CVNG 2006 STRUCTURAL DESIGN I

MASONRY DESIGN

OUTLINE OF TOPICS

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Delivery Media: ☑ Oral ☑ Blackboard ☐ Handouts ☐ Slides/Transparencies ☑ Internet

Equipment: ☐ Slide Projector ☐ Transparency Projector ☑ Computer Projector

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Learning Outcome: To perform the structural design of common masonry walls in out-of-plane bending.

Scope/Limitations: IBC 2009; ASTM; Hollow Unit Masonry Only; Cantilever Walls Without Openings; Unreinforced Walls Under Combined Axial Load and Out-of-Plane Bending (Vertical-Spanning), and Reinforced Walls Under Combined Axial Load and Out-of-Plane Bending (Vertical-Spanning).

Primary Approach: Procedure-Based; Example-Based.

TOPICS

1.0 Review of Masonry as a Construction Material
  - 1.1 Uses of Masonry and Types of Section
  - 1.2 Masonry Structural Systems
  - 1.3 Properties of Masonry

2.0 Hollow Unit Unreinforced Masonry Walls Under Combined Axial Load and Out-of-Plane Bending (Vertical-Spanning)
  - 2.1 Design Procedure
  - 2.2 Design Example

3.0 Hollow Unit Reinforced Walls Under Combined Axial Load and Out-of-Plane Bending (Vertical-Spanning)
  - 3.1 Slender Wall Design Procedure
  - 3.2 Design Example

1.0 Review of Masonry as a Construction Material

1.1 Uses of Masonry and Types of Section

Masonry is moreso a type of construction than a construction material. Masonry comprises of masonry units, mortar and concrete filler (called grout) that form the constituents of many types of masonry structural systems: walls; columns; arches; beams, and floors. However individual units also have extensive application as: wall, floor and roofing tiles; veneer (or backing); pavers; tunnel, drain and refractory linings, and sewer pipe.

Masonry units are typically made in relatively small sizes to be sufficiently light that it can be handled by an individual. There are several types of masonry unit in terms of form and basic material. With respect to the former there are solid and voided units where the voids can be vertical or horizontal. In terms of basic materials, the main types are:

1. Burned or unburned clay
2. Stone
3. Adobe
4. Shale
5. Concrete
6. Glass

The Caribbean region is prone to hurricane and earthquakes and as such, structural masonry must be reinforced. The following information is based primarily on burned clay masonry units (classified as clay brick and tile), and concrete masonry block units, as these are the principal types used for reinforced masonry wall construction.

The main types of masonry walls are: single-leaf (wythe) hollow unit; single-leaf (wythe) solid unit; double-leaf (wythe) hollow unit; double-leaf (wythe) solid unit; cavity; composite, and veneer.

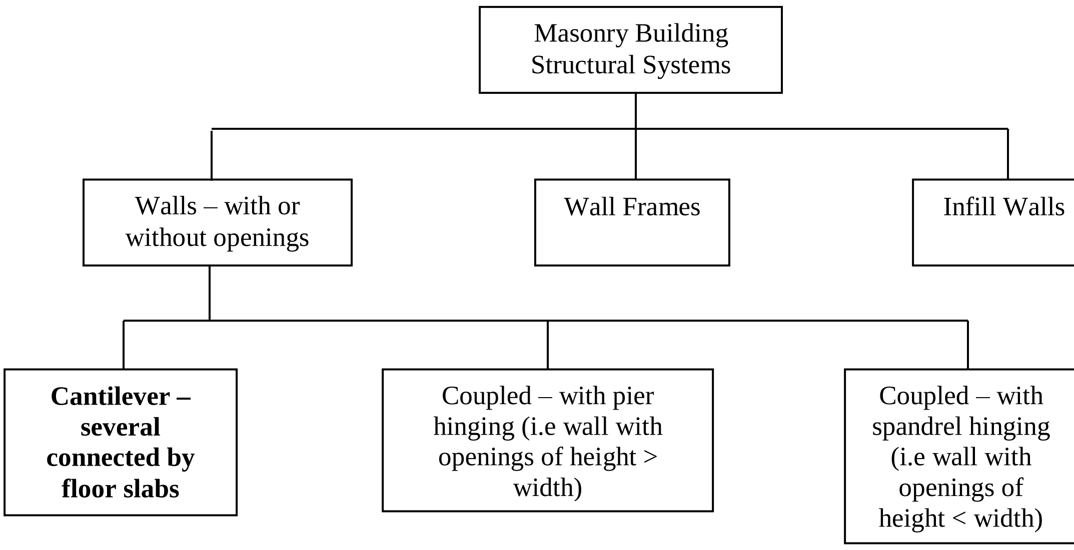
The single-wythe hollow or solid unit walls can be fully or partially grouted. The double leaf is essentially two single-leaf walls placed side-by-side without a space between and connected together using either horizontal metal ties, or by bonding blocks at right angles to the run of the wall. Cavity walls are like double leaf walls except that there is a space between the wythes that is filled with concrete. Composite walls are the same as double-wythe or cavity walls except that the wythes are made of different types of masonry unit or a different material. Veneer walls are double wythe walls where one of the wythes is unreinfored. This unreinfored layer is mainly used for aesthetic reasons.

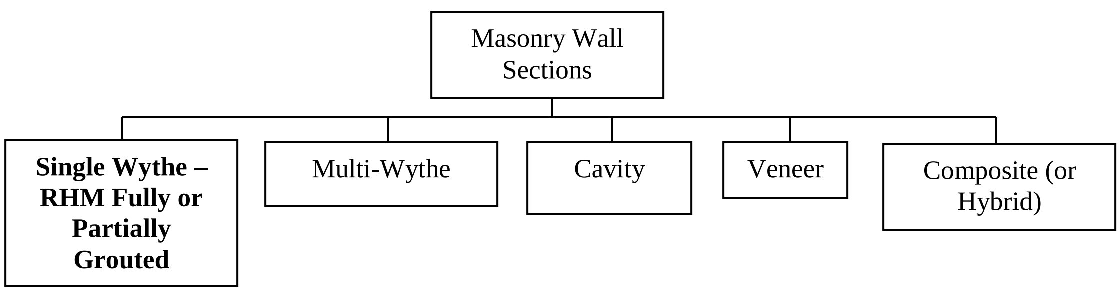
In the Caribbean practice, the main type of reinforced masonry wall used is the 150 and 200mm single-wythe hollow unit wall that is partially or fully grouted. These walls are typically of concrete vertically-celled hollow units though there is the recent availability in Trinidad and Tobago of a fired clay vertically-celled hollow unit block.

The main type of single-storey residential construction in Trinidad and Tobago is based on a 100mm fired clay hollow unit where the cells are horizontal and therefore unreinforced. An unreinforced 100mm concrete block is also extensively used in mass housing projects but the cells are vertical and too small to reliably accept reinforcement. Recent research has indicated that masonry wall construction based on these types of units are unsafe for the seismic conditions of Trinidad and Tobago and a new Residential Building Code is in progress that will disallow its use for any load-bearing functions.

