SEISMIC DESIGN OF RAMMED EARTH BUILDINGS IN NEW ZEALAND

Paul Jaquin

eZED, Queenstown, New Zealand
pauljaquin@gmail.com

Introduction

This paper presents an approach to the seismic design of rammed earth buildings, as adopted by the author in New Zealand. The approach covers derivation of the seismic loading and assessment of the ductility and system behaviour to determine the demands on the structure. The capacity of the rammed earth elements in their in- and out-of plane direction is then described, together with the design of bond beams and foundations.

The merits of this analysis approach are discussed, together with opportunities for refinement and requirements for further research.

Stabilised rammed earth and reinforcement

Structural philosophy

Rammed earth buildings in New Zealand are typically designed with solid reinforced rammed earth walls with vertically running steel reinforcing bars placed centrally in the wall, reinforced concrete foundations and reinforced concrete bond beams which also act as lintels. The rammed earth buildings discussed in this paper are typically cement stabilised.

Vertical loads such as the weight of the roof, are resisted by the walls in direct compression and by the reinforced concrete bond beam acting as a lintel over window and door openings.

Lateral loads such as earthquake and wind loads present a horizontal force to the building and are resisted in the following way:

The reinforced rammed earth walls span vertically between the foundations and the bond beam, transferring the horizontal force to the bond beam. The bond beam then spans horizontally to return rammed earth walls. These walls act in their plane as shear walls to resist the overturning forces, and transfer a push-pull to a foundation beam (Figure 1).

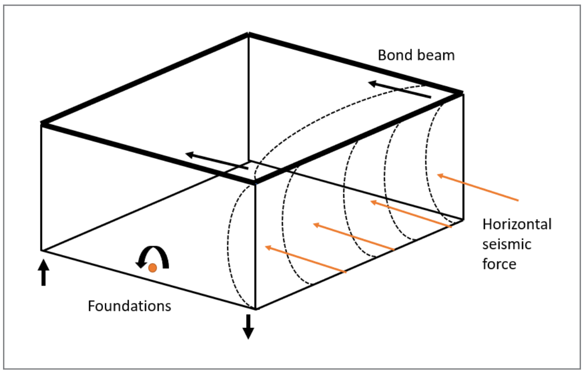

Figure 1. Lateral load resisting system for rammed earth buildings.

Seismic demand

The seismic demand force is calculated by assessing the seismic weight of the building and then multiplying it by an appropriate lateral force coefficient. This is similar in principle to f = ma, force is mass x acceleration; Newton's second law.

The seismic weight is made up of the permanent and variable loads on the structure. The permanent loads of the structure comprise the floor, roof and walls and the variable loads on the structure comprise the weight of people and furniture inside the building.

The lateral force coefficient is determined by reviewing the building's earthquake zone factor (Hazard Factor), the time period of its response, and the soil type, and proximity to local faults.

The Hazard Factor is the relative level of seismicity for a building's location in New Zealand. The whole of New Zealand has been mapped and so every proposed building site has an expected ground acceleration.

To determine the factor, a number of metrics are reviewed including known faults, return periods and expected magnitudes of earthquakes.

The seismic demand in the New Zealand codes is typically limited to horizontal ground accelerations. Vertical ground accelerations are only taken into account in specific circumstances.

One issue with rammed earth is that it is relatively heavy and therefore presents a higher weight compared to lighter weight equivalent structures e.g. timber. There is therefore more force on the building when compared to a lighter weight equivalent structure.

Ductility

In rammed earth reinforced with steel, ductility allows the reduction of the engineering demand of forces on a building because of the presence of ductile responding elements which provide energy dissipation in an earthquake.

Whilst it is possible to design reinforced rammed earth as a ductile structure, there is probably currently, insufficient research to enable this type of design. This would allow for a more efficient and potentially less expensive building solution.

Typically in New Zealand, buildings are designed following capacity design principles, which aim to ensure that a building avoids collapse in a design level earthquake by undergoing controlled ductile behaviour.

