Design of Walls for In-Plane Loads and Seismic Detailing

AIA COURSE NO. TMS20220302

March 2, 2022

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Course Description

Shear walls are critical building elements to resist in-plane loads and are, for masonry, the wind and seismic-force-resisting system. This session will review Allowable Stress Design of shear walls, along with both seismic detailing requirements and minimum/maximum detailing requirements for such walls. Design for in-plane shear, including shear friction, and in-plane flexure will be explored and examples provided. The effect of openings will also be examined.

Learning Objectives

- Introduce masonry shear walls and applied loads on these critical elements
- Discuss seismic detailing requirements for masonry shear walls
- Review the Allowable Stress design provisions for masonry shear walls for combined axial load and bending and for shear
- Discuss maximum and minimum reinforcement limits and detailing of shear walls when using Allowable Stress Design

Special Thanks:

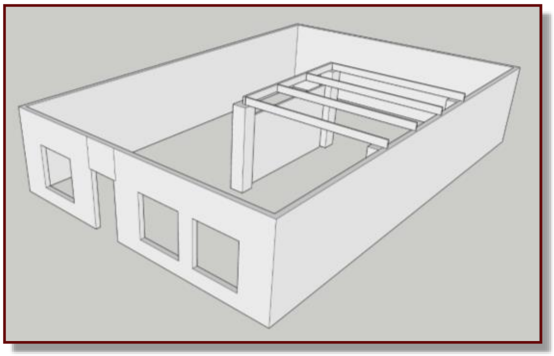
- Basis for presentation and some graphics… SD session by:
  - John M. Hochwalt, P.E., S.E.,
  - Director of Engineering,
  - KPFF Consulting Engineers-Seattle Structural Group

Tonight's Outline

- Wall Design Process
- Wall Detailing Requirements (Primarily Seismic)
  - By Seismic Design Category
  - By Wall Type
- In-Plane Wall Design
  - Flexure + Axial
  - Shear
  - Shear Friction

Wall Design Process

Wall Design Process



- Often Architectural Functionality Determines Location and Extent of Masonry Walls
  - Be involved early
  - Use as many walls as possible
  - Align walls in plan and elevation
- Out-of-Plane Design
  - Estimate reinforcing (Session 3)
    - Out of plane design often controls
    - Additional vertical reinforcement may be required
    - Shear reinforcement may be required
  - Consider detailing requirements (tonight)
  - Design for second order effects (Session3)
- In-Plane Design (tonight)

Be Considerate Early!

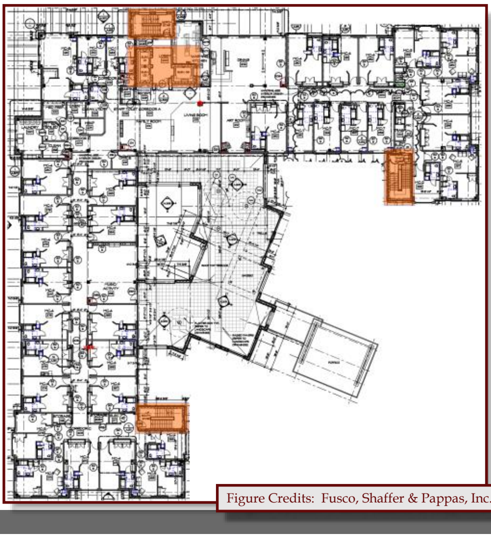
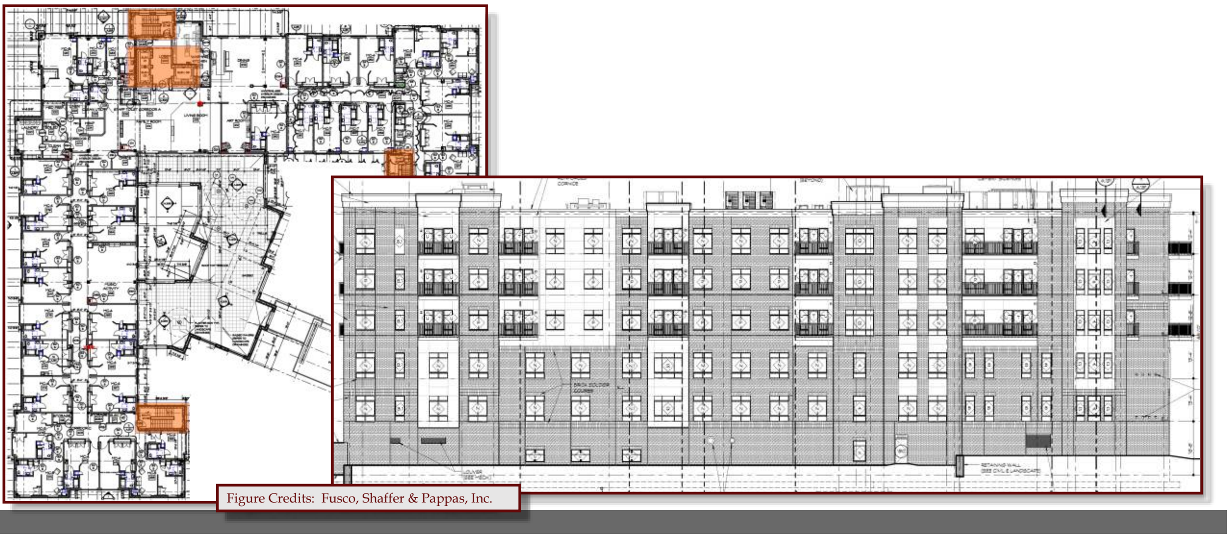


Figure Credits: Fusco, Shaffer & Pappas, Inc.

