Architecture 504
Masonry Structures

Strength Design

- TMS Chap 9

Frank Lloyd Wright's iconic Ennis House sells for a record-setting $18 million

By Alexander Walter | Oct 17, '19 3:31 PM EST

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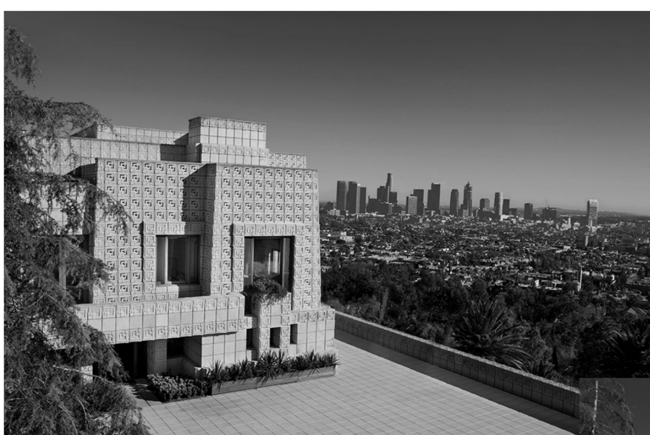
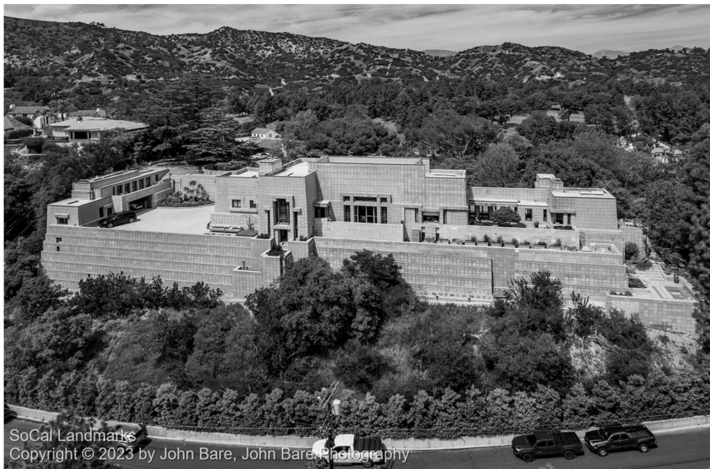
Photo: Mary E. Nichols, via Realtor.com

> *After an incredible publicity blitz and well over a year on the market, Frank Lloyd Wright's world-renowned Ennis House — tucked into the foothills of Los Feliz [...] — has sold for $18 million to an as-yet-unidentified buyer. That number, while significantly below the $23 million ask, ranks it as the priciest Wright-designed home ever sold, easily eclipsing the previous high-water mark set by the Storer House in nearby Hollywood Hills, which was purchased in 2013 for $6.8 million [...]* — Variety

