Engineering Design of Earth Buildings

NZS 4297:1998

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This Standard was prepared by the New Zealand-only sub-committee, BD/83/2, of the Joint Australia/New Zealand Technical Committee BD/83 Earth Buildings for the Standards Council established under the Standards Act 1988. Sub-committee BD/6/2 consisted of representatives of the following organizations:

Hugh Morris	Auckland University
Miles Allen	Earth Building Association of New Zealand
Thijs Drupsteen	Earth Building Association of New Zealand
Bob Gilkison	Earth Building Association of New Zealand
Graeme North	Earth Building Association of New Zealand *(Chair)*
Richard Walker	Instituion of Professional Engineers New Zealand
Min Hall	New Zealand Instiute of Architects
Jenny Christie	Victoria University of Wellington

Published by Standards New Zealand, the trading arm of the Standards Council, Private Bag 2439, Wellington 6020.
Telephone: (04) 498 5990, Fax: (04) 498 5994.
E-mail: snz@standards.co.nz
Website: www.standards.co.nz

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RELATED DOCUMENTS

Reference is made in this Standard to the following:

NEW ZEALAND STANDARDS

NZS/AS 1530:- - - -	Methods for fire tests on building materials, components and structures
Part 4-1990	Fire-resistance test of elements of building construction
NZS 3101:1995	Concrete structures Standard
NZS 3109:1997	Concrete construction
NZS 3402:1989	Steel bars for the reinforcement of concrete
NZS 3421:1975	Hard drawn steel wire for concrete reinforcement
NZS 4203:1992	General structural design and design loadings for buildings
NZS 4214:1997	Methods of determining the total thermal resistance of parts of buildings
NZS 4218:1996	Energy efficiency - Housing and small building envelope
NZS 4229:1986	Code of practice for concrete masonry buildings not requiring specific design
NZS 4230:1990	Code of practice for the design of masonry structures
NZS 4298:1998	Materials and workmanship for earth buildings
NZS 4299:1998	Earth buildings not requiring specific design
NZS 4402:- - - -	Methods of testing soils for civil engineering purposes
Part 2, Section 1:1986	Test 2.1 Determination of the water content
Part 4, Section 1.1:1986	Test 4.1.1 New Zealand standard compaction test
NZS 4702:1982	Metal-arc welding of grade 275 reinforcing bar
NZS 6507:-	Materials testing machines and force verification equipment
Part 1:1986	Specification for the grading of the forces applied by materials testing machines

[NOTE – NZS/AS denotes an Australian Standard approved for adoption in New Zealand without technical change].

AUSTRALIAN STANDARDS

AS 3610-1995 Formwork for concrete

AS 3700-1988 Masonry in buildings

BRITISH STANDARD

BS EN ISO 10319 Geotextiles. Wide-width tensile test

OTHER PUBLICATIONS

CSIRO Australia (Division of Building, Construction and Engineering). Bulletin 5: Earth-wall construction (4th edition, 1987).

New Zealand Building Industry Authority Approved Document B1 Structure, Verification Method 4: Foundations (September 1993).

New Zealand National Society for Earthquake Engineering, The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings, (June 1996).

UBC. Uniform Building Code, International Conference of Building Officials, 1994.

Dowrick, D.J. Seismic Hazard Estimates for the Auckland Area, and Their Design and Construction Implications, Bulletin of NZNSEE Vol. 25, No. 3, September 1992.

Oliver, D. and Whybrid, D. Commercial Engineered Aggregate Construction, Proceedings of Economics in Building Conference, Brisbane, Australia, September 1991.

Yttrup, P. Strength of Earth Masonry (Adobe) Walls Subjected to Lateral Wind Forces, Proceedings, 7th International Brick Masonry Conference, Melbourne, February 1985.

The users of this Standard should ensure that their copies of the above-mentioned New Zealand Standards or of overseas Standards approved as suitable for use in New Zealand are the latest revisions or include the latest amendments. Such amendments are listed in the annual Standards New Zealand *Catalogue* which is supplemented by lists contained in the monthly magazine *Standards* issued free of charge to committee and subscribing members of Standards New Zealand.

FOREWORD

General

This standard and the associated NZS 4298 *Materials and workmanship for earth buildings* and NZS 4299 *Earth buildings not requiring specific design* extend the range of construction and structural design standards to cater for the growing interest in earth building. Earth is becoming increasingly important in the context of the modern desire for construction materials which are less highly processed and have low toxicity. These standards formalize the current state-of-the-art knowledge of design and construction using a building method that has provided satisfactory shelter to millions of people around the world over many centuries. As earth is a heavy, low-strength material, its use in construction is expected to essentially be limited to single storey walls and ground floors.

The enthusiastic support of Yvonne Rust as a prime promoter of the need for earth building standards in New Zealand is recognized and the role of the Earth Building Association of New Zealand in supporting the development of this suite of standards is acknowledged. Many other people and organizations, too numerous to name have also made valuable contributions.

Earth wall construction includes a diverse range of techniques to build either monolithic walls or ones made from individually laid bricks. The action of the complete wall in respect of strength, deformation and damage depends very much on the standard of workmanship, and, in the case of earth brick walls, the strength and durability of the individual components and their arrangements. Frequently earth buildings are constructed from local soils available near the construction site. Because of these variables, and because of the restricted availability (compared with other materials) of rigorous laboratory test results, the performance of some elements under severe deformation is less well known or predictable than with other materials. However, earth wall construction is one of the oldest building techniques in the world and earth walls have performed adequately in many situations.

These three new standards have been prepared with the intention of seeking Building Industry Authority acceptance for referencing in the New Zealand Building Code Approved Documents.

It is always a challenge in writing building standards to balance the need for versatility and flexibility with the need to keep it simple and compact. The scope of these standards therefore excludes items such as vaults and domes and walls which curve for lateral stability. The fact that something is not covered by a standard does not mean it is prohibited. What it does mean is that if one is wishing to build, say a dome, some other means of proving compliance with the requirements of the Building Code will need to be found. Such proof can rely in part but not solely on these standards.

The process of earth building usually involves the following steps, not necessarily in this order:

(1) Locate suitable building site.
(2) Select a preferred earth building technique.
(3) Consider suitability of local or nearby subsoils for various construction methods.
(4) Carry out field tests of possible construction soils to check their suitability for the preferred construction method. Modify method if necessary.
(5) Carry out pre-construction testing of earth building material. Modify mix as required.
(6) Design building and obtain building consent.
(7) Carry out site work and building construction including quality control testing.
(8) Obtain Code Compliance Certificate.

The manner in which the three standards cover these steps is set out below.

Engineering design of earth buildings
NZS 4297 is primarily aimed at structural and performance aspects of step 6. Together with NZS 4298, it gives limitations to consider for steps (1), (2), (3), (4), (5) and (7). It is intended for use by structural engineers. Other publications and expert help can provide additional advice covering all these points and issues of aesthetics.

In New Zealand, the seismic provisions of NZS 4297 will govern design in most cases. Many of the structural design principles are chosen to be similar to those for masonry (reinforced or unreinforced) and reinforced concrete, and it is assumed that users of this standard will have a knowledge of design in these materials. However, earth has unique characteristics that need to be considered apart from other forms of masonry.

Limit State Design Principles have been used in the formulation of this standard to be consistent with other material design standards. Durability is important and is covered by a design method which relates required durability test results to the annual rainfall and exposure of a building site.

Out-of-plane loading on unreinforced vertically spanning walls has been approached as ultimate limit state design based on the failure mode of walls at large deformation. Earthquake loads are analysed using the energy method proposed by the New Zealand National Society for Earthquake Engineering for strength assessment of unreinforced masonry earthquake risk buildings.

Materials and workmanship for earth buildings
NZS 4298 sets out requirements for the materials and workmanship requirements for the use of unfired earth in the form of adobe, pressed earth brick, rammed earth or poured earth. NZS 4298 gives significant help for steps 4, 5, 6 and 7 noted above. It applies to buildings which

are designed in accordance with NZS 4297 *Engineering design of earth buildings* and NZS 4299 *Earth buildings not requiring specific design*.

Commentary to this standard takes heed of the long history of successful earth building worldwide. A feature of this experience is the diversity of building methods.

It is necessary to demonstrate that earthen materials used (with or without admixtures) produce results meeting at least the minimum standards of strength and durability. Tests and the required results are detailed so that assurance can be given that the earth building material will meet building code requirements.

Earth buildings not requiring specific design
NZS 4299 is the earth building equivalent of NZS 3604 but with its coverage limited to foundations, floor slabs and walls. It is intended that owner-builders or supervising owners with appropriate experienced help will be able to use NZS 4299 alongside NZS 4298 to carry out steps (1) to (8).

Again balancing the need for versatility and flexibility with the need for simplicity has produced restrictions on the scope of buildings covered. More ambitious structures can be designed by a structural engineer using NZS 4297.

REVIEW OF STANDARDS

Suggestions for improvement of this Standard will be welcomed. They should be sent to the Chief Executive, Standards New Zealand, Private Bag 2439, Wellington 6020.

NOTES

NEW ZEALAND STANDARD

ENGINEERING DESIGN OF EARTH BUILDINGS

1 GENERAL

1.1 Objective
The objective of this Standard is to provide for the structural and durability design of earth buildings. The Standard is intended to be approved as a means of compliance with clauses B1 and B2 of the New Zealand Building Code.

1.2 Scope

1.2.1
The scope of this Standard is limited to unfired earthen wall building materials defined herein as adobe, pressed brick, poured earth or rammed earth and which contain clay and silt and which rely on the clay and silt particles present to achieve satisfactory performance with or without chemical stabilization. Earth building materials to which this Standard applies shall comply with NZS 4298 *Materials and workmanship for earth buildings*.

C1.2.1
This Standard sets minimum criteria. Parties are at liberty to set higher standards for any matters referred to in this Standard.

1.2.2
Earth construction in accordance with this Standard shall not exceed 6.5 m in height from the top of the footing to the top of the earth wall.

C1.2.2
Design using procedures and/or material properties not described in this Standard may be carried out when it can be shown by one of the following methods that the elements so designed have adequate performance at the serviceability limit state and at the ultimate limit state:

(a) A special study; or

(b) Experimental verification; or

(c) Rational design based on accepted engineering principles; or

(d) Verified service history.

Aspects of designs which rely on any of (a) to (d) above are outside the scope of this Standard as a means of compliance with the New Zealand Building Code and must be treated as alternative solutions.

The purpose of this clause is to acknowledge new design practices and the use of newly developed material properties that may go further than this Standard permits, provided that the acceptability of such methods or approaches can be clearly demonstrated by way of the options listed.

Alternative design methods, material properties or structural systems must be supported by one or more thorough experimental studies, or demonstrated service history.

➤

Compliance of alternative solutions with the New Zealand Building Code may be required to be demonstrated when seeking a building consent.

Cement as a stabilizer may contribute substantially to strength in mixtures with a high proportion of sand. Where strength is almost entirely reliant on cement or other stabilizer, the masonry standard or the standard appropriate to that material should be used.

1.2.3
This Standard applies to earth wall items including house and building walls, boundary fences, outbuildings, garden walls, furniture, footings, fireplaces and such like. This Standard also covers components of any of the foregoing including bricks, pieces and such like.

C1.2.3
Retaining walls are excluded from this Standard.

1.2.4
This Standard applies to New Zealand and its offshore islands.

1.3 Interpretation

1.3.1
For the purposes of this Standard the word "shall" refers to practices that are mandatory for compliance with this Standard, while the word "should" indicates a recommended practice.

1.3.2
Cross-references to other clauses or clause subdivisions within this Standard quote the number only, for example: "... as required by 3.3.2.3(d) for shored construction".

1.3.3
The full titles of reference documents cited in this Standard are given in the list of Related documents immediately preceding the Foreword.

1.3.4
Clauses prefixed by "C " and printed in italic type are comments, explanations, summaries of technical background, recommended practice or suggest approaches which satisfy the intent of the Standard. Corresponding mandatory clauses are not always present. They are not to be taken as the only or complete interpretation of the corresponding clause nor should they be used for determining in any way the mandatory requirements of compliance within this Standard. The Standard can be complied with if the comment is ignored.

C1.3.4
There is a need for background comment and explanation on topics other than those within mandatory clauses. This is to enhance the relatively small pool of earth building experience and as a means of meeting the challenge of writing this first performance based suite of earth building standards. Accordingly, the unusual format of having commentary clauses which have no corresponding mandatory clause has been adopted .

1.3.5
Provisions in this Standard that are in non-specific or in unquantified terms (such as where provisions are required to be appropriate, adequate, suitable, relevant, satisfactory, acceptable, applicable or the like and the Standard does not describe how to achieve this) are outside the scope of this Standard as a means of compliance with the New Zealand Building Code and must be treated as alternative solutions.

1.3.6
The terms “normative” and “informative” have been used in this Standard to define the application of the Appendix to which they apply. A “normative” appendix is an integral part of a Standard, whereas an “informative” appendix is only for information and guidance. (There are no informative appendices in this Standard).

1.4 Construction review

Construction review shall be carried out in accordance with clause 1.4 of NZS 4298.

