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DEVELOPMENT OF THE NEW ZEALAND EARTH BUILDING STANDARDS NZS 4297:2020, NZS 4298:2020 AND NZS4299:2020

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SUMMARY

The New Zealand Earth Building Standards NZS 4297, NZS 4298 and NZS 4299 published in 1998 were updated in 2020 to provide for lower density earthen materials and a greater range of earth building techniques and for internal adobe walls fixed to timber framing. Sustainable low energy, low carbon construction methodologies need to be more widely used in New Zealand and around the world. These updated standards incorporate the findings from surveys of the performance of earth buildings following the recent earthquakes in New Zealand. Full scale out of plane and in plane testing of adobe walls and evaluation of the test results provided the basis for incorporating these materials within the new Standards.

BACKGROUND AND CONSTRUCTION TECHNIQUES

Buildings that use earth walls utilise a very environmentally appropriate construction material for houses and buildings on moderate sized plots of land. These building techniques have low embodied energy, low carbon and most of the materials can be returned to the earth at the end of life. In the past earth buildings have provided sustainable living for more than half the people on the planet. Modern use of these materials needs to be more widely implemented.

The earth building techniques most commonly used currently in New Zealand include adobe, rammed earth, cob, pressed brick, rammed earth block and internal adobe veneer.

Adobe is an air dried brick made from a puddled earth mix cast in a mould and which contains a mixture of clay, sand, silt and aggregate. Sometimes contains a small proportion of straw and in New Zealand is usually un-stabilised with cement. In the past 15 years, low density adobes with a mix of clay, sand, silt and a large proportion of wood fibre are being more widely used.

Rammed earth is a monolithic wall panel comprising well graded sandy or gravelly soils, usually stabilised with 5 to 10 percent cement, and compacted between temporary moveable formwork.

Cob is a mix of moist clay, silt and sand placed directly on the wall usually without formwork. The mix can also contain gravel, pumice, straw or other fibres.
Pressed bricks are a mix of clay, silt, sand and aggregate, usually stabilised with cement in New Zealand, and made in a mechanical press either machine or hand operated. The “CINVA ram” is one type of common hand press.

Rammed earth blocks are similar to pressed bricks but the mix of clay, silt, sand and aggregate is stabilised with cement and compacted into the mould with a mechanical tamper.

Internal adobe veneer comprises internal adobe bricks fixed to timber studs to create an internal wall surface.

THE NEW ZEALAND EARTH BUILDING STANDARDS

The first edition of the three standards, NZS 4297, NZS 4298 and NZS 4299, published in 1998, has been a significant resource for building consent authorities determining compliance with the New Zealand Building Code and has provided guidance to designers, builders and others involved in the construction of earth walled buildings in New Zealand and elsewhere in the world. There has been no failure reported to date of any earth building constructed in accordance with the 1998 suite of earth building standards.

The first edition of the three standards was updated in 2020 and the scope enlarged to include a greater range of densities, particularly low density earth building materials, which provide improved thermal performance and improved seismic performance.

NZS 4297:2020 Engineering design of earth buildings

NZS 4297 is intended for use by structural engineers and specifies design requirements and methodologies for earth buildings not exceeding 6.5 m in height for reinforced walls and 3.3 m for restricted applications of unreinforced walls and for earth materials with a dry density of 800 to 2200 kg/m^3. Minimum wall thickness is 250 mm.

NZS 4298:2020 Materials and construction for earth buildings

NZS 4298 defines the materials and workmanship requirements to construct earth walls designed in accordance with NZS 4297 and NZS 4299 and specifies simple low cost material tests for determining the strength, durability and construction requirements of earth wall materials.

NZS 4299:2020 Earth buildings not requiring specific engineering design

NZS 4299:2020 is the earth building equivalent of NZS 3604:2011 Timber-framed buildings but limited to single storey buildings and foundations, floor slabs, earth walls, structural diaphragms and bond beams and including internal adobe brick veneer.

SURVEYS OF EARTH BUILDINGS AFTER THE RECENT EARTHQUAKES

The updated standards incorporate the findings from surveys done after the recent earthquakes in New Zealand to evaluate the performance of earth buildings.

Darfield 2010 Earthquake

A reconnaissance survey of 14 earth walled buildings in the Canterbury area was undertaken following the Darfield 4th September 2010 magnitude 7.1 earthquake as reported in the NZSEE Bulletin *(Morris et al. 2010).* Reinforced earth houses constructed since the 1990's generally performed well. Several older unreinforced earth buildings suffered significant damage and required repair or reconstruction.

