New Zealand: Aseismic Performance-Based Standards, Earth Construction, Research, and Opportunities

Hugh Morris

Abstract: *New Zealand has a combination of owner-built earth buildings and high-value earth houses built by contractors. This paper outlines the historical context of earth construction, comments on the status of conservation, gives an overview of the development of the New Zealand earth building standards, and identifies research opportunities.*

Introduction

In 1998 a suite of three limit state earth building standards was published in New Zealand for Design, Materials and Workmanship, and Earth Buildings Not Requiring Specific Design. The standards were developed by a committee of architects, engineers, and builders to cover adobe, rammed earth, and pressed brick construction.

A modest amount of research was undertaken to confirm parameters for the standards. Tests included in-plane testing for a range of reinforcement types, bond testing of unstabilized abobe, and durability. Concepts in the standards that relate to out-of-plane performance using an energy method are outlined, as is the need for further theoretical research, testing, and review.

Reinforcement is required within the walls of adobe buildings in most parts of New Zealand and is predominantly of steel and plastic geogrid. This has been successfully implemented, but further research and testing of geogrid-reinforced walls are needed. Other key aseismic features are timber diaphragms and bond beams. Developments are continuing on fiber-reinforced earth wall panels and thermal performance of earth materials and buildings. Reliable low-cost test methods to predict durability are needed, but reliable verification procedures also need to be developed. A method of measuring surface erosion of existing houses with 3-D stereophotogrammetry is showing promise. Verification of low-cost durability evaluation methods is a major research need.

New Zealand Seismicity

New Zealand is on the boundary of the same Pacific tectonic plate as is the western seaboard of America and has a similar seismic hazard level to that of California. The tectonic context is the Pacific Plate subducting the Indo-Australian Plate to the north and east, and the plates shearing along the length of the South Island, as shown in figure 1 (National Earthquake Information Center 2003). South of the country, the reverse subduction occurs, with the Pacific Plate overriding the Indo-Australian Plate. The surface evidence of the tectonic movement consists of the 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.

Earthquakes and Their Influence on Construction

New Zealand's first human inhabitants were Maori from Polynesia, who arrived around AD 1200 and lived in houses predominantly made of timber and reeds (Best 1974). The Maori passed on an oral history of major

FIGURE 1 New Zealand seismicity, 1900–2002, and major earthquake events and volcanoes. Detail of USGS poster (National Earthquake Information Center 2003). Credit: U.S. Geological Survey, Department of the Interior.

earthquakes; however, their lightweight housing was not seismically vulnerable.

Captain James Cook landed in New Zealand in 1769, and slow British settlement followed, with housing ranging from crude huts made of reeds to two-story timber-framed houses, including some of stone and brick. Settlement accelerated in the 1840s, and when the town of Wellington had reached a population of forty-five hundred, in 1848, citizens experienced high-intensity shaking from a major earthquake of M_L7.5 (magnitude based on the energy released similar to the Richter scale) centered across the straits in the upper South Island. This was soon overshadowed by MMI X intensity (Modified Mercalli intensity in Roman numerals, based on the severity of damage) caused by the M_L 8.2 earthquake of 1855, with an epicenter at a distance of about 20 km (12.4 miles). Most masonry buildings were damaged by this quake, so from that time, timber houses were usually constructed (Downes 1995; Grapes, Downes, and Goh 2003).

There were other significant earthquakes, but it was a major event in 1931 (M_L 7.9, intensity MMI X) in Hawkes Bay, on the east coast of the North Island, that resulted in New Zealand's largest natural disaster. This quake killed 256 people and demolished a number of buildings in Napier; the center of town was devastated by the resulting fire. The New Zealand Standards Institution was then formed, and the first building code was published in 1935 (Conly 1980). Building standards for all significant structures have been enforced by territorial authorities (i.e., councils) since that time.

History of Earth Buildings

A large number of temporary earth buildings were built during the gold rush days in the 1860s, but few remain because roof materials were removed for reuse, and the walls degraded quickly in the damp climate (Allen 1990). Of the more permanent buildings, approximately 121 earth houses constructed between 1840 and 1870 still exist; an additional 168 survive from 1870 to 1910. There was little activity from that time until the 1940s, when a number of houses were built of cement-stabilized earth with technical support from P. J. "Pip" Alley (Alley 1952), an enthusiastic academic at Canterbury University who was involved in a short burst of activity to cover materials shortages that followed World War II. Earth housing declined again until the late 1980s, when growing interest in environmentally friendly and sustainable buildings led to an upsurge of earth building construction (Allen 1997). Some 30 to 40 earth buildings are now built each year, which corresponds to approximately 0.15% of new houses countrywide. In some localities over 1% are constructed of earth.

Of the extant older earth buildings, those of adobe and cob construction are the most common. The main forms of earth construction at present in New Zealand are adobe, rammed earth, and pressed brick. Adobe bricks usually use straw in the mix, and there is a range of construction, from small owner-built houses up to luxury homes built by specialist contractors. Some mid-range adobe houses are shown in figures 2 and 3.