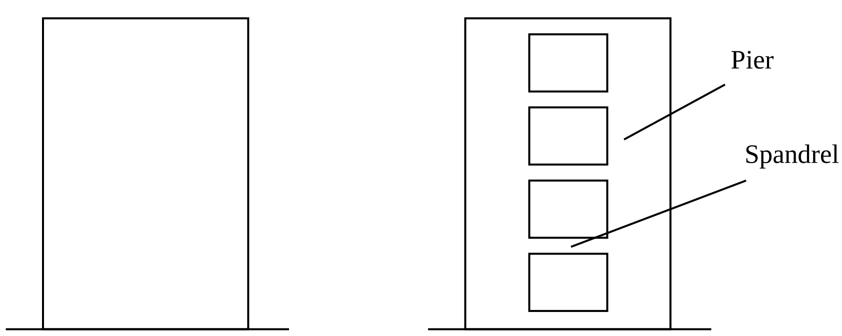
The design of masonry walls in the Caribbean is based on U.S codes of practice and therefore the following terminology is based on the ASTM standards. As such, the vertically-celled concrete hollow unit is called a block, the aforementioned vertically-celled hollow clay unit is called a brick, and horizontally-celled hollow clay units are called structural tiles. A unit is considered to be solid if its net solid area is more than 75 percent of its gross area. In local parlance, probably based on U.K terminology, all hollow units are called blocks and only units without voids are called bricks.

1.2 Masonry Structural Systems





In masonry design and construction practice, there are a number of structural systems and wall section types that the designer can choose from as indicated above. Two main types of walls are cantilever walls and coupled walls. The typical wall is a cantilever wall – it is fixed at the base but free at the top like a cantilever. A cantilever wall may have openings. The coupled wall is like a cantilever wall with openings but with the openings arranged in such a manner that the wall behaves like two cantilever walls linked by a (spandrel or coupling) beam.



Typical cantilever wall   Coupled wall (with spandrel hinging)

A masonry wall frame system is like a reinforced concrete frame system, but where the beam and column members are of masonry. In a masonry infilled-frame, the frame is of reinforced concrete or structural steel, and the infill is of masonry. This system is actually a hybrid structure where the overall response is contributed to by the properties of both the frame and the infill.

Only the cantilever beam without openings is considered herein.

The entire design process of the masonry superstructure must consider – 1) the scheme selection, 2) the analysis methodologies, 3) the critical elements design including the grout and mortar mix design, and 4) the connection design including ties and anchors. The design considerations presented herein are for design against collapse and does not consider the serviceability states of durability, fire resistance, deflection, cracking, vibration, sound transmission, or thermal control.

At present there are three alternative design philosophies that can be applied to the design of reinforced masonry block structures. In chronological order these are – the empirical, the allowable stress method, and the ultimate strength method.

With the general increase in rationalism and decrease in empiricism in structural design, the empirical approach is least used. In the U.S, it appears that the allowable stress approach is still mainly used (via ACI 530) but this is changing rapidly. The current trend is the increasing use of the ultimate strength method. This is because of its more rational basis and more economical usage of materials. In U.S practice, the UBC and the recent IBC present ultimate strength design procedures. The allowable stress and empirical approaches are also presented as alternatives. The NEHRP recommendations are also based on the ultimate strength method but rather than calculate element capacities, the ACI 530 allowable stresses are increased by a factor of 2.5. The relevant section of the Caribbean's CUBiC code is mainly based on North American practice, though conversion to the ultimate state by the 2.5 factor is also discussed.

1.3 Properties of Masonry

Clay Hollow Brick (Vertical Cell) Units

Hollow bricks are hollow units similar in size and shape to hollow concrete block, except that they are made of fired clay or shale.

Other significant features of this product include:

1. Very high compressive strengths can be developed.
2. Face shell thickness is, as with concrete block, sufficient to provide stability and sound mortar beds.
3. Cross-web requirements are similar to concrete block.
4. The cell sizes and areas are adequate for placement of the grouted reinforcement and the insulating fill.
5. It provides for valid fire ratings, either hollow or filled with grout or insulation, and with or without plaster coats.

The following table describes the main properties of clay hollow block (vertical core) units.

PROPERTIES OF HOLLOW CLAY BLOCK
VERTICAL CELL UNITS

PROPERTY	DESIGNATED BY	**PURPOSE**	**NOTES**
Grade	SW; MW (i.e severe or moderate weathering).	Long term service life; based on durability.	For blocks, durability is mainly resistance to frost/thaw action; based on U.S weathering index (i.e. average number of freezing cycle days times average annual winter rainfall in inches). C/B ratio along with compressive strength and total absorption now recognised as more reliable indicators of durability.
Block Type	HBS (Hollow Brick Standard); HBX (Extra); HBA (Architectural Variation); HBB	HBS is the typical; HBX is for greater dimensional precision; HBA is for architectural effects; HBB is for when large variations in size, colour, or texture is allowed.	In the existing TTBS standard, Block Type is Grade.
Block Class	H40V (25% to 40% area is void); H60V (40% to 60% area is void)	To distinguish between hollow, solid and tile units; to ensure adequate web and face shell thicknesses.	If the void area is less than 25%, the unit is considered a solid unit rather than a hollow unit; if the void area is greater than 60% it is considered a tile. Solid units and tiles have separate standards.
Total Absorption	Water absorbed after 24hr submersion in cold water, expressed as % of total dry weight of the unit	Measures the ability to form a good bond with the mortar. Poor bond occurs if the unit floats thus increasing the w/c ratio at the interface.	Partial indicator of durability.
Saturation Coefficient	C/B Ratio (cold to boiling); ratio of percent of water absorbed (the boiling water immersion period is 5 hr).	Represents the portion of the total pore space that is readily filled with water.	Caters for differences in raw material or manufacturing process on durability. If no differences, then either compressive strength or total absorption correlates well with freeze/thaw resistance.
Initial Rate of Absorption	Weight of water absorbed per unit area in 1 minute.	Measures the unit's suction ability via capillary action; also measures water-tightness. If too high, less water is available for the hydration of the mortar in the cement;	Suction has little bearing on the transmission of water through the unit leading to leakage. This is mostly via spaces between the unit and mortar interface and under a pressure differential between the inside and outside wall surfaces. If greater than 40g/min, the unit should be prewetted 24hr before laying.

		hence it measures the tendency for reduced mortar tensile bond strength.	
Compressive Strength	Maximum load (in kN or lbs) per unit gross area that the unit can sustain in compression.	All load-resisting and stiffness properties of the unit, as well as durability, correlates directly with the compressive strength.	Strength of the unit is not the same as strength of the masonry which is unit + mortar + grout (if any). Masonry compressive strength is determined by prism testing and measured in terms of net area.
Modulus of Elasticity	Compressive force required for unit axial deformation.	Measures the deformability of the unit.	Important for serviceability requirements of structural design. Directly correlates with compressive strength.
Flexural Strength	Strength under transverse bending; also called the modulus or rupture.	Enables calculation of the load required to initiate cracking in a structural element.	Important for serviceability requirements of structural design.

The following are typical property values.