Christchurch 2011 Earthquake

A reconnaissance survey of 26 earth walled buildings in the Christchurch area was undertaken following the Christchurch 22 February 2011 magnitude 6.3 earthquake as reported in the NZSEE Bulletin *(Morris and Walker 2011).* This earthquake caused comparable patterns of damage as the Darfield 2010 Earthquake except for unreinforced pressed brick buildings which performed particularly badly. Some older unreinforced rammed earth buildings constructed between 1950 and 1980, all of which had reinforced concrete bond beams and foundations, performed relatively well with only minor cracking.

Kaikoura 2016 Earthquake

A reconnaissance survey of 42 earth wall and straw bale wall buildings in the North Canterbury, Kaikoura and Marlborough areas was undertaken following the Kaikoura 14 November 2016 magnitude 7.8 earthquake. This survey covered a major proportion of the known earth buildings in the region and was done by a team of three engineers experienced with earth buildings, Hugh Morris, Thijs Drupsteen and Richard Walker and an experienced architect of earth buildings Graeme North. Eighteen of the forty-two buildings inspected experienced an estimated Modified Mercali Intensity (MMI) 7 or greater shaking. A summary of these 18 buildings with MMI 7 or greater shaking, and in addition a recently constructed adobe house with MMI 6 shaking, is shown in Table 1. This Table includes their location, wall material, construction date where known, estimated MMI and Damage State.

Table 1. Summary of buildings inspected after the Kaikoura November 2016 Earthquake

Ref No	Location	Wall Material	Constr. Date	MMI	Damage State
4	Greta Valley	Adobe	2011	6	A
5	Leader Valley, Waiau	Rammed earth block	1990s	8	E2
6	South Kaikoura	Rammed earth block	1993	7	C3
7	South Kaikoura	Rammed block veneer	2000	7	C3
8	Hapuku	Strawbale	1999	7	B2
9	Hapuku	Strawbale	1999	7	A
10	Inland Rd, Lyford	Strawbale	2016	8	D1
11	Inland Rd, Lyford	Log	2015	8	E2
20	Clarence River	Strawbale	2000s	9	A
21	Clarence River	Strawbale	2000s	9	A
22	Kekerengu	Cob	1860s	8	C3
23	Kekerengu	Cob	1860s	8	D1
24	Redwood Pass, Seddon	Rammed earth	1991	7	B2
25	Dumgree Road, Seddon	Cob	1840s	7	E2
26	Dumgree Road, Seddon	Cob	1850s	7	D2
27	Altimarloch, Awatere	Cob	1860s	7	E2
28	Welds Hill, Awatere	Cob	1850s	7	E3
30	Medway Rd, Awatere	Cob	1860s	7	E1
31	Upton Downs, Awatere	Cob	1850s	7	E2

Notes: *Damage State* A – None, B – Slight, C – Moderate with cracking damage,
D – Extensive crack damage, E – Very extensive damage with partial collapse.
Scale subdivided further with 3 more serious than 1.

Several old cob buildings in the Awatere Valley in Marlborough constructed in the 1800s, some of which were in poor condition before the earthquake, were subject to estimated MMI 7 and suffered extensive damage. In an area of very high ground accelerations close to a major fault, a reinforced rammed earth block house with very high walls and insufficient wall bracing also suffered extensive damage. The single storey section of this house with low walls and adequate wall bracing was undamaged. A large rammed earth block building with a timber framed upper storey, south of Kaikoura and subject to estimated MMI 7 suffered moderate damage with some cracking of the earth walls which were subsequently successfully repaired by a team of earth building specialists. A reinforced adobe house at Greta Valley constructed in accordance with NZS 4299:1998 and subject to estimated MMI 6 performed well with no damage visible. A reinforced rammed earth house near Seddon subject to MMI 7 shaking performed well with only slight damage. Straw bale houses generally performed well despite experiencing high shaking intensities of MMI 8 and 9. A log house near Lyford with MMI 8 was severely damaged.

Conclusions for Earth Buildings following the New Zealand Earthquakes

Conclusions for the performance of earth walled buildings following the Kaikoura 2016 Earthquake were similar to those for the Darfield 2010 and Christchurch 2011 Earthquakes.

Reinforced earth houses performed well provided the overall wall bracing was adequate and detailing of the reinforcement and connections were generally in accordance with the New Zealand Earth Building Standards published in 1998.

Older unreinforced adobe and cob buildings in areas of strong shaking suffered significant damage and required repair of the walls or reconstruction.

Unreinforced pressed brick buildings performed badly.

Earth buildings with tall gable end walls performed badly in areas of strong shaking particularly if they were unreinforced or had insufficient wall bracing.

