Design of Tall Masonry Walls

Session 2

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MASONRY SEMINAR
Masonry Institute of Hawaii
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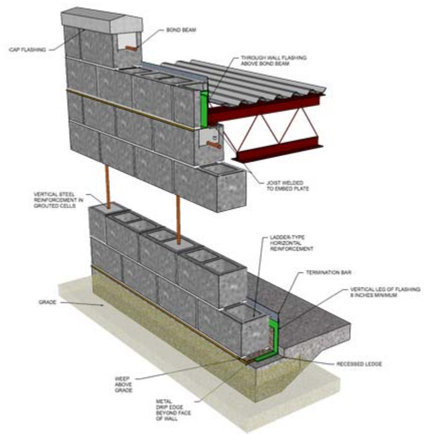
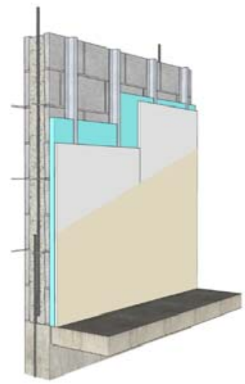
Outline

- Over view of Single wythe walls
- Present ASD Reinforced Masonry Wall Design Provisions
- Present SD Code provisions Masonry Wall Design Provisions
- Present Tall Wall Design Examples

Single Wythe Walls





Exterior Load Bearing and Non Loadbearing single Wythe Masonry Walls

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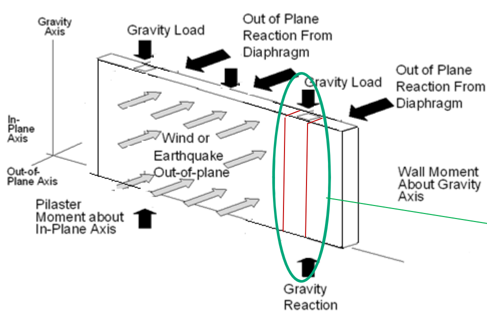
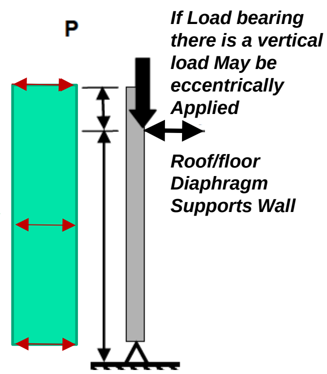
Exterior Reinforced Masonry RM Typically subjected to <u>Axial and Flexure Loads</u>





CODE - COMBINED LOADING – GIVES ASSUMPTIONS AND SAYS USE MECHANICS – THUS INTERACTION DIAGRAMS – CODE SECTION 8.3 (ASD) – 9.3 (SD)

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Flexure and Axial Load with Reinforced Masonry

- ASD – Discuss Code Provisions and Interaction diagrams - Use TMS 402 -13 (IBC 2015)
  - reinforced masonry walls
  - Present design techniques and aids for design problems involving combinations of flexure and axial force
  - interaction diagrams by hand and by spreadsheet
- Repeat with strength design

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Design for Axial Forces and flexure- (OOP) ASD Interaction Diagrams

Code Section 8.3

COMBINED AXIAL STRESS AND COMPRESSION BENDING STRESS = just add f_a+f_b (no interaction equation)

- Maximum compressive stress in masonry from axial load plus bending must not exceed (0.45) f'_m
- Axial compressive stress must not exceed allowable axial stress from Code 8.2.4.1 – Axial forces limited Eq.8-21 or 8-22. Note same result .
- Limit tension stress in reinforcing to F_s – usually 32,000 psi – Compression steel similar if tied (not usual – columns)

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Limit P applied ≤ P allowable (axial compressive capacity)

Code Equations (8-21) and (8-22)

Slenderness reduction coefficients – same as unreinforced masonry. Compression reinforcing must be tied as per 5.3.1.4 to account for it. i.e. F_S = 0 (compression) if not tied.

$$P_a = (0.25\, f'_m\, A_n + 0.65\, A_{st}\, F_s)\left[1 - \left(\frac{h}{140r}\right)^2\right] \quad \text{for } \frac{h}{r} \le 99 \qquad (8\text{-}21)$$

$$P_a = (0.25\, f'_m\, A_n + 0.65\, A_{st}\, F_s)\left(\frac{70r}{h}\right)^2 \quad \text{for } \frac{h}{r} > 99 \qquad (8\text{-}22)$$

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Axial Compression in Bars Can be accounted for if tied as:

<u>5.3.1.4 Lateral ties ..:</u>

- (a) Longitudinal reinforcement .. enclosed by lateral ties at least 1/4 in …diameter.
- (b) Vertical spacing of lateral ≤16 longitudinal bar diameters, lateral tie bar or wire diameters, or least cross-sectional dimension of the member.
- (c) Lateral ties shall be arranged such that every corner and alternate longitudinal bar shall have lateral support provided by the corner of a lateral tie with an included angle of not more than135 degrees. No bar … farther than 6 in. (152 mm) clear… from such a laterally supported bar. Lateral ties … in either a mortar joint or in grout. Where longitudinal bars … circular ties shall be 48 tie diameters.
- d) Lateral ties shall be located ….one-half lateral tie spacing above the top of footing or slab in any story, …one-half a lateral tie spacing below the lowest horizontal reinforcement in beam, …
- (e) Where beams or brackets frame into a … not more than 3 in…. such beams or brackets.

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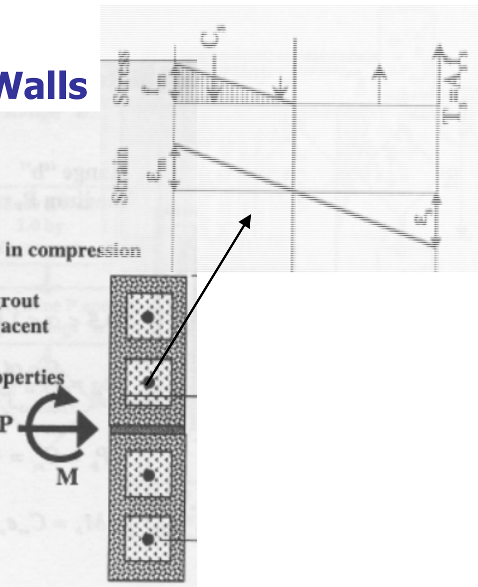
Allowable – Stress
Interaction Diagrams Walls

1. plane sections remain plane after bending
   - shear deformations neglected
   - strain distribution linear with depth
2. neglect all masonry in tension
3. neglect steel in compression unless tied
4. stress-strain relation for masonry is linear in compression
5. stress-strain relation for steel is linear
6. perfect bond between reinforcement and grout
   - strain in grout is equal to strain in adjacent reinforcement
7. grout properties same as masonry unit properties



+ Assume Solid grouted and

Singly reinforced wall bending out of plane

Bars in center of wall thickness

rom Dan Abrams- Masonry Structures Class Notes next 10 Slides

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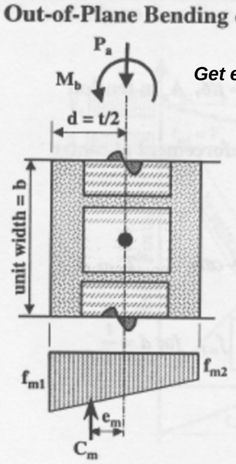
Axial Force-Moment Interaction Diagram

Out-of-Plane Bending of Reinforced Wall



Get equivalent force couple at Centerline of wall thickness

Range "a":
large P, small M, $e=M/P < t/6$

$$P_a = 0.5(f_{m1} + f_{m2})A$$

$$M_a = 0.5(f_{m1} - f_{m2})S \quad \text{where } S = bt^2/6$$

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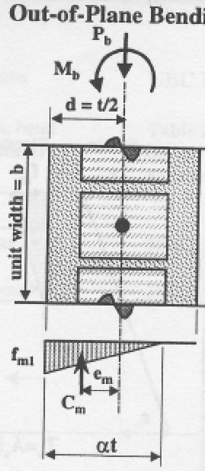
Axial Force-Moment Interaction Diagram