Be Considerate Early!



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Be Considerate Early!

Figure Credits: Fusco, Shaffer & Pappas, Inc.

Wall Detailing

- Seismic Design Category
- Non-Participating Walls
- Participating Walls

Detailing - Seismic Design Category

- Determined by ASCE 7
- Based on Risk Category and Ground Motions
  - Risk category – hazard to public, essential services
  - Ground motion – history of seismic activity
- Ranges from A to F

Detailing – Element Classification

- Types of Walls (TMS 402-16: Section 7.3)
  - Participating = part of the lateral force resisting system = shear wall
  - Non-Participating = not part of the seismic-force-resisting system
    - must be isolated in their own plane from the seismic-force-resisting system.
  - Consider story drift and displacement amplification factor (C_d)
    - Out of plane drift of LFRS and/or diaphragm
    - Caution for mixed LFRS's in particular

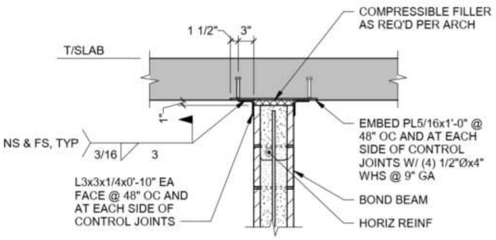


Figure Credit: John Hochwalt, KPFF

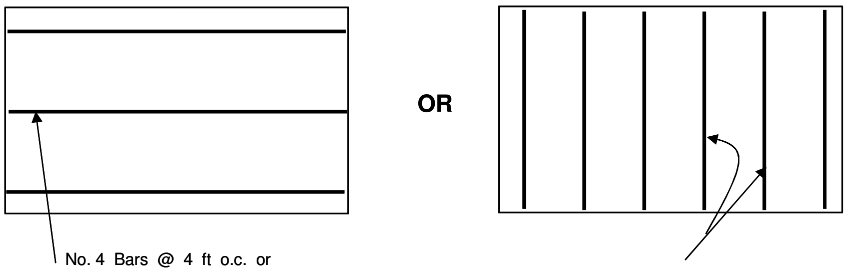
Detailing – Non-Participating (A, B)

- Seismic Design Category A and B (TMS 402-16: 7.4.1, 7.4.2)
  - Design as reinforced or unreinforced
  - No minimum area of steel
  - Must isolate in its own plane (TMS 402-16: 7.3.1)
  - Remember about out-of-plane movement
    - Most walls are pinned at the top
    - Connectors
    - Isolation joints
    - Wall design assumptions

Detailing – Non-Participating (C+)

- Seismic Design Category C and Higher (TMS 402-16: 7.4.3.1, 7.4.4.1, 7.4.5.1)
  - Design as reinforced or unreinforced
  - Must prescriptively reinforce in ***either*** horizontal or vertical direction
    - Joint reinforcement or bars in bond beams at 48” o.c., max.
    - Or, minimum vertical steel at 120” o.c., max.
    - Minimum bar size = #4
    - Edge reinforcement at 16” from top, bottom and ends
  - SDC D+: Minimum vertical reinforcement spacing decreases to 48” o.c., max.
  - SDC E and F: If not laid in running bond, horizontal reinforcement is required and spacing is decreased to 24” o.c., max.
  - Must isolate in its own plane (TMS 402-16: 7.3.1)

Detailing – Non-Participating (C+)



No. 4 Bars @ 4 ft o.c. or
W1.7 Joint Reinforcement
@ 16 in. o.c.

For SDC C, No. 4 Bars @ 10 ft o.c.
For SDC D, E, and F, No. 4 Bars @ 4 ft o.c.

TMS MDG-2016 Figure 10.4-5

Not laid in running bond, SDC E+:

- 0.0015 of gross area
- 24” max spacing

- 8”: #5 @ 24”
- 10”: (2) #4 @ 24”
- 12”: (2) #5 or #6 @ 24”

Detailing – Participating

Shear Wall Type	Permitted Design Methods (TMS 402 Section)	Prescriptive Reinforcement Requirements	SDC Limits from TMS 402	Additional ASCE Restrictions
Empirically Designed Masonry Shear Wall	A.3	None (TMS 402 7.3.2.1)	SDC A	Not recognized
Ordinary Plain (Unreinforced) Masonry Shear Wall	8.2 or 9.2	None (TMS 402 7.3.2.2)	SDC A, B	-
Detailed Plain (Unreinforced) Masonry Shear Walls	8.2 or 9.2	TMS 402 7.3.2.3 See MDG Figure 10.4-1	SDC A, B	-
Ordinary Reinforced Masonry Shear Walls	8.3 or 9.3	TMS 402 7.3.2.4 See MDG Figure 10.4-1	SDC A, B, C	160 foot maximum height in SDC C
Intermediate Reinforced Masonry Shear Walls	8.3 or 9.3	TMS 402 7.3.2.5 See MDG Figure 10.4-3	SDC A, B, C	-
Special Reinforced Masonry Shear Walls	8.3 or 9.3, or Appendix C	TMS 402 7.3.2.6 See MDG Figure 10.4-4	SDC A, B, C, D, E, F	160 foot maximum height in SDC D and E; 100 foot maximum height in SDC F.

