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
ACI = American Concrete Institute
$ASCE$ = American Society of Civil Engineers
b = width, often cross-sectional
C = name for a compression force
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
e = eccentric distance of application of a force (P) from the centroid of a cross section
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_x = moment of inertia with respect to an x-axis
j = multiplier by effective depth of masonry section for moment arm, jd
k = multiplier by effective depth of masonry section for neutral axis, kd
L = name for length or span length
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
r = radius of gyration
S = section modulus
= type of masonry mortar
S_x = section modulus with respect to an x-axis
t = name for thickness
T = name for a tension force
T_s = tension force in the steel reinforcement for masonry design
TMS = The Masonry Society
w = name for distributed 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

Reinforced 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

f'_m = masonry prism compressive strength from testing

Reinforcing steel grades are the same as those used for reinforced concrete beams.

Units can be brick, concrete or stone.

Mortar consists of masonry cement, lime, sand, and water. Grades are named from the word MASONWORK, with average strengths of 2500psi, 1800 psi, 750 psi, 350 psi, and 75 psi, respectively.

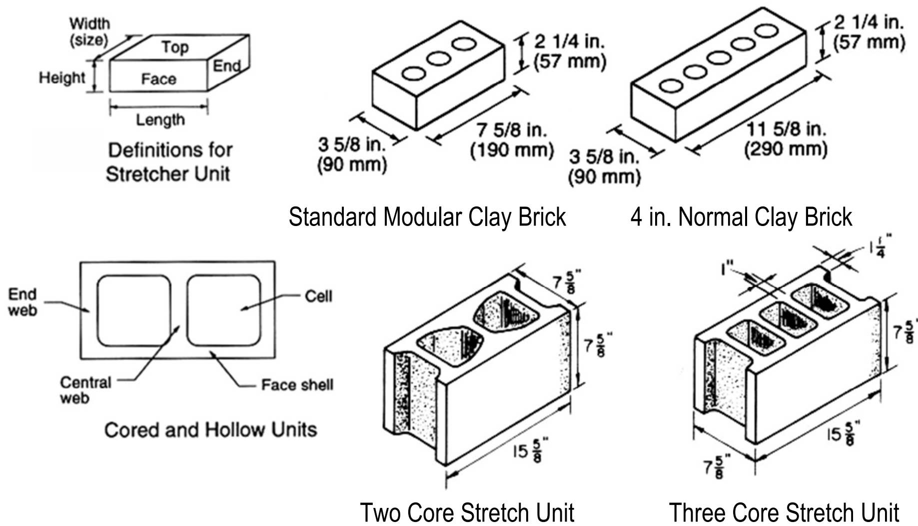
Grout is a flowable mortar, usually with a high amount of water to cement material. It is used to fill voids and bond reinforcement.

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.

Sizes

Common sizes for clay brick and concrete masonry units (CMU) are shown in the figure, along with definitions.

Typical section properties for CMU's are provided for reference at the end of the document.



Allowable Stress Design

For unreinforced masonry, like masonry walls, tension stresses are allowed in flexure. Masonry walls typically see compression stresses too.

For reinforced masonry, the steel is presumed to resist *all* tensile stresses and the tension in the masonry is ignored.

Factors of Safety are applied to the limit stresses for allowable stress values:

bending (unreinforced)	$F_b = 1/3\, f'_m$
bending (reinforced)	$F_b = 0.45\, f'_m$
bending (tension/unreinforced)	table 2.2.3.2
beam shear (unreinforced for flexure)	$F_v = 1.5\sqrt{f'_m} \le 120$ psi
beam shear (reinforced) – $M/(Vd) \le 0.25$	$F_v = 3.0\sqrt{f'_m}$
beam shear (reinforced) – $M/(Vd) \ge 1.0$	$F_v = 2.0\sqrt{f'_m}$
Grades 40 or 50 reinforcement	$F_s = 20$ ksi
Grades 60 reinforcement	$F_s = 32$ ksi
Wire joint reinforcement	$F_s = 30$ ksi

