Seismic Design and Performance of Confined Masonry Buildings

Course No: S02-036
Credit: 2 PDH

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. What is Confined Masonry?

Confined Masonry is a construction system where the walls are built first, and the columns and beams are poured in afterwards to enclose (confine) the wall.

1.1 Why Confined Masonry?

1. Unreinforced masonry (URM) and non-ductile reinforced concrete frame constructions exhibited poor seismic performance during the past earthquakes, resulted in unacceptably huge loss of lives and properties.

Figure 1. Collapse of unreinforced masonry building, California 1933

A warning placard at an URM's entrance in California. Such placards are now required statewide, enforceable with penalties upon building owners and local government.

A warning placard at an URM's entrance in California.

Such placards are now required statewide, enforceable with penalties upon building owners and local government.

Figure 2. Warning placard

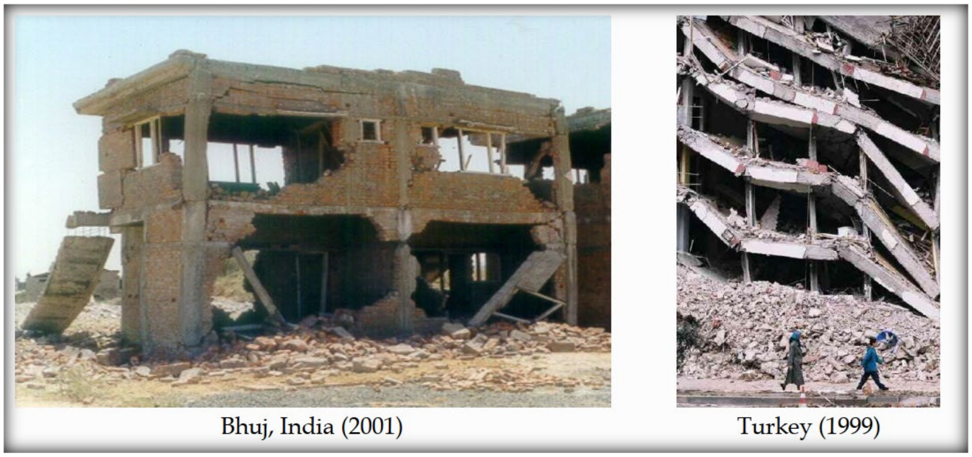


Figure 3. Collapse of non-ductile RC frame buildings

To overcome the deficiencies of URM and non-ductile reinforced concrete (RC) frame system, different methods of reinforcing masonry panels have been developed over the years.

2. Confined masonry (CM) construction has evolved based on the satisfactory performance in past earthquakes.

    a. First introduced in Italy as an alternative to URM buildings which were almost completely destroyed in the 1908 Messina earthquake
    b. Practiced in Chile since 1930's and in Mexico since 1940's
    c. Popular for low-rise residential buildings in many countries, of South and Central America, Asia and Eastern Europe

3. During one of the Chilean Earthquakes only 16% of confined masonry houses were partially collapsed as compared to collapse percentage of 57% for unreinforced brick masonry buildings
4. Provide fair amount of in-plane shear capacity, out-of-plane stability and ductility - preferred especially in higher seismic zones

Figure 4. Confined masonry building in M8.0 2007 Pisco, Peru Eqk (Collapse of nearby adobe house)

2. Structural Component of Confined Masonry

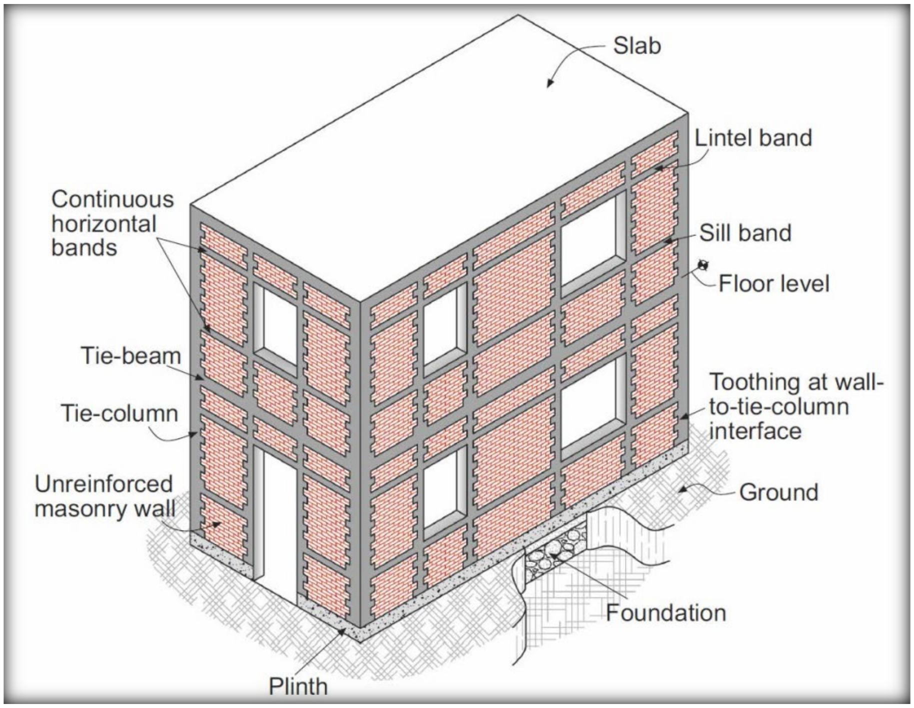


Figure 5. Structural Component

a. Masonry Walls

Masonry walls transfer the loads of the upper slabs to the foundation successfully. The walls in the confined masonry act as the bracing panels, which resist horizontal earthquake forces. The walls of this type of masonry are confined by concrete tie-beams and tie-columns to ensure satisfactory earthquake performance.

b. Confining Elements

The confining elements provide restraint to masonry walls and protect them from complete disintegration, even in the event of a major earthquake. These elements resist gravity loads and have an essential role in ensuring the vertical stability of a building in an earthquake.

c. Slabs (Floor and Roof)

The slab of the confined masonry helps in transmitting both gravity and lateral loads to the walls. In an earthquake, the piece behaves like horizontal beams and is called diaphragms.

d. Plinth Beam or Band

The plinth band transfers the load from the walls down to the foundation by protecting the ground floor walls from excessive settlement in soft soil conditions.

e. Foundation

The foundation acts typically as in conventional masonry by transferring the load from the structure to the ground.

3. Difference between Confined Masonry Construction and RCC Frame Construction

Table 1. Difference between confined masonry and RC frame construction.

	Confined Masonry Construction	**RC Frame Construction**
Gravity and lateral load-resisting system	Masonry walls are the main load-bearing elements and are expected to resist both gravity and lateral	RC frames resist both gravity and lateral loads through their relatively large beams,

	loads. Confining elements (tie-beams and tie-columns) are significantly smaller in size than RC beams and columns.	columns, and their connections. Masonry infills are not load-bearing walls.
Foundation construction	Strip footing beneath the wall and the RC plinth band.	Isolated footing beneath each column.
Superstructure Construction sequence	1. Masonry walls are constructed first. 2. Subsequently, tie-columns are cast in place. 3. Finally, tie-beams are constructed on top of the walls, simultaneously with the floor/roof slab construction.	1. The frame is constructed first. 2. Masonry walls are constructed at a later stage and are not bonded to the frame members; these walls are nonstructural, that is, non-load bearing walls.

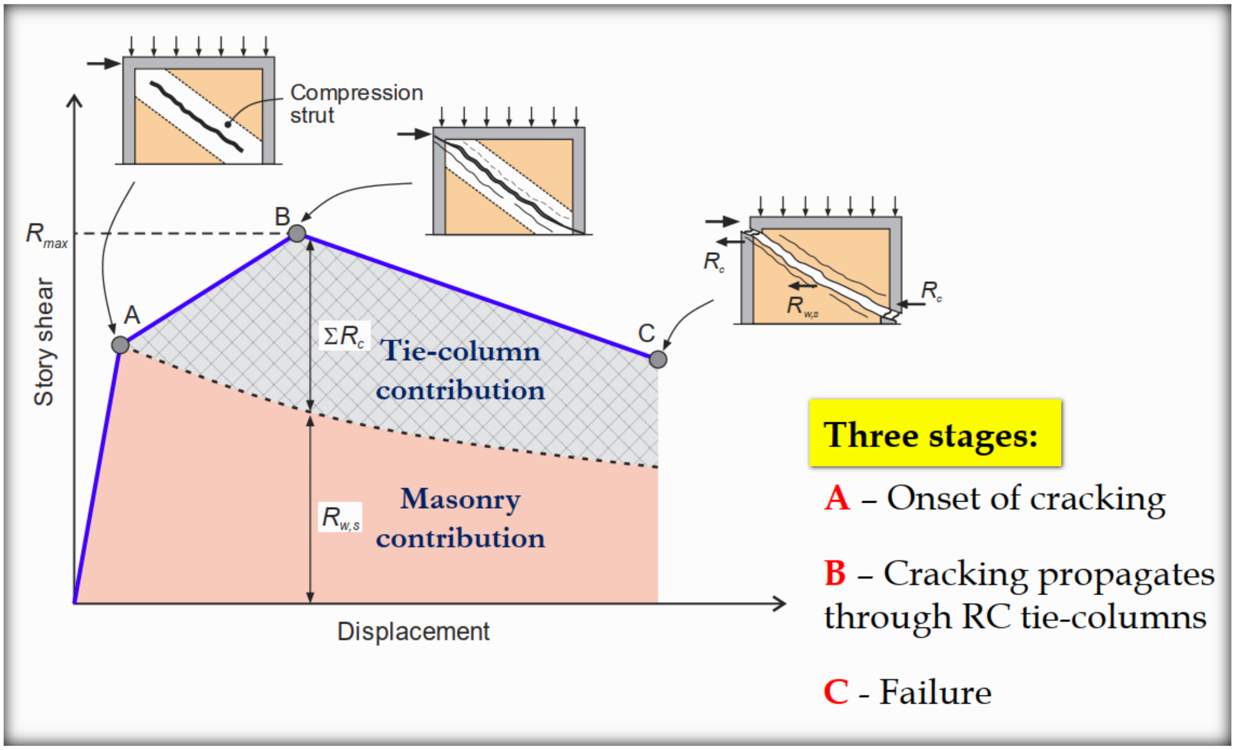


Figure 6. Confined Masonry Walls Under Lateral Loads

4. Factors Influencing the Seismic Resistance of Confined Masonry

The factors or components of the confined masonry which influence the seismic resistance are detailed below:

a. Wall Density

General studies have shown that the building having more wall density suffers less damage than the ones having less wall density. The wall density is calculated as the transverse area of walls in each principal direction divided by the total floor area of the building. The above reason is why each country codes provide the minimum wall density requirement for different storied buildings, based on their traditional way of wall construction. A survey done during the Llolleo earthquake in 1985 showed that the damage that occurred to the confined masonry with 1.15% wall density was very less compared to the masonry building with 0.5% wall density.

b. Masonry Units and Mortar

The tests have shown that the lateral load resistance of confined masonry walls strongly depends on the strength of the masonry units and the mortar used. The walls built using low-strength bricks or non-grouted hollow block units had the lowest strength, while the ones made using grouted or solid units had the most significant advantage.

c. Tie-Columns

The provision of closely spaced transverse reinforcement (ties) at the top and bottom ends of tie-columns results in improved wall stability and ductility in the post-cracking stage. Tie-columns significantly influence the ductility and stability of cracked confined masonry walls.

d. Horizontal Wall Reinforcement

The provision of horizontal wall reinforcement in the building with more than four stories has a beneficial effect on wall ductility. Walls with horizontal reinforcement showed a more uniform distribution of inclined shear cracks than the unreinforced specimens. The horizontal reinforcement is provided in the form of one or two wires laid in the mortar bed joints, as shown in the figure below:

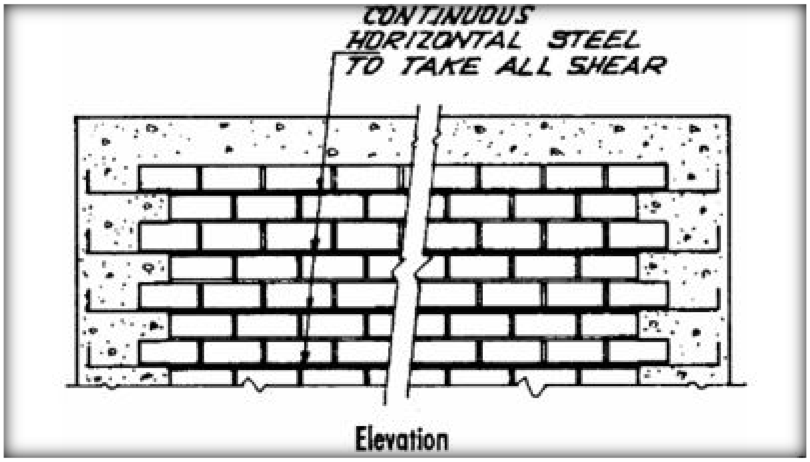


Figure 7. Horizontal Wall Reinforcement

2.1 Role of Wall-to-Tie-column Interface

Good bonding between a masonry wall and adjacent RC tie-columns can be achieved by:

1) **'toothing'** at the wall-to-tie-column interface.
2) providing **dowels** anchored into RC tie-columns.

'Toothing' is also referred to as '**shear-key'** and '**toothed shear-key**'.

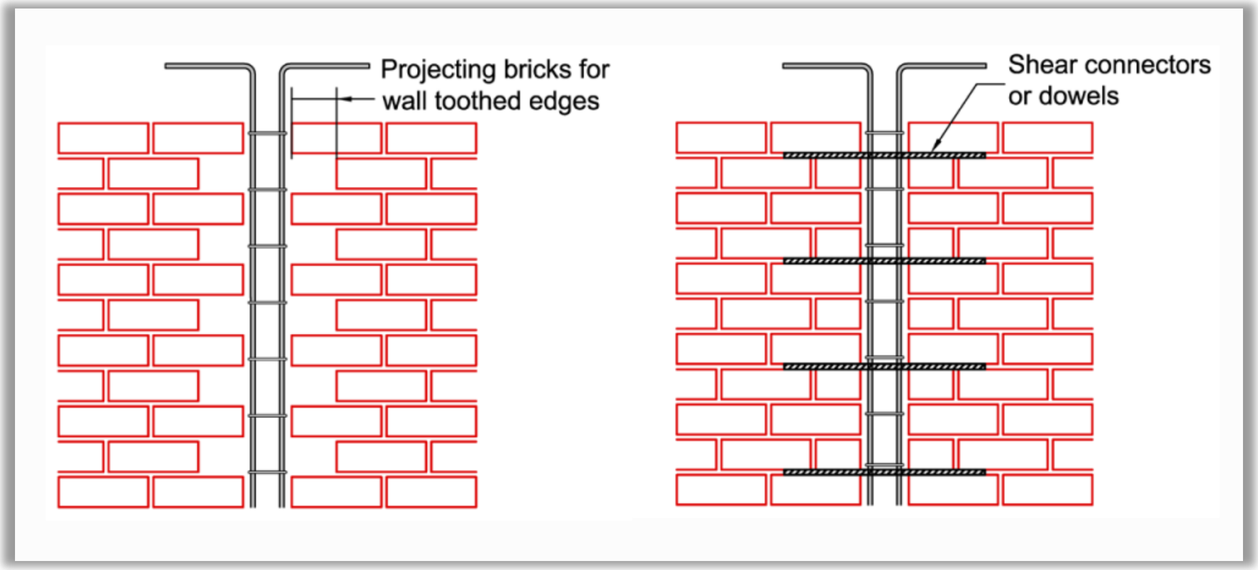


Figure 8. Toothing

3.1 Advantages of Confined Masonry

1. It enhances the stability and integrity of masonry walls for in-plane and out-of-plane earthquake loads.
2. It enhances the strength (resistance) of masonry walls under lateral earthquake loads.
3. It reduces the brittleness of masonry walls under earthquake loads and hence improving their earthquake performance.

4.1 Applications of Confined Masonry

1. The practice of confined masonry construction started in Chile in the 1930s after the 1928 Talca earthquake (Magnitude 8.0) that affected a significant number of unreinforced masonry buildings.
2. Subsequently, the 1939 earthquake (Magnitude 7.8) that struck the mid-southern region of the country revealed the excellent performance of confined masonry buildings.
3. The confined masonry construction was introduced in Mexico City, Mexico, in the 1940s to control the wall cracking caused by large differential settlements under the soft soil conditions, which later became famous for its excellent earthquake performance.
4. The use of confined masonry in Colombia dates from the 1930s, and it is currently widely used for housing construction, from single-story dwellings to five-story apartment buildings.

5. Design Considerations

5.1 Building Configuration

A. A regular building configuration is one of the key requirements for satisfactory earthquake performance:

  a) The building plan should be of a regular shape.
  b) The building's length-to-width ratio in plan shall not exceed 4.
  c) The walls should be built in a symmetrical manner.
  d) The walls should be placed as far apart as possible, preferably at the façade, to avoid twisting (torsion) of the building in an earthquake.

B. There are at least two lines of walls in each orthogonal direction of the building plan, and the walls along each line extend over at least 50% of the building dimension.