TMS MDG-2016 Table 10.3-1 / TMS 402-16: Table CC-7.3.2-1

Detailing – Participating (A)

- SDC A:
  - ASCE 7 Exempt from seismic requirements (ASCE 7 11.7)
    - Compliance with structural integrity provisions of ASCE 7 1.4 required.
  - TMS 402
    - Have to pick a wall type and detail accordingly
    - Includes Ordinary Plain (unreinforced)
      - Design as unreinforced
      - No minimum reinforcing required
    - Also Includes Detailed Plain (unreinforced)
      - Design as unreinforced
      - Minimum prescriptive reinforcing required
        - Vertical: #4 bar trim and edge steel and at 120” o.c., max.
        - Horizontal: Joint reinforcement or #4’s in bond beams at 120” o.c., max.

Detailing – Participating (B+)

- SDC B+:
  - ASCE 7
    - Must pick a permitted wall type per ASCE 7 Table 12.2-1. Types:
      - Special reinforced masonry shear walls (F max, 100’ max. height in F, 160’ in D and E)
      - Intermediate reinforced masonry shear walls (C max)
      - Ordinary reinforced masonry shear walls (C max, 160’ max. height in C)
      - Detailed plain masonry shear walls (B max)
      - Ordinary plain masonry shear walls (B max)
    - Must decide “Building frame” versus “Bearing wall”
      - “essentially complete space frame providing support for vertical loads.”
    - Chapter 14 not adopted by IBC

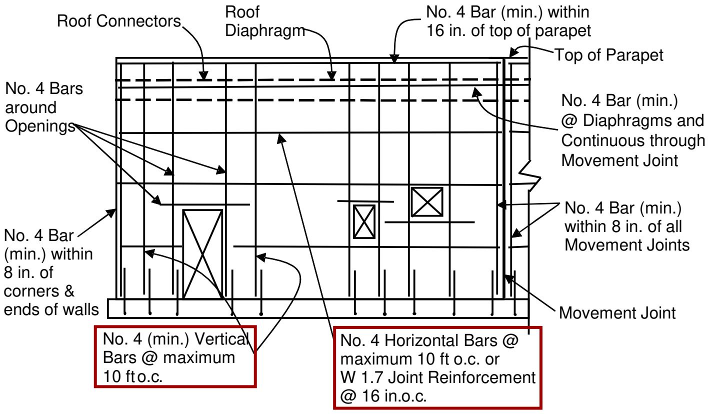
Detailing – Participating (B+)

- SDC B+ (continued):
  - TMS 402 Provides:
    - Minimum detailing requirements based on wall type
    - Minimum detailing and material requirements based on SDC
    - Additional design requirements for special walls
  - SDC Based Requirements
    - SDC D+
      - Type S or M Mortar:
        - Fully grouted: cement-lime, masonry cement, or mortar cement.
        - Partially grouted: cement-lime or mortar cement.
      - Lateral Ties: Anchor with 135 or 180 degree hook

Detailing – Participating (Wall Type)

- Intermediate Reinforced Masonry Shear Wall
  - Same as Detailed Plain
- Intermediate Reinforced Masonry Shear Wall
  - Same as Detailed Plain except vertical spacing 48” o.c. or less
- Special Reinforced Masonry Shear Wall
  - Same as IRMSW except:
    - Maximum spacing 48” or less, not more than 1/3 of wall height or length
    - Minimum cross-sectional area of vertical reinforcement = 1/3 of the required shear reinforcement
    - Sum of horizontal and vertical reinforcement not less than 0.002 A_g
    - Minimum cross-sectional area of steel = 0.0007 A_g

Detailing – Detailed Plain Ordinary Reinforced



Roof Connectors

Roof Diaphragm

No. 4 Bar (min.) within 16 in. of top of parapet

Top of Parapet

No. 4 Bars around Openings

No. 4 Bar (min.) @ Diaphragms and Continuous through Movement Joint

No. 4 Bar (min.) within 8 in. of all Movement Joints

No. 4 Bar (min.) within 8 in. of corners & ends of walls

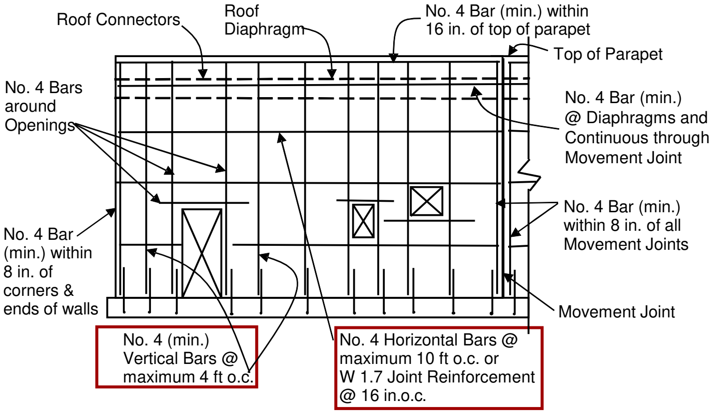
Movement Joint

No. 4 (min.) Vertical Bars @ maximum 10 ft o.c.

No. 4 Horizontal Bars @ maximum 10 ft o.c. or W 1.7 Joint Reinforcement @ 16 in.o.c.