where f'_m = specified compressive strength of masonry

Internal Equilibrium for Bending

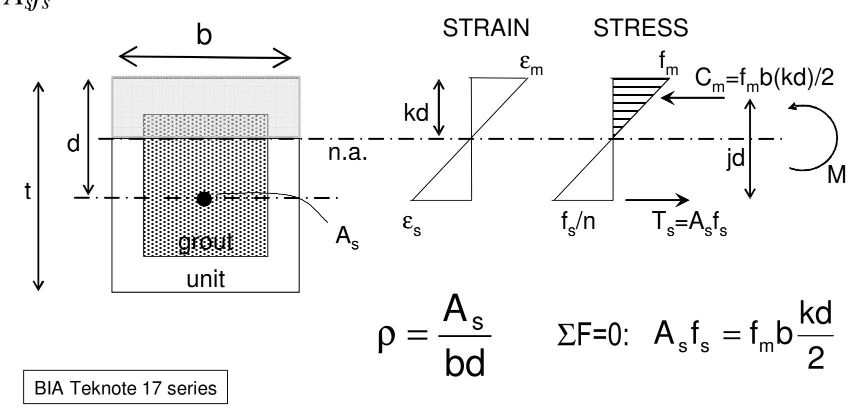
C_m = compression in masonry = stress x area = $f_m \dfrac{b(kd)}{2}$

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

$C_m = T_s$ and •

$$M_m = T_s(d - kd/3) = T_s(jd)$$

$$M_s = C_m(jd)$$



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

where

- f_m = compressive stress in the masonry from flexure
- f_s = tensile stress in the steel reinforcement
- kd = the height to the neutral axis
- b = width of stress area
- d = effective depth of section = depth to n.a. of reinforcement
- jd = moment arm from tension force to compression force
- A_s = area of steel
- $n = E_s/E_m$ used to transform steel to equivalent area of masonry for elastic stresses
- ρ = reinforcement ratio

Criteria for Beam Design

For flexure design:

$$M_m = f_m b \frac{kd}{2} jd = 0.5 f_m bd^2 jk \text{ or } M_s = A_s f_s jd = \rho bd^2 jf_s$$

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

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

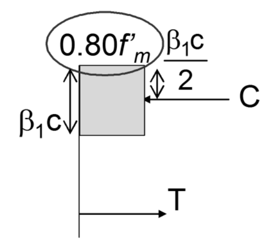
$$F_{vs} = 0.5\left(\frac{A_v F_s d}{A_{nv} s}\right)$$

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

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

<u>Load and Resistance Factor Design</u>

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 $0.80f'_m$.



Criteria for Column Design

(Masonry Joint Code Committee) Building Code Requirements and Commentary for Masonry Structures define a column as having b/t < 3 and h/t > 4.

where

b = width of the "wall"
t = thickness of the "wall"
h = height of the "wall"

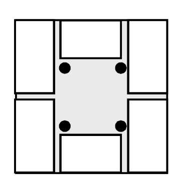
A slender column has a minimum dimension of 8" on one side and h/t ≤ 25.

Columns must be reinforced, and have ties. A minimum eccentricity (causing bending) of 0.1 times the side dimension is required.

Allowable Axial Load for Reinforced Masonry

$$P_a = \left[0.25 f'_m A_n + 0.65 A_{st} F_s\right]\left[1 - \left(\frac{h}{140r}\right)^2\right]$$ for h/t ≤ 99

$$P_a = \left[0.25 f'_m A_n + 0.65 A_{st} F_s\right]\left(\frac{70r}{h}\right)^2$$ for h/t > 99



Allowable Axial Stresses for Unreinforced Masonry

$$F_a = 0.25 f'_m \left[1 - \left(\frac{h}{140r}\right)^2\right] \qquad \text{for h/t} \le 99$$

$$F_a = 0.25 f'_m \left(\frac{70r}{h}\right)^2 \qquad \text{for h/t} > 99$$

where

h = effective length
r = radius of gyration
A_n = effective (or net) area of masonry
A_{st} = area of steel reinforcement
f'_m = specified masonry compressive strength
F_s = allowable compressive stress in column reinforcement with lateral confinement.

<u>Combined Stresses</u>

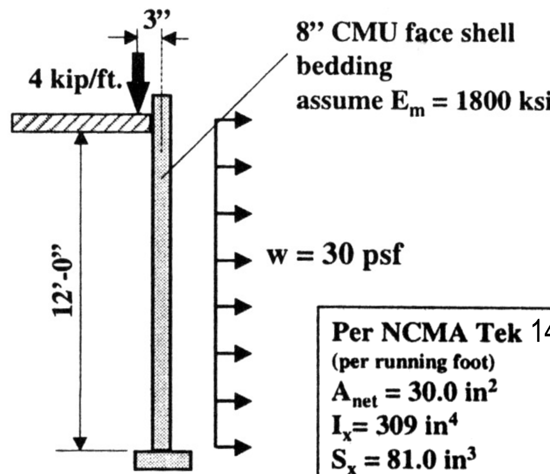
When maximum moment occurs somewhere other than at the end of the column or wall, a "virtual" eccentricity can be determined from *e = M/P*.

