Seismic Research on Earth Building related to the 1998 New Zealand Earth Building Standards

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ABSTRACT

New Zealand is seismically active, has about 700 existing earth buildings and an increasing number of modern earth buildings. In 1998 a suite of limit state earth building standards were published, **NZS 4297** ***Engineering Design of Earth Buildings***, **NZS 4298** ***Materials and Workmanship for Earth Buildings*** and **NZS 4297** ***Earth Buildings Not Requiring Specific Design***. The standards cover adobe, rammed earth and pressed brick construction.

A modest amount of research was undertaken to confirm parameters for the standards. Test procedures and results of in-plane testing for a range of reinforcement methods and bond testing of unstabilised abobe and in-plane testing cement stabilised rammed earth will be presented. The basis of some of the provisions in the standards and the concepts related to out-of-plane performance using an energy method and collapse mechanism demonstrated using a computer model and discussed. Current developments in fibre reinforced earth wall panels will be overviewed.

This paper also outlines the seismic context of New Zealand the main types of modern earth buildings and their aseismic features. Earth houses are either owner built or high value housing built by contractors. There is an active earth building association of enthusiasts, builders and architects with a few engineers.

Nueva Zelanda es un país que presenta actividad sísmica, posee alrededor de 700 edificios de tierra existentes y una cifra de modernos edificios de tierra que va en aumento. En 1998, una serie de normas en referencia al estado-limite de los edificios de tierra fue publicada. La norma **NZS 4297: Diseño** ***en Ingeniería para Edificios de Tierra***, la norma **NZS 4298:** ***Materiales y Calidad en la Ejecución para Edificios de Tierra*** y la **NZS 4297:** ***Edificios de Tierra sin Requerimientos de Diseño Específicos***. Estas normas son aplicables a las construcciones en adobe, tierra apisonada y ladrillo prensado.

Un modesto número de investigaciones fue adelantado con el fin de confirmar los parámetros establecidos en las normas mencionadas. Los procedimientos y resultados de las pruebas de carga, en la dirección del plano, para diferentes métodos de refuerzo y pegado en adobe no estabilizado y las pruebas de carga en el plano, para tierra apisonada estabilizada con cemento, serán presentados. Por otra parte, las bases de algunas de las reglas planteadas en las normas y los conceptos relacionados con el desempeño con cargas fuera de su plano, usando un método de energía y un mecanismo de colapso, que será demostrado usando un modelo computarizado, serán también objeto de discusión. Adicionalmente, se presentará un breve resumen acerca de los avances logrados en la técnica de muros de tierra reforzados con fibras.

Este artículo describe a grandes rasgos el contexto sísmico de Nueva Zelanda, los principales tipos de edificaciones de tierra modernas y sus características anti-sísmicas. Las

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casas de tierra bien pueden ser construidas por sus propietarios o viviendas de alto costo construidas por contratistas. Existe una asociación activa dedicada a la construcción de tierra conformada por entusiastas, constructores y arquitectos con unos pocos ingenieros.

INTRODUCTION

New Zealand Tectonic Context

New Zealand is on the boundary of the same tectonic plate as Central America and eastern South America. As can be seen from the maps from the Global Seismic Hazard Assessment Program it has seismic hazard of an almost similar level.

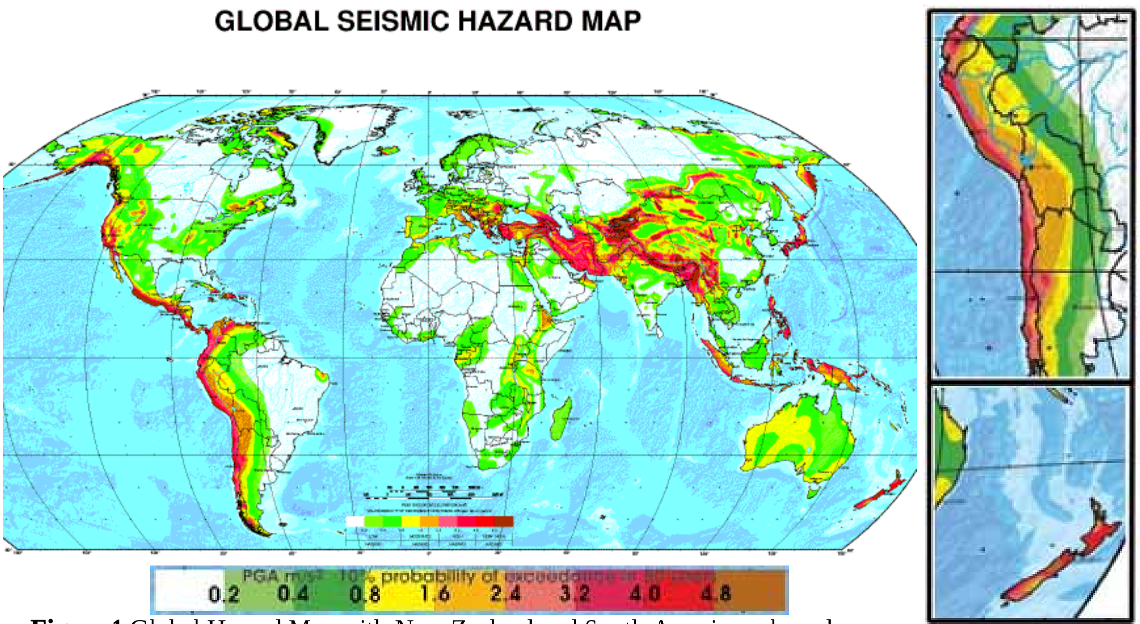


Figure 1 Global Hazard Map with New Zealand and South America enlarged. (Global Seismic Hazard Assessment Program, 2000)

The considerable seismic activity in New Zealand is due to the Pacific tectonic plate subducting the Indo-Australian plate to the north and east and the plates shearing along each other in the south island. In the southern ocean the reverse occurs with the Pacific plate overriding the Indo-Australian plate.

The tectonic movement is evidenced by a substantial mountain peaks and the Alpine fault along the west coast of the South Island and a lower elevation mountain range that continues to the eastern corner of the North Island.

