Manual for Seismic Resilient Construction and Retrofitting of Rammed earth and Stone masonry Houses in Bhutan

March 2023

Project on Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan
in the framework of SATREPS Project

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Bhutanese buildings are traditionally constructed using rammed earth, stone masonry, and adobe masonry, integrated timber members. The majority of households in the country continue to reside in such traditional houses. Furthermore, almost all new house constructions in rural areas are carried out using traditional materials and techniques. Hence, it is imperative to understand that such traditional houses are not just a representation of our unique architecture but also are socially and economically viable for the community.

However, due to its location in the Himalayan region, Bhutan is inherently vulnerable to natural disasters, especially earthquakes. The last two earthquakes of 2009 and 2011 caused significant damage to a remarkable number of traditional houses. These events have raised serious concern regarding the seismic performance of those structure. Since then, the Royal Government of Bhutan has initiated several programs and research projects aimed at improving seismic strength of traditional structure which is crucial to develop the disaster resilient society.

Our joint research project titled*" Evaluation and Mitigation of Seismic Risk for Composite Masonry Buildings in Bhutan"* conducted the first ever scientific experiments, including the static loading tests on full-scale houses as well as the shaking table tests on various types of specimens. The project was jointly implemented by the experts from RGoB and Japanese universities, in the framework of the Science and Technology Research Partnership for Sustainable Development (SATREPS) supported by the Government of Japan (JICA & JST).

This *Manual for Seismic Resilient Construction and Retrofitting of Rammed earth and Stone masonry Houses* is the key output of the project, which was developed based on the results of the above-mentioned scientific experiments conducted in Bhutan. The manual provides practical and easy-to-follow advice for building earthquake-resistant traditional Bhutanese houses.

It is hoped that this manual will play an important role in helping to improve seismic resilience of traditional rammed earth and stone masonry houses and contribute to the safe society.

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Foreword

In Bhutan, except for the capital and some urban areas where reinforced concrete buildings with up to five stories above ground and brick buildings with up to two stories above ground are found, most private houses and public facilities are built by non-engineers using Rammed earth or Random stone masonry. The recent statistics by the National Statistics Bureau of Bhutan show that 66 % of households in the country, especially 83% of households in rural areas, live in such traditional buildings. However, these traditional structures are vulnerable to earthquakes. In the past, earthquakes in eastern Bhutan (September 21, 2009, M6.1) and the India-Nepal border region (India-Sikkim earthquake, September 18, 2011, M6.9) have destroyed or partially destroyed many of these rammed earth and stone masonry buildings in Bhutan.

Thus, most of the world's human suffering from earthquakes is caused by the collapse of fragile houses made of earth and stone in developing countries. Therefore, countermeasures against this problem are a top priority. On a global scale, there is a general awareness among the people in Bhutan regarding measures to improve the seismic performance of existing structures. However, there are no guidelines for traditional Bhutanese buildings. Hence, they tend to follow overseas guidelines such as Indian Standards.

Here, to mitigate the possible future earthquake disaster in Bhutan, our SATREPS (Science and Technology Research Partnership for Sustainable Development) project focuses on developing and disseminating effective earthquake resistant. Guidelines for traditional buildings based on experimental work and structural analysis and further knowledge gained through seismic observation and social and economic survey of Bhutan. This will be an indispensable support to scientific and technological development.

This manual for seismic resilient construction and retrofitting of rammed earth and stone masonry houses consists of five chapters.

- Chapter 1 shows graphically new seismic resilient houses such as wall layout and configuration, doors and windows, and reinforcement measures.
- Chapter 2 provides three model plans of the seismic resilient houses recommended by the SATREPS project.
- Chapter 3 deals with the construction procedure by using pictograms and figures from material selection, foundation, reinforced concrete (RC) band and post, stonework and ramming earth, and upper structures. Here, a checklist is also provided.
- Chapter 4 covers the retrofit of an existing house.
- Chapter 5 presents structural calculations for rammed earth and stone masonry houses in-plane and out-of-plane directions.

I hope this manual is useful to guide for mitigating the seismic risk of rammed earth and stone masonry houses in Bhutan.

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5. Mr. Pema, Executive Engineer, Ministry of Home Affairs
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7. Mr. Kunzang Tenzin, Deputy Executive Engineer, Ministry of Home Affairs
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Chapter 1. Seismic Resilient House

1.1. Wall Layout and Configuration

1.1.1. Walls should enclose the space. Don’t keep the wall open-ended.
1.1.2. Longer wall needs a cross wall at 18 feet/ 5.4 meters or less.
1.1.3. House with cross walls creating a box-like effect has higher seismic resistance.
1.1.4. House without cross walls and with large openings has weaker seismic resistance.
1.1.5. Height of the floor shall be less than 10 feet/ 3 meters.

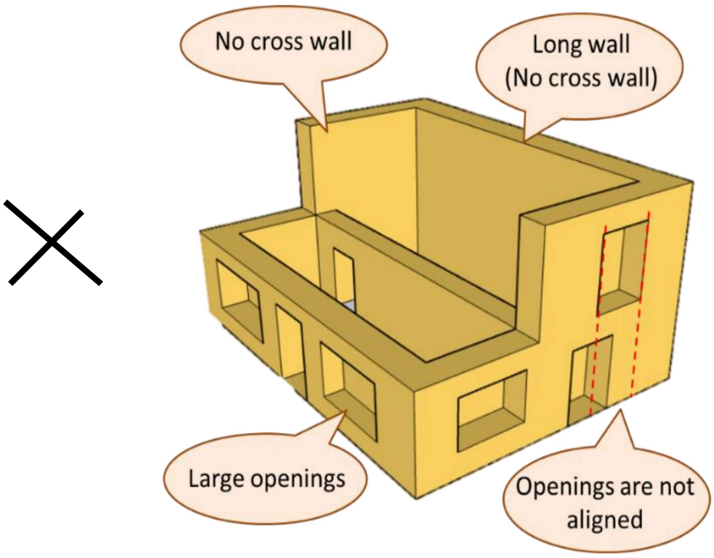


Figure 1. House with inappropriate wall layout and opening.

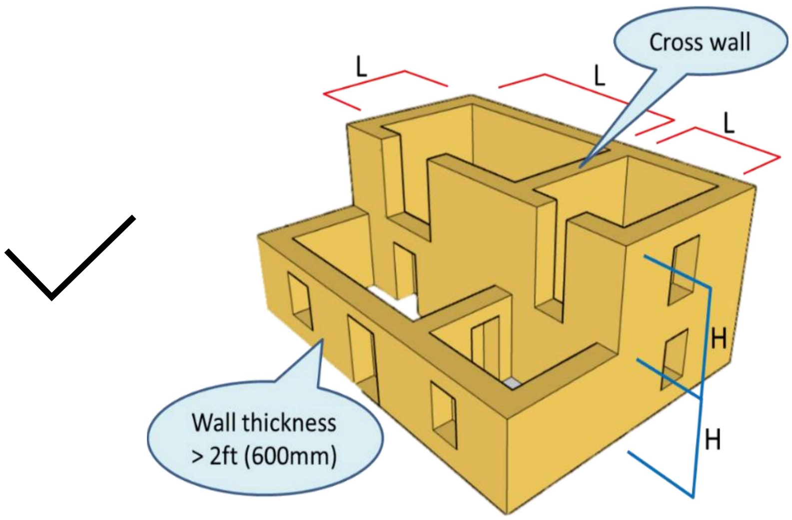


Figure 2.House with appropriate wall layout and opening.

1.2. Doors and Windows

1.2.1. Opening width (W) of windows and doors in the wall should be kept minimal.
1.2.2. Larger W reduces the seismic strength of the house.

W/L Measurement of W

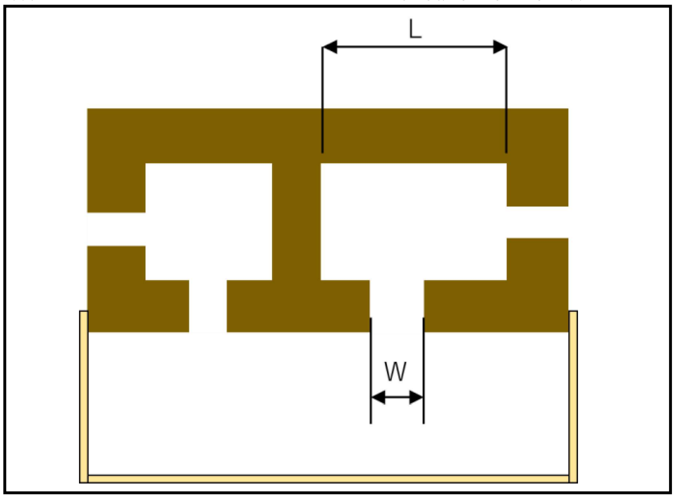


Figure 3. Floor layout with wall and opening.

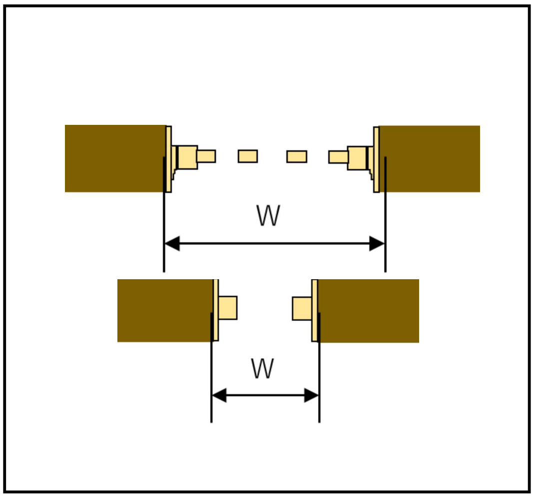


Figure 4. Window opening

1.3. Reinforcement Measures

Adaptation of the reinforcement measures shown in the below figure is recommended.

