Outline of Presentation

- Components
- Basic Design Requirements
- Allowable Stresses
- Design of Unreinforced Masonry
- Design of Reinforced Masonry
- Stability Requirements
- Strength Design of Slender Walls and Shear Walls
- Earthquake Resistant Design
- Strengthening of Masonry Buildings for Earthquake
- Confined Masonry

Masonry Structures

Session 25
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S-8A SEng PRP Training Program

Components

Relevant Chapters of BNBC 2020

- Part 5 Chapter 2 Sec 2.2.4
- Part 6 Chapter 7
- Part 7

Mortar

Table 6.7.1: Mix Proportion and Strength of Commonly used Mortars

Grade of Mortar	Mix Proportion by Volume [1, 2]		Minimum Compressive Strength at 28 days, N/mm²
	Cement	Sand	
M1		3	10
M2		4	7.5
M3	1	5	5
M4		6	3
M5		7	2
M6		8	1

Components

- Masonry unit
- Mortar
- Grout
- Reinforcement
- Metal ties and anchors

Grout

ASTM C476

TABLE 1 Conventional Grout Proportions by Volume

Type	Parts by Volume of Portland Cement or Blended Cement	Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition	
			Fine	Coarse
Fine grout	1	0–1/10	2¼ –3 times the sum of the volumes of the cementitious materials	...
Coarse grout	1	0–1/10	2¼ –3 times the sum of the volumes of the cementitious materials	1–2 times the sum of the volumes of the cementitious materials

Masonry Units

- Common building clay bricks (BDS 208)
- Burnt clay hollow bricks (BDS 1263)
- Burnt clay facing bricks (BDS 1250)
- Hollow concrete blocks (BDS EN 772)
- Others

Basic Design Requirements

Reinforcement

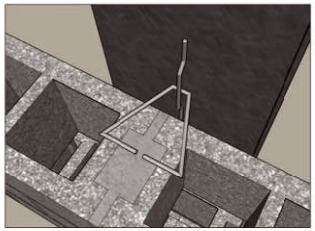
- ASTM A82/A82M: Cold Drawn Steel Wire for Concrete Reinforcement
- ASTM A615/A615M: Deformed and Plain Billet Steel Bars
- ASTM A996/A996M: Rail-Steel Deformed and Plain Bars
- ASTM A996/A996M: Axle-Steel Deformed and Plain Bars
- ASTM A706/A706M: Low-Alloy Steel Deformed Bars
- ASTM A767/A767M: Zinc-Coated (Galvanized) Steel Bars
- ASTM A775/A775M: Epoxy - Coated Reinforcing Steel Bars

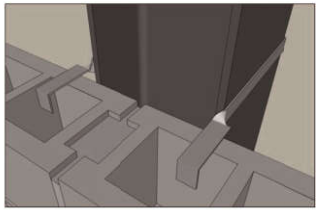
Design Considerations

- Working stress design
- Linear stress-strain distribution
- Small eccentricity of loading

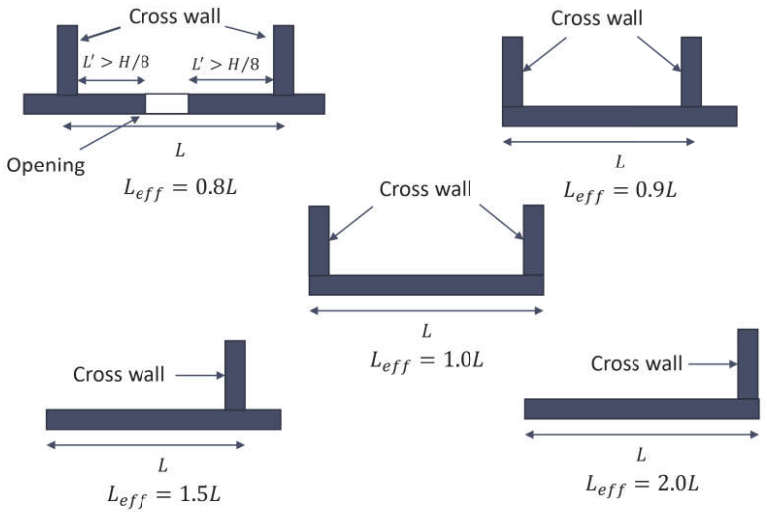
Metal Ties and Anchors

- ASTM A82/A82M: Wire Anchor and Ties
- ASTM A1008/A1008M: Sheet Metal Anchors and Ties

