>
<td>1075</td>
</tr>
<tr>
<td>A. Orduña, G. Roeder, J.C. Araiza</td>
<td></td>
</tr>
<tr>
<td>Disgregative Phenomenon of Antique Mortars</td>
<td>1083</td>
</tr>
<tr>
<td>M.R. Migliore, F.S. Letizia, E. Ruocco</td>
<td></td>
</tr>
<tr>
<td>Analysis of Historic Rammed Earth Construction</td>
<td>1091</td>
</tr>
<tr>
<td>P.A. Jaquin, C.E. Augarde, C.M. Gerrard</td>
<td></td>
</tr>
<tr>
<td>Three-Dimensional Finite Element Analysis of Taj Mahal Structure</td>
<td>1099</td>
</tr>
<tr>
<td>M.N. Viladkar, N.M. Bhandari, P.N. Godbole, D.N. Trikha</td>
<td></td>
</tr>
<tr>
<td>Limit Analysis of Three-dimensional Masonry Structures</td>
<td>1107</td>
</tr>
<tr>
<td>S. Pantano, A. Perretti, P.P. Rossi</td>
<td></td>
</tr>
<tr>
<td>On Drilling DOF’s of Membrane Elements and Application to Historical Structures</td>
<td>1117</td>
</tr>
<tr>
<td>A. Mena, Y.M. Fahjan</td>
<td></td>
</tr>
</tbody>
</table>
Damage Model with Crack Localization – Application to Historical Buildings

R. Clemente, P. Roca, M. Cervera

Limit Analysis of Masonry Constructions by 3d Funicular Modelling

P. Roca, A. Andreu, L. Gil

Nonlinear Analysis and Strengthening Design of an Italian Masonry Monumental Building

F. Angotti, L. Aprile, M. Orlando, B. Ortolani, A. Vignoli

Issues about the Dynamic Behaviour of Rigid Free-standing Blocks under Earthquake Ground Motion

C. Casapulla, P. Jossa, A. Maione

In-Plane Collapse Behaviour of Masonry Walls with Frictional Resistances and Openings

C. Casapulla, D. D’Ayala

Monitoring and Modelling Strategies for the World’s Largest Elliptical Dome at Vicoforte

M.A. Chiorino, R. Roccati, C. D’Addato, T. Aoki, C. Calderini, A. Spadafora

Non Linear Modelling of the Elliptical Dome of Vicoforte

C. Calderini, M.A. Chiorino, S. Lagomarsino, A. Spadafora

Tension Ring in Masonry Domes

M.N. Varma, R.S. Jangid, V.G. Achwal

Event-by-event Strategies for Modeling Amsterdam Masonry Structures

J.G. Rots, B. Belletti, M. Boonpichetvong, S. Invernizzi

Circular, Pointed and Basket-handle Arches: A Comparison of Structural Behavior of Masonry Spans

A. Romano, J.A. Ochsendorf

Design Aspects in Seismic Isolation Churches

G. Cuomo, A. De Luca, E. Mele, A. Romano

Simplified Evaluation of the Horizontal Capacity of Masonry Arches

A. Giordano, A. De Luca, E. Mele, A. Romano

The Modern Methods of Analysis in Reconstruction of the Historical Buildings

M. Czeslaw, M. Mikolaj

Functions of the Modern Techniques and their Influence on Analyses in Reconstruction of Historic Buildings

M. Mikolaj, M. Czeslaw
A New Code Approach to the Seismic Vulnerability Assessment of Historic Masonry Buildings.................................................................................................................. 1247

D. Sonda, F. da Porto, M.R. Valluzzi

The Physical and Numerical Modelling of a Repaired Masonry Arch Bridge .................. 1255

M. Miri, T.G. Hughes

Structural Assessment and Seismic Vulnerability Analysis of the Reggio Emilia Cathedral, Italy......................................................................................................................... 1263

F. Casarin, C. Modena

A Multiscale Approach for the Analysis Of Block Masonry under Damage and Friction..... 1271

G. Salerno, G. Uva

Analysis of Masonry Vaulted Systems: The Barrel Vaults .................................................. 1279

A. Baratta, O. Corbi

A Theoretical and Experimental Stress Distribution in Reinforced No-Tension Walls ........ 1289

A. Baratta, I. Corbi

Finite Element Modelling of Dieh-Dou buildings in Taiwan............................................... 1297

P.-H. Tsai, D. D’Ayala, G. Lewis

Innovative and Traditional Materials

Modern Application of the Traditional Log Construction Technique ................................. 1307

J. Heikkilä

The Installation of Protective Construtions for Covering Archeological Excavation Sites and Medieval Buildings ................................................................. 1315

J. Šekularac, N. Šekularac

Weathering Forms and Properties of Laterite Building Stones used in Historic Monuments of Western India ....................................................................................... 1323

A.K. Kasthurba, M. Santhanam, M.S. Mathews

Changing and Development of the Construction Tecnology during the Westernisation Period in Ottoman Architecture ............................................................. 1329

U. Yergün

Consolidation of Tuff: In situ Polymerization or Traditional Methods? .............................. 1339