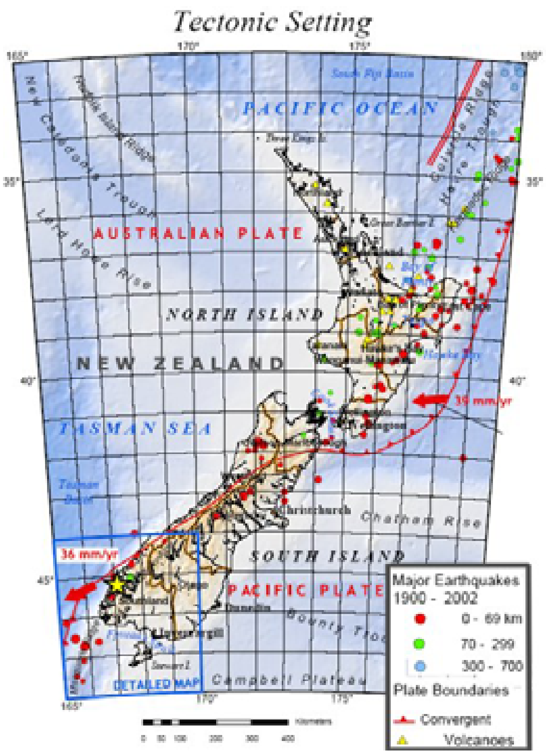


Figure 2 New Zealand Seismicity 1900-2002 showing major earthquake events and volcanoes. *Extracted and modified from a poster.* (National Earthquake Information Center USGS, 2003)

There are geothermal hot springs in a number of places and in the central North Island there are mud pools, geysers, geothermal power stations and a string of active volcanoes that stretch north east into the Pacific Ocean.

Lake Taupo, the largest in New Zealand formed in the crater of a rhyolitic volcano that is earths largest eruption in the last 5000 years in the world's most productive rhyolitic field (10 times the erupted volume of famous Krakatoa event, 1883). There is no evidence of human habitation prior to the thirteenth Century AD so the only historical record is from the writings of China and Rome which seem to relate to the Taupo eruption when the sky around the globe was 'as red as blood' around 180AD.(King, 2004)

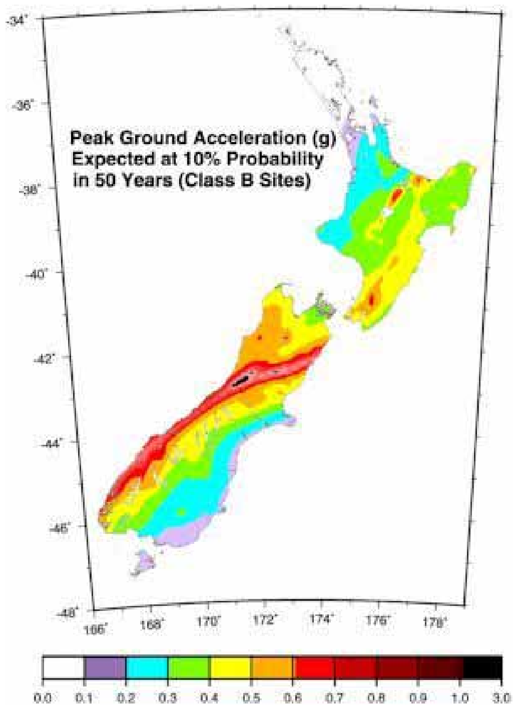


Figure 3 More refined view of New Zealand Seismicity from (Geological and Nuclear Sciences, 2004)

Historic Earthquakes

The first human inhabitants were Maori from Polynesia who arrived around 1200AD. (King, 2004) A major earthquake in approximately 1460AD was recalled by oral tradition for 18 generations by the time it was recorded (Rogers, 1996). Maori obviously were concerned by the seismic activity and honoured a god of earthquakes and volcanoes called Ruamoko (Erlbeck, 1998).

British explorer Captain James Cook landed in 1769 and although European settlement began slowly there were soon reports of earthquakes. The first significant British settlements began 1840's and the town of Wellington had a population of around 4500 in 1848 when a major earthquake, estimated at M_L7.5 in Marlborough in the upper South Island, caused Modified Mercalli MM VIII intensity shaking in Wellington. This was soon overshadowed by MM X intensity from the M_L 8.2 earthquake of 1855 with an epicentre in the Wairarapa at a distance of about 20km. (Downes, 1995),(Grapes, Downes & Goh, 2003)

In 1929 there was an earthquake near Murchison of Richter magnitude M_L7.8 that gave an intensity assessed at MM IX in the town. In 1931 the major event M_L7.9 intensity MM X occurred in Hawkes Bay on the East Coast of the North Island. This killed 256 people (NZ's largest disaster) demolishing a number of buildings in central Napier which then was devastated by the resulting fire. (Conly, 1980)

There have been a number of moderate events since that time but the surprisingly few major events have all been at a distance from major cities. The most recent major earthquake was the August 2003 event of magnitude M_w 7.2 in Fiordland a remote sparsely inhabited area at the bottom of the South Island (National Earthquake Information Center USGS, 2003).

CONSTRUCTION AND LEGISLATION IN NEW ZEALAND

House Construction in New Zealand

New Zealand has a temperate climate and was heavily forested so Maori houses were predominantly made of timber and reeds as shown in figure 4. (Best, 1974) Early colonial housing ranged from crude huts to two storey houses. After the 1855 earthquake that so badly hit Wellington most masonry buildings were damaged so from that time house construction was predominantly in timber.

Figure 4 Early Maori housing – low earthquake vulnerability

Following the 1931 Hawkes Bay earthquake a New Zealand Standards Institution was started in 1932 and in 1935 the first building code was published. (Conly, 1980) Building standards have been relatively rigorously enforced by Territorial Authorities (ie. Councils) since that time and there is an expectation that building standards will be upheld for all significant structures. New Zealand researchers made world leading contributions to seismic design of reinforced concrete structures during the 1970's and has continued active research in many other areas of earthquake engineering including aseismic masonry.

Masonry construction has also been constructed with high quality expectations. Over the last century very little pure masonry house construction has been undertaken with by far the bulk of houses being timber or timber frame with a single skin masonry veneer with fixings to the frame. Over the last 50 years there has been considerable use of filled hollow concrete block masonry that has been well reinforced particularly in basements, retaining walls or lower floors. In recent years hollow concrete masonry has been used partially filled for whole houses and the number of two storey masonry houses has increased.

Figure 5 Basement for house with earth retaining masonry basement – close-ups of reinforcing and cleanout cells.

The large expensive home illustrated in figure 5 is reinforced concrete masonry with considerable reinforcement evident, grout filled cells have inspection vents to clear any debris and ensure maximum bond and filling of cells. Horizontal reinforcement is in regular bands with some full concrete bond beams.