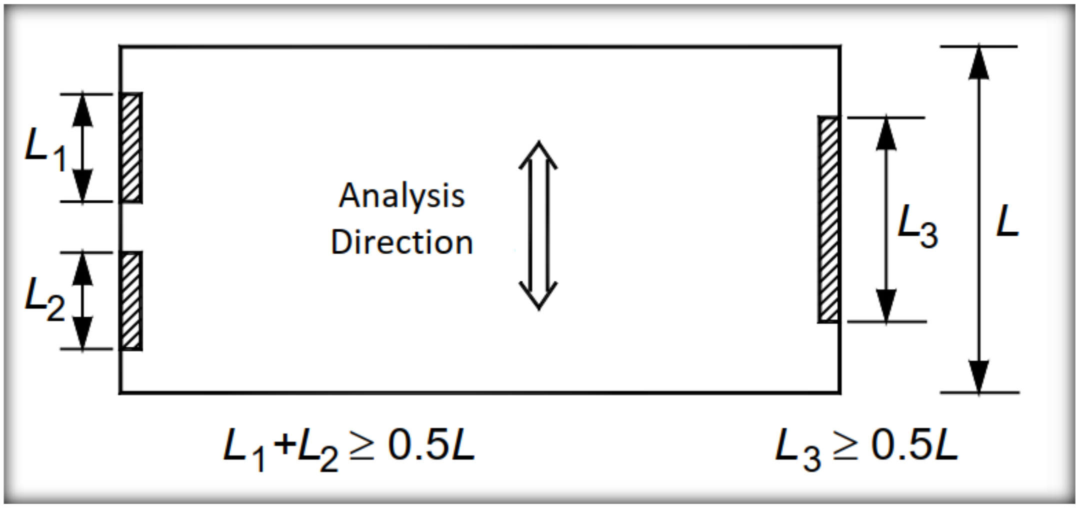
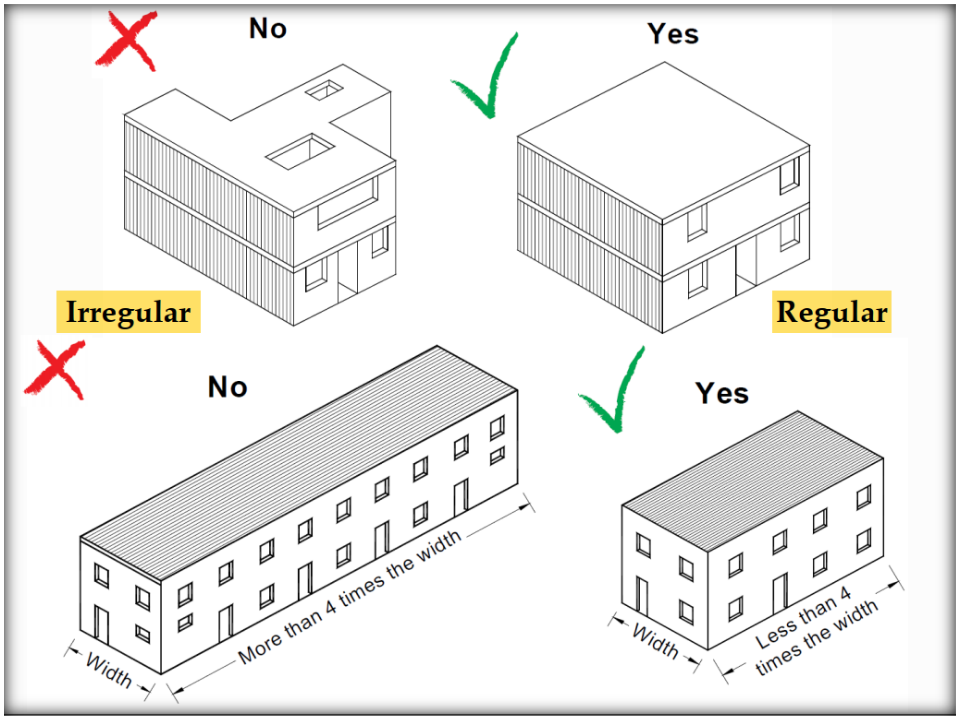