M. Camaiti, L. Dei, V. Errico
Analysis of the System of Construction in the Traditional Ahmedabad Houses: Query in seismic resistance ................................................................. 1347
A.N. Modan, N. Chhaya, V. Shah

Composite Reinforcements with iNorganic Matrices for Masonry Structures ............... 1357
A. Viskovic, F. Fumagalli

Combined Author Index, Volumes 1, 2 and 3 .............................................................. 1367
Contents
Volume 3

Intervention Techniques, Restoration and Strengthening

Protection from the Effect of Horizontal Forces of Remains of High Walls within Hilandar Monastery Block, on Holy Mount in Greece ............................................................. 1375
N. Šekularac, J.I. Šekularac

Experimental and Numerical Analysis for the Strengthening Intervention of the Bell-tower of St. Sisto’s Church in Bergamo ................................................................. 1381
B. Balduzzi, D. Mazza, D. Papis, C. Rossi, P.P. Rossi

The Restoration Study of the Connections Between the Stone Blocks in the Steps of the Temple of Apollo Epikourios ................................................................. 1389
K.A. Papadopoulos

Study on Steel Reinforced Concrete Composite Beams Strengthened with Steel Plates or CFRP Sheets ................................................................. 1397
X. Li, X. Gu, Z. Zhao, W. Zhang, Y. Ouyang

Stone Surface Protection by Fluoropolymers from the Decay Caused by Mural Writings .... 1405
M. Licchelli, J.S. Marzolla, F. Carò, G. Moggi

Safety Assessment and Strengthening of Existing Steel Frames Containing Semi-rigid Joints 1413
W. Zhang, Q. Zhang, X. Gu, J. Lu, Y. Li, Q. Fu

Monitoring the Dismantlement of Four Flying Buttresses ........................................ 1421
P. Smars, L. Schueremans, K. Van Balen

Reconstruction Post-War 1945 – Structures and Materials in Le Havre ................. 1429
I.P. Cruz, G. Nieuwmeijer, G.J. Arends

Retrofitting of Masonry Arch Bridges with FRP .................................................. 1439
G. Buffarini, P. Clemente, G. de Felice

Repair of Cracked Historical Masonry Structures by use of the Flexible Joint Method (FJM) - Laboratory Tests ................................................ 1447
A. Kwiecień, B. Zajac, J. Kubica

Retrofitting and Reinforcement of a Wire Suspended Bridge in Portugal .................. 1455
L. Miranda, J. Guedes, A. Costa
Strengthening of Neapolitan Domes Between the XVII and XVIII Century:Historical and Structural Analysis ................................................................. 1463

M. Lippiello, L. Dodaro, M.R. Gargiulo

Static History and Structural Assessment of Masonry Domes.
The Treasure of St. Gennaro’s Chapel in Naples........................................ 1471

V. Russo, G.P. Lignola, E. Cosenza, G. Tucci

Preservation of Temples in Mỹ Sơn (Vietnam) ..................................... 1479

L. Binda, P. Condoleo, M. Cucarzi, Le Thành Vinh, P. Pichard, H.D. Kính

Investigations of Historical Structures - A Study of Rational and Irrational Forces .......... 1487

S. Basu

Increasing Durability of Building Stones to Mitigate Structural Pathology of
Historic Structures ................................................................................... 1495

A. Moropoulou, N. Kouloumbi, A. Konstanti, G. Haralampopoulos, P. Michailidis

Structural Rehabilitation Historical Buildings Affected by Subsidence in Mexico City ...... 1503

R. Meli, A.R. Sánchez-Ramírez

Restoration of Wood Structures at Federal University of Rio de Janeiro .................. 1511

M. Hoirisch, R.T.M. Ribeiro

Revitalization of Historical Apartment Houses .......................................... 1519

P. Berkowski, G. Dmochowski, M.Y. Minch, J.P. Szolomicki, M. Konopka

Seismic Behaviour and Retrofitting

Modelling and Analysis of an Italian Medieval Castle Under Earthquake Loading: Diagnosis and
Strengthening ........................................................................................... 1529

M. Betti, M. Orlando, A. Vignoli

Seismic Evaluation and Strengthening of a Heritage Masonry Building .................... 1537


Seismic Vulnerability Assessment of Qutb Minar, India .................................. 1545

S. Chandran, A.M. Prasad, M.S. Mathews

Analysis of the Seismic Behaviour of a Masonry Bell Tower ............................ 1555

A. Azorín, F. Pallarés, S. Ivorra, M. Martin

Medieval Walls System Against Earthquakes Types:
Structural Model and Qualitative Aspects .................................................. 1563

M.J. Cassinello
Analysis of Damages to Vaulted Structures, Arg-e-Bam and Bam Area, Iran........................ 1571
S. Maini

The Pompeii Basilica: Knowledge for Conservation in Seismic Region ................................. 1579
G. de Martino, G.P. Lignola, E. Cosenza

Structural Behaviour of a Masonry Wall under Horizontal Cyclic Load;
Experimental and Numerical Study ......................................................................................... 1587
A. Costa, B. Silva, A. Costa, J. Guedes, A. Arede

Approach to Assess the Seismic Risk of Historical Churches................................................. 1595
M. Urban, S. Sperbeck, U. Peil

Seismic Vulnerability Study of Historical Monuments:  
An analytical Study of Gol Gumbaz ......................................................................................... 1603
L. Mathew, Arun M.P.