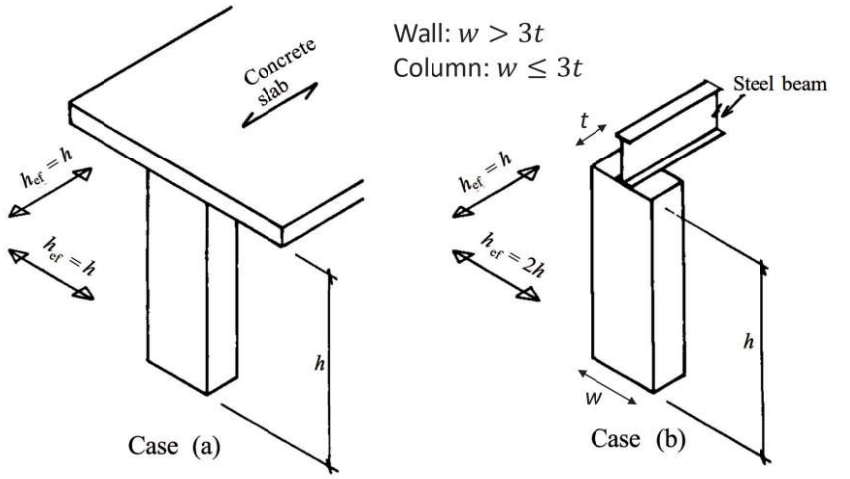




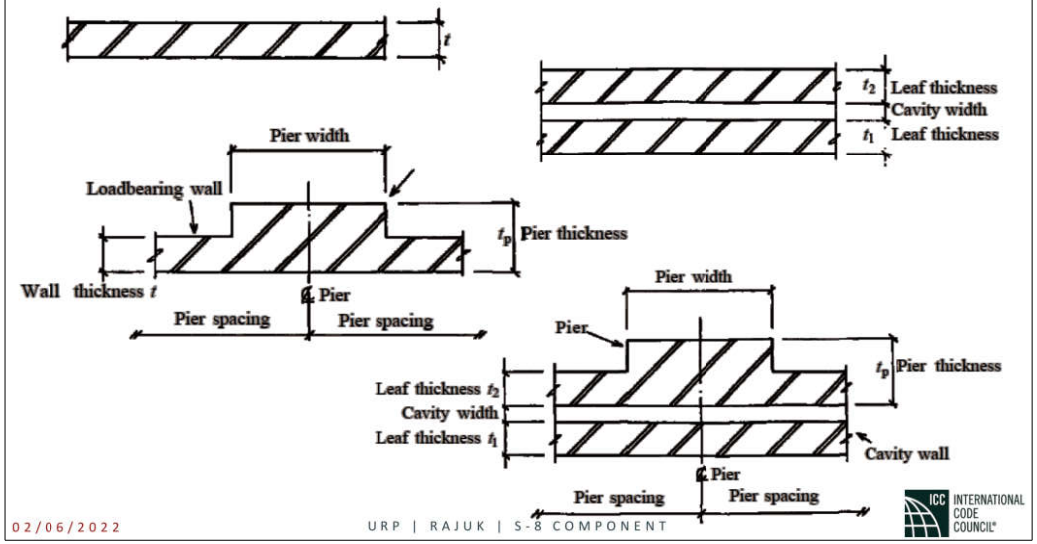
Effective Length



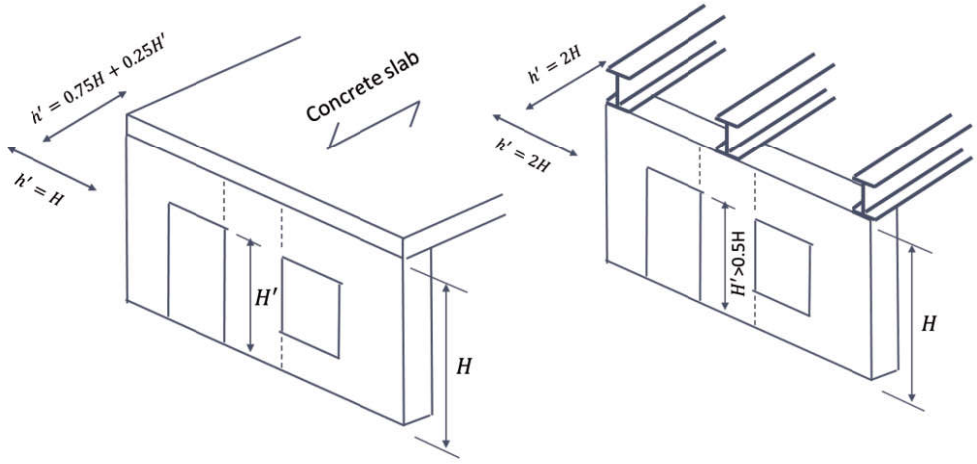
Effective Height



Effective Thickness

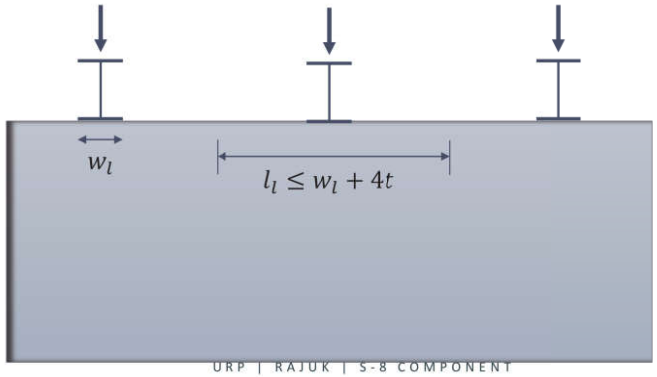


Effective Height of a Wall with Opening

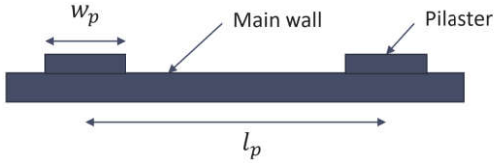


Loads

- Loads and load combination according to Part 6 Chapter 2.
- The angle of dispersion of vertical load on walls shall be taken as not more than 30° from the vertical.



Effective Thickness



$$t_{eff} = kt_w$$

l_p/w_p	Stiffening Coefficient, k*		
	$t_p/t_w = 1$	$t_p/t_w = 2$	$t_p/t_w = 3$
6	1.0	1.4	2.0
8	1.0	1.3	1.7
10	1.0	1.2	1.4
15	1.0	1.1	1.2
20 or more	1.0	1.0	1.0

* Linear interpolation is permitted for obtaining intermediate values of *k*

Minimum Design Demension

- Load bearing walls: $t \geq 250$ mm
- Parapet:
  - $t \geq 200$ mm
  - $h \leq 4t$

Slenderness Ratio

- Walls:
  - Slenderness ratio = lesser of h'/t_{eff} or L_{eff}/t_{eff}