<u>Masonry Columns and Walls</u>

There are no modification factors, but in addition to satisfying $\frac{f_a}{F_a} + \frac{f_b}{F_b} \le 1.0$, the tensile stress cannot exceed the allowable: $f_b - f_a \le F_t$ or the compressive stress exceed allowable for reinforced masonry: $f_a + f_b \le F_b$ provided $f_a \le F_a$.

Example 1

Determine if the unreinforced CMU wall can sustain its loads with the wind. Specify a mortar type and unit strength per MSJC.



Per NCMA Tek 14-1B:
(per running foot)
A_{net} = 30.0 in^2
I_x = 309 in^4
S_x = 81.0 in^3
r = 3.21"

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \le 1.0 \qquad F_b = \tfrac{1}{3} f'_m \qquad f_b = \frac{M}{S} \qquad f_a = \frac{P}{A}$$

$$F_a = 0.25 f'_m \left[1 - \left(\frac{h}{140r} \right)^2 \right] \; for \; \frac{h}{r} \le 99$$

$$F_a = 0.25 f'_m \left(\frac{70r}{h} \right)^2 \; for \; \frac{h}{r} > 99$$

$$\frac{h}{r} = \frac{12\,ft(12in)}{3.21in} = 44.9 \; so \; F_a = 0.25 f'_m \left[1 - \left(\frac{12 \cdot 12in}{140 \cdot 3.21in} \right)^2 \right] = 0.224 f'_m$$

$$f_a = \frac{4k(1000\,^{lb}/_{k})}{30in^2} = 133\,psi$$

Case "A" with wind

at midheight of wall : (1 ft·kips/ft^2) (ft) (in/ft)

$$M = \frac{Pe}{2} + \frac{wh^2}{8} = \frac{4\,kip \times 3''}{2} + \left[\frac{(0.030)(12)^2}{8} \right] \times 12 = 12.5\,kip-in.$$

$$f_b = \frac{12{,}500\,lb-in}{81.0\,in^3} = 154\,psi \qquad f_b \le 1/3 f'_m$$

tension criterion : $\qquad f'_m \ge 154/(1/3) = 462$ psi

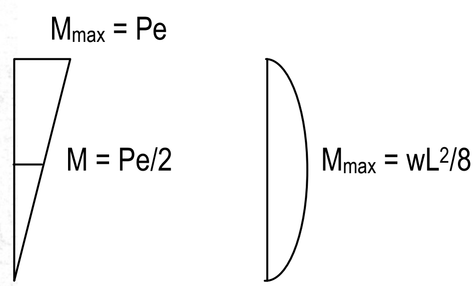
$$-f_a + f_b = F_t$$

$$-133\,psi + 154\,psi = 21\,psi$$

$$F_{t\,req'd} = 21\,psi$$

compression criterion :

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} < 1 \qquad \frac{133}{0.224 f'_m} + \frac{154}{0.333 f'_m} = 1; \qquad f'_m = 1056\,psi$$



Moment distribution from eccentricity

Moment distribution from distributed wind load

Case "B" without wind

at top of wall : M = Pe = 12.0 kip - in.

$$f_b = 12{,}000\,lb-in/81\,in^3 = 148\,psi$$

tension criterion : $-f_a + f_b = F_t$

$$-133\,psi + 148\,psi = 15\,psi \qquad F_{t\,req'd} = 15\,psi$$

Per MSJC Table 2.2.3.2, use PCL Type N mortar F_t = 25 psi

compression criterion : $\dfrac{f_a}{F_a} + \dfrac{f_b}{F_b} \le 1.0$

$$\frac{133}{0.224 f'_m} + \frac{148}{0.333 f'_m} = 1.00 \qquad f'_m = 1038\,psi$$

f'_m = 1056 psi (governs)

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

Direction of flexural tensile stress and masonry type	Mortar types			
	Portland cement/lime or mortar cement		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.