The Antiseismic Rehabilitation of Marchesale Castle at San Giuliano di Puglia................. 1609
M. Indirli, R. Cami, B. Carpani, C. Algeri, P. Panzeri, G. Rossi, L. Piova

Effects of Dome System on the Seismic Behaviour of Ottomans Historical Structures ...... 1617
Y.M. Fahjan, H. Keypour

Earthquakes and Monuments - The Role of Materials in the  
Earthquake Protection of Monuments..................................................................................... 1625
A. Moropoulou, E. Aggelakopoulou, A. Bakolas

An outline of the Seismic Behavior of Historical Structures in  
North Western Anatolia ........................................................................................................... 1633
A. Ilki, M. Ispir, C. Demir, N. Kumbasar, S. Akman

Non-Linear Dynamic Analyses for Seismic Assessment of Ancient Masonry Towers ...... 1641
A. Menon, C.G. Lai, G. Macchi, A. Pavese

Seismic Analysis of Historical Structures Using Passive Control Systems....................... 1651
C.A. Syrmakezis, P.G. Asteris, A.K. Antonopoulos, O.A. Mavrouli, S.E. Sourtzi

FRP Mesh Technique for Retrofitting Historical Structures: A Proposal .............................. 1659
H.C. Uzoegbo, R. Senthivel, A. Madan

Indo-Italian Joint Research Programme on Seismic Vulnerability of  
Historical Centres in South India............................................................................................ 1667
G. Magenes, G. Macchi, A. Pavese, A.M. Prasad, G.R. Dodagoudar,  
M.S. Mathews, D. Menon, C. Lai, A. Penna, A. Menon
Seismic Rehabilitation of Cultural Heritage Through Timber Slabs and Ties ....................... 1675
G. Cuomo, A. De Luca, E. Mele

Seismic Response of Heritage Stone-Masonry Buildings ....................................................... 1683
M. Tomažević, M. Lutman

Case Studies

Survey and Restoration: The Case of the Block Between Vicolo II and Vicolo III at the Giudecca of Ortigia, Sicily.................................................................................. 1697
F. Braga, G. Monti, D. Liberatore, G. Scalora

Analysis of surface Patina on the Church of Nossa Senhora do Rosario, Ouro Preto, Brazil ................................................................................................................... 1707
C.C. Gaylarde, G.E. Englert

Roofing as an Essential Element of Structural Integrity ......................................................... 1715
S.Y. Harris

Constructive Analysis of the Arches and Ribs of the Vault on High Altar of “Santa Maria” Church of Tolosa (Basque Country) ................................................................. 1723
A. Garay, I. Rodriguez-Maribona, J. Domingo, J.A. Ibáñez

Church of Saint-James at Leuven (B) - Structural Assessment and Consolidation Measures .................................................................................................................. 1729
L. Schueremans, K. Van Balen, K. Brosens, D. Van Gemert, P. Smars

Investigation on the Limestone Ashlar Masonry in the São Francisco Monastery ............ 1739
M.M. de Oliveira, R. Muñoz, K.M.A.F. Cerqueira

Reconstruction Moni Hilandariou: An Historic Reinstatement Project on Mount Athos, Greece ............................................................................................................ 1747
M. Milojevic

Vulnerability Evaluation of the Old Building Stock in Historical Areas. The Case of the Old City Centre of Coimbra, in Portugal ......................................................... 1755
R.S. Vicente, H. Varum, J.A.R Mendes da Silva, C. Pereira, V. Silva

The Golden Gate, Porta Aurea of Diocletian’s Palace in Split, Outline of Historical Changes and Proposal for Reconstruction of Today’s Condition ......................... 1763
E. Lokošek, H. Podnar

Partial Collapse of a XII Century Church due to a Wrong Retrofit ..................................... 1771
N. Augenti
Reconstructive Hypothesis of the Historical Aviary in Prince Doria Palace, Genoa (Italy) ......................................................... 1779
S. Podestà, S. Resemini

Stability of Masonry Dome: Special Emphasis on ‘Golagumbaz’ ........................................ 1789
M. Varma, R. Bansod, N.R. Varma, P. Varma, P. Varma

Pathologies Caused by Man on the Foundations of Historic Buildings ........................... 1795
F. Vegas, C. Mileto, A. Martínez, A. Alonso, J.L. Calabuig

Structural Analysis of Historic Temple of Augustus in Ankara, Turkey ............................. 1803
A. Turer, T. Eroglu

A Shrine for Education: Government College of Engineering, Pune, a Case-study ................ 1811
M. Latkar

The French Panthéon: Structural Analyses from XVIII Century to Modern Times ............. 1819
C. Blasi, E. Coïsson

Structural Intervention in a Historical Chapel ................................................................. 1827
E. Júlio, D.D. da Costa, P.M. Tiago

Relief, Analysis and Modelling of the Masonry Structures of the Palace of Diocletian in Split ....................................................... 1835
G. Boghetich