  - Slenderness ratio ≤ 20
- Columns:
  - Slenderness ratio = h'/t_{eff}
  - Slenderness ratio ≤ 12

Allowable Compressive Stresses

- If no special inspection all the allowable stresses shall be reduced by 50%.
- Axial compressive stress
  - URM

$$F_a = \frac{f'_m}{5}\left[1 - \left(\frac{h'}{42t}\right)^3\right]$$

  - RM

$$F_a = \left(\frac{f'_m}{5} + \frac{A_s}{1.5A_g}F_{sc}\right)\left[1 - \left(\frac{h'}{42t}\right)^3\right]$$

- Compressive stress in Flexure

$$F_b = 0.33f'_m \leq 10\ \mathrm{N/mm^2}$$

Allowable Stresses

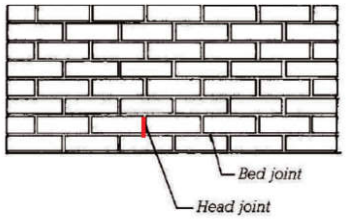
Allowable Tensile Stress

Table 6.7.2: Flexural Tension, Ft

Masonry	Normal to Bed Joints N/mm²	Normal to Head Joints N/mm²
Solid Units	0.20	0.40
Hollow Units	0.12	0.25

Table 6.7.3: Tension Normal to Head Joints, Ft

Masonry	Clay Units N/mm²	Concrete Units N/mm²
Solid Units	0.35	0.40
Hollow Units	0.22	0.25



- For Types M_3 and M_4 mortar, the values shall be reduced by 25 percent.