Ennis House – Frank Loyd Wright



Ennis House – Frank Loyd Wright



Ennis House – Frank Loyd Wright

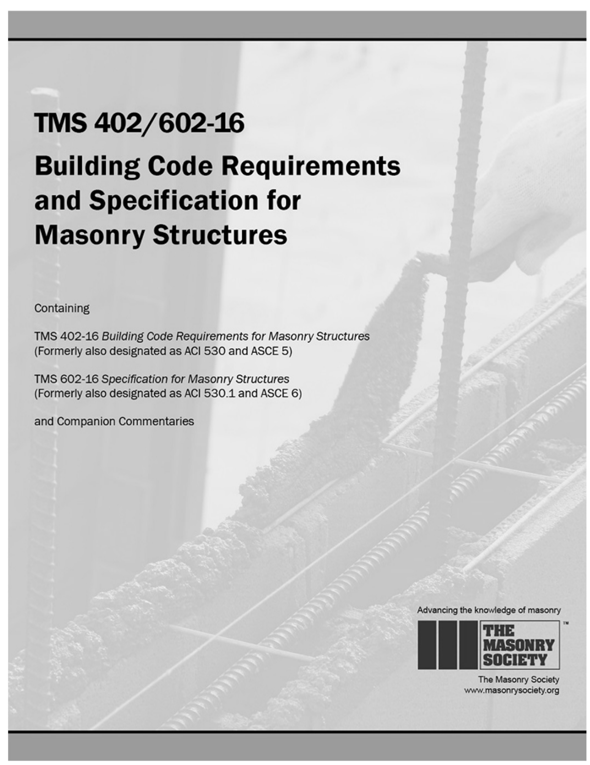
Ennis House – Frank Loyd Wright

Design Options

Empirical
- TMS 402 Appendix A

Allowable Stress Design (ASD)
- TMS 402 Chap. 8

Strength Design
- TMS 402 Chap. 9

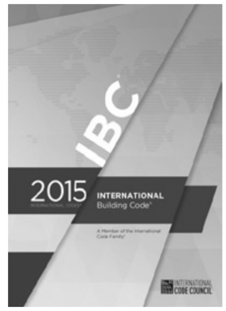


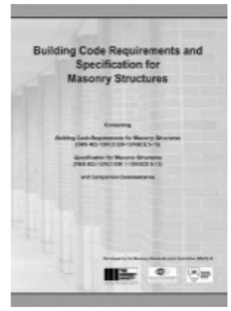
Design Options

Empirical
- TMS 402 Appendix A

Allowable Stress Design (ASD)
- TMS 402 Chap. 8

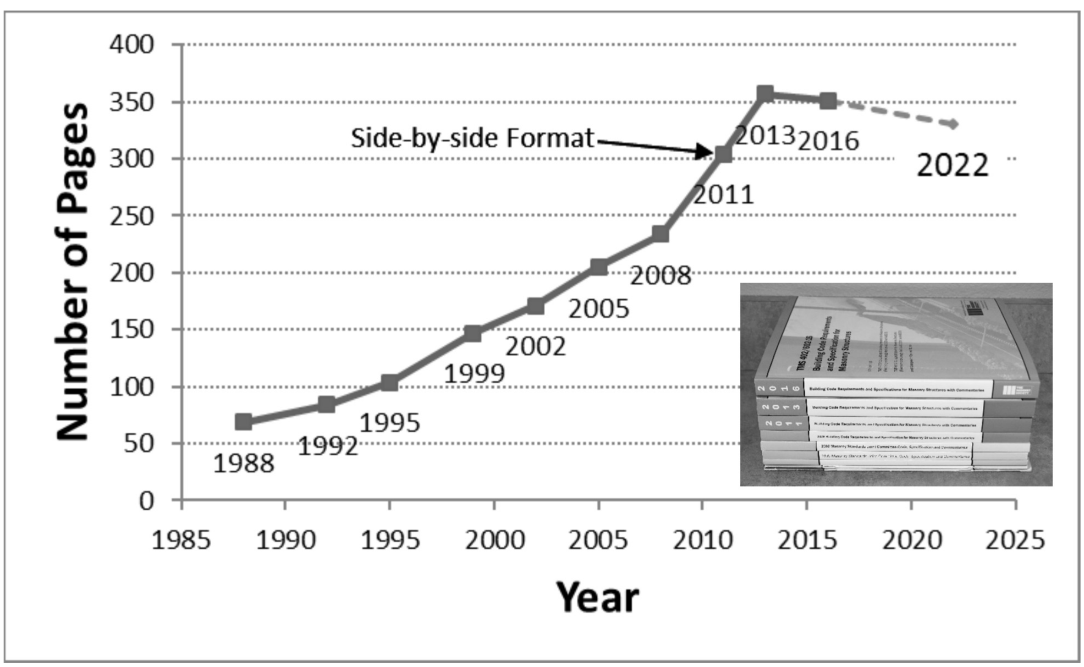
Strength Design
- TMS 402 Chap. 9
- IBC Section 2108
  - mostly references TMS 402
  - steel development length capped at 72 d_b
  - Mechanical and welded splices





TMS 402

Development



TMS 402 Chapter 9

9.1 General

9.1.1 Scope

9.1.2 Required strength

9.1.3 Design strength

9.1.4 Strength-reduction factors

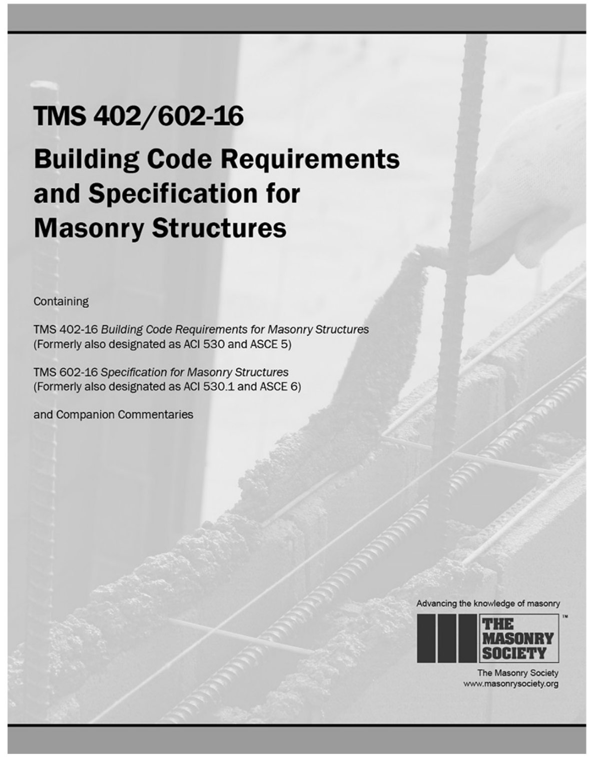
9.1.5 Deformation requirements

9.1.6 Anchor bolts embedded in grout

9.1.7 Shear strength in Multiwythe elements

9.1.8 Nominal bearing strength

9.1.9 Material properties



TMS 402 Chapter 9

Strength Design Method

Strength Required by Loads < Strength of Masonry

γ Pu > ø Pn

- 1.4 D
- 1.2 D + 1.6 Lr + 0.5(Lr or S)
- 1.2 D + 1.6(Lr or S) + (L or 0.5W)
- 1.2 D + 1.0W + L + 0.5(Lr or S)
- 0.9D + 1.0W
- 1.2D + Ev + Eh + L + 0.2S
- 0.9D - Ev + Eh

(Equation 9-11) for h/r < 99

$$P_n = 0.80\left\{0.80 A_n f'_m \left[1 - \left(\frac{h}{140r}\right)^2\right]\right\}$$

(Equation 9-12) for h/r > 99

$$P_n = 0.80\left[0.80 A_n f'_m \left(\frac{70r}{h}\right)^2\right]$$

TMS 402 Chapter 9

9.1.4 Strength-reduction factors, ø

Action	Reinforced Masonry	Unreinforced Masonry
combinations of flexure and axial load	0.90	0.60
shear	0.80	
bearing	0.60	
anchor bolts: pryout	0.50	
anchor bolts: controlled by anchor bolt steel	0.90	
anchor bolts: pullout	0.65	