Out-of-Plane Bending of Reinforced Wall



Range "b"
medium P, medium M, $e > t/6$, A_s in compression

$0.5 < \alpha < 1.0$ for section with reinforcement at center

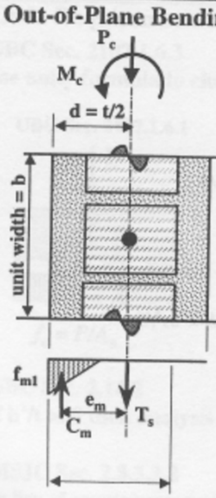
$$e_m = \frac{t}{2} - \frac{\alpha t}{3} \qquad \alpha t = kd$$

$$P_b = C_m = \frac{f_{m1}}{2}\alpha t b$$

$$M_b = C_m e_m$$

Axial Force-Moment Interaction Diagram

Out-of-Plane Bending of Reinforced Wall



Range "c" small P, large M, $e > t/6$, A_s in tension

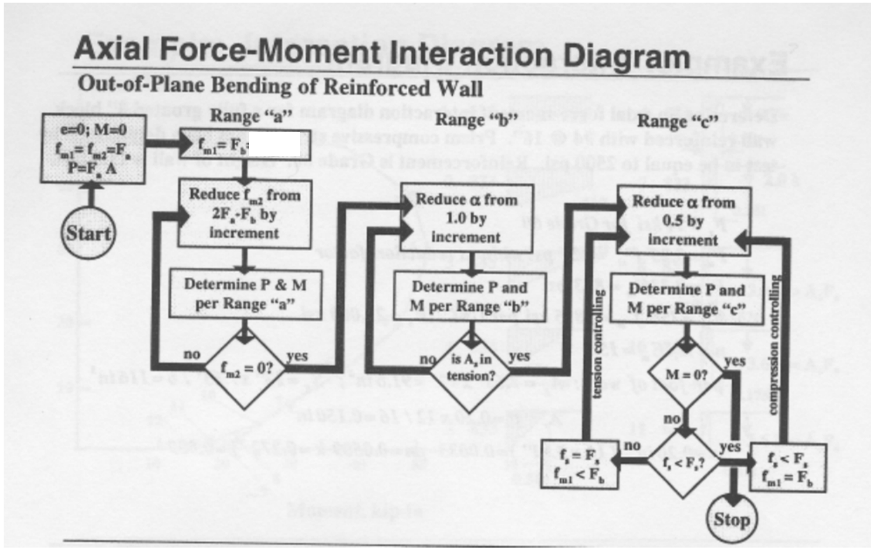
$\alpha < 0.5$ for section with reinforcement at center

$$e_m = \frac{t}{2} - \frac{\alpha t}{3} \qquad \alpha t = kd$$

$$P_c = C_m - T_s \qquad C_m = \frac{f_{m1}}{2}\alpha t b \qquad T_s = A_s f_s$$

$$\frac{f_s}{n} = \left[\frac{d - \alpha t}{\alpha t}\right] f_{m1} = \left[\frac{0.5 - \alpha}{\alpha}\right] f_{m1} \quad for\ d = \frac{t}{2}$$

$$M_c = C_m e_m + T_s\left(d - \frac{t}{2}\right)$$



Axial Force-Moment Interaction Diagram
Out-of-Plane Bending of Reinforced Wall
Range "a"
Range "b"
Range "c"
Start
Reduce f_{m2} from $2F_a$-F_b by increment
Determine P & M per Range "a"
f_{m2} = 0?
Reduce α from 1.0 by increment
Determine P and M per Range "b"
is A_s in tension?
Reduce α from 0.5 by increment
Determine P and M per Range "c"
M = 0?
f_s < F_s?
tension controlling
compression controlling
Stop
no
yes

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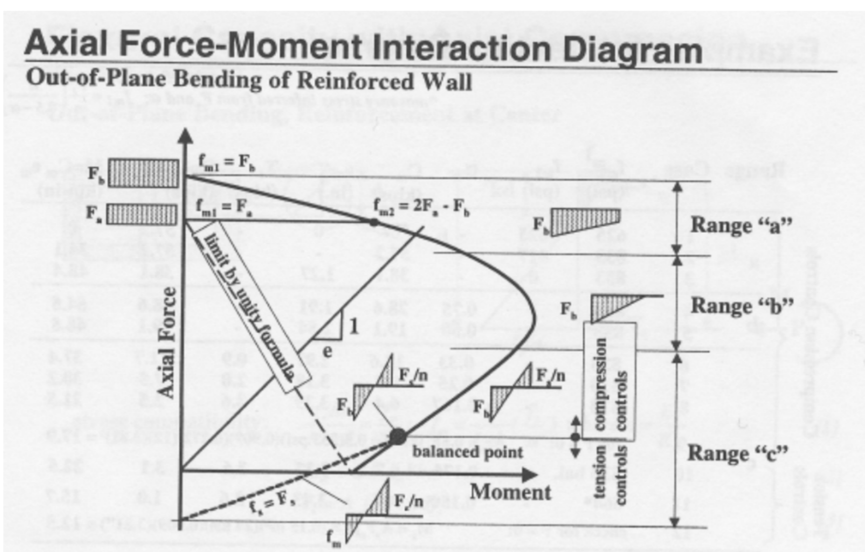

Axial Force-Moment Interaction Diagram
Out-of-Plane Bending of Reinforced Wall
$f_{m1} = F_b$
$f_{m1} = F_a$
$f_{m2} = 2F_a - F_b$
limit by unity formula
Axial Force
Moment
balanced point
$f_s = F_s$
Range "a"
Range "b"
Range "c"
compression controls
tension controls

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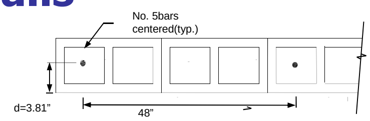
Allowable – Stress Interaction Diagrams Walls



- Example 1(10.4-2 & 10.4-3 & 10.4-4 MDG)
  - 8" CMU with #5 @ 48 in OC
  - f'_m = 2000 psi Based on Effective width = 48 in., h=16.7 ft
- For M = 0 , P cutoff - Equation 8-21 or 8-22

$$\frac{h}{r} = \frac{16.67\,\text{ft} \times 12\,\text{in./ft}}{2.20\ \text{in.}} = 90.9 < 99$$

$$P_a = \left(0.25\ f'_m\ A_n + 0.65\ A_{st} F_s\right)\left(1 - \frac{h}{140\ r}\right)^2$$

$$= \left(0.25 \times 2{,}000\ \text{psi} \times \left(7.63\ \text{in.} \times 48\,\text{in.}\right) + 0\right)\left(1 - \frac{16.67}{140 \times 2.2}\right)^2$$

$$= 26{,}429\ lb = 26.4\ \text{kips}$$

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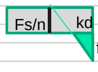
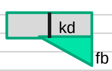
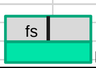
Spreadsheet for calculating allowable-stress M-N diagram for solid masonry wall							
16.67 Ft Wall w/ No. 5 @ 48in (Centered)				NOTE BASED ON 1 ft of Wall and Not EFFECT			
total depth, t	7.625				Wall Height, h	16.67	feet
f'm, fprimem	2000				Radius of Gyration, r	2.20	in
Em	1800000				h/r	90.9	
Fb	900.00				Reduction Factor, R	0.578	
Es	29000000				Allowable Axial Stress, Fa	289	psi
Fs	32000				Net Area, An	365.7	in^2
d	3.8125				Allowable Axial Compr, Pa	26429	lb
kbalanced	0.311828						
tensile reinforcement, As/beff	0.31	#5 @ 48 Centered					
width, beff	48						
because compression reinforcement is not tied, it is not counted							
	k	**kd**	**fb**	**Cmas**	**fs**	**Axial Force**	**Moment**
			(psi)	**(lb)**	**(psi)**	**(lb)**	**(lb-in)**
Points controlled by steel	0.01	0.04	20	18	-32000	-2475	17
	0.05	0.19	105	478	-32000	-2360	448
	0.1	0.38	221	2019	-32000	-1975	1861
	0.15	0.57	351	4811	-32000	-1277	4356
	0.2	0.76	497	9087	-32000	-208	8084
	0.25	0.95	662	15145	-32000	1306	13232
	0.24	0.92	627	13774	-32000	963	12078
	0.3	1.14	851	23366	-32000	3362	20044
Points controlled by masonry	0.311828	1.19	900	25679	-32000	3940	21931
	0.4	1.53	900	32940	-21750	6549	27210
	0.5	1.91	900	41175	-14500	9170	32704
	0.6	2.29	900	49410	-9667	11603	37675
	0.8	3.05	900	65880	-3625	16189	46047
	1	3.81	900	82350	0	20588	52327
	1.2	4.58	900	98820	0	24705	56513
	1.4	5.34	900	115290	0	28823	58606
	1.6	6.10	900	131760	0	32940	58606
	1.8	6.86	900	148230	0	37058	56513
	2	7.63	900	164700	0	41175	52327
Pure compression			900	329400	0	329400	0
Axial Force Limits						26429	0
						26429	58606

$$n = \frac{E_s}{E_m} = \frac{29{,}000{,}000}{900 \times 2000} = 16.11$$







Fb= 0.25 f'mR+?