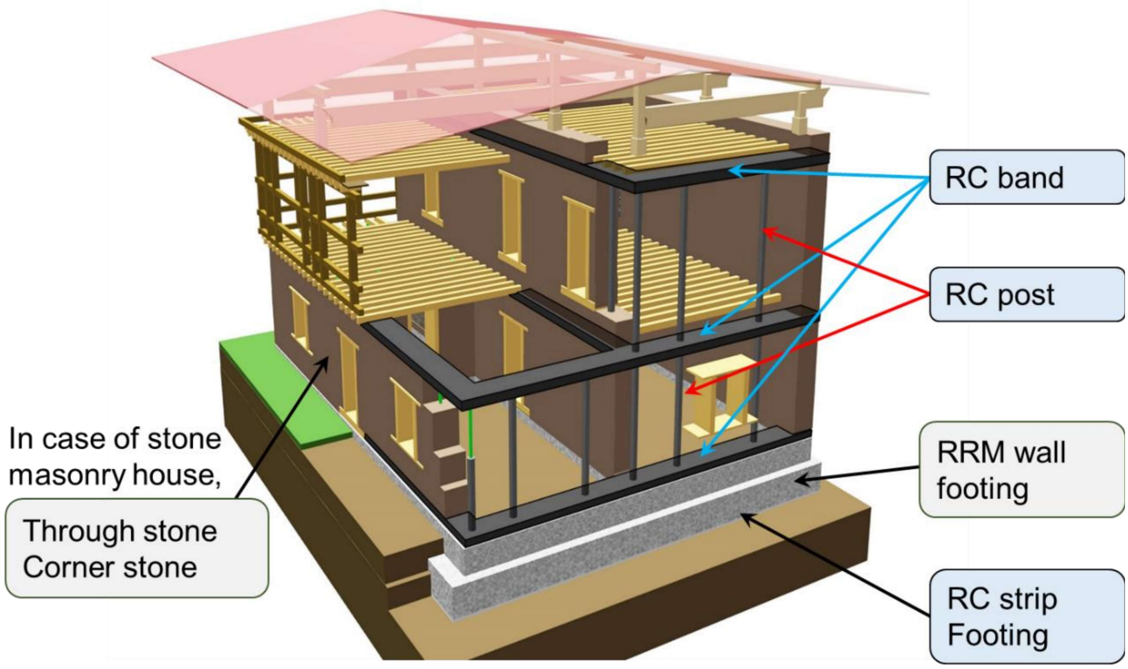
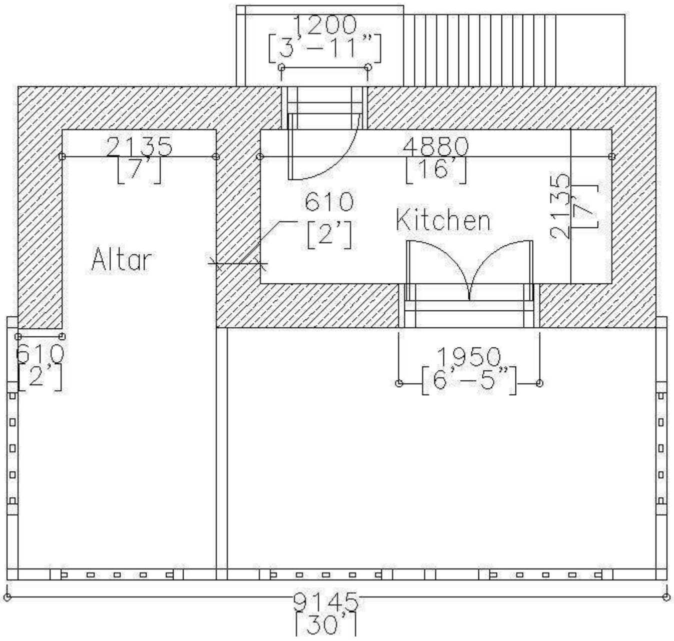


Figure 5. Cross section of Building - (By. Kunzang Dorji, Graphics Designer, Ministry of Home Affairs)

Chapter 2. Model Plans of the Seismic Resilient House

The houses that are built according to the following three plans with the reinforcement specified in chapter 3 are seismic resilient, proven by the structural calculation and the experiments implemented by the SATREPS-Bhutan project. The seismic resilient level in the above context means it fulfills the seismic demand of zone V as per clause 6.4.2 of IS 1893 (Part1): 2016.

2.1. Plan.1



Floor height:
GF:3.0m
1 F:3.0m

Figure 6. First Floor Plan

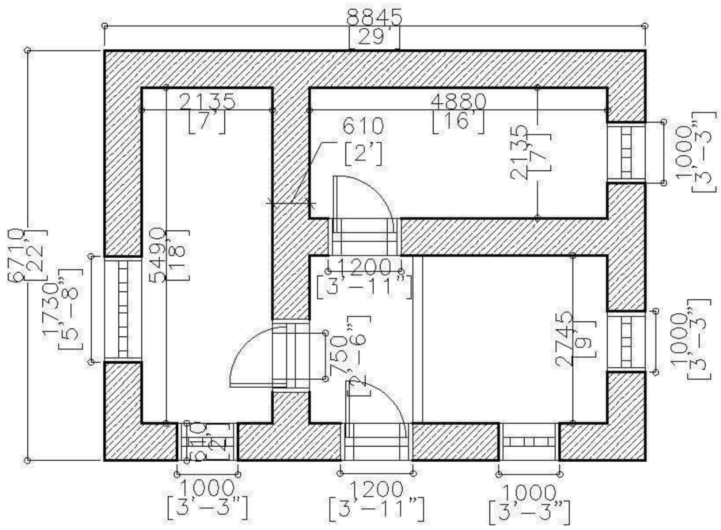


Figure 7. Ground Floor Plan

2.2. Plan 2.

Floor height:
GF:3.0m
1 F:3.0m

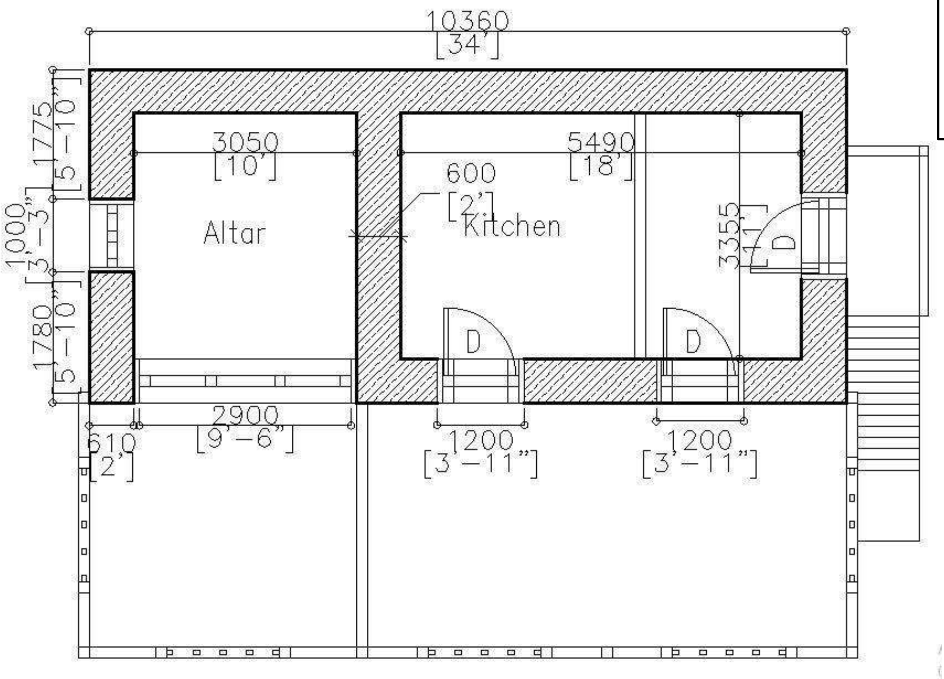


Figure 8. First Floor Plan.

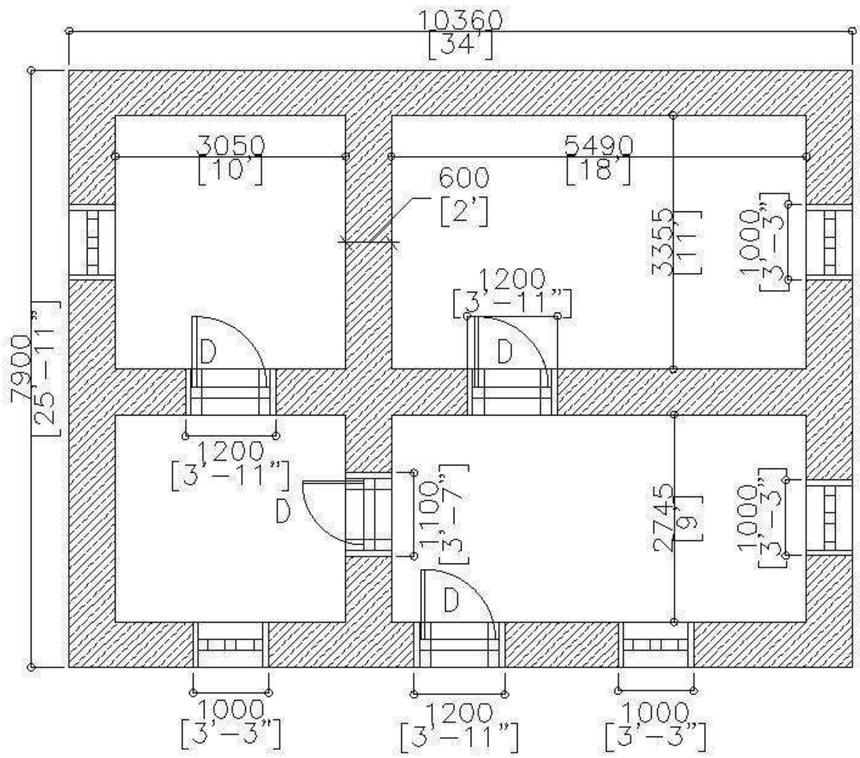


Figure 9.Ground Floor Plan

2.3.Plan 3.

Floor height:
GF:3.0m
1 F:3.0m

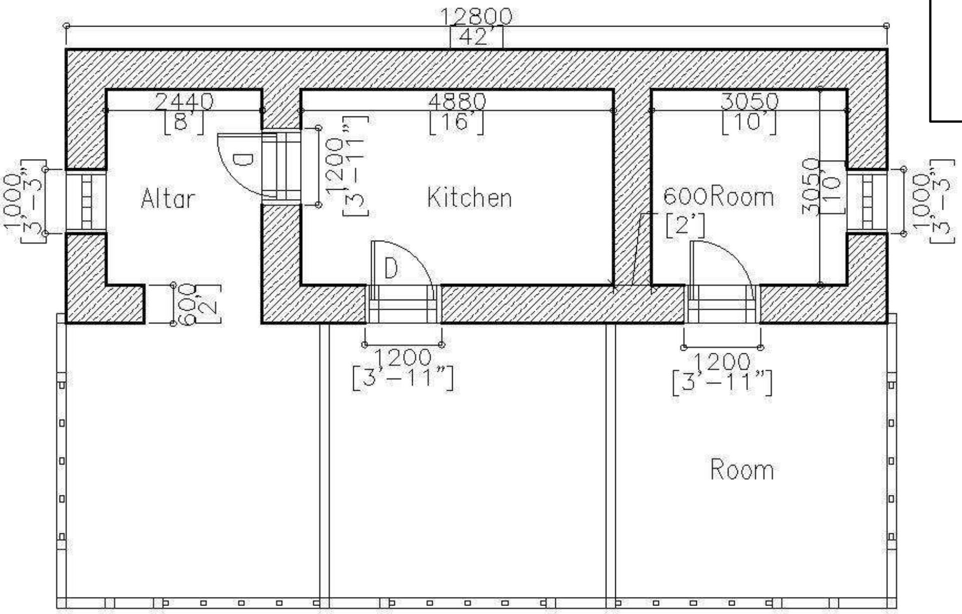


Figure 10. First Floor Plan.