TMS MDG-2016 Table 10.4-1

Detailing – Intermediate Reinforced



Roof Connectors

Roof Diaphragm

No. 4 Bar (min.) within 16 in. of top of parapet

Top of Parapet

No. 4 Bars around Openings

No. 4 Bar (min.) @ Diaphragms and Continuous through Movement Joint

No. 4 Bar (min.) within 8 in. of all Movement Joints

No. 4 Bar (min.) within 8 in. of corners & ends of walls

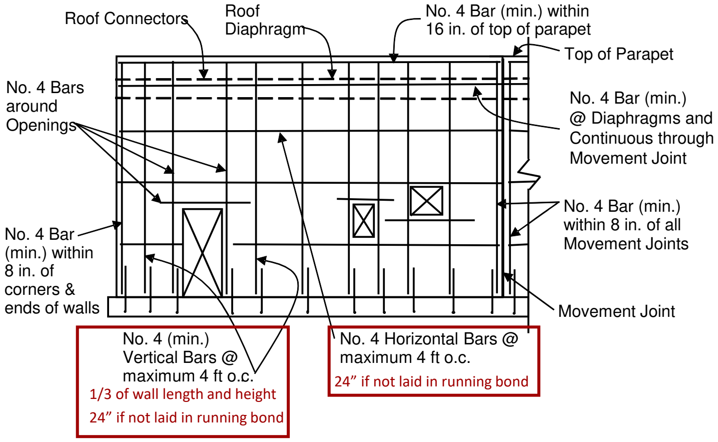
Movement Joint

No. 4 (min.) Vertical Bars @ maximum 4 ft o.c.

No. 4 Horizontal Bars @ maximum 10 ft o.c. or W 1.7 Joint Reinforcement @ 16 in.o.c.

TMS MDG-2016 Table 10.4-2

Detailing – Special Reinforced



Roof Connectors

Roof Diaphragm

No. 4 Bar (min.) within 16 in. of top of parapet

Top of Parapet

No. 4 Bars around Openings

No. 4 Bar (min.) @ Diaphragms and Continuous through Movement Joint

No. 4 Bar (min.) within 8 in. of all Movement Joints

No. 4 Bar (min.) within 8 in. of corners & ends of walls

Movement Joint

No. 4 (min.) Vertical Bars @ maximum 4 ft o.c.

1/3 of wall length and height

24” if not laid in running bond

No. 4 Horizontal Bars @ maximum 4 ft o.c.

24” if not laid in running bond

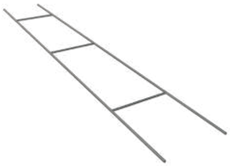
TMS MDG-2016 Table 10.4-3

Detailing – Special Reinforced

- Special Walls – Minimum Reinforcement Ratios
  - Vertical: 0.0007 of gross cross-sectional area
  - Horizontal:
    - Running Bond: 0.0007
    - Not Laid in Running Bond: 0.0015
  - Total: 0.002

Reinforcement Ratio	6 in. wall		8 in. wall		12 in. wall	
	A_s (in.^{2}/ft)	Possibilities	A_s (in.^{2}/ft)	Possibilities	A_s (in.^{2}/ft)	Possibilities
0.0007	0.047	No. 4 @ 48 in.	0.064	No. 4 @ 32 in. No. 5 @ 48 in.	0.098	No. 4 @ 24 in. No. 5 @ 32 in. No. 6 @ 48 in.
0.0010	0.068	No. 4 @ 32 in. No. 5 @ 48 in.	0.092	No. 4 @ 24 in. No. 5 @ 40 in. No. 6 @ 48 in.	0.140	No. 4 @ 16 in. No. 5 @ 24 in. No. 6 @ 32 in.
0.0013	0.088	No. 4 @ 24 in. No. 5 @ 40 in.	0.119	No. 4 @ 16 in. No. 5 @ 32 in. No. 6 @ 40 in.	0.181	No. 4 @ 8 in. No. 5 @ 16 in. No. 6 @ 24 in.

Shear Design - Detailing



- Joint reinforcing may be used to resist shear
    - SDC A through SDC C+: No restrictions (unlike SD)
    - SDC D: Special RMSW - joint reinforcing can not be used to resist shear…
        - “Horizontal reinforcement required to resist in-plane shear . . . shall be embedded in grout.” (TMS 7.3.2.6 (b))

Figures from Wire-Bond

Shear Design - Detailing

- Terminating shear reinforcement (TMS 6.1.7.1)
    - Wall ends: “shall be bent around the edge vertical reinforcing bar with a 180-degree standard hook.”
    - Wall intersections: “shall be bent around the edge vertical reinforcing bar with a 90-degree standard hook and shall extend horizontally into the intersecting wall a minimum distance at least equal to the development length.”
    - Joint Reinforcement:

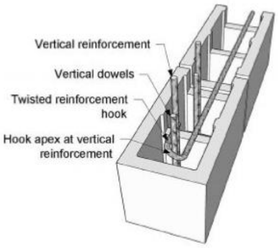
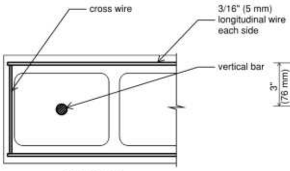
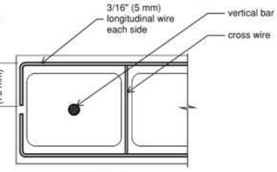


Figure 6.2.4-1 180-Degree Hook in Shear Reinforcement at End of Wall
(Baltimore and Chandler, 2019).