Figure 9. Building Plan

C. The walls should always be continuous up the building height – vertical offsets are not permitted.

D. Openings (doors and windows) should be placed in the same position on each floor.



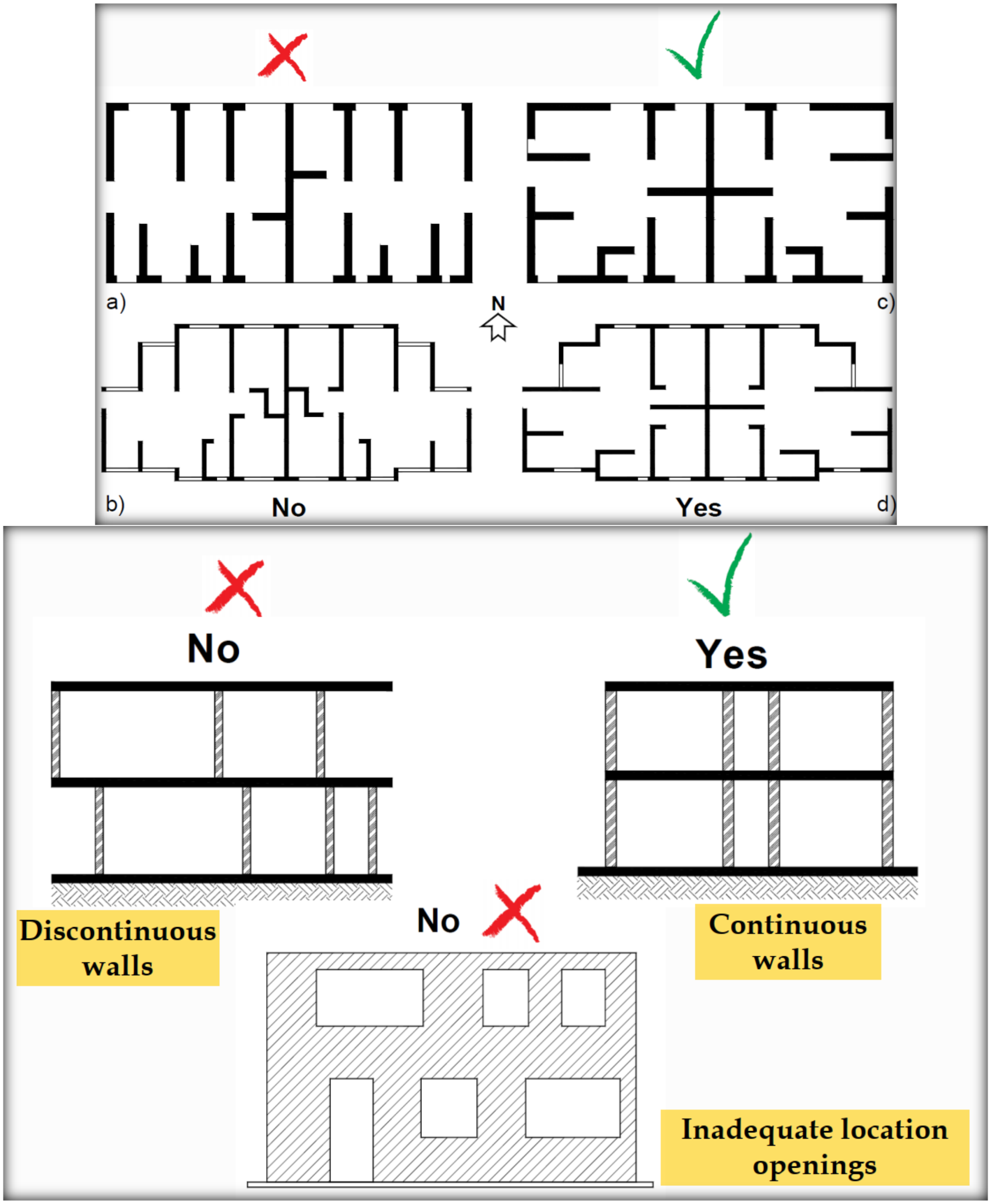


Figure 10. Design Considerations

6.1 Minimum Design Dimensions Requirements

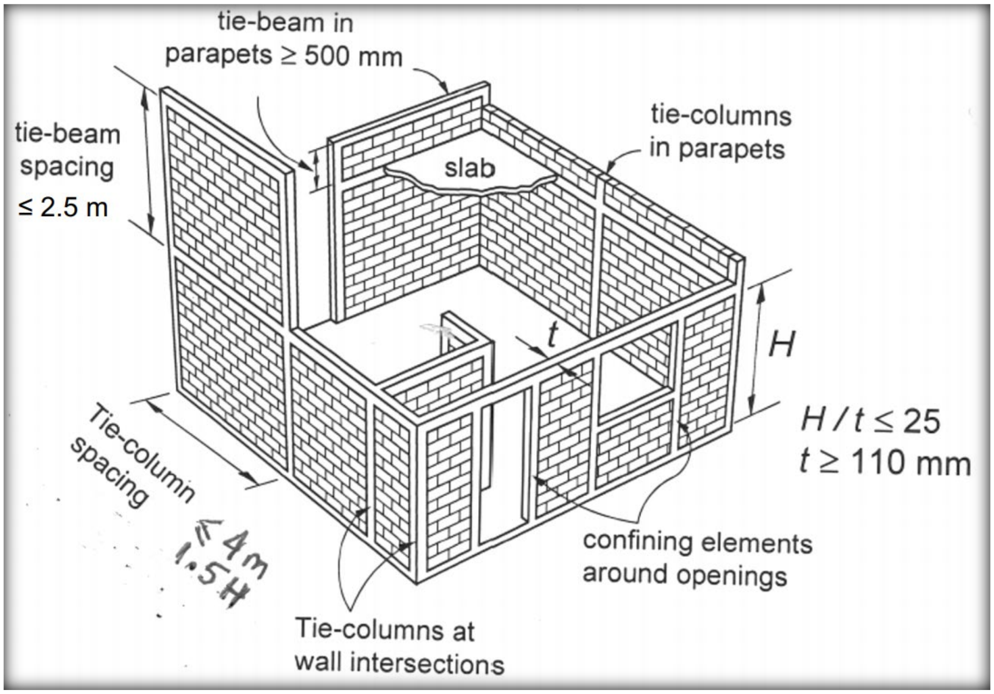


Figure 11. Design Requirements

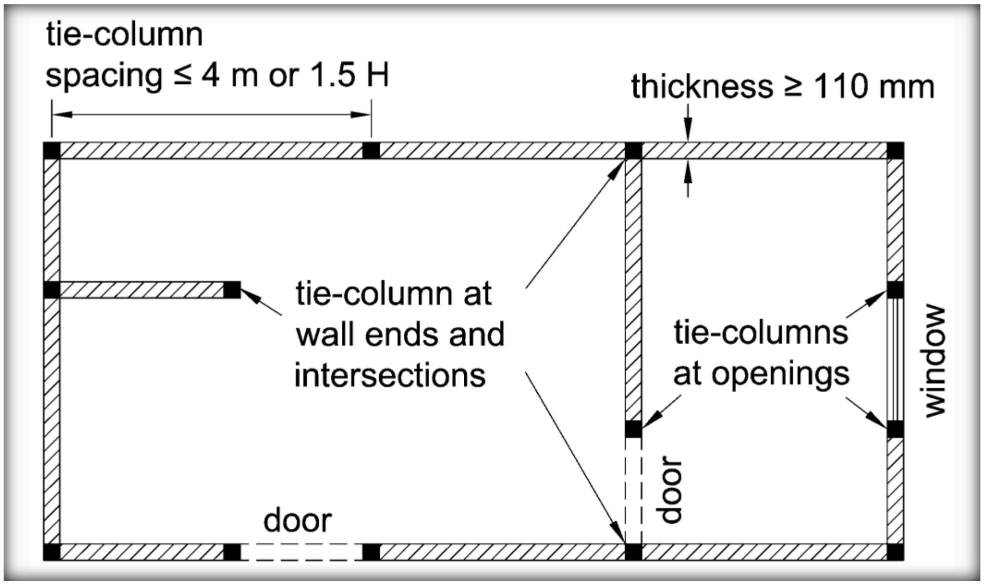


Figure 12. Tie Column & Beam

Minimum tie-column and tie-beam dimensions (depth × width) shall be 150 mm × t (*where t is wall thickness*).

7.1 Minimum Dimension of Masonry Walls

i. Wall thickness (t) should not be less than 110 mm.
ii. Maximum wall height/thickness (H/t) ratio shall not exceed 25.
iii. Unsupported wall height (H) shall not exceed 2.5 m
iv. Height-to-width ratio of wall should be kept less than 2 for the better lateral load transfer.

8.1 Parapets

i. When a parapet is not confined by tie-beams, height should not exceed 500 mm.
ii. Otherwise the height limit is 1.2 m.

9.1 Wall with Openings

The presence of large openings have a negative effect on seismic performance buildings, especially if openings are not confined.

Size of Opening
Large opening - total area > 10% of wall panel area, and
Small opening - total area ≤ 10% of wall panel area.

Figure 13. Sikkim Earthquake 2011

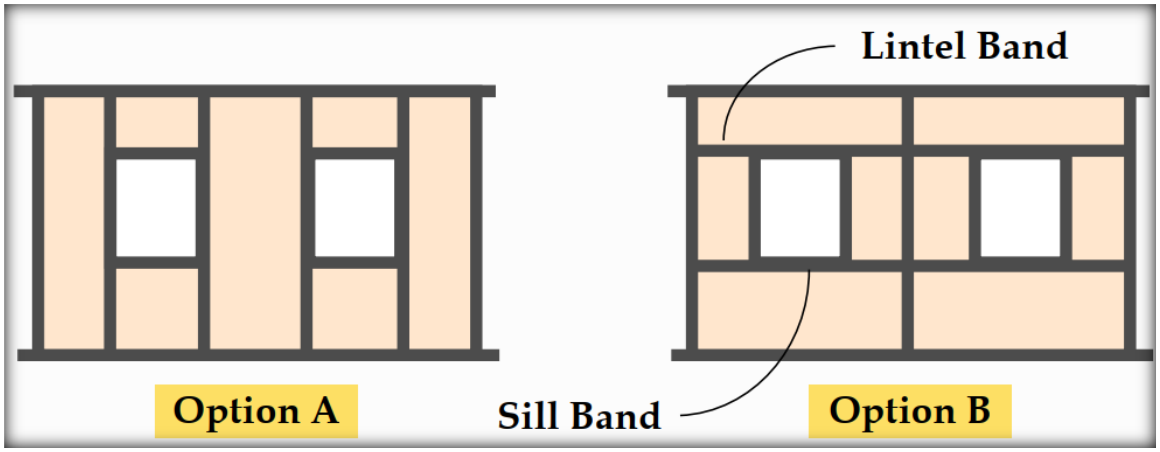


Figure 14. Lintel band & Still band

When reinforced concrete tie-columns are not provided at the ends of an opening, contribution of wall to seismic resistance of the building should be disregarded but should be strengthened per IS 4326.

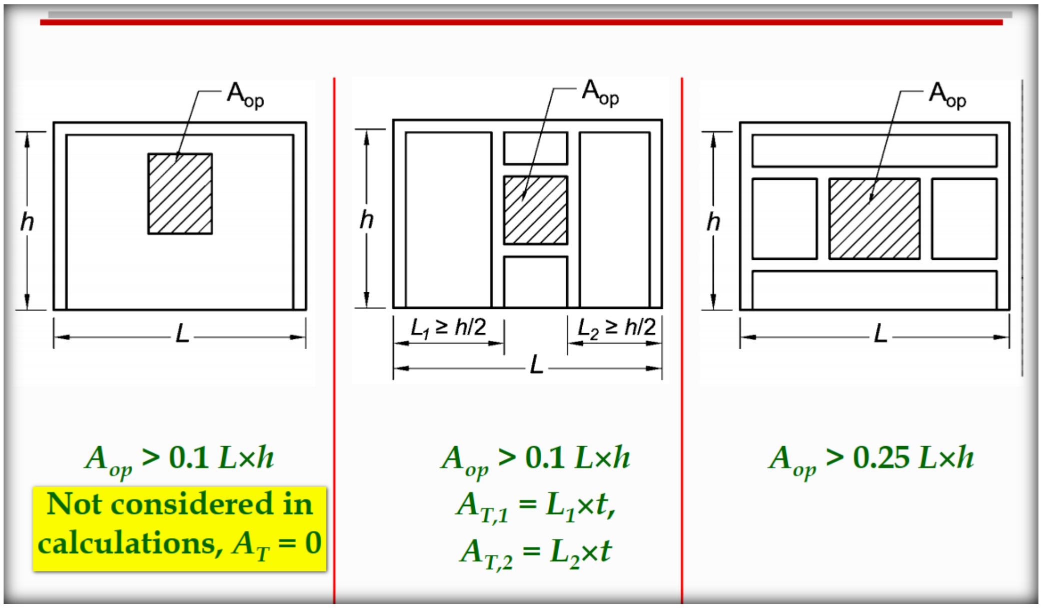


Figure 15. Large openings

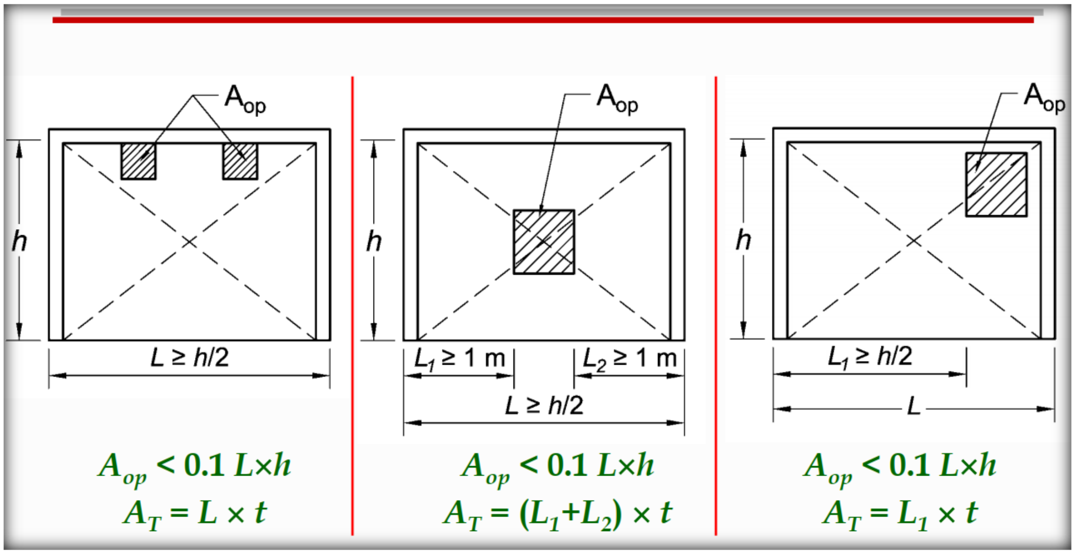


Figure 16. Small openings

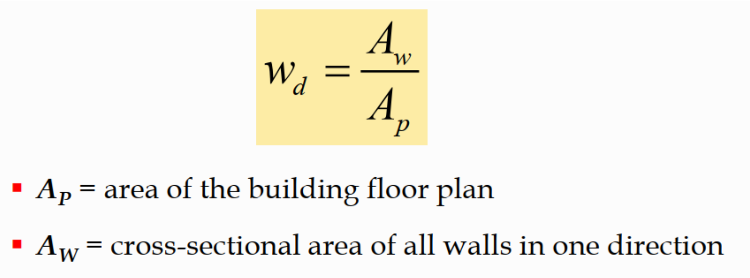
Small opening can be ignored when it is located outside the diagonals

6. Design of Confined Masonry Building

10.1 Wall Density Requirements

Wall density w_d is a key indicator of safety for low-rise confined masonry buildings subjected to seismic and gravity loads

Provide a initial assessment on required wall area
Confined masonry buildings with adequate wall density resist the effects of major earthquakes without collapse



$$w_d = \frac{A_w}{A_p}$$

- A_P = area of the building floor plan
- A_W = cross-sectional area of all walls in one direction

Figure 17. Wall density equation

Wall density value should be determined for both directions of the building plan.