Some timber framed buildings with thin pressed brick veneer suffered some damage due to inadequate fixing of the brick ties to the timber frame.

Some limited minor cracking can be expected in most earth buildings following major earthquakes, particularly adjacent to windows and door openings. This cracking is generally of no structural significance if the buildings are provided with vertical and horizontal reinforcing. Cracking was generally more widespread and much more structurally significant in older unreinforced earth buildings.

The earth walls of some older buildings had weakened earth wall material due to damage from wind driven rain which may have contributed to failure of the earth walls.

Well constructed strawbale walled buildings generally performed well following the Kaikoura Earthquake.

Recommendations for Earth Building Standards following the New Zealand Earthquakes

1. Double skin earth masonry walls, and unreinforced earth walls thinner than 250 mm and not supported by timber framing, should be **excluded** from the New Zealand Earth Building Standards.

2. Two storey buildings and unreinforced earth walled buildings should be **excluded** from the revision of NZS 4299 in all earthquake zones.

3. Vertical and horizontal reinforcing should be provided for all earth walled buildings in all earthquake zones.

4. The height of earth walls and particularly gable end walls should be appropriate to the earthquake zone and the maximum wall heights should be clearly specified for each earthquake zone.

5. Earth buildings in earthquake zone 4 should be specifically excluded from the scope of NZS 4299 and shall require specific design.

6. A section should be included in the revision of NZS 4299 for internal adobe brick veneer with maximum wall heights specified for each of the earthquake zones and construction and fixing details clearly specified and detailed.

7. The weather protection provisions in NZS 4299 should apply to earth walled houses specifically designed by a structural engineer.

INTERNAL ADOBE BRICK VENEER

Several houses have been built in New Zealand with internal adobe brick veneer walls and there is a growing demand for internal adobe brick veneer walls which provide the aesthetic, acoustic, hygrothermal and other benefits of earth but place the thermal mass within the insulated envelope. These walls comprise adobe bricks, typically 150 mm wide, well fixed with brick ties to a timber frame. Construction details for adobe brick veneer walls have evolved, particularly over the past ten years, and recommended typical cross-sections and construction details are shown in NZS 4299:2020.

Tests on adobe brick veneer walls were done in Nelson in 2016 as described in *Morris et al. (2017) "Out of plane adobe wall veneer performance from a novel quasi-static and dynamic tilt test"*. The adobe veneer test walls were constructed on a hinged reinforced concrete foundation beam which could be tilted forwards and backwards up to 80 degrees from the vertical. This tilting simulates quasi-static out of plane forces on an adobe brick veneer wall during an earthquake with the greater the tilting from the vertical, the greater the simulated earthquake forces. The adobe brick veneer walls performed well in the tests and much better than expected and provided the information to be able to include internal adobe brick veneer walls in the revised 2020 edition of NZS 4299.

LOW DENSITY EARTH BUILDING MATERIALS

Low density earth building materials are being used increasingly in New Zealand particularly for adobe bricks. The low density adobe bricks have a density of typically 900 to 1200 kg/m^3 compared to the traditional adobe bricks of 1600 to 1800 kg/m^3 and provide better thermal insulation performance and have a lower earthquake bracing demand due to their lighter weight.

FULL SCALE TESTS OF LOW DENSITY ADOBE WALLS

Out of plane tests on wall panels of low density adobe were done in Nelson in 2017 using the same hinged foundations and test procedure used for the out of plane tests on adobe veneer walls in 2016. Details of the tests and test results are reported in *Xiao, Y. (2017) "Full scale testing of out of plane performance of light adobe earth walls for wind and earthquake."* The tilting of the panels was done using a 7 tonne excavator. The test arrangement is shown in Photograph 1. Both the 2.4 m high and 3.0 m high walls performed well and did not fail after being subjected to tilting both ways and then to 80 degrees. At 80 degrees tilt and a loading equivalent of 1 g the deflection of the 3.0 m high wall at mid span was 39 mm. A larger deflection at mid-span was recorded during the tilt test on the 2.4 m high wall than on the 3.0 m high wall. At 80 degrees tilt the deflection was 48 mm. This was partly due to the nuts not being fully tightened at the top of the partly post-tensioned vertical reinforcing for the 2.4 m high wall. Additional loads were applied to the light adobe walls when tilted at 70 degrees using sandbags. Seventy-eight sandbags weighing 15 kg each were spread evenly over the tilted wall to provide a static loading equivalent of 2 g lateral acceleration as shown in Photograph 2. The uniformly distributed load was approximately equivalent to 2.9 kPa. Dynamic loading was applied by shaking the 3.0 m high wall at 80 degrees tilt with one layer of sandbags to produce a loading equivalent up to 2.2 g in an upward direction and 3.1 g in the downward direction. This loading would be equivalent to a very large earthquake with levels of shaking generally greater than experienced in the Christchurch 2011 and Kaikoura 2016 Earthquakes. The 3.0 m high light adobe wall performed well despite failure of one of the timber top-plate connections to the test rig. Only cracks along mortar joints were observed with no failure across the adobe bricks and no dislodged bricks. The full-scale tilt tests showed that light adobe with a density of 1000 kg/m^3 is suitable for the ultimate design loads in earthquake prone areas and very high wind zones provided the adobe wall is reinforced in accordance with the New Zealand Earth Building Standards.