Conservation

New Zealand was not significantly populated by Europeans until the 1840s, so its heritage buildings are very recent when compared internationally. There was little conservation expertise until the 1980s, when

FIGURE 2 Typical midrange adobe home in New Zealand.

FIGURE 3 Typical midrange adobe home in New Zealand.

serious conservation plans were written and ICOMOS (the International Council on Monuments and Sites) was established in New Zealand, with a conservation charter completed in 1993.

The Historic Places Trust was established by an act of Parliament in 1954; the trust actively preserved historic buildings, purchased several dozen (mostly timber) structures, and placed many more on a register. However, no restriction was put on many lower-ranked historical buildings. Considerable damage was done to buildings as they were repaired by well-meaning amateurs. A more serious problem is particularly evident on Auckland's main street. During the 1970s and 1980s, a number of beautiful old buildings were largely demolished. Only their historical frontage was retained, then incorporated into new buildings in a superficial attempt at conservation.

Much of the very early New Zealand settlement occurred in the far north of the country, where seismicity is low. Two of the prominent historical buildings still standing are a tannery and a bookbindery that were developed in French provincial style for Roman Catholic bishop Pompallier. A French architect directed the construction of lower walls of pisé (rammed earth) fabricated from local soils and crushed shells, with earth panels within the timber-framed second story. In 1967 Pompallier House came under the Historic Places Trust, and in 1990 a major conservation effort was undertaken by a local enthusiast who managed reconstruction of a major wall section using original materials and methods. The decision to return the building to its original form has been the subject of differing conservationist opinions.

Another notable example of an 1850s earth building that has survived three major earthquakes (MMI VII or greater) is Broadgreen House, near Nelson in the upper South Island (fig. 4). The apparent factors that account for the good performance of this large two-story cob building are 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 50 cm (19.5 in.) thick earth walls of the ground floor reach 2.7 m (8.9 ft.) to the first floor, giving a height-to-thickness ratio of 5.4, which complies with present design criteria for unreinforced earth walls in New Zealand.

FIGURE 4 Broadgreen House, with lower-story cob walls.
Photo: Richard Walker.

Design Guidelines and Standards

In the 1980s considerable earth construction was undertaken in Nelson, a seismically active area at the northern end of the South Island. Two engineers became actively involved and did most of the design work. Engineer Gary Hodder wrote a design guide (Hodder 1991) that allowed prospective owners and architectural designers to do preliminary designs before seeking approval from him or another engineer for verification and sign-off. Hodder recognized that more work was needed, and in 1991 the Earth Building Association (EBANZ) took the initiative to develop guidelines for earth buildings that paralleled the New Zealand building standards for other materials (www.earthbuilding.co.nz; current membership of 275).

In 1993 the project was formally adopted jointly by Standards New Zealand and Standards Australia. A valuable exchange of experience and technical expertise came from the collaboration. However, the difficulty of satisfying the national requirements of both New Zealand and Australia led to a disbanding of the joint effort and the formation of separate committees in 1997. A major point of difference was the regulatory environment around house construction in New Zealand, which is partly due to New Zealand's higher seismic risk. The final years of writing were completed as a Standards New Zealand project. Standards Australia went on to support the publication of *The Australian Earth Building Handbook* (Walker and Standards Association of Australia 2002), and the Earth Building Association of Australia went on to produce *Building with Earth Bricks and Rammed Earth in Australia* (Andrews and Gales 2004).

New Zealand Building Legislation

The New Zealand *Building Act 2004* (New Zealand 2004) established a framework of building controls and construction that must comply with the mandatory New Zealand Building Code. Approved documents provide methods of compliance with the Building Code, and New Zealand Standards are one way to comply with the code.

The first such approved document for nonengineered construction was NZS 3604, *Code of Practice for Light Timber Frame Buildings Not Requiring Specific Design* (Standards New Zealand 1978). Timber is used in over 90% of New Zealand house construction, so this established the precedent for this type of document. Earth building standards have needed to provide a comparable level of detail to satisfy the territorial authorities and builders familiar with NZS 3604. The latest version, *NZS 3604: 1999 Timber Framed Buildings* (Standards New Zealand 1999) now has four hundred pages with numerous tables and well-drawn diagrams that allow builders and architectural designers to design houses to resist earthquake and wind loads.

New Zealand Earth Building Standards

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 seven 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 1998a) specifies design criteria, methodologies, and performance aspects for earth-walled buildings and is intended for use by structural engineers.

Limit state design principles were used in the formulation of this standard, so that it would 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 (21.3 ft.) in this standard. The design methodologies are discussed in more detail later in this paper.