1.5 Seismic zones

Seismic loads shall be in accordance with NZS 4203 *General structural design and design loadings for buildings* with the following proviso that for Auckland and Northland, the seismic design shall be as follows:

For areas north-west of the 0.6 contour for the seismic zone factor, Z, shown on figure 4.6.2 of NZS 4203, the seismic zone factor shall be determined from figure 1.1 with the proviso that the minimum value of the seismic zone factor shall be 0.40.

C1.5
The concept of reduced requirements for Auckland and Northland are based on the paper Seismic Hazard Estimates for the Auckland Area, and Their Design and Construction Implications by David J. Dowrick, first presented at the Pacific Conference on Earthquake Engineering, Auckland, November 1991. (Paper reprinted in revised form in the Bulletin of the N.Z. National Society for Earthquake Engineering Vol. 25, No. 3, September 1992).

Seismic design for Northland would normally be for detailing for robustness and to avoid collapse in the extreme seismic event.

1.6
The design of a structure or part of a structure to which this Standard is applied shall be the responsibility of the design engineer.

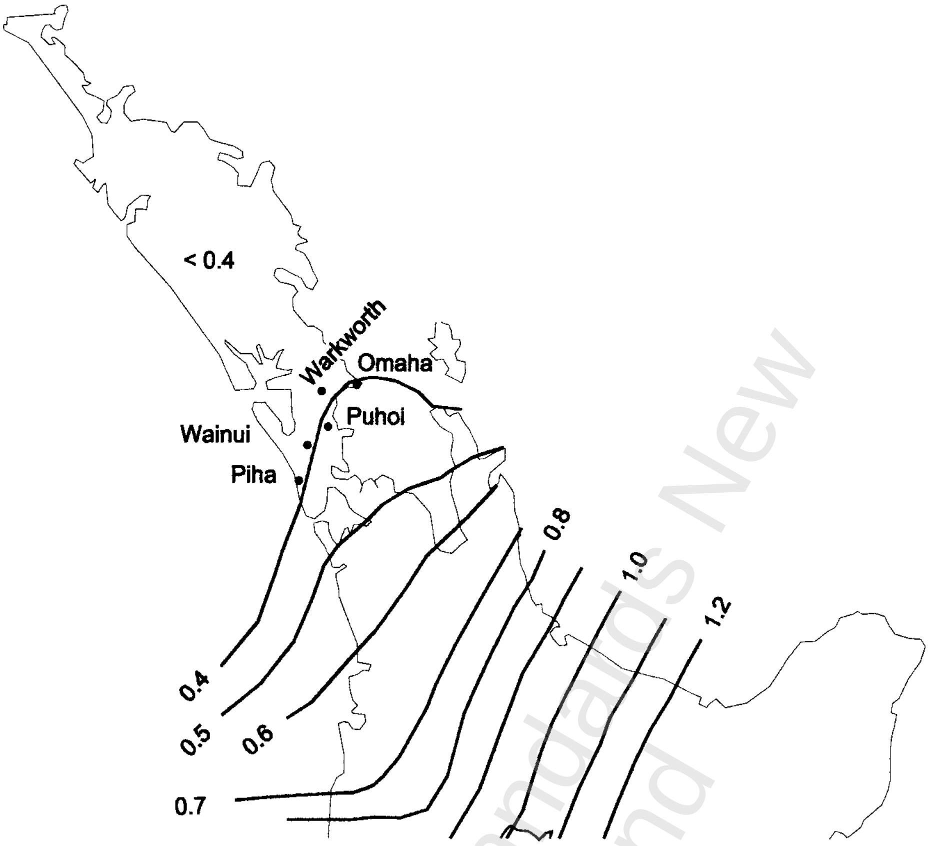


Figure 1.1 – Zone factor, *Z*, for Auckland and Northland

2 DEFINITIONS

2.1 General

For the purposes of this Standard the following definitions shall apply:

ADOBE. An air dried brick made from a puddled earth mix cast in a mould and which contains a mixture of clay, sand and silt. Sometimes contains straw or a stabilizer. Also known as mud-brick.

ASPHALT, or ASPHALT EMULSION. See bitumen.

BITUMEN EMULSION. Bitumen globules of microscopic size that are surrounded by and suspended in a water medium. When used as a stabilizer it is usually of the slow breaking cationic type. Also known as asphalt.

BOND BEAM. A continuous horizontal structural member in a wall which provides continuity and structural strength.

BOND, OVERLAPPING. The bond when the units of each earth brick course overlap the units in the preceding course by between 25 % and 75 % of the length of the units.

BRACING. Any method employed to provide lateral support to a building.

BRICK. A discrete unit of earth masonry.

CELL. A hole through or along an earth brick unit in the plane of a wall.

CHARACTERISTIC STRENGTH. An estimate of the lower 5 % value determined with 75 % confidence from tests on a representative sample of full size specimens.

CHARACTERISTIC UNCONFINED COMPRESSIVE STRENGTH. The characteristic strength determined from compressive strength tests to which an aspect ratio correction factor has been applied.

CINVA BRICK. A pressed earth brick meeting the dimensional and strength requirements of section 6 of NZS 4298.

CLAY. A fine grained, natural, earthy material composed primarily of hydrous aluminium silicates with grain diameters less than 0.002 mm.

COLD JOINT. In rammed earth construction, the joint which occurs when construction has been interrupted long enough for some degree of drying or curing to take place before fresh material is placed.

COLUMN. An isolated, reinforced, vertical load-bearing member subjected primarily to compression having a cross section with a length to breadth ratio between 3 and 0.33.

COMPRESSIVE STRENGTH. A physical property of a material that indicates its ability to withstand compressive forces, usually expressed in kPa or MPa.

CONTROL JOINT. A joint necessary to allow an earth wall to expand and contract or otherwise move.

CURING. The action of water acting over time in a stabilized soil mass causing the mass to be cemented together by the stabilizer.

DAMP PROOF COURSE. A durable waterproof material placed between materials as a protection against moisture movement. A painted on or a sheet damp proof course is referred to as a damp proof membrane.

DESIGN ENGINEER. A person who, on the basis of experience or qualifications, is competent to design structural elements of the building under consideration to safely resist the design loads or effects on the building.

DIAPHRAGM. A member such as a floor or ceiling capable of transferring loads in its own plane to boundary members.

DIMENSION. (When used to describe earth brick units or types of construction.) Nominal dimensions. Actual dimensions shall be used for the purpose of calculation.

DUCTILITY. The ability of a material, structural component or structure to deform or dissipate energy beyond its elastic limit i.e. into the post-elastic range.

DURABLE. Resistant to wear and decay. Durability has a corresponding meaning.

EARTH (for earth building). Natural sub-soil comprised of varying percentages of clay, silt, sand and gravel which is unfired and is free of significant organic matter.

ELASTIC RESPONSE. The response range of a structure where the deformation is in direct proportion to the force applied (i.e. the material, structural component or structure obeys Hooke's law.)

EROSION. The physical and chemical processes by which earth building material is worn away. It includes the processes of weathering and mechanical wear.

FLEXURAL TENSILE STRENGTH. (Also known as modulus of rupture or flexural strength). Flexural strength of the material as measured in accordance with Appendix J of NZS 4298.

FLUE. An enclosed continuous horizontal or vertical space in an earth brick element formed by the cells of the units which make up that member.

FOOTING. That portion of a foundation bearing on the ground. It may be spread out to provide an increase in bearing area or an increase in stability.

FOUNDATION. Those parts of a building transmitting and distributing loads to the ground, through a footing.

FOUNDATION WALL. See WALL.

GABLE. The triangular part of an outside wall between the planes of the roof and the lines of the eaves.

GROUND LEVEL

FINISHED GROUND LEVEL. The ground level after all backfilling, landscaping and surface paving have been completed.

GROUT. A liquid mixture of cement, sand and water, with or without small aggregate, used to fill cavities after bricks and reinforcing have been placed.

LIMIT STATE

SERVICEABILITY LIMIT STATE. The state at which a structure becomes unfit for its intended use through deformation, vibratory response, degradation or other operational inadequacy.

ULTIMATE LIMIT STATE. The state at which the strength or ductility capacity of the structure is exceeded, when it cannot maintain equilibrium and becomes unstable.

MORTAR. The bedding material in which earth brick units are bedded.

PARTITION. See WALL.

P-DELTA EFFECT. Refers to the structural actions induced as a consequence of gravity loads being displaced laterally due to the action of earthquake or wind forces or other effects.

PERPEND. The perpendicular joint between two bricks.

PIER. (Also known as pilaster). A member similar to a column except that it is bonded into a wall. The thickness of a pier includes the thickness of the associated wall.

POST-ELASTIC BEHAVIOUR. The large deformations accompanying small increase in force after the elastic limit has been reached.

POURED EARTH. An earth building technique in which earth and water, with or without stabilizer, is poured into moulds in place on the wall being constructed. The moulds are removed when the earth is strong enough to maintain its shape.

PRESSED EARTH BRICK (or PRESSED BRICK). An earth brick that is made in a mechanical press, either machine operated or hand operated.

RAMMED EARTH. Damp or moist soil, with or without stabilizer, that is tamped in place between temporary moveable formwork. Also known as pisé.

RAMMED EARTH WALL PANEL. A section of rammed earth wall being of full height of the finished section but of length that is built at one stage.

REINFORCED EARTH CONSTRUCTION. Any earth structure into which reinforcing is so bedded and bonded that the two materials act together in resisting forces.

REINFORCEMENT. Any form of steel reinforcing rod, bar or mesh that complies with the relevant requirements of NZS 3109, or plastic or other material cited in this Standard capable of imparting tensile strength to the earth building material.

SAND. Individual rock or mineral fragments that range in diameter from 0.06 mm to 2.0 mm.

SHRINKAGE. The decrease in volume of earth material or mortar caused by curing or the evaporation of water. Expressed as a percentage of linear dimension.

SILT. Individual mineral particles in a soil that range in size from the upper limit of clay (0.002 mm) to the lower limit of fine sand (0.06 mm).

SOIL. See earth.

SPACING. The distance at which members are spaced measured centre to centre.

STABILIZATION. The improvement of the performance of earth building material properties by the addition of materials which bind the earth particles. Stabilization may increase the resistance of earth to moisture, reduce volume changes or improve strength or durability.

STABILIZER. A material which is used for stabilization.

STABILIZED ADOBE. Adobe bricks which have a stabilizer added, typically cement or bitumen emulsion.

STABILIZED POURED EARTH. Poured earth which has had a stabilizer added, usually cement.

STABILIZED PRESSED BRICK. Pressed brick which has had a stabilizer added, usually cement.

STABILIZED RAMMED EARTH. Rammed earth which has had a stabilizer added, usually cement.

STRENGTH

DESIGN. The nominal strength of a member section multiplied by the appropriate strength reduction factor.

NOMINAL. The theoretical strength of a member section using the section dimensions as detailed and the characteristic strengths of the reinforcement and the strength of the earth.

OVERSTRENGTH. Overstrength is used in seismic design. This increased value takes into account factors that may contribute to strength such as higher than specified strengths of the steel and earth, strain hardening and additional reinforcement placed for construction and otherwise unaccounted for in the calculations.

WALL

EXTERNAL WALL. An outer wall of a building.

LOADBEARING WALL. A wall supporting vertical loading from floors, ceiling joists, roof, or any combination thereof.

NON-LOADBEARING WALL. A wall other than a loadbearing wall.

PARTITION. A light timber wall which is used within the building.

STRUCTURAL WALL. Any wall which because of its position and shape contributes to the rigidity and strength of the building.

WALL THICKNESS. Minimum thickness of wall remaining after any chasing, raking or tooling of mortar joints.

2.2 Notation

In this Standard, symbols shall have the following meanings. Other symbols, or other meanings for symbols listed below, that are defined immediately adjacent to formulae or diagrams, shall apply only to those formulae or diagrams. Use of these symbols is subject to the following:

(a) Where non-dimensional ratios are involved, both the numerator and denominator are expressed in consistent units; and

(b) Dimensional units used, expressions or equations shall be consistent unless otherwise specified.

