Masonry Design

Notation:

A = name for area
A_n = net area, equal to the gross area subtracting any reinforcement
A_{nv} = net shear area of masonry
A_s = area of steel reinforcement in masonry design
A_{st} = area of steel reinforcement in masonry column design
A_v = area of concrete shear stirrup reinforcement
ACI = American Concrete Institute
$ASCE$ = American Society of Civil Engineers
b = width, often cross-sectional
= total width of material at a horizontal section
C_m = compression force in the masonry for masonry design
CMU = shorthand for concrete masonry unit
d = effective depth from the top of a reinforced masonry beam to the centroid of the tensile steel
D = shorthand for dead load
e = eccentric distance of application of a force (P) from the centroid of a cross section
E = shorthand for earthquake load
E_m = modulus of elasticity of masonry
E_s = modulus of elasticity of steel
f_a = axial stress
f_b = bending stress
f_m = calculated compressive stress in masonry
f'_m = masonry design compressive stress
f_s = stress in the steel reinforcement for masonry design
f_v = shear stress
F_a = allowable axial stress
F_b = allowable bending stress
F_s = allowable tensile stress in reinforcement for masonry design
F_t = allowable tensile stress
F_v = allowable shear stress
F_{vm} = allowable shear stress of the masonry
F_{vs} = allowable shear stress of the shear reinforcement
h = name for height
= effective height of a wall or column
I_n = moment of inertia of the net section
j = multiplier by effective depth of masonry section for moment arm, jd
k = multiplier by effective depth of masonry section for neutral axis, kd
K = type of masonry mortar
L = shorthand for live load
M = internal bending moment
= type of masonry mortar
M_m = moment capacity of a reinforced masonry beam governed by steel stress
M_s = moment capacity of a reinforced masonry beam governed by masonry stress
$MSJC$ = Masonry Structural Joint Council
n = modulus of elasticity transformation coefficient for steel to masonry
$n.a.$ = shorthand for neutral axis (N.A.)
N = type of masonry mortar
$NCMA$ = National Concrete Masonry Association
O = type of masonry mortar
P = name for axial force vector
P_a = allowable axial load in columns
P_e = critical (Euler) buckling load
Q = first area moment about a neutral axis
r = radius of gyration
s = spacing of stirrups in reinforced masonry
S = type of masonry mortar
= section modulus
t = name for thickness
T_s = tension force in the steel reinforcement for masonry design
TMS = The Masonry Society
V = internal shear force
W = shorthand for wind load

β_1 = coefficient for determining stress block height, *c*, in masonry LRFD design

ε_m = strain in the masonry

ε_s = strain in the steel

ρ = reinforcement ratio in masonry design

ρ_b = balanced reinforcement ratio in masonry design

Σ = summation symbol

Masonry Design

Structural design standards for reinforced masonry are established by the *Masonry Standards Joint Committee* consisting of ACI, ASCE and The Masonry Society (TMS), and presents allowable stress design as well as limit state (strength) design.

Materials

Designation	strength range
M	2500 psi
S	1800 psi
N	750 psi
O	350 psi
K	75 psi

Masonry mortars are mixtures of water, masonry cement, lime, and sand. The strengths are categorized by letter designations (from MaSoNwOrK).

f'_m = masonry prism test compressive strength

Deformed reinforcing bars come in grades 40, 50 & 60 (for 40 ksi, 50 ksi and 60 ksi yield strengths). Sizes are given nominally as # of 1/8".

Clay and concrete masonry units are porous, and their durability with respect to weathering is an important consideration. The amount of water in the mortar is important as well as the absorption capacity of the units for good *bond*; both for strength and for weatherproofing. Because of the moisture and tendency for shrinkage and swelling, it is critical to provide control joints for expansion and contraction.

Masonry Walls

Masonry walls can be reinforced or unreinforced, grouted or ungrouted, single wythe or cavity, prestressed or not. Cavity walls will require ties to force the two walls separated by the cavity to act as one.

From centuries of practice, the height to thickness ratio is limited because of slenderness (h/t < 25 or 35 depending on code). Most walls will see bending from wind or eccentricity along with bearing (combined stresses).