Compressive Strength of Masonry

ASTM E447: Prism Test

- Test prior to construction: A set of five masonry prisms
- Testing during construction:
  - When full allowable stresses are used in design: A set of three prisms for each 500 square meters of wall.
  - When 50% of the allowable stresses are used in design: No test.

Allowable Stresses in Reinforcement

- Tensile stress
  - Deformed bars: $F_s = 0.5f_y \leq 165$ N/mm²
  - Ties, anchors and plain bars: $F_s = 0.4f_y \leq 135$ N/mm²
- Compressive stress
  - Shear walls: $F_{sc} = 0.4f_y \leq 165$ N/mm²
  - Flexural members: $F_{sc} = 0.5f_y \leq 165$ N/mm²
- Bond stress
  - Plain Bars: 0.30 N/mm²
  - Deformed Bars: 1.0 N/mm²

Allowable Shear Stress

- Shear stress for flexural members
  - URM : $F_v = 0.083\sqrt{f'_m} \leq 0.25$ N/mm²
  - RM: $F_v = 0.25\sqrt{f'_m} \leq 0.75$ N/mm²
- Shear stress for shear walls
  - URM
    - For clay units: $F_v = 0.025\sqrt{f'_m} \leq 0.40$ N/mm²
    - For concrete units:
      - M1 or M2 Mortar: 0.20 N/mm²
      - M3 Mortar: 0.12 N/mm²

Modulus of Elasticity

a) Modulus of Elasticity for Masonry:

$E_m = 750f'_m \leq 15{,}000$ N/mm²

b) Modulus of Elasticity for Steel

$E_s = 2{,}00{,}000$ N/mm²

c) Shear Modulus of Masonry

$G = 0.4E_m$ N/mm²

Allowable Shear Stress for RM Shear Walls

Table 6.7.4: Allowable Shear Stress for Reinforced Masonry Shear Walls, F_v

Masonry Wall	*M/Vd*	F_v, N/mm²	Maximum Allowable N/mm²
Masonry taking all shear	< 1	$\frac{1}{36}\left(4 - \frac{M}{Vd}\right)\sqrt{f'_m}$	$\left(0.4 - 0.2\frac{M}{Vd}\right)$
	≥ 1	$0.083\sqrt{f'_m}$	0.17
Reinforcement taking all shear	< 1	$\frac{1}{24}\left(4 - \frac{M}{Vd}\right)\sqrt{f'_m}$	$\left(0.6 - 0.2\frac{M}{Vd}\right)$
	≥ 1	$0.125\sqrt{f'_m}$	0.37

Design of Reinforced Masonry

Design of Unreinforced Masonry

Assumptions and Stresses

- Assumptions:
  a) Masonry carries no tensile stress.
  b) Reinforcement is completely bonded.
- Members Subjected to Axial Compression:

$$f_a = \frac{P}{A_e}$$

- Members Subjected to Shear Force:

$$f_v = \frac{V}{bjd}; \qquad A_v = \frac{sV}{F_s d}; \quad s \le \frac{d}{2} \text{ or } 600 \text{ mm}$$

- Members Subjected to Flexural Stress:

$$f_b = \frac{M}{bd^2}\left(\frac{2}{jk}\right); \qquad f_s = \frac{M}{A_s jd}.$$

Design of Unreinforced Masonry

- Members Subjected to Axial Compression:

$$f_a = \frac{P}{A_e}$$

- Members Subjected to Flexure:

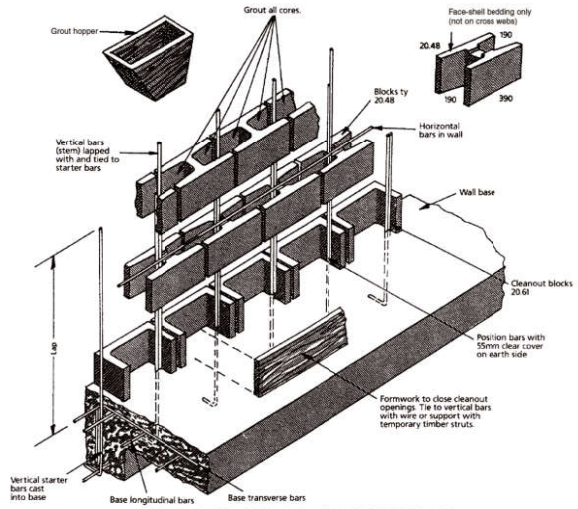
$$f_b = \frac{Mc}{I}$$

- Members Subjected to Shear:

$$f_v = \frac{V}{A_e}$$

Stability Requirements

Reinforcement Requirements and Details



Stability Requirements

- Height to width ratio of building does not exceed 2.