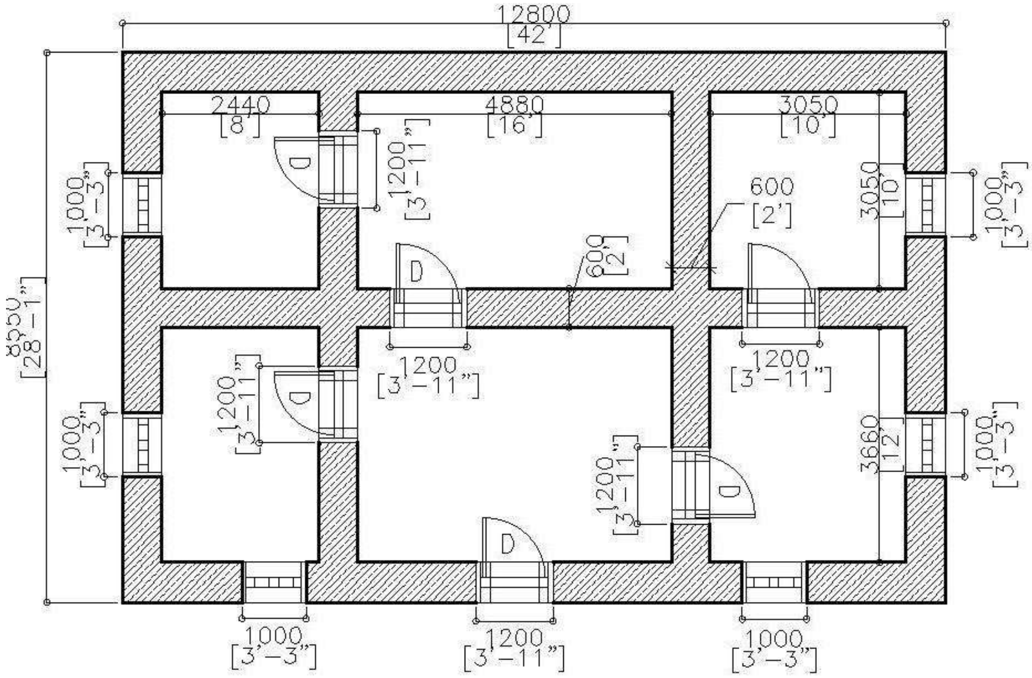


Figure 11. Ground Floor Plan

Chapter 3: Construction Procedure

3.1. Material

3.1.1. Stone

i. Gneiss, Quartzite, Granit, and Limestone are recommended for construction.
ii. Don't use a round shape of stones, and if river stone is used, dress it in shape.

3.1.2. Cement mortar

i. Thoroughly mix the dry ingredients of cement 1 and sand 3 in volume, before adding water.
    a. Use fresh and lump-free cement.
    b. Use sand of particle size 1-2mm. Don't use sand with large amounts of silt or clay.
    c. Measure the materials using a measured cubic-foot box to mix in the proper mix ratio.
ii. Mix potable and debris-free water to (i).
    a. Water quantity shall be 0.5 times the cement quantity (water/cement ratio: 0.5)
    b. Do not add water running, but from a container to avoid adding an excess amount of water.

3.1.3. Soil for ramming

i. Remove pebbles larger than 1 cm from the soil.
    a. If the soil is too dry, add water little by little from a container to avoid adding an excess amount of water.
    b. If the soil is too clayey, add sand appropriately.
ii. Test the soil to ensure its quality.

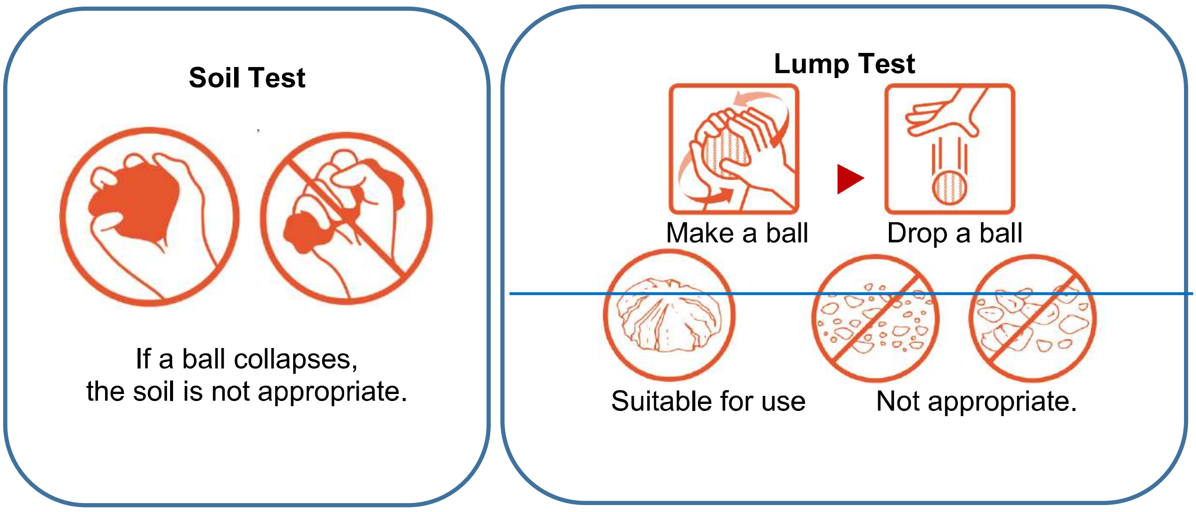


Figure 12. Soil test for rammed earth wall

3.1.4. Concrete (M20)

i. Maintain the mix proportion of cement, sand and aggregate as 1: 1.5: 3, before adding water.
   a. Use fresh and lump-free cement.
   b. Use sand of particle size 1-2mm. Don't use sand with large amounts of silt or clay.
   c. Use aggregate of high gradation, tough, uniform texture and colour, and free from mud and other foreign materials.
   d. Measure the materials using a measured cubic-foot box to maintain the mix ratio in volume.
   e. Add clean and potable water to the dry mix.
   f. Water quantity shall be 0.5 times the cement quantity (water/cement ratio: 0.5)
   g. Do not add running water, but from a container to avoid adding an excess amount of water.
   h. To maintain the consistency of the concrete mix, carry out the slump test (Figure13).

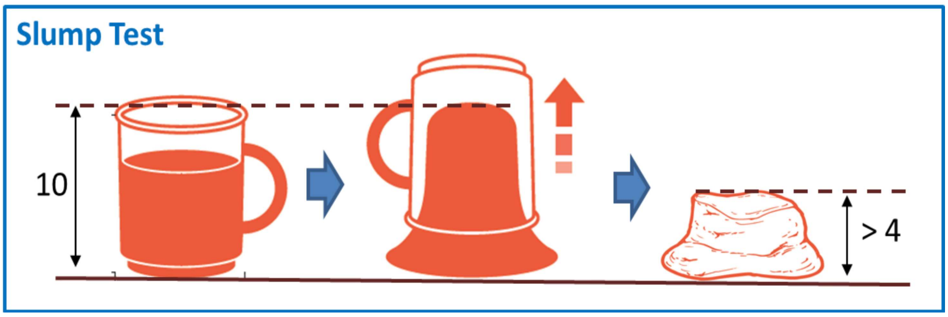


Figure 13. Workability test for concrete

3.1.5. Steel rebar

i. Use steel rebar of yield strength 500 MPa or higher (HYSD).
ii. Plain bars should not be used.

Figure 14. Deformed rebar

3.2. Foundation

3.2.1. Earthwork

i. The foundation of the building should be laid on stable ground.
ii. Minimum depth of 3 feet should be provided from the natural ground level.
iii. The width of the foundation shall be twice the thickness of the wall.
(When the wall thickness is 2 feet/ 600mm, the foundation shall be 4 feet/ 1.2m wide)

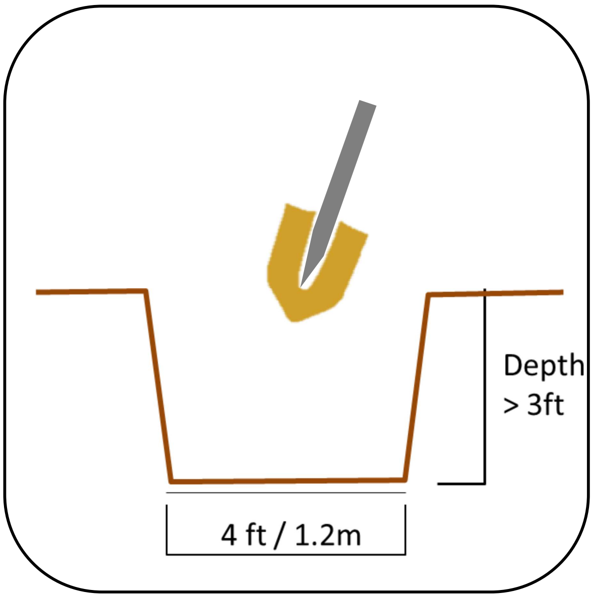


Figure 15. Earthwork for foundation

3.2.2. Reinforced Concrete (RC) strip footing

i. Provide stone soling of the thickness of 6 inches/ 150 mm.
ii. Place 3 nos of 12mm diameter longitudinal bar with 8mm diameter distribution bar at 8 inches/ 200 mm c/c.
Maintain minimum concrete cover of 3 inches/ 75mm.
iii. Place the vertical rebar 12mm diameter with the development length not being less than 1.5 feet/ 450mm at:
- L corner
- T junction
- 8 inches/ 200 mm from the opening, and
- The interval of 4 feet/ 1.2m as it necessitates.

iv. Cast M20 grade concrete with a thickness of 7.2 inches/ 180mm, and cure for a week at least.

