SEISMIC STRENGTHENING OF
ADOBE-MUDBRICK HOUSES

By
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EXECUTIVE SUMMARY

This thesis presents the research and development of a low-cost, low-tech reinforcement system to improve the earthquake resistance of adobe mudbrick houses. The outcome of this research project is a reinforcement system which can be readily implemented by rural homeowners in developing countries using locally available resources (materials, tools and skills), without the need for ongoing external support. The proposed reinforcement system incorporates bamboo poles placed vertically against the walls, and connected with through-wall string ties, and strands of wire running horizontally. A continuous timber ring beam is placed on top of the walls. The system can be used for new-build constructions, as well as for the retrofit-strengthening of existing dwellings. The system has the potential to substantially and sustainably reduce the vulnerability of traditional adobe houses around the world.

This thesis describes the multi-disciplinary approach undertaken for this project, which includes field research in El Salvador, review of literature, extensive experimental testing, Experimental Modal Testing and Analysis (EMTA) and the development of dissemination and implementation initiatives. A number of further research needs are also identified.

Field research in El Salvador

In early 2001, the small Central America nation of El Salvador was rocked by two major earthquakes, registering $M_w$ 7.7 and $M_w$ 6.6. The earthquakes claimed almost 1,200 lives and affected over 1.6 million people. More than 110,000 adobe houses were destroyed.

The field research component of this thesis has involved a variety of post-earthquake relief, research and reconstruction activities in El Salvador since 2001. The following aspects are presented in this thesis:

- Case study of adobe in El Salvador, including a discussion of the history and use of adobe housing, as well as some of the common features and deficiencies in traditional adobe houses.
• Evaluation of the features and effects of the 2001 El Salvador earthquakes, with a particular focus on the impacts to adobe housing.

• A review of reconstruction activities and improved adobe initiatives (promotion, training and construction projects) one year after the earthquakes.

• The design and construction of an improved adobe child-care centre in a small rural community in El Salvador.

• A review of the general state of housing reconstruction and the housing deficit in El Salvador in 2005.

• An assessment of the challenges and opportunities for the widespread implementation and acceptance of safer adobe construction and retrofit-strengthening techniques.

Literature review

Substantial seismic adobe research has been undertaken in Peru, Mexico, the U.S.A. and Colombia since the 1970s. To date, experimental testing has tended to focus on qualitative results (observations). Research findings have been included in a variety of adobe guidelines and manuals. These research and dissemination activities have made a significant contribution to the current state-of-knowledge. Despite these efforts, however, there has been a lack of large-scale application and community-level acceptance of these practices. The main reason for this lack of broadscale uptake is that most of the proposed systems are too complex and/or too complicated to be widely used without sustained external intervention.

Experimental testing

The experimental testing component of this research project is divided into four main phases:

• Static testing of adobe prisms to determine characteristic material properties (compressive, shear and tensile bond strengths). It was found that significant improvements in the shear and flexural bond strength of adobe masonry can be practically achieved by: (i) wetting the surface of each brick prior to laying;
(ii) using a thin mortar joint; and/or (iii) applying a modest compressive load during curing.

- Shake table testing of eleven 1:2 scale u-shaped adobe wall units, representing traditional and improved adobe structures. Each specimen was subjected to a series of simulations, using a modified input time history from the El Salvador earthquake of January 13, 2001. For each specimen a unique ‘time scaling factor’ was determined, based on the relationship between the natural frequency of the specimen and the dominant frequency range of the input excitation. This factor was used to time scale the input spectra to ensure dynamic similitude (between specimens) and induce damaging near-resonance conditions. Qualitative and quantitative data from each test was collected and analysed, as discussed below.

- Shake table testing of a 1:2 scale model adobe house, which was retrofit-strengthened with external vertical bamboo, external horizontal wire, and a timber ring beam. Detailed analysis of results were undertaken, as discussed below.

- Detailed analysis of results from the shake table testing of the u-panel units and the model house. This included a review and comparative analysis of the qualitative results (observations, photographs, video footage) and quantitative results (displacement-time records, relative deformation, and vertical and horizontal flexure). Common crack patterns (vertical corner cracking, vertical midspan cracking, and horizontal and diagonal cracking) were observed. These damages were due to combinations of overturning, vertical flexure and horizontal flexure. The most successful improvement systems were seen to reduce movement in the wall units and enhance the overall strength of the structure. Such systems effectively delayed the onset of initial cracking, and reduced the severity of cracking during repeated high intensity simulations. Most importantly, collapse of reinforced structures was prevented in all tests. Results from the preparation and testing were used to develop a ‘specimen rating matrix’ which presents the seismic capacity, cost and complexity of each reinforcement system. The matrix highlights the important of considering the technical and practical aspects of any proposed reinforcement system. These factors could be incorporated in a detailed multi-criteria evaluation matrix,
which would be a useful tool in the planning and realisation of any construction and implementation project.