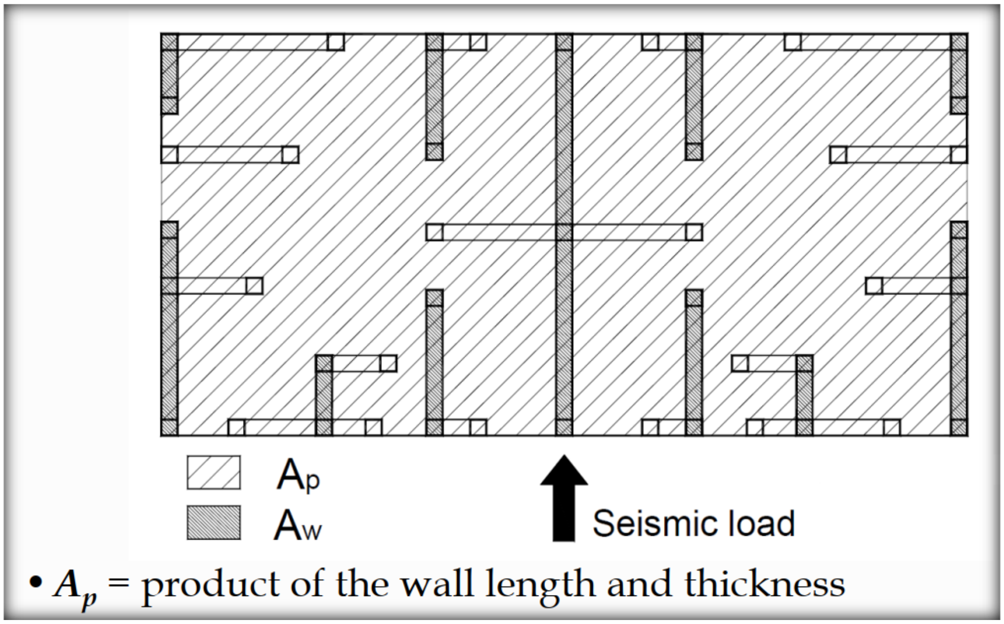


Figure 18. Building plan Area

11.1 Requirements of Simple Building

Exterior walls extend over at least 50% of the length of each end of the building plan at each story.

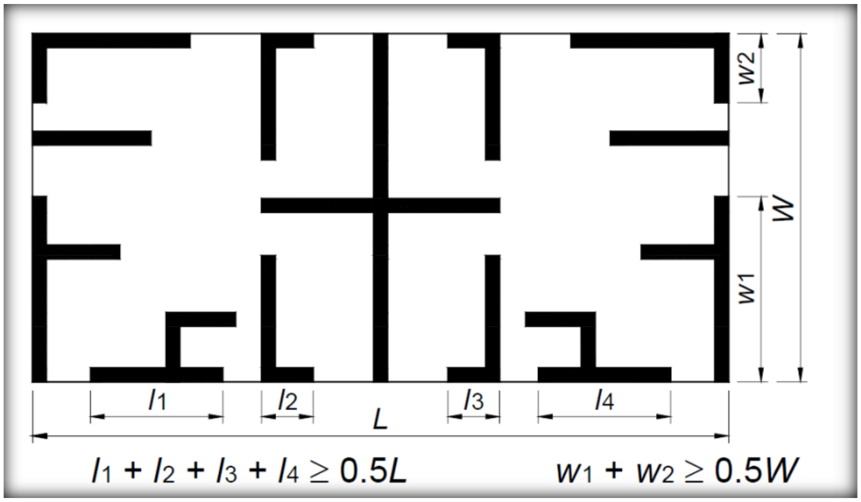


Figure 19. Exterior Walls

Exterior walls extend over at least 50% of the length of each end of the building plan at each story.

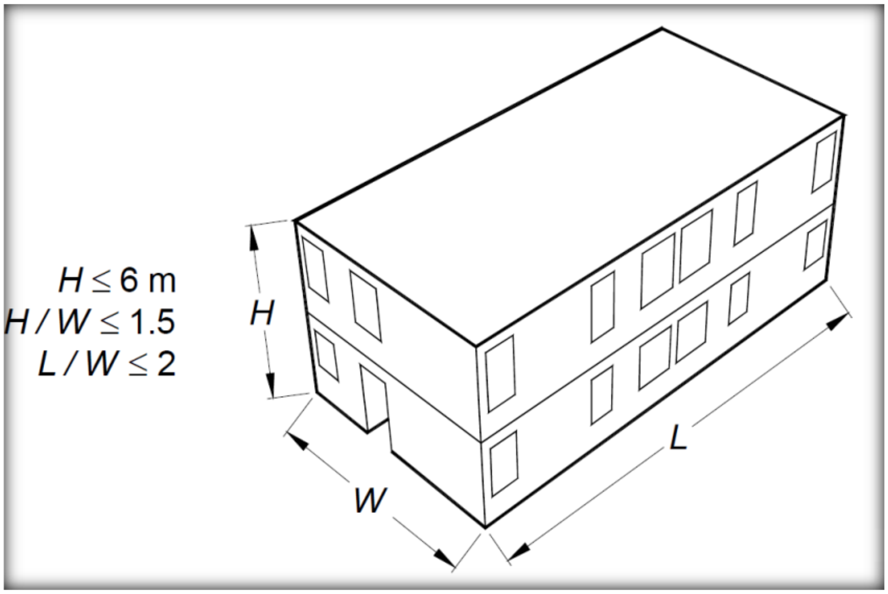


Figure 20. Exterior building plan

12.1 Limit State Design of Confined Masonry Walls

Design loads (F_d)

$$F_d = \gamma_f \times \text{Characteristic loads}$$

γ_f= partial safety factor

- 1.5DL + 1.5LL
- 1.5DL + 1.5(WL or EL)
- 0.9 DL + 1.5(WL or EL)
- 1.2DL+1.2LL+1.2(WL or EL)

Design strength of materials (f_d)

$$f_d = \frac{\text{Characteristic strength of material}}{\gamma_m}$$

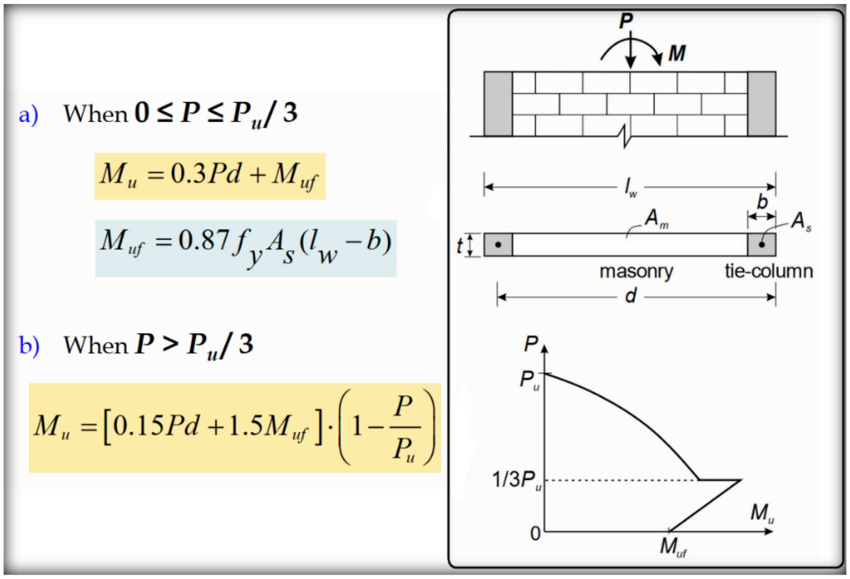
****Partial safety factor, γ_m should be taken as 2.0 for masonry, 1.5 for concrete and 1.15 for steel**

Axial Load Resistance (P_u)

$$P_u = k_s \left(0.4 f_m A_m + 0.45 f_{ck} A_c + 0.75 f_y A_s\right)$$

A_m = Net area of masonry
A_c = cross-sectional area of concrete excluding reinforcing steel
A_{st} = Area of steel
f_y = yield strength of the reinforcing steel
k_s = stress reduction factor as in Table 9 of IS:1905-1987