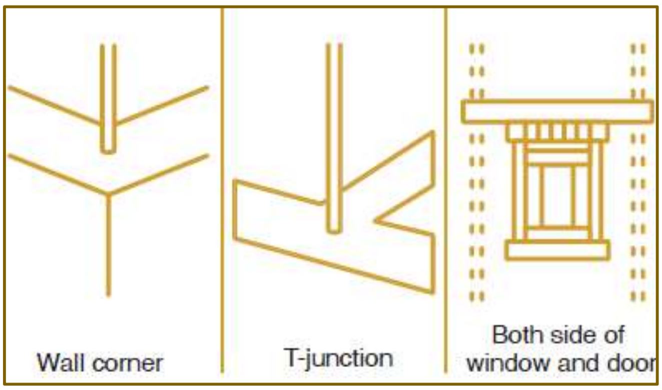


Figure 16. Vertical reinforcement location

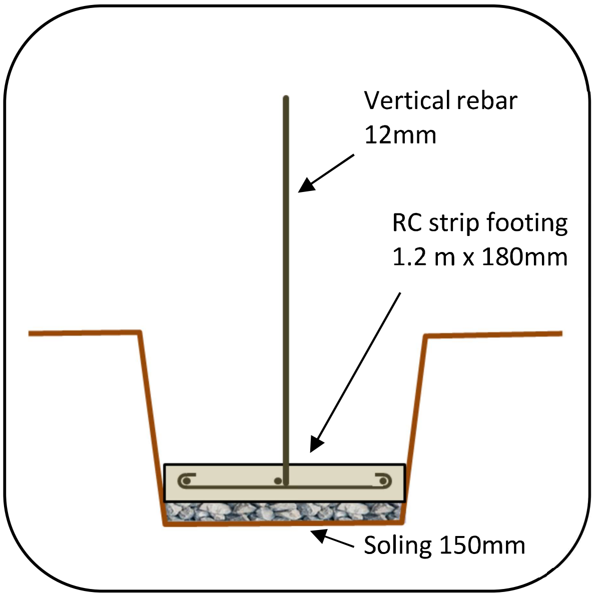


Figure 17. Vertical reinforcement in RC footing

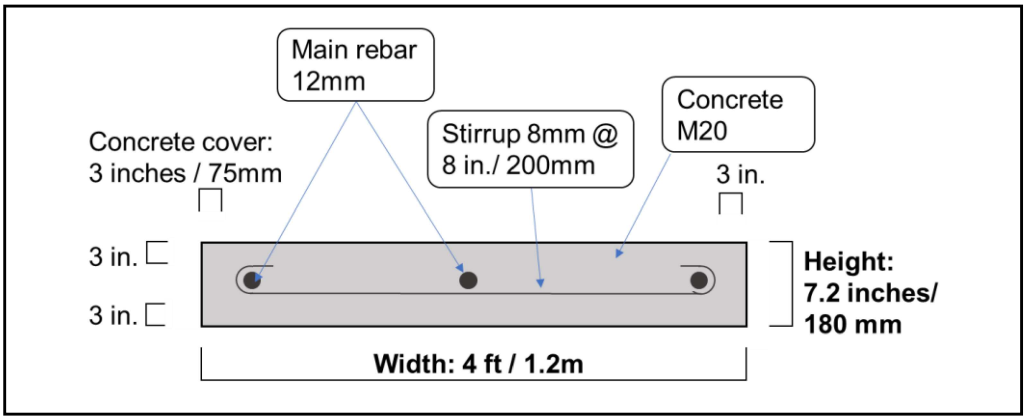


Figure 18. RC strip footing sectional detail.

3.2.3. Random Rubble Masonry (RRM) wall footing.

i. Place a PVC pipe or any other suitable pipe of diameter 90 to 110 mm around the vertical rebar.
   a. Ensure that the vertical rebar is centrally placed in the pipe in order to maintain enough concrete cover for the rebar.

ii. Lay the stones around the PVC pipe in a single lift.

iii. Cast M20 grade concrete inside the pipe.
   a. Use a tamping rod to properly fill the pipe with concrete.

iv. Slowly pull out the pipe while tamping with the rod.

Repeat the same process (step i to iv above) until the construction of the RRM wall footing of 3 feet/ 900mm wide and 1.5 feet/ 450mm high is complete.

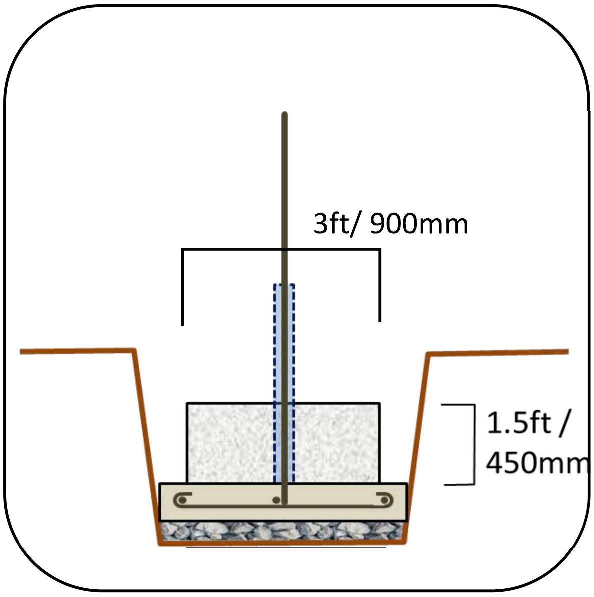


Figure 19. Sectional detail of RRM wall footing

v. On the footing, construct a stone wall following the same process (step i to iv above) up to the plinth level.

vi. In case of rammed earth construction, the grove for ju-shing shall be kept at the required interval just below the RC band.

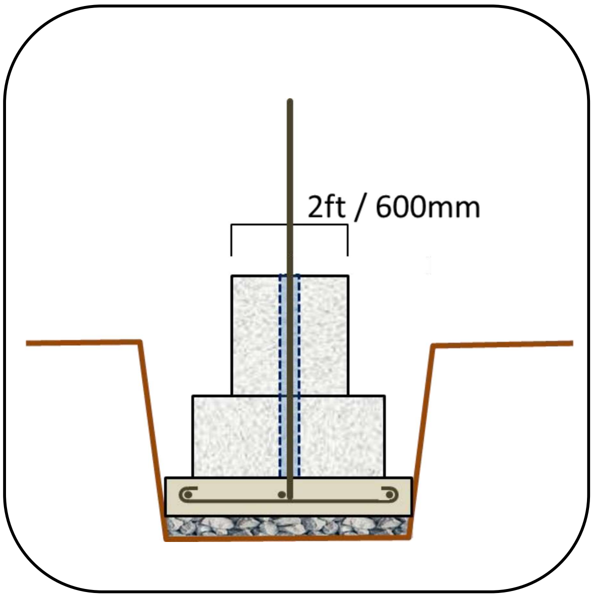


Figure 20. Foundation cross section

3.3. RC band and post

3.3.1. RC band in the plinth level

i. At the plinth level, place four longitudinal rebar of 16mm diameter and stirrup of 8 mm diameter at 150mm c/c.
   a. Overlapping of the rebar of 16mm diameter should be more than 3 feet/ 900mm
   b. Outer size of the stirrup shall be 120mm by 500mm in case of the wall thickness of 2 feet/ 600mm (or 350mm if the band needs to be concealed) to maintain concrete cover at least 2 inches/ 50mm.

ii. Provide shuttering for the RC band of height 225mm and width same as the wall thickness, or 150mm inside from the external wall face if the band needs to be concealed for aesthetic reasons.(When the wall thickness is 2 feet/ 600mm, the band width is 2 feet/ 600mm or 1.5 feet/ 450mm)

iii. Cast M20 grade concrete and cure for a week at least.

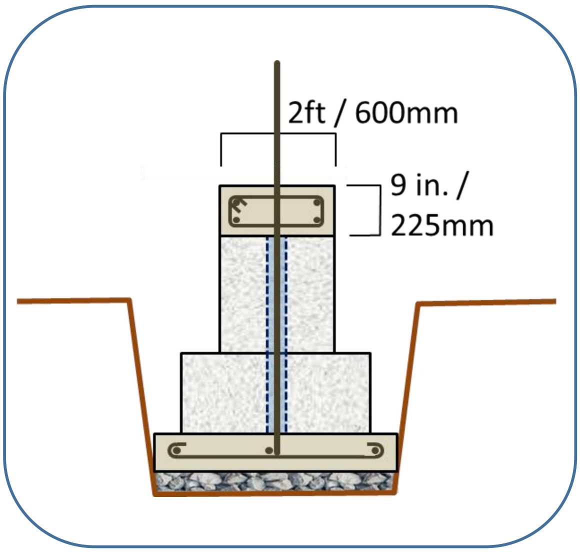


Figure 21. Wall cross section showing plinth band detail.

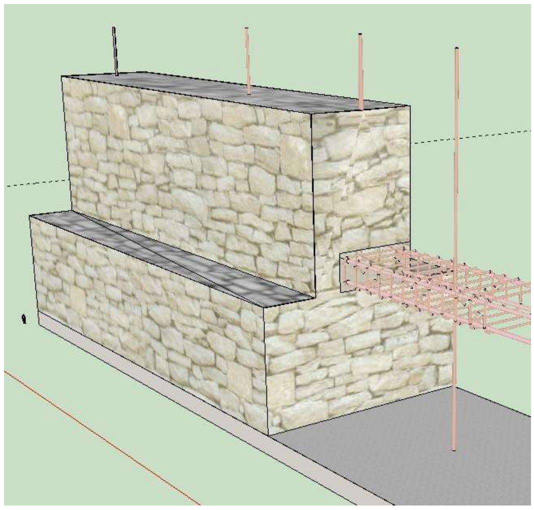


Figure 22. RC band embedded inside wall.