TMS 402 Chapter 9 Strength Design $Pu \leq Pn$

Section 9.2 Unreinforced (plain) masonry

9.2.1 Scope

9.2.2 Design criteria (uncracked)

9.2.3 Design assumptions

- strain proportional to distance from N.A.
- flexural tension proportional to strain
- flexural comp. + axial comp. proportional to strain
- stresses in reinforcement are not accounted for

$$f_t = \frac{Mc}{I} - \frac{P}{A}$$

9.2.4 Nominal flexural and axial strength

- compressive stress ≤ 0.80 f'm
- tensile stress ≤ fr

(Equation 9-11) for h/r < 99

$$P_n = 0.80\left\{0.80 A_n f'_m\left[1-\left(\frac{h}{140r}\right)^2\right]\right\}$$

9.2.5 Axial tension

- tension resistance shall be neglected

(Equation 9-12) for h/r > 99

$$P_n = 0.80\left[0.80 A_n f'_m\left(\frac{70r}{h}\right)^2\right]$$

9.2.6 Nominal shear strength

(3.8 Anv √f'm or 300 Anv)

TMS 402 Chapter 9

Table 9.1.9.2 Modulus of Rupture

Masonry Type	Mortar Type			
	Portland cement/lime or mortar cement		Masonry Cement	
	M or S	N	M or S	N
Normal to Bed Joints				
Solid Units	133	100	80	51
Hollow Units[1]				
Ungrouted	84	64	51	31
Fully Grouted	163	158	153	145
Parallel to bed joints in running bond				
Solid Units	267	200	160	100
Hollow Units				
Ungrouted and partially grouted	167	127	100	64
Fully grouted	267	200	160	100
Parallel to bed joints not laid in running bond				
Continuous grout section parallel to bed joints	335	335	335	335
Other	0	0	0	0

Reinforced Masonry Analysis - procedure

for axial compression using TMS 402 (2016)
Strength Design (LRFD) – **non-reinforced**

Given: applied load, geometry, material
Find: axial compressive load capacity, Pn

1. Determine the masonry strength, f'm, based on unit strength, fu, and mortar type
2. Find the net area, A_n, and r (see TEK 14-1B)
3. Calculate h/r
4. Choose the axial strength equation, Pn:
   If h/r < 99 use TMS 402 eq.9-11
   If h/r > 99 use TMS 402 eq.9-12
5. Calculate øPn where ø for axial force = 0.60
6. Check that øPn is greater than Pu.

(Equation 9-11) for h/r < 99

$$P_n = 0.80\left\{0.80 A_n f'_m\left[1-\left(\frac{h}{140r}\right)^2\right]\right\}$$

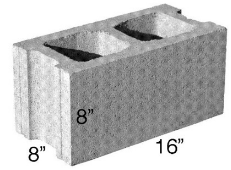
(Equation 9-12) for h/r > 99

$$P_n = 0.80\left[0.80 A_n f'_m\left(\frac{70r}{h}\right)^2\right]$$

Masonry Strength

TMS 602 – Table 2 – s18

Masonry strength, f'm, based on unit strength, fu, and mortar type M, S or N



Concrete Masonry

Table 2 — Compressive strength of masonry based on the compressive strength of concrete masonry units and type of mortar used in construction

Net area compressive strength of concrete masonry, psi (MPa)[1]	Net area compressive strength of ASTM C90 concrete masonry units, psi (MPa)	
	Type M or S mortar	Type N mortar
1,750 (12.07)	---	2,000 (13.79)
2,000 (13.79)	2,000 (13.79)	2,650 (18.27)
2,250 (15.51)	2,600 (17.93)	3,400 (23.44)
2,500 (17.24)	3,250 (22.41)	4,350 (28.96)
2,750 (18.96)	3,900 (26.89)	-----
3,000 (20.69)	4,500 (31.03)	-----

[1] For units of less than 4 in. (102 mm) nominal height, use 85 percent of the values listed.

Reinforced Masonry Analysis

for axial compression using TMS 402 (2016)
Strength Design – **non-reinforced**

Section Properties of Concrete Masonry Walls TEK 14 – 1B

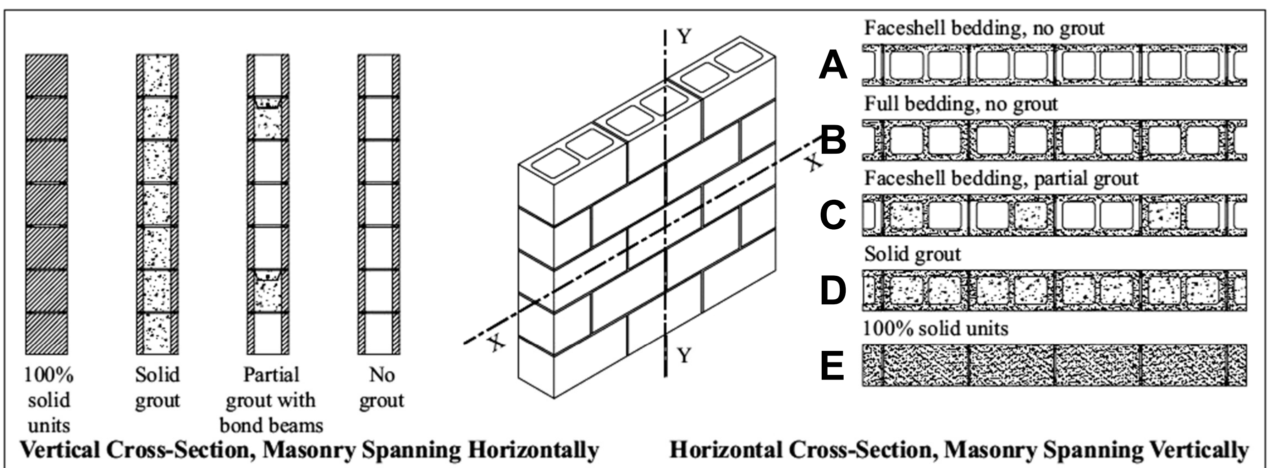


Figure 3—Horizontal and Vertical Cross-Sections

Reinforced Masonry Analysis

for axial compression using TMS 402 (2016)
Strength Design – **non-reinforced**

Section Properties of Concrete Masonry Walls TEK 14 – 1B

Table 3—8-inch (203-mm) Single Wythe Walls, 1¼ in. (32 mm) Face Shells (standard)