Photographs 1 and 2 – Full scale out of plane tests of low density adobe walls

In plane tests on low density adobe walls were done in Nelson in 2019 by two University of Auckland students supervised by Hugh Morris of the University of Auckland as reported in *Greaney, S.A. (2019) "In plane Seismic Testing of Lightweight Adobe Walls."* Greaney reports that both the low density adobe walls tested showed the ability to respond in a ductile manner, satisfying the seismic load requirements of a structural system with a ductility of at least 2 with flexure being the critical failure mode through extension of the HD12 tension anchor. Greaney reports that the performance of the low density adobe walls exceeded the design bracing capacities nominated in NZS 4299:2020. The 1.36 m long by 2.1 m high wall with a design bracing capacity of 288 bracing units equivalent to 14.4 kN carried a load of 35 kN without collapse before the maximum deformation of the load system was reached. The 1.33 m long by 2.4 m high wall with a design bracing capacity of 216 bracing units equivalent to 10.8 kN carried a load of 27 kN without collapse before the maximum deformation of the load system was reached. The 2.1 m high wall recorded an average ductility of 2.6, and the 2.4 m high wall recorded an average ductility of 2.4. In plane deflection of the walls was identified as a key limitation although in practice the mass of the roof structure will likely result in deflections lower than those observed in the tests.

STRUCTURAL FEATURES FOR NZS 4297:2020

The structural design principles in NZS 4297:2020 are similar to those for unreinforced and reinforced masonry and reinforced concrete. However earth materials have some different characteristics and much lower strengths which need to be considered.

Design strengths

Strengths to be used for the design of earth buildings are provided in NZS 4297:2020. Two grades of earth are specified. Standard Grade has a design compressive strength of 0.5 MPa for earth wall density of 1400 to 2200 kg/m^3, and 0.35 MPa for earth wall density of 800 to 1400 kg/m^3. These strengths can be obtained by well constructed earth building materials and verified with a small amount of testing and as specified in NZS 4298:2020. Special Grade requires more testing so that higher design strengths up to 10 MPa may be used.

Structural ductility factor and structural performance factor

The structural ductility factor in NZS 4297:2020 is 1.25 for reinforced walls designed for nominal ductility and 1.0 for unreinforced earth walls and elastically responding reinforced earth walls. The structural performance factor is defined as equal to 0.9. These factors are more conservative than those in the NZS 4297:1998 which specified a structural ductility factor of 2 for reinforced walls and a structural performance factor of 0.67.

STRUCTURAL FEATURES FOR NZS 4299:2020

Earthquake Zones and Site Subsoil Classification

The earthquake zones and site subsoil classification for determining the wall bracing demand are the same as both *NZS 3604:2011 Timber-framed buildings* and *NZS 4229:2013 Concrete masonry buildings not requiring specific engineering design*. Earth buildings in earthquake zone 4 with Z > 0.46 are outside the scope of NZS 4299:2020 and require specific design.

Height of Earth Walls

The maximum height of earth walls measured from the top of the concrete foundation to the underside of the top plate or bond beam is 3.05 m in New Zealand earthquake zones 1 and 2, and 2.75 m in zone 3. The maximum height of gable walls is 3.6 m in zone 1, 3.3 m in zone 2 and 3.05 m in zone 3.

Reinforced Earth Walls

All earth walls within the scope of NZS 4299:2020 are required to have both vertical and horizontal reinforcing with the exception of internal adobe brick veneer which is required to be well fixed to timber framing. The provision for reinforcing is more stringent than the 1998 edition which allowed for unreinforced earth walls in earthquake zone 1.