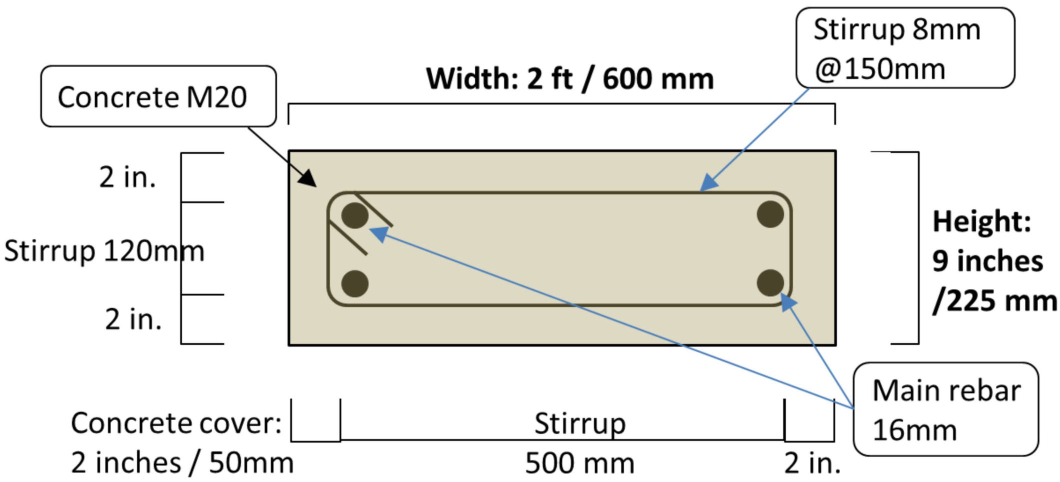


Figure 23. Sectional detail of RC band

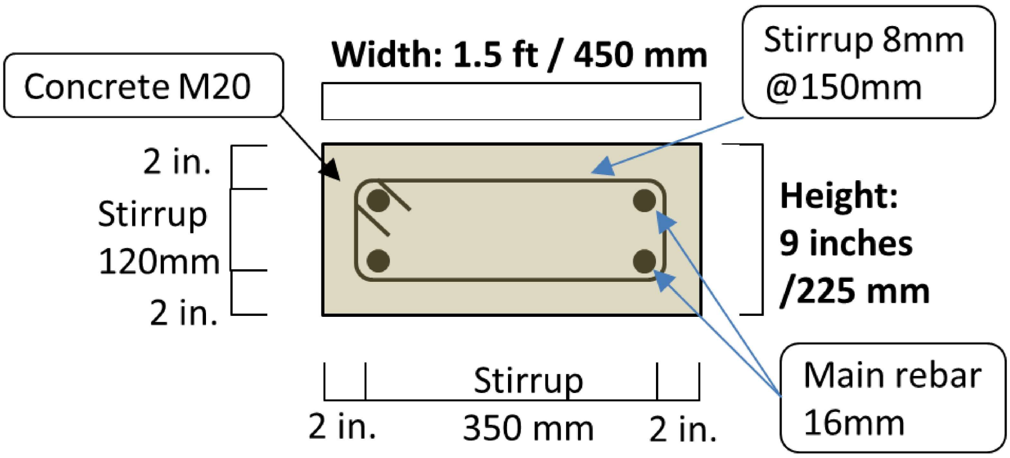


Figure 24. Sectional detail of RC band embedded inside from external wall

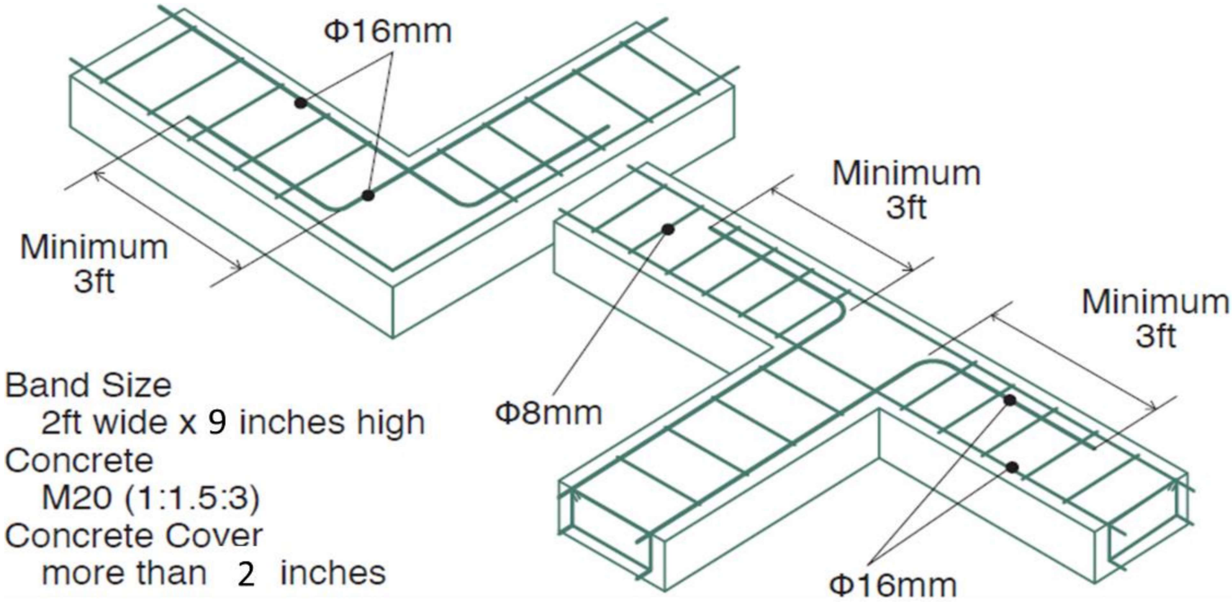


Figure 25. RC band reinforcement layout plan at corners and T-junction

3.3.2. Reinforced Concrete Post(RC Post)

Vertical rebar

a. In case the vertical rebar erected from the RC footing has to be joined, provide an overlapping length of more than 2.5 feet/ 750mm.
b. The lapping zone shall be the mid height of the two floors.
c. The lapping location shall be randomly arranged.
d. The top of the rebar shall bend in the RC band. The development length shall be 1.5 feet/ 450mm.

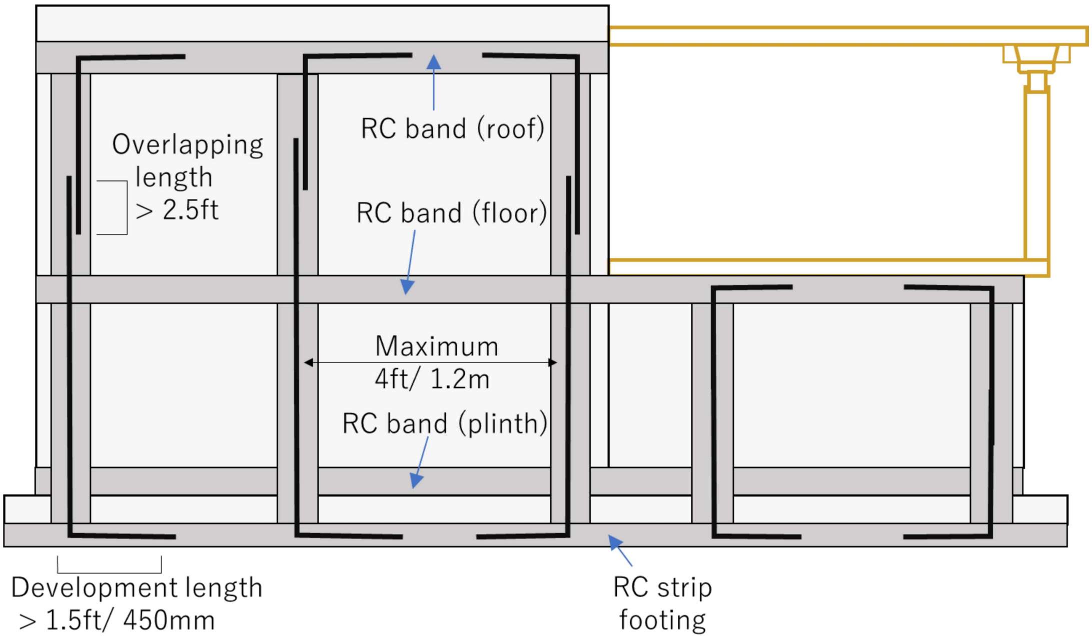


Figure 26. Cross section of house showing vertical reinforcement

For Stone masonry wall

i. Place a PVC pipe or any other suitable pipe of diameter 90 to 110 mm around the vertical rebar.
   a. Ensure that the vertical rebar is centrally placed in the pipe in order to maintain enough concrete cover for the rebar.
ii. Lay the stones around the PVC pipe in a single lift.
iii.
iv. Cast M20 grade concrete inside the pipe.
   a. Use a tamping rod to properly fill the pipe with concrete.
v. Slowly pull out the pipe while tamping with the rod.

Repeat the same process (step i to iv above) until the stone wall construction is complete.

For Rammed earth wall

Start the below process after the concrete setting, and 24 hours after concrete casting for the band.

i. Place a PVC pipe or any other suitable pipe of diameter 90 to 110 mm around the vertical rebars.
   a. The pipe shall be vertically cut into half in order to remove it after the concrete setting.
   b. The post to be constructed at one time shall be taller than the formwork. If a longer pipe is used to cast a taller post, concrete curing time would be minimized.
   c. Ensure that the vertical rebar is centrally placed in the pipe in order to maintain enough concrete cover for the rebar.
ii. Cast M20 grade concrete inside the pipe.
   a. Use a tamping rod to properly fill the pipe with concrete.
iii. Remove the pipe after concrete setting, and 24 hours after concrete casting.
iv. Cure the concrete minimum for a week by using the gunny bag method.

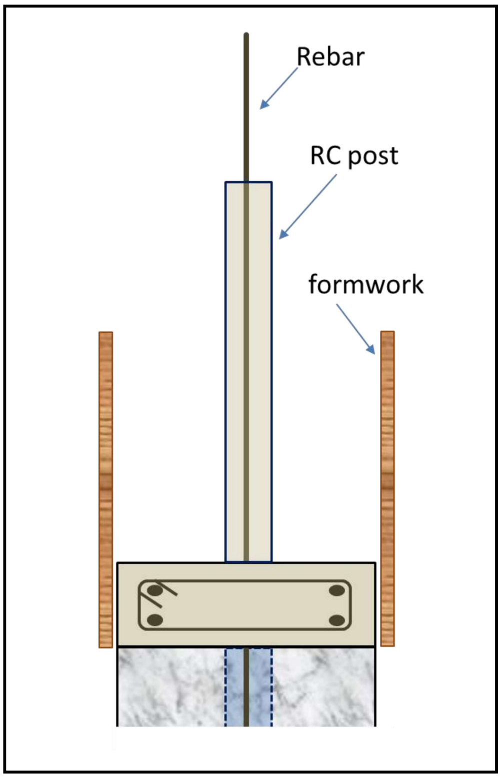


Figure 27. RC post and formwork

3.4. Stonework

a. The wall shall be constructed with good bonding between stones. There should not be a continuous vertical mortar line.

b. The height of the wall constructed in one lift shall not be more than 2 feet / 600mm.