This involves designing the structure to behave in a ductile manner at certain locations therefore protecting other elements.

Brittle elements such as glass, cast iron, and unreinforced rammed earth have a limited capacity for deforming without losing strength. Put simply, they break when they are bent.

Ductile elements such as steel, and reinforced concrete and reinforced rammed earth can withstand repeated displacement without a significant loss of strength. E.g. they will bend and deform but will not break. In bending and deforming, the energy of the earthquake is absorbed by the building and it may be that some elements destroy themselves, in order to protect the rest of the structure.

In reinforced rammed earth and reinforced concrete the yielding of the steel is used to provide ductility and the energy dissipation necessary to protect from collapse. (BRANZ, 2022)

Due to a lack of significant testing around the behaviour of rammed earth under cyclic loads, the ductile nature of reinforced rammed earth is not fully adopted and elements are designed for an elastic response.

Element design

Rammed earth walls out of plane, in plane, foundations and bond beams are the elements. Each of the elements are described and discussed below.

Out of plane design of the walls

Out of plane design is the design of the wall to resist loading perpendicular to the plane of the wall.

The rammed earth walls are typically a minimum of 350mm (14 inches) thick, with a central reinforcing bar, spaced at around 600mm (24 inches or 2 feet) centres. The steel bars are ribbed, and usually made from galvanised steel.

The wall acts as a reinforced beam spanning vertically between the foundations and the bond beam. When a load is applied perpendicular to the plane of the wall, this puts the central bar in tension and the face of the rammed earth wall into compression. The wall is designed in the same way as a reinforced concrete or masonry beam.

There is an unreinforced section between the vertical bars and the rammed earth spans horizontally between those vertical column elements. Since the vertical central reinforcement is anchored at the foundations and bond beam level, the tensile action provided by the central bar prevents the outside

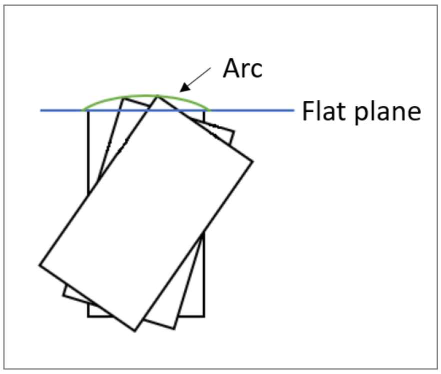

Figure 2. Arc described by point on rectangle, when rectangle topples.

corners of the wall from lifting, providing additional out of plane capacity which is not accounted for in the design. Figure 2 shows this action, as the rectangle which represents the wall is seen to topple and the top corner describes an arc during this process. The arc is prevented from being created because the bond beam restrains the wall from overturning via tension in the bars.

This failure mode is limited by the compression capacity of the rammed earth at the interface of the bond beam and the rammed earth. Due to the relatively weak nature of the rammed earth, care must also be taken to ensure that the wall is not over reinforced in the out of plane direction, which would lead to a brittle rather than ductile response.

The New Zealand earth building code (NZS4298) also recommends that due to the potential for erosion and loss of thickness of wall, the walls be designed for a 5% reduction in thickness.

In plane design of the walls

The lateral resistance of the building is provided by the in-plane resistance of the reinforced rammed earth, with the seismic loads transferred via the bond beam to the head of the rammed earth walls in plane. The walls are designed in a similar manner to concrete or masonry shear walls, with the overturning moment resisted by the end bars acting in tension and the toe of the rammed earth acting in compression.

The ultimate capacity of the wall is determined by the yield strength of the end bar, with the overturning moment assessed by reviewing the strain distribution along the length of the wall. Occasionally the walls can be designed as T or L shapes with the reinforcement in the flange or stem appropriately sized for alternating directions.