CLASS H60V: HOLLOW BRICKS MINIMUM THICKNESS OF FACE SHELLS AND WEBS, IN. (MM)

Nominal width of units	Face shell thicknesses: Solid	Face shell thicknesses: Cored or double shell	End shells or end webs
3 and 4 (76 and 101)	3/4(19.05)	...	3/4 (19.05)
6 (152)	1 (25.4)	1 1/2 (38)	1 (25.4)
8 (203)	1 1/4 (32)	1 1/2 (38)	1 (25.4)
10 (254)	1 3/8 (35)	1 3/8 (41)	1 1/8 (29.5)
12 (306)	1 1/2 (38)	2 (50)	1 1/8 (29.5)

Physical Requirements

	Compressive strength (hollow brick in bearing position) gross area, min. psi (MPa)		Water absorption by 5-h boiling, max. %		Saturation coefficient, max	
Designation	Average of 5 brick	Individual	Average of 5 brick	Individual	Average of 5 brick	Individual
Grade SW	3000 (20.7)	2500 (17.2)	17.0	20.0	0.78	0.80
Grade MW	2500 (17.2)	2200 (15.2)	22.0	25.0	0.88	0.90

Structural Clay Load-bearing Wall Tile

This tile unit is covered by ASTM designation C34, which defines two grades of structural clay tile: LBX and LB. Also, UBC Standard 24-8 covers these products. Grade LBX tile is suitable for general use in load-bearing walls and adaptable for use in severe weather conditions, provided that it is burned to the normal maturity of the clay. It is also suitable for the direct application of stucco. Grade LB tile must be used only when the wall is not exposed to severe weathering action or for exposed masonry protected with a facing of 3 in. or more of other masonry. Tile of Grade LBX can be accepted under all conditions in lieu of grade LB. The units range in thickness from 4 to 12 in in the following nominal dimensions: 12x12, 8x12, 6x12, 8x8, and 5 1/3 x 12.

The following table lists the absorption and compressive strength requirements of structural clay tile, both load-bearing (C34) and nonload-bearing (C56), as well as for facing tile (C212). Glazed units (C126) are also listed.
The non load-bearing units (C56) may be used for nonstructural partitions. They are excluded from use in earthquake zones 2, 3, and 4, because all masonry there must be reinforced, which requires a structural masonry unit. Since they are nonstructural in function, no strength requirement is listed in the table.

PHYSICAL REQUIREMENTS FOR CLAY TILE

	Absorption %, 1-hr boiling		Minimum compression strength' (lb/in^2) End constr. tile		Side constr. tile	
Type and grzde	Average of five tests	Indiv.	Min. average of five tests	Indiv. Min.	Min. average of five tests	Indiv. min.
Load-bearing (C34)						
LBX	16	19	1400	1000	700	500
LB	25	28	1000	700	700	500
Nonload-bearing (C56)						
NB	-	28				
Facing tile (C212)						
Types						

FTX	9	11				
FTS	16	19				
Classes						
Standard			1400	1000	700	500
Special duty			2500	2000	1200	1000
Glazed units (C 126)			3000	2500	2000	1500

'Compression strength based on gross area (obtained as a product of horizontal face dimension as placed in the wall times its thickness). 1MPa = 145 psi.

Hollow Concrete Block

Solid concrete units are commonly called concrete bricks, whereas hollow units are known as concrete blocks, hollow blocks, or cinder blocks. Hollow units have net cross-sectional area in every plane parallel to the bearing surface with less than 75% of the cross-sectional area in the same plane. If this ratio is 75% or more, the unit is categorized as solid (Portland Cement Association 1991).

Concrete masonry units are manufactured using a relatively dry (zero-slump) concrete mixture consisting of portland cement, aggregates, water, and admixtures. Type 1 cement is usually used to manufacture concrete masonry units; however, Type III is sometimes used to reduce the curing time. Air-entrained concrete is sometimes used to increase the resistance of the masonry structure to freeze and thaw effects and to improve workability, compaction, and molding characteristics of the units during manufacturing. The units are molded under pressure, then cured, usually using low-pressure steam curing. After manufacturing, the units are stored under controlled conditions so that the concrete continues curing.

Concrete masonry units can be classified as load-bearing (ASTM C90) and nonload-bearing (ASTM C129). Load-bearing units must satisfy a higher minimum compressive strength requirement than non-load-bearing units.

Load-bearing concrete masonry units are manufactured in two grades: N and S. Grade N units are used for walls above and below grade that may or may not be exposed to moisture or weather. Grade S units are for above grade exterior walls with weather-resistant protective coating, or for walls not exposed to the weather.

Grade N units are of two types: Type I, moisture-controlled units, and Type II, non-moisture-controlled units. Type I units are used in dry climates, whereas Type II are used in humid climates.

The moisture content is controlled in Type I units to limit the amount of shrinking due to moisture loss after construction. Type I units must have low moisture content when delivered to the job site. In addition, they must be protected from rain, and other moisture before being used. If moisture content is not reduced in the units before using them, drying shrinkage will occur, which might cause cracking when climatic balance is achieved.

In humid areas, moisture control of the concrete blocks is not required hence the Type II units are permitted in such cases, but they should not be very moist during construction in order to avoid excessive drying shrinkage, which might cause cracking. They should be stored long enough to achieve climatic balance depending on the material used, moisture content in the units, and humidity conditions. Type II units are more commonly used in construction than Type I.

Mortar, Grout and Plaster

Mortar is a mixture of portland cement, lime, sand, and water. Adding a small percentage of lime to the cement mortar makes the mortar "fat" or "rich," which increases its workability. Mortar can be classified as lime mortar or cement mortar. Lime mortar is made of lime, sand, and water, whereas cement (or cement-lime) mortar is made of lime mortar mixed with portland cement (Portland Cement Association 1987).

Mortar is used for the following functions:

· bonding masonry units together

· serving as a seating material for the units

· leveling and seating the units

· providing aesthetic quality of the structure

Lime mortar gains strength slowly with a typical compressive strength of 0.7 MPa to 2.8 MPa (100 psi to 400 psi). Cement mortar is manufactured in four types: M, S, N, and O. Type M has the lowest amount of hydrated lime, whereas type O has the highest amount. The compressive strength of mortar is tested using 50-mm cubes according to ASTM C109. The minimum average compressive strengths of types M, S, N, and O at 28 days are 17.2 MPa, 12.4 MPa, 5.2 MPa, and 2.4 MPa (2500 psi, 1800 psi, 750 psi, and 350 psi) (ASTM C270).

Mortar starts to bind masonry units when it sets. During construction, bricks and blocks should be rubbed and pressed down in order to force the mortar into the pores of the masonry units to produce maximum adhesion. It should be noted, however, that mortar is the weakest part of the masonry wall. Therefore, thin mortar layers generally produce stronger walls than do thick layers.