3.4.1. Through stone

i. The length of the through stone shall be the same as the wall thickness.

ii. If stones of appropriate size aren't available, use the reinforced concrete material of the dimension 4 x 4 inches (100 x 100mm) of the wall thickness.

iii. Maximum spacing between the through stones shall be 4 feet /1.2m horizontally and 2 feet / 600mm vertically.

3.4.2. Corner stone

i. Provide corner stones at the inner and outer corners.

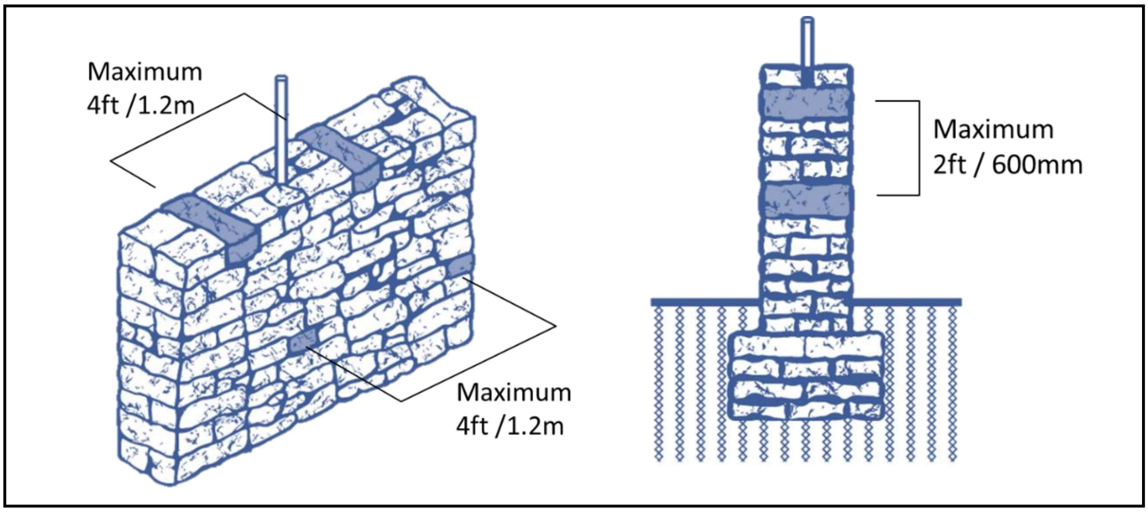


Figure 28. Through stones location in the wall

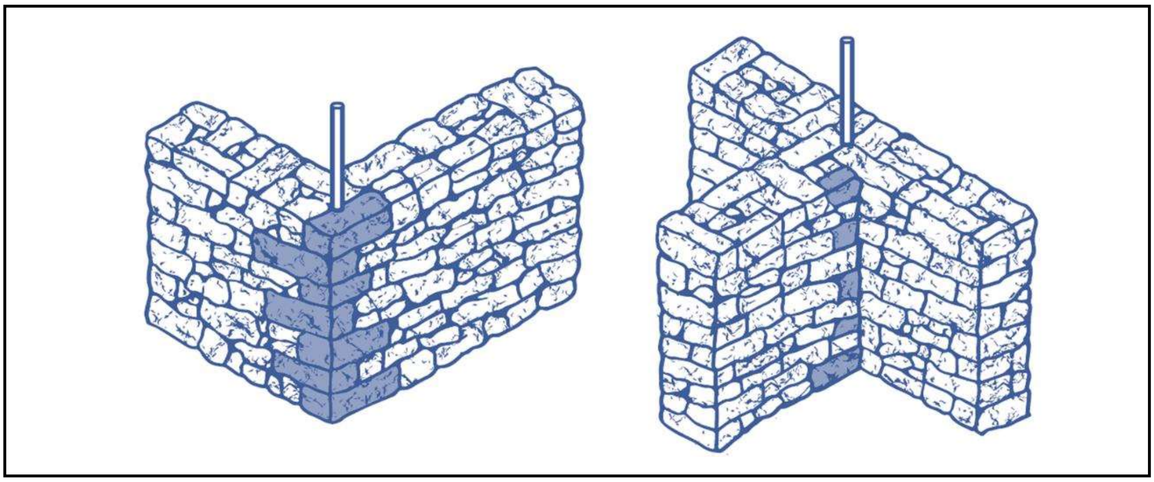


Figure 29. Corner stone position

3.5. Ramming earth

3.5.1. Formwork

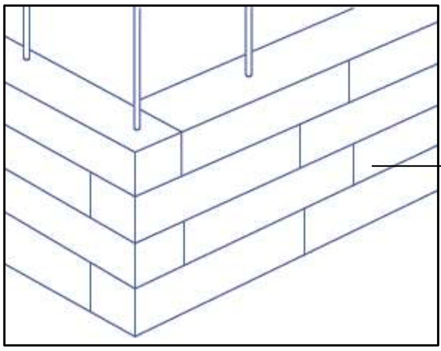
i. Place the ju-shing across the wall through grooves kept below the band.
ii. Set the wooden formwork for ramming the wall.

3.5.2. Ramming of one layer

i. Fill the formwork with 4 inches/ 100mm of soil.
ii. Use the right tool to compact the edge and plane.
iii. Compact the soil until it is 2 inches/ 50mm thick (Half of 4 inches).
iv. Compact soil properly around the RC post using the right tool of smaller dimensions.

3.5.3. Construction of wall

i. Repeat the same process of ramming (step i to iv above) to complete one rammed earth block. If the height of the formwork is 2 feet/ 600mm, repeat twelve times.
ii. Repeat the same process to set a formwork and complete ramming.
iii. The formwork shall be provided in a staggered pattern.



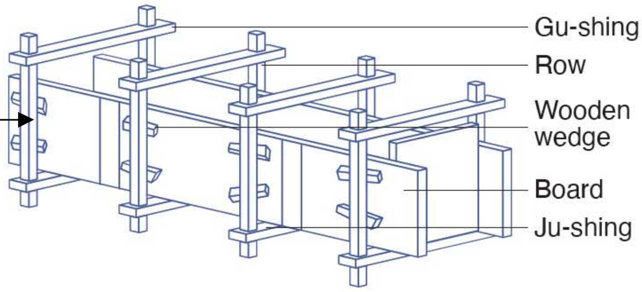


Figure 30. Rammed earth wall block arrangement (staggered pattern)

3.6. Construction of the upper structure

3.6.1. Sill and lintel bands (Optional)

i. A sill band and lintel band may be provided at the sill and lintel level respectively.
ii. The height of the band shall be 6 inches/ 150mm and the width same as the wall thickness, or 6 inches/ 150mm inside from the external wall face if the band needs to be concealed for aesthetic reasons.
(When the wall thickness is 2 feet/ 600mm, the band width is 2 feet/ 600mm or 1.5 feet/ 450mm)
iii. Provide 2 nos of 12mm diameter longitudinal bar with 8mm diameter distribution bar at 8 inches/ 200 mm c/c.

3.6.2. RC band in the upper level

i. Once the wall height reaches floor level, construct an RC band on the wall in the same process in III. 1..
ii. The vertical rebar shall be anchored in the topmost RC band as shown in III. 2..

3.6.3. Wooden joist

i. If applicable, the joists would be anchored to the RC band using bolts and nuts.

3.6. 4. Roof (Optional)

i. For roof construction, follow the Windstorm Resilient Roofing System (guideline) 2017.

3.7. Check List

I. Material

Stone Masonry house:

- ☐ Is the stone size appropriate?
- ☐ Was the mortar mixture found appropriate by the test?

Rammed earth house:

- ☐ Was the soil mixture found appropriate by the tests?

II. Foundation

- ☐ Excavated 3 feet trench to construct a foundation?
- ☐ Maintained appropriate overlapping length of the rebar for the RC strip footing? (It should be more than 3ft for the main rebar of the RC foundation; more than 2 feet for the vertical rebar)
- ☐ Placed vertical rebars at all the necessary locations?
- ☐ Maintained enough concrete cover for the RC foundation? (It should be more than 3 inches)
- ☐ Was concrete filled up properly around the vertical rebar?
- ☐ Kept the adequate concrete curing period ?

III. Reinforcement Concrete band and post

- ☐ Maintained appropriate overlapping length? (It should be more than 3 feet for the main rebar of the RC band; more than 2 feet for the RC post)
- ☐ Maintained enough concrete cover for the RC band? (It should be more than 2 inches)
- ☐ Was concrete filled up properly around the vertical rebar?
- ☐ Kept the adequate concrete curing period?

IV. Stonework

- ☐ Was the stonework done with good bonding?
- ☐ Were through stones and corner stones located in appropriate spacing?

V. Ramming Earth

- ☐ Was any provision kept for fixing ju-shings?
- ☐ Was the soil compacted until it is 2 inches thick?
- ☐ Was the soil around the RC post compacted well?
- ☐ Were the formworks arranged in a staggered pattern?

Chapter 4. Retrofit of an existing house

4.1. Overview

The seismic behavior of an existing building is affected by its original structural inadequacies, material degradation and changes carried out during use over the years such as new additional parts. The need to improve the ability to withstand seismic forces arises usually from the evidence of damage and poor behavior during recent earthquakes. It can also arise also from calculations or comparisons with similar buildings that have been damaged in other places.

4.2. Wire mesh on walls

For Rammed Earth house

1. Use two types of wire mesh, 12G wire mesh as the main retrofitting mesh and 16G wire mesh for lapping at the corner and along the height of the walls to connect two parts of the main wire mesh.
2. Use of 12mm diameter threaded bar through ju-shing holes (@4 feet/ 1.2m c/c) anchored both inside and outside using nuts and washer plates. Anchor the wire mesh also at the bottom of the wall.
3. Apply a 30mm thick cement mortar plaster (cement: sand at 1:3) on top of the mesh.

For Stone Masonry house

1. Wire mesh retrofitting anchored with steel dowel rods.
2. Use of two types of wire mesh, 12G wire mesh as the main retrofitting mesh and the second 16G wire mesh for lapping at the corner and along the height of the walls to connect two parts of the main wire mesh.
3. Use of 8mm diameter dowel bar (@ 4 feet/ 1.2m c/c) to anchor the mesh to the wall. The dowel bar is 90 degrees bent. Nails of the required length can also be used.
4. Apply a 30mm thick cement mortar plaster (cement: sand at 1:3) on top of the mesh.