This second example in figure 6 is another large masonry house showing the concrete bond beams at floor and roof levels.

Figure 6 Two storey masonry home with concrete bond beam

Earth Building Technology in New Zealand

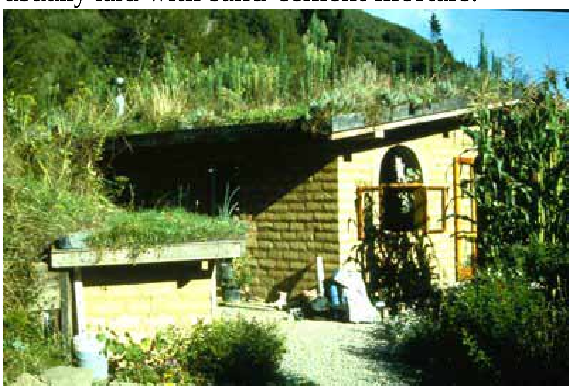
A large number of temporary earth buildings were built during gold rush days in the 1860's but few remain after roof materials were reused and walls soon degraded in the damp climate. (Allen, 1990) Of the more permanent buildings approximately 390 earth houses still exist that were constructed between 1840 and 1910. The growing interest in more environmentally friendly and sustainable buildings in the late 1980's has led to an upsurge of earth building construction (Allen, 1997) with around 30 - 40 earth buildings now being built each year. This around 0.15% of the total but in some areas of New Zealand over one percent of new houses are constructed with earth.

Figure 7 Broadgreen House, Lower storey cob walls(Broadgreen Society Inc)

A notable example of an earth building that has survived three major earthquakes (MMVII or greater) is Broadgreen House near Nelson in the upper South Island which was constructed in the 1850s. The apparent factors that account for the good performance of this large two storey cob building were: the low height to thickness ratio of the earth walls, the relatively few openings, sufficient earth bracing walls in each direction, the first floor acting as a structural diaphragm, and relatively good quality earth wall construction. The 500 mm thick earth walls of the ground floor reach 2700mm to the first floor giving a height to thickness ratio of 5.4 which complies with present design criteria for un-reinforced earth walls in New Zealand.

Figure 8 Pressed Earth Brick House with close view of lintel detail

The main forms of earth construction at present in New Zealand are adobe, rammed earth and pressed brick. Adobe and cob are the most common types of older earth buildings still existing today. Rammed earth comprises monolithic wall panels constructed with damp well graded sandy soils compacted in 100 to 150 mm thick layers between temporary movable formwork. In New Zealand the soils are usually stabilised with 5 to 10 percent cement. Pressed bricks use similar soils to rammed earth and are formed in a mechanical press which is either hand or machine operated. Pressed bricks are usually laid with sand-cement mortars.



Adobe bricks sometimes use straw or a cement stabiliser which is also used in mortar in the walls.

The range of construction is from small owner built houses through to luxury homes built by specialist contractors.

Figure 9 An adobe house with a herb garden on the earth roof

Figure 10 High quality abobe home $600m^2$ (6000 sq ft) 5 bedrooms, 4 bathrooms, 4 car garage recently sold for just over US$1.2 million" (Peter Young, 2005)

Increasing Earth Construction and EBANZ

There was very little earth housing in the 1920's and 30's with a short burst during the materials shortages after World War II, the significant growth in interest has come since the 1980's. The enthusiasm of the earth Building Association has been very influential in the success and spread of earth buildings in New Zealand.

EBANZ was founded in 1988 with around 20 members with the mission of "promoting the art and science of earth building". They ran workshops in various towns and started a newsletter, ran a conference in 1989 and set up design guidelines. In 1990 this received a boost when Miles Allen and Waldo Granwal from the University of Auckland School of Architecture organised an international conference "Earthbuilding for the 90's". EBANZ publishes a bi-monthly magazine runs a website (www.earthbuilding.co.nz) and has a current membership of 275 who are interested public, owner builders, prospective home owners, 10 earth contractors, 5 block manufacturers, about 15 architects and designers and 6 engineers. Members have written several guide documents, published books and held displays at a number of Eco Shows and field days.

In 1991 EBANZ took the initiative to develop guidelines for Earth buildings and in 1994 the Standards Association of New Zealand took responsibility to develop formal standards with the committee chairman being the then chair of EBANZ, Graeme North.

New Zealand Building Legislation

Construction in New Zealand is governed by the *Building Act* (Building Act, 2004) which has a framework of building controls, the Building Regulations contain the mandatory New Zealand Building Code. Approved Documents provide methods of compliance with the Building Code and may cite documents such as the New Zealand Standards as a way to comply with the Code.

About 90% of New Zealand housing is timber so approved document NZS 3604 *Code of Practice for Timber Framed Buildings not requiring specific design* (Standards New Zealand 1978) established the precedent for this type of document. *NZS 3604 Timber Framed Buildings* (Standards New Zealand 1999) is now 400 pages with numerous tables and well drawn diagrams that allow builders and architectural draftspeople to design houses to resist earthquake and wind loads. NZS 4229 *Concrete Masonry Buildings Not Requiring Specific Engineering Design* (Standards New Zealand, 1986) was not as comprehensive but available and has subsequently been updated (Standards New Zealand, 1999).

THE NEW ZEALAND EARTH BUILDING STANDARDS

Overview

Three comprehensive performance based standards for earth walled buildings were published in 1998. Substantial documents were needed for design and construction that used a performance based approach to comply with the general standards framework, these have been approved as a means of compliance with the New Zealand Building Code. The standards were prepared by a joint technical committee of engineers, architects, researchers and builders and were developed over a period of 7 years. These documents have made a significant contribution to the increased acceptance of earth building in New Zealand.

The standards are described below and some of the supporting research follows in a subsequent section.

Engineering Design of Earth Buildings

NZS 4297 Engineering Design of Earth Buildings (Standards New Zealand, 1998) specifies design criteria, methodologies and performance aspects for earth wall buildings and is intended for use by structural engineers.

Limit-state design principles were used in the formulation of this standard to be consistent with other material design standards. Earthquake loads are more critical than wind loads for most earth buildings in New Zealand and earth wall heights are limited to 6.5 m in this standard. The design methodologies are discussed in more detail later in this paper.

Materials and Workmanship for Earth Buildings

Figure 11 Cover of NZS 4298

NZS 4298 Materials and Workmanship for Earth Buildings (Standards New Zealand 1998), 82 pages, defines the material and workmanship requirements to produce earth walls which, when designed in accordance with NZS 4297 or NZS 4299, will comply with the requirements of the New Zealand Building Code. Requirements are given for all forms of earth construction but more specifically for adobe, rammed earth and pressed brick.