Materials and Workmanship for Earth Buildings

NZS 4298: Materials and Workmanship for Earth Buildings (Standards New Zealand 1998b) defines the material and workmanship requirements to produce

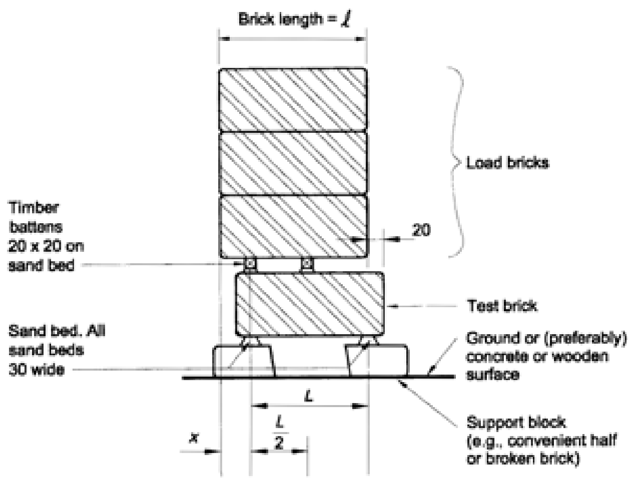


FIGURE 5 Stacked brick modulus of rupture test (measurements are in millimeters). Originally published in NZS 4298 (Standards New Zealand 1998b, 66). Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz.

earth walls, which, when designed in accordance with NZS 4297 or NZS 4299 (Standards New Zealand 1998c), 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 and includes a number of simple, low-cost test procedures that 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 of the earth wall materials. Compression tests require a laboratory, but two simple field procedures are detailed for modulus of rupture tests of earth bricks, including the stacked brick test (fig. 5). A brick drop test is also specified for simple field testing of earth bricks.

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

- Standard Grade, with a design compressive strength of 0.5 MPa (72.5 psi), which can be obtained by low-strength materials with a minimal amount of testing.
- Special Grade, which requires more testing to reasonably predict the characteristic strength. Earth stabilized with cement may achieve strengths of up to 10 MPa (1450.4 psi). More complex engineered structures would be of Special Grade.

Further technical details are available elsewhere (Walker and Morris 1998; Morris and Walker 2000). NZS 4298 also includes durability requirements, which are significant in the temperate New Zealand climate.

Earth Buildings Not Requiring Specific Design

NZS 4299: 1998 Earth Buildings Not Requiring Specific Design (Standards New Zealand 1998c) provides methods and details for the design and construction of earthen-walled buildings not requiring specific engineering design. The document will be mainly used for designing houses, and users will include those in the earth building industry, such as builders, architects, engineers, students, and building authority staff.

This standard covers buildings with single-story earth walls and a timber-framed roof, or single lower-story earth walls with timber second-story 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 *NZS 3604: 1999 Timber Framed Buildings* (Standards New Zealand 1999), or specific design could be undertaken by a certified professional engineer.

NZS 4299: 1998 Earth Buildings Not Requiring Specific Design (Standards New Zealand 1998c) is the earth wall construction equivalent of NZS 3604, with a 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; the “bracing capacity” is provided by the nominated bracing walls, as shown in figure 6. This methodology is familiar to designers and builders, almost all of whom are using the same approach with NZS 3604 for timber-framed buildings (Standards New Zealand 1999).

Many construction details that have been proved in earth buildings constructed in New Zealand during the past twenty years are included in the standard. Specific details from the standard are shown in figures 7 and 8. Figure 9 shows the reinforcement being placed during construction.

Design Approach

Design methodologies for earth buildings in New Zealand have been adapted from existing masonry and concrete standards. The approach in the standards is based on reinforced concrete design 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: 1998 Earth Buildings Not Requiring Specific Design* (Standards New Zealand 1998c), 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 stories were assumed to be distributed by concrete or timber bond beams or structural ceiling, roof, or first-floor diaphragms to transverse earth bracing walls.

Out-of-Plane Loads

Ultimate strength reinforced concrete theory is cautiously used as the basis 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 out-of-plane analysis section near the end of this paper.

Using the energy method, unreinforced earth walls for low-earthquake zones (zone factor $Z \leq 0.6$) were found to be satisfactory for the maximum wall heights permitted in the standard. For example, the failure of a 2.7 m (8.9 ft.) high and 28 cm (10.9 in.) thick wall was calculated to occur at 178% of the calculated demand requirement with $Z \leq 0.6$.

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 2.4 m long, 2.4 m high, and 28 cm thick (7.9 ft. long, 7.9 ft. high, and 10.9 in. thick) with typical details in accordance with the standard (see fig. 8) was calculated to be 30 kN (6744 lb.). The bracing capacity provided by a similar-sized unreinforced earth wall in a low earthquake zone was calculated to be 10 kN (2248 lb.).

Statistics for Testing

Because users may undertake tests to establish the earth material strength, some simple statistics are required to establish the characteristic values. Soils used in earth building are quite variable, but the compressive strengths of dried or compressed earth materials usually have a coefficient of variation (C_v) between 0.15 and 0.3. No sets of test data large enough to establish the underlying statistical population distribution were found.