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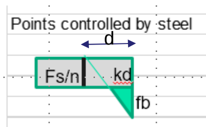
k	kd	fb (psi)	Cmas (lb)	fs (psi)	Axial Force (lb)	Moment (lb-in)
0.01	0.04	20	18	-32000	-2475	17
0.05	0.19	105	478	-32000	-2360	448
0.1	0.38	221	2019	-32000	-1975	1861
0.15	0.57	351	4811	-32000	-1277	4356
0.2	0.76	497	9087	-32000	-208	8084
0.25	0.95	662	15145	-32000	1306	13232
0.24	0.92	627	13774	-32000	963	12078
0.3	1.14	851	23366	-32000	3362	20044



$$f_b = \frac{\frac{F_s}{n}}{d-kd} \times kd = \frac{\frac{32{,}000}{16.11}}{3.81-0.38} \times 0.38 = 221\,\text{psi}$$

$$C_{mas} = 1/2 \times fb \times kd \times b = 1/2 \times 221 \times 0.38 \times 48 = 2{,}019\,\text{lb}$$

$$P = C_{mas} - (A_s \times F_S) = 2019 - (0.31 \times 32{,}000) = -7{,}901\,\text{lb}$$

For b_{eff} for 1 ft of wall = $1/4 \times -7901 = -1975$ lb per foot of wall

$$M = C_{mas} \times e_m - T_s(d_s - \frac{t}{2}) =$$

$$M = 2019 \times \left(\frac{7.625}{2} - \frac{0.38}{3}\right) - T_s(0) = 7{,}437\,\text{lb.in}$$

For b_{eff} for 1 ft of wall = $1/4 \times 7437 = 1{,}860$ lb.in per foot of wall

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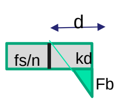
0.311828	1.19	900	25679	-32000	3940	21931
0.4	1.53	900	32940	-21750	6549	27210
0.5	1.91	900	41175	-14500	9170	32704
0.6	2.29	900	49410	-9667	11603	37675
0.8	3.05	900	65880	-3625	16189	46047
1	3.81	900	82350	0	20588	52327
1.2	4.58	900	98820	0	24705	56513
1.4	5.34	900	115290	0	28823	58606
1.6	6.10	900	131760	0	32940	58606
1.8	6.86	900	148230	0	37058	56513



$$F_b = \frac{\frac{f_s}{n}}{d-kd} \times kd = \frac{\frac{f_s}{16.11}}{3.81-1.53} \times 1.53 = 900\,\text{psi}$$

$$f_s = 21{,}750\,psi$$

$$C_{mas} = 1/2 \times F_b \times kd \times b = 1/2 \times 900 \times 1.53 \times 48 = 32{,}940\,\text{lb}$$

$$P = C_{mas} - (A_s \times F_S) = 32{,}940 - (0.31 \times 21{,}750) = 26{,}198\,\text{lb}$$

For b_{eff} for 1 ft of wall = $1/4 \times 26{,}198 = 6549$ lb per foot of wall

$$M = C_{mas} \times e_m - T_s(d_s - \frac{t}{2}) =$$

$$M = 32940 \times \left(\frac{7.625}{2} - \frac{1.53}{3}\right) - T_s(0) = 108{,}702\,\text{lb.in}$$

For b_{eff} for 1 ft of wall = $1/4 \times 108{,}702 = 27{,}200$ lb.in per foot of wall

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Points controlled by masonry

k	kd	fb (psi)	Cmas (lb)	fs (psi)	Axial Force (lb)	Moment (lb-in)
0.311828	1.19	900	25679	-32000	3940	21931
0.4	1.53	900	32940	-21750	6549	27210
0.5	1.91	900	41175	-14500	9170	32704
0.6	2.29	900	49410	-9667	11603	37675
0.8	3.05	900	65880	-3625	16189	46047
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1.2	4.58	900	98820	0	24705	56513
1.4	5.34	900	115290	0	28823	58606
1.6	6.10	900	131760	0	32940	58606
1.8	6.86	900	148230	0	37058	56513

$$C_{mas} = 1/2 \times F_b \times kd \times b = 1/2 \times 900 \times 3.81 \times 48 = 82{,}350 \text{ lb}$$

$$P = C_{mas} - (A_s \times F_S) = 82{,}350 - (0.31 \times 0) = 82{,}350 \text{ lb}$$

For b_{eff} for 1 ft of wall = $1/4 \times 82{,}350 = 20{,}587$ lb per foot of wall

$$M = C_{mas} \times e_m - T_s(d_s - \frac{t}{2}) =$$

$$M = 82{,}350 \times \left(\frac{7.625}{2} - \frac{3.81}{3}\right) - T_s(0) = 209{,}170 \text{ lb.in}$$

For b_{eff} for 1 ft of wall = $1/4 \times 209170 = 52{,}300$ lb.in per foot of wall

Spreadsheet for calculating allowable-stress M-N diagram for solid masonry wall

16.67 Ft Wall w/ No. 5 @ 48in (Centered) NOTE BASED ON 1 ft of Wall and Not EFFECT

total depth, t	7.625		Wall Height, h	16.67	feet
f'm, fprimem	2000		Radius of Gyration, r	2.20	in
Em	1800000		h/r	90.9	
Fb	900.00		Reduction Factor, R	0.578	
Es	29000000		Allowable Axial Stress, Fa	289	psi
Fs	32000		Net Area, An	365.7	in^2
d	3.8125		Allowable Axial Compr, Pa	26429	lb
kbalanced	0.311828				
tensile reinforcement, As/beff	0.31	#5 @ 48 Centered			
width, beff	48				

because compression reinforcement is not tied, it is not counted

	k	kd	fb (psi)	Cmas (lb)	fs (psi)	Axial Force (lb)	Moment (lb-in)
Points controlled by steel	0.01	0.04	20	18	-32000	-2475	17
	0.05	0.19	105	478	-32000	-2360	448
Fs/n kd	0.1	0.38	221	2019	-32000	-1975	1861
	0.15	0.57	351	4811	-32000	-1277	4356
fb	0.2	0.76	497	9087	-32000	-208	8084
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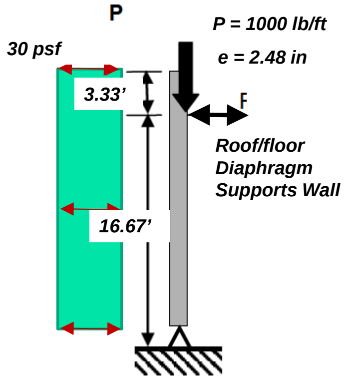
	1.6	6.10	900	131760	0	32940	58606
	1.8	6.86	900	148230	0	37058	56513
	2	7.63	900	164700	0	41175	52327
Pure compression			900	329400	0	329400	0
Axial Force Limits fs						26429	0
		Fb= 0.25 f'mR+?				26429	58606

MDG



Ex 1 -

- If P = all dead load
- Check .6D + .6W at mid-height
- Would also have check other load combos
- 0.6D + .6W at mid-height often governs

Per foot of wall analysis

- P at mid-height including weight of wall
- P= 987 lb/ft (0.6 D)
  and M = 7,425 lb.in/ft (0.6D+0.6W)

- You would need to look at other load cases and at the top of the wall.

- Also Check shear – won't govern.

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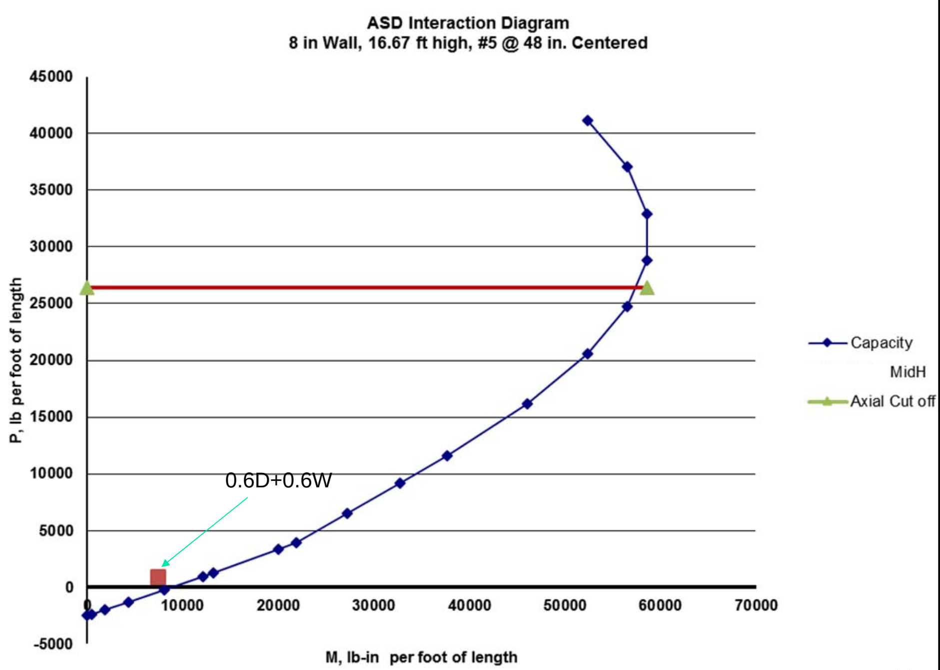

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Strength Interaction Diagrams

Code Section 9.3

- for reinforced masonry
  - flexural tensile strength of masonry is neglected
  - equivalent rectangular compressive stress block with maximum stress 0.80 f'_m , $\beta_1 = 0.80$
  - stress in tensile reinforcement proportional to strain , but not greater than f_y
  - stress in compressive reinforcement calculated like stress in tensile reinforcement , but neglected unless compressive reinforcement is laterally tied
  - Note ϕ = for combined axial and flexure = 0.9

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Strength Interaction Diagrams . . .