**Experimental Modal Testing and Analysis (EMTA)**

EMTA was undertaken in conjunction with the experimental testing of the u-shaped wall units and the model house. EMTA was used to determine the dynamic characteristics (natural frequencies, damping ratios and mode shapes) of specimens both prior to and during shake table testing. Results highlighted the discontinuities introduced by internal vertical reinforcement (increased damping, decreased stiffness) and the changes in dynamic properties during the strengthening process prior to shake table testing. The influence of penetrations (windows and doors) was clearly evident. EMTA during the shake table testing showed the progressive loss of stiffness, and the general increase in modal damping, of the specimens as the level of damage increased. The mode shapes matched the flexure graphs produced during the experimental testing. EMTA was demonstrated to be a useful tool to reflect the physical response and changes in dynamic characteristics of adobe structures. Results provide greater insight into the structural behaviour than observations alone, and may be a practical tool for damage detection and condition monitoring of adobe structures.

**Dissemination and implementation**

The framework of two initiatives for the dissemination and implementation of research findings are presented in this thesis. These initiatives are designed to transfer the outcomes of seismic adobe research and application activities to communities around the world where people continue to live in vulnerable adobe houses. These initiatives included:

- The World Adobe Forum: a website dedicated to the sharing of information about safer adobe construction.
- A sample implementation program designed to increase the desire, capacity and confidence of local homeowners and builders to retrofit and/or construct safer adobe houses.
Further research

A number of further research needs have been identified and presented in this thesis. These research needs relate to both technical and practical aspects of improved adobe, and include:

- Post-earthquake reconnaissance.
- Further experimental testing of adobe bricks, prisms, wall units and model houses (static, quasi-static and dynamic testing).
- Development of a reliable numerical model through nonlinear heterogeneous Finite Element (FE) modelling.
- Extensive parametric studies (using the validated FE model) to assess a broad range of design and construction variables and improvement systems, without the need for resource-intensive physical testing.
- Implementation and application activities, including an evaluation of the effectiveness of promotion and training programs, and the development of a comprehensive multi-criteria evaluation tool.

This thesis highlights the importance of a multi-disciplinary approach which considers both the social and technical aspects of disaster mitigation activities. This approach is necessary to ensure the development of solutions which are socially-appropriate (low-cost and low-tech) and technically-sound (seismically safe). Such solutions have the opportunity to significantly reduce the vulnerability of adobe houses around the world.
CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

[Signature]

Dominic Dowling

August 2006
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PUBLICATIONS

The following publications have been generated as part of this research. Components from some of these publications have been reproduced in this thesis.