Damage and Retrofitting of the Castle in Melfi (Italy) after the 1694 Earthquake: Structural Interpretation of a Historical Accomplishment ................................................... 1843
L. Sorrentino, D. Acito

Survey, Analysis and Structural Modelling of Ancient Masonry Building: the Case of the “Insula del Centenario [ IX, 8 ]” at Pompeii ...................................................... 1851
A. Custodi, L. Sciortino

Mutidisciplinary Data Collection for Structural Analysis: Application to the Studies for Conservation and Restoration of the “Insula del Centenario” [IX, 8] in Pompeii ............... 1859
A. Custodi, L. Sciortino, G. Castellazzi

The Monumental Bridge of Monte Carmelo (Italy): Strategies for the Historical and Architectonical Preservation ...................................................... 1867
C. Calderini, S. Lagomarsino, S. Resemini
Altarpieces Constructive Systems and Material Characterization, SC, Brasil ...................... 1877
M.A. Nunes, Â. do Valle, S.C.B. Nappi

Rehabilitation of an Historical Theatre in Italy ................................................................. 1885
R. Tomasi, F. Ferrario, M. Piazza

FE modelling and Dynamic Testing of Historic Aspendos Theatre in Antalya, Turkey ...... 1893
A. Turer, B. Boz

Study of the Deformation of Koyna Region Using Global Positioning System................. 1901
M.N. Kulkarni, K. Sakr, N. Radhakrishnan

Possible Geometric Genesis of a Medieval Cathedral (Alba, Piedmont, Italy)................. 1907
F. Antonino, G. Pistone, D. Zorgniotti

Structural Damages in the S. Francisco Church (Évora-Portugal) ................................... 1917
A.S. Gago, A. Lamas

Load Carrying Column Reconstruction in Greenhouse State Chateau Lednice, Czech Republic .......................................................................................................................... 1925
M. Bajer, J. Kala, J. Hirš, S. Buchta

A Method for Risk Maps in Archeological Sites: The Case Study of the Domus Tiberii on the Palatine Hill in Rome ................................................................. 1933
M.G. Filetici, E. Speranza, G. Carluccio, V.A. Marchetti

Case Study on a Historical Building Structure Strengthened by CFRP ............................... 1941
X. Gu, X. Yin, X. Li, W. Zhang, Y. Ouyang

Structural Seismic Risk Assessment of Traditional Masonry Buildings: The Case of the Historical Italian Town of Laino Castello ........................................ 1949
G. Uva, M. Mezzina, F. Porco, I. Trulli, G. Porco

Structural Analysis of the Church of Sint Lambertus in Maastricht ............................... 1957
I.A.E. de Vent, G.J. Hobbelman

Gubbio: Bargello Palace, the Restoration of a Medieval Italian Building .................... 1965
A. Bazzoffia

Pondicherry: Modern Technologies Approach in the Message of the Past .................... 1973
B. Bartoli

A Case Study on the Restoration and Strengthening of a Historic Stadium In China ....... 1981
G.-W. Su, J. Zhu, M.-Z. Wang
Case Study of Structural Health Monitoring of an Age Old Stone Masonry Arch Bridge...... 1989
D. Bandyopadhyay

The Façade and the Rose-window of Troia Cathedral (Apulia, Italy).............................. 1997
D. Liberatore, G. Spera, M. Mucciarelli, N. Masini, A. Calia, A. Capriuoli, V. Racina, L. Nuzzo, E. Rizzo, L. Binda, L. Cantini

Stress Analysis of San Vitale’s Basilica in Ravenna:
Current State and Mid-Term Predictions ................................................................. 2005
A. Taliercio, L. Binda

FE Modelling and Material Characterization of Tahir ile Zühre Mescidi, Konya, Turkey .... 2013
Y.D. Aktaş, A. Türer, E.N. Caner-Saltık

Earthquake Analysis of Historical Church of St Sergius and Bacchus, Istanbul-Turkey .... 2023
A. Koçak, A.G. Demir

Survey, Digital Reconstruction, Finite Element Model of the
Augustus Bridge in Narni (Italy) ............................................................................... 2035
A. Cecchi, A. Passerini

Case Study of Masonry Pillars Reinforcement in a Medieval Church ....................... 2043
P. Rapp, P.W. Sielicki

An Analysis of Porched Courtyards in Mosques of the Classical Ottoman Period......... 2051
A. Erdem, R. Ozakin

Multi-Hazard Risk Management for Heritage Buildings: Case Study Buranhpur Fort ....... 2059
N. Mehrotra

Late Submission

Construction Techniques and Materials of the 19th Century Military Buildings of Istanbul.. 2069
A. Çiftçi

Investigation of Mortar Mixtures to be used in Repair of Historical Structures............... 2075
S.E. Pusat, F. Aköz

Combined Author Index, Volume 1,2 and 3 .............................................................. 2085
Experimental Investigation on the Structural Behaviour and
Strengthening of Three-Leaf Stone Masonry Walls

D.V. Oliveira and P.B. Lourenço
University of Minho, Department of Civil Engineering, Guimarães, Portugal

E. Garbin, M.R. Valluzzi and C. Modena
Department of Construction and Transportation Engineering, University of Padova, Padova, Italy