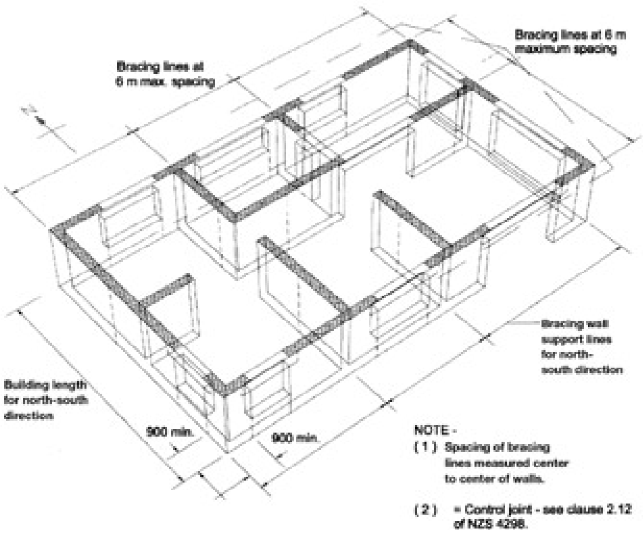


FIGURE 6 Bracing line method of assessing lateral resistance. Originally published in NZS 4299 (Standards New Zealand 1998c, 47). Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz.

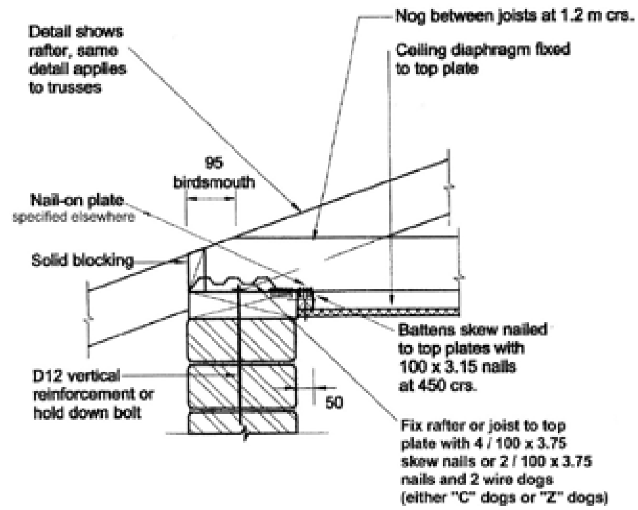
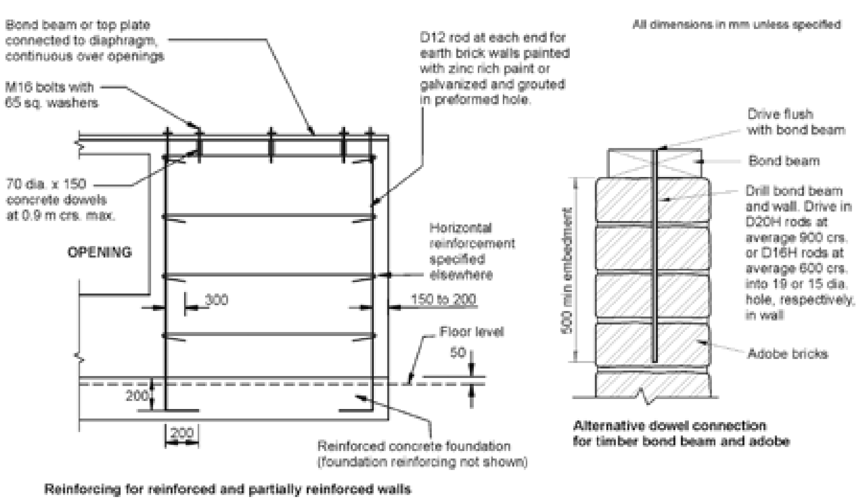


FIGURE 7 Diaphragm ceiling detail from NZS 4299 (note that the illustrated steel connector has now been replaced with other nailed and "wire dog" details). Originally published in NZS 4299 (Standards New Zealand 1998c, 71). Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz.



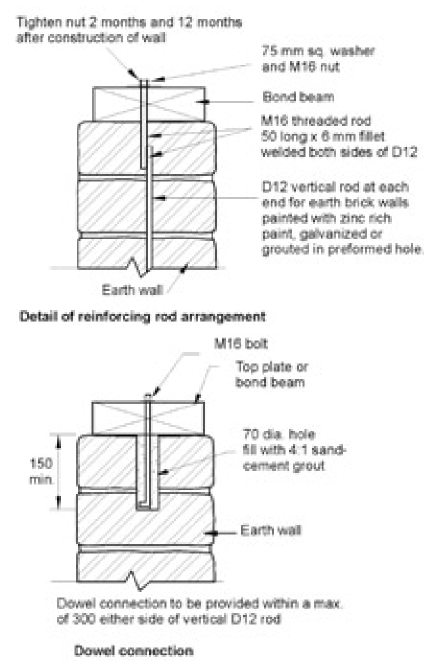


FIGURE 8 Typical NZS 4299 reinforced wall detail—polypropylene geogrid or steel used horizontally. Originally published in NZS 4299 (Standards New Zealand 1998c, 57). Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz.

FIGURE 9 Geogrid reinforcement at corner joint. Photo: Richard Walker.

The Australian Masonry Standard AS 3700 (Standards Association of Australia 1991) determines the characteristic strength from 30 specimen tests. This is not viable for a simple house because of the effort to construct specimens and the cost of testing. A 5-specimen simplified approximation is used to determine the characteristic strength

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

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 and 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 NZS 4298 is given in table 1, where the lowest three values of a series of ten results are used to determine the characteristic strength. If there were between 20 and 29 samples, then the lowest four values would be used to determine the characteristic strength. Coefficients would be selected from a similar table with different values.