The suite of standards is primarily intended for small-scale construction so a number of simple low cost test procedures are defined in the Materials and Workmanship standard. This testing can be done by the person responsible for the construction of the building in the presence of the owners or the controlling building authority as required.

Compression or simplified ‘modulus-of-rupture’ tests are specified for determining the strength requirements of the earth wall materials. Compression tests need to be done in a laboratory but two simple test procedures are detailed for the ‘modulus-of-rupture’ test (one is shown in fig . 12) and a brick drop test is also specified for simple field testing of earth bricks.

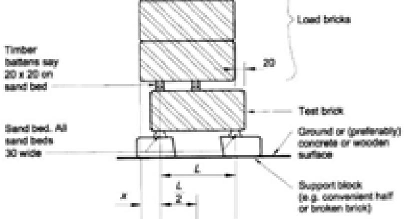


Figure 12 Modulus of Rupture Test

Two grades of earth wall material are covered within the standard:

Standard Grade with a design compressive strength of 0.5 Mpa which can be obtained by low strength materials with a minimal amount of testing, or

Special Grade which requires more testing to reasonably predict the characteristic strength. Earth stabilised with cement may achieve strengths of up to 10 Mpa. More complex engineered structures would be of Special Grade.

More detail is available on this standard elsewhere (Walker and Morris, 1998), NZS4298 includes substantial sections on durability which are significant in the temperate climate.

Earth Buildings Not Requiring Specific Design

NZS 4299 Earth Buildings Not Requiring Specific Design (Standards New Zealand 1998), 122 pages, provides methods and details for the design and construction of earth walled buildings not requiring specific engineering design. The document will be mainly used for designing houses but users will include a range of people in the earth building industry including builders, architects, engineers, students and building authority staff.

This standard covers buildings with single storey earth walls and a timber framed roof, or single lower storey earth walls with timber second storey walls and a light timber framed roof. The scope is limited to footings, floor slabs, earth walls, bond beams and structural diaphragms. The design of the timber roof structure would be covered by NZS3604 *Timber Framed Buildings* (Standards New Zealand 1999) or specific engineering design.

NZS 4299 Earth Buildings Not Requiring Specific Design is the earth wall construction equivalent of NZS 3604 with similar methodology. It is intended to provide a means of compliance with the New Zealand Building Code.

Earth buildings covered by this standard resist horizontal wind and earthquake loads by load bearing earth bracing walls that act in-plane in each of the two principal directions of the building. A simple design methodology uses tables in terms of “bracing units” for determining the “bracing demand” required for the building and the “bracing capacity” is provided by the nominated bracing walls as shown in figure 13.

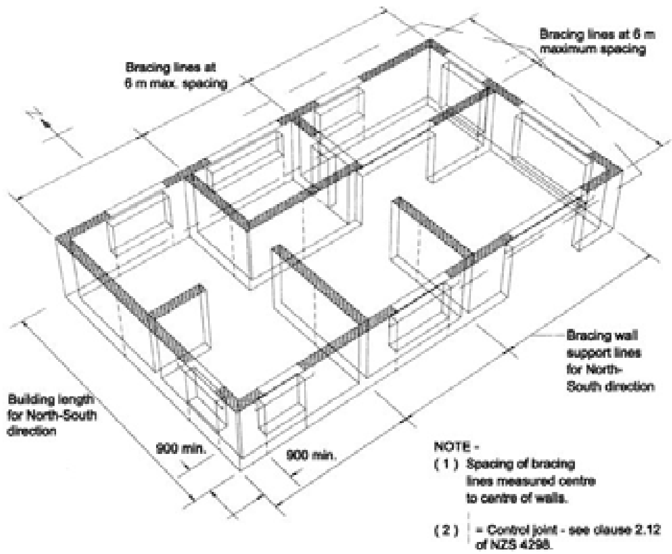
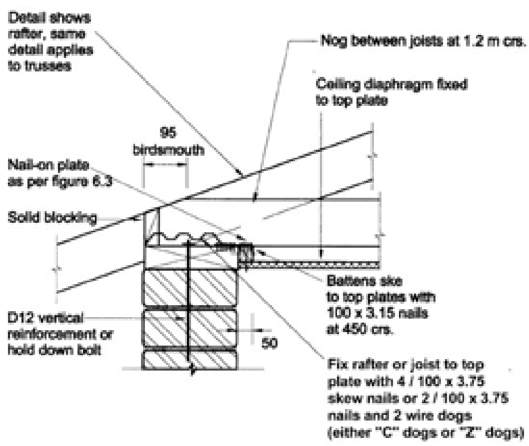


Figure 13 Bracing line method of assessing lateral resistance NZS4299



Many construction details which have been proved in earth buildings constructed in New Zealand during the past 12 years are included in the standard. Specific examples are shown in figures 14 and 15.

Figure 14 Diaphragm ceiling detail from NZS4299 (Note the illustrated Nailon steel connector has been replaced with other nail and “wire dog” details)