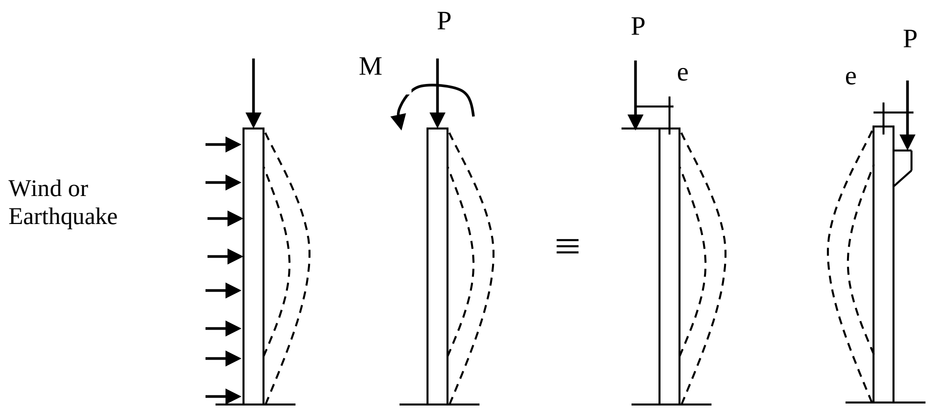
Grout is a high-slump concrete consisting of portland cement, lime, sand, fine gravel, and water. Grout is used to fill the cores or voids in hollow masonry units for the purpose of: 1) bonding the masonry units, 2) bonding the reinforcing steel to the masonry, 3) increasing the bearing area, 4) increasing fire resistance, and 5) improving the overturning resistance by increasing the weight.

Plaster is a fluid mixture of portland cement, lime, sand, and water, which is used for finishing either masonry walls or framed (wood) walls. Plaster is used for either exterior or interior walls. Stucco is plaster used to cover exterior walls. The average compressive strength of plaster is about 13.8 MPa (2000 psi) at 28 days.

CONCRETE MASONRY UNITS

UNIT	ASTM	GRADE	Minimum f_m', (MPa)		Max Absorption (kg/m^3); oven-dry; normal weight concrete
			Av. of 3	Individual	
Brick	C55	N	24.1	20.7	160
		S	17.3	13.8	208
Solid Load-Bearing	C145	N	12.4	10.3	208
		S	8.3	6.9	-
Hollow Load-Bearing	C90	N	6.9	5.5	208
		S	4.8	4.1	-
Hollow Non-Load Bearing	C129	N	4.1	3.5	-

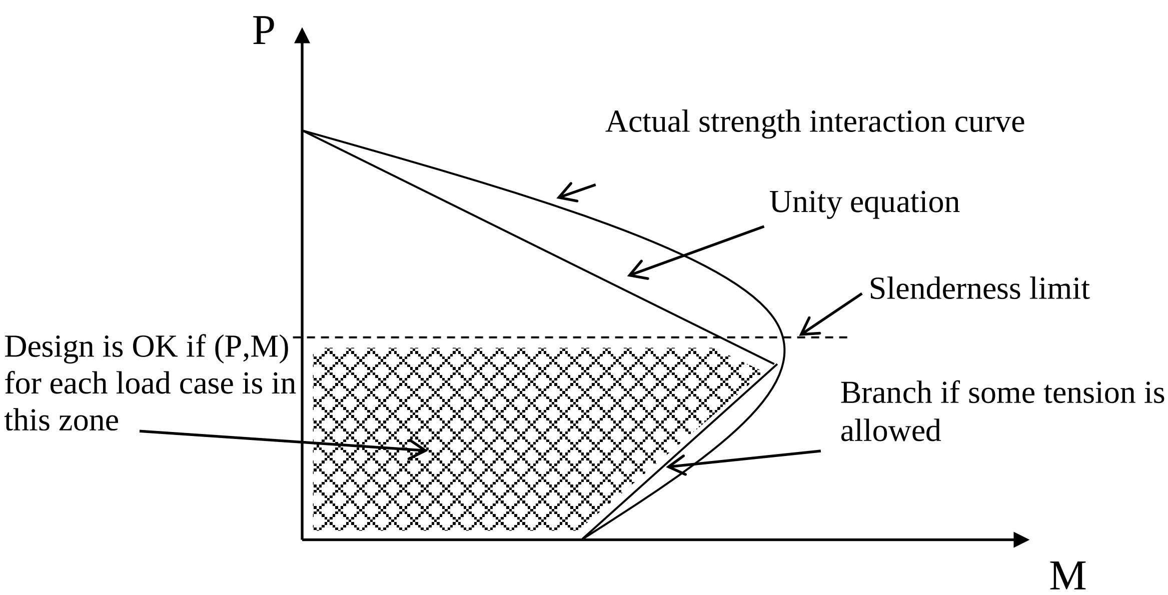
2.0 Design Procedures for Unreinforced Hollow Unit Masonry Walls Under Combined Axial Load and Out-of-Plane Bending (Vertically Spanning)



Introduction

A wall may have reinforcement but is considered unreinforced if the steel content is less than the minimum recommended for a reinforced wall (i.e. 0.07% of gross cross-sectional area vertical and horizontal, but 0.2% total). In this case, the reinforcement is to be neglected in the calculation. All walls, even if its main functions is as a partition wall, must be designed or checked for out-of-plane loading. This is because every wall is load-bearing as it must at least carry its own weight. And every wall carries some out-of-plane bending moment due to the eccentricity of its self-weight, on account of the impossibility to construct a perfectly vertical wall.

The axial load is the sum of the self-weight of the wall, and any bearing stress on the wall, say from a floor. (Unreinforced load-bearing walls shall not be used in highly seismic areas).



<u>Design Intention</u>

- Each section must not be too slender and hence buckle under the axial load, and the section must be of sufficient strength to withstand the factored combined (axial plus bending) compressive stresses.
- There shall be no cracking at any section of the wall, but the bending tensile stresses in the wall need not be zero, but must be less than a certain limit. Hence, cracking occurs at a section when the net tensile stress exceeds this limit, called the modulus of rupture.

<u>Design Equations (Criteria)</u>

The wall section is satisfactory if:

$$(P_u / \phi P_n) + (f_b/F_b) \le 1 \qquad (1) \text{ (Maximum compression)}$$

$$f_b - (P_u/A_n) \le f_r \qquad (2) \text{ (Maximum net tension)}$$

P_u = factored axial load
ϕ = strength reduction (construction quality) factor
P_n = nominal axial strength

f_b = compressive stress due to out-of-plane bending under factored loads
F_b = ultimate compressive stress in bending = 0.85 f_m'

f_r = modulus of rupture for out-of-plane bending

$$\phi P_n = \phi\, A_n\, f_m' \,[1 - (h/140r)^2] \qquad \text{for } (h/r) < 99 \qquad (3)$$

$$= \phi\, A_n\, f_m' \,(70r/h)^2 \qquad \text{for } (h/r) \ge 99 \qquad (4)$$

Equation (1) is the Unity Equation. Equations (3) and (4) place limits on the range of stresses due to slenderness effects, and is a relatively recent improvement over the former traditional arbitrary slenderness limits.