Research in Support of the Earth Building Standards

There were many contributors to the earth building standards, as well as a depth of knowledge based on local experience. This gave access to informal literature based on personal experimentation and results of laboratory 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 undertaken under my supervision were:

Table 1 Determination of characteristic compressive strength for earth material using a series of ten specimen tests (from Standards New Zealand 1998b, 52). Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz

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

$f' = x_3^{1-\varepsilon}\,(x_2 x_1)^{\varepsilon/2}$ where, for n = 10–19, 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

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

therefore $f' = x_3^{1-3.31}\,(x_2 x_1)^{3.31/2} = 1.84^{-2.31}\,(1.75 \times 1.45)^{1.66} = 1.14$

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

- 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 35 × 35 cm (13.7 × 13.7 in.) soil-cement beams with longitudinal pretensioning.
- Investigations of the performance of soil-cement, comparing compaction, cement contents, and strength.
- Determination of the approximate tensile strength of soil-cement using the diametral tensile strength method to compare with compressive strength.
- Plotting of stress-strain curves to determine the approximate elastic modulus of soil-cement.
- Evaluation of height-to-width ratios for compression tests.
- Influence of wetting time and mortar thickness on mortar bond.
- Drip test and spray test comparisons.
- Development of the surface soak test.
- Diagonal compression tests on 1.2 m (3.9 ft.) wall panels with differing reinforcement.

Student work on the bond strength and similar work on rammed earth was reported at the SimsoAdobe conference in Peru (Morris 2005).

Shabani Gurumo (Gurumo 1992) did the 1.2 m (3.9 ft.) adobe wall panel tests with differing reinforcement regimes. The results clearly indicated that diagonal compression with reinforcement carried almost twice the load of unreinforced adobe.

Gurumo also tested out-of-plane flexural bond strength with a simple bond wrench, giving variable but extremely low bonds of around 50 kPa (7.25 psi). This may have been due to the experience of the masons with adobe and to inadequate soaking of the bricks, but it has led to a conservative expectation for the standards.

A near full-scale 1.8 × 1.8 m (5.9 × 5.9 ft.) adobe wall panel was quasi-statically earthquake tested, with horizontal slowly reversing in-plane loads applied to the top edge of the wall. Subsequent to this, a 1.2 × 1.8 m (3.9 × 5.9 ft.) wall panel was similarly tested by student Bernard Jacobson. Figure 10 is a plot of the load deformation performance of the top of the

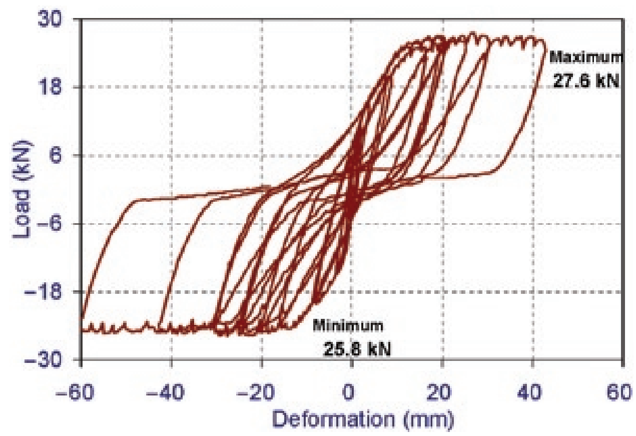


FIGURE 10 Cyclic load performance of a 1.2 × 1.8 m (3.9 × 5.9 ft.) adobe wall.

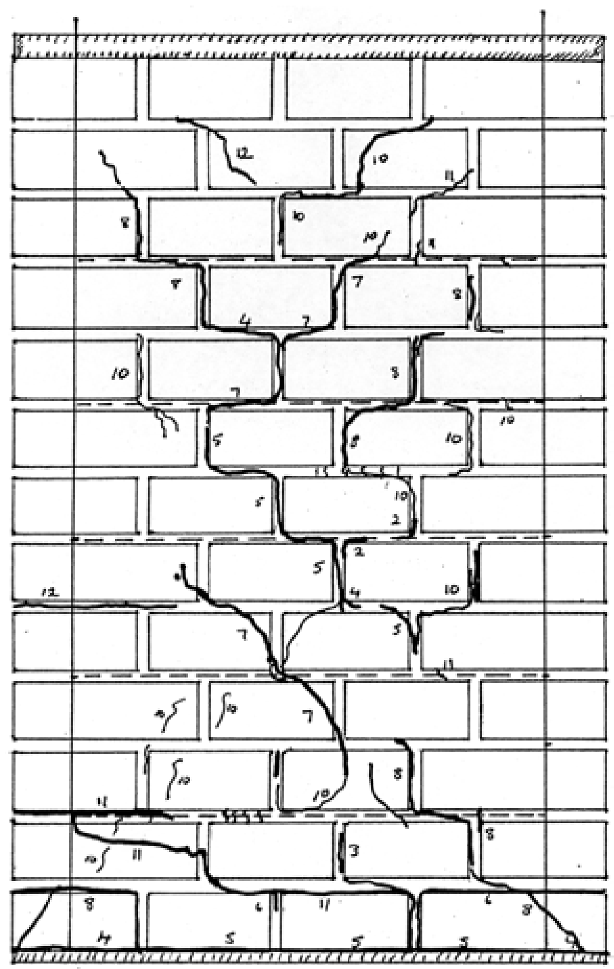


FIGURE 11 Crack pattern of an adobe wall, showing the load progression.