A_b area of earth cross section

A_{de} effective area of dispersion of the concentrated load in the member at mid-height

A_{ds} bearing or dispersion area of the concentrated load

A_{st} area of reinforcing steel

A_s area of tensile reinforcement

A_{sv} area of shear reinforcement

A_1 area under response acceleration versus wall displacement curve

a width of stress block at ultimate limit state

a_e response acceleration to induce wall failure

a_{cr}, $a_{1/2}$, $a_{3/4}$, a_u acceleration at cracking, 1/2 cracked, 3/4 cracked and ultimate moment condition respectively

a_v coefficient for assessing slenderness ratio

a_1 distance from the end of the wall or pier to the nearest end of the bearing area

b eaves width (mm)

C_{pi} basic horizontal seismic coefficient for a part at level i from NZS 4203

d_b bar diameter

d depth of section in the direction of shear

E_e modulus of elasticity of earth

E_s modulus of elasticity of reinforcing steel

e eccentricity of vertical force

f_d compressive stress acting on a section under the design loading – N^*/A_b

f_e compressive strength of earth wall construction

f_{ea} adjusted compressive strength for multiple brick construction

f_{eb} tensile flexural bond strength

f_{es} shear strength of earth

f_{et} flexural tensile strength of earth

f_n total nominal shear stress

f_{sy} lower yield strength of shear reinforcement

f_y lower characteristic yield strength of reinforcement

f'_{uc} unconfined compressive strength of sample

h height of earth wall in metres above the plane being considered; or
height of a member; or
clear height of a member between horizontal lateral supports; or
for a member without top horizontal support, the overall height from the bottom lateral support;

I moment of inertia of wall section

k reduction factor for slenderness and eccentricity

k_b concentrated bearing factor

k_m multiple brick factor

k_v shear factor

k_1 rainfall factor

k_2 wall orientation factor

k_3 eaves factor

k_4 locality factor

L clear length of a wall between vertical lateral supports; or
for a wall without a vertical support at its end or at a control joint, the length to that unsupported end or control joint; or
clear length of the wall or pier

L_e dispersion zone length

M_{ch} design flexural strength of the wall

M_{cr}, $M_{1/2}$, $M_{3/4}$, M_u moment in wall at cracking, 1/2 cracked, 3/4 cracked and ultimate condition respectively

M_n nominal flexural strength of a section

M^* design bending moment acting on the cross section of a member at the ultimate limit state determined from loads complying with NZS 4203

M^*_{dh} design horizontal flexural bending moment on a wall

N^* design axial load at the ultimate limit state determined from NZS 4203

N_o nominal compressive strength of an earth cross section short enough for slenderness effects to have no influence

P gravity load per unit length at top of wall

p annual rainfall (mm)

R thermal resistance in $m^2.{}^oC/W$
vertical reaction at crack

S_r slenderness ratio

S_n nominal strength at the ultimate limit state for the relevant action of moment, axial load, shear and torsion

S^* design action at the ultimate limit state

s spacing of shear reinforcement measured perpendicular to shear force

t thickness or depth of wall perpendicular to the axis under consideration

t_w overall dimensions thickness of a wall or isolated pier, taking into account any joint raking which is deeper than 3 mm

V_n nominal shear strength of a section

$V_{(z)}$ site wind speed at height z for the direction under consideration at the ultimate limit state (m/s)

V^* design shear force acting on the cross section of a member at ultimate limit state determined from NZS 4203

W self weight of wall under investigation

w_{cr}, $w_{1/2}$, $w_{3/4}$, w_u distributed lateral load required to induce corresponding wall moment

Z earthquake zone factor

Z_u the lateral section modulus of the earth wall based on the gross cross section

γ density of wall material

Δ_{cr}, $\Delta_{1/2}$, $\Delta_{3/4}$, Δ_u displacement at centre of wall at cracking, 1/2 cracked, 3/4 cracked and ultimate conditions

δ coefficient of variation

μ structural ductility factor, as defined in NZS 4203

ϕ capacity reduction factor

3 PERFORMANCE CRITERIA

3.1 Notation

R thermal resistance in $m^2.^oC/W$

3.2 Durability

Compliance with this section is necessary to satisfy the requirements of clause B2 of the New Zealand Building Code to provide for a building life of not less than 50 years.

3.2.1

An earth wall will be deemed to comply with the durability performance criteria if, provided that normal surface maintenance has been carried out, its thickness has not decreased by more than 5 % nor by more than 30 mm at any point during the building's life.

Normal maintenance of earth building material shall include the repair of damage or deterioration of the wall surface including any surface coating and the removal of any source of moisture which is capable of causing localised elevation of earth wall moisture content. Such sources may include plumbing or roofing leaks, channelling of rainwater, bridging or other loss of integrity of the damp proof course, vegetation or build up of ground levels. Repair of earth building material is to be carried out using the same material as that from which the earth wall is constructed and be applied in accordance with NZS 4298. Curing of repair mixtures containing lime or cement shall be carried out in accordance with the provisions of NZS 4298. Surface coatings which are impervious to water vapour and air shall not be used.

C3.2.1 General

Earth walls are particularly susceptible to moisture, whether this is from rising damp, water ingress from the top, driving rain, water splashing, or moisture generated internally in a building. For this reason it is important that any design considers the need to protect earth walls from excessive moisture. Care is to be taken with all weathering details including flashings and eaves protection of wall tops. Any applied coatings or surface finishes shall provide permeability to prevent moisture becoming trapped inside an earth wall.

A structure is durable if it withstands wear and deterioration throughout its intended life without the need for undue maintenance. Deterioration of earth walls depends on the severity of wind-driven rain, on the orientation of the wall, on the weather resistance of the wall material, on surface coatings, and on the surface finish and on the degree of stabilization of the material.

3.2.2
Walls shall be considered satisfactory in terms of 3.2.1 above if the erodibility index of a sample (as determined in accordance with Appendices D or E of NZS 4298) is less than or equal to the Limiting Erodibility Index determined in accordance with Appendix A of this Standard.

3.3 Strength

3.3.1 *Limit state for strength*

3.3.1.1
The required characteristic unconfined compressive strength of wall units or rammed earth samples shall be stated on the drawings and in the specifications.

3.3.1.2
The characteristic unconfined compressive strength shall be determined in accordance with Appendix B of NZS 4298.

3.3.2 *Testing*
Testing shall be carried out in accordance with clause 2.3 of NZS 4298 for standard grade earth materials and in accordance with clause 2.4 of NZS 4298 for special grade earth materials.

C3.3.2
Standard grade earth materials are the minimum grade of earth materials to be used for construction complying with NZS 4299 or for specific designs in accordance with this Standard utilizing the design strengths of table 4.1.

The required testing includes both a testing regime for determining acceptable materials prior to construction commencing and quality control tests to be conducted during construction.

3.4 Shrinkage

C3.4.1 *General*
Unstabilized earth walls rely mainly on the presence of clay to maintain their integrity. The amount and type of clay present influences the amount of shrinkage that takes place as the walls or bricks dry out. Whilst the presence of shrinkage cracks in individual bricks may sometimes be a feature of adobe construction, there is a need to limit cracks in completed walls to an acceptable size.

Cement stabilized walls or bricks generally have low clay contents but there is still some shrinkage due to the cement and clay content.

3.4.2
Control joints shall be included to take account of shrinkage. Detailing shall ensure that movement at control joints can take place whilst still maintaining structural integrity and water tightness. Cracking which does not affect structural integrity may be plastered.

C3.4.2
Detailing of the frames for doors and windows needs to take account of both the vertical and horizontal shrinkage of earth building materials. Limiting cracks to maintain integrity against insects is important but is not a Building Code requirement.

3.5 Thermal insulation

3.5.1

Unless determined otherwise by testing in accordance with NZS 4214, *R* may be taken as given by 3.5.2.

3.5.2

The static thermal resistance of walls consists of the thermal resistance of the wall material plus the thermal resistance to convection and radiation at the surfaces, the latter being expressed as a constant "air" resistance. For earth walls the thermal resistance, *R*, may be taken as 2.04 times the wall thickness in metres plus 0.12. The units are in m^2. ºC/W.

C3.5.2

The thermal performance of earth walls is greatly improved by the effect of thermal mass due to an effect known as "thermal lag". The value of static thermal resistance given above can therefore be taken as a conservative measure of the thermal performance of earth walls. The thermal lag for earth walls is of the order of 7 to 10 hours for a 280 mm wall. At present there is no simple method for taking thermal lag into account but this Standard does not preclude the use of more sophisticated computer programs which deal with this.

A minimum external wall thickness of 280 mm is generally required to satisfy without additional insulation, the New Zealand Building Code requirements of clauses E3 and H1 for insulation. In satisfying the Building Code requirements the whole building is to be considered. Reference should be made to NZS 4218.

3.6 Fire

Clause 5.5.1 provides values of fire resistance ratings for earth wall construction.

4 GENERAL CONSTRUCTION AND DESIGN REQUIREMENTS

4.1 Notation

E_e modulus of elasticity of earth

E_s modulus of elasticity of reinforcing steel

f_e compressive strength of earth wall construction

f_{ea} adjusted compressive strength for multiple brick construction

f_{eb} tensile flexural bond strength

f_{es} shear strength of earth

f_{et} flexural tensile strength of earth

f_n total nominal shear stress

f'_{uc} unconfined compressive strength of sample

h height of earth wall in metres above the plane being considered

k_m multiple brick factor

Z earthquake zone factor

δ coefficient of variation

μ structural ductility factor

4.2 Scope

This section contains the general requirements for all types of earth buildings of brick type or solid homogenous structure.

4.3 General principles and requirements for construction

4.3.1 *Earth building materials*
Earth building materials shall comply with NZS 4298.

4.3.2 *Design objectives*
In addition to meeting the specific engineering design requirements of this section, the design engineer shall take account of the shape and dimensions of walls and construction practices including methods of positioning reinforcement and placing and compacting of grout.

C4.3.2
Design and detailing should be such as to promote the following:

(a) Walls of consistent quality;

(b) Development of bond of grout to both reinforcement and bricks (where applicable);

(c) Control of shrinkage and settlement of earth and, where used, mortar and grout;

(d) Avoidance of corrosion of reinforcement;

(e) Minimizing of adverse weathering effects of types which adversely affect structural adequacy and serviceability.

4.4 Standard grade earth construction

Earth materials for standard grade earth construction shall comply with clause 2.3 of NZS 4298.

4.4.1 *Limitations*
Standard grade earth construction shall only be carried out within the following limitations:

(a) The floor live load on suspended floors shall not exceed 1.5 kPa or 2.0 kPa on domestic balconies as provided for in NZS 4203. Suspended floors shall have a dead load of less than 0.9 kPa.

(b) Buildings shall be Category IV or V buildings as described in table 2.3.1 of NZS 4203.

(c) In areas where the NZS 4203 seismic zone factor is greater than 0.6 the ground floor plan area shall not exceed:

  (i) 600 m^2 for single-storey earth buildings

  (ii) 200 m^2 for two-storey earth buildings

  (iii) 300 m^2 for two-storey buildings where the upper storey is constructed of timber and the walls of the lower storey are of earth

(d) The total height of the earth wall, including any gable end, from the lowest concrete foundation top surface adjoining shall not exceed 6.5 m.

4.4.2 *Design strengths*
Strengths used in design shall be as given in table 4.1.

Table 4.1 – Strengths (MPa) to be used for design of standard grade earth wall construction

Compressive strength (flexural, direct compression or bearing)	$f_e = 0.5$
Maximum total nominal shear stress	$f_n = 0.09$
Shear strength of earth for wind loading and for seismic load with elastic response	$f_{es} = 0.08$
Shear strength of earth for limited ductile (μ = 2.0) seismic loading	$f_{es} = 0.0$
Shear strength of steel reinforced earth	$f_{es} = 0.35$
Tensile/flexural bond strength	$f_{eb} = 0.02$
Flexural tensile strength	$f_{et} = 0.1$

C4.4.2
A wide variety of bond strengths have been encountered by earth building practitioners. Unstabilized earth brick construction has been found to have considerable bond strength, and values of 50 kPa have been measured, but zero bond strength has also been encountered. Up to 260 kPa bond has been measured in cement stabilized in situ *adobe construction. Up to 890 kPa flexural tensile strength has been tested for cement-stabilized pressed brick. However, little is known about the as-built flexural strength of rammed earth panels and how this is affected by "cold joints" etc. In view of all these uncertainties and variabilities therefore, designers may only use a higher tensile/flexural bond strength if substantiated by pre-testing.*

The in-wall strengths of table 4.1 are less than the strength test results obtained in the laboratory. Modifications for aspect ratio, characteristic strength, and mortar effects as outlined in this Standard all bring about reductions.

4.4.3 *Multiple brick factor for out-of-plane wall strength*
Where an earth wall panel is 10 or more bricks long the compressive strength shall be increased by the multiple brick factor k_m. The adjusted compressive strength shall be used in establishing out-of-plane flexural strength.

$$f_{ea} = k_m f_e$$

where

k_m is 1.15

f_{ea} is the adjusted compressive strength.

If the coefficient of variation (δ) is established as 0.35 or higher from the test results of 30 or more specimens, then k_m shall be taken as 1.3.

C4.4.3
The compressive strength f_e is based on statistical analysis. Where multiple bricks are working in parallel the probability of one brick failing or causing significant strength loss is less. Weaker earth bricks have lower stiffness, allowing load sharing with stronger, stiffer bricks. Design strengths for materials with δ > 0.35 are reduced significantly to allow for the material variation. Walls of these materials benefit the most from load sharing.

4.5 Special grade earth construction

4.5.1 *Compressive and flexural strengths*
The compressive strength f_e and the flexural tensile strength f_{et} shall be established using the test methods of the Appendices of NZS 4298.