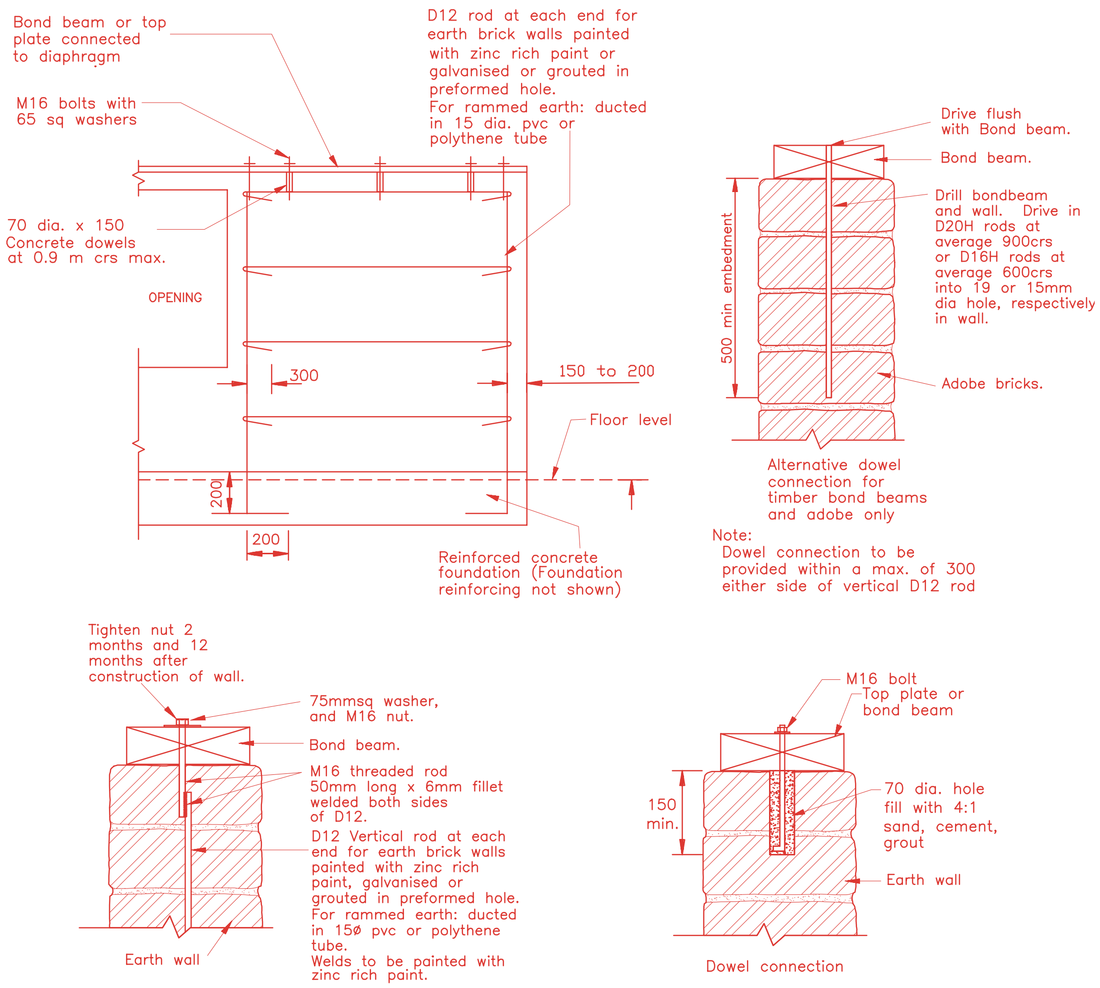


Figure 15 Typical reinforced wall detail from NZS4299 – Polypropylene geogrid is also used horizontally

Design Approach

Design methodologies for earth buildings in New Zealand have been adapted from existing masonry and concrete standards. The design approach in the standards is based on reinforced concrete theory and uses limit state design principles for both elastic and limited ductile response. The structural ductility factor was taken as 2.0 for reinforced earth walls, 1.25 for the narrower Cinva brick walls, and 1.0 (equivalent to elastic response) for unreinforced and partially reinforced earth walls.

In *NZS 4299 Earth Buildings not Requiring Specific Design*, the earth walls were designed as spanning between the reinforced concrete foundation at the bottom of the wall and the top plate or bond beam at the top of the wall. Loads from the tops of walls, roofs and timber second storeys were assumed to be distributed by concrete or timber bond beams or structural ceiling or roof or first floor diaphragms to transverse earth bracing walls.

The 1992 loadings standard (Standards NZ 1992) defines Earthquake Zones, in these high risk zones the earth buildings require specific engineering design is required for unreinforced earth walls.

Out-of-Plane Loads

Ultimate strength reinforced concrete theory is used for designing reinforced earth walls. Generally vertical reinforcing is considered to provide the tensile force for reinforced earth wall panels to work in flexure against out-of-plane face loading.

An energy method is used for assessing the ultimate limit state seismic out-of-plane resistance of unreinforced walls spanning vertically. Rather than elastic strength at first cracking, the energy approach is based on the collapse mechanism when the displacement of the wall moves beyond stability. The method is described with some questions in the Future Development section at the end of this paper.

Using the energy method, unreinforced earth walls for low earthquake zones (zone factor Z<= 0.6) were found to be satisfactory for the maximum wall heights permitted in the standard. For example the failure of a 2700 mm high and 280mm thick wall was calculated to occur at 178 % of the calculated demand requirement with Z<= 0.6.

In-Plane Loads

Earth bracing walls provide seismic load resistance in each principal direction of the building. Reinforced earth walls are reinforced vertically and horizontally to provide some in plane ductility and to develop extra shear strength.

The reinforcement permits the use of smaller seismic design loads when a planned ductile failure mode is designed for the structure. The designed failure mode is in-plane bending of the earth bracing walls with yielding of vertical reinforcing at each end of the wall. Shear failure of these walls is prevented typically by the use of well distributed horizontal reinforcing. Vertical reinforcement is kept to a reasonable minimum to limit in plane shear loads and foundation forces.

Unreinforced walls provide considerably less bracing capacity without the vertical and horizontal reinforcement. Shear failure is prevented solely by the shear strength of the earth.

The maximum bracing capacity provided by a reinforced earth wall, 2400 mm long, 2400 mm high and 280 mm thick with typical details in accordance with the standard, see Figure 3, was calculated to be 30 kN. The bracing capacity provided by a similar sized unreinforced earth wall in a low earthquake zone was calculated to be 10 kN.

Statistics for Testing

Because users may undertake tests to establish the earth material strength it requires that some simple statistics be applied to establish the characteristic value. Soils used in earth building are very variable but the compressive strengths of dried or compressed earth materials usually have a C_V between 0.15 and 0.3. No sets of test data large enough to reasonably determine the underlying population distribution were located. The Australian Masonry Standard AS3700 (Standards Australia 1988) determines the characteristic strength from 30 specimen tests. This is not viable for a simple house due to the effort to construct specimens and the cost of testing . A 5 specimen simplified approximation is used to determine the characteristic strength

$$f' = \left(1 - 1.5\frac{x_s}{x_a}\right)x_1 \qquad (1)$$

Where x_1 is the lowest of the five results, x_s is the standard deviation and x_a is the mean.
The standard includes the more reliable Ofverbeck Power Method (Hunt & Bryant, 1996) for sample sizes of 10 to 29. This method, which is presented in a simplified form, is not dependant on knowing the population distribution to determine the characteristic strength.

An example from NZS4298 is included below where the lowest 3 values of a series of ten results are used to determine the characteristic strength.