FIGURE 12 Detail of reinforcement, with vertical rods in holes through the adobes and horizontal reinforcement wrapped around the vertical rods. Now geogrid is more typically used for horizontal reinforcement.

wall. This graph shows that slipping in the mortar planes provided effective ductility to the wall system (Morris 1993). Figure 11 illustrates the crack patterns in a wall with both horizontal and vertical reinforcing, as observed by Jacobson. It shows the crack growth progression of the wall as the reversing loads were applied; the load to the right is recorded as positive. Figure 12 shows the reinforcing detail during demolition following the wall tests.

Soil-cement rammed earth walls were tested and carried much higher loads, but they required reinforcement to prevent brittle failure. These adobe walls with internal reinforcing behaved in a ductile manner in-plane, but they are low in strength. This requires most walls within a structure to be available to provide the needed bracing strength.

None of the above testing was definitive, but it did give indicative performance in setting values for the standards. The most significant need is for tests of a large enough number of specimens to establish a proper statistical basis for what is a quite variable material.

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 (often the 5 percentile value). If one brick from 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 ten bricks are working together in a row.

Recent Research and Future Development

Natural Fiber Reinforced Soil-Cement

Recent research work in Auckland has involved the use of native flax fiber (similar to sisal fiber) to reinforce soil-cement to make monolithic walls. This offers the possibility of thinner walls but raises the issue of thermal performance. With the building regulations for thermal performance focused on insulation, this presents a challenge to prove the effectiveness and value of thermal mass. Existing earth buildings have been monitored for thermal performance, and this has been used to check the calibration of a thermal performance model (Tenorio et al. 2006). This will allow the evaluation of various thicknesses and configurations.

Durability

The durability of earth walls is of concern in both temperate and tropical climates. A need exists for a test approach that is simple and low in cost. The New Zealand standards have two tests modified from those developed in Australia. The accelerated spray test uses an expensive standard nozzle and sprays a very severe jet, as shown in figure 13. This can cause the failure of otherwise satisfactory adobe materials. This severe test is complemented by a very simple drip test, where water drops 40 cm (15.6 in.) onto the surface. This technique was checked by some simple laboratory experiments that considered raindrop energies, but the test needs field verification.

FIGURE 13 Accelerated degradation water spray test.

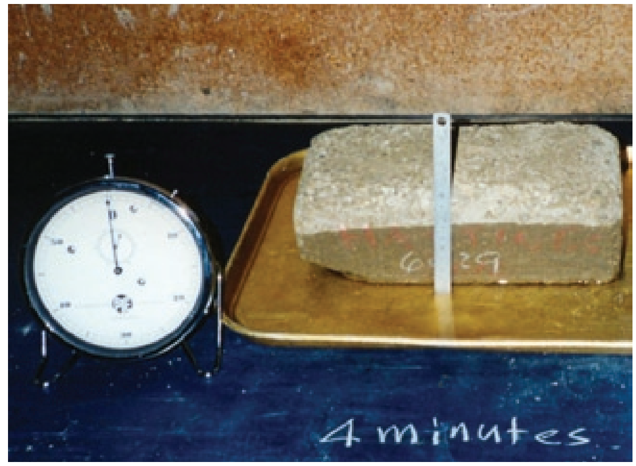


FIGURE 14 Surface soak test. Note that the moisture has nearly penetrated the soil-cement brick after four minutes.

With guidance from members of the New Zealand Earth Building Standards Committee, I also developed a surface wetting and drying test in which moisture penetration and surface effects from a single soaked surface are observed. The brick sits 1.5 mm (0.06 in.) off the bottom of a tray, and the water depth is maintained at 10 mm (0.4 in.) (as shown in fig. 14) for a fixed time, after which the deterioration is evaluated. This test is repeatable because of its ease of setup, and it has a number of empirical visual checks that indicate suitability; but only a limited number of trials were undertaken.

Kevan Heathcote (2002) was involved in experimentation on soil-cement blocks for a number of years, and he proposed the use of a different nozzle for the spray test. This approach does not simulate the effects of wetting and drying or account for thermal effects. Kerali did an excellent analysis of the erosion process for stabilized earth blocks (Kerali 2001) and proposed a slake test (Kerali and Thomas 2004). These only partially represent the erosion criteria he identified and will be much too severe for adobe. Hall looked into the soil constituents and proposed a wick soakage test for pore suction, based on a masonry approach, but this does not simulate rain erosion (Hall 2004).