Site Earthquake Factor

The site earthquake factor for the calculation of the earthquake bracing demand provides for three different earthquake zones and three different site subsoil classes with soil classes D and E combined similar to NZS 3604:2011. The site earthquake factors vary from 0.30 for an earth building on soil classes A and B and in earthquake zone 1 to 1.09 for an earth building on soil classes D and E in earthquake zone 3. The structural ductility factor of 1.25 and structural performance factor of 0.9 were used to calculate the site earthquake factor. With reference to the in-plane testing done and reported by *Greaney (2019)* the structural ductility factor of 1.25 is considered conservative but appropriate. A structural ductility factor of 2 was used for the calculation of the earthquake bracing demand in the 1998 edition of NZS 4299.

Bracing Demand

The design bracing demand for each direction in the building is the greater of either the wind or earthquake bracing demands. The earthquake bracing demand is usually greater than the wind bracing demand for earth buildings except for some buildings with low density earth walls in very high wind zones and low earthquake zones.

The wind bracing demand is determined using the procedure in NZS 3604. The earthquake bracing demand is determined from the site earthquake factor, building and wall and roof dimensions and areas and earth wall density. A step by step procedure is specified in NZS 4299:2020 and a worked example is provided in the Appendices. The design approach is more procedural than in NZS 4299:1998 and NZS 4229:2013 due to the wide range of densities of earth wall materials included in the scope of NZS 4299:2020 and the provision for different earthquake zones and site subsoil classes.

Bracing Capacity

The bracing capacities of the heavy reinforced earth walls in NZS 4299:2020 with a density of 1400 to 2200 kg/m^3 are the same as those used in NZS 4299:1998. The bracing capacities for low density reinforced earth walls of 800 to 1400 kg/m^3 are specified to be 80 percent of the bracing capacities of reinforced heavy earth walls. For example a 2.4 m high and 1.2 m long low density reinforced earth wall is assigned a bracing capacity of 210 bracing units equivalent to 10.5 kN. With reference to the results of the full scale in plane testing of low density adobe walls done in 2019, as documented by *Greaney (2019),* the bracing capacities specified in NZS 4299:2020 are considered appropriate.

Foundation and Wall Construction Details

Foundation and wall construction details that have been developed and proven in New Zealand over the past 30 years including the details for vertical and horizontal reinforcing are provided in NZS 4299:2020.

Structural Diaphragms and Bond Beams

Roof and ceiling structural diaphragms supporting the tops of earth walls are an essential feature for the good performance of earth buildings during earthquakes and high winds. NZS 4299:2020 provides the requirements and typical construction details for structural diaphragms and for timber and reinforced concrete bond beams.

Internal Adobe Brick Veneer Walls

Provision is made in NZS 4299:2020 for internal adobe brick veneer walls up to 3.6 m high in earthquake zones 1 and 2 and up to 3.2 m high in earthquake zone 3. The wall bracing design for timber framed walls enclosing adobe brick veneer walls shall be in accordance with NZS 3604. The procedure for determining the additional wall bracing demand for the adobe veneer walls and the additional requirements for the wall bracing are specified in NZS 4299:2020. The site earthquake factors for calculating the additional wall bracing demand for adobe brick veneer walls are the same as those used for calculating the earthquake bracing demand for the reinforced earth walls assuming nominal ductility.

A structural performance factor of 0.7 and a ductility factor of 2 were used for the design of the timber studs for the adobe veneer walls. This is conservative compared to the design of studs for NZS 3604 where a structural performance factor of 0.7 and a structural ductility factor of 3.5 were used as described in *BRANZ (2013), Engineering Basis of NZS 3604*.

For simplicity the most conservative Soil Class E was used for the derivation of the horizontal design coefficient for the design of the studs for the calculations for the tables in NZS 4299:2020 which specify the sizes and spacing of studs for different wall heights and two different adobe veneer wall masses.

LIGHT EARTH METHOD AND STRAWBALE WALLS

NZS 4299:2020 includes new informative appendices intended to provide guidance on the placement and finishing of straw bales and light earth method (LEM) materials within specifically designed timber walls. The number of homeowners wanting to build with straw bales or LEM materials in New Zealand is growing. These methods have almost a hundred years of history in Europe and USA and modern styles are increasingly used overseas.

CONCLUSIONS

The revised New Zealand earth building standards incorporate the experience gained from the construction, performance and evaluation of earth buildings since the publication of the first world leading suite of earth building standards in 1998. These revised standards provide for an increased variety of earth building techniques and a range of densities of earth wall materials from dense rammed earth walls with a density up to 2200 kg/m^3 to low density adobe bricks with a density of 800 kg/m^3. Earth wall materials require minimal processing, have low toxicity and are available locally. The revised earth building standards published in 2020 will enable the use of a range of local earthen materials with very low embodied energy within a decarbonising building industry.

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