For number of specimens in the sample, *n*, from 10 to 19 the characteristic strength is:

For $n = 10 - 19$

$f' = x_3^{1-\varepsilon}.(x_2.x_1)^{\varepsilon/2}$ where ε is given by:

n	10	11	12	13	14	15	16	17	18	19
ε	3.31	3.12	2.96	2.80	2.66	2.53	2.41	2.29	2.19	2.08

CB4.2

Example

For a series of 10 test results for which the lowest 3 values are 1.45, 1.75 and 1.84. For n = 10 the ε value is 3.31

therefore $f' = x_3^{1-3.31}.(x_2.x_1)^{3.31/2} = 1.84^{-2.31}.(1.75 \times 1.45)^{1.655} = 1.14$

Note that x_1, x_2, x_3, x_4 *are the lowest, second lowest, third lowest, fourth lowest test results*

For between 20 and 29 samples the lowest four values would be used and the characteristic strength with coefficients from a similar table.

RESEARCH IN SUPPORT OF THE EARTH BUILDING STANDARDS

Initial Work

There were many contributors to the earth building standards and a depth of knowledge based on local experience. This gave access to informal literature based on personal experimentation and results of lab testing associated with previous buildings. The standards committee also compiled the best of the literature we could locate. For my part there were a range of practitioners who suggested research and contributed to a variety of experimentation that gave a feeling for the materials and an overview of the problem.

Some of the tests that were undertaken were:

- In-plane performance of a full size Light Earth Method (LEM) wall. Straw was compacted with a small amount of clay into a timber frame and then surfaced with a thick lime plaster.
- In-situ testing of parts of a rammed earth house in Wellington, prior to demolition.
- Approximate Modulus of Rupture testing of small soil-cement beams.
- Flexural tests on 350mm x 350mm soil-cement beams with longitudinal pre-tensioning .
- Investigations of the performance of soil-cement comparing compaction, cement contents and strength
- Determining the approximate tensile strength of soil-cement using the Diametral Tensile Strength method to compare with compressive strength.
- Plotting stress strain curves to determine the approximate elastic modulus of soil-cement.
- Evaluation of height to width ratio’s for compression tests.

An undergraduate student Anthony Fairclough, (Fairclough ,1993) tested and compared the properties of 50 soil-cement specimens compacted in the standard compaction (Proctor mould) apparatus.

Student Research on Adobe

The experimental work performed on adobes was supplied from one adobe manufacturer in Nelson. The adobes were made from a clayey soil (35% clay, 40% silt, 25% fine sand) mixed with straw (6:1 by volume) and the mortar was the same soil mixed with some crusher dust (5:1)to reduce shrinkage. The clay soil used had a specific gravity of 2.65, shrinkage limit 9.5%, Plastic Limit 9.5% and Liquid Limit 41%. Bricks were 260mm x 260mm x 120mm with a compression strength of 1.4MPa (H/W 2:1) and approximate tensile strength (MOR) of 390kPa. Four block prisms compression tested at 56 days also gave 1.4MPa (H/W 2:1)

Alison Wakelin (Wakelin, 1992) investigated the bond strength of adobe in shear. She did a limited number of tests with a small vertical load to represent the load condition on adobes near the bottom of a wall. She soaked the adobes between 1 minute and 4 minutes. Adobes immersed for 1 minute or more gave a significant increase in bond over unsoaked adobe. There was no bond improvement after 4 minutes of soaking but the adobes became difficult to handle. Varying mortar thicknesses from 15mm to 40mm made little difference to the shear bond strength but laying for rough surfaced adobe bricks was easier with mortar thicknesses over 20mm.

Shabani Gurumo (Gurumo, 1992) did a series of tests investigated the performance of five 1.2m adobe wall panel tests with differing reinforcement regimes. Diagonal compression tests were performed on an unreinforced adobe panel, adobe panels reinforced with trimmed reinforcing mesh, and panels reinforced with plain rods anchored to an end block. The results are reported in more detail (Morris, 1993) and clearly indicated that diagonal compression with reinforcement was substantially better.

This work was used to determine likely in-plane stresses and near full sale scale adobe wall panels were tested subsequent to this.

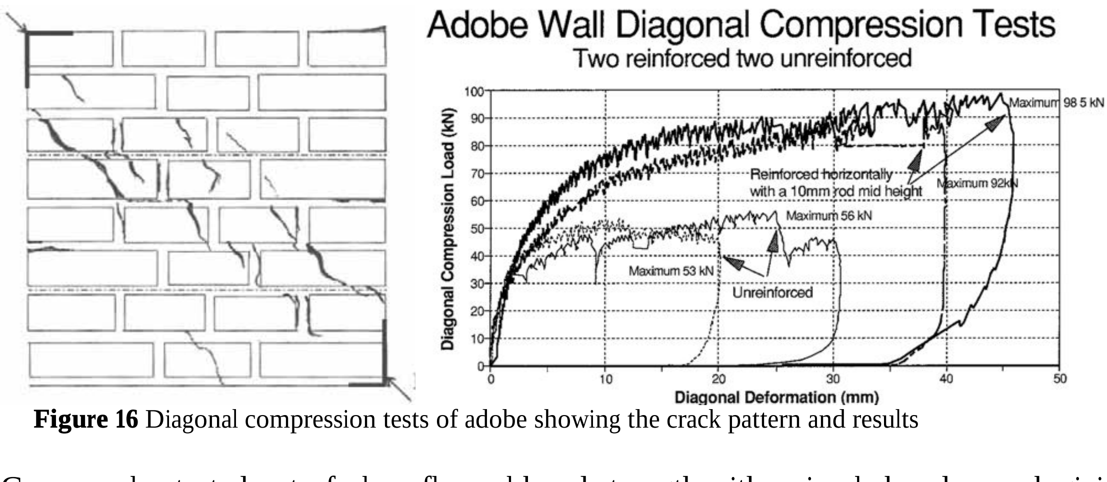


Figure 16 Diagonal compression tests of adobe showing the crack pattern and results

Gurumo also tested out-of-plane flexural bond strength with a simple bond wrench giving variable but extremely low bond of around 50kPa, (11 tests, minimum 16kPa to max. 91kPa) for these walls. This may have been due to the experience of the masons with adobe and certainly inadequate soaking of the bricks. A second series of tests was done with bricks soaked and achieved an average 185kPa bond (7 tests, 90kPa - 298kPa).

These tests did not give definitive answers but did give indicative performance in setting values for the standards.