Bond beam design

A reinforced concrete bond beam is provided at the head of the walls to transfer the horizontal seismic force into the return walls. The bond beam acts in the horizontal plane spanning between return walls. The bond beam is usually the same width as the wall. (350mm, 14 inches), and the span is usually limited to a room size of around 6 metres (approx. 20 feet). Roof trusses are usually used and are fixed down to the bond beam. The bond beams also act as lintel over the window openings and are reinforced accordingly.

Foundation design

Reinforced concrete foundations are typically used. The foundation is typically the same width as the rammed earth wall and integral to a concrete floor slab. The reinforcement is sized to resist the moment provided by the overturning force from a wall across an opening or at adjacent wall elements.

Due to the relative heavy weight of the rammed earth and the high seismic loads, the overturning moments induced in the foundation sometimes require a reasonable size of concrete foundation beam. The beam depth can also be defined by the suitable level for adequate bearing, frost heave or expansive soils.

In some instances, earthquakes can cause liquefaction of the ground, such as occurred in the Christchurch, New Zealand earthquakes of 2010/2011. Liquefaction can cause water to come to the ground surface inducing voids below the ground which can lead to ground surface settlement. This can be somewhat mitigated by ground improvement measures such as gravel rafts or stiffened foundations. In the case of rammed earth buildings any liquefaction causing differential settlement would be hard to mitigate and therefore building without ground improvement measures in liquefaction-prone areas is not usually undertaken.

Open questions

This paper describes a conventional approach to rammed earth design based on established engineering principles. However these principals have typically been developed for reinforced concrete and masonry and there is a much smaller body of knowledge relating to rammed earth.

The following items are in need of review and could enable more efficient and appropriate rammed earth design.

Bond between the rammed earth and reinforcing bar – the rammed earth is typically cement-stabilised. However, the New Zealand earth building code allows for reinforcement of unstablised rammed earth. Where the rammed earth is unstabilised it is difficult to understand the relationship of the bond between the rammed earth and the rebar. Not a lot of testing has been done in this area. Originally, unstabilised rammed earth walls had the propensity to shrink vertically and therefore it has been proposed that the reinforcing bars be sleeved in PVC pipe, to ensure there is no bond between the rammed earth and the rebar. This changes the stress block, however, the design still provides a couple to resist the overturning moment. The strength of the bond between the rammed earth and reinforcing bar has not been subject to as much testing as for concrete and therefore the development length for plane bars and hooks within rammed earth is not necessarily the same as for concrete.

The fact that we use cement stabilised rammed earth with a compressive strength of around 7MPa would suggest that the behaviour of rammed earth would be similar to that of low strength mortar however, the behaviour of lower strength unstabilised rammed earth may differ.

Corrosion of reinforcement - Steel reinforcement in reinforced concrete is typically protected from corrosion by a depth of cover to the reinforcement. This depth ranges from 50mm to 75mm (2 – 3 inches) depending on the environment. Stabilised rammed earth is considered to be slightly more susceptible to water ingress and therefore the reinforcement may require protection from corrosion. This can be provided by galvanized reinforcing bars, however, given the cement content and strength of the stabilised rammed earth and the large amount of cover, to the reinforcing bars, the requirement for galvanised reinforcing bars could be questioned.

Full scale seismic testing – There has been some testing of rammed earth under seismic loading, particularly assessing the displacement response under cyclic loading. Further testing of full scale walls is to be encouraged.

References

BRANZ. (2022, July 31). *Capacity Design*. Retrieved from Seismic Resiliance : seismicresiliance.org.nz

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ASTM E2392/E2392M-10 2016 Standard Guide for the Design of Earthern Wall Building Systems

New Zealand Standard NZS1170.5 Structural Design Actions – Earthquake Actions – New Zealand

Paul Jaquin *is a structural and geotechnical engineer in Queenstown for eZED, working on Sustainable Building projects around Otago, Southland and wider New Zealand. Paul is also a highly cited academic, with specific expertise in rammed earth construction and unsaturated soil mechanics, and has published a number of books and papers relating to earth construction.*