Moment resistance due to combined axial load and in-plane bending



a) When $0 \le P \le P_u/3$

$$M_u = 0.3Pd + M_{uf}$$

$$M_{uf} = 0.87 f_y A_s (l_w - b)$$

b) When $P > P_u/3$

$$M_u = \left[0.15Pd + 1.5M_{uf}\right] \cdot \left(1 - \frac{P}{P_u}\right)$$

Figure 21. Moment Resistance

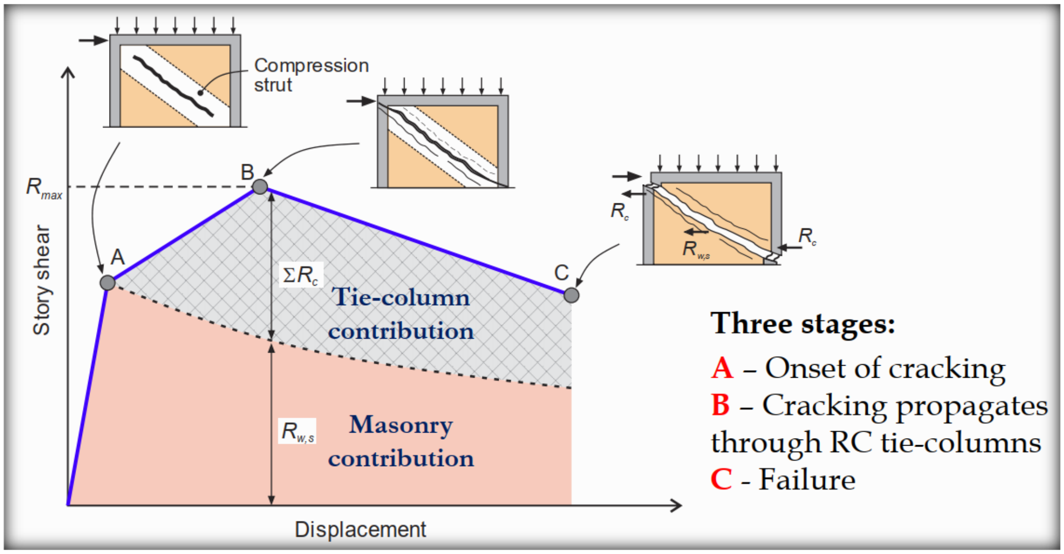


Figure 22. Shear Design

****Contribution of reinforced concrete tie-columns is not considered in the design to increase a safety margin.**

13.1 Design for Shear

Masonry shear resistance (V_u)

$$V_u = 0.8\left(0.5 v_m A_T + 0.4 P_d\right) f \le 1.5 v_m A_T$$

Where P_d is the design compressive axial load which shall include permanent loads only and with the partial safety factor of 1.0, and υ_m is masonry shear strength.

$$v_m = 0.18\sqrt{f_m}$$

$$\begin{array}{ll} f = 1.55 & \text{if } H/L \le 0.2 \\ f = 1.7 - 0.7\,H/L & \text{if } 0.2 < H/L \le 1.0 \\ f = 1.0 & \text{if } H/L > 1.0 \end{array}$$

<u>Design of Tie-Columns and Tie-Beams</u>

Minimum amount of longitudinal reinforcement

****Total area of reinforcement should be not less than 0.8 % of the gross cross-section area of the column**

Minimum amount of transverse reinforcement (ties)

Transverse reinforcement in the form of closed stirrups (ties) with the minimum area ASC equal to

$$A_{sc} = 0.002s \times h_c$$

Where h_c is the dimension of tie-column or tie-beam in the wall plane and s is the tie spacing. Tie spacing (s) should not exceed the lesser of 200 mm and 1.5t

7. Construction of Confined Masonry Walls

Masonry walls were constructed on top of the RC plinth band (at the ground floor) or the RC slabs (at upper story levels).

Figure 23. Bricks immersed in water before construction

The confined masonry walls were 230 mm thick (one brick thick) and were constructed in English bond. Horizontal mortar bed joint was about 10 to 12 mm thick.

Figure 24. Wall construction

Toothing at the wall to tie-column interface

Toothing is important for achieving a satisfactory bond between masonry walls and adjacent RC tie-columns

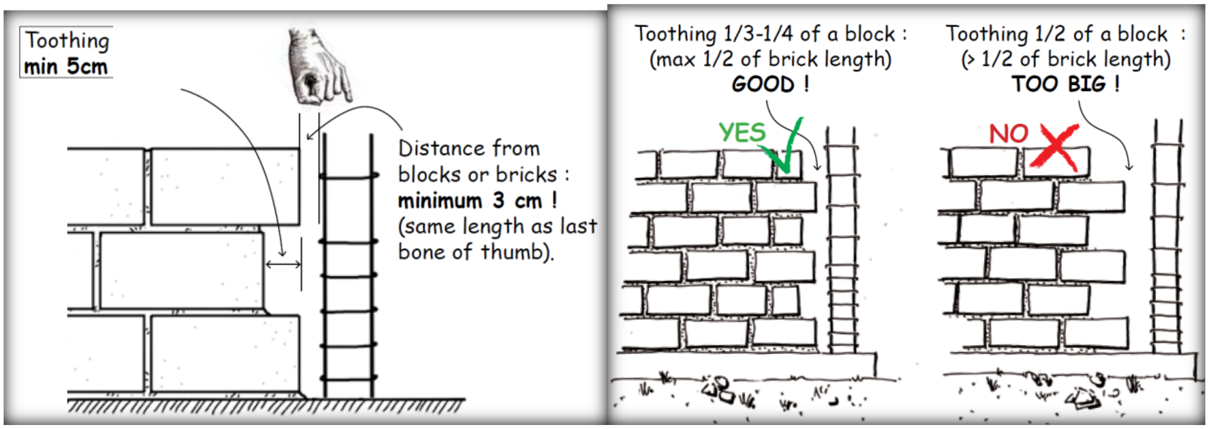
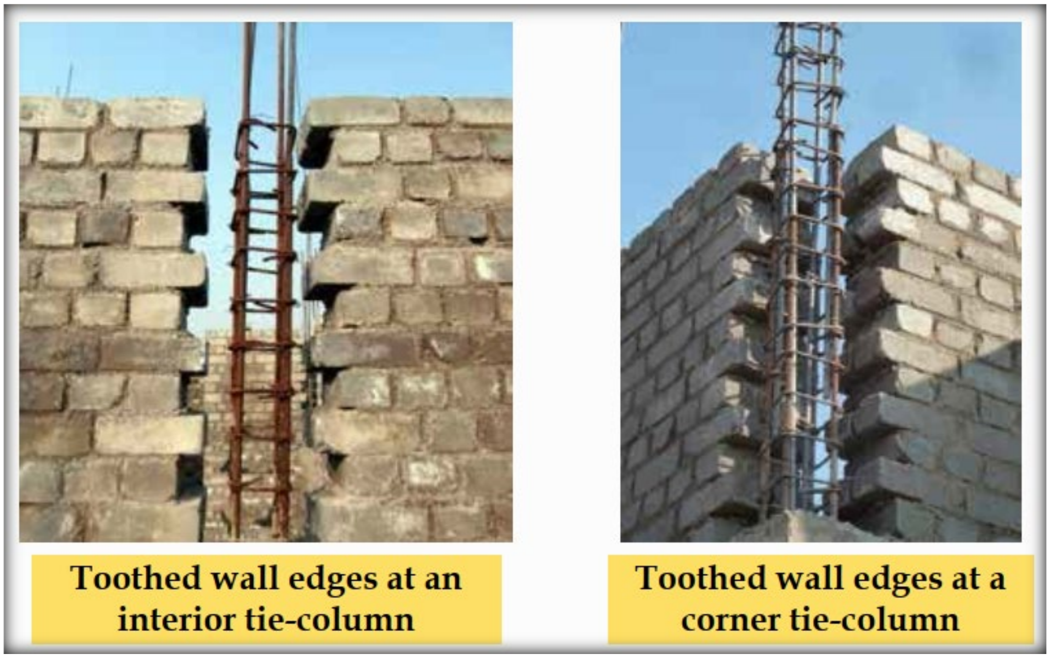


Figure 25. Toothing at the wall to tie-column interface



Toothed wall edges at an interior tie-column

Toothed wall edges at a corner tie-column

Figure 26. Toothed wall edges

Figure 27. Toothing at cross wall intersections

14.1 Wall construction stages

1.5 m of wall height (approximately one-half of the overall story height) was to be constructed in one lift, followed by casting of RC tie-columns.

Construction suspended for 3-4 days for the wall to achieve sufficient strength so that the concrete for the tie-columns could be poured. This procedure was repeated at each story level.

Wall construction completed up to 1.5 m height (one lift)

Tie-column construction completed up to 1.5 m height

Figure 28. Sequence of wall and tie-column construction

15.1 Reinforced concrete lintel bands

Building RC bands is common for load-bearing masonry construction.
RC lintel bands were constructed atop the openings (doors and windows) at each story level. First, reinforcement cages were assembled on the ground. Subsequently, formwork was set in place and concrete was poured. The upper courses of the brick masonry wall beneath the band had to be wetted before the concrete was poured to prevent the bricks from absorbing water from the fresh concrete.

Figure 29. Construction of RC lintel bands

Figure 30. Masonry and RC-tie-column construction above the lintel band level

16.1 Construction of Reinforced Concrete Tie-column

RC tie-column act in unison with the masonry walls to ensure the seismic safety of a confined masonry building.