To be able to accurately develop testing approaches for durability, an absolutely key requirement is a test rig that can represent accelerated climate conditions, so that various tests can be calibrated. From initial investigations it is clearly necessary to develop test equipment to simulate repeated rain strike with wind and cyclic temperature effects, to be able to define and calibrate low-cost procedures.

Another approach is to monitor weather conditions precisely and to measure surface degradation on real buildings as a function of time. A number of methods for obtaining a surface mold were attempted, but all damaged the surface of adobe. John Morris of the University of Auckland Department of Computer Science has recently supervised experimental work using stereophotogrammetry to give precise, noninvasive measurements of surface degradation (Lin 2006; Lin, Morris, and Govignon 2007). Figures 15 and 16 show the laboratory test camera arrangement, which has the capability of precise adjustment. The data projector is used to create a Gray code line shift pattern of light for calibration.

Figures 17 and 18 show a photograph and 3-D surface model of an adobe brick. We intended to set up a weather station adjacent to existing buildings and create contour plots of surface degradation by photographing and plotting sample wall areas each six months.

Out-of-Plane Analysis

The standards need review or further development in the area of unreinforced out-of-plane performance. Background information on the out-of-plane procedures in *NZS 4297: 1998 Engineering Design of Earth Buildings* (Standards New Zealand 1998a) is discussed below.

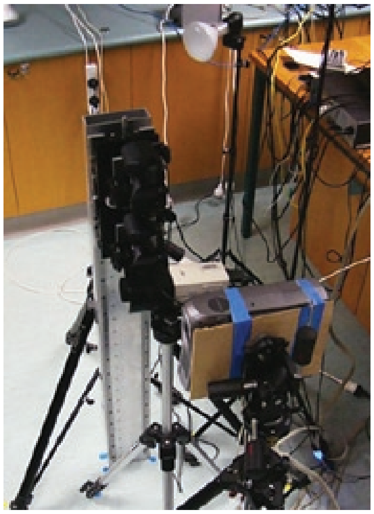


FIGURE 15 Stereo cameras set up with light projector and video for calibration. Photo: John Morris, University of Auckland.

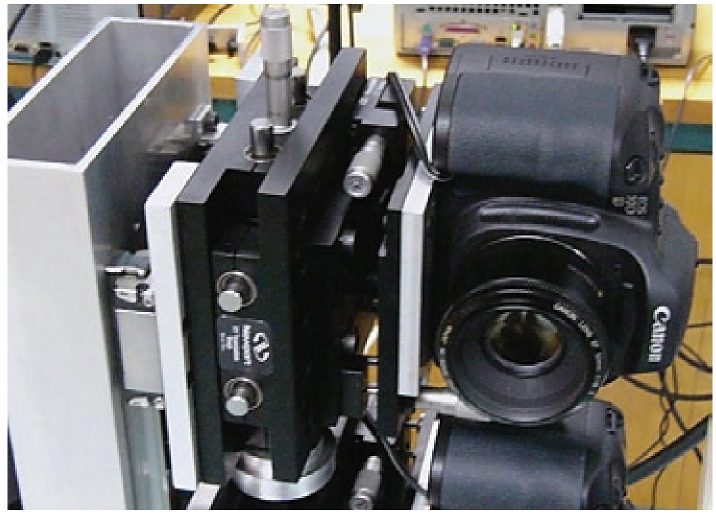


FIGURE 16 Close-up of a camera and adjustment apparatus. Photo: John Morris, University of Auckland.

Peter Yttrup (Yttrup 1981) recognized that when the strength of the earth material is exceeded, causing a horizontal crack in the wall, this is not the critical condition for wall collapse due to very high wind forces. He proposed that the full overturning equilibrium be considered, to more realistically determine the wind resistance of thick-wall earth buildings. Later Priestley proposed an energy method for determining earthquake instability as a criterion to take into account the collapse mechanism in unreinforced masonry (Priestley 1985). A procedure was developed and was published in *Guidelines for Assessing and Strengthening Earthquake Risk Buildings,* issued as a draft in 1995 (New Zealand National Society for Earthquake Engineering 1995). This procedure was slightly refined and incorporated in NZS 4297 for out-of-plane calculations for unreinforced earth brick or adobe walls (Standards New Zealand 1998a).

FIGURE 17 Three-dimensional extrusion of photograph of adobe block.