3a: Horizontal Section Properties (Masonry Spanning Vertically)

	Unit	Grout spacing (in.)	Mortar bedding	Net cross-sectional properties[A] A_n (in.^{2}/ft)	I_n (in.^{4}/ft)	S_n (in.^{3}/ft)
A	Hollow	No grout	Face shell	30.0	308.7	81.0
B	Hollow	No grout	Full	41.5	334.0	87.6
D/E	100% solid/solidly grouted		Full	91.5	443.3	116.3
C	Hollow	16	Face shell	62.0	378.6	99.3
↓	Hollow	24	Face shell	51.3	355.3	93.2
	Hollow	32	Face shell	46.0	343.7	90.1
	Hollow	40	Face shell	42.8	336.7	88.3
	Hollow	48	Face shell	40.7	332.0	87.1
	Hollow	72	Face shell	37.1	324.3	85.0
	Hollow	96	Face shell	35.3	320.4	84.0
	Hollow	120	Face shell	34.3	318.0	83.4

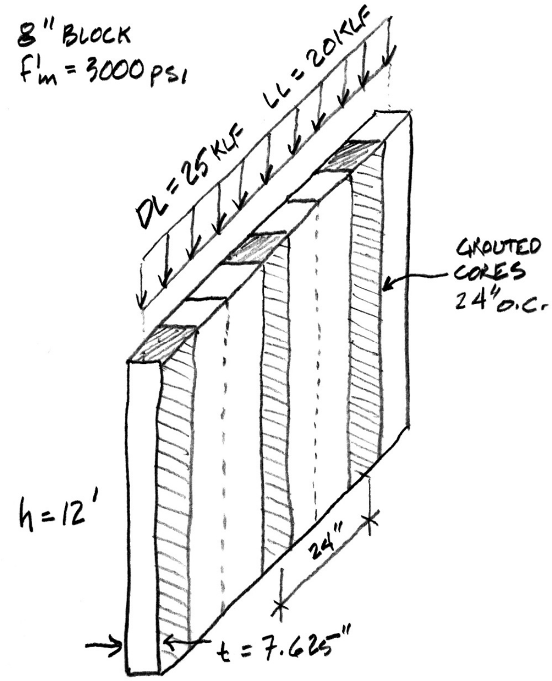
Reinforced Masonry Analysis

for axial compression using TMS 402 (2016)
Strength Design – **non-reinforced**

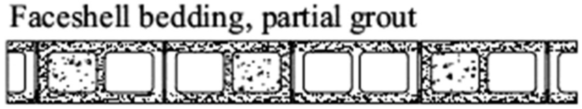
Example Problem

Given: geometry: 8" block, grouted 24" o.c.
material: f'm = 3000 psi
Find: check pass/fail for the given loading

1. Determine the masonry strength, f'm, based on unit strength, fu, and mortar type. (given f'm = 3000 psi)



Faceshell bedding, partial grout



Reinforced Masonry Analysis

for axial compression using TMS 402 (2016)
Strength Design – **non-reinforced**

2. Find the net area, A_n, and radius of gyration, r_{avg} (see TEK 14-1B)

Unit	Grout spacing (in.)	Mortar bedding	A_n (in.²/ft)	I_n (in.⁴/ft)	S_n (in.³/ft)	A_{avg} (in.²/ft)	I_{avg} (in.⁴/ft)	S_{avg} (in.³/ft)	r_{avg} (in.)
3a: Horizontal Section Properties (Masonry Spanning Vertically)			Net cross-sectional properties[A]			Average cross-sectional properties[B]			
Hollow	No grout	Face shell	30.0	308.7	81.0	41.5	334.0	87.6	2.84
Hollow	No grout	Full	41.5	334.0	87.6	41.5	334.0	87.6	2.84
100% solid/solidly grouted		Full	91.5	443.3	116.3	91.5	443.3	116.3	2.20
Hollow	16	Face shell	62.0	378.6	99.3	65.8	387.1	101.5	2.43
Hollow	24	Face shell	51.3	355.3	93.2	57.7	369.4	96.9	2.53
Hollow	32	Face shell	46.0	343.7	90.1	53.7	360.5	94.6	2.59
Hollow	40	Face shell	42.8	336.7	88.3	51.2	355.2	93.2	2.63
Hollow	48	Face shell	40.7	332.0	87.1	49.6	351.7	92.2	2.66
Hollow	72	Face shell	37.1	324.3	85.0	46.9	345.8	90.7	2.71
Hollow	96	Face shell	35.3	320.4	84.0	45.6	342.8	89.9	2.74
Hollow	120	Face shell	34.3	318.0	83.4	44.8	341.0	89.5	2.76
3b: Vertical Section Properties (Masonry Spanning Horizontally)									
Hollow	No grout	Face shell	30.0	308.7	81.0	40.5	330.1	86.6	2.86
Hollow	No grout	Full	30.0	308.7	81.0	41.5	334.0	87.6	2.84
100% solid/solidly grouted		Full	91.5	443.3	116.3	91.5	443.3	116.3	2.20
Hollow	16	Face shell	60.8	376.0	98.6	71.2	397.4	104.2	2.36
Hollow	24	Face shell	50.5	353.6	92.7	61.0	374.9	98.3	2.48
Hollow	32	Face shell	45.4	342.4	89.8	55.8	363.7	95.4	2.55
Hollow	40	Face shell	42.3	335.6	88.0	52.8	357.0	93.6	2.60
Hollow	48	Face shell	40.3	331.1	86.9	50.7	352.5	92.5	2.64
Hollow	96	Face shell	35.1	319.9	83.9	45.6	341.3	89.5	2.74
Hollow	120	Face shell	34.1	317.7	83.3	44.6	339.0	88.9	2.76