A_n = net cross-sectional area of wall
f_m' = specified masonry compressive strength at 28 days (MPa).
h = effective height
r = wall radius of gyration = $\sqrt{(I/A_n)}$
I = moment of inertia
$f_b = M_u/S$
$e_{min} = 0.1t$

<u>Load Factors and Combinations</u>

Dead = 1.4D
Dead plus Live = 1.2D + 1.6L
Dead plus Live plus Wind = 1.2D + 1.0L + 1.6W
Dead plus Live plus Earthquake = 1.2D + 1.0L + 1.0E
Dead plus Earthquake (dead load effect is beneficial) = 0.9D + 1.0E
Dead plus Wind (dead load effect is beneficial) = 0.9D + 1.6W

<u>Capacity Reduction Factors, ϕ</u>

ϕ = 0.8

<u>Typical Effective Heights</u>

- Building walls with lowest block bearing on RC foundation = 1.2 x actual wall height
- External walls but separated from frame = 1.0 x actual wall height

Modulus of Rupture, f_r

Ungrouted or partially-grouted wall in running bond = 0.69 MPa for type M or S mortar, but 0.52 MPa for type N mortar.

Fully grouted wall in running bond = 1.1 MPa for type M or S mortar, but 0.82 MPa for type N mortar.

Specified masonry compressive strength at 28 days, f_m'

Note that this is the net area compressive strength.

ASTM C652 unit ungrouted walls of mortar comprised of 1:3 cement:sand by volume (i.e. type M mortar) then f_m' = 8 MPa

ASTM C90 unit ungrouted walls of mortar comprised of 1:3 cement:sand then f_m' = 7 MPa

Higher values for f_m' can be used if substantiated by appropriate prism test data.

Typical Wall Section Properties

WALL MASONRY UNIT TYPE	Wall Self-Weight kN/m^2 vertically	A_n (cm^2/m length)	I (cm^4/m length)	S (cm^3/m length)	r (mm/m length)
ASTM C652 (Clay Vertical Cell):					
100mm					
Ungrouted; face-shell only mortar	0.93	380.9	4641.7	1042.8	114.1
Fully grouted (i.e. 100% cells filled)	2.03	888.7	5856.7	1316.9	84.1
150mm					
Ungrouted; face-shell only mortar	1.38	694.0	18020.6	2585.4	167.4
Fully grouted (i.e. 100% cells filled)	3.17	1396.6	22662.3	3251.9	132.5
ASTM C90 (Concrete Vertical Cell):					
100mm					
Ungrouted; face-shell only mortar	1.40	380.9	5187.8	1128.8	120.8
Fully grouted (i.e. 100% cells filled)	2.16	920.5	6498.4	1413.6	87.5
150mm					
Ungrouted; face-shell only mortar	1.65	507.8	17747.6	2488.6	194.1
Fully grouted (i.e100% cells filled)	3.25	1417.7	24300.6	3402.4	135.0
200mm					
Ungrouted; face-shell only mortar	2.15	634.8	42184.7	4353.8	267.4
Fully grouted (i.e. 100% cells filled)	4.34	2454.6	121775.8	9943.8	231.6

Note: Use linear interpolation of the above values for partially-grouted walls, with grouting expressed as a percentage.

A. Design Example

Check the design adequacy of a 150mm unreinforced concrete block wall 6.1m long x 4.0m high that is proposed as an external non load-bearing wall for a frame building under an unfactored wind load of $1.5kN/m^2$. Treat the wall as separate from the frame on the sides, but held in place at the top and bottom. Use f_m' = 7 MPa. Comment on the result.

Check the mid-height of the wall, where the BM is the greatest.

Max moment due to wind = $1.5 \times 4^2/8 = 3$ kNm (/m length of wall)

Dead load:

Wall self-weight = 1.65 kN/m^2 vertically (tables above),

= 1.65 x 4 = 6.6 kN (/m length of wall).

At mid-height, dead load = 6.6/2 = 3.3 kN
Using a load factor of 1.2 on the dead load effects,
factored dead load, P_u = 1.2 x 3.3 = 3.96 kN

Additional moment due to minimum eccentricity:
0.1 x 0.15 x 3.3 = 0.05 kNm

Axial Load Capacity:

Note that in these calculations, the wall thickness is taken as 140mm and not 150mm. The latter is the "nominal" thickness whereas the actual thickness is usually approximately 10mm less.

ϕ = 0.8
$A_n = 5.08 \times 10^{-2}$ m^2 (/m length)
Wall effective height = 1.0 x actual height = 4.0m
r = 0.194 mm/m
h/r = 4/0.194 = 20.6 < 99,
$[1 - (h/140r)^2] = 1 - (4.0/(140 \times 0.194))^2 = 0.978$
Hence axial load capacity, $\phi P_n = \phi A_n f_m' [1 - (h/140r)^2] = 0.8 \times 5.08 \times 10^{-2} \times 7.0 \times 10^3 \times 0.978 = 278.1$ kN (/m length)

Factored bending stress due to wind:
$S = 2.49 \times 10^{-3}$ m^3 (/m length)

Using a load factor of 1.6 on the wind load effects and 1.2 on the dead load effects, factored bending stress, $f_b = ((1.6 \times 3.0)+(1.2 \times 0.05))/ 2.49 \times 10^{-3} = 1951.8$ kN/m^2 = 1.95 MPa

Ultimate bending compressive stress, $F_b' = 0.85 f_m' = 0.85 \times 7.0 = 5.9$ MPa

Hence from equation (1), (3.96/278.1)+(1.95/5.9) = 0.34 < 1 : OK

Check for cracking using equation (2):

Since in this case the dead load effect is beneficial, use the 0.9D + 1.6W load combination.

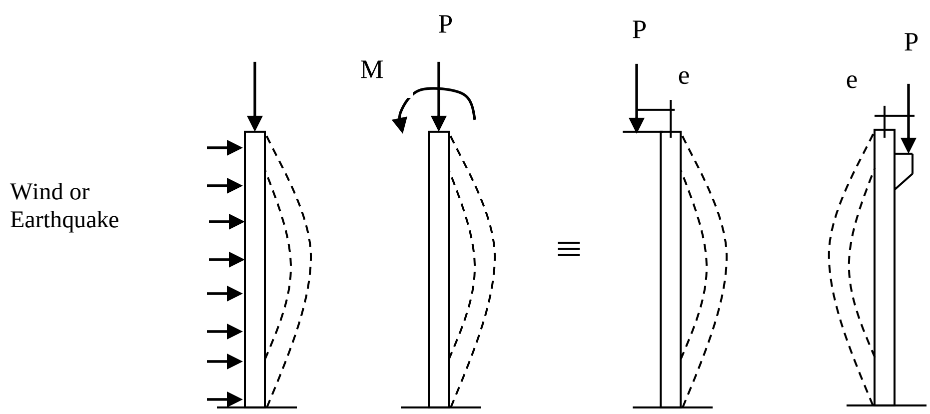
$f_b = ((1.6 \times 3.0) + (0.9 \times 0.05))/2.49 = 1.94$ MPa

$(P_u/A_n) = 0.9 \times 3.3/5.08 \times 10 = 0.06$ MPa

$f_b - (P_u/A_n) = 1.94 - 0.06 = 1.88$ MPa > 0.69 (f_r): NOT OK (cracking).

Two possibilities exist to make the wall adequate: (1) the wall may be grouted to (a) reduce the cracking stress by increasing the dead load and, (b) increase the modulus of rupture or, (2) the wall may be reinforced. In this case, option 1 appears more feasible given the extent of increased weight possible without going against eq (1) (i.e. 0.34 vs. 1.0).