Where f_e is based on the testing of individual specimens rather than prisms with mortar joints the following relationship between the unconfined compressive strength of the sample (f'_{uc}) and the wall strength (f_e) shall be taken as follows:

Adobe and poured or rammed earth $f_e = f'_{uc}$

Pressed earth bricks (including cinva brick) $f_e = 0.5 \times f'_{uc}$

4.5.2 *Brick compressive strength derived from flexural tensile strength*
In the absence of compression tests, where testing for flexural tensile strength to Appendix J of NZS 4298 has been done, the compressive strength shall be calculated from the flexural tensile strength as follows:

$f_e = 3.5\ f_{et}$

> ***C4.5.2***
> *The formulae for compression strength derived from flexural tensile strength are based on conservative test results. Compression tests are likely to give higher f_e / f_{et} ratios.*

4.5.3 *Joint strength*
Where the compressive strength is greater than 6 MPa, the joint strength shall be taken into account for earth brick walls. Such considerations are outside the scope of this Standard.

4.5.4 *Shear strength*
The shear strength of earth, f_{es}, shall be given by the greater of:

$f_{es} = 0.07\ f_e$ .... (Eq. 4-1)

or

$f_{es} = (70 + 5\ h)$ kPa .... (Eq. 4-2)

where h is in metres.

4.5.5 *Flexural tensile strength*
In the absence of flexural tensile strength test results, but where testing for compressive strength in accordance with Appendix A of NZS 4298 has been carried out, the flexural tensile strength, f_{et}, shall be taken as 0.10 f_e for earth building materials with a compressive strength less than 6 MPa. For materials with a strength of 6 MPa and above the flexural tensile strength shall be determined by testing in accordance with NZS 4298.

4.5.6 *Modulus of elasticity of earth*
The modulus of elasticity, E_e, for earth wall construction shall be taken as 300 x f_e.

> ***C4.5.6***
> *The modulus of elasticity of soil cement varies depending on the type of soil and increases approximately linearly with strength. This formula will give a low average estimate for silty soils. An appropriate higher value should be used if a low value will give non-conservative results.*

For silty or poorly graded materials the Modulus of Elasticity lies in the range 120 kPa –3 GPa. For silty-sandy clays, and poorly graded sands 3 GPa – 7 GPa, silty sands and sandy clays nearer 7 GPa, gravely soils 7 GPa – 20 GPa.

Where the modulus of elasticity is critical it should be established by test. Such testing should establish the internal modulus of elasticity. Internal measurement, by deformation measuring equipment attached to the specimen, will give substantially higher values than the modulus measured from external deformation measurements because of test system effects.

4.5.7 *Modulus of elasticity of steel*
The modulus of elasticity, E_s, of non-prestressed steel reinforcement shall be taken as 200 GPa.

4.6 General principles for design

4.6.1
Earth walls shall be a minimum of 250 mm thick except for cinva brick walls which may be 130 mm thick.

C4.6.1
Walls less than 280 mm may require additional insulation to meet thermal insulation requirements of the New Zealand Building Code clauses E3 and H1.

4.6.2
Maximum slenderness ratio, S_r, shall be as follows:

	Earthquake zone factor:	Z ≤ 0.6	Z > 0.6
(a) Unreinforced loadbearing wall		10	6
(b) Reinforced loadbearing wall		16	10
(c) Unreinforced columns		4	3
(d) Reinforced columns		8	6
(e) Unreinforced non-loadbearing wall		12	8
(f) Reinforced non-loadbearing wall		18	12
(g) Reinforced cinva brick		24	16

Unreinforced walls higher than 3.3 m and unreinforced columns higher than 2.4 m shall have their dimensions assessed by special study. Such a study is outside the scope of this Standard.

C4.6.2
The values in 4.6.2 are recognized best practice based on data from overseas codes and experience in New Zealand.

4.6.3
Adequate lateral restraint shall be provided at wall tops by a diaphragm, bond beam, or other similar device. Lateral restraints shall be constructed from timber, steel, reinforced concrete or reinforced masonry or a combination of these. They shall be designed to resist loads and actions imposed on them. Such design is outside the scope of this Standard.

4.6.4
Bracing shall be distributed around the building to provide for:

(a) Out of plane effects;

(b) Torsion at each floor level and of the building as a whole.

C4.6.4
Designs should minimize the eccentricity of walls about the centre of mass of a building.

4.7 Principles and requirements additional to 4.6 for members designed for seismic loading

4.7.1 *Methods of design*

4.7.1.1
To provide minimum resistance for the appropriate combination of gravity and seismic loads specified by NZS 4203, design methods of sections 5, 6, 7, 8 and 9 of this Standard which are applicable to the structural systems shall be used.

4.7.1.2
Limited ductile and elastic response methods are applicable, but ductile methods shall not be used unless supported by a special study. Such special study is outside the scope of this Standard.

4.7.1.3
In the case of limited ductile design, all the shear strength of the wall shall be supplied by the shear reinforcing i.e. the shear strength contribution of the earth shall be neglected.

C4.7.1.3
Designers should note that the overall shear strength of the gross wall area is limited by the provisions of table 4.1 and 4.7.1.3.

4.7.1.4
The interaction of all structural and non-structural elements which, due to seismic displacements, may affect the response of the structure or the performance of non-structural elements, shall be considered in the design of that structure.

4.7.1.5
Consequences of failure of elements that are not a part of the intended primary system for resisting seismic forces shall also be considered.

4.7.1.6
Floor and roof systems in buildings shall be designed to act as horizontal structural elements, where required, to transfer seismic forces to frames or structural walls.

C4.7.1.7
Where higher strength materials are used, the more detailed methods of AS 3700 or NZS 4230 may be used where materials have similar strengths to fired clay or concrete masonry to utilize higher strengths than are available with this Standard. Designs so based are outside the scope of this Standard.

4.7.1.8
Structural systems and design methods, other than those covered in this Standard, may be used if it can be shown by analysis or experiment based on accepted engineering principles, that adequate strength, stiffness, and ductility for the anticipated seismic movements have been provided. Designs so based are outside the scope of this Standard.

C4.7.1.8
Post-and-beam construction is one such building system that is covered by this clause.

4.7.2 *Seismic loading*

4.7.2.1
In the derivation of the lateral seismic loading to be considered with the appropriate factored gravity load, the structural ductility factor, μ, as defined in NZS 4203 shall be taken as 1.0 for unreinforced walls and elastically responding reinforced walls and 2.0 for reinforced walls designed for limited ductility. The exception is cinva brick walls designed for limited ductility which shall be designed for a structural ductility factor of 1.25.

4.7.2.2
The structural performance factor, S_p, as defined in NZS 4203 shall be taken equal to 0.67.

4.7.2.3
Where appropriate, effects of concurrency in two-way horizontal force resisting systems shall comply with requirements of NZS 3101.

4.7.3 *Assumptions and methods of analysis*

4.7.3.1
In determining the minimum strengths for members designed for the maximum effects of factored static loads determined by elastic analysis, or for effects derived from other analysis, as permitted by NZS 4203, the capacity reduction factors specified in section 5 shall be used.

4.7.3.2
Redistribution of the design moments obtained from elastic analyses shall not be allowed.

4.7.4 *Material properties*

4.7.4.1
Structural ductility factors shall be as in 4.7.2.1.

4.7.4.2
Earth shall be pre-tested to the requirements of NZS 4298 demonstrate the strengths to be used in design if higher strengths than those given by 4.4.2 are to be used.

4.7.4.3
The grade of reinforcement used shall be only that specified except that substitution of higher grades of reinforcement may be made provided that there are no detrimental effects on structural performance.

C4.7.4.3
The presence of greater than allowed for reinforcement strength may cause an undesired change in the mode of failure at ultimate limit state or may cause the condition imposed by 6.3.4 to be violated promoting the possibility of brittle failure of earth in place of ductile yielding of steel.

4.7.5 *Stiffness*

4.7.5.1
Allowances shall be made for the effects of cracking on the stiffness of various structural members, where applicable, for the purpose of estimating periods of vibration and structural deformations, to comply with the requirements of NZS 4203.

4.7.5.2
In the estimation of stiffness or deformations of shear walls and other deep members, allowance shall be made for shear distortions, and distortions of anchorages and foundations, where appropriate.

C4.7.6
Structures with limited ductility. In structures with limited ductility, the system as a whole or the primary lateral load resisting components are not considered to be capable of sustaining the inelastic displacements that are expected in fully ductile structures, without significant loss of strength or reduction in energy dissipating capacity.

4.7.7 *Elastically responding structures*
Structures which are expected to respond elastically to large earthquake motions, in accordance with 4.7.1.1, shall be designed to withstand loads derived assuming elastic response. They are exempt from the additional seismic requirements of all relevant sections of this Standard, provided that the earthquake design load used is that specified by NZS 4203 for these types of structures. For such structures strength design procedures in accordance with the general principles and requirements of the relevant sections of this Standard shall be used.

4.7.8 *Foundations*
General design principles for concrete foundations shall comply with the requirements of sections 4 and 15 of NZS 3101.

4.7.9 *Structures incorporating mechanical energy dissipating devices*
General design principles shall comply with the requirements of NZS 3101.

5 STRENGTH AND SERVICEABILITY

5.1 Notation

f_y lower characteristic yield strength of reinforcement

h clear height of a member between horizontal lateral supports; or
for a member without top horizontal support, the overall height from the bottom lateral support

L clear length of a wall between vertical lateral supports; or
for a wall without a vertical support at its end or at a control joint, the length to that unsupported end or control joint

S_n nominal strength at the ultimate limit state for the relevant action of moment, axial load, shear and torsion

S^* design action at the ultimate limit state

ϕ capacity reduction factor

5.2 General

5.2.1
Structures and structural members shall be designed to have design strengths at least equal to the required strengths calculated for the factored loads and applied forces in such combinations as are stipulated in NZS 4203.

5.2.2
Structural members shall meet all requirements of this Standard to ensure adequate performance at the serviceability limit state and at the ultimate limit state in such combinations as are stipulated in NZS 4203.

5.3 Ultimate limit state

5.3.1 *General requirements*

5.3.1.1
The design strength of a member or cross section in terms of load, moment, shear, or stress shall be taken as the nominal strength, S_n, calculated in accordance with the requirements and assumptions of this Standard, multiplied by a capacity reduction factor, ϕ.

The design strength of a member or cross section shall be equal to or greater than the applied action, S^*, resulting from the design loads of NZS 4203.

5.3.1.2
In general terms 5.3.1.1 is expressed as:

$$S^* \leq \phi S_n \qquad \text{(Eq. 5.1)}$$

where S is replaced by the actions of moment, axial force, shear or torsion as appropriate.

> ***C5.3.1.2***
> *These values are similar to those for concrete masonry.*

5.3.1.3 *Capacity reduction factors*
The capacity reduction factors shall be as follows:

ϕ = 0.60 for axial compression and bearing
ϕ = 0.80 for flexure
ϕ = 0.70 for shear
ϕ = 0.70 for metal connections embedded in earth.
ϕ = 0.60 for flexure determined using Appendix B.

5.3.1.4
Design shall not be based on a lower characteristic yield strength for reinforcing steel, f_y , in excess of 485 MPa.

5.3.2 *Additional requirements for members designed for seismic loading*
When the design moments, axial loads, or shear forces for a section are derived from overstrengths of adjacent members or sections, in accordance with capacity design principles, a strength reduction factor $\phi = 1$ shall be adopted.

5.4 Serviceability

5.4.1 *Deflection*

5.4.1.1
Members subject to flexure shall be designed to have adequate stiffness to limit deflections or any deformations which may adversely affect the serviceability of the structure under service loads to the values required by NZS 4203.

5.4.1.2
The minimum thickness in the horizontal direction, where the walls are not supporting or attached to partitions or other construction likely to be damaged by large deflections, shall not be less than the

following (unless computation of deflections indicates that lesser thickness may be used without adverse effects):

Simply supported	*h* /18 or *L*/18
One end continuous	*h* /21 or *L*/21
Both ends continuous	*h* /22 or *L*/22
Cantilever	*h* /8 or *L*/8

C5.4.1.2
These values are based on values given in AS 3700 and NZS 4230.

5.4.1.3
Computed deflections for seismic design under elastic response shall be limited to *h* /150.

5.4.2 *Shrinkage and thermal control joints*
Where control of cracking is required, the position of joints shall be as detailed in clause 2.12 of NZS 4298 and shall be detailed in the drawings and specifications.

5.5 Other considerations

5.5.1 *Fire resistance*
The fire resistance of earth construction shall be taken as 120/120/120 for a wall thickness of 150 mm unless proved greater than that by testing in accordance with NZS/AS 1530.

C5.5.1
CSIRO (Australia) Bulletin 5 gives further details on fire tests and AS 3700 on fire design.

5.5.2 *Water penetration*
The structure shall be detailed such that the effects of water and moisture penetration do not affect the durability of the structure nor its contents. Such detailing is outside the scope of this Standard.

5.5.3 *Shear on bolted connections in earth*

5.5.3.1
The design strength in shear of bolts embedded in earth shall be limited to the values given in table 5.1 multiplied by the strength reduction factor given by 5.3.1.3.

C5.5.3.1
The values of table 5.1 are based on the methods of the UBC.

For pre-tested reinforced or unreinforced earth the bolt nominal shear strength values may be established by computation, testing, or a combination of these two methods. Such methods are outside the scope of this Standard.