Table 3—8-inch (203-mm) Single Wythe Walls, 1¼ in. (32 mm) Face Shells (standard)

Reinforced Masonry Analysis

for axial compression using TMS 402
(2016) Strength Design – **non-reinforced**

FROM TEK 14-01B FOR 8" CMU
SINGLE WYTHE
HOLLOW BLOCK
GROUT @ 24" O.C.
FACE SHELL MORTAR

3. Calculate h/r

$A_n = 51.3 \text{ in}^2$

$r_{avg} = 2.53 \text{ in}$

$h/r = 12 \; \frac{144''}{2.53''} = 56.92 < 99 \therefore$ EQ 9-11

4. Choose the axial strength equation, Pn:
   If h/r < 99 use TMS 402 eq.9-11
   If h/r > 99 use TMS 402 eq.9-12

(Equation 9-11) for h/r < 99

$$P_n = 0.80\left\{0.80 A_n f'_m \left[1-\left(\frac{h}{140r}\right)^2\right]\right\}$$

Reinforced Masonry Analysis

for axial compression using TMS 402 (2016) Strength Design – **non-reinforced**

(Equation 9-11) for h/r < 99

$$P_n = 0.80\left\{0.80 A_n f'_m \left[1-\left(\frac{h}{140r}\right)^2\right]\right\}$$

5. Calculate øPn
   where ø for axial force = 0.60
   (unreinforced)

$$P_n = 0.8\left[0.8 A_n f'_m \left(1-\frac{h}{140r}\right)^2\right]$$

$$P_n = 0.8\left[0.8\left(51.3\tfrac{in^2}{FT}\right)(3\text{ KSI})\left(1-\left(\frac{144''}{140(2.53'')}\right)^2\right)\right]$$

$$P_n = 0.8\left[123.12(0.835)\right] = 0.8\left[102.77\right]$$

$$P_n = 0.8\left[102.77\right] = 82.2\ K/FT$$

$$\phi P_n = 0.6(82.2\text{ KLF}) = 49.33\text{ KLF}$$

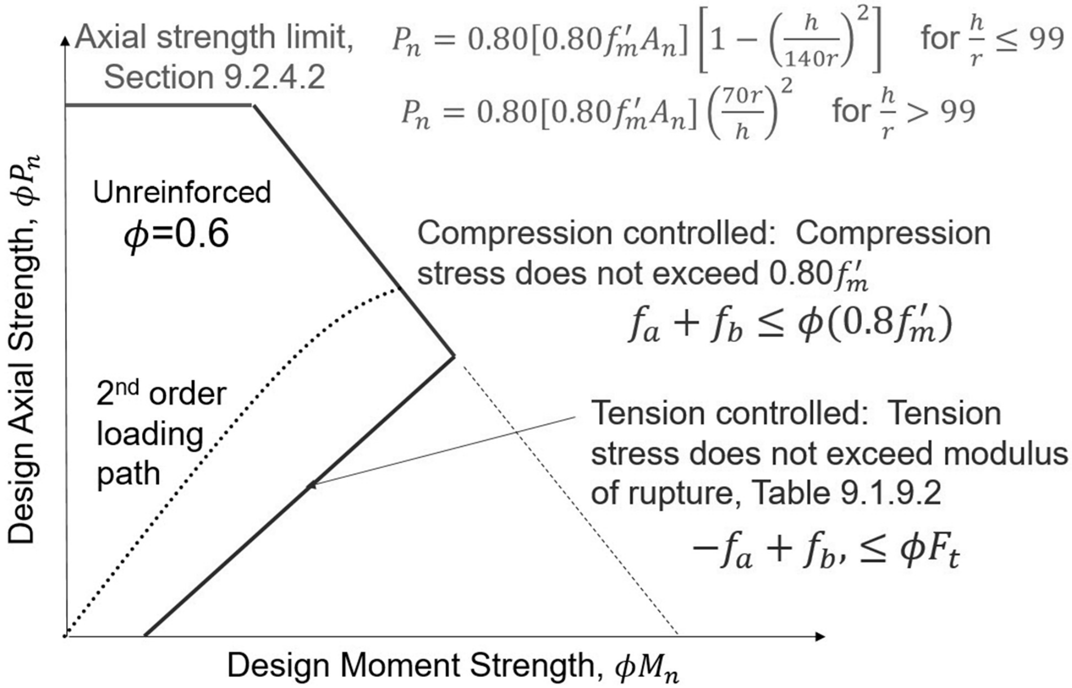
$$P_u = 1.2(25\text{ KLF}) + 1.6(20\text{ KLF}) = 62\text{ KLF}$$