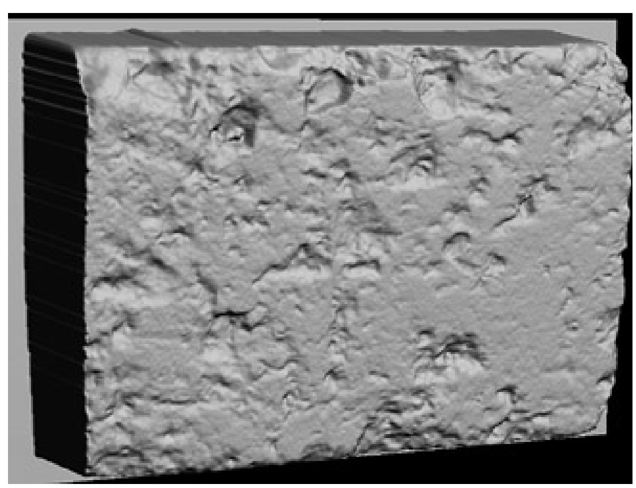
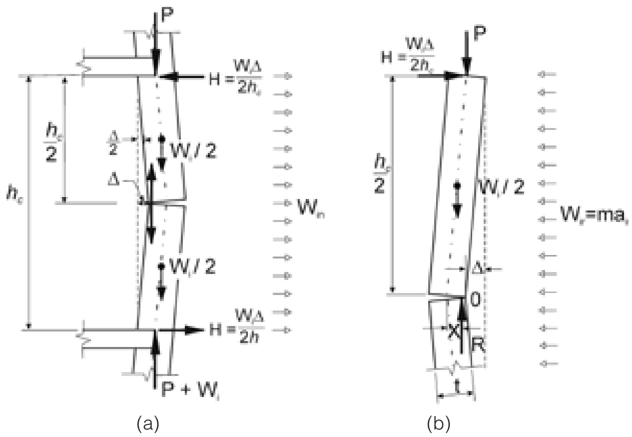


FIGURE 18 Three-dimensional surface model derived from stereophotographs.



FIGURES 19A AND 19B Moment equilibrium parameters for determining the out-of-plane performance of unreinforced walls in low-earthquake zones. Forces on face-loaded wall, including lateral reactions (a), and moment equilibrium for face-loaded wall (b) are shown (*P* = gravity load per unit length at top of wall; *W* = self-weight of wall under investigation; Δ = displacement at center of wall; *h* = height of wall between horizontal restraints; *R* = vertical reaction at crack; *t* = wall thickness). (Originally published in *NZS 4297* [Standards New Zealand 1998a, 53].) Content reproduced from NZS4299/NZS4297/NZS4298 with the permission of Standards New Zealand under License 000738. www.standards.co.nz.

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, there was very little comment at the time the standards were published. Another revision of the earthquake society guidelines was recently released, and the procedure has been updated (New Zealand Society for Earthquake Engineering 2006). However, the new procedure needs to be evaluated for earth buildings. The procedure is based on the assumption that the out-of-plane wall segments need to reach an unstable failure point for collapse to occur. Figures 19a and 19b, from *NZS 4297: 1998 Engineering Design of Earth Buildings* (Standards New Zealand 1998a), set the parameters for this calculation.

Blaikie and Davey have further developed this concept using time history analyses, and they challenge some of the earlier ideas as being nonconservative (Blaikie and Davey 2002; 2005). This concept is still rather simplistic, and the Blaikie approach only represents the vertical direction of span. More sophisticated modeling is required to represent spanning in both directions and to determine at what point vertical cracks at the edges of wall panels will allow spans to act only in the vertical direction.

It is important to investigate the actual rocking performance of structures with little tensile strength. Analytical models can be tuned to give very realistic model responses, but the material parameters that produce the realistic performance are usually incorrect. The critical material characteristics need to be identified and understood for proper analysis. There is a need for shake table testing on stacked adobe blocks to establish the performance in this most simple situation, to identify key parameters for analysis. This will provide initial data for full analyses, which should be followed by verification using full-scale shake table tests.

Strength Determination

A major concern is that there needs to be consistency in testing procedures used, so that results are comparable among researchers. In much of the literature on adobe and earth buildings, there is no definition of the height-to-width ratio, moisture content, or loading rate of compression specimens at the time of testing. This makes an enormous difference, and if combined, the effects of the lowest height-to-width ratio and low moisture content could theoretically produce results that are two times that of a tall specimen with high moisture content. Moisture content in a dry wall in service may be in the range of 4%–8%, whereas the great difficulty of drying materials to exactly the right moisture content means that during testing it could be as high as 10%–15%, or even oven dried. Standard reporting procedures, loading rates, platen constraints, and specimen preparation are needed if researchers and practitioners are to be able to compare results. In the longer term, earth specimens should be conditioned under standard temperature and humidity for a fixed period before testing. If it is not possible to undertake testing in a standard manner, this practice would at least allow differences to be understood if specimen size and orientation, moisture content at the time of test, and loading rate are defined with the results.

Conclusion

New Zealand has a small number of earthen buildings within a highly seismic area, and conservation of historical buildings in New Zealand has only recently been undertaken with scientific rigor. The application of the comprehensive suite of earth building standards has worked well in the New Zealand context and facilitated the adoption of this environmentally suitable technology in a tightly regulated environment. The analysis method for out-of-plane performance of unreinforced earth brick walls in the New Zealand earth building standards has been progressive, but it would benefit from further verification and revision. Many parameters reported in the literature are not well specified, and standardization of measurement is needed even for a parameter as simple as compressive strength.

There was a range of research carried out on adobe to obtain indicative strengths for the standards, but testing with large numbers of samples for statistical reliability is needed. Research is under way to investigate the thermal performance of rammed earth and fiber-reinforced soil-cement to determine the acceptable limits on wall thickness. Durability is a major issue for earthen structures exposed to moist environments. Also needed are methods for testing, laboratory calibration for testing, and measurement of existing structures.

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