6.1.8.1.3.1 (a)



6.1.8.1.3.1 (b)

Shear Design – Shear Walls Detailing

- ASD Shear Wall Detailing (TMS 8.3.5.2)
  - Shear reinforcement provided when $F_v > F_{vm}$
  - General Shear Provisions (TMS 8.3.5.2.1)
    - Shear reinforcement provided parallel to the direction of the applied shear force
    - Spacing, minimum of:
      - d/2
      - 48”
  - Shear Wall Provisions(TMS 8.3.5.2.2)
    - Transvers reinforcement must be provided - at least 1/3 of shear reinforcement
    - Transverse reinforcement shall be uniformly distributed
    - Transverse reinforcement spacing shall not exceed 8 ft.

Shear Design – Special Walls Detailing

- Special Shear Wall Detailing (TMS 7.3.2.6.1.1)
  - If reinforcing is required to resist shear, then
    - Spacing, minimum of:
      - 1/3 wall height
      - 1/3 wall length
      - 48” for running bond
      - 24” for non laid in running bond:
    - Joint reinforcing not permitted (shall be embedded in grout)
    - Vertical reinforcement must be at least 1/3 of shear reinforcement
    - 180-degree hook in Chapter 6 controls over “standard hook”

Shear Design – Special Walls Detailing

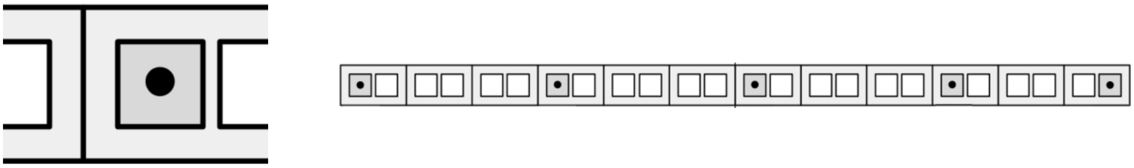
- Special Shear Wall Detailing (TMS 8.3.4.4)
- The **<u>ONE and ONLY</u>** ASD special condition: ρ_{max} for SRMSW's
- **<u>IF:</u>**
  - $\frac{M}{Vd_v} \geq 1.0$ **<u>AND</u>** $P > 0.05 f'_m A_n$
- **<u>THEN:</u>**
  - $\rho_{max} = \frac{n f'_m}{2 f_y (n + \frac{f_y}{f'_m})}$
- Does NOT apply to out-of-plane direction!

In-Plane Wall Design

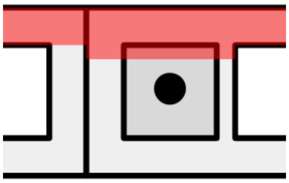
- Axial Design (done as part of out-of-plane)
- Flexure + Axial Design
- Shear Design
- Shear Friction Design

Flexure + Axial Design

- Same concepts as Session 3
- No second order effects
- Fully or partially grouted
- Distributed (multiple layers) or clustered reinforcing

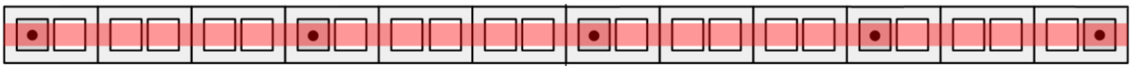


Flexure + Axial Design



Partially Grouted Masonry Shear Wall Concerns:

- Out-of-Plane – Explicitly accounted for
- In-Plane
  - Design as fully grouted if axial force is small and compression wholly within grouted end zone
  - Approximate with equivalent thickness
  - Account for the open cores



Flexure + Axial Design

Partially Grouted – Equivalent thickness approximation

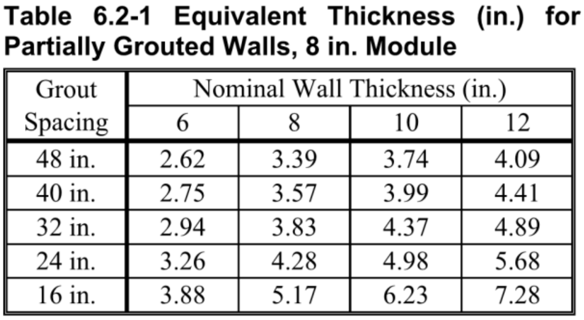


Table 6.2-1 Equivalent Thickness (in.) for Partially Grouted Walls, 8 in. Module

Grout Spacing	Nominal Wall Thickness (in.)			
	6	8	10	12
48 in.	2.62	3.39	3.74	4.09
40 in.	2.75	3.57	3.99	4.41
32 in.	2.94	3.83	4.37	4.89
24 in.	3.26	4.28	4.98	5.68
16 in.	3.88	5.17	6.23	7.28

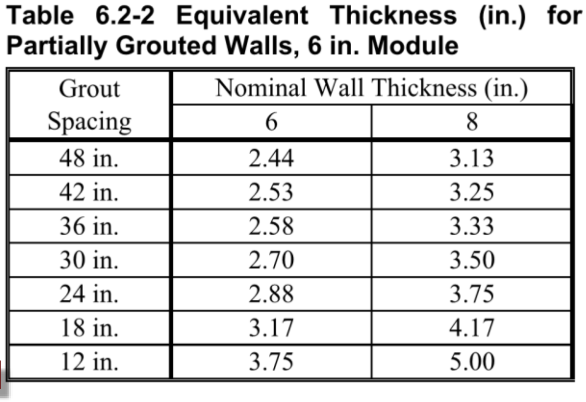


Table 6.2-2 Equivalent Thickness (in.) for Partially Grouted Walls, 6 in. Module

Grout Spacing	Nominal Wall Thickness (in.)	
	6	8
48 in.	2.44	3.13
42 in.	2.53	3.25
36 in.	2.58	3.33
30 in.	2.70	3.50
24 in.	2.88	3.75
18 in.	3.17	4.17
12 in.	3.75	5.00