6. Check that øPn is greater than Pu.

$$P_u = 62\text{ KLF} > 49.3\text{ KLF} = \phi P_n \quad \therefore \text{NG!}$$

TMS 402 Chapter 9

Interaction Diagram



TMS 402 Chapter 9

Moment Magnification

Design for magnified moment: $M_u = \psi M_{u,0}$

$$\psi = \frac{1}{1 - \frac{P_u}{P_e}} = \frac{1}{1 - \frac{P_u}{A_n f'_m \left(\frac{70r}{h}\right)^2}}$$

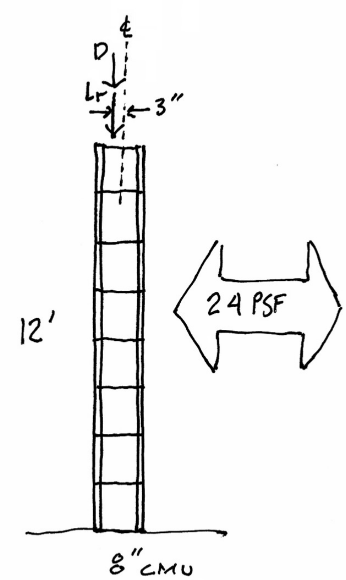
- Can take ψ = 1 if h/r ≤ 45
- Can take ψ = 1 if 45 < h/r ≤ 60 and nominal strength reduced by 10%

Unreinforced Masonry Wall

example

Given:
h = 12 ft
t = 8 in hollow CMU, fu = 2000 psi
type S mortar, face shell bedding, no grout

Loading:
D = 1 k/ft + selfweight of 30 psf
Lr = 0.5 k/ft (w/ e=3 in.)
W = 24 psf (+ or -)



Load Combinations

1.4D

$1.2D + 1.6L_r$

$1.2D + 1.0W + 0.5L_r$

0.9D + 1.0W

Unreinforced Masonry Wall
example

f'm = 2000 psi (TMS 602 – table 2 – s18)

Table 2 — Compressive strength of masonry based on the compressive strength of concrete masonry units and type of mortar used in construction

Net area compressive strength of concrete masonry, psi (MPa)[1]	Net area compressive strength of ASTM C90 concrete masonry units, psi (MPa)	
	Type M or S mortar	Type N mortar
1,750 (12.07)	---	2,000 (13.79)
2,000 (13.79)	2,000 (13.79)	2,650 (18.27)
2,250 (15.51)	2,600 (17.93)	3,400 (23.44)
2,500 (17.24)	3,250 (22.41)	4,350 (28.96)
2,750 (18.96)	3,900 (26.89)	-----
3,000 (20.69)	4,500 (31.03)	-----

[1] For units of less than 4 in. (102 mm) nominal height, use 85 percent of the values listed.

Unreinforced Masonry Wall
example

Section Properties of Concrete Masonry Walls
TEK 14 – 1B

using A – faceshell bedding, no grout

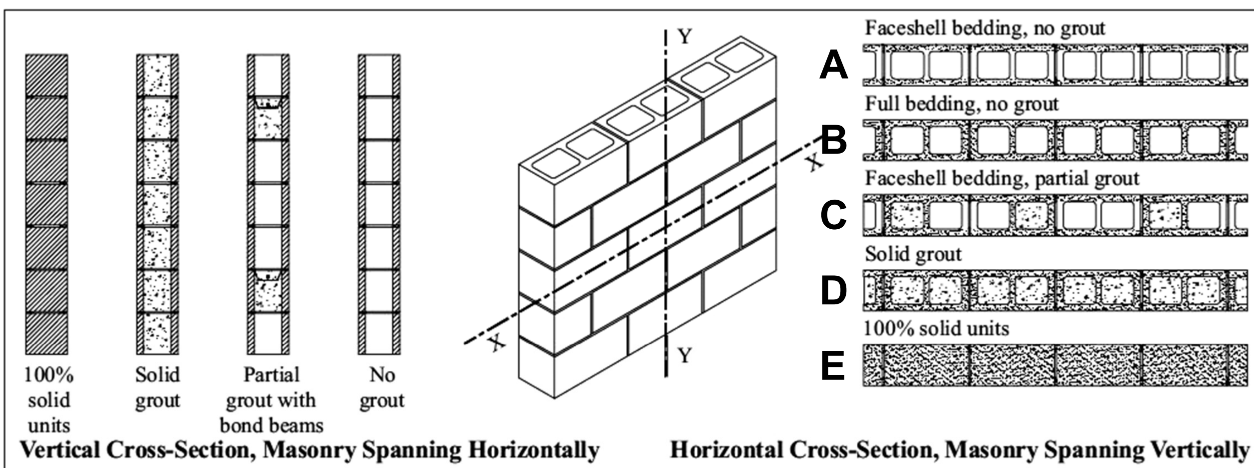


Figure 3—Horizontal and Vertical Cross-Sections

Unreinforced Masonry Wall
example

A_n = 30 in²/ft
S_n = 81 in³/ft
r_{avg} = 2.84 in

$$\frac{h}{r} = \frac{144in.}{2.84in.} = 50.7$$

(TEK 14 – 1B)