- vary strain (stress) gradient and position of neutral axis to generate combinations of P and M – using max stress in masonry = 0.8 f'_m over a compression block and max steel stress = f_y
- Also limit $P_{u\ applied}$ to $\leq \phi\ P_n$ - Eq 9-19 and Eq 9-20

$$P_n = 0.8(.80 f'_m (A_n - A_{st}) + A_{st}\ f_y) \underbrace{\left[1 - \left(\frac{h}{140r}\right)^2\right]}_{R_2} \quad \text{for } \frac{h}{r} \leq 99 \qquad \text{Eq 9-19}$$

$$P_n = 0.8(.80 f'_m (A_n - A_{st}) + A_{st}\ f_y) \left(\frac{70r}{h}\right)^2 \quad \text{for } \frac{h}{r} > 99 \qquad \text{Eq 9-20}$$

R

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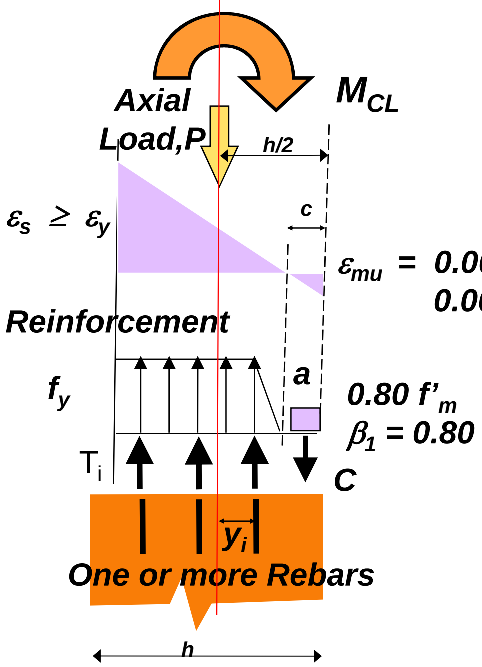

Assumptions of Strength Design

- Locate neutral axis based on extreme - fiber strains
- Calculate compressive force C
- $P = C - \Sigma Ti$ (reduced?)
- $M_{CL} = C(h/2\text{-}a/2) \pm \Sigma\ T_i\ y_i$

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Strength Interaction Example

- vary c / d from zero to a large value
  - when $c = c_{balanced}$, steel is at yield strain , and masonry is at its maximum useful strain
  - when $c < c_{balanced}$, $f_s = f_y$
  - when $c > c_{balanced}$, $f_s < f_y$
- Compute nominal axial force and moment
  - $\phi\ P_n = \phi\ \Sigma\ f_i$
  - $\phi\ M_n = \phi\ \Sigma\ f_i \times y_i$ (measured from centerline)
  - $\phi = 0.9$
- Can do hand Calc. method like before

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Design of Walls for Out-of–Plane Loads: TMS 402 Section 9.3.5

FOR SD MUST ALSO

- **Limit** Maximum reinforcement by 9.3.3.5
- **Check** Nominal shear strength by 9.3.4.1.2
- **Add P Delta Effects to Applied moments**

Three procedures for computing out – of – plane moments and deflections - **Load Side**

- Second – order analysis - **Computer**
- Moment magnification method **(new)**
- Complementary moment method; additional moment from P – δ effects – **Slender wall analysis**

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Design of Walls for Out-of–Plane Loads: TMS 402 Section 9.3.5.4.3

- Moment Magnification all loads

$$M_u = \psi\ M_{u,0} \qquad (9-31)$$

$$\psi = \frac{1}{1-\dfrac{P_u}{P_e}} \qquad (9-32)$$

$$P_e = \frac{\pi^2 E_m I_{eff}}{h^2} \qquad (9-33)$$

- $M_u < M_{cr}$: $I_{eff} = 0.75 I_n$
- $M_u \geq M_{cr}$: $I_{eff} = I_{cr}$

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Design of Walls for Out-of–Plane Loads: TMS 402 Section 9.3.5.4.2

- Complementary Moment – Iterative? For $P_u/A_g \leq 0.2\ f'_m$

$$M_u = \frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + P_u \delta_u \qquad (9-27)$$

$$P_u = P_{uw} + P_{uf} \qquad (9-28)$$

$$\delta_u = \frac{5 M_u h^2}{48 E_m I_n} \qquad (9-29)$$

$$\delta_u = \frac{5 M_{cr} h^2}{48 E_m I_n} + \frac{5(M_u - M_{cr})h^2}{48 E_m I_{cr}} \qquad (9-30)$$

- Eq. 9-29 for $M_u < M_{cr}$
- Eq. 9-30 for $M_u \geq M_{cr}$
- Also Limited to $h/t \leq 30$ other wise P limited to $0.05 f'_m A_n$

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Design of Walls for Out-of–Plane Loads: TMS 402 Section 9.3.5.4.2

- Or Solve Equations for M_u - 2 eq. 2 unknowns
- $M_u < M_{cr}$

$$M_u = \frac{\dfrac{w_u h^2}{8} + P_{uf}\dfrac{e_u}{2}}{1 - \dfrac{5 P_u h^2}{48 E_m I_n}}$$

- $M_u \geq M_{cr}$

$$M_u = \frac{\dfrac{w_u h^2}{8} + P_{uf}\dfrac{e_u}{2} + \dfrac{5 M_{cr} P_u h^2}{48 E_m}\left(\dfrac{1}{I_n} - \dfrac{1}{I_{cr}}\right)}{1 - \dfrac{5 P_u h^2}{48 E_m I_{cr}}}$$

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Design of Walls for Out-of–Plane Loads: TMS 402 Section 9.3.5.4.5

- I_{cr}

$$I_{cr} = n\left(A_s + \frac{P_u}{F_y}\frac{t_{sp}}{2d}\right)(\mathrm{d} - \mathrm{c})^2 + \frac{\mathrm{bc}^3}{3}$$

$$c = \frac{A_s F_y + P_u}{0.64 f'_m b}$$

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Design of Walls for Out-of–Plane Loads: Design Procedure

- Estimate amount of reinforcement from the following equations.
  - This neglects P – δ effects. Can estimate increase in moment, such as 10%, for a preliminary estimate of amount of reinforcement.

$$a = d - \sqrt{d^2 - \frac{2[P_u(d - t/2) + M_u]}{\phi(0.8 f'_m b)}}$$

$$A_s = \frac{0.8 f'_m ba - P_u / \phi}{f_y}$$

Or take max moment and d-a/2 ~ .9 $dA_sF_y = M_u$

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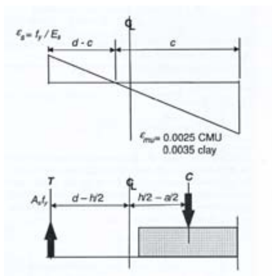
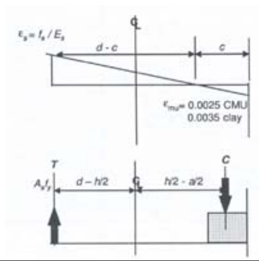
DESIGN of REINF MASONRY WALLS Strain Diagrams





- Find c balanced

$$c = d\left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \varepsilon_{y}}\right)$$

- For c values less than the balanced value steel yields before ult. strain in masonry
- for c above the balanced value steel does not yield at ult. strain in masonry

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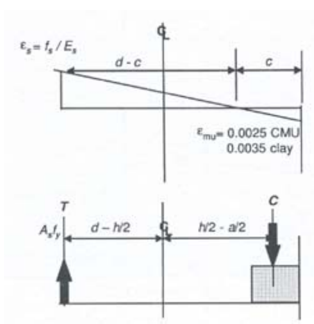
DESIGN of REINF MASONRY WALLS Strain Diagrams



- For c values less than the balanced value, steel yields before ult. strain in masonry

$$C = 0.80\,c\,(0.80\,f_m^{'})b$$

$$T = A_s f_y$$

$$P_n = C - T$$

$$M_n = T\left(d - \frac{h}{2}\right) + C\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right)$$

Note β_1 = 0.8 in masonry

& ϕ = 0.9

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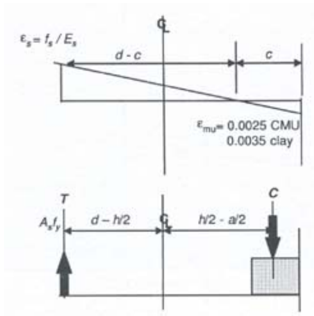
DESIGN of REINF MASONRY WALLS Strain Diagrams



- For c values greater than the balanced value, steel does not yield before ult. strain in masonry

$$\frac{\varepsilon_s}{\varepsilon_{mu}} = \frac{d-c}{c}$$

$$\varepsilon_s = \varepsilon_{mu}\left(\frac{d-c}{c}\right)$$

$$f_s = E_s \varepsilon_s$$

$$C = 0.80\,c\,(0.80\,f_m^{'})b$$

$$T = A_s f_s$$

$$P_n = C - T$$

$$M_n = T\left(d - \frac{h}{2}\right) + C\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right)$$

Note β_1 = 0.8 in masonry

& ϕ = 0.9

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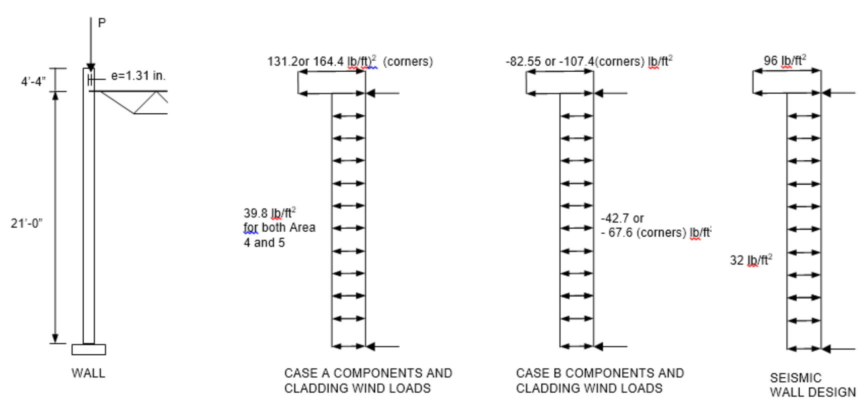
DESIGN of REINF MASONRY WALLS Example 2



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DESIGN of REINF MASONRY WALLS MDG Examples DPC 2 SD

Got SD loads

See example

Then guessed

A_s to use

Take max.