TMS Strength Design of Masonry

Flexure + Axial Design

Distributed (Smeared) Reinforcement – Approximate Method

- Methods for flexural + axial design with distributed reinforcing
  - Approximate with Equivalent Thickness if partially grouted
  - Exact (strain compatibility analysis)

- Commercial software / spreadsheets commonly used

- Start with vertical reinforcement required for out-of-plane loads

Flexure + Axial Design

Distributed (Smeared) Reinforcement – Approximate Method

- Check to see if masonry or steel stress will control
- Simplified method from the MDG-2016:
- Solve $k = \frac{M + P\frac{d_v}{6}}{\frac{1}{3}d_v^2 F_b t_{sp} - P\frac{d_v}{3}}$ (MDG-2016 Figure 11.4-7)
- Compare to $k_{bal} = \frac{n}{n + \frac{F_s}{F_b}}$ (MDG-2016 Eqn. 11.4-8)
  - With Grade 60 Reinforcement:
    - $k_{bal} = 0.312$ for concrete masonry, or
    - $k_{bal} = 0.368$ for clay masonry

Flexure + Axial Design

Distributed (Smeared) Reinforcement – Approximate Method

- If k exceeds k_{bal}, then masonry stress controls
  - $A^*_{s,req'd} = \frac{\frac{1}{2}k d_v F_b t_{sp} - P}{\frac{1}{2}\frac{(1-k)^2}{k} d_v n F_b}$ (MDG-2016 Figure 11.4-7)

Flexure + Axial Design

Distributed (Smeared) Reinforcement – Approximate Method

- If k is less than k_{bal}, then steel stress controls
- From MDG-2016 Figure 11.4-7:
- Solve k from the quadratic equation:
  - $\left(\frac{1}{3}d_v^2F_s\frac{t_{sp}}{n}+P\frac{d_v}{3}\right)k^2+\left(M-P\frac{d_v}{6}\right)k-\left(M+P\frac{d_v}{6}\right)=0$
- Then, solve $A^*_{s,req'd}$:
  - $A^*_{s,req'd}=\frac{\frac{1}{2}(kd_v)F_s(\frac{k}{1-k})\frac{1}{n}t_{sp}-P}{\frac{1}{2}(1-k)F_sd_v}$

Flexure + Axial Design

Distributed (Smeared) Reinforcement – Approximate Method

- Once $A^*_{s,req'd}$ is known, then MDG-2016 Table 11.4.2 can be used to determine required reinforcement based on bar size and spacing (on an area per lineal foot basis)
- Remember $A^*_{s,req'd}$ is likely in area of steel per inch…

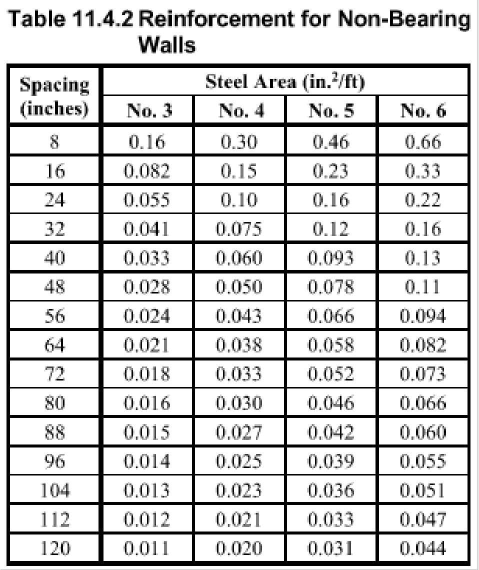


Table 11.4.2 Reinforcement for Non-Bearing Walls

Spacing (inches)	Steel Area (in.^{2}/ft)			
	No. 3	No. 4	No. 5	No. 6
8	0.16	0.30	0.46	0.66
16	0.082	0.15	0.23	0.33
24	0.055	0.10	0.16	0.22
32	0.041	0.075	0.12	0.16
40	0.033	0.060	0.093	0.13
48	0.028	0.050	0.078	0.11
56	0.024	0.043	0.066	0.094
64	0.021	0.038	0.058	0.082
72	0.018	0.033	0.052	0.073
80	0.016	0.030	0.046	0.066
88	0.015	0.027	0.042	0.060
96	0.014	0.025	0.039	0.055
104	0.013	0.023	0.036	0.051
112	0.012	0.021	0.033	0.047
120	0.011	0.020	0.031	0.044

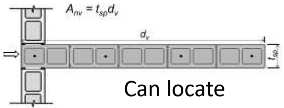
Flexure + Axial Design

End Zone (Clustered) Reinforcement – Approximate Method

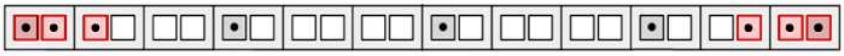
Assume no axial load (conservative)

Estimate area of steel required as if in a single layer (Sessions 2 and 3)

- Assume d = 0.9 d_v and then, as before jd as 90% of d
- $A_{s,reqd} \sim \frac{M}{F_s jd} = \frac{M}{F_s 0.81 d_v}$ (Pure Flexure = conservative)