Designers wishing to utilize higher values than in table 5.1 are referred to the paper Commercial Engineered Aggregate Construction by Oliver and Whybrid (Innovation and Economics in Building Conference, Brisbane, Australia 23-24 September 1991). That document gives working loads for high quality rammed earth.

Table 5.1 – Nominal strength in shear of bolts in standard grade earth wall material

Diameter of bolt (mm)	**Strength in shear** (kN)
16	1.8
20	2.6
24	4.4

NOTE - A ϕ factor in accordance with 5.3.1.3 is to be applied to these strength values.

5.5.3.2
Bolts shall be protected from corrosion in accordance with clause 2.6.7 of NZS 4298.

C5.5.3.2
In dry interior situations, the protected environment where the bolt is situated may provide sufficient corrosion protection for plain steel bolts.

5.5.3.3
Bolts shall be embedded in earth mortar or sand/cement grout, in accordance with 5.5.3.6.

5.5.3.4
Loads on bolts shall take into account:

(a) Impact loads;

(b) Vibratory loads;

(c) Effect of volumetric changes due to shrinkage, creep, and temperature;

(d) All other loads.

5.5.3.5
The minimum edge distance for bolts for standard grade earth construction measured to the centreline of the bolt shall not be less than the required embedment length except where:

(a) The load is reduced in the same proportion as the edge distance is reduced;

(b) The bolts are confined by reinforcing, then the edge distance may be reduced by 50 % but shall not be less than 100 mm.

5.5.3.6
The minimum bolt embedment shall be 3/4 of the wall thickness with a minimum length of 200 mm. Where the wall is so thin that this is not possible, the nominal strength given by table 5.1 shall be reduced by the ratio

$$\frac{\text{embedded bolt length (mm)}}{200}$$

5.5.3.7
The embedded end of the bolt shall retain its normal head with a galvanized steel washer of minimum dimensions 50 x 50 x 3 mm or 55 diameter x 3 mm.

6 FLEXURE WITH OR WITHOUT AXIAL LOAD

6.1 Notation

A_b	area of earth cross section
a_1	distance from the end of the wall or pier to the nearest end of the bearing area
A_{de}	effective area of dispersion of the concentrated load in the member at mid height
A_{ds}	bearing or dispersion area of the concentrated load
A_s	area of tensile reinforcement
a_v	coefficient for assessing slenderness ratio
e	eccentricity of vertical force
f_e	compressive strength of earth wall construction
f_{et}	flexural tensile strength of earth
f_y	lower characteristic yield strength of reinforcement
h	height of member
k	reduction factor for slenderness and eccentricity given in table 6.1
k_b	concentrated bearing factor
L	clear length of the wall or pier
L_e	dispersion zone length
M_{ch}	design flexural strength of the wall
M^*	design bending moment acting on the cross section of a member, determined from loads complying with NZS 4203
M^*_{dh}	design horizontal flexural bending moment on wall
M_n	nominal flexural strength of a section
N^*	design axial load at the ultimate limit state acting on a section determined from NZS 4203
N_o	nominal compressive strength of the cross section, short enough for slenderness effects to have no influence
S_r	slenderness ratio
t	thickness or depth of wall perpendicular to the principal axis under consideration
t_w	overall thickness of a wall or isolated pier, taking into account any joint raking which is deeper than 3 mm
Z_u	the lateral section modulus of the earth wall based on the gross cross section
μ	structural ductility factor as defined in NZS 4203
ϕ	capacity reduction factor

6.2 Scope

6.2.1 *General*
The provisions of this section shall apply to the design of members for flexure with or without axial load.

6.2.1.1
The following values of the structural ductility factor, μ, shall apply for earthquake loading design to NZS 4203. The structural ductility factor, μ, shall be taken as 2.0 for limited ductility reinforced earth, and except for cinva brick walls where a value of 1.25 shall be used. For elastically responding reinforced earth and unreinforced earth, μ, shall be taken as 1.0.

6.2.2 *Flexure*
Members subjected primarily to flexure shall be designed as beams, if reinforced or to the provisions of 6.4 if unreinforced.

6.2.3 *Compression*

6.2.3.1
A member which is subjected to a design axial load, N^*, in excess of 0.5 $f_e A_b$ shall be designed to have the total axial load carried by a core of timber, reinforced concrete or steel.

6.2.3.2
When the design axial load on the member cross section, N^*, is less than 0.5 $f_e A_b$, then the member shall be designed as a wall or column.

6.2.3.3
Unreinforced earth in flexure with or without compression shall be designed in accordance with 6.4.

6.2.3.4
Due account shall be taken of combined tension and wall flexure by the methods of this section and Appendix B.

> ***C6.2.3.4***
> *This may occur in high wind load situations.*

6.2.4 *Uplift*
Account shall be taken of uplift by the methods of this section and Appendix B. Account shall be taken of the lowering of wall bending strength due to the effective reduction of gravity axial loads because of wind uplift. The tensile strength of the wall material shall be assumed to be zero.

> ***C6.2.4***
> *The tensile strength of earth walls is close to zero so dead load of wall material is needed to resist uplift. Any connection to the top of the wall needs to be embedded either full depth to the foundation or to a depth such that the self weight of the wall material attached to the connector is greater than the design uplift force. The effects of reduced axial compressive load on wall strength is considered in the methods of Appendix B.*

6.3 General principles and requirements

6.3.1 *Structural end of an earth member*
The structural end of an earth wall or column supporting vertical loads shall be the vertical surface in the member across which longitudinal shear cannot be transferred, and shall include:

(a) The actual end or vertical face of the member;

(b) A control joint in the member; and

(c) A vertical mortar joint in earth construction (other than perpend joints in normal overlapping bond).

6.3.2 *Column construction*

6.3.2.1
Minimum column dimensions shall be 250 mm square if reinforced, 580 mm square if unreinforced. The maximum slenderness ratio of a column shall be as stated in 4.6.2.

6.3.2.2
Columns shall be constructed so that any vertical flue shall have a minimum clear dimension of 60 mm and a minimum area of 9000 mm^2.

6.3.2.3
A column flue containing 4 bars shall have minimum clear flue dimensions of 150 mm x 150 mm.

6.3.3 *General design assumptions*

6.3.3.1
Strength design of members for flexure with or without axial loads shall be based on 6.4 if unreinforced, and on rational assumptions given in 6.3.3.2 and on satisfaction of applicable conditions of equilibrium, if reinforced.

6.3.3.2
The relationship between earth compressive stress distribution and earth strain shall be considered satisfied at an extreme fibre compression stress of f_e with a triangular or trapezoidal earth stress distribution.

C6.3.3.2
The relationship between earth wall compressive stress and strain may be assumed to be rectangular, trapezoidal, parabolic or any other shape that results in prediction of strength in substantial agreement with results of comprehensive tests. Stress distributions other than triangular or trapezoidal are outside the scope of this Standard.

Earth walls and columns are often designed on the basis of ultimate strength reinforced concrete theory where $M^* \leq \phi M_n$ *and* $M_n = A_s f_y jd$ *where jd is a proportion of d, the distance from the extreme compression fibre to the centroid of the tension reinforcement.*

6.3.4 *Longitudinal reinforcement in flexural members*
The failure mode in bending is to be a tension initiated failure.

C6.3.4
It is recommended that the tensile strength of reinforcement should be no greater than 75 % of the available flexural compressive strength of the section.

6.3.5 *Compression reinforcement in members*
Compression bar reinforcement shall not be relied upon to enhance the strength of earth members.

6.3.6 *Distribution of flexural reinforcement*
The flexural tension bar reinforcement shall be evenly distributed within the flexural tension zones of a member cross section.

C6.3.6
This clause prescribes the distribution of flexural reinforcement to control flexural cracking in flexural members.

6.3.7 *Longitudinal reinforcement in columns*

6.3.7.1
The diameter of longitudinal reinforcement used in a column shall not be greater than 16 mm.

6.3.7.2
The minimum longitudinal reinforcement for a column shall be 1 bar of 12 mm diameter.

6.4 Unreinforced earth

6.4.1 *General*
Unreinforced earth shall include all forms of earth construction such as rammed earth, adobe, poured earth, pressed brick, whether stabilized or unstabilized.

C6.4.1
Although the methods of this clause have been adopted from AS 3700 unreinforced masonry section and strictly speaking apply to brick constructions only, they are also (conservatively) specified for rammed earth as little is known about the tensile continuity between one rammed earth layer and the next.

6.4.2 *Basis of design*
Each unreinforced earth member shall be designed to comply with 6.4.3 to 6.4.5, taking into account the strength of the material and the further provisions in 7.3.1 as applicable for the relevant type of member.

6.4.3 *Design for compressive forces and vertical bending*

6.4.3.1 *General*
Unreinforced earth members resisting compressive forces, with or without simultaneously acting bending moments, shall be designed to comply with 6.4.3.2. Design for concentrated loads on members shall comply with 6.4.3.3, and design for lightly loaded members under the action of transient out-of-plane forces shall comply with 6.4.4 or 6.4.5, as appropriate. The compressive strength depends upon the following factors:

(a) Slenderness;

(b) Effective eccentricity of loading at each end;

(c) Characteristic compressive strength of the earth;

(d) Cross-sectional area of the earth.

In a wall or isolated pier subject to compression and bending, the vertical and bending forces shall be combined at top and bottom of the member by regarding the vertical force as acting at statically equivalent effective eccentricities, *e*, at each end. In this calculation, the most unfavourable disposition of live loads shall be considered. The load combination shall be such that under the worst loading conditions, the equivalent effective eccentricity at any point does not exceed $t_w/6$.

C6.4.3.1
Torsion due to earthquake forces should be minimized in seismic areas by having the combined centre of mass of all the walls in plan close to the centre of resistance.

6.4.3.2 *Uniaxial bending and compression on uniform symmetrical members*
A member shall be designed such that the following relationship is satisfied:

$$N^* \leq k \phi N_o \quad \text{(Eq. 6-1)}$$

where

$$N_o = f_e A_b \quad \text{(Eq. 6-2)}$$

Table 6.1 – Reduction factor (*k*) for slenderness and eccentricity

Slenderness ratio (S_r)	**Reduction factor (k)**				
	Eccentricity to thickness ratio (e/t_w)				
	≤0.05 (Note 5)	**0.10**	**0.20**	**0.30**	**0.33**
6	1.00	0.78	0.56	0.38	0.32
8	0.94	0.73	0.54	0.34	0.29
10	0.88	0.67	0.49	0.31	0.25
12	0.82	0.62	0.45	0.27	0.22
14	0.76	0.56	0.40	0.23	0.18
16	0.70	0.51	0.35	0.20	0.15
18	0.64	0.45	0.31	0.16	0.11

NOTE –
(1) Values above the dashed line correspond to failure by crushing.
Values below the dashed line correspond to failure by lateral instability.
(2) Refer to 4.6.2 for the maximum allowable slenderness ratios.
(3) Linear interpolation may be used between the values given in the tables.
(4) *e* = the larger eccentricity, at either top or bottom.
(5) The values of *k* for e/t_w = 0.05 are only applicable to columns.

C6.4.3.2
Table 6.1 is a truncated version of table 5.1 from AS 3700.

6.4.3.3 *Evaluation of slenderness ratio*
The slenderness ratio of a member about a given principal axis shall be as follows:

For a vertical member that is laterally supported along one or both of its top and bottom ends:

$$S_r = a_v h/t \qquad \text{(Eq. 6-3)}$$

where

a_v = 0.75 for a member laterally supported and rotationally restrained at both top and bottom; or

= 0.85 for a member laterally supported at both top and bottom and rotationally restrained at only one of these; or

= 1.00 for a member laterally supported and rotationally free at both top and bottom; or

= 2.00 for a member laterally supported and rotationally restrained at only its bottom.

6.4.3.4 *Concentrated loads*

6.4.3.4.1 *General*
Each concentrated compression load acting on an earth compression member shall be assumed to disperse through the earth construction as provided in 6.4.3.4.2, and each cross section within that zone of dispersion shall be designed to comply with 6.4.3.4.3.

6.4.3.4.2 *Dispersion of a concentrated load through the earth construction*
A concentrated load acting on a member shall be assumed to disperse through the earth construction at an angle of 45º (from the horizontal) from the perimeter of the bearing area of the load to the mid depth of the member, but this dispersion is not to extend:

(a) Into the dispersion zone of an adjacent concentrated load on the member; or

(b) Beyond the structural end of the earth construction in the member as defined in 6.3.1.

C6.4.3.4.2
Special care is required in the detailing of the support of concentrated loads at or near the end of a wall. Figure 6.1 illustrates the principles of 6.4.3.4.2.