ABSTRACT: A large part of historical structures, currently in the European urban centres, is
built with stone masonry walls, frequently constituted by multiple leaves. A common typology
encountered is the three-leaf stone masonry wall, which is characterized by a substantial pres-
ence of voids in the inner leaf and prone to brittle collapse mechanisms. Nevertheless, the
knowledge of the mechanical behaviour of three-leaf masonry walls and guidelines for proper
design and control of the interventions are limited. As support for the rehabilitation design
phase, some analytical approaches are available in literature. A comprehensive experimental
study on the structural behaviour of three-leaf stone masonry walls has been planned at Univer-
sity of Minho, considering different strengthening techniques using GFRP (glass fibre rein-
forced polymer) materials, pozzolana-lime based mortar and lime-based grout. In the paper the
experimental plan and the first experimental results on materials and three-leaf stone masonry
walls are presented and discussed.

1 INTRODUCTION

A large part of historical structures, currently in the European urban centres, was built with
stone masonry walls, frequently constituted by multiple leaves having little or no connection be-
tween them, and built with various materials, different types of stones and usually poor mortars.
The common typology encountered is the three-leaf stone masonry wall, which is characterized by a
substantial presence of voids in the inner leaf (Binda et al. 1999) and prone to brittle collapse
mechanisms. The mechanisms consist in the detachment of the external leaves and the out-of-
plane material expulsions, both under compression and shear-compression loading (Valluzzi et

Nevertheless, the knowledge of the mechanical behaviour of three-leaf masonry walls and
guidelines for proper design and control of the interventions are limited. Such limitations lead to
rehabilitation design of masonry buildings performed with inadequate reliable studies. More-
ever, for conservation purposes an increased sensitivity in the choice of consolidation materials
is required. The materials should be mechanically, physically and chemically compatible with
the original ones to assure effectiveness and durability of the strengthening and repair interven-
tions (Valluzzi et al. 2004, Modena 1997).

As support for the rehabilitation design phase, some analytical approaches are available in lit-
erature concerning unstrengthened and injected walls. They are based on simplified formula-
tions, which depend on few parameters easily detected by in situ survey and/or experimental
tests (Valluzzi et al. 2004, Toumbakari et al. 2004).

A comprehensive experimental study on the structural behaviour of three-leaf stone masonry
walls has been planned at University of Minho. The experimental campaign consists in sixteen
stone masonry walls designed for compressive tests in different strengthening conditions: trans-
versal connections of the external leaves by GFRP (glass fibre reinforced polymer) ties, bed
joint structural repointing with GFRP rods and combination of the two previous techniques. Further developments will consist in the application of the injection technique with lime-based grout applied both individually or combined with the previous strengthening techniques. The combination of these techniques can provide useful information in order to evaluate the different strengthening configurations that can be applied to restore the masonry deficiencies noticeable on site. The subsequent repair of the tested wall specimens is also an approach under consideration whenever possible.

The aims of the planned research are to characterize the behaviour of the stone masonry three-leaf walls under different strengthening configurations and developing a suitable contribution for analytical models and design guidelines. In the paper the experimental work plan and the first experimental results on materials and three-leaf stone masonry walls are presented and discussed in detail.

A preliminary bibliographic study was also performed, both on the geometrical characteristics of the three-leaf walls and on the constitutive materials used (Valluzzi et al. 2004, Valluzzi 2000, Toumbakari 2002, Binda et al. 1999, Rodrigues et al. 2003, Bartos et al., 1999) in order to produce masonry specimens representative enough of the existing three-leaf stone masonry walls. For that, an experimental investigation has been done in order to select adequate materials that correctly simulate the historical three-leaf stone masonry in laboratory conditions. Granite stone and pozzolanic mortars, for bed joints and repointing purposes, were selected to build the walls. Aiming at representing as much as possible the traditional construction techniques still in use, a professional mason was hired to build all the specimens.

Furthermore, experimental tests on specimens reproducing the external and the internal leaves have also been performed.

2 STRENGTHENING TECHNIQUES

A brief description regarding the three main different reinforcing techniques adopted in the project is hereafter given. These techniques aim to solve specific structural deficiencies of three-leaf stone masonry walls, as follows:

- lacking of the connection among the leaves;
- reduction of the horizontal dilation due to creep damage;
- weakness of the internal core.

The transversal tying through the thickness of multi-leaf walls is aimed to improve the connection among the leaves, in particular between the external leaves, in order to reduce the transverse deformation. For this purpose, stainless steel bars or FRP bars can be used. The bars can be easily inserted into drilled holes through the thickness of the walls and then anchored. In case of steel bars, the anchoring phase is achieved by bending the bar from the outside into a mortar joint previously grooved and then refilled with new mortar, whereas the anchoring of FRP bars is slightly more complicate because usually these bars can not be bent without their failure. In this last case, the anchorage can be achieved by using special anchoring elements (like angle bars or connector developed on purpose) or relying on the bond behaviour between the FRP bar and the mortar, developed along the thickness of the external leaf. In order to improve this last anchoring mechanism, a local grout injection around the tie can be applied instead.