Allowable Stresses

- If tension stresses result, the allowable tensile strength for unreinforced walls must not be exceeded. These are relatively low (40 – 70 psi) and are shown in Table 2.2.3.2.
- If compression stresses result, the allowable strength (in bending) for unreinforced masonry $F_b = 1/3\ f'_m$
- If compression stresses result, the allowable strength (in bending) for reinforced masonry $F_b = 0.45\ f'_m$
- Shear stress in unreinforced masonry cannot exceed $F_v = 1.5\sqrt{f'_m} \leq 120$ psi.
- Shear stress in reinforced masonry for M/(Vd) ≤ 0.25 cannot exceed $F_v = 3.0\sqrt{f'_m}$
- Shear stress in reinforced masonry for M/(Vd) ≥ 1.0 cannot exceed $F_v = 2.0\sqrt{f'_m}$
- Allowable tensile stress, F_s, in grades 40 & 50 steel is 20 ksi, grade 60 is 32 ksi, and wire joint reinforcement is 30 ksi..

where f'_m = specified compressive strength of masonry

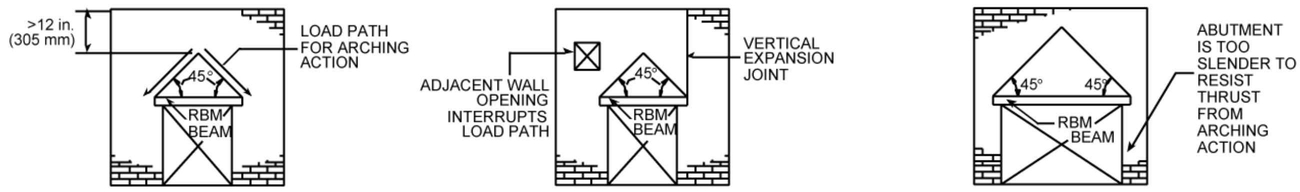
Table 2.2.3.2 — Allowable flexural tensile stresses for clay and concrete masonry, psi (kPa) (F_t)

Direction of flexural tensile stress and masonry type	Mortar types: Portland cement/lime or mortar cement (PCL)		Mortar types: Masonry cement or air entrained portland cement/lime	
	M or S	N	M or S	N
Normal to bed joints				
Solid units	53 (366)	40 (276)	32 (221)	20 (138)
Hollow units[1]				
Ungrouted	33 (228)	25 (172)	20 (138)	12 (83)
Fully grouted	86 (593)	84 (579)	81 (559)	77 (531)
Parallel to bed joints in running bond				
Solid units	106 (731)	80 (552)	64 (441)	40 (276)
Hollow units				
Ungrouted and partially grouted	66 (455)	50 (345)	40 (276)	25 (172)
Fully grouted	106 (731)	80 (552)	64 (441)	40 (276)
Parallel to bed joints in masonry not laid in running bond				
Continuous grout section parallel to bed joints	133 (917)	133 (917)	133 (917)	133 (917)
Other	0 (0)	0 (0)	0 (0)	0 (0)

1 For partially grouted masonry, allowable stresses shall be determined on the basis of linear interpolation between fully grouted hollow units and ungrouted hollow units based on amount (percentage) of grouting.

Loads on Lintels in Masonry Walls

Arching action is present in masonry walls when there is an opening and sufficient wall width on either side of the opening to resist the arch thrust. A lintel is required to support the weight of the wall material above the opening. When arching action is present, the weight that must be supported can be determined from a 45 degree angle. This area may be a triangle, or trapezoid if the wall height above the lintel is less than half the opening width. The distributed load is calculated as height x wall thickness x specific weight of the masonry.

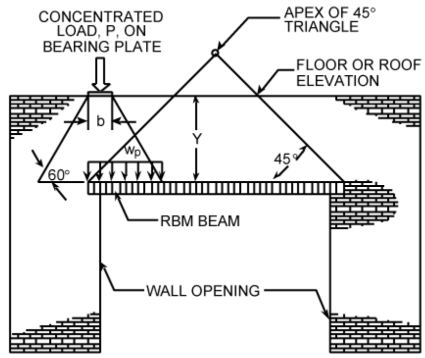


(a) ARCHING ACTION WILL OCCUR. DESIGN BEAM FOR TRAINGULAR LOADING.

(b) ARCHING ACTION WILL NOT OCCUR. DESIGN BEAM FOR ENTIRE WALL AREA.

(b) ARCHING ACTION WILL NOT OCCUR. DESIGN BEAM FOR ENTIRE WALL AREA.

When there are concentrated loads on the wall, the load can be distributed to a width at the lintel height based on a 60 degree angle.