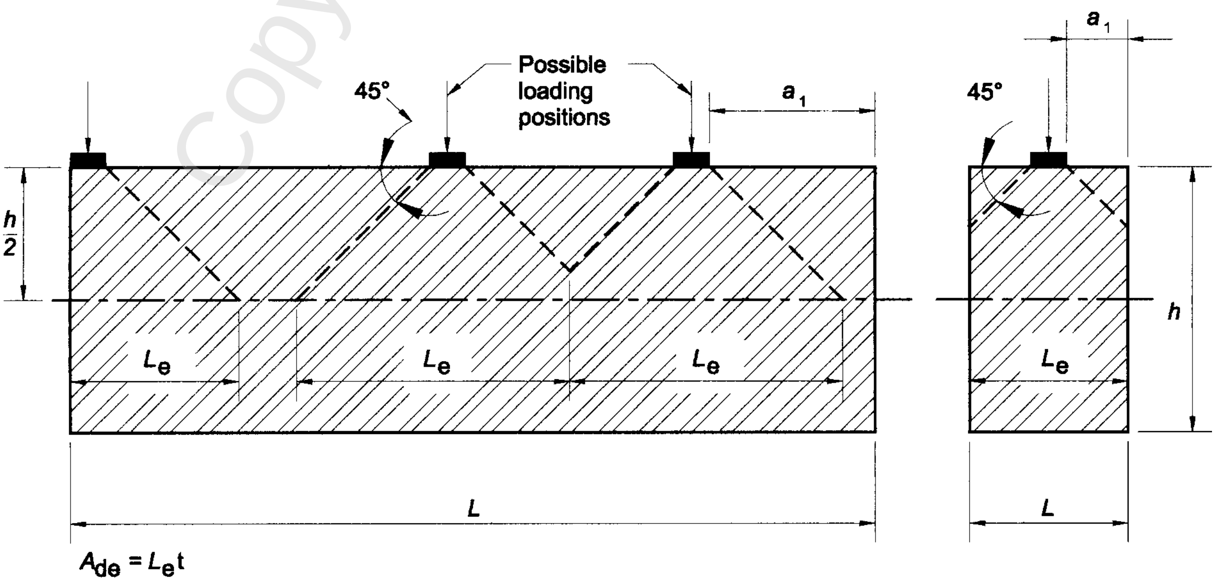


Figure 6.1 – Loading positions and effective areas of dispersion

6.4.3.4.3 *Load capacity under a concentrated load*
Where a member is of uniform and symmetrical cross section, it shall be designed to comply with 6.4.3.4.2, except that:

(a) The design axial load (N^*) acting on any given cross section shall include the design concentrated load, plus that portion of the other compressive forces that act on the cross-sectional area (A_b) under consideration;

(b) The design bending moment (M^*) acting on the same cross section under consideration shall include the bending moment, if any, from the design concentrated load, plus that portion of the bending moment from other loads and forces that act on that cross-sectional area (A_b);

(c) In addition, the member shall be designed to satisfy the following equation for each cross section within the zone of dispersion of the concentrated load:

$$N^* \leq \phi\, k_b\, N_o \qquad \text{(Eq. 6-4)}$$

where k_b is given by 6.4.3.4.4.

6.4.3.4.4 *Concentrated bearing factor* (k_b)
The value of the concentrated bearing factor (k_b) for use in clause 6.4.3.4.3 shall be:

(a) For cross sections at a distance greater than 0.25 h below the level of the bearing of the concentrated load on the member:

$k_b = 1.00$

(b) For cross sections at a distance within 0.25 h below the level of the bearing of the concentrated load on the member:

(i) Other than as in (ii) below (including ungrouted hollow unit brickwork):

$k_b = 1.00$

(ii) In solid or cored unit brickwork or in grouted brickwork:

$$k_b = \frac{0.55\left(1+0.5\frac{a_1}{L}\right)}{\left(\frac{A_{ds}}{A_{de}}\right)^{0.33}}\ ;\ \text{or}$$

$k_b = 1.50 + \frac{a_1}{L}$ whichever is less, but k_b is not less than 1.

where

A_{ds} = bearing or dispersion area of the concentrated load at the design cross section under consideration

A_{de} = effective area of dispersion of the concentrated load in the member at mid-height
= $L_e t$ (for L_e see figure 6.1)

a_1 = distance from the end of the wall or pier to the nearest end of the bearing area

L = clear length of the wall or pier (see figure 6.1).

NOTE – Where concentrated loads are applied in close proximity to each other, the value of A_{ds} and A_{de} shall be calculated in accordance with 6.4.3.4.2(a).

6.4.4 *Design for horizontal bending from transient out-of-plane forces*

6.4.4.1 *General*

The design of an unreinforced earth wall, or portion thereof, to withstand horizontal bending from out-of-plane wind loads, earthquake loads or similar forces of a short-term transient nature, shall comply with 6.4.4.2 or 6.4.5, provided that :

(a) For earth brick walls, the wall has all perpends completely filled;

(b) For pressed earth brick or adobe, the wall, or that part being designed for horizontal bending, has at least 4 contiguous courses of earth bricks acting together in horizontal bending.

6.4.4.2 *Horizontal bending with tension stresses permitted*

A wall complying with the requirements of 6.4.4.1 shall be proportioned so that the following relationship is satisfied under each combination of simultaneously acting design horizontal bending moment (M^*_{dh}):

$M^*_{dh} \leq M_{ch}$ .... (Eq. 6-5)

where

$M_{ch} = 0.40\ \phi\ f_{et}\ Z_u$ for earth brick walls, or .... (Eq. 6.6)

$M_{ch} = \phi\ f_{et}\ Z_u$ for rammed or poured earth walls .... (Eq. 6.7)

> ***C6.4.4.2***
> *The factor of 0.40 allows for bricks laid in overlapping bond which, conservatively, have 40 % of the wall height available to resist horizontal moments when the bending strength of the mortar is ignored.*

6.4.5 *Out of plane strength for vertical bending*

The lateral out-of-plane (face) load strength of unreinforced earth walls spanning vertically shall be calculated using the virtual work propped cantilever strength analysis methods of Appendix B. P- delta seismic effects shall be considered. Out of plane action can be maintained only if individual bricks are restrained from slipping or rotating.

> ***C6.4.5***
> *A virtual work strength analysis method is outlined in the paper by YTTRUP, P. Strength of earth masonry (adobe) walls subjected to lateral wind forces. Proceedings, 7th International Brick Masonry Conference, Melbourne, February 1985.*

6.5 Principles and requirements additional to 6.3 for members not designed for seismic loading

6.5.1 *Strength calculations*

6.5.1.1

Columns shall be designed for the most unfavourable combination of design moment, M^*, and design axial load, N^*.

6.5.1.2

Unreinforced columns shall be designed as short walls to the method of 6.4.3.2.

6.5.1.3

If e/t_w exceeds 0.2 then flexure about both axes shall be considered together. The combined action shall not put any part of the section into tension.

6.5.2 *Composite columns*
Where other material column sections are built into earth walls, or columns, the strength of the earth shall not be included in the calculation of the strength of the column section.

6.6 Principles and requirements additional to 6.3 for members designed for seismic loading

6.6.1 *Strength calculations*
Columns of earth shall not be used to provide main structure lateral load restraint unless they contain other material sections which can resist the whole of the lateral load.

7 SHEAR

7.1 Notation

A_b area of earth cross section

A_s area of tensile reinforcement

A_{sv} area of shear reinforcement

d depth of section in the direction of shear

f_d compressive stress acting on section under the design loading

f_{es} shear strength of earth

f_n total nominal shear stress

f_{sy} lower characteristic yield strength of shear reinforcement

f_y lower characteristic yield strength of reinforcement

h height of member

k_v shear factor as given in 7.3.1.2

L clear length of the wall or pier

s spacing of shear reinforcement measured perpendicular to direction of shear force

t thickness or depth of wall perpendicular to the axis under consideration

V^* design shear force acting on the cross section of a member at ultimate limit state, assessed from NZS 4203

V_n nominal shear strength of the section (kN)

δ coefficient of variation

μ structural ductility factor

ϕ capacity reduction factor

7.2 Scope

7.2.1
Provisions of this section apply to design of earth walls for shear and torsion with flexure and with or without axial load. Design of earth walls for shear and torsion shall be in accordance with established principles for reinforced concrete, as set out in NZS 3101, section 9 modified by the requirements of this section. Where no specific requirements are given in this section, the appropriate requirements of NZS 3101 section 9 shall apply.

7.3 General principles and requirements

7.3.1 *Unreinforced earth*

7.3.1.1 *Shear capacity*
The design of an unreinforced earth wall subject to shear forces, with or without simultaneous compressive forces acting across the shear plane, shall be such that the following relationship is satisfied under each combination of simultaneously acting design shear force, V^*, and (minimum) compressive stress (f_d) acting at the cross section under consideration:

$$V^* \leq \phi[f_{es}A_b + k_v f_d A_b] \qquad \text{(Eq. 7-1)}$$

or

$$V^* \leq 5\phi f_{es}A_b \qquad \text{(Eq. 7-2)}$$

whichever is less.

Limited ductility seismic design principles shall not be applied to unreinforced earth.

> ***C7.3.1.1***
> *The factor of 5 term in equation 7-2 places an upper limit on the influence of vertical load. Vertical reinforcement pretension may be taken into account in calculating f_d provided the pretension is maintained after shrinkage has taken place.*

7.3.1.2 *Shear factor (k_v)*
The value of k_v for use in 7.3.1.1 shall be:

(a) At membrane-type damp-proof courses, flashings, and similar locations having low friction resistance:

$$k_v = \text{zero} \qquad \text{(Eq. 7-3)}$$

(b) At mortar bed-joints:

$$k_v = 0.30. \qquad \text{(Eq. 7-4)}$$

> ***C7.3.1.2***
> *Testing may be used to establish values for k_v different to those given by 7.3.1.2. Such testing is outside the scope of this Standard. The value of k_v from equation 7.4 necessitates reinforcement penetrating damp proof membranes to ensure shear continuity.*

7.3.1.3 *Development of longitudinal shear strength*
Where it is necessary to transfer shear forces across wall intersections and vertical mortar joints in earth brick construction, the bonding or tying across the shear plane shall be an overlapping bond.

7.3.1.4 *Design of shear walls*

7.3.1.4.1 *General*
Shear walls shall be designed to comply with 6.4.2 to 6.4.5, 7.3.1.1, and in accordance with the provisions of 7.3.1.4.2 and 7.3.1.4.3.

7.3.1.4.2 *Two or more shear walls acting together*
Where lateral forces are resisted by 2 or more shear walls acting together, the load and force actions shall be distributed between the shear walls using structural analysis principles, taking into account the relative stiffnesses of the walls under these actions, and the effects of openings, if any, in the walls.

7.3.1.4.3 *Design for compression and in-plane lateral forces*
The strength capacity of a shear wall under compression and flexure in the direction of the length of the wall shall be assessed on the basis of the properties of the whole monolithic cross section of the wall.

C7.3.1.4.3
Where "T" or "L" sections are considered, there should be adequate shear connection strength between the elements and a conservative approach should be taken. Such considerations are outside the scope of this Standard.

7.3.2 *Reinforced earth*

7.3.2.1
Design of wall cross sections subject to in-plane shear shall be based on:

$$V^* \leq \phi V_n \quad \text{(Eq. 7-5)}$$

where V^* is the design shear force at the section derived from factored load on the structure and V_n is the nominal shear strength of the section computed with the shear strength f_{es} from :

(a) Under elastic response or serviceability limit state conditions

$$V_n = f_{es} t d + A_{sv} f_{sy} d/s + k_v f_d t d$$

but

$$V_n < 5 f_e t d \quad \text{(Eq. 7-6)}$$

or

(b) Under limited ductility seismic response

$$V_n = A_{sv} f_{sy} d/s \quad \text{(Eq. 7-7)}$$

For in-plane shear walls with $L < h$, d, shall be taken as 0.8 L, unless otherwise determined from a strain compatibility analysis.

C7.3.2.1
Overturning or flexure may be critical even for low aspect ratio walls. Vertical reinforcement pretension will contribute to available shear strength under serviceability conditions and may be taken into account for elastically responding structures provided the pretension is maintained after shrinkage has taken place. No contribution from pretension shall be permitted for limited ductile structures.

7.3.2.2
For walls with $L \geq h$, d shall be taken as equal to L.

7.3.2.3
In determining shear strength, V_n, effects of axial tension, including tension from creep and shrinkage and from differential temperature, shall be considered wherever applicable.

7.3.3 *Shear reinforcement details*

7.3.3.1
Shear reinforcement shall consist of:

(a) Steel of either normal or high strength (either deformed or plain) except as provided by 8.3.9; or

(b) Welded wire fabric within the plane of the member with wires cut to form “ladders” or “fish bones”; or

(c) Polypropylene biaxial geogrid or similar with square or rectangular apertures. The quality control strength of the geogrid shall be determined in accordance with BS EN ISO 10319. The geogrid to be cut into strips to form ladders of reinforcement.

C7.3.3.1
Other types of reinforcing may be used subject to rational engineering analysis but are outside the scope of this Standard.

Examples of shear reinforcement are shown in figure 5.5 of NZS 4299.

7.3.3.2
Bars or wires used as shear reinforcement shall be anchored at both ends according to 8.3.4.5 to develop the lower characteristic yield strength of reinforcement.

C7.3.3.2
Some practitioners also specify “sensible minimums” horizontal reinforcing at every fourth course or every 600 mm whichever is least whether the design calculations require them or not.