Can locate reinforcement in flanges if intersection is properly detailed per TMS 402-16 5.1.1.2.5

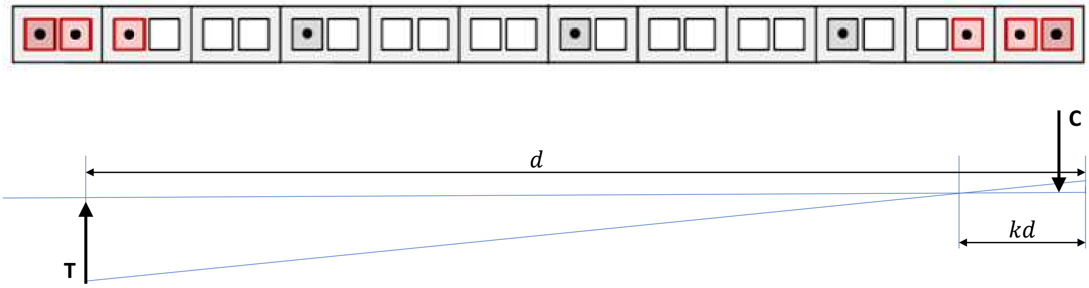


Flexure + Axial Design

End Zone (Clustered) Reinforcement – Exact Method

Include Axial Load

Interaction Diagram



Flexure + Axial Design

End Zone (Clustered) Reinforcement – Exact Method

Include Axial Load

Interaction Diagram – same as for walls with out of plane loads, except:

- Axial force will be greater and shear load will be MUCH Greater
- d will be MUCH greater!
- If the shear wall isn't fully grouted, check to make sure that kd is less than solid grouted length at ends

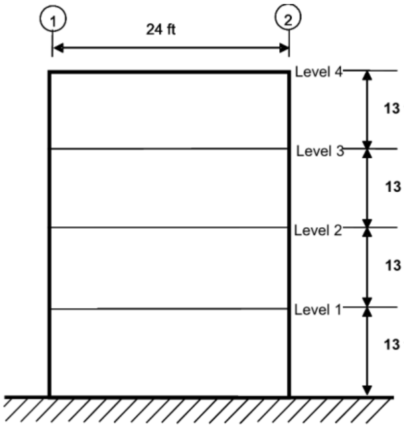
---

Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

Ordinary Reinforced Clay Masonry Shear Wall

- Nominal 6" units (5.5"), 6" module
- Running bond
- Fully grouted, $t = 5.5"$
- f'_m = 2900 psi
- $P = 124.8\ kips$
- $V = 56\ kips$
- $M = 2{,}180\ kip - ft$
- $S_{DS} = 0.24\ (SDC = B)$



Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

Ordinary Reinforced Clay Masonry Shear Wall

- f'_m = 2900 psi
- $E_m = 700(2900psi) = 2{,}030{,}000\ psi$
- $n = \frac{29{,}000{,}000psi}{2{,}030{,}000psi} = 14.3$
- $F_b = 0.45f'_m = 0.45(2900psi) = 1305psi$
- $F_s = 32{,}000psi$

Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – Approximate Method

- Solve $k = \frac{M+P\frac{d_v}{6}}{\frac{1}{3}d_v^2 F_b t_{sp} - P\frac{d_v}{3}} = \frac{2180k-ft.+124.8k\frac{24ft.}{6}}{\frac{1}{3}(24ft.)^2(1.305ksi)(\frac{5.5in.}{\frac{12in.}{ft.}})-124.8k\frac{24ft.}{3}} = 0.172$
- $0.172 < 0.368\ (clay\ masonry)$ so, allowable steel stress controls
- Solve k from the quadratic equation:
  - $\left(\frac{1}{3}d_v^2 F_s \frac{t_{sp}}{n} + P\frac{d_v}{3}\right)k^2 + \left(M - P\frac{d_v}{6}\right)k - \left(M + P\frac{d_v}{6}\right) = 0$

Flexure + Axial Design - Example

Masonry Designers’ Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – Approximate Method

- Solve k from the quadratic equation:
  - $\left(\frac{1}{3}d_v^2 F_s \frac{t_{sp}}{n} + P\frac{d_v}{3}\right)k^2 + \left(M - P\frac{d_v}{6}\right)k - \left(M + P\frac{d_v}{6}\right) = 0$
  - $\left(\frac{1}{3}(24ft.)^2(32ksi)\frac{\frac{5.5in.}{\frac{12in.}{ft.}}}{14.3} + 124.8k\frac{24ft.}{3}\right)k^2 + \left(2180k - ft. - 124.8k\frac{24ft.}{6}\right)k - \left(2180k - ft. + 124.8k\frac{24ft.}{6}\right) = 0$
  - $29{,}360k^2 + 1618k - 2679 = 0$
  - $k = 0.275$

Flexure + Axial Design - Example

Masonry Designers’ Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – Approximate Method

- Then, solve $A^*_{s,req'd}$:
  - $A^*_{s,req'd} = \frac{\frac{1}{2}(kd_v)F_s(\frac{k}{1-k})\frac{1}{n}t_{sp} - P}{\frac{1}{2}(1-k)F_s d_v}$
  - $A^*_{s,req'd} = \frac{\frac{1}{2}(0.275)(24ft)\left(\frac{12in.}{ft.}\right)32ksi\left(\frac{0.275}{1-0.275}\right)5in. - 124.8k}{\frac{1}{2}(1-0.275)(32ksi)(24ft.)(\frac{12in.}{ft.})} = 0.0179\frac{in.^2}{in.}$
- Since clay masonry module is 6”, not 8”, cannot use Table 11.4.2
- Solve spacing, try #5 bars:
  - $s = \frac{A_{bar}}{A^*_{s,req'd}} = \frac{0.31in.^2}{0.0179\frac{in.^2}{in.}} = 17.3in.$ Use s =18”

Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – Approximate Method

- Also, check maximum axial load:
- Radius of Gyration, r:
  - $r = \frac{I_n}{A_n} = \frac{t_{sp}}{\sqrt{12}} = \frac{5.5 in.}{\sqrt{12}} = 1.59 in.$
- Slenderness Ratio, $\frac{\mathrm{h}}{r}$;
  - $\frac{h}{r} = \frac{13.33 ft.(\frac{12 in.}{ft.})}{1.59 in.} = 100.8$
- Calculate allowable axial load

Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

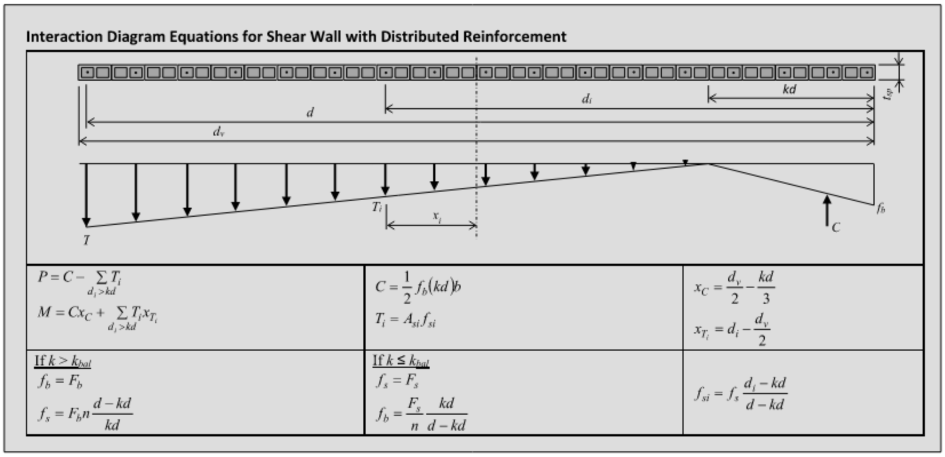
Distributed (Smeared) Reinforcement – <u>Interaction Diagram</u>

- Develop per MDG-2016 Example 11.4-7

Flexure + Axial Design - Example

Masonry Designers’ Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – <u>Interaction Diagram</u>



Interaction Diagram Equations for Shear Wall with Distributed Reinforcement

$$P = C - \sum_{d_i > kd} T_i$$

$$M = Cx_C + \sum_{d_i > kd} T_i x_{T_i}$$

$$C = \frac{1}{2} f_b (kd) b$$

$$T_i = A_{si} f_{si}$$

$$x_C = \frac{d_v}{2} - \frac{kd}{3}$$

$$x_{T_i} = d_i - \frac{d_v}{2}$$

<u>If $k > k_{bal}$</u>

$$f_b = F_b$$

$$f_s = F_b n \frac{d - kd}{kd}$$

<u>If $k \le k_{bal}$</u>

$$f_s = F_s$$

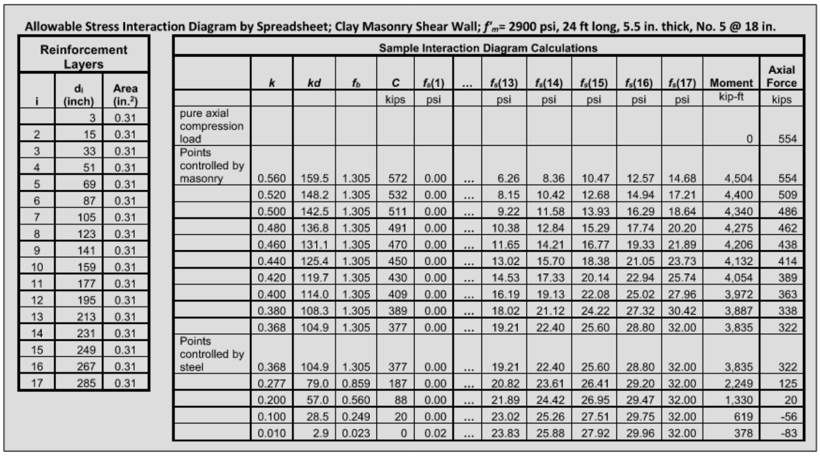
$$f_b = \frac{F_s}{n} \frac{kd}{d - kd}$$

$$f_{si} = f_s \frac{d_i - kd}{d - kd}$$

Flexure + Axial Design - Example

Masonry Designers’ Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – <u>Interaction Diagram</u>



Allowable Stress Interaction Diagram by Spreadsheet; Clay Masonry Shear Wall; f'_m= 2900 psi, 24 ft long, 5.5 in. thick, No. 5 @ 18 in.

Reinforcement Layers

i	d_i (inch)	Area (in.^{2})
	3	0.31
2	15	0.31
3	33	0.31
4	51	0.31
5	69	0.31
6	87	0.31
7	105	0.31
8	123	0.31
9	141	0.31
10	159	0.31
11	177	0.31
12	195	0.31
13	213	0.31
14	231	0.31
15	249	0.31
16	267	0.31
17	285	0.31

Sample Interaction Diagram Calculations