Moment and back calculated

A_{sreq}

$1.2D + 1.6L_r + 0.5W$:

$P_u = 1.2 \times (11{,}900\text{ lb} + 4\text{ ft }(1{,}190\text{ lb/ft}))/4\text{ ft}$
$+ 1.6 \times (11{,}500\text{ lb})/ 4\text{ ft} + 0.5 \times (-31{,}700\text{lb})/4\text{ ft}$
$= 5640\text{ lb per ft of wall}$

$M_u = (1.31\text{ in.}/2)\times(1.2 \times 11{,}900\text{ lb} + 1.6\times 11{,}500\text{ lb.} - 0.5\times 31{,}700\text{ lb.}) / 4\text{ ft}$
$\pm 0.5 \times 23{,}600\text{ lb-in. /ft}$
$= 14{,}600\text{ lb-in. /ft} = 1{,}210\text{ lb-ft per ft of wall}$

$1.2D + 1.0W + 0.5L_r$:

$P_u = 1.2\times(11{,}900\text{lb} + 4\text{ ft }(1{,}190\text{ lb/ft}))/4\text{ ft}$
$+ 1.0 \times (-31{,}700\text{ lb})/4\text{ ft} + 0.5\times (11{,}500\text{ lb})/ 4\text{ ft}$
$= -1{,}490\text{ lb (uplift) per ft of wall}$

$M_u = (1.31\text{ in.}/2)\times(1.2\times 11{,}900\text{ lb} + 1.0\times(-31{,}700\text{ lb}) + 0.5\times 11{,}500\text{ lb}) / 4\text{ ft}$
$\pm 1.0 \times (-23{,}600\text{ lb-in. /ft})$
$= -25{,}500\text{ lb-in. /ft} = -2{,}120\text{ lb-ft per ft of wall}$

$(1.2 + 0.2\,S_{DS})\,D + \rho Q_e$ (Since $L = 0$ and $S = 0$)

$P_u = 1.2 \times (11{,}900\text{ lb} + 4\text{ ft }(1{,}190\text{ lb}))/4\text{ ft} \pm 1.0\times(3{,}330\text{ lb})/4\text{ ft}$
$= 4{,}170\text{ lb per ft of wall (negative is typically critical)}$

$M_u = 1.2 \times (1.31\text{ in.}/2\ (11{,}900\text{ lb}))\ /\ 4\text{ ft} + 1.0\times 21{,}100\text{ lb-in. /ft}$
$= 23{,}400\text{ lb-in. /ft} = 1{,}950\text{ lb-ft per ft of wall}$

$0.9D + 1.0W$:

$P_u = 0.9\times(11{,}900\text{ lb} + 4\text{ ft }(1{,}190\text{ lb}))\ /\ 4\text{ ft} + 1.0\times(-31{,}700\text{ lb})\ /\ 4\text{ ft}$
$= -4{,}180\text{ lb per foot of wall (uplift)}$

$M_u = (1.31\text{ in. }/2)\times(0.9\times 11{,}900\text{ lb} + 1.0\times(-31{,}700\text{ lb}))/\ 4\text{ ft} \pm 1.0\times 23{,}600\text{ lb-in. /ft}$
$= -27{,}040\text{ lb-in. /ft} = -2{,}250\text{ lb-ft per ft of wall}$

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Develop ID

21 ft solid 8 in CMU #5 @ 16"							
Spreadsheet for calculating SD moment-axial force interaction diagram for solid masonry wall							
reinforcement at mid-depth							
specified thickness	7.625	in.		Wall Height, h		21.0	feet
e_{mu}	0.0025			Radius of Gyration, r		2.20	in
f'_m	2,000	psi			h/r	114.5	
f_y	60,000	psi		Reduction Factor, R		0.373	
E_s	29,000,000	psi					
d	3.81	in.		Net Area, An		91.5	
(c/d)balanced	0.547			Peak Axial Compr, ϕP_a		39,265	
tensile reinforcement area	0.2325	**No. 5 @ 16 in.**					
effective width	12	in.					
phi	0.9						
because compression reinforcement is not laterally supported , it is not counted							

	c/d	***c***	***C_{mas}***	***f_s***	**Moment**	**Axial Force**
			lb	**psi**	**ΦM_n, lb-in**	**(ΦP_n, lb)**
Points controlled	0.01	0.0381	585	-60,000	1,969	-12,028
by steel	0.15	0.5715	8,778	-60,000	28,283	-4,655
	0.20	0.762	11,704	-60,000	36,918	-2,021
	0.30	1.143	17,556	-60,000	52,985	3,246
	0.32	1.21158	18,610	-60,000	55,707	4,194
	0.33	1.2573	19,312	-60,000	57,492	4,826
	0.4	1.524	23,409	-60,000	67,447	8,513
Balanced point	0.547169811	2.084717	32,021	-60,000	85,810	16,264
	0.80	3.048	46,817	-18,125	109,261	38,343
Points controlled	0.90	3.429	52,669	-8,056	115,701	45,717
by masonry	1.10	4.191	64,374	0	123,758	57,936
	1.3	4.953	76,078	0	125,390	68,470
	1.6	6.096	93,635	0	115,797	84,271
	1.8	6.858	105,339	0	101,375	94,805
	2.1	8.001	122,895	0	67,702	110,606
	2.5	9.525	146,304	0	329	131,674

Maximum $0.05f'_m$	9,150					
Maximum $0.2\ f'_m$	36,600				M	P

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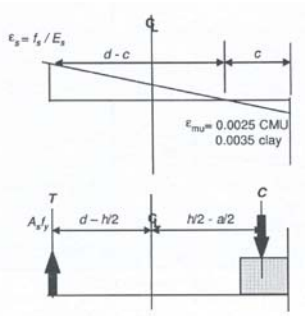
Develop ID

c/d	c	C_{mas}	f_s	Moment	Axial Force
		lb	psi	ΦM_n, lb-in	$(\Phi P_n$, lb)
0.30	1.143	17,556	-60,000	52,985	3,246

steel controls



$$C_{mas} = 0.8 \times c \times 0.8 f'_m \times b = 0.8 \times 1.143 \times .8 \times 2000 \times 12 =$$
$$= 17{,}566 \text{ lb per foot of wall}$$

$$P = C_{mas} - (A_s \times F_y) = (17{,}556 - (0.2325 \times 60{,}000)) = 3606 lb$$

$$\phi P_n = 0.9 \times 3{,}606 \text{ lb } = 3{,}245 \text{ lb per foot of wall}$$

$$M = T\left(d - \frac{h}{2}\right) + C_{mas}\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) =$$

$$M = 60000 \times 0.02325 \times \left(\frac{7.625}{2} - \frac{7.625}{2}\right) + 17655\left(\frac{7.626}{2} - \frac{(.8)1.143}{2}\right) =$$

$$= 58{,}872 \text{ lb.in per foot of wall} \quad \phi M = 52{,}985 \text{ lb.in per foot of wall}$$

Develop ID

21 ft solid 8 in CMU #5 @ 16"

Spreadsheet for calculating SD moment-axial force interaction diagram for solid masonry wall

reinforcement at mid-depth

specified thickness	7.625	in.	Wall Height, h	21.0	feet
e_{mu}	0.0025		Radius of Gyration, r	2.20	in
f'_m	2,000	psi	h/r	114.5	
f_y	60,000	psi	Reduction Factor, R	0.373	
E_s	29,000,000	psi			
d	3.81	in.	Net Area, An	91.5	
(c/d)balanced	0.547		Peak Axial Compr,ϕP_a	39,265	
tensile reinforcement area	0.2325	**No. 5 @ 16 in.**			
effective width	12	in.			
phi	0.9				