7.3.3.3
Shear reinforcement shall be evenly distributed through the height of the wall.

7.3.3.4
Polypropylene geogrids used as shear reinforcement shall be anchored to vertical reinforcing at each end of bracing walls with a 6 x 20 mm HDPE bodkin or 6 mm diameter minimum steel rod, threaded through the geogrid.

7.4 Principles and requirements additional to 7.3 for members designed for seismic loads

7.4.1 *Shear strength*

7.4.1.1
The provisions of 7.4 shall apply to members whose required nominal shear strength under seismic loading corresponds to a structural ductility factor μ of ≤ 2.0. For members whose required ideal shear strength under seismic loading corresponds to $2.0 \geq \mu \geq 1.25$, provisions shall be obtained by linear interpolation between the requirements of 7.3 and 7.4.

7.4.1.2
The design shear force in members subjected primarily to flexure shall be determined from considerations of static transverse forces on the member, with the flexural overstrength being developed at the most probable location of critical sections within the member or in adjacent members, together with the gravity load at the appropriate load factor.

7.4.1.3
Shear strength provided in limited ductile walls shall have a suitable margin over required in-plane flexural strengths. The overstrength of the wall due to in-plane flexure shall be calculated to be a minimum of $1.25/\phi$. Where the limited ductile wall is less than 1.4 m long the influence on flexural overstrength shall also be considered for a soil compression overstrength factor of a minimum of 4 unless the overstrength factor is determined from knowledge of the earth strength coefficient of variation. Such determination is outside the scope of this Standard.

C7.4.1.3
For limited ductile wall design a flexural mode of failure is required. This clause includes an allowance of 1.25 A_s f_y factor to account for steel overstrength.

In short walls the length of the compression zone is significant in determining the moment capacity and allowance for the earth material overstrength should be made. In variable materials the calculated value of characteristic strength may sometimes be well below the actual strength. Where the coefficient of variation is 0.2 the given overstrength is 4 based on (population average compressive strength) / (5 percentile of sample characteristic strength). For a coefficient of a variation, δ of 0.25 compressive overstrength is about 6, and for δ of 0.35 could be 10 or higher.

7.4.1.4
The design shear force in members subjected to combined flexure and axial load shall be determined from considerations of static forces on the member, with the worst likely combination of the maximum likely end moments, and where appropriate with flexural overstrength being developed at critical sections.

7.4.1.5
Where a structure is designed to perform with limited ductility, then appropriate redistribution of shear loads shall be carried out.

7.4.1.6
In applying equation 7-4 to design of cross sections where the shear force is calculated in accordance with 7.4.1.1 and 7.4.1.2, a capacity reduction factor $\phi = 1.0$ shall be adopted.

7.4.1.7
Total nominal shear stress, f_n, shall not exceed the maximum grade-dependent values, f_{es}, listed in table 4.1 and 4.5.4.

7.4.2 Shear strength provided by earth

7.4.2.1
In all potential plastic hinge regions of columns and walls, for $\mu = 2.0$, the shear stress, f_{es}, shall be assumed to be zero for any seismic load combination.

7.4.2.2
For $\mu \leq 1.25$, the shear strength of the earth may be utilized and horizontal reinforcement is not mandatory.

8 REINFORCEMENT – DETAILS, ANCHORAGE AND DEVELOPMENT

8.1 Notation

d_b bar diameter

f_y lower characteristic yield strength of reinforcement

8.2 Scope

8.2.1
Provisions of section 8 shall apply to detailing of reinforcement, including spacing and cover, and design of anchorage, development and splices.

8.3 General principles and requirements for members designed for seismic loading

8.3.1 *Steel reinforcement*

8.3.1.1
Reinforcing bars shall conform to NZS 3402. Hard drawn mild steel wire shall conform with NZS 3421.

8.3.1.2
Reinforcement details shall be in accordance with clause 2.6 of NZS 4298.

8.3.1.3
Joint reinforcement, where permitted to be used by this Standard may be fabricated in a form of a lattice truss with two 4 mm diameter mild steel wires connected by a 2 mm diameter lattice welded to them and the whole assembly hot dipped galvanized after fabrication. A "fish bone" or ladder cut from welded steel mesh reinforcing may be used.

C8.3.1.3
Other types of joint reinforcement which satisfy the requirements of this Standard and NZS 4298 may be used.

8.3.2 *Spacing of reinforcement*

8.3.2.1
The clear distance between parallel reinforcing bars in a layer shall be not less than the nominal diameter of the bars, nor less than 25 mm.

8.3.2.2
The nominal maximum size of soil particles shall not be larger than 3/4 of the minimum clear spacing between the individual reinforcing bars or bundles.

8.3.3 *Mechanical anchorage*

8.3.3.1
Anchorage of reinforcing shall be one of:

(a) An anchorage in concrete to NZS 3101;

(b) (i) A maximum 6 mm bar standard hooked 300 mm around a minimum 12 mm bar for adobe;

(ii) Maximum 10 mm bar for rammed earth and pressed brick hooked 300 mm around a minimum 12 mm bar.

(c) Anchorage to a timber block or plate such that the provisions of 8.3.3.2 are complied with and the full tensile strength of the reinforcing bar is able to be developed.

8.3.3.2
Earth material in contact with anchorages shall have adequate bearing strength in accordance with 6.4.3.4.

8.3.4 *Splices in reinforcement – General*

8.3.4.1
Splices of reinforcement shall be indicated on the design drawings or in specifications. Splices embedded in earth material (rather than in cement grout filled cores) shall be welded or mechanically joined in accordance with 8.3.4.4.

C8.3.4.1
Tests may be used to confirm that the ultimate strength of the bar is developed by lapped splices however such testing is outside the scope of this Standard.

8.3.4.2
Except as provided herein, all welding of reinforcing bars shall conform to NZS 4702.

8.3.4.3
Welds shall not be made closer than 10 d_b from bends. Hard drawn steel wire reinforcing shall not be welded.

C8.3.4.3
Bars not conforming to NZS 3402 may be welded provided the welding technique and local control of conditions shall have been demonstrated by tests to produce welds that have the required mechanical and metallurgical properties. Such welds are outside the scope of this Standard.

8.3.4.4
Welded splices or mechanical connections satisfying the following conditions, shall be used:

(a) Lap welded splices designed in accordance with NZS 3101; or

(b) Full strength welded splices in which the bars are butt welded to develop in tension the breaking strength of the bar; or

(c) High strength welded splices in which the bars are butt welded to develop in tension 1.6 f_y or the breaking strength of the bar, whichever is smaller; or

(d) Mechanical connections which are defined as a connection which relies on mechanical interlock with the bar deformations to develop the connection capacity. A high strength mechanical connection shall develop in tension or compression, as required, not less than 1.6 f_y or the breaking strength of the bar, whichever is smaller. When tested in tension or compression as appropriate, the change of length at a stress of 0.7 f_y in the bar, and measured over the full length of the connection system shall be not more than twice that of an equal length of unspliced bar.

8.3.4.5
Shear reinforcing shall be anchored at ends by one of:

(a) Providing a 180º bend with a 300 mm return around another bar; or

(b) Embedment in concrete or grout sufficient to develop the tensile strength of the reinforcement which has bearing area to earth which complies with 6.4.3.4.

(c) Anchorage to a timber block or plate in accordance with the requirements of 8.3.3.1(c).

C8.3.4.5
Care should be taken to ensure adequate anchorage for shear reinforcement.

The method of (a) above is not recommended for horizontal shear reinforcing greater than 6 mm diameter.

Mechanical anchorage may be used but the design of such anchorages is outside the scope of this Standard.

8.3.5 *Protection for reinforcement*
The minimum cover of earth or grout, whichever is applicable, provided for reinforcing bars shall be as shown in clause 2.6.7 of NZS 4298.

8.3.6 *Protection of exposed reinforcing bars and fittings*
Exposed reinforcing bars, inserts and plates intended for bonding with future extensions shall be protected from corrosion.

8.3.7 *Covers required for fire protection*
Where fire design requires a fire-protection covering greater than the earth protection specified in, clause 2.6.7 of NZS 4298 such greater thickness shall be used.

8.3.8 *Wall reinforcement*
Wall reinforcement shall be in accordance with sections 6, 7 and 9.

8.3.9 *Deformed/undeformed reinforcement*
In rammed earth, to minimize the risk of horizontal cracking caused by “hang-up” on deformations, round steel vertical bars shall be used. These shall be oiled or encased in plastic sleeves.

9 FOUNDATIONS

9.1 Notation

μ structural ductility factor

9.2 General principles and requirements
Foundations shall be of reinforced concrete the same width of the earth wall that it supports, or of solid-filled reinforced concrete masonry fired brick or stone masonry. Reinforced concrete masonry shall be the same width as the wall above, except that a 240 mm wide masonry footing may support a 300 mm wide earth wall. For walls wider than 300 mm reinforced concrete footings shall be used and they shall be the full width of the wall.

9.2.1
Foundations shall be designed using the methods of the New Zealand Building Code Verification Method B1/VM4.

C9.2.1
Components such as concrete block, ceramic brick or stone masonry to give a fair-finish to the outer exposed above-ground face of the reinforced concrete foundation may be used.

9.3 Loads and reactions

9.3.1 *Proportions, loads and depths*

9.3.1.1
Foundations shall be proportioned to resist the design loads and induced reactions, in accordance with the appropriate design requirements of this Standard.

9.3.1.2
Base area of foundations shall be determined from external forces and moments resulting from factored loads, transmitted by the foundation to the soil, and soil strengths selected through principles of soil mechanics.

9.3.1.3
The foundation system of all structures shall be carried to depths such that adequate bearing is secured. Due allowance shall be made for the effects of seasonal changes of moisture, lateral movement of the ground and movements of ground in unstable areas.

9.3.1.4
When combinations of deep and shallow foundations are necessary, differential settlement and torsional effects shall be considered in the design of foundation members and the provision of control joints.

9.3.1.5
Long-term settlements shall not impair the serviceability of the superstructure by cracking or movement.

9.3.2 *Construction of foundations*

9.3.2.1
Concrete shall be ordinary grade or higher as defined in NZS 3109.

9.3.3 *Moments in strip foundations*

9.3.3.1
Reinforcement shall be provided to the top and bottom of strip foundations to resist design loads and shall be not less than 200 mm^2 of steel in total. Design shall be in accordance with NZS 3101.

9.3.4 *Shear in strip foundations*

9.3.4.1
Minimum shear reinforcement shall be provided and its spacing shall be at no further apart than 600 mm centre to centre. Design shall be in accordance with NZS 3101.

9.3.5 *Minimum foundation height above finished ground level*

9.3.5.1
Where finished ground is a paved surface, the top of the foundation (i.e. the base of the earth wall) shall be no less than 150 mm above the finished paved surface level.

9.3.5.2
The height of the foundation (i.e. the base of the earth wall) shall be no less than 225 mm above finished ground where this is soil, loose gravel or other unpaved surface.

C9.3.5.2
The purpose of this clause is to prevent moisture damage to the base of earth walls. Compliance will require careful design consideration and plan detailing of the proposed finished ground types and heights at all points around the structure.

9.3.5.3
The top of the foundation under the earth walls shall be cleaned of any laitance, be roughened to 5 mm amplitude and have 2 coats bituminous sealer applied so as to form a water impermeable layer.

9.4 Principles and requirements additional to 9.3 for foundations designed for seismic loading

9.4.1
The foundation design shall be in accordance with the provisions of this Standard using the factored loading specified in NZS 4203, as modified by this Standard.

9.4.2
The foundation system shall maintain its ability to support the design gravity loads while maintaining the chosen earthquake energy dissipating mechanism in the structure.

9.4.3
All members shall comply with the additional principles and requirements for members designed for seismic loadings as set down in the relevant sections of this Standard. However, flexural members not designed for ductile behaviour which have an ideal strength not less than the greatest total seismic load that can be transmitted to them from the superstructure, need not comply with these requirements.

9.4.4
The foundations of shear walls shall have adequate overturning resistance to carry the overstrength flexural capacity as defined in 7.4.1.3 if $\mu > 1.0$.

APPENDIX A
METHOD FOR DURABILITY DESIGN
(Normative)

A1 NOTATION

b	eaves width (mm)
h	height of wall to eaves (mm)
p	annual rainfall (mm)
k_1	rainfall factor
k_2	wall orientation factor
k_3	eaves factor
k_4	locality factor
$V_{(z)}$	site wind speed at height z for the direction under consideration at the ultimate limit state (m/s)

A2

For a given locality and geometry of wall, the Limiting Erodibility Index (LEI) shall be calculated as follows:

Limiting Erodibility Index = $k_1\ k_2\ k_3\ k_4$ (rounded down to nearest whole number)

where

k_1 = Rainfall factor

$$= \frac{500}{\sqrt[3]{p} \times V_{(z)}}$$

k_2 = Wall orientation factor
= 1.4 for walls not facing predominant wind driven rain
= 1 elsewhere

k_3 = Eaves factor

$$= 1 + \frac{2b}{h}$$

k_4 = 1.0 except for wind region I (Northland) as defined by clause 5.4 of NZS 4203

where

k_4 = 0.93.