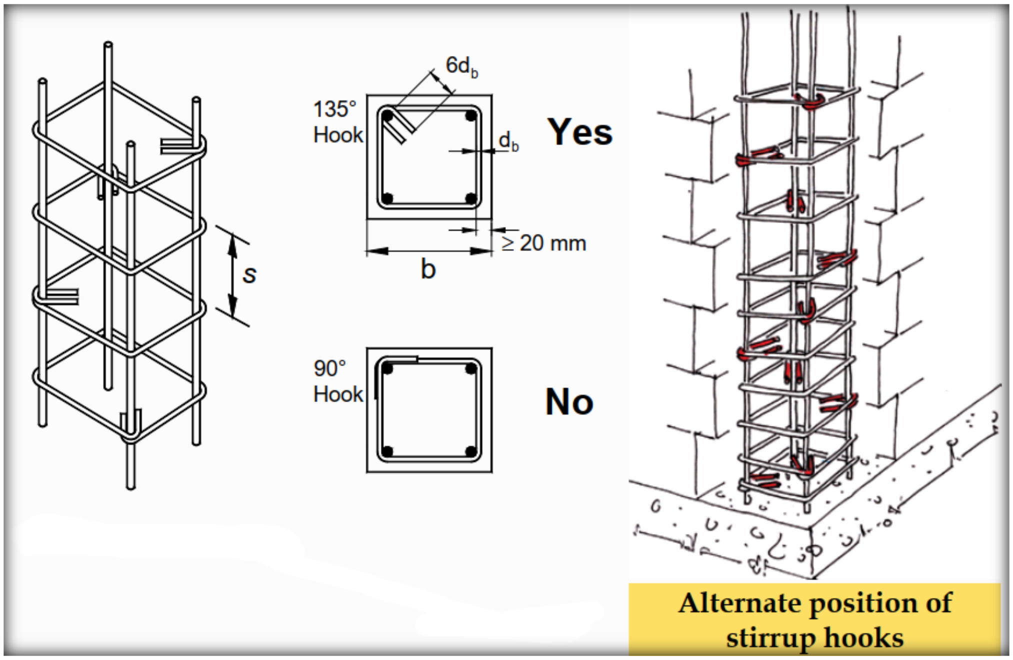


Figure 31. Construction of Reinforces Concrete Tie-column

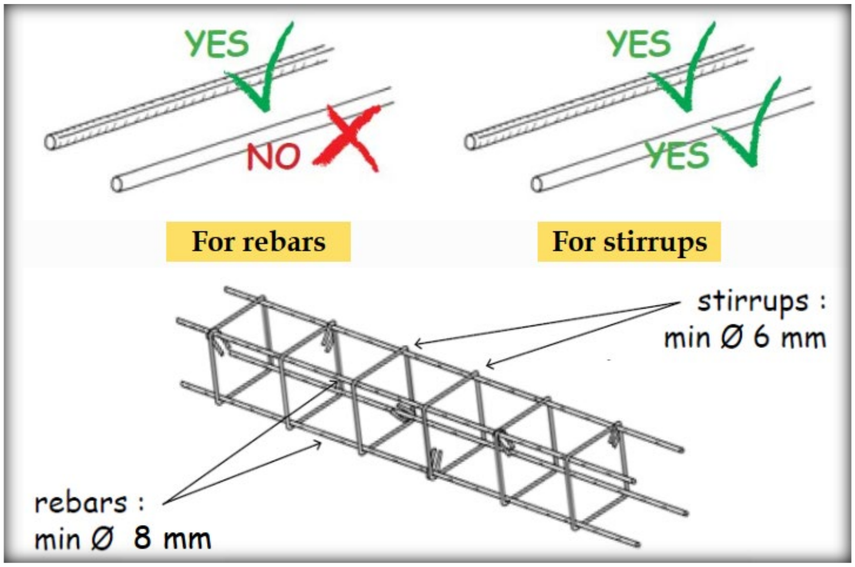


Figure 32. Construction of Reinforced Concrete Tie-column- Rebars

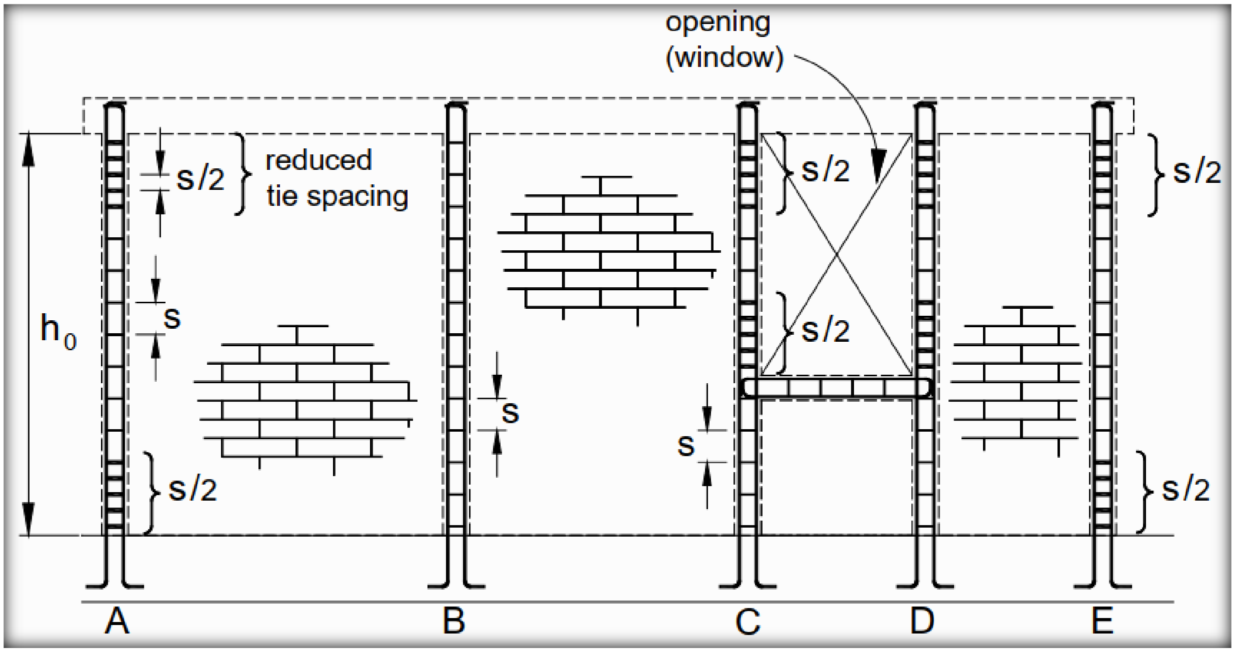


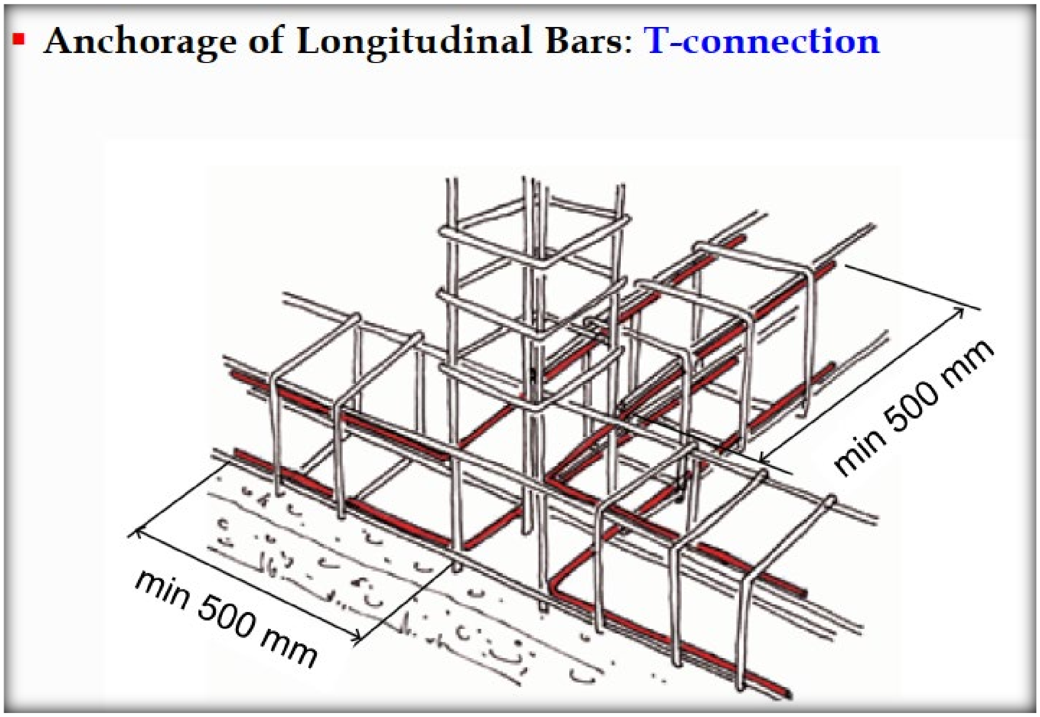
Figure 33. Spacing of transverse reinforcement (ties) in tie-columns