3.0 Design Procedures for Reinforced Hollow Unit Masonry Walls Under Combined Axial Load and Out-of-Plane Bending (Vertically Spanning)

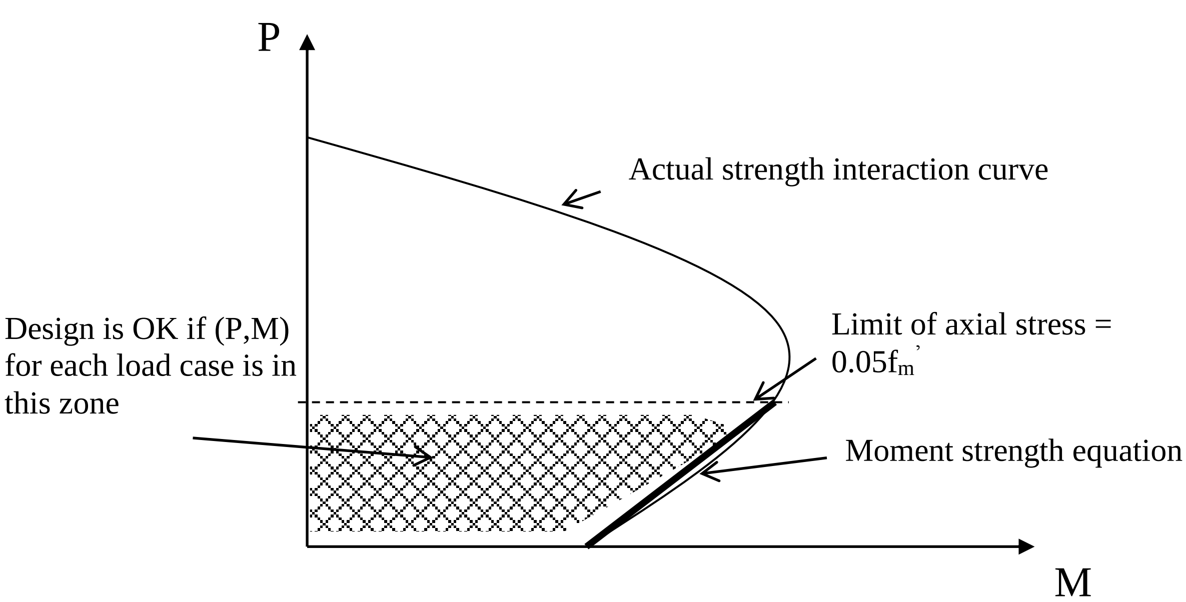


Introduction

The axial load is the sum of the self-weight of the wall, and any load on the wall, say from a floor. When divided by the net cross-sectional area of the wall, it is termed the "bearing stress". As mentioned in the previous section, all walls, even if its main function is as a shear wall, must be designed or checked for out-of-plane loading. This is because every wall is load-bearing as it must at least carry its own weight. And every wall carries some out-of-plane bending moment due to the eccentricity of its self-weight, on account of the impossibility to construct a perfectly vertical wall.

The following procedure for reinforced masonry walls under combined axial load and bending is called the Slender Wall procedure because it is not based on the calculation of the wall's slenderness. Therefore, walls that were previously considered too slender are allowed in the procedure, provided the bearing stress is sufficiently low.

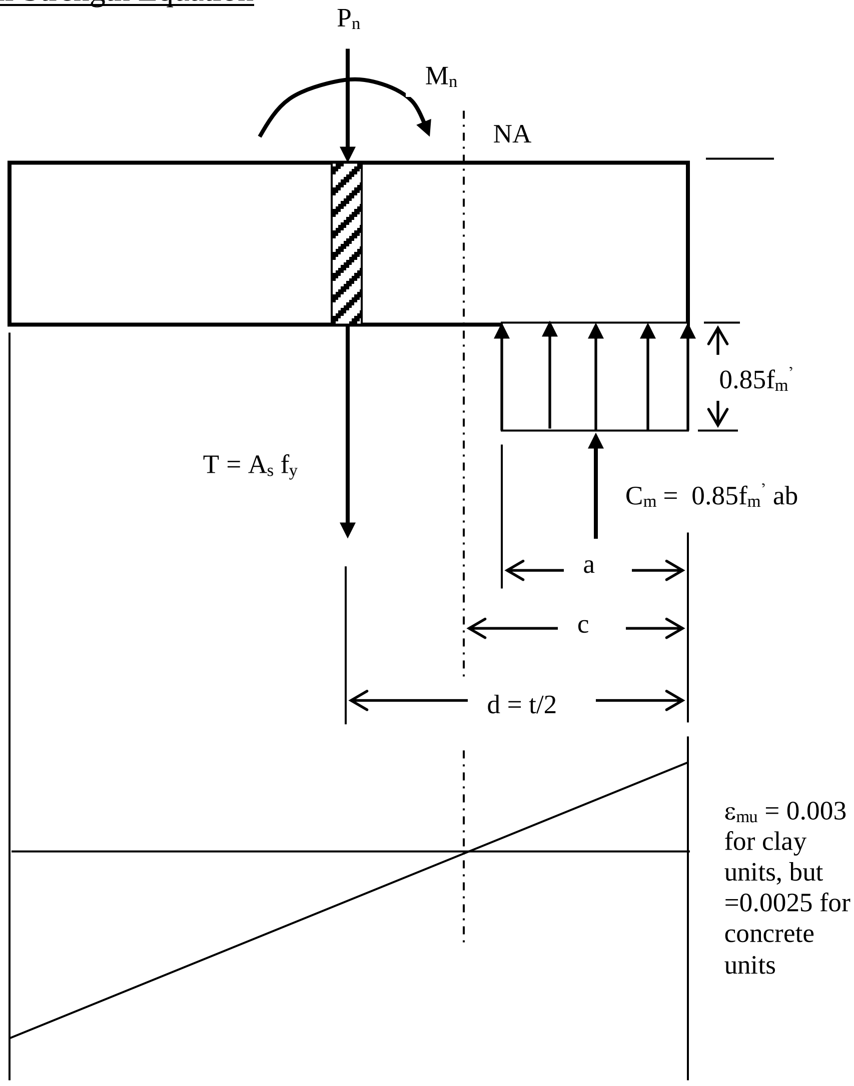
Since the walls are slender, it is presumed that under service loads, the mid-span deflection may be too large. Therefore, the procedure includes a check for excessive deflection due to both the deflection under the applied loads, and additional deflection due to the P-Δ effect.



Design Intention

The axial load increases the applied bending moment due to its eccentricity. The axial load also introduces additional moment and deflection via the P-Δ effect. The design intention is to control the bending behaviour such that the response is ductile at failure, and that the service load deflection is acceptable.