The bed joint structural repointing has been recently considered for the strengthening and repair of historic brick structures exhibiting horizontal dilation due to creep damage (Valluzzi et al. 2005). When stone masonry walls show a regular bond arrangement of the units with aligned horizontal bed joints, this technique can also be applied on such walls. The technique is performed by removing an external layer of the horizontal joints (up to about 6-8 cm), and placing into the groove one or two small diameter reinforcing bars (stainless steel or FRP bars can be adopted). In the case of multi-leaf walls, transversal short links can be inserted into drilled holes successively sealed to improve the confining action of the bars and to tie the external leaf of the wall.

The injection is aimed to improve the weakness of the internal core, filling the voids in the inner core, and to improve its adherence to the external leaves. Several studies have been performed in the last years concerning the feasibility of this technique and its mechanically, physically and chemically compatibility (Valluzzi 2000, Toumbakari 2002, Binda et al. 1994).
Nowadays the trend is using grout mainly based on lime, in particular when the restoration works deal with historical constructions. The injection is typically performed injecting the grout starting from the bottom of the wall and reaching progressively the top. Usually, for three-leaf walls the used pressure is very low and not exceeding 50-100 kPa to avoid the undesired detachment of the external leaves.

3 CHARACTERIZATION OF THE WALL COMPONENTS

3.1 Stone

The major part of ancient buildings located in the North of Portugal is made of granite. Therefore, in order to assure an effective representativeness, a granitic stone, locally available, was used in all tests concerning the behaviour of three-leaf walls. Aiming at characterizing its mechanical behaviour, six cylindrical stone specimens of $\phi 100 \times 200 \text{ mm}^3$ were tested. A monotonic compressive load was applied under displacement control in a static fashion until the complete loss of strength capacity was attained, see Fig. 1a. In order to assess the Young’s modulus and Poisson’s ratio, four strain gauges attached to each specimen, equally spaced around the perimeter and placed at mid-height, were used, see Fig. 1b.

Considering all stone specimens tested, an average compressive strength of 52.2 MPa was obtained, whereas for the mechanical properties, averages values of 20.6 GPa and 0.24 (assessed within the [30%–60%] stress range) were computed for the Young’s modulus and the Poisson’s ratio, respectively. These values can be considered typical of the material, see Vasconcelos (2005) for details. For all the three measured parameters, coefficients of variation around 20% were observed, which can be considered perfectly acceptable given the nature of the material.

![Testing setup: (a) testing equipment; (b) strain gauges arrangement.](image)

3.2 Mortar

For a reliable experimental simulation of the structural behaviour of ancient masonry components, the selection of an appropriate mortar is a key issue in the sense that ancient mortars and binders were completely different from the ones used nowadays (Klirca, 2004). Aiming at obtaining a low strength compressive mortar and representative of old existing mortars, a pozzolana-lime based mortar was used to build the prisms and walls. Based on a preliminary composition study developed by the authors, a binder/sand ratio equal to 1:3, and a water/binder ratio equal to 0.8 were selected (all ratios in weight), see Oliveira et al. (2006a) for further details. In addition, a pozzolanic drier (10% on binder weight) was used to improve the construction procedure of the walls.

In order to assess the mechanical behaviour of mortar, cubic specimens of $50 \times 50 \times 50 \text{ mm}^3$ were sampled during the construction of the walls and tested under compressive loading at the age of 7, 28 and 90 days. Average compressive strengths of 0.5 MPa, 2.9 MPa and 2.2 MPa were observed at the aforementioned ages, respectively. Each value was obtained considering the average of three specimens. Considering the available data in literature, the adopted mortar composition can be considered representative of ancient mortars in terms of compressive strength.
3.3 External leaf

In order to obtain a good insight into the structural behaviour of each one of the leaves, a set of prisms representing both the external and internal layers were built. The stone masonry prisms were composed of three stones and two masonry joints, built carefully in order to simulate as much as possible the external leaves. During the construction of the walls, in both series a total of nine prisms with average dimensions of $150 \times 150 \times 320$ mm$^3$ (height/width ratio of 2.1) were built and tested under uniaxial compressive loading and at a displacement control rate of $10 \mu$m/s, see Fig. 2a. The prisms were tested after about 60 days of curing.

![Figure 2: Prisms representative of the external leaf: (a) prisms prior testing; (b) typical failure pattern.](image)

An average compressive strength of 7.7 MPa and a coefficient of variation of 28% were computed. As reported in the literature, see Oliveira et al. (2006b) and others, the use of several stone pieces assembled in one prism is likely to originate lower maximum strength values in comparison to the monolithic stone specimens. Here, a reduction of 85% was observed when shifting from stone specimens to stone masonry prisms. However, the high coefficient of variation found, caused by different average values rising from the two series, seems to indicate that such a reduction is also due to the workmanship effect and that more research is needed in order to assess the effect of mortar joints. The typical failure pattern observed is dominated by the formation of vertical cracks that progressed through the entire prism, see Fig. 2b.

3.4 Internal leaf

Typically, the internal leaf of multi-leaf walls is composed of poor materials, as wastes obtained from the rough-shaping of the stones placed in the outer leaves, and mortar.