CA2

For example if a wall is located in an area where the annual rainfall is 600 mm, where the ultimate design wind speed 40 m/s and the wall is 2400 high with 400 mm eaves and faces the pre-dominant wind direction then the required LEI for this wall would be:

$$LEI = \frac{500}{\sqrt[3]{600} \text{ x } 40} \times 1.0 \times \left(1 + \frac{2 \times 400}{2400}\right) \text{x } 1 = 1.98 = 1 \quad \text{(Rounded down to whole number)}$$

In this case the erodiblity Index of the wall sample as determined in accordance with Appendix D of NZS 4298 would need to be ≤ 1 for the wall to be considered satisfactory. The method of Appendix E can not be used in this case as the minimum LEI this method can confirm is 2.

Wind driven rain is a serious consideration for durability. These formulae rationally express the observed performance of earth walls and are conservative. They will be able to be refined as more detailed climate information and test results become available.

Surface erosion is initially caused by the impact of rain drops. The erosion is more severe if the surface is wet and softened and continues as dislodged material is transported away by surface flow.

Rain drop impact effect is related to drop momentum and so energy depends on drop size and velocity. Maximum drop sizes occur in very short intense storms which have less significant material softening and less continuous surface flow to transport dislodged particles. The annual average rainfall, p, is widely known and is therefore utilized with a conservative scaling factor rather than commissioning special studies to derive charts for critical storm durations.

Eaves overhangs have historically been effective in protecting earth walls, the k_3 factor increases for the width of overhang but is less effective on higher walls.

APPENDIX B
METHOD FOR DETERMINATION OF SEISMIC RESISTANCE OF UNREINFORCED EARTH WALLS

(Normative)

B1 Notation

a Width of stress block at ultimate limit state

a_e response acceleration to induce wall failure

a_{cr}, $a_{1/2}$, $a_{3/4}$, a_u acceleration at cracking, 1/2 cracked, 3/4 cracked and ultimate moment condition respectively

A_1 area under response acceleration versus wall displacement curve

C_{pi} basic horizontal seismic coefficient for a part at level i from NZS 4203

E_e modulus of elasticity of earth wall material

f_e compressive strength of earth wall construction

h height of wall between horizontal restraints

I moment of inertia of wall section

k_{cr} initial wall stiffness

M_{cr}, $M_{1/2}$, $M_{3/4}$, M_u moment in wall at cracking, 1/2 cracked, 3/4 cracked and ultimate condition respectively

P gravity load per unit length at top of wall

R vertical reaction at crack

t wall thickness

w_{cr}, $w_{1/2}$, $w_{3/4}$, w_u distributed lateral load required to induce corresponding wall moment

W self weight of wall under investigation

γ density of wall material

Δ_{cr}, $\Delta_{1/2}$, $\Delta_{3/4}$, Δ_u displacement at centre of wall at cracking, 1/2 cracked, 3/4 cracked and ultimate conditions

μ structural ductility factor

ϕ capacity reduction factor

B2 General

This method involves plotting the response acceleration versus wall displacement curve from 4 calculated points. The equal energy principle is used to determine the equivalent elastic response acceleration at which failure is considered to occur. This involves calculating the area under the response acceleration versus wall displacement curve.

The following assumptions are made in the model on which this method depends:

(a) The wall cracks at mid height;

(b) The wall is adequately restrained by connections to floor diaphragm, roof diaphragm, bond beam, foundation or other structure at its top and bottom;

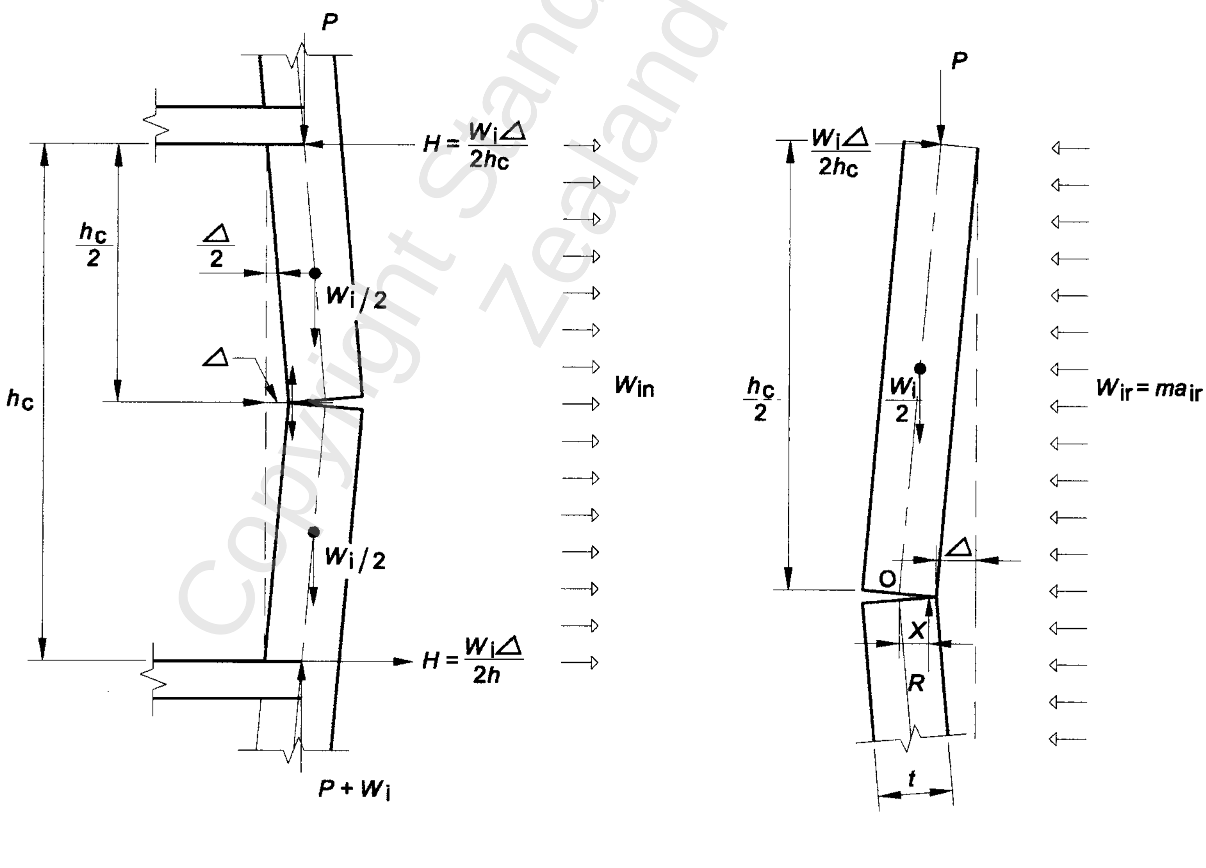
(c) At the ultimate limit state the compression stress block in the wall is rectangular with a maximum value of 0.85 f_e;

(d) At loads less than the ultimate limit state the compressive stress distribution in the wall material is triangular;

(e) The peak vertical ground acceleration under earthquake loading is 2/3 the peak horizontal ground acceleration;

(f) The vertical reactions at the top and bottom of a wall section act at the centreline of the wall.

The structural model for this method is illustrated in figure B1.



(A) FORCES ON FACE-LOADED WALL INCLUDING LATERAL REACTIONS

(B) MOMENT EQUILIBRIUM FOR FACE-LOADED WALL

Figure B1 – Summary of loads, forces and actions on unreinforced earth wall

B3 Procedure steps

B3.1

The response acceleration versus wall displacement curve is plotted at 5 points represented by:

(a) At cracking with zero compression at one face;

(b) When 1/2 cracked with zero compression at the wall centreline;

(c) When 3/4 cracked with zero compression is at the 3/4 point across the wall thickness;

(d) At the ultimate load;

(e) Before loading, at zero acceleration and zero displacement.

Calculations are performed for a unit length of wall. The assumed stress distributions are shown in figure B2.

> ***CB3.1***
> *A spreadsheet may be conveniently set up to perform the calculations described.*

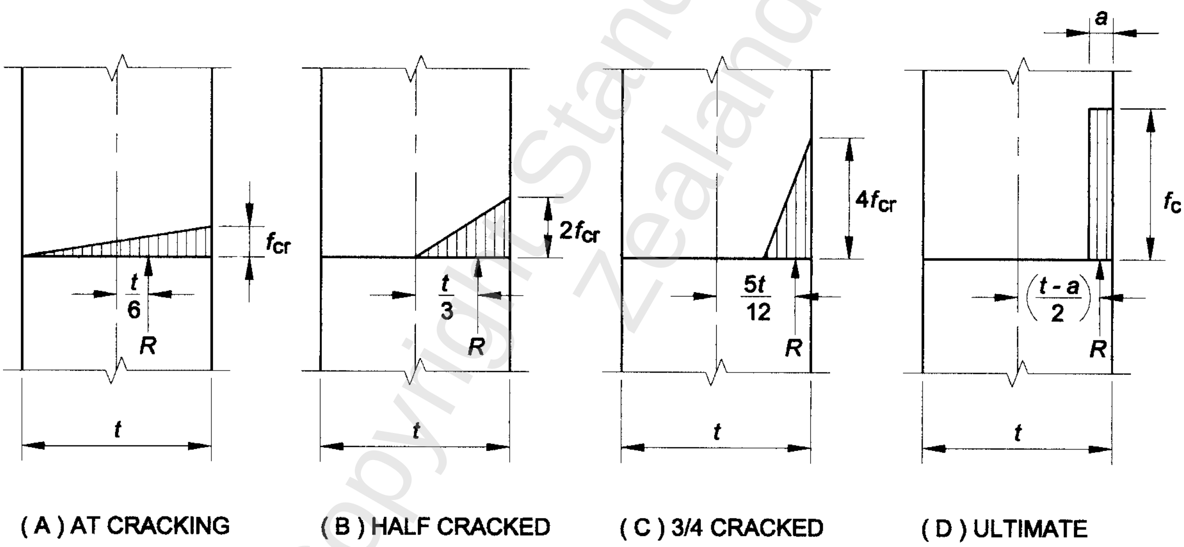


Figure B2 – Stress distributions and actions at the 4 crack states

B3.2

Calculate the gravity load, P, at the top of the wall under investigation and the self weight, W, of the wall under investigation.

B3.3

Determine from NZS 4203 for μ = 1.0 the design acceleration, C_{pi}, for parts for the wall in question.

B3.4
Determine *R* from:

$$R = \left(1 - \frac{2}{3}C_{pi}\right)\left(P + \frac{1}{2}W\right)$$

B3.4.2
At wall cracking determine:

$$M_{cr} = \frac{Rt}{6} \quad \text{(kN-m/m)}$$

$$w_{cr} = \frac{8M_{cr}}{h^2} \quad \text{(kN/m)}$$

$$\Delta_{cr} = \frac{5}{384}\frac{w_{cr}h^4}{E_e I} \quad \text{(mm)}$$

where

$$I = \frac{t^3}{12}$$

The acceleration required to cause cracking is calculated from:

$$a_{cr} = \frac{8R}{h^2\gamma t}\left[\frac{t}{6} - \Delta_{cr}\right] \quad \text{(g)}$$

B3.4.3
At wall 1/2 cracked determine:

$$M_{1/2} = 2M_{cr} \quad \text{(kN-m/m)}$$

$$w_{1/2} = \frac{16M_{cr}}{h^2} \quad \text{(kN/m)}$$

$$\Delta_{1/2} = \frac{16M_{cr}}{h^2} \quad \text{(mm)}$$

$$a_{1/2} = \frac{8R}{h^2\gamma t}\left[\frac{t}{3} - \Delta_{1/2}\right] \quad \text{(g)}$$

B3.4.4
At wall 3/4 cracked determine:

$M_{3/4} = 2.5\ M_{cr}$ (kN-m/m)

$$w_{3/4} = \frac{20M_{cr}}{h^2} \quad \text{(kN/m)}$$

$\Delta_{3/4} = 16\Delta_{cr}$ (mm)

$$a_{3/4} = \frac{8R}{h^2\gamma t}\left[\frac{5}{12}t - \Delta_{3/4}\right] \quad \text{(g)}$$

B3.4.5
A wall ultimate moment:

$$M_u = R\left(\frac{t}{2} - \frac{a}{2}\right) \quad \text{(kN-m/m)}$$

where

$$a = \frac{R}{0.85f_e} \quad \text{(kN/m)}$$

$w_u = 0$

$$\Delta_u = \frac{t}{2} - \frac{a}{2} \quad \text{(mm)}$$

$a_u = 0$

B3.5
Plot response acceleration, a, (y-axis) against wall displacement, Δ (x-axis) including (0,0).

B3.6
Measure the area under the curve plotted = A_1 (mm x g units)

B3.7
Determine response acceleration to induce wall failure, a_e, from:

$$a_e = \phi\sqrt{2k_{cr}A_1} \quad \text{(g)}$$

where

initial wall stiffness

$k_{cr} = a_{cr} / \Delta_{cr}$

B4 Ultimate strength criterion
The wall shall be designed such that:

$a_e > C_{pi}$

CB4
Reference: New Zealand National Society for Earthquake Engineering 4 June 1996. The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings (Draft for general release for comment for the Building Industry Authority).

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