Wall Strength Equation



P_n = nominal axial load on the wall
M_n = nominal moment
NA = Neutral axis
C_m = Compressive force
f_m' = Masonry compressive strength
a = Depth of compressive stress block
b = length of wall considered
c = NA depth
d = Depth to centre of rebar
t = Wall nominal thickness
T = Tensile force in rebar
A_s = Cross-sectional area of rebar
f_y = Yield strength of rebar
ε_{mu} = Masonry Ultimate Compressive Strain

Consider a wall section as shown, subjected to a load $P_n = P_u/\phi < P_b$. Therefore, the axial load is sufficiently small, that the capacity of the section is defined by the lower portion of the interaction curve, and the wall fails in primary tension failure (under-reinforced or ductile failure).

Applying vertical equilibrium, $\Sigma F_y = 0$,

$C_m = P_n + T$

$\therefore\ 0.85\ f_m'\ ab = P_n + A_s\ f_y$

$\therefore\ a = (P_n + A_s\ f_y) / (0.85\ f_m'\ b)$

Define an "effective steel area in tension" as A_{eff}.

$A_{eff} = (P_n + A_s\ f_y)/\ f_y$

Taking moments about C_m, we get,

$M_n - P_n(d – a/2) – T(d – a/2) = 0$

$M_n - P_n(d – a/2) – A_s\ f_y\ (d – a/2) = 0$

$M_n – (P_n + A_s\ f_y\ ) (d – a/2) = 0$

$M_n = (P_n + A_s\ f_y\ ) (d – a/2) = A_{eff}\ f_y\ (d – a/2)$

This equation is the solid line shown on the previous interaction curve.
The wall strength is acceptable if M_u (required strength based on factored loads) < ϕM_n.

Note:- The above is for solid walls or partially grouted walls of reinforcement spacing < 6t (i.e. a partially grouted wall of spacing less than 6t is considered equivalent to a solid wall since it is empirically known that for the entire length of a partially-grouted wall the compression face shell experiences a bending compression strain if the spacing is less than the 6t).

Design Criteria

Assumption: The wall is pinned at top and bottom edges and the load is uniformly distributed over the face.

If $(P_{sw} + P_{sf}) /A_g < 0.05f_m'$:
P_w = Weight of wall tributary to section under consideration,
P_f = Load from tributary floor or roof area,
A_g = Wall gross area.

Factored applied moment, $M_u^{(i+1)} = (w_u h^2/8) + P_{uf}\ e/2 + P_u\ \Delta_u^{(i)}$ (1)
(at wall mid-height)

where:

w_u = factored applied uniformly distributed load on wall face
h = wall effective height
$P_u = P_{uw} + P_{uf}$
e = eccentricity of P_{uf} ; e should be a minimum of 0.1t
P_{uw} = factored weight of wall tributary to section
P_{uf} = factored load from tributary floor or roof load
Δ_u = deflection due to factored loads.

Therefore,

Nominal out-of-plane moment strength, $M_n = A_{se} f_y (d – a/2)$ (2)

where, $A_{se} = (A_s\ f_y + P_u) / f_y$ (3)
$a = (A_s\ f_y + P_u) / 0.85\ f_m'\ b$ (4)
where, d = distance from compressive face to centroid of vertical steel,
b = width of the wall under consideration (usually1m for fully

grouted walls, or partially grouted walls of spacing < 6t).

<u>If $(P_{sw} + P_{sf}) / A_g > 0.05f_m'$:</u>

Equations (1) to (4) apply but the maximum $(P_w + P_f) / A_g$ must be less than $0.2f_m'$, and the slenderness ratio must not exceed 30.

The slenderness ratio is the ratio of the effective wall height divided by the wall thickness.

Effective height:

Case 1: (e.g. Building walls with lowest block bearing on RC foundation)
At top = Rotation fixed and translation free
At bottom = Rotation free and translation fixed
Effective wall height = 1.2 x actual wall height

Case 2: (e.g. External building walls but separated from frame)
At top = Rotation free and translation fixed
At bottom = Rotation free and translation fixed
Effective wall height = 1.0 x actual wall height

Case 3: (e.g. Retaining walls)
At top = Rotation free and translation free
At bottom = Rotation fixed and translation fixed
Effective wall height = 2.0 x actual wall height

These formulae are best applied via a procedure. This is especially so since in accounting for the P-Δ effect in M_u in equation (1), M_u depends on the deflection, which in turn depends on M_u, hence iteration is required. Also, as deflection computations are required, we need to consider certain service load conditions. The following procedure[1] is recommended.

<u>Slender Wall Design Procedure</u>

Step 1. Assume the percentage of grout and determine the service (unfactored) and ultimate (factored) loads.

Step 2. Select trial reinforcement and determine

$P_b = 0.85\, f_m'\, a_b b - A_s f_y$ (5)

where a_b (mm) = $451.13d/(600.0 + f_y)$; f_y in MPa; d in mm (6)

Note: Eq (6) follows from the observation that at the balanced condition, the NA depth is approximately 1.33 times the rectangular compressive stress block depth.

Step 3. Check that $P_u < \phi P_b$ for tension to govern and that $(P_w + P_f) / A_g < 0.05f_m'$.

Step 4. Determine the deflection parameters:

$\rho_g = A_s/bt = ½ (A_s/bd) = ½ \rho$
$I_{gross} = bt^3/12$
$M_{cr} = bt^2 f_r/6$; $f_r = 0.21\sqrt{f_m'}$ for partially grouted walls, $= 0.33\sqrt{f_m'}$ for fully grouted walls; f_m' in MPa; $f_r < 0.86$ MPa for partially-grouted and < 1.62 MPa for fully-grouted.
$k = \sqrt{(2\rho n + (\rho n)^2)} - \rho n$; take $n = E_{steel}/E_{masonry}$
$I_{cr} = (b(kd)^3)/3 + nA_s(d - kd)^2$

Step 5. Determine the mid-height moment and deflection due to the service loads:
s = service; w = self-weight; f = floor load ; u = ultimate

$$M_s^{(i+1)} = (wh^2/8) + P_{sf}\, e/2 + P_s\, \Delta_s^{(i)} \quad (P_s = P_{sw} + P_{sf}) \qquad (7)$$

Set $\Delta_s^{(0)} = 0$, and get $\Delta_s^{(i+1)}$ iteratively from,

$$\Delta_s^{(i+1)} = 5M_{cr}\, h^2/48E_mI_{gross} + 5(M_s^{(i+1)} - M_{cr}) h^2/48E_mI_{cr} \qquad (8)$$

If the second term on the RHS of (8) is negative, set the value of this term to zero.

Step 6. Check that $\Delta_s^{(i+1)} < 0.007h$

Step 7. Determine the applied factored moment at mid-height:

$$M_u^{(i+1)} = (w_uh^2/8) + P_{uf}\, e/2 + P_u\, \Delta_u^{(i)}$$

Calculate initial iteration $M_u^{(1)}$ for $\Delta_u = 0$.

for $M_u^{(1)} < M_{cr}$:

$$\Delta_u^{(i+1)} = 5M_u^{(i+1)}\, h^2/48E_mI_{gross} \qquad (9)$$

for $M_{cr}<M_u^{(i+1)}<M_n$:

$$\Delta_u^{(i+1)} = 5M_{cr}\, h^2/48E_mI_{gross} + 5(M_u^{(i+1)} - M_{cr}) h^2/48E_mI_{cr} \qquad (10)$$

$$M_u^{(i+1)} = (w_uh^2/8) + P_{uf}\, e/2 + P_u\, \Delta_u^{(i)} \qquad (11)$$

Step 8. Determine M_n

Step 9. Check that $M_u < \varphi M_n$

<u>Control of Wall Performance (Assurance of Under-reinforced Behaviour)</u>

The maximum vertical steel content, $\rho_{g,max} < 0.5\rho_b$, where

$$\rho_b = (451.13/(600 + f_y)) \times \phi\, (0.85f_m'/f_y) \quad \text{where } f_m', f_y \text{ in MPa} \qquad (12)$$

<u>Load Factors and Combinations</u>

Use the values previously given for the case of unreinforced walls.