Books


Book chapters


Conference papers


(* indicates peer-reviewed publications)
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<td>Australian Standard</td>
</tr>
<tr>
<td>ASIA</td>
<td>Asociación Salvadoreña de Ingenieros y Arquitectos (Salvadoran Association of Engineers and Architects) [El Salvador]</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials [U.S.A.]</td>
</tr>
<tr>
<td>b</td>
<td>Breadth / width</td>
</tr>
<tr>
<td>BSSC</td>
<td>Building Seismic Safety Council [U.S.A.]</td>
</tr>
<tr>
<td>CAFOD</td>
<td>Catholic Agency for Overseas Development (NGO) [United Kingdom]</td>
</tr>
<tr>
<td>CIA</td>
<td>Central Intelligence Agency [U.S.A.]</td>
</tr>
<tr>
<td>COEN</td>
<td>Comité de Emergencia Nacional (National Emergency Committee) [GOES]</td>
</tr>
<tr>
<td>COSMOS</td>
<td>Consortium of Organizations of Strong-Motion Observation Systems</td>
</tr>
<tr>
<td>CoV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>d</td>
<td>Depth</td>
</tr>
<tr>
<td>DIGESTYC</td>
<td>Dirección General de Estadísticas y Censos (General Office of Statistics and Censuses) [GOES]</td>
</tr>
<tr>
<td>DIN</td>
<td>Deutsches Institut für Normung [Germany]</td>
</tr>
<tr>
<td>E</td>
<td>East</td>
</tr>
<tr>
<td>ECLA/CEPAL</td>
<td>Economic Commission for Latin America and the Caribbean / Comisión Económica para América Latina y El Caribe [UN]</td>
</tr>
<tr>
<td>EERI</td>
<td>Earthquake Engineering Research Institute [U.S.A.]</td>
</tr>
<tr>
<td>EGPA</td>
<td>Estimated peak ground acceleration</td>
</tr>
<tr>
<td>EMTA</td>
<td>Experimental Modal Testing and Analysis</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Compressive strength</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency [U.S.A.]</td>
</tr>
<tr>
<td>FRF</td>
<td>Frequency Response Function</td>
</tr>
<tr>
<td>FUNDASAL</td>
<td>Fundación Salvadoreña de Desarrollo y Vivienda Mínima (Salvadoran Development and Minimum Housing Foundation) [NGO, El Salvador]</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity (9.81 ms$^{-2}$)</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>GOES</td>
<td>Gobierno de El Salvador / Government of El Salvador</td>
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<tr>
<td>GSAP</td>
<td>Getty Seismic Adobe Project [U.S.A.]</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IAEE</td>
<td>International Association for Earthquake Engineering</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organisation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>IZIIS</td>
<td>Institute of Earthquake Engineering and Engineering Seismology, Skopje, Macedonia.</td>
</tr>
<tr>
<td>kg</td>
<td>Kilograms</td>
</tr>
<tr>
<td>kPa</td>
<td>Kilopascals</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>LSM</td>
<td>Low Strength Masonry</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer (displacement transducers)</td>
</tr>
<tr>
<td>m</td>
<td>Metres</td>
</tr>
<tr>
<td>MAC</td>
<td>Modal Assurance Criterion</td>
</tr>
<tr>
<td>MDOF</td>
<td>Multi-degree-of-freedom</td>
</tr>
<tr>
<td>MIF</td>
<td>Mode Indicator Function</td>
</tr>
<tr>
<td>mm</td>
<td>Millimetres</td>
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<tr>
<td>MPa</td>
<td>Megapascals</td>
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<tr>
<td>MSJC</td>
<td>Masonry Standards Joint Committee [U.S.A.]</td>
</tr>
<tr>
<td>n</td>
<td>Number of specimens</td>
</tr>
<tr>
<td>N</td>
<td>Newtons</td>
</tr>
<tr>
<td>N</td>
<td>North</td>
</tr>
<tr>
<td>NC</td>
<td>Not Captured</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-Governmental Organisation</td>
</tr>
<tr>
<td>NISEE</td>
<td>National Information Service for Earthquake Engineering</td>
</tr>
<tr>
<td>NR</td>
<td>Not Reported</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>P</td>
<td>Maximum load</td>
</tr>
<tr>
<td>p.a.</td>
<td>Per annum</td>
</tr>
<tr>
<td>PUCP</td>
<td>Pontificia Universidad Católica del Perú (Catholic University of Peru)</td>
</tr>
<tr>
<td>RESESCO</td>
<td>Reglamento Para la Seguridad Estructural de las Construcciones (Regulation for the Structural Security/Safety of Constructions) [El Salvador]</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>s</td>
<td>Seconds</td>
</tr>
<tr>
<td>S</td>
<td>South</td>
</tr>
<tr>
<td>S.A.</td>
<td>Surface Area</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<tr>
<td>SDOF</td>
<td>Single-degree-of-freedom</td>
</tr>
<tr>
<td>ST</td>
<td>Shake table</td>
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<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>TRS</td>
<td>Test Response Spectrum</td>
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<tr>
<td>UCA</td>
<td>Universidad Centroamericana ‘José Simeón Cañas’ [El Salvador]</td>
</tr>
<tr>
<td>UES</td>
<td>Universidad de El Salvador (University of El Salvador)</td>
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</tbody>
</table>
UN       United Nations
UNAM     *Universidad Nacional Autónoma de México*
UNDP     United Nations Development Program
USGS     United States Geological Survey [U.S.A.]
UTS      University of Technology, Sydney, Australia
VMVDU    *Vice-Ministerio de Viviendas y Desarrollo Urbano* (Vice-Ministry of Housing and Urban Development) [GOES]
W        West
w.r.t.   with respect to
τ        Shear strength
ζ        Damping ratio
To the people of El Salvador, whose indefatigable spirit and courage endures and inspires, despite a history of war, oppression, corruption, and natural disasters.