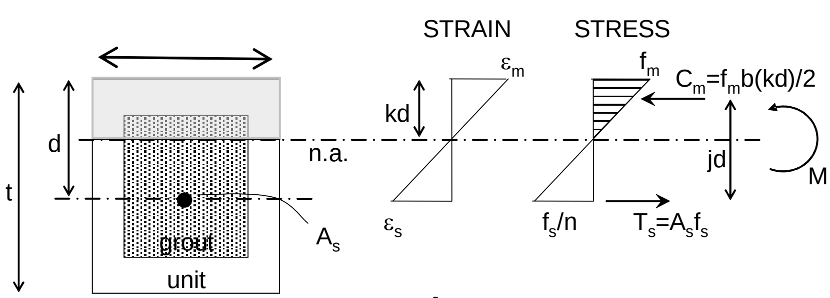
<u>Reinforced Masonry Members</u>

For stress analysis in masonry flexural members

- the strain is linear
- the compressive stress in the masonry is linear
- the tensile stress in the steel is *not at yield*
- any masonry in tension is assumed to have <u>no strength</u>
- the steel can be in tension, and is placed in the bottom of a beam that has positive bending moment

Load Combinations

D
$D+L$
$D + 0.75(L_r \text{ or } S \text{ or } R)$
$D + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
$D + (0.6W \text{ or } 0.7E)$
$D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$
$D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$
$0.6D + 0.6W$
$0.6D + 0.7E$



Internal Equilibrium

$$\rho = \frac{A_s}{bd} \qquad \Sigma F=0: \ A_s f_s = f_m b \frac{kd}{2}$$

C_m = compression in masonry = stress x area = $f_m \dfrac{b(kd)}{2}$

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T_s = tension in steel = stress x area = $A_s f_s$

$C_m = T_s$ and $\bullet M_m = T_s(d-kd/3) = T_s(jd)$ and $M_s = C_m(jd)$

where f_m = stress in mortar at extreme fiber
kd = height to neutral axis
b = width of section
f_s = stress in steel at d
A_s = area of steel reinforcement
d = depth to n.a. of reinforcement
j = (1 –k/3)

For flexure design:

$M \le M_m$ *or* M_s
so, $M_m = T(jd) = 0.5 f_m b d^2 jk$ and $M_s = C(jd) = \rho b d^2 j f_s$

The design is adequate when $f_b \le F_b$ in the masonry and $f_s \le F_s$ in the steel.

Shear Strength

Shear stress is determined by $f_v = V/A_{nv}$ where A_{nv} is net shear area. Shear strength is determined from the shear capacity of the masonry and the stirrups: $F_v = F_{vm} + F_{vs}$. Stirrup spacings are limited to d/2 but not to exceed 48 in.

where:

$$F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75\left(\frac{M}{Vd}\right)\right)\sqrt{f'_m}\right] + 0.25\frac{P}{A_n}$$ where M/(Vd) is positive and cannot exceed 1.0

$$F_{vs} = 0.5\left(\frac{A_v F_s d}{A_{nv} s}\right)$$

($F_v = 3.0\sqrt{f'_m}$ when M/(Vd) ≥ 0.25)

($F_v = 2.0\sqrt{f'_m}$ when M(Vd) ≥ 1.0.) Values can be linearly interpolated.

Table B.2 BALANCED SECTION PROPERTIES FOR RECTANGULAR MASONRY SECTIONS WITH TENSION REINFORCEMENT

Reinforcement	f'_m (psi)	Modular Ratio $n = E_s/E_m$	$F_b = f'_m/3$ (psi)	Balanced Section Properties: k	j	K	$p = A_s/bd$
	With Special Inspection—Full Code Values						
Grade 40 F_y = 40 ksi	1350	22	450	0.333	0.889	66.6	0.00375
	1500	20	500	0.333	0.889	74.0	0.00416
	2000	15	667	0.333	0.889	89.7	0.00556
	4000	7.5	1333	0.333	0.889	197.0	0.01111
Grade 60 F_y = 60 ksi	1350	22	450	0.273	0.909	55.8	0.00256
	1500	20	500	0.273	0.909	62.0	0.00284
	2000	15	667	0.273	0.909	82.7	0.00379
	4000	7.5	1333	0.273	0.909	165.4	0.00758

Reinforcement Ratio

The amount of steel reinforcement is *limited*. Too much reinforcement, or *over-reinforced* will not allow the steel to yield before the concrete crushes and there is a sudden failure. A beam with the proper amount of steel to allow it to yield at failure is said to be *under reinforced*.

The reinforcement ratio is a fraction: $\rho = \frac{A_s}{bd}$ and must be less than ρ_b where the balanced reinforcement ratio is a function of steel strength and masonry strength.