Table 6.7.9: Thickness and Spacing of Stiffening Walls

Thickness of Load Bearing Wall to be Stiffened (mm)	Height of Storey not to Exceed (m)	Stiffening Wall *		
		Thickness not less than		Maximum spacing (m)
		1 to 3 storeys (mm)	4 and 5 storeys (mm)	
100	3.2	100	-	4.5
200	3.2	100	200	6.0
300	3.4	100	200	8.0
above 300	5.0	100	200	8.0

* Storey height and maximum spacing as given are centre to centre dimensions.

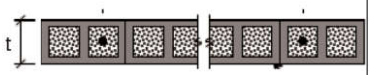
Reinforcement Requirements and Details

- Maximum reinforcement size:
  - 35 mm
  - 6% of cell area without splice
  - 12% of cell area with splice
- Spacing of longitudinal reinforcement:
  - Clear distance between parallel bars $\geq d_b$ or 25 mm
  - Clear distance from any surface of masonry unit $\geq$ 6 mm for fine grout or 12 mm for coarse grout
- Clear Cover
  a) 20 mm when not exposed to weather
  b) 40 mm when exposed to weather
  c) 50 mm when exposed to soil

Deflection Calculation

$$M_{cr} = Sf_r$$

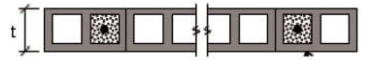
When $M_{ser} \leq M_{cr}$, $\Delta_s = \frac{5M_s h^2}{48E_m I_g}$



Fully Grouted

When $M_{cr} < M_{ser} < M_n$, $\Delta_s = \frac{5M_{cr}h^2}{48E_m I_g} + 5\frac{(M_{ser}-M_{cr})h^2}{48E_m I_{cr}}$

$\Delta_s \leq 0.007h$



Partially Grouted

Table 6.7.13: Values of the Modulus of Rupture, f_r

Type of Masonry	Fully Grouted	Partially Grouted
Solid Masonry	$0.17\sqrt{f'_m} \leq 0.65$ N/mm²	Not allowed
Hollow Unit Masonry	$0.33\sqrt{f'_m} \leq 1.2$ N/mm²	$0.21\sqrt{f'_m} \leq 0.65$ N/mm²

Strength Design of Slender Walls and Shear Walls

Design of Shear Walls

- For axial load and axial load with flexure $\phi = 0.65$
- For members with f_y less than 410 N/mm² and with symmetrical reinforcement, ϕ may be increased linearly to 0.85 as ϕP_n decreases from $0.10f'_m A_e$ or $0.25P_b$ to zero.
- For shear $\phi = 0.60$. The shear strength reduction factor may be increased to 0.80 for any shear wall when its nominal shear strength exceeds the shear corresponding to development of its nominal flexural strength for the factored load combination.

Design of Slender Walls

$$\frac{P_w + P_f}{A_g} \leq 0.04f'_m; \qquad f'_m \leq 40 \text{ N/mm}^2$$

$$t \geq 150 \text{ mm}$$

$$\rho_{max} \leq 0.5\rho_b$$

$$M_u = \frac{w_u h^2}{8} + P_u \frac{e}{2} + \left(P_{uw} + P_{uf}\right)\Delta_u$$

Earthquake Resistant Design

Nominal Strength

- f'_m shall not be less than 7 N/mm^2 or greater than 20 N/mm^2.
- Axial strength: $P_o = 0.85 f'_m (A_e - A_s) + f_y A_s$
- Shear strength:

Table 6.7.14: Maximum Nominal Shear Strength Values

$\frac{M^*}{Vd}$	$\frac{V_n}{A_e\sqrt{f'_m}}$
≤ 0.25	72.0
≥1.00	48.0

* M is the maximum bending moment that occurs simultaneously with the shear load V at the section under consideration. Interpolation may be by straight line for *M/Vd* values between 0.25 and 1.00.