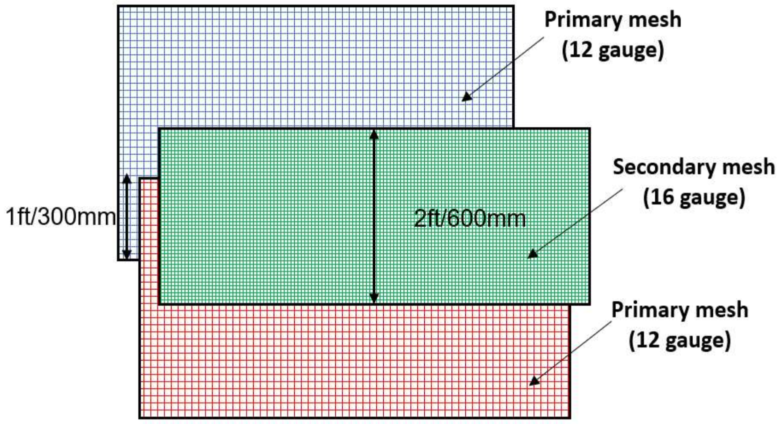


Figure 31. Mesh lapping detail

Figure 32. Threaded bar for outer & inner mesh connection

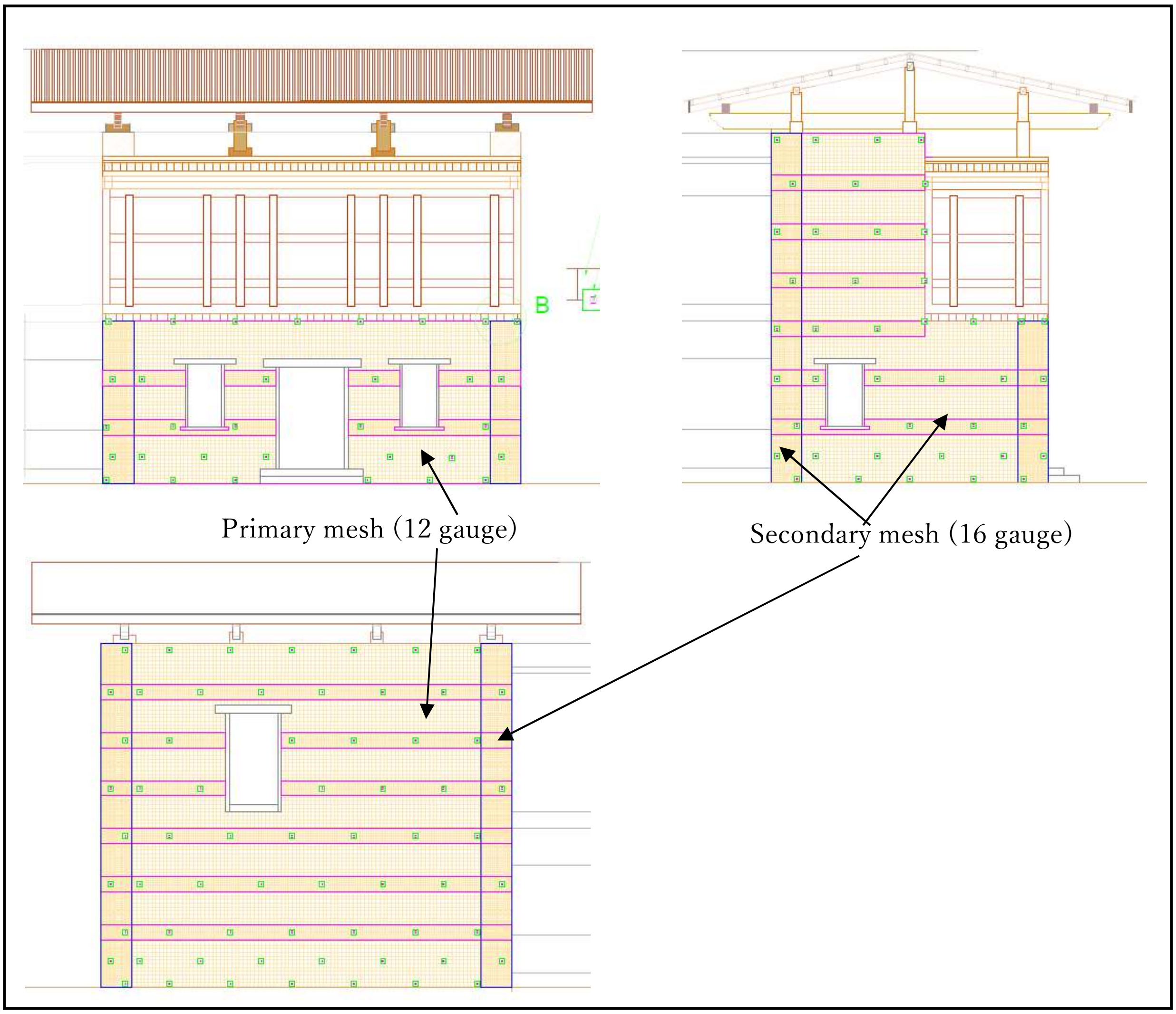


Figure 33. Mesh layout on the wall

Chapter 5. Structural Calculation

5.1. Loads and external forces.

5.1.1. Kind of loads and external forces

Loads and external forces as factors for structural calculation are:

i. permanent load (dead load);
ii. imposed load (live load);
iii. seismic force.

a. Permanent load (Dead load)

The permanent load is the load of each of the components of the building, including building equipment. It depends on the structural type of the building, finishing material of the components, etc. For special cases, the permanent load is determined according to the actual conditions.

b. Imposed load (live load)

The imposed load is the load of furniture, occupants, etc. It depends on the use of the building. For special cases, the imposed load is determined according to the actual conditions.

c. Seismic force

The seismic force is determined by calculating the inertial force that is generated through the movement of both the ground and the building. That is, horizontal force (seismic shear force) generated in the building. It is calculated incorporating the vibration characteristics of the building, the conditions of the ground, and other conditions.

5.1.2. Seismic action

a. General principles

Earthquakes cause random motion of ground which can be resolved in any three mutually perpendicular directions. This motion causes the structure to vibrate. The vibration intensity of ground expected at any location depends upon the magnitude of earthquake, the depth of focus, distance from the epicentre and the strata on which the structure stands. The predominant direction of vibration is horizontal.

The response of the structure to the ground vibration is a function of the nature of foundation soil; materials, form, size and mode of construction of the structure; and the duration and the intensity of ground motion. This standard specifies design seismic coefficient for structures standing on soils or rocks which will not settle or slide due to loss of strength during vibrations.

The seismic coefficients recommended in this guideline are based on IS 1893. It is well understood that the forces which structures would be subjected to in actual earthquakes, would be very much larger than specified in this guideline as basic seismic coefficient. In order to take care of this gap, for special cases importance factor and performance factor (where necessary) are specified in this guideline elsewhere.

b. Assumptions

The following assumptions shall be made in the earthquake resistant design of structures:

(a) Earthquake causes impulsive ground motion which is complex and irregular in character, changing in period and amplitude each lasting for small duration. Therefore, resonance of the type as visualized under steady state sinusoidal excitations will not occur as it would need time to build up such amplitudes.

(b) Earthquake is not likely to occur simultaneously with wind or maximum flood or maximum sea waves.

(c) The value of elastic modulus of materials, wherever required, may be taken as for static analysis unless a more definite value is available for use in such condition.

c. Design seismic coefficient for in-plane direction

The earthquake force experienced by a structure depends on its own dynamic characteristics in addition to those of the ground motion.

Unless otherwise stated, the seismic zone factor (Z) in different zones shall be taken. This value should be derived from seismography.

The design seismic forces for in-plane direction shall be computed on the basis of importance of the structure and its soil-foundation system. Seismic force above the ground level is calculated by following formula:

$$Q_i = W_i \cdot C_i \qquad (5\text{-}1)$$

$$C_i = A_i \cdot A_h$$

$$A_h = \frac{\left(\frac{Z}{2}\right)\left(\frac{S_a}{g}\right)}{\left(\frac{R}{I}\right)}$$

where:

Q_i: the seismic shear force of point "i" (the height from ground level) (kN)

C_i: the seismic shear coefficient of point "i"

W_i: permanent load added to imposed load above point "i" (+snow load, in heavy snow areas) (kN)

A_h: the design horizontal seismic coefficient

A_i: vertical distribution factor

$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i\right)\frac{2T}{1+3T}$$

T: design fundamental natural period (s)

T=0.03H: This value should be derived from experiment (see Experimental result and data).

H: Height of rammed earth wall (m)

$$\alpha_i = \frac{W_i \text{ (Total permanet load added to imposed load above story } i\text{)}}{W \text{ (Total permanet load added to imposed load)}}$$

Z: the seismic zone factor (0.36). This value should be derived from seismography.

I: importance factor for the corresponding structures (see Table 5-1). When not specified, the minimum values of I shall be.

R: response reduction factor for the corresponding structures (see Table 5-2).

$\frac{S_a}{g}$: design acceleration coefficient for different types, normalized with peak ground acceleration, corresponding to natural period T of structure. This value should be derived from observation of surface layer of ground.

$$\frac{S_a}{g} = \begin{cases} \text{For rocky or hard soil sites} \begin{cases} 2.5 & 0 < T < 0.40 \\ \dfrac{1}{T} & 0.40 < T < 4.00 \\ 0.25 & T > 4.00 \end{cases} \\ \text{For medium stiff soil sites} \begin{cases} 2.5 & 0 < T < 0.55 \\ \dfrac{1.36}{T} & 0.55 < T < 4.00 \\ 0.34 & T > 4.00 \end{cases} \\ \text{For soft soil sites} \begin{cases} 2.5 & 0 < T < 0.67 \\ \dfrac{1.67}{T} & 0.67 < T < 4.00 \\ 0.42 & T > 4.00 \end{cases} \end{cases}$$

Table 1. Values of importance factor, I

Structure	Values of Importance Factor, *I*
Critical and lifeline structures	1.5
Business continuity structures	1.2
The rest	1.0

Table 2. Values of response reduction factor, R

Structure (Load bearing masonry wall buildings)	Values of Response Reduction Factor, *R*
Unreinforced	1.5
Reinforced with horizontal RC bands	2.5
Reinforced with horizontal RC bands and vertical bars at corners of rooms and jambs of openings	3.0

d. Design seismic coefficient for out-of-plane direction

The design seismic forces for out-of-plane direction shall be computed same as that for in-plane direction. Seismic force as the uniformly distributed load applied to walls is calculated by following formula:

$$\omega_i = \frac{\kappa_i \cdot w_i}{h_i} \qquad (5\text{-}2)$$

$$\kappa_i = A_h \cdot A_i$$

where:

- ω_i: uniformly distributed load applied to the wall of point "*i*" (kN/m)
- w_i: weight of the wall of point "*i*" (kN)
- h_i: height of the wall of point "*i*" (m)
- κ_i: horizontal seismic coefficient of the wall in out-of-plane direction of point "*i*"
- A_h: the design horizontal seismic coefficient (see Equation 5-1)
- A_i: vertical distribution factor (see Equation 5-1)

5.2. Structural calculation for new construction

5.2.1. Calculation for in-plane direction

Allowable unit stress calculation has been prepared for the seismic design of new construction structures. For large-scale earthquake motions, extraordinary earthquakes which could occur once in the lifetime of the building. Working stress must be less than allowable stress for both superstructures and foundation.