Flexure Design of Reinforcement

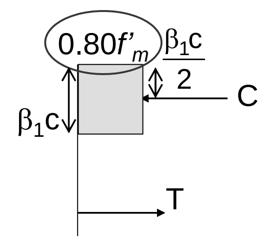
One method is to choose a reinforcement ratio, find steel area, check stresses and moment:

1. find ρ_b and assume a value of $\rho < \rho_b$
2. find k, j and calculate $bd^2 = \frac{M}{\rho j F_s}$ where F_s is allowed stress in steel.

   Choose nice b & d values.
3. find $A_s = \frac{M}{F_s jd}$
3. check design for $M < M_s = A_S F_S (jd)$
4. check masonry flexural stress against allowable: $f_m = \frac{M}{0.5bd^2 jk} < F_b$

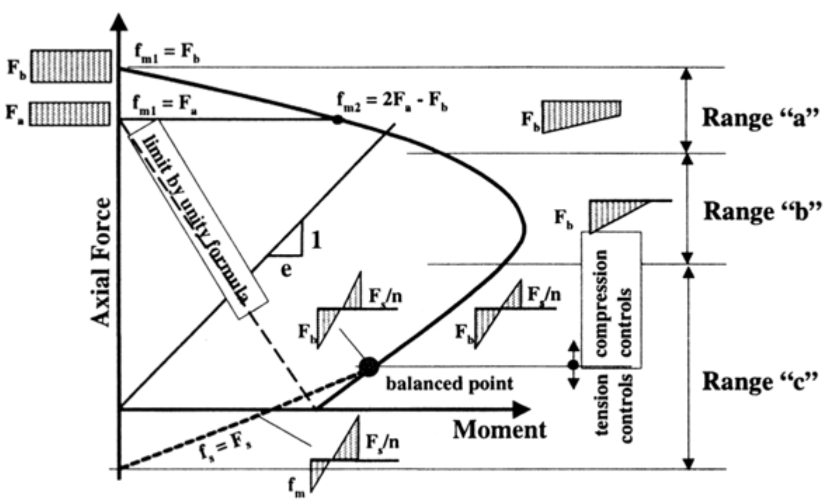
Load and Resistance Factor Design

The design methodology is similar to reinforced concrete ultimate strength design. It is useful with high shear values and for seismic design. The limiting masonry strength is $0.80f'_m$.



Force-Moment Interaction

Combined stresses and the reduction of axial load with moment is similar to that for reinforced concrete column design as shown in the interaction diagram:



Reinforcement is typically placed in the center of walls. Grouting is placed in hollows with reinforcing, while other hollows may be empty. Stirrups are avoided.

Biaxial bending can occur in columns and stresses must satisfy:

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1$$

When maximum moment occurs somewhere other than at the end of the column or wall, a "virtual" eccentricity can be determined from $e = M/P$.

Masonry Columns

Columns are classified as having b/t < 3 and h/t > 4. Slender columns have a minimum side dimension of 8" and must have h/t ≤ 25. They must be designed with an eccentricity of 10% of the side dimension, and satisfy the interaction relationship of $\frac{f_a}{F_a}+\frac{f_b}{F_b}\le 1$, the tensile stress cannot exceed the allowable: $f_b - f_a \le F_t$ and the compressive stress exceed allowable for reinforced masonry: $f_a + f_b \le F_b$ provided $f_a \le F_a$.

For purely axial loading, the capacity P_a depends on the slenderness ratio of h/r:

unreinforced

$$P_a = [0.25 f'_m A_n]\left[1-\left(\frac{h}{140r}\right)^2\right] \qquad \text{for h/r} \le 99$$

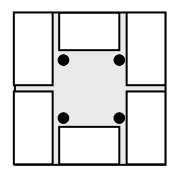
$$P_a = [0.25 f'_m A_n]\left(\frac{70r}{h}\right)^2 \qquad \text{for h/r} > 99$$

reinforced

$$P_a = [0.25 f'_m A_n + 0.65 A_{st} F_s]\left[1-\left(\frac{h}{140r}\right)^2\right] \qquad \text{for h/r} \le 99$$

$$P_a = [0.25 f'_m A_n + 0.65 A_{st} F_s]\left(\frac{70r}{h}\right)^2 \qquad \text{for h/r} > 99$$

where h = effective length
r = least radius of gyration
A_n = net area of masonry
A_{st} = area of steel reinforcement
f'_m = specified masonry compressive strength
F_s = allowed compressive strength of reinforcement



The least radius of gyration can be found with $\sqrt{\frac{I}{A}}$ for a rectangle with side dimensions of b & d as:

$$r = \sqrt{\frac{\frac{db^3}{12}}{bd}} = \sqrt{\frac{b^2}{12}} = \frac{b}{\sqrt{12}}$$

where b is the smaller of the two side dimensions.