General

- All masonry structures constructed in the Seismic Zones 2, 3 and 4 shall be designed in accordance with these provisions.
- Crushing strength not less than 12 N/mm^2 shall be used.
- Mortar not leaner than M_3 shall be used.

Boundary Member

- Boundary members shall be provided when the failure mode is flexure and the maximum extreme fibre stress exceeds $0.2f'_m$.
- When the failure mode is flexure, boundary member shall be provided to confine all vertical reinforcement whose corresponding masonry compressive stress exceeds $0.4f'_m$. The minimum length of the boundary member shall be 3 times the thickness of the wall.
- Boundary members shall be confined with minimum of 10 mm diameter bars at a maximum of 200 mm spacing.

Band

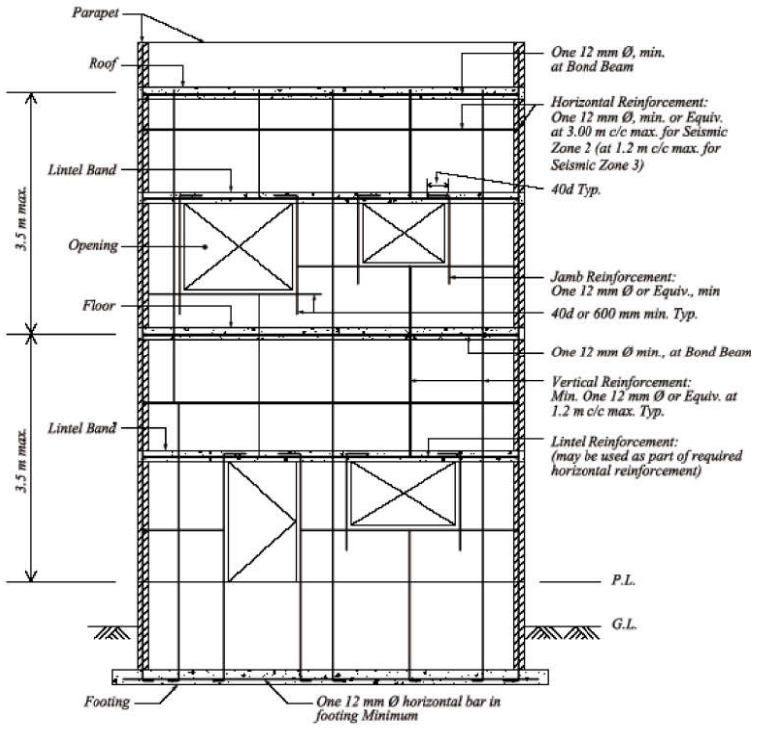
- The band shall be made of reinforced concrete with f_c' not less than 20 N/mm2 or reinforced brickwork in cement mortar not leaner than 1: 4.
- The bands shall be to the full width of the wall and not less than 75 mm in depth and shall be reinforced.

Table 6.7.16: Band Reinforcement

Seismic Zones	Plain Mild Steel Bars	High Strength Deformed Bars	Links
2, 3	2 - 12 mm dia, one on each face of the wall with suitable cover	2 - 10 mm dia, one on each face of the wall with suitable cover	6 mm dia, 150 mm c/c
4	2 - 16 mm dia, one on each face of the wall with suitable cover	2 - 12 mm dia, one on each face of the wall with suitable cover	6 mm dia, 150 mm c/c

Provisions for Seismic Zone 2 and 3

- Vertical reinforcement of at least 12 mm diameter shall be provided continuously from support to support at each corner, at each side of each opening, at the ends of walls and at a maximum spacing of 1.2 m horizontally throughout the wall.
- Horizontal reinforcement not less than 12 mm diameter shall be provided:
  - at the bottom and top of wall openings and shall extend at least 40 bar diameters, with a minimum of 600 mm, past the opening,
  - continuously at structurally connected roof and floor levels and at the top of walls,
  - at the bottom of the wall or in the top of the foundations when dowelled to the wall.