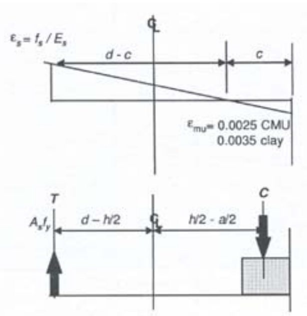
because compression reinforcement is not laterally supported , it is not counted

	c/d	c	C_{mas}	f_s	Moment	Axial Force
			lb	psi	ΦM_n, lb-in	$(\Phi P_n$, lb)
Points controlled	0.01	0.0381	585	-60,000	1,969	-12,028
by steel	0.15	0.5715	8,778	-60,000	28,283	-4,655
	0.20	0.762	11,704	-60,000	36,918	-2,021
	0.30	1.143	17,556	-60,000	52,985	3,246
	0.32	1.21158	18,610	-60,000	55,707	4,194
	0.33	1.2573	19,312	-60,000	57,492	4,826
	0.4	1.524	23,409	-60,000	67,447	8,513
Balanced point	0.547169811	2.084717	32,021	-60,000	85,810	16,264
	0.80	3.048	46,817	-18,125	109,261	38,343
Points controlled	0.90	3.429	52,669	-8,056	115,701	45,717
by masonry	1.10	4.191	64,374	0	123,758	57,936
	1.3	4.953	76,078	0	125,390	68,470
	1.6	6.096	93,635	0	115,797	84,271
	1.8	6.858	105,339	0	101,375	94,805
	2.1	8.001	122,895	0	67,702	110,606
	2.5	9.525	146,304	0	329	131,674

Maximum 0.05f'_m	9,150			
Maximum 0.2 f'_m	36,600		M	P

Develop ID

	c/d	c	C_{mas}	f_s	Moment	Axial Force
			lb	psi	ΦM_n, lb-in	(ΦP_n, lb)
Masonry controls	0.90	3.429	52,669	-8,056	115,701	45,717



$$C_{mas} = 0.8 \times c \times 0.8 f'_m \times b = 0.8 \times 3.429 \times .8 \times 2000 \times 12 =$$

$$= 52{,}669 \text{ lb per foot of wall}$$

$$\varepsilon_s = \varepsilon_{mu}\left(\frac{d-c}{c}\right) = 0.0025\left(\frac{3.81 - 3.429}{3.429}\right) = 0.000278$$

$$fs = 29{,}000{,}000 \times 0.00278 = 8{,}056\, psi$$

$$P = C_{mas} - (A_s \times F_s) = (52{,}669 - (0.2325 \times 8056)) = 50{,}796\, lb$$

$$\phi P_n = \ 0.9 \times 50796 \text{ lb } = 45{,}716 \text{ lb per foot of wall}$$

$$M = T\,(d - \frac{h}{2}) + C_{mas}(\frac{h}{2} - \frac{\beta_1 c}{2}) =$$

$$M = 8{,}056 \times 0.02325 \times \left(\frac{7.625}{2} - \frac{7.625}{2}\right) + 52669(\frac{7.626}{2} - \frac{(.8)3.429}{2}) =$$

$$= 128{,}428 \text{ lb.in per foot of wall} \quad \phi M = 115{,}600 \text{ lb.in per foot of wall}$$

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Develop ID

Get all the points and cut off any above max P

Also calc. 0.05f'mAn and 0.2f'mAn

These are cutoffs for P-Δ methods

21 ft solid 8 in CMU #5 @ 16"

Spreadsheet for calculating SD moment-axial force interaction diagram for solid masonry wall

reinforcement at mid-depth

specified thickness	7.625 in.		Wall Height, h	21.0 feet
e_{mu}	0.0025		Radius of Gyration, r	2.20 in
f'_m	2,000 psi		h/r	114.5
f_y	60,000 psi		Reduction Factor, R	0.373
E_s	29,000,000 psi			
d	3.81 in.		Net Area, An	91.5
(c/d)balanced	0.547		Peak Axial Compr,ϕP_a	39,265
tensile reinforcement area	0.2325	**No. 5 @ 16 in.**		
effective width	12 in.			
phi	0.9			

because compression reinforcement is not laterally supported , it is not counted

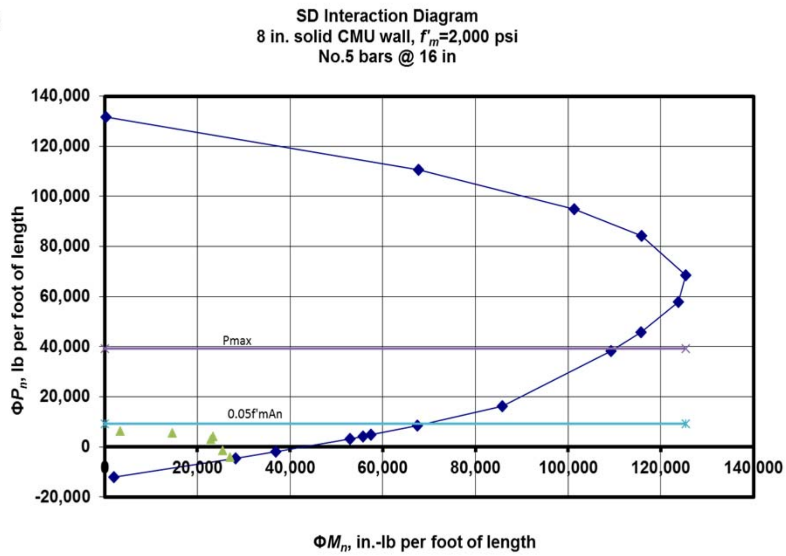
	c/d	c	C_{mas}	f_s	Moment	Axial Force
			lb	psi	ΦM_n, lb-in	(ΦP_n, lb)
Points controlled	0.01	0.0381	585	-60,000	1,969	-12,028
by steel	0.15	0.5715	8,778	-60,000	28,283	-4,655
	0.20	0.762	11,704	-60,000	36,918	-2,021
	0.30	1.143	17,556	-60,000	52,985	3,246
	0.32	1.21158	18,610	-60,000	55,707	4,194
	0.33	1.2573	19,312	-60,000	57,492	4,826
	0.4	1.524	23,409	-60,000	67,447	8,513
Balanced point	0.547169811	2.084717	32,021	-60,000	85,810	16,264
	0.80	3.048	46,817	-18,125	109,261	38,343
Points controlled	0.90	3.429	52,669	-8,056	115,701	45,717
by masonry	1.10	4.191	64,374	0	123,758	57,936
	1.3	4.953	76,078	0	125,390	68,470
	1.6	6.096	93,635	0	115,797	84,271
	1.8	6.858	105,339	0	101,375	94,805
	2.1	8.001	122,895	0	67,702	110,606
	2.5	9.525	146,304	0	329	131,674

Maximum 0.05f'_m	9,150			
Maximum 0.2 f'_m	36,600		M	P
		P_{max}	0	39,265
			125,390	39,265
		0.2 f'_m	0	36,600

42

Develop ID

Plot ID



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Add P-D effects to applied Moments – Complementary Method or Moment Magn. methods

Complementary Method $M_u = \frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + P_u \delta_u$ (9 – 27)

- Or Solve Equations for M_u - 2 eq. 2 unknowns
- $M_u < M_{cr}$

$$M_u = \frac{\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2}}{1 - \frac{5 P_u h^2}{48 E_m I_n}}$$

- $M_u \geq M_{cr}$

$$M_u = \frac{\frac{w_u h^2}{8} + P_{uf}\frac{e_u}{2} + \frac{5 M_{cr} P_u h^2}{48 E_m}\left(\frac{1}{I_n} - \frac{1}{I_{cr}}\right)}{1 - \frac{5 P_u h^2}{48 E_m I_{cr}}}$$

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Add P-D effects to applied Moments – Complementary Method or Moment Magn. methods

Moment Mag. Method

$$M_u = \psi\ M_{u,0} \qquad (9-31)$$

$$\psi = \frac{1}{1-\frac{P_u}{P_e}} \qquad (9-32)$$

$$P_e = \frac{\pi^2 E_m I_{eff}}{h^2} \qquad (9-33)$$

1.2D+1.6Lr+0.5W load combination

$$M_u = \text{first order moment} = 14.6 \text{ kips.in/ft of wall}$$

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Add P-D effects to applied Moments – Complementary Method or Moment Magn. methods

Moment Mag. Method – Get I_g and I_{cr}

$$I_g = \frac{bt^3}{12} = \frac{12\text{ in.}(7.63\,in.)^3}{12} = 443.in^3$$

$$n = \frac{E_s}{E_m} = \frac{29{,}000{,}000\text{psi}}{900(2{,}000\text{psi})} = 16.11$$

$$A_s = \frac{0.31\text{ in.}^2(12\text{ in.})}{16\text{ in.}} = 0.232\text{ in.}^2$$

$$c = \frac{A_s f_y + P_u}{0.64 f'_m b} = \frac{0.232\text{in.}^2(60{,}000\text{psi}) + 5{,}640\text{lb}}{0.64(2{,}000\text{psi})(12\text{ in.})} = 1.273\text{ in.} \quad \text{TMS 402 Equation 9-35}$$

$$I_{cr} = n\left(A_s + \frac{P_u}{f_y}\frac{t_{sp}}{2d}\right)(d-c)^2 + \frac{bc^3}{3} \qquad \text{Equation 9-34}$$

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Add P-D effects to applied Moments – Complementary Method or Moment Magn. methods

$$I_{cr} == 16.1\left(0.232\text{ in.}^2 + \frac{5{,}640\text{lb}}{60{,}000\text{psi}} \times \frac{7.63\text{in.}}{2(3.81\text{in.}^2)}\right)(3.81\text{in.} - 1.27\text{in.})^2 = 33.9.in^4 / ft$$