In this work, the internal leaves, as well as the specimens aimed to describe the structural behaviour of these leaves, were built with granite scabblings poured into alternate layers with mortar and avoiding any compaction in order to create a certain amount of internal voids. During the construction of the walls, a total of six cylindrical specimens of $\varnothing 150 \times 300$ mm$^2$ were built following the same procedure used for the internal layers leaves, see Fig. 3a.

After a period of approximately 60 days of curing, the specimens were tested under uniaxial compressive loading at a displacement control rate of $5 \mu$m/s. From the tests, an average compressive strength of 292 kPa and a coefficient of variation of 46% were obtained. As expected, a very low strength was achieved given the weak bond between mortar and granite scabblings. This idea is further validated by the failure pattern found, characterized by the partial disintegration of the specimen, see Fig. 3b.

As happened with the prisms representative of the external leaf, the average compressive strength of the specimens representative of the internal leaf found in each series shows an important variation (405 kPa and 178 kPa), which justifies the high coefficient of variation. In addition, the coefficient of variation found in each series was below 25%, which seems to indicate
that within a same series the mason followed a same procedure. These differences are most
likely due to differences in the construction process, which again stresses the important role of
workmanship.

Considering the aforementioned average values, the compressive strength of the internal leaf
is approximately 4% of the external leaf compressive strength. This clearly indicates that in the
multi-leaf walls, most of the load is transmitted by the external layers.

![Figure 3: Specimens representative of the internal leaf: (a) specimens prior testing; (b) typical failure modes.](image)

3.5 FRP bars and injection material

The wall strengthening, to be discussed later in the paper, was achieved by means of transversal
tying of the external walls by resorting to GFRP bars anchored along the thickness of the exter-
nal leaves. This means that the bond between the bar and the injected grout was considered
enough to transmit the load from the leaf to the GFRP rod. In addition, the tensile strength of
the GFRP bar (a value of 760 MPa was provided by the manufacturer) is high enough to prevent
its brittle tensile failure.

As aforementioned, the holes drilled to insert the GFRP bars were injected with a commercial
lime-based grout able to fill in the hole as well as the surrounding voids. In order to assess the
mechanical behaviour of the grout injection, cubic specimens of 50×50×50 mm³ were sampled
during the injection of the holes and tested under uniaxial tensile and compressive loading. The
grout specimens were tested after approximately 30 days of curing, raising an average compres-
sive strength of 17.6 MPa and an average tensile strength of 291 kPa.

4 EXPERIMENTAL TESTS ON THREE-LEAF WALLS

4.1 Test specimens

Wall specimens of 600 mm long, 300 mm thick and 1100 mm high have been designed, see
Fig. 4a. The external layers have a thickness of approximately 100 mm and they are made of
roughly shaped granite stones bonded with lime-based mortar and aligned bed joints. No trans-
versal connection between the external layers by means of stone blocks was provided. The gran-
ite used to build the specimens is from a quarry in the Northern part of Portugal and the mortar
is composed by a binder of lime and pozzolana. The mechanical properties of these materials
have been discussed in detail in section 3.

4.2 Test program

The test program on walls is summarized in Table 1, being based on compressive tests on six-
ten three-leaf walls, strengthened by resorting to different techniques: transversal tying with
GFRP rods, bed joint structural repointing with GFRP rods and the combination of the two pre-
vious techniques. During the experimental program, the strengthening techniques are not ap-
plied consecutively on fixed series of walls, but they will be spread over the series of walls in
order to minimize the influence of the construction phase, instead. In fact, the first two series of
walls (see Table 2) have concerned a first characterization of the behaviour of plain and transversal tied three-leaf stone masonry walls. After approximately 60 days of curing the walls were placed between two steel plates lightly post-tensioned by means of steel bars and transported to the testing frame, see Figs. 4b and 4c.

Figure 4: Three-leaf wall specimens: (a) schematic geometry (units in cm); (b) transport of the wall to the testing frame; (b) wall before testing.

Walls 1W1 through 2W4 were tested under monotonic compressive loading, using a 2 MN steel frame, see Fig. 5a. All the tests were performed under displacement control at a displacement increment rate of 3 µm/s. In order to prevent the total collapse of the walls, tests were stopped during the softening branch when specimens were about to fail. Ten displacement transducers (lvdt’s) were adopted according to Fig. 5b. Applied displacements and corresponding loads were duly recorded at a frequency of 1 Hz.

<table>
<thead>
<tr>
<th>Type of strengthening</th>
<th>Number of walls to be tested</th>
<th>Number of wall tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstrengthened (U)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Transverse tying (T)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Bed joint structural repointing (B)</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Combination of transverse tying and bed joint structural repointing (T+B)</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Experimental campaign, walls designed for compressive testing

<table>
<thead>
<tr>
<th>Series</th>
<th>Number of walls</th>
<th>Type of strengthening</th>
<th>Wall’s label</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2</td>
<td>U×2</td>
<td>1W1, 1W2</td>
</tr>
<tr>
<td>II</td>
<td>4</td>
<td>U×1 and T×3</td>
<td>2W1 and 2W2, 2W3, 2W4</td>
</tr>
</tbody>
</table>

4.3 Transversal tying

The walls 2W2, 2W3 and 2W4 were strengthened by means of two GFRP bars of 10 mm diameter. For that, two holes of 20 mm diameter were drilled at specimens’ third high, as illustrated in Figs. 6a and 6c. The holes were made coincident as much as possible with bed joints. Afterwards, the bars were inserted through the thickness of the wall and the holes were injected with a lime-based grout in order to anchor the strengthening. The walls were strengthened after a period of 30 days curing.