Near Full Scale Adobe Tests

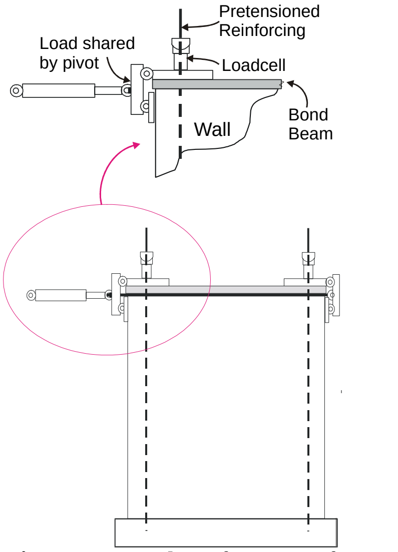


Figure 17 Load configuration for in-plane panel tests

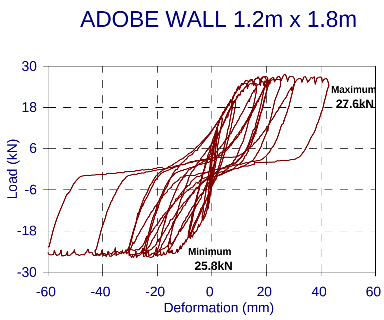


Figure 18 Cyclic load performance of 1.2m x 1.8m adobe wall

Using a test layout similar to figure 17, several near full-scale adobe walls were tested in-plane. Anchorage problems with a 1.8m x 1.8m wall meant the results were not as tidy as those for the 1.2m x 1.8m shown.

Figure 18 shows how slipping in the mortar planes gave effective ductility in a wall with both horizontal and vertical reinforcing (Morris, 1993). Figure 19 shows the crack growth progression of the wall as the reversing loads were applied – load to the right is recorded as positive. Figure 19 shows the reinforcing detail during demolition following the wall tests.

Several soil-cement rammed earth walls 1.8m wide and 2.4m high were tested, the first gave an equivalent shear stress of 241kPa before the concrete base of the test system delaminated. A later 1.8m x 2.4m test was reinforced vertically at each end and carried a maximum load of 90kN, an equivalent horizontal shear of 143kPa (Walker and Morris, 1998). Rammed earth walls reach much higher strengths but require reinforcement to prevent brittle failure.

These adobe walls with internal reinforcing behave in a ductile manner in-plane but they are low strength. This requires most walls within a structure to be available to provide the needed bracing strength.

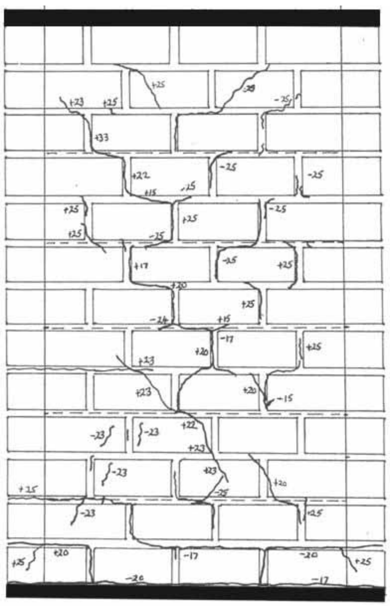


Figure 19 Crack pattern of the adobe wall showing the load progression

Figure 20 Reinforcement detail - vertical rods in holes through the adobes and horizontal reinforcement wrapped around the vertical rods, now geogrid is more typical for horizontal reinforcement

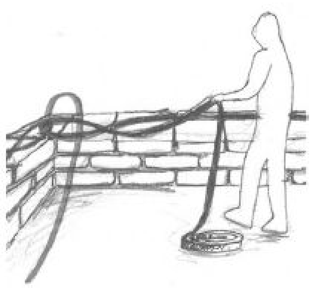
Statistics for Out-of-Plane Wall Strength

Some statistical simulation was done to establish a suitable parameter to take into account the averaging effect of multiple blocks acting together. This is significant given the high coefficient of variation for earth materials.

The reliability of wall strengths can be considerably higher than the characteristic strength of one brick, usually around the 5 percentile value. If one brick from of a row of bricks is weaker than the others then there will be load sharing with the adjacent stronger bricks. A Monte-Carlo simulation of the strengths of individual blocks according to the coefficients of variation was run to determine the reliable strength for different numbers of bricks in layers. The 15% increase in strength (k_m factor of 1.15) is permitted for the normal range of coefficients of variation (C_V), for a higher C_V the characteristic strength will be lower as a proportion of the average so when enough tests establish the C_V with enough reliability a k_m of 1.3 is allowed where more than 10 bricks are working together in a row.

RECENT RESEARCH AND FUTURE DEVELOPMENT

Research in Wellington



Recently Andrew Charleson presented interesting work that he and Matthew French are doing at Victoria University of Wellington. (Charleson & French, 2005) There they have developed a way to recycle tyres to create a strip that can be used as reinforcement for adobe walls. They are developing an innovative test regime for measuring performance of out-of-plane walls spanning laterally that can be set up at low cost. Andrew also runs the Earthquake Hazard Centre which has a newsletter and website on seismic performance intended as a support for developing regions. (Earthquake Hazard Centre, 2002)

Natural Fibre Reinforced Soil-Cement

The most recent research work in Auckland has not been on adobe but using native flax fibre to reinforce soil-cement to make monolithic walls. This has meant a extracting a fibre, that is similar to sisal, chopping it and mixing it with soil-cement to create an earth wall material that has some ductility and tensile strength.

This research is intended to assist Maori to develop a housing material that has a long life for use on communal land. While many Maori are well educated and middle class, it aims to provide a low cost housing alternative in low socio-economic and rural areas and provide a business opportunity for local builders. Substantial government research funding has been competitively obtained for this work which is reported by Morgan. (Morgan, 2005)

Figure 21 Fibre from New Zealand flax, MOR test of fibre reinforced soil-cement beams

As expected the flax fibre makes a significant improvement to flexural tensile behaviour which is no longer brittle. Compression stress strain results for soil-cement cylinders also indicate an increased ductility with fibre. The peak load for a particular plain soil-cement occurs at 2-3% strain and drops off to 80% at about 4-5% strain. The same soil-cement with 0.75% fibre by dry weight reaches its peak load at 4% strain and maintains the load to well over 10% strain before the load drops below 90% of the peak value.

Figure 22 Flax bag, skirt and cloak as displayed in the Auckland War Memorial Museum

The research program for UKU (fibre reinforced soil-cement) includes investigating thermal performance, durability, panel strength as well as technology transfer. The cultural attachment to the fibre is also seen as a significant factor in achieving community involvement and technology transfer. Flax and flax fibre is used, and has been used historically, in a vast variety of ways in Maori culture. Two examples are shown in the flax skirt and bag in figure 22.