From TMS 402 Table 9.1.9.2 , f_r = 163 psi

$$M_{cr} = \left(f_r + \frac{P}{A_g}\right)S = \left(163psi + \frac{5{,}640\text{ lb}}{12\text{ in.}(7.63\text{in.})}\right)(12\text{ in.})(7.63\text{ in.})^2 / 6 = 26{,}150\text{ lb.in/ft}$$

As M_u = 14,600 lb-in is less than M_{cr}=26,150 lb-in then

I_{eff} = 0.75 (I_n)

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Add P-D effects to applied Moments – Complementary Method or Moment Magn. methods

$$P_e = \frac{\pi^2 E_m I_{eff}}{h^2} = \frac{\pi^2 900(2{,}000\text{psi})(443\text{in}^4)(0.75)}{(21\text{ ft} \times 12\text{ in./ft})^2} = 93{,}000\text{ lb}$$

$$\psi = \frac{1}{1 - \frac{P_u}{P_e}} = \frac{1}{1 - \frac{5{,}640\text{ lb}}{93{,}000\text{ lb}}} = 1.06$$

M_u = 1.06 (14.6 kip.in/ft) =15.5 kip.in/ft which is still below the capacity envelope

Check other Load cases

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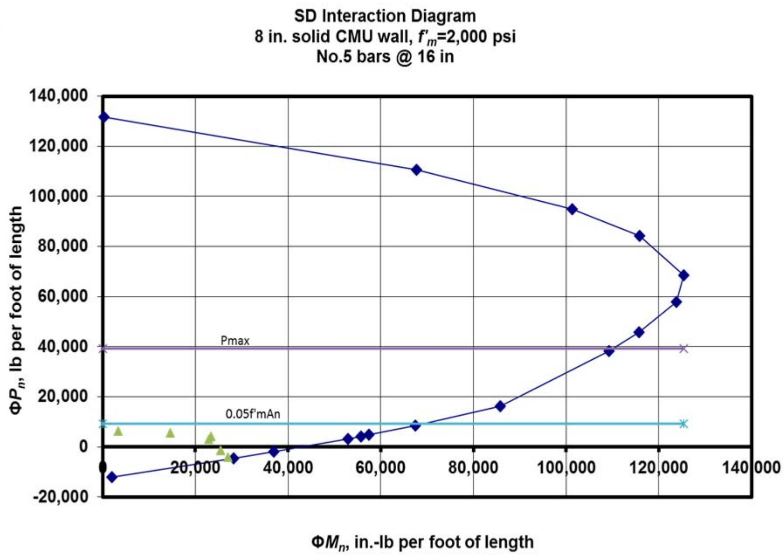
Develop ID

Plot ID



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DESIGN of REINF MASONRY WALLS - Out of Plane loads – Axial and flexure

- Must check Max Reinforcing 9.3.3.5 Comm.

$$\rho_{\max} = \frac{0.64 f'_m \left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \alpha \varepsilon_y} \right) - \frac{P}{bd}}{f_y}$$

P load $D + 0.75\ L + 0.525\ Q_e$ load combination and α = 1.5 for walls loaded OOP. The force per foot of wall is:
P = (11,900 lb/4 + 1,190 lb)+ 0.75×11,500 lb/4 + 0.525×3,330 lb/4 = 6,760 lb

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DESIGN of REINF MASONRY WALLS - Out of Plane loads – Axial and flexure

- Must check Max Reinforcing 9.3.3.5 Comm.

$$\rho_{\max} = \frac{0.64 \times 2{,}000 \text{ psi} \times \left(\dfrac{0.0025}{0.0025 + 1.5 \times 0.00207} \right) - \dfrac{6{,}760 \text{ lb}}{12 \text{ in.} \times 3.81 \text{ in.}}}{60{,}000 \text{ psi}} = .00705$$

This would allow an area of steel of up to As = 0.00705 × 12 in. × 3.81 in. = 0.322 in² per foot of wall, which is more than 0.233 in²/ft provided using No. 5 bars at 16 in. on center.

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DESIGN of REINF MASONRY WALLS - Out of Plane loads – Axial and flexure

- Should check shear but never a problem out of plane for LB and non LB walls.

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DESIGN of REINF MASONRY WALLS - Out of Plane loads – Axial and flexure -

How high can you go?

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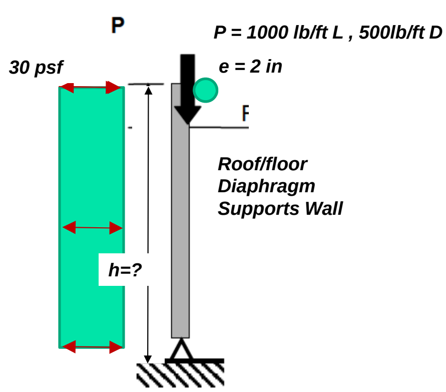
For this Loading



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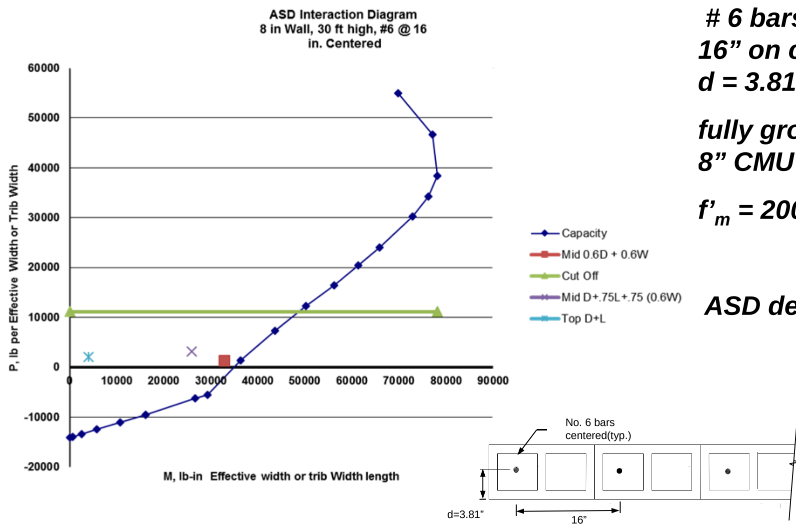
8" CMU



ASD

H = 30 ft

 # 6 bars at 16" on center d = 3.81"

fully grouted 8" CMU

f'_m = 2000 psi

ASD design

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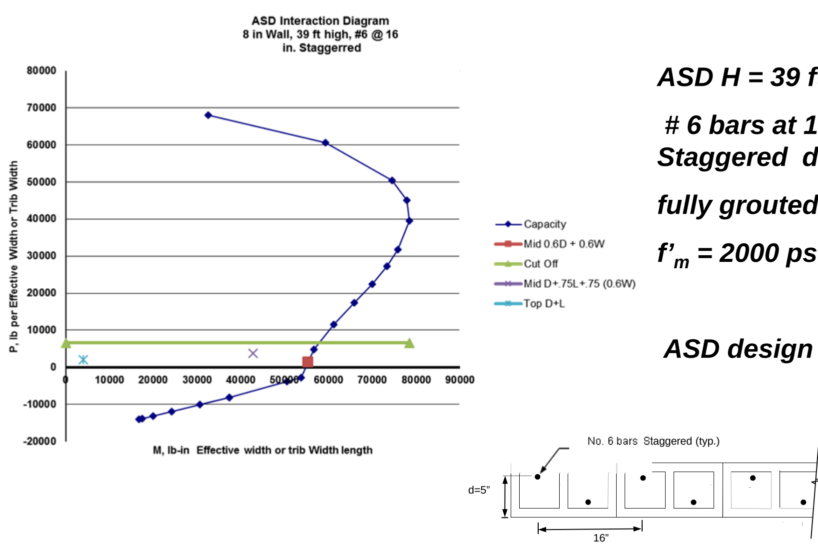
How high - 8" CMU?