<u>Capacity Reduction Factors</u>

<u>Under Caribbean conditions, it is recommended that $\phi = 0.65$</u>

Design Example

Design a 150 mm clay block wall of units compliant with ASTM C652 to carry a roof dead load of 4.4 kN/m with a 100mm eccentricity in addition to a lateral wind load of 1.0 kN/m^2. The wall is 4.8m high and is simply supported at top and bottom. The wall is fully grouted and f_m' was lab-tested as 14.0 MPa. The wall's self-weight at mid-span is 7 kN/m.

Note that in the calculations, the wall thickness is taken as 140mm and not 150mm. The latter is the "nominal" thickness whereas the actual thickness is usually approximately 10mm less.

Step 1: Determine the service and ultimate loads.

P_{sf} = 4.4 kN/m
P_{sw} = 7.0 kN/m
w_s = 1.0 kN/m^2
P_{uf} = 1.2 x 4.4 = 5.3 kN/m
P_{uw} = 1.2 x 7.0 = 8.4 kN/m
w_u = 1.6 x 1.0 = 1.6 kN/m^2

Step 2: Try 16mm high tensile rebar at 600mm spacing and determine P_b:

a_b = 451.13 x 70/(600 + 410) = 31.3 mm
P_b = 0.85 x 14000 x 31.3 x 10^{-3} x 1 – (2x10^{-4} x 410000/0.6) = 250.6 kN (/m)

Step 3: Check if tension governs and axial stress is sufficiently low to neglect slenderness.

P_u = 5.3 + 8.4 = 13.7 < 0.65 x 250.6 = 162.9 kN: OK

$(P_{sf} + P_{sw})/A_g$ = (4400+7000)/(1000x140) = 0.081 < 0.05 x 14 = 0.70 MPa : OK

Step 4. Determine the deflection parameters:

[$\rho_g = A_s/bt = ½ (A_s/bd) = ½ \rho$
$I_{gross} = bt^3/12$
$M_{cr} = bt^2 f_r/6$; $f_r = 0.21\sqrt{f_m'}$ for partially grouted walls, = $0.33\sqrt{f_m'}$ for fully grouted walls; f_m' in MPa; f_r < 0.86 MPa for partially-grouted and < 1.62 MPa for fully-grouted.
$k = \sqrt{(2\rho n + (\rho n)^2)} - \rho n$; take $n = E_{steel}/E_{masonry}$
$I_{cr} = b(kd)^3)/3 + nA_s(d- kd)^2$]

ρ = (200/0.6)/(1000 x 70) = 0.00476; ρ_g = 0.00238
I_{gross} = 1 x 0.14^3/12 = 2.29x10^{-4} m^4 (/m)
f_r = 0.33√(14) = 1.24 MPa (< 1.62 MPa OK)
M_{cr} = 1 x 0.14^2 x 1240/6 = 4.05 kNm
E_{clay} = 750f_m' = 750x14 = 10500 MPa
n=200/10.5=19.04
k= √((2x0.00476x19.04)+$(0.00476x19.04)^2$)-(0.00476x19.04) = 0.345
I_{cr} = $(0.345x0.07)^3$/3 + 19.04x333x$10^{-6}$$(0.07-0.345x0.07)^2$ = 0.18 x10^{-4} m^4 (/m)

Step 5. Determine the mid-height moment and deflection due to the service loads:

$M_s^{(i+1)} = wh^2/8 + P_{sf}\, e/2 + P_s\, \Delta_s^{(i)}$ $(P_s = P_{sw} + P_{sf})$

Set $\Delta_s^{(0)} = 0$,

$\Delta_s^{(i+1)} = 5M_{cr}\, h^2/48E_m I_{gross} + 5(M_s^{(i+1)} - M_{cr})\, h^2/48E_m I_{cr}$

Hence, $M_s^{(1)} = (1 \times 4.8^2/8) + (4.4x0.1x0.5) = 3.1$ kNm < M_{cr} (=4.05 kNm)

Given the low moment in this case it is not necessary to iterate.
$\Delta_s^{(1)} = 5x3.1x4.8^2/(48x10.5x10^6x2.29x10^{-4}) = 3.1 \times 10^{-3}$ m

Step 6. Check service deflection:

Max. allowable def. = 0.007x4800=33.6>3.1mm OK

Step 7. Determine the applied factored moment at mid-height:

$M_u^{(i+1)} = w_u h^2/8 + P_{uf}\, e/2 + P_u\, \Delta_u^{(i)}$

Calculate initial iteration $M_u^{(1)}$ for $\Delta_u^{(0)} = 0$.

$M_u^{(1)} = 1.6x4.8^2/8 + 5.3x0.1x0.5 = 4.87$ kNm (/m) > M_{cr}
$\Delta_u^{(1)} = 5x4.05x4.8^2/(48x10.5x10^6x2.29x10^{-4}) +$
$5(4.87\text{-}4.05)x4.8^2/(48x10.5x10^6x0.18x10^{-4}) = 0.0145$ m

$M_u^{(2)} = 4.87 + (5.3+8.4)x0.0145 = 5.07$ kNm
$\Delta_u^{(2)} = 5x4.05x4.8^2/(48x10.5x10^6x2.29x10^{-4}) +$
$5(5.07\text{-}4.05)x4.8^2/(48x10.5x10^6x0.18x10^{-4}) = 0.017$ m

$M_u^{(3)} = 4.87 + (5.3+8.4)x0.017 = 5.1$ kNm
$\Delta_u^{(3)} = 5x4.05x4.8^2/(48x10.5x10^6x2.29x10^{-4}) +$
$5(5.1\text{-}4.05)x4.8^2/(48x10.5x10^6x0.18x10^{-4}) = 0.0173$ m

Consecutive values very close so stop iterating.

Step 8. Determine M_n:

$A_{se} = (333x10^{-6}x410000+(5.3+8.4))/410000 = 366x10^{-6}$ m^2

$M_n = 366x10^{-6}$ x 410000(0.07 – 0.0122/2) = 9.6 kNm (/m)

Step 9. Check that $M_u < \phi M_n$:

5.1 < 0.65x9.6 = 6.24 kNm :OK

Check for ductility: $\rho_b = (451.13/(600 + f_y)) \times 0.65x0.85(f_m'/f_y)$
= (451.13/(600+410))(0.55(14/410))
= 0.0084, hence $\rho_b/2 = 0.0042 > 0.00238$ (= ρ_g) OK.