**Length over which the reduced tie spacing - twice the column dimension (*2b* or *2t*), or $h_o/6$

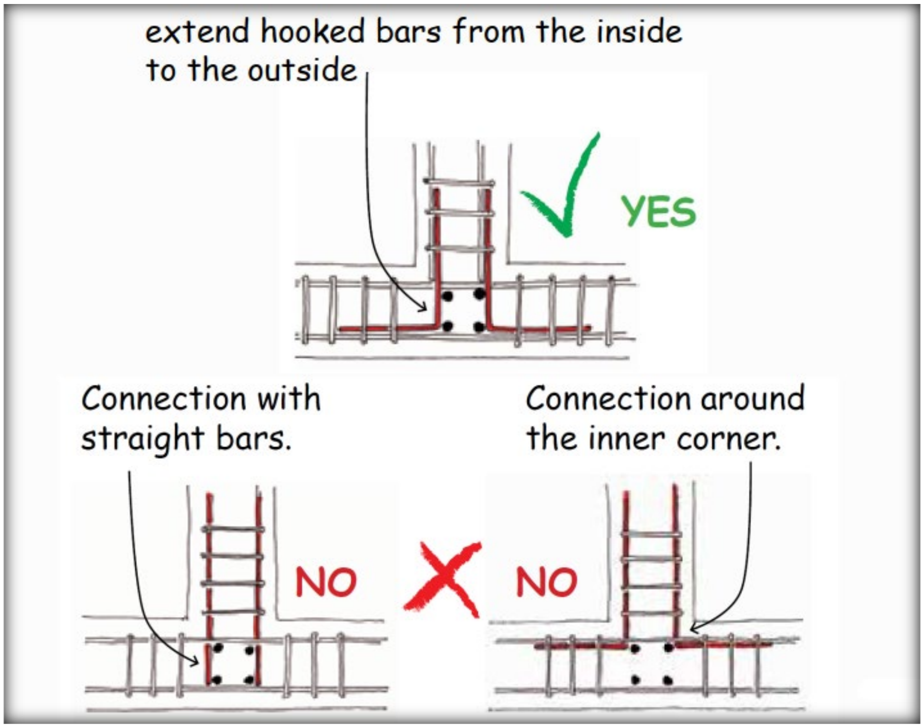
17.1 Construction Sequence of Reinforced Concrete Tie-column

Casting the concrete in RC tie-columns at each story level was done in two stages: First, a masonry wall was constructed up to the specified height equal to approximately one-half of the story height. Next, concrete was poured to the same height in adjacent tie-columns.

Figure 34. Anchorage of Longitudinal Bars: T-connection



- **Anchorage of Longitudinal Bars**: T-connection

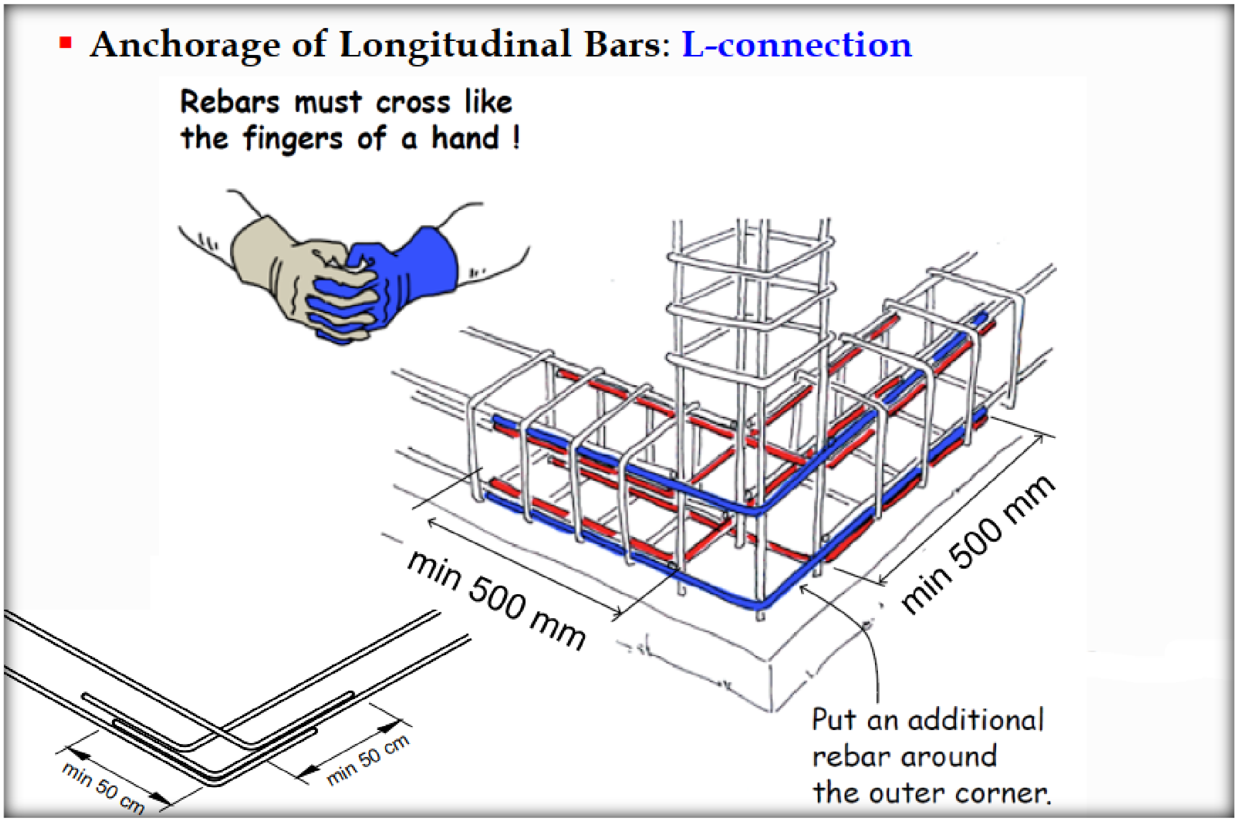


extend hooked bars from the inside to the outside

Connection with straight bars.

Connection around the inner corner.

Figure 35. Construction of Reinforced Concrete Tie-beam

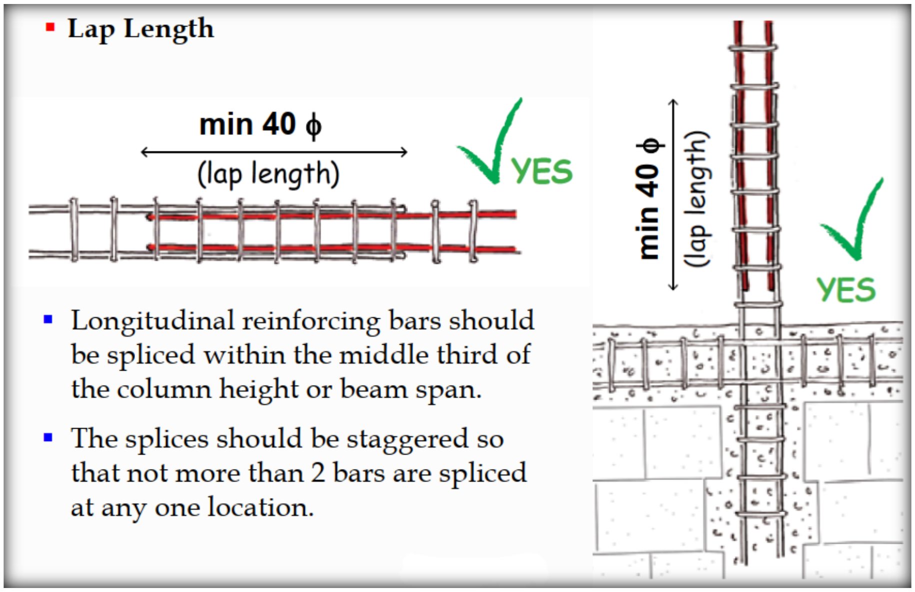


- **Anchorage of Longitudinal Bars:** **L-connection**

Rebars must cross like the fingers of a hand !

Put an additional rebar around the outer corner.

Figure 36. Anchorage of Longitudinal bars



- **Lap Length**

- Longitudinal reinforcing bars should be spliced within the middle third of the column height or beam span.
- The splices should be staggered so that not more than 2 bars are spliced at any one location.

Figure 37. Construction of Reinforced Concrete Elements - Lap Length

Figure 38. Construction of Slab

Summary

Confined masonry construction is commonly adopted in countries/regions with very high seismic risk, such as, Mexico, Chile, Peru, Indonesia, China, etc.

If properly built, shows satisfactory seismic performance Confined masonry construction have been exposed to several earthquakes:

- 1985Mexico City (Magnitude 8.0) 2
- 001El Salvador (Magnitude 7.7)
- 2003Bam, Iran (Magnitude 6.6)
- 2007Pisco, Peru (Magnitude 8.0)
- 2010Chile (Magnitude 8.8)
- 2010 Haiti (Magnitude 7.0)

Confined masonry buildings performed very well in these major earthquakes – some buildings were damaged but no human losses.

Confined masonry construction is a most suitable alternative for low- and medium-rise buildings of unreinforced masonry and non-ductile RC frames.

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