ASD H = 39 ft

 # 6 bars at 16" on Staggered d = 5"

fully grouted 8" CMU

f'_m = 2000 psi

ASD design

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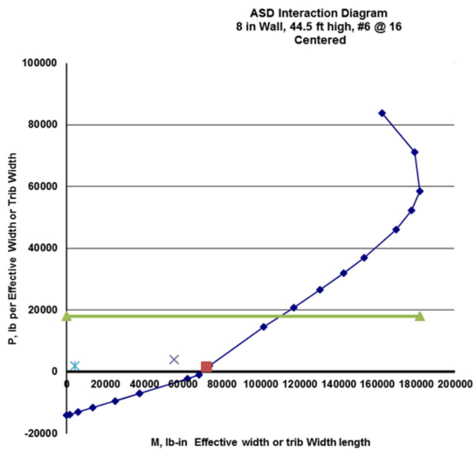
Try 12" CMU



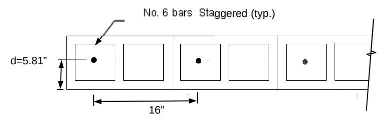
ASD H = 44.5 ft

 # 6 bars at 16" on Centered d = 5.81"

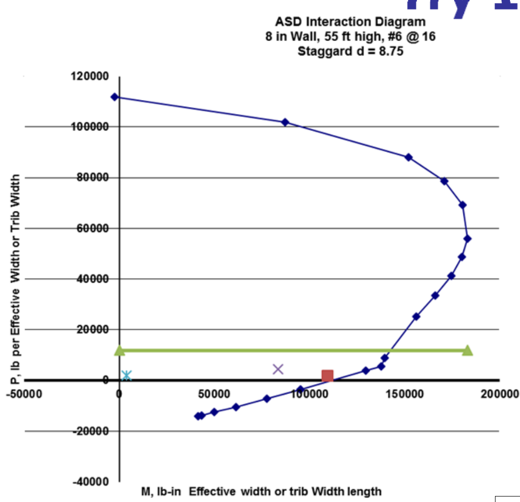
fully grouted 12" CMU

f'$_m$ = 2000 psi

ASD design



Try 12" CMU



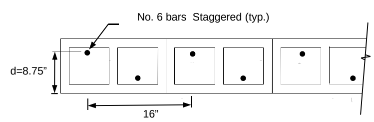
ASD H = 55 ft

 # 6 bars at 16" on Centered d = 5.81"

fully grouted 12" CMU

f'$_m$ = 2000 psi

ASD design



8” CMU – Be careful with P Δ moments - SD

SD

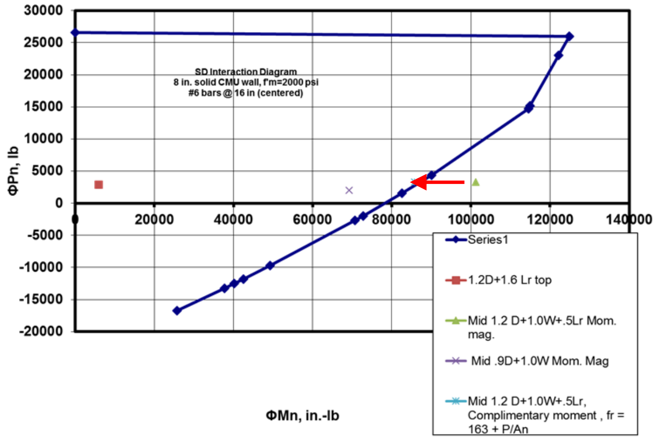
H = 30 ft

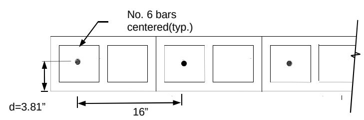
 # 6 bars at 16” on center d = 3.81”

fully grouted 8” CMU

f’$_m$ = 2000 psi

SD design





Be careful with f_r – Very slender walls - use complementary Method and account for P/A for Cracking moment

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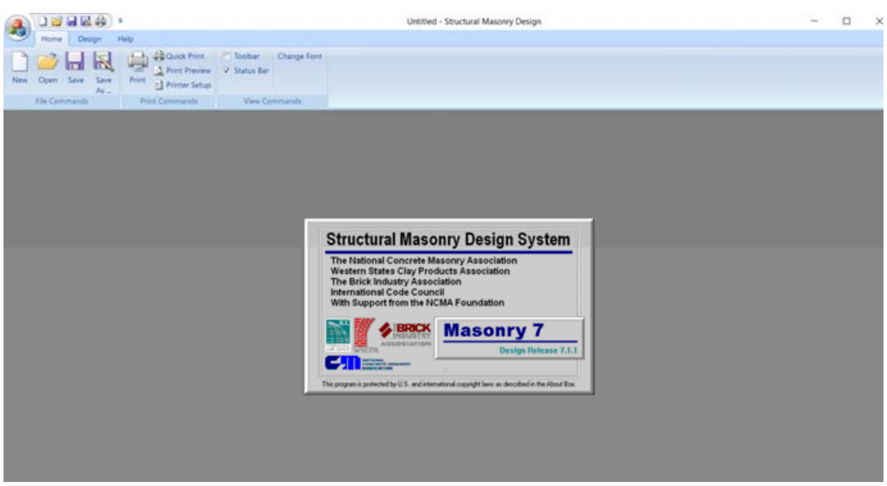
Try Structural Design Software – NCMA.org



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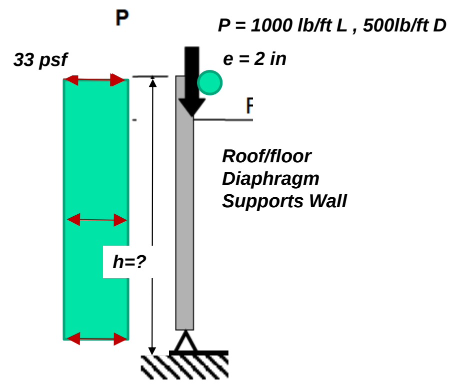
Try Structural Design Software – NCMA.org



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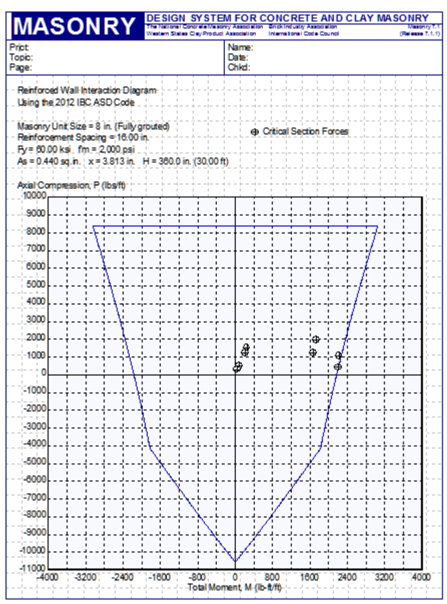
Try Structural Design Software – NCMA.org



H = 30 ft

 # 6 bars at 16" on center
d = 3.81"

fully grouted 8" CMU

f'_m = 2000 psi

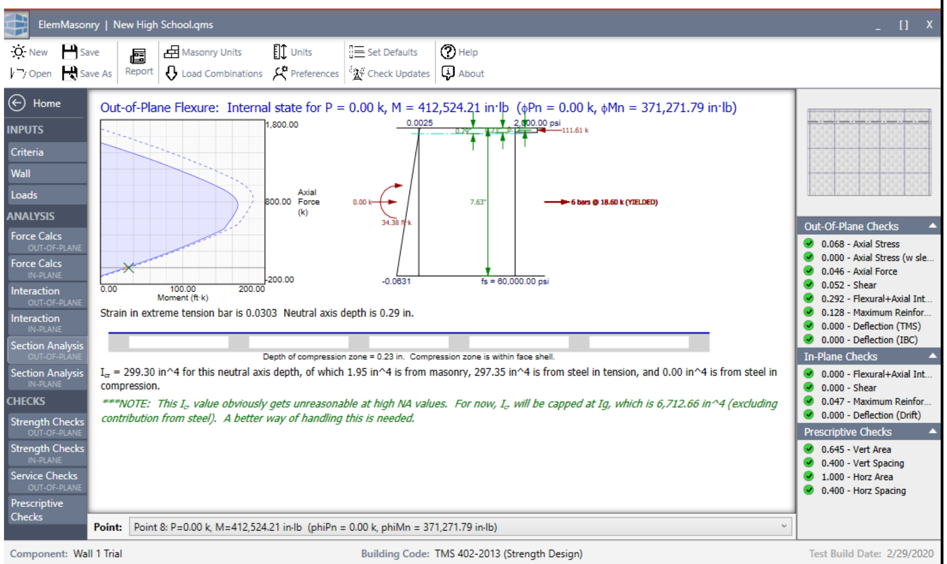
ASD design

SD slightly higher

Offset bars higher

12 " CMU higher

Try New Elem software – NCMA.org – Coming soon



Evolution of Design

With these changes…new tools are needed.

Direct Design

3DiQ

MasonryiQ

Masonry Design Software Plug-In For Revit

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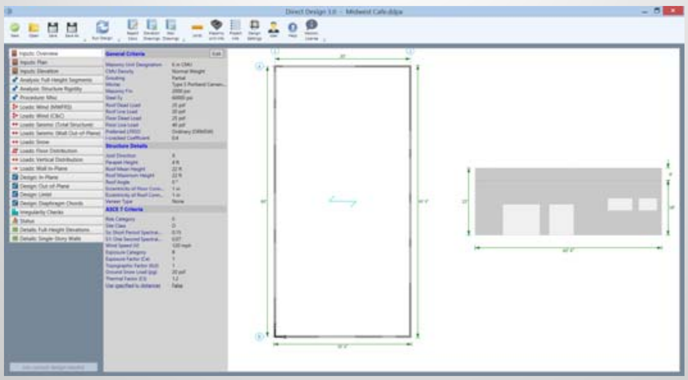
Software Inputs

What you need to design a project:

- Building location; and
- Building dimensions



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Summary

- Over view of Single wythe walls
- Presented ASD Reinforced Masonry Wall Design Provisions
- Presented SD Code provisions Masonry Wall Design Provisions
- Presented Wall Design Examples

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J.B. SPEED SCHOOL
OF ENGINEERING

THANK YOU !

QUESTIONS?

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Masonry Institute of Hawaii

Masonry Institute of Hawaii

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