Unit	Grout spacing (in.)	Mortar bedding	A_n (in.²/ft)	I_n (in.⁴/ft)	S_n (in.³/ft)	A_{avg} (in.²/ft)	I_{avg} (in.⁴/ft)	S_{avg} (in.³/ft)	r_{avg} (in.)
3a: Horizontal Section Properties (Masonry Spanning Vertically)			Net cross-sectional properties[A]			Average cross-sectional properties[B]			
Hollow	No grout	Face shell	30.0	308.7	81.0	41.5	334.0	87.6	2.84
Hollow	No grout	Full	41.5	334.0	87.6	41.5	334.0	87.6	2.84
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100% solid/solidly grouted		Full	91.5	443.3	116.3	91.5	443.3	116.3	2.20
Hollow	16	Face shell	60.8	376.0	98.6	71.2	397.4	104.2	2.36
Hollow	24	Face shell	50.5	353.6	92.7	61.0	374.9	98.3	2.48
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Hollow	40	Face shell	42.3	335.6	88.0	52.8	357.0	93.6	2.60
Hollow	48	Face shell	40.3	331.1	86.9	50.7	352.5	92.5	2.64
Hollow	96	Face shell	35.1	319.9	83.9	45.6	341.3	89.5	2.74
Hollow	120	Face shell	34.1	317.7	83.3	44.6	339.0	88.9	2.76

Table 3–8-inch (203-mm) Single Wythe Walls, 1¼ in. (32 mm) Face Shells (standard)

Unreinforced Masonry Wall example

Load Combinations

1.4D
$1.2D + 1.6L_r$
$1.2D + 1.0W + 0.5L_r$
0.9D + 1.0W

Determine the controlling load combination

A. $1.2D + 1.0W + 0.5L_r$ Wind pressure (compression on outside)
B. $1.2D + 1.0W + 0.5L_r$ Wind suction (compression on inside)
C. 0.9D + 1.0W Wind pressure (compression on outside)
D. 0.9D + 1.0W Wind suction (compression on inside)

Load Combination	Tensile Stress (psi)
$1.2D + 1.0W + 0.5L_r$ wind pressure	?
$1.2D + 1.0W + 0.5L_r$ wind suction	?
0.9D + 1.0W wind pressure	?
0.9D + 1.0W wind suction	?

Unreinforced Masonry Wall example

Load Combinations

1.4D

$1.2D + 1.6L_r$

$1.2D + 1.0W + 0.5L_r$

$0.9D + 1.0W$

Determine the controlling load combination

A. $1.2D + 1.0W + 0.5L_r$ Wind pressure (compression on outside)

B. $1.2D + 1.0W + 0.5L_r$ Wind suction (compression on inside)

C. $0.9D + 1.0W$ Wind pressure (compression on outside)

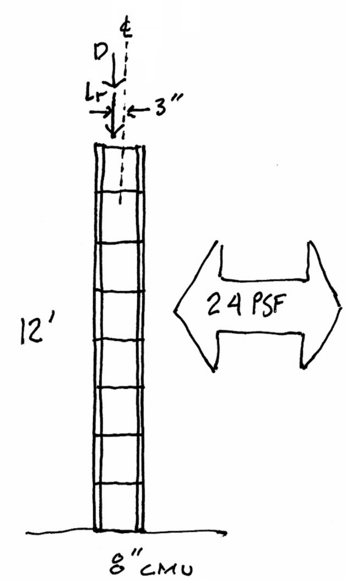
D. $0.9D + 1.0W$ Wind suction (compression on inside)

Load Combination	Tensile Stress (psi)
$1.2D + 1.0W + 0.5L_r$ wind pressure	5.9 psi
$1.2D + 1.0W + 0.5L_r$ wind suction	40.4 psi
$0.9D + 1.0W$ wind pressure	12.4 psi
$0.9D + 1.0W$ wind suction	47.6 psi

Unreinforced Masonry Wall
example

Given:
- h = 12 ft
- t = 8 in hollow CMU, fu = 2000 psi
- type S mortar, face shell bedding, no grout

Loading:
- D = 1 k/ft + selfweight of 30 psf
- Lr = 0.5 k/ft (w/ e=3 in.)
- W = 24 psf (+ or -)