Future Development and Research

The key area where I believe the standards need review or further development is in the area of unreinforced out-of–plane performance. The background and some recent ideas for the out-of-plane procedures in NZS *4297 Engineering Design of Earth Buildings* are discussed below.

Peter Yttrup (Ytrrup, 1981) recognised that when the elastic strength is exceeded is not the critical condition under wind forces, he proposed that the overturning equilibrium be considered in determining wind resistance of earth buildings. Later Priestley proposed an energy method for accounting for earthquake instability as a criteria to take into account the collapse mechanism in unreinforced masonry. (Priestley 1985) A procedure was developed for using this and was published in a *Guidelines for Assessing and Strengthening Earthquake Risk Buildings* issued as a draft in 1995 (NZ National Society for Earthquake Engineering, 1995). The final revision is due for release in the next few months. This procedure was slightly refined and incorporated in NZS4297 for out-of-plane calculations for unreinforced earth brick or adobe walls.

NZS 4297 is the first publication of this procedure within design standards and while it had been through some review prior to the draft documents we had very little comment at the time the standards were published. Comment is still invited.

The procedure is based on the out-of-plane wall segments needing to reach an unstable failure point for collapse. Figure 23 from NZS *4297 Engineering Design of Earth Buildings* sets the parameters for this calculation.

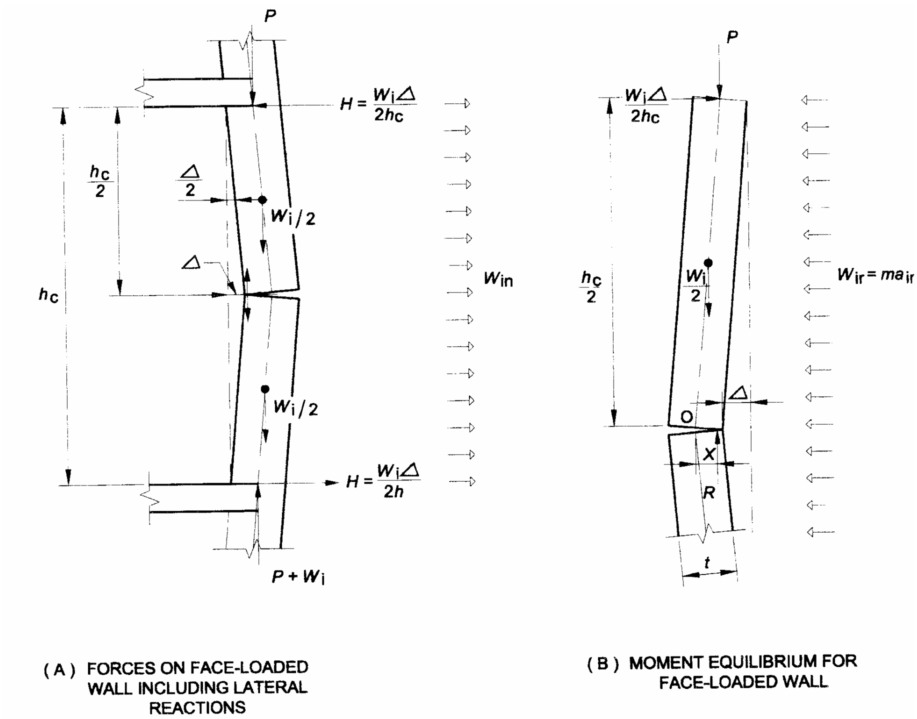


Figure 23 Moment equilibrium parameters for determining the out-of-plane performance of unreinforced walls in low earthquake zones

Blakie and Davey have further developed this concept using time history analyses and challenge some of the earlier ideas as non-conservative (Blaikie & Davey, 2005, 2002). My concern is that the concept is rather simplistic and the Blaikie approach still only represents one direction, vertical, of span. The paper by Jaramillo similarly points this out and proposes a methodology for considering horizontal spanning walls (Jaramillo, 2002).

It seems that more sophisticated modelling is required to represent spanning in both directions and to determine at what point cracking at the edges allows spans to act only in the vertical direction. Walls that only just survive earthquakes need to be observed for Out-of-plane cracking and near toppling to identify this. With good collated results from the increasing number of shake table tests taking place, it would allow adequate data to verify the various methods of analysis.

Modern computer hardware and software offers the capability to pre-process real time simulations of the dynamic performance of walls. With well established parameters and the verification described above discrete element analysis, as reported by Alexandris (Alexandris et al, 2004), and other masonry researchers, could provide real insights or even new design approaches to determine appropriate design values. Simulations such as shown in figure 24 are undoubtedly achievable.

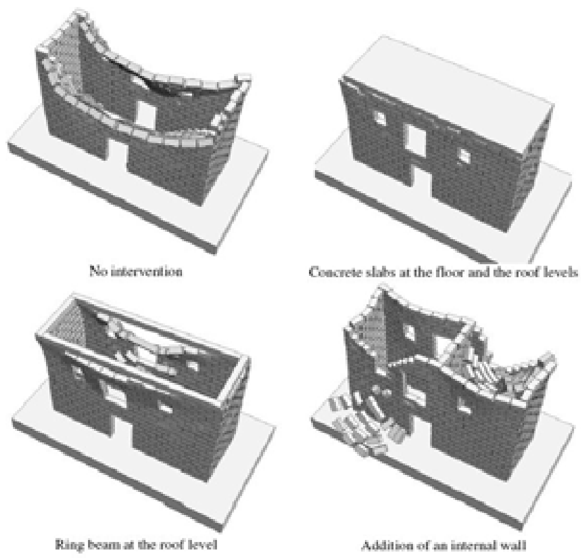


Figure 24 Collapse simulations of stone masonry (Alexandris et al, 2004)

CONCLUSIONS

New Zealand is in a highly seismic area that has a small number of earth buildings. The introduction of a suite of building standards and the activity of the Earth Building Association of New Zealand has accelerated the adoption of this environmentally suitable technology. Research is underway to incorporate native fibres with soil-cement to create an earth material that is more resilient for earthquake resistance and appealing both environmentally and culturally to the Maori people.

Research has been carried out to confirm parameters used in the standards and those relating to adobe have been outlined. The analysis method for out-of-plane performance of unreinforced earth brick walls in the New Zealand earth building standards has been progressive but would benefit from further verification. Computer software presents the opportunity to investigate this if good data on failure modes is available to confirm the results.

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