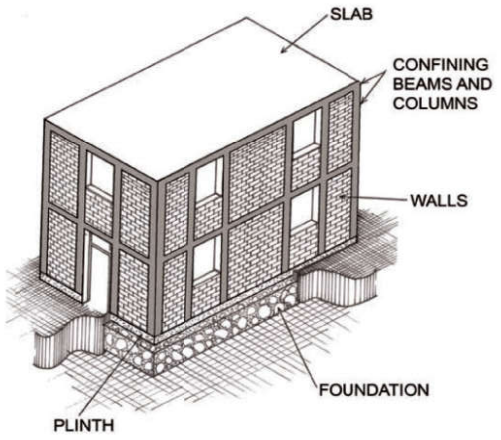
Provisions for Seismic Zone 4

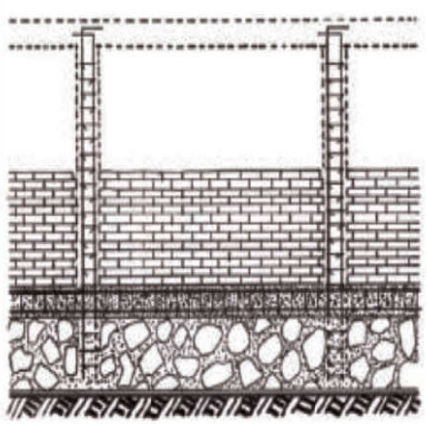
- All masonry structures built in Seismic Zone 4 shall be designed and constructed in accordance with requirements for Seismic Zone 2 and 3.
- The sum of the areas of horizontal and vertical reinforcement shall be at least 0.002 times the gross cross-sectional area of the wall.
- The area of reinforcement in either direction shall not be less than 0.0007 times the gross cross-sectional area of the wall.
- The spacing of reinforcement shall not exceed 1.20 m.
- The diameter of reinforcing bar shall not be less than 10 mm.

Confined Masonry

Strengthening of Masonry Buildings for Earthquake

Confined Masonry





Seismic Zones	No. of Storey	Strengthening Arrangements to be Provided.
1	Up to 4	a) Masonry mortar shall not be leaner than M_3
2, 3	Up to 2 with pitched roof	a) Masonry mortar shall not be leaner than M_3 b) By lintel and roof band (Sec 7.8.6.3) c) By vertical reinforcement at corners and junctions of walls (Sec 7.8.6.4) d) Bracing in plan at tie level for pitched roof*
	3 to 4	a) Masonry mortar shall not be leaner than M_3 b) By lintel and roof band (Sec 7.8.6.3) c) By vertical reinforcement at corners and junctions of walls (Sec 7.8.6.4) d) Vertical reinforcement at jambs of openings (Sec 7.8.6.5) e) Bracing in plan at tie level for pitched roof*
4	Up to 4	a) Masonry mortar shall not be leaner than M_3 b) By lintel and roof band (Sec 7.8.6.3) c) By vertical reinforcement at corners and junctions of walls (Sec 7.8.6.4) d) Vertical reinforcement at jambs of openings (Sec 7.8.6.5) e) Bracing in plan at tie level for pitched roof*

- At tie level all the trusses and the gable end shall be provided with diagonal bracing in plan so as to transmit the lateral shear due to earthquake force to the gable walls acting as shear walls at the ends.

Vertical and Horizontal Confining Elements

- Vertical confining elements should be placed:
  - (a) at the free edges of each structural wall element;
  - (b) at both sides of any wall opening with an area of more than 1.5 m^2;
  - (c) within the wall, if necessary, in order not to exceed a spacing of 5 m between the confining elements;
  - (d) at the intersections of structural walls, wherever the confining elements imposed by the above rules are at a distance larger than 1.5 m.
- Horizontal confining elements shall be placed in the plane of the wall at every floor level and in any case with a vertical spacing of not more than 4 m.

Comparison with RC Frame

Component	Confined masonry construction	RC frame construction
Gravity and lateral load-resisting system	Masonry wall: Main load bearing component. Tie beams and columns: Confining component only.	Beams and columns: Main load bearing components. Masonry wall: Non-load bearing infill only.
Foundation construction	Strip footing	Isolated footing
Superstructure construction sequence	First walls and then columns and beams and floors at last.	First columns, then beams and floors and walls at last.