Stresses acting upon the sections of elements necessary for structural resistance must be calculated by the following formula:

G+P+K (5-3)

where:

G: Permanent load (dead load);
P: Imposed load (live load);
K: Seismic force.

It shall be confirmed that working stresses do not exceed the allowable unit stresses in temporary load case.

Calculated stress < Allowable unit stress (5-4)

Values of allowable unit stress are available based on the results of material tests (see Experimental results and data). The allowable unit shear stress shall be assumed to be equal to the tensile strength.

Values of working shear stress acting by seismic force are calculated by following formula:

$$Q_{ij} = \frac{A_j}{\sum_{j=1}^{3} A_j} \times Q_i$$

$$\tau_j = \frac{Q_{ij}}{A_{Wj}} \tag{5-5}$$

where:

Q_i: the seismic shear force of point "i" (see Equation 5-1)
Q_{ij}: the seismic shear force applied to wall "j" of point "i"
A_j: the load area of wall "j"
τ_j: working shear stress of wall "j"
A_{Wj}: effective sectional area of wall "j"

The load area shall be calculated with the center-to-center distance to adjacent walls. The effective sectional area of wall must be calculated with the wall length without openings (see Figure 5-1).

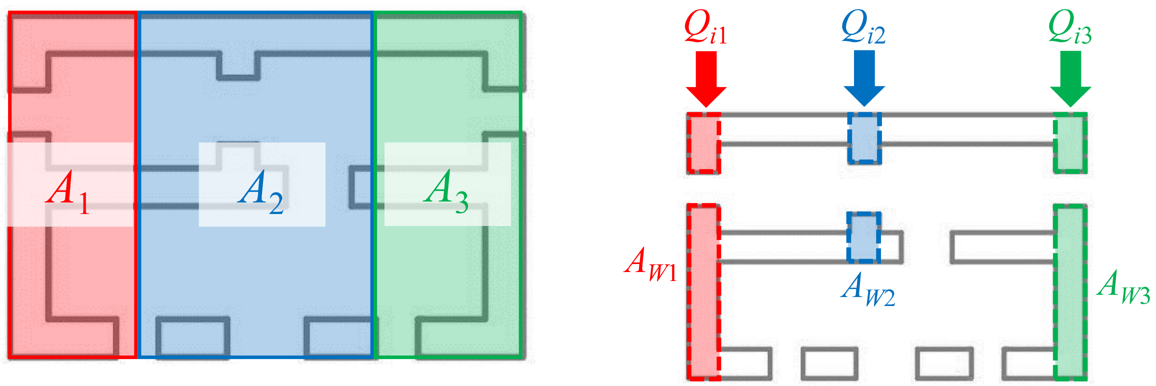


Figure 34. Example of load area and effective sectional area of walls

5.2.2. Calculation for out-of-plane direction

Strength of wall in out-of-plane direction must be satisfied in following formula:

$$\sigma_c + \sigma_b \le \sigma_{cW} \quad \text{when} \quad \sigma_c \ge \sigma_b$$
$$\sigma_b - \sigma_c \le \sigma_{tW} \quad \text{when} \quad \sigma_c < \sigma_b \tag{5-6}$$

where:

$\sigma_c = N/A$; Axial force of wall / sectional area of wall (N/mm^2)

$\sigma_b = M/Z$; Bending moment of wall / sectional modulus of wall in out-of-plane direction (N/mm^2)

Axial force and bending moment of wall shall be calculated assuming a cantilever beam with uniformly distributed load as seismic force (see Equation 5-2). Figure 5-2 (a) shows the example of mechanical model for wall in two-story structure. Axial force and bending moment of wall are calculated by following formula:

$$N(x) = (h_1 + h_2 - x)Dt\rho \quad (0 \le x \le h_2) \tag{5-7}$$

$$M(x) = \begin{cases} (\omega_1 h_1 + \omega_2 h_2 - \omega_1 x/2)x - \omega_1 h_1^2/2 - \omega_2 h_2 (h_1 + h_2/2) & (0 \le x \le h_1) \\ \{\omega_2 h_2 - \omega_2 (x - h_1)\}x + \omega_1 h_1^2/2 + \omega_2 (x - h_1) \cdot (x + h_1)/2 - \omega_1 h_1^2/2 & \\ -\omega_2 h_2 (h_1 + h_2/2) & (h_1 \le x \le h_1 + h_2) \end{cases} \tag{5-8}$$

where:

$N(x)$: axial force of point "x"

$M(x)$: bending moment of point "x"

x: distance from the ground

h_1: height of ground floor

h_2: height of first floor

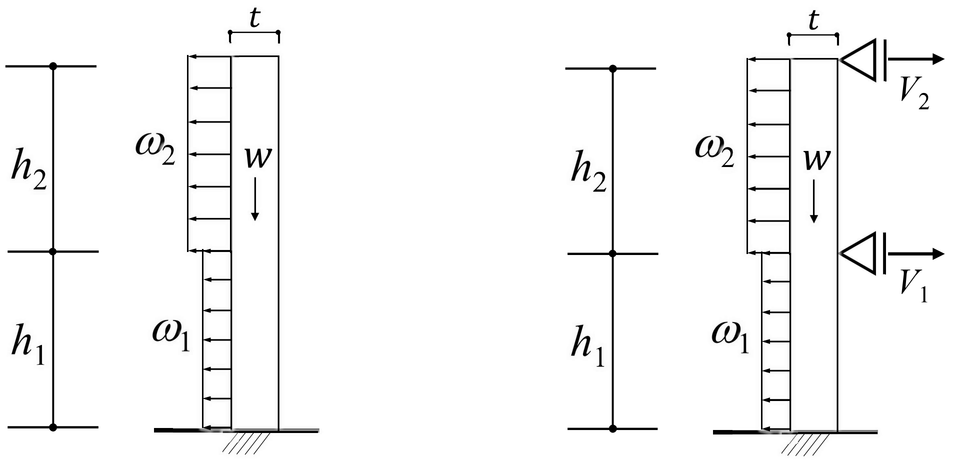
D: length of wall

t: thickness of wall

ρ: density of wall

ω_1: the uniformly distributed load applied to wall of ground floor (see Equation 5-2)

ω_2: the uniformly distributed load applied to wall of first floor (see Equation 5-2)



(a) Without RC beams and RC post (b) With RC beams and RC post

Figure 35. Example of mechanical model of wall in two-storey structure

In case of reinforcing with RC beams and RC post, axial force and bending moment of wall shall be calculated assuming a cantilever beam supported at floor level on each storey as shown in Figure 5-2 (b). Axial force and bending moment of wall are calculated by following formula:

$$N(x)=(h_1+h_2-x)Dt\rho \quad (0\le x\le h_2) \qquad (5\text{-}9)$$

$$M(x)=\begin{cases}\{\omega_1(h_1-x)+\omega_2h_2-V_1-V_2\}x+\omega_1(x-h_1)\cdot(x+h_1)/2-\omega_2h_2(h_1+h_2/2) \\ +V_1h_1+V_2(h_1+h_2) \quad (0\le x\le h_1) \\ \{\omega_2h_2-\omega_2(x-h_1)-V_2\}x+\omega_2(x-h_1)\cdot(x+h_1)/2-\omega_2h_2(h_1+h_2/2) \\ +V_2(h_1+h_2) \quad (h_1\le x\le h_1+h_2)\end{cases} \qquad (5\text{-}10)$$

$$V_1=\frac{\omega_1h_1^2(h_1^2+6h_1h_2+6h_2^2)}{4h_1h_2(3h_1+4h_2)}+\frac{\omega_2h_2^2(6h_1^2+10h_1h_2+3h_2^2)}{4h_1h_2(3h_1+4h_2)} \qquad (5\text{-}11)$$

$$V_2=\frac{-\omega_1h_1^3+6\omega_2h_1h_2^2+6\omega_2h_2^3}{4h_2(3h_1+4h_2)} \qquad (5\text{-}12)$$

where:

$N(x)$: axial force of point "x"
$M(x)$: bending moment of point "x"
x: distance from the ground
h_1: height of ground floor
h_2: height of first floor
D: length of wall
t: thickness of wall
ρ: density of wall
ω_1: the uniformly distributed load applied to wall of ground floor (see Equation 5-2)
ω_2: the uniformly distributed load applied to wall of first floor (see Equation 5-2)
V_1: horizontal reaction force at first floor level
V_2: horizontal reaction force at first floor ceiling level

RC beams must be designed so that the horizontal force, caused by the reaction force V_1 and V_2, which shall be assumed to be uniformly distributed load do not exceed the allowable strength. RC posts must be installed within 1200mm intervals so that adjacent walls behave as one during an earthquake.

5.3. Seismic evaluation of existing structures

5.3.1. Judgement on seismic safety for in-plane direction

Generally, the effects of the structural defects such as cracking, deflection, aging, and the like, on the seismic performance of a structure is not negligible. However, in this guideline, the seismic performance of an existing structure shall be assumed to be same as that of a new construction structure on the premise that it will be repaired. Therefore, the seismic safety for in-plane direction shall be judged based on the structural calculation for new construction (see 5.2.1).

5.3.2. Judgement on seismic safety for out-of-plane direction

The seismic safety for out-of-plane direction also shall be judged based on the structural calculation for new construction (see 5.2.2).

5.3.3. Design of seismic reinforcement

If Equations (5-4) and (5-6) are satisfied, the structure may be assessed to be "Safe - the structure possess the seismic capacity required against the expected earthquake motions". Otherwise, the structure should be assessed to be "Unsafe - the structure may collapse against the expected earthquake motions", in seismic safety. In this case, the seismic reinforcement is required based on this manual (see Chapter 4).