The voids adjacent to holes were injected as well and the absence of compaction in the inner core allowed the leakage of grout though the lateral sides during the injection process, as shown in Fig. 6b. This implies that some parts of the inner core had their weakness improved.
4.4 Test results

In this section, the main results concerning the testing of the three-leaf walls (three plain and three strengthened by transversal tying) are discussed. Table 3 presents the compressive strength of all walls (the coefficient of variation is indicated inside brackets). The unstrengthened walls present an average compressive strength of 1.8 MPa, whereas for the strengthened walls an average compressive strength of 3.1 MPa is achieved. This increase in strength, of about 71% in average terms, is mostly due to the confinement effect produced by the GFRP bars.

<table>
<thead>
<tr>
<th>Wall's label</th>
<th>$f_c$ (MPa)</th>
<th>Wall's label</th>
<th>$f_c$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1W1</td>
<td>2.4</td>
<td>2W2</td>
<td>3.3</td>
</tr>
<tr>
<td>1W2</td>
<td>1.7</td>
<td>2W3</td>
<td>2.6</td>
</tr>
<tr>
<td>2W1</td>
<td>1.4</td>
<td>2W4</td>
<td>3.5</td>
</tr>
<tr>
<td>average</td>
<td>1.8 (26%)</td>
<td>average</td>
<td>3.1 (15%)</td>
</tr>
</tbody>
</table>

Fig. 7 illustrates the axial stress-strain curves computed for the walls. The plain walls (Fig. 7a) present a similar behaviour. The response is characterized by two localized stiffness degradation zones, the first occurring at a stress level of approximately 0.6 MPa, most probably related to the initial separation of the external leaf, and the second close to the peak load, although in wall 1W2 the separation of the external layer seems to be happened for a higher stress level.

Fig. 7b shows that the strengthened walls present analogous stress-strain curves, characterized by progressive stiffness degradation along with the increase of normal stress, although wall 2W2 failed prematurely in a brittle fashion, most likely caused by some construction defect.
Fig. 7 seems also to indicate that the value of the elastic modulus of the walls is not markedly affected by the presence of the two GFRP bars.

Besides the compressive strength increment, the strengthening originated also an increase in the axial deformation prior to failure. This has been made possible by the existence of the transversal GFRP bars that changed the failure pattern. In fact, the failure of the plain walls was dominated by the development of horizontal plastic hinges along bed joints, leading to the formation of a mechanism, as illustrated in Fig. 8, and the typical detachment of the external leaves (global mechanism). However, for the strengthened walls, the GFRP bars provided an effective connection of the external leaves allowing the wall to behave approximately as a single layer, as illustrated by the visible vertical cracks registered close to failure and the absence of significant horizontal cracks, see Fig. 9. For the strengthened walls, failure occurred at a local level caused by the instability of one or more stone units (local mechanism).

In the strengthened walls, failure occurred always before the loss of bond between the GFRP bars and the injected grout. Since a high GFRP-grout bond strength can hardly be expected, this behaviour indicates that the GFRP is most likely submitted to low stress levels.

Figure 7: Axial stress-strain diagrams: (a) unstrengthened walls; (b) strengthened walls (the 2W1 curve is also represented).

Figure 8: Failure of wall 2W1 (unstrengthened): (a) crack pattern close to failure; (b) rotation of the external leaf.
CONCLUDING REMARKS

This paper presents the first results of an experimental program concerning the structural assessment of three-leaf stone masonry walls.

The mechanical characterization of the wall’s materials and components has been performed in order to better understand the global behaviour of the walls. Given the remarkable difference in terms of load capacity, the external leaves of the three-leaf stone masonry walls under analysis carry most of the applied load.

The use of transversal GFRP ties through the wall thickness, bond to the external leaves by means of a lime-based grout, has shown to be an effective strengthening technique. The average compressive strength was increased about 71% with regard to the plain walls. The typical failure mode was shifted from out-of-plane movement of the external leaves, due to the development of horizontal plastic hinges (global mechanism), to the formation of a dominant vertical cracking pattern and the localized loss of equilibrium at some stone units (local mechanism).

Finally, the results presented in the paper show that the influence of workmanship and the variability of natural and handmade materials should be considered when dealing with ancient building constructions.

ACKNOWLEDGEMENTS

The authors want to acknowledge Rui Silva for his assistance in the experimental activity and data elaboration and the technical staff at the Laboratory of Civil Engineering at the University of Minho. Acknowledgements are also due to “Fondazione Gini” and to the companies Fradical, Mapei and Augusto Ferreira & Filhos for providing raw materials and workmanship.

The financial support provided by the Portuguese Science and Technology Foundation through the POCI/ECM/58987/2004 project is gratefully acknowledged.

REFERENCES