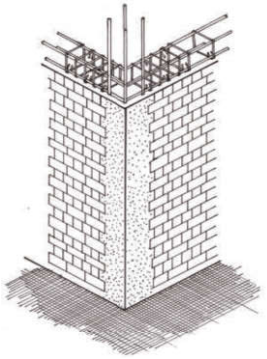
Confined Masonry Details

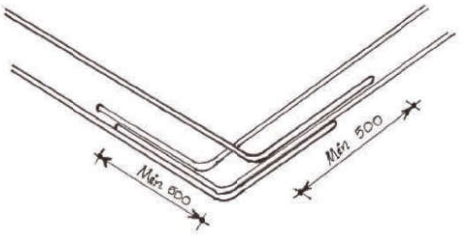
- Confining elements should have a cross-sectional area not less than 0.02 m^2, with a minimum dimension of 150 mm in the plan of the wall.
- The longitudinal reinforcement may not have a cross-sectional area less than 300 mm^2, nor than 1 percent of the cross-sectional area.
- Stirrups not less than 6 mm in diameter and spaced not more than 300 mm should be provided.
- Column ties should preferably have 135° hooks. . At a minimum, 6 mm ties at 200 mm spacing should be provided. It is recommended to use 6 mm ties at 100 mm spacing in the column end-zones

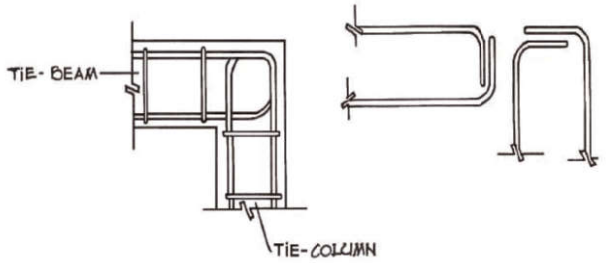
Architectural Guideline

- Building length-to-width ratio should not exceed 4.
- The walls should be continuous up.
- Openings should be placed in the same position.
- At least two fully confined walls in each direction.
- Minimum wall density and maximum building height:
  - For seismic zones 1 and 2: 2% and 4-storey
  - For seismic zone 3: 4% and 3-storey
  - For seismic zone 4: 5% and 2-storey

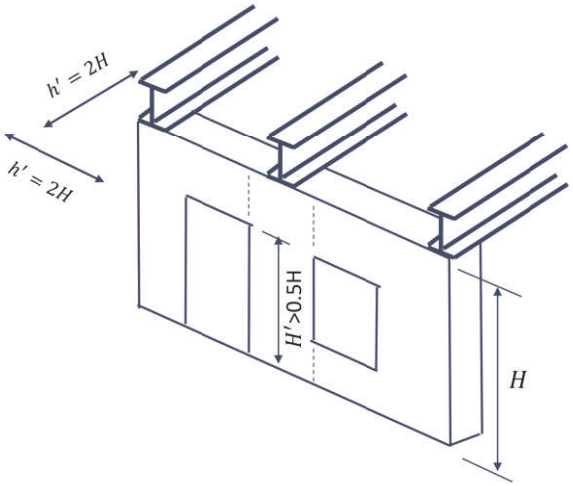
Questions?
Thank you

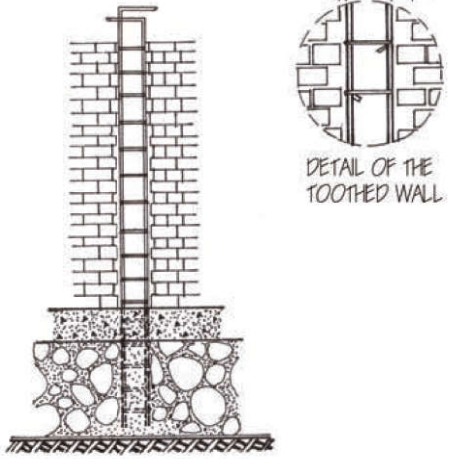




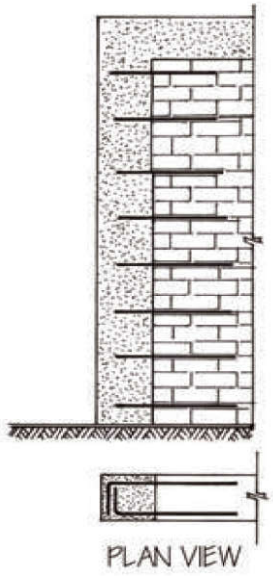


Effective Height of a Wall with Opening





DETAIL OF THE TOOTHED WALL



PLAN VIEW

Effective Height of a Wall with Opening