Load Combinations

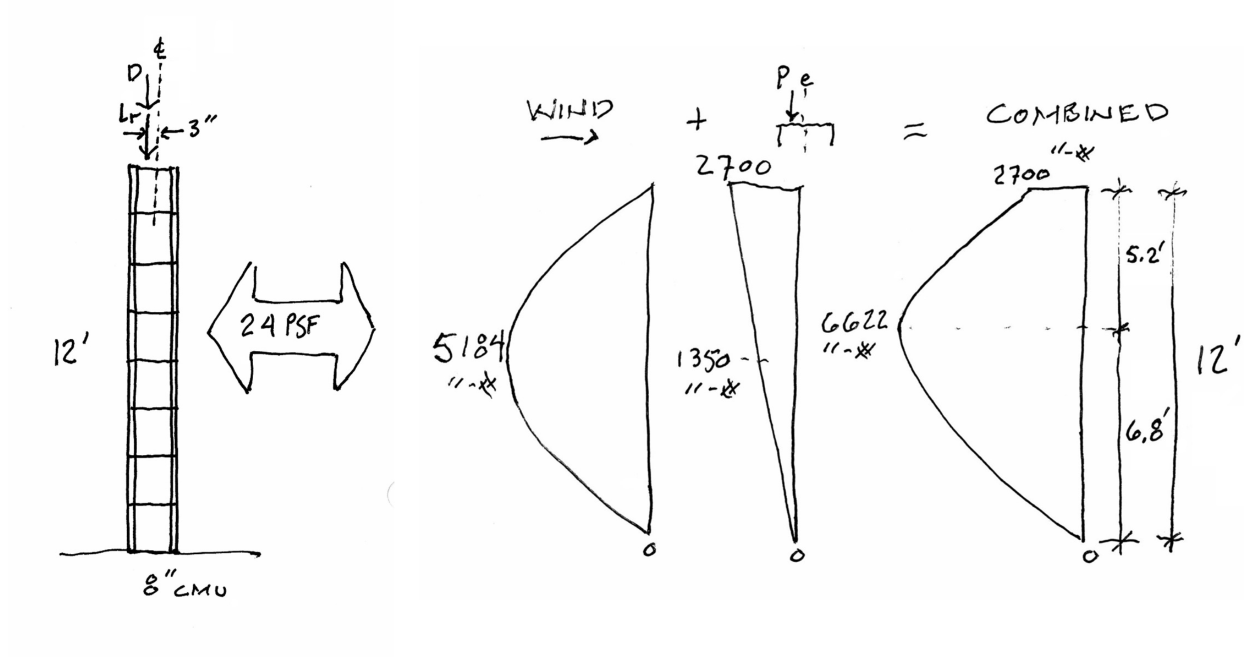
1.4D

$1.2D + 1.6L_r$

$1.2D + 1.0W + 0.5L_r$

$0.9D + 1.0W$

Unreinforced Masonry Wall
example



Unreinforced Masonry Wall example

0.9D + 1.0W - Wind suction (compression on inside face of wall)

Location of max moment, x

$$x = \frac{h}{2} - \frac{M_{uf}}{w_u h} = \frac{144in.}{2} - \frac{2700\,\frac{lb \cdot in.}{ft}}{24\,\frac{lb}{ft^2}(12ft)} = 62.6in.$$

Factored axial load, P_u

$$P_u = 0.9\left(1000\,\frac{lb}{ft} + 30\,\frac{lb}{ft^2}\left(\frac{62.6in.}{12in./ft}\right)\right) = 1041\,\frac{lb}{ft}$$

Moment at top of wall, M_{uf}

$$M_{uf} = P_{uf}e = 0.9\left(1000\,\frac{lb}{ft}\right)(3.0in.) = 2700\,\frac{lb \cdot in.}{ft}$$

Maximum combined moment, $M_{u,0}$

$$M_{u,0} = \frac{M_{uf}}{2} + \frac{w_u h^2}{8} + \frac{M_{uf}^2}{2w_u h^2}$$

$$= \frac{2700\frac{lb \cdot in.}{ft}}{2} + \frac{24\frac{lb}{ft^2}(12ft)^2\left(12\frac{in.}{ft}\right)}{8} + \frac{\left(2700\frac{lb \cdot in.}{ft}\right)^2}{2\left(24\frac{lb}{ft^2}\right)(12ft)^2\left(12\frac{in.}{ft}\right)}$$

$$= 1350 + 5184 + 88 = 6622\,\frac{lb \cdot in.}{ft}$$

Unreinforced Masonry Wall example

0.9D + 1.0W - Wind suction (compression on inside face of wall)

9.2.4.3 *P-Delta effects*

9.2.4.3.1 Members shall be designed for the strength level axial load, P_u, and the moment magnified for the effects of member curvature, M_u.

9.2.4.3.2 The magnified moment, M_u, shall be determined either by a second-order analysis, or by a first-order analysis and Equations 9-13 and 9-14.

$$M_u = \psi M_{u,0} \qquad \text{(Equation 9-13)}$$

$$\psi = \frac{1}{1 - \dfrac{P_u}{A_n f'_m \left(\dfrac{70r}{h}\right)^2}} \qquad \text{(Equation 9-14)}$$

9.2.4.3.3 A value of $\psi = 1$ shall be permitted for members in which $h/r \le 45$.

Moment Magnifier:

$$\psi = \frac{1}{1 - \dfrac{P_u}{A_n f'_m \left(\dfrac{70r}{h}\right)^2}} = \frac{1}{1 - \dfrac{1041\dfrac{lb}{ft}}{\left(30\dfrac{in.^2}{ft}\right)(2000psi)\left(\dfrac{70\ \ 2.84}{144}\right)^2}} = 1.01$$

Unreinforced Masonry Wall example

0.9D + 1.0W - Wind suction (compression on inside face of wall)

Moment Magnifier: $\psi = 1.01$

Compression Stress:

$$\frac{P_u}{A_n} + \frac{\psi M_{u,0}}{S_n} = \frac{1041\frac{lb}{ft}}{30\frac{in.^2}{ft}} + \frac{1.01\left(6622\frac{lb\cdot in.}{ft}\right)}{81.0\frac{in.^3}{ft}} = 34.7 + 82.6 = 117.3\ psi$$

Nominal Strength = 0.8(2000 psi) =1600 psi
(f'm)

Design Strength = 0.6(1600 psi) = 960 psi **OK**

Tension stress:

$$+\frac{P_u}{A_n} - \frac{\psi M_{u,0}}{S_n} = +34.7 - 82.6 = 47.9\ psi\ tension$$

Nominal Strength = 51 psi
(f_r)

Design Strength = 0.6 (51 psi) = 30.6 psi **NG!**

Unreinforced Masonry Wall example

0.9D + 1.0W - Wind suction (compression on inside face of wall)

What to do to make wall work? (short of reinforcing wall)

1. Increase wall size, say to 12 in. ($S_n = 139.6\ in^3/ft$). Maximum tensile stress is 12.7 psi.

2. Grout wall. (w-wall = 75 psf; $A_n = 91.5\ in^2/ft$; $S_n = 116.3\ in^3/ft$; $f_r = 163$ psi) Maximum tensile stress of 45.3 psi is less than design stress of 0.6(163) = 97.8 psi

3. Use Portland cement/lime or mortar cement (modulus of rupture is 84 psi). Maximum tensile stress of 47.2 psi is less than design stress of 0.6(94)=50.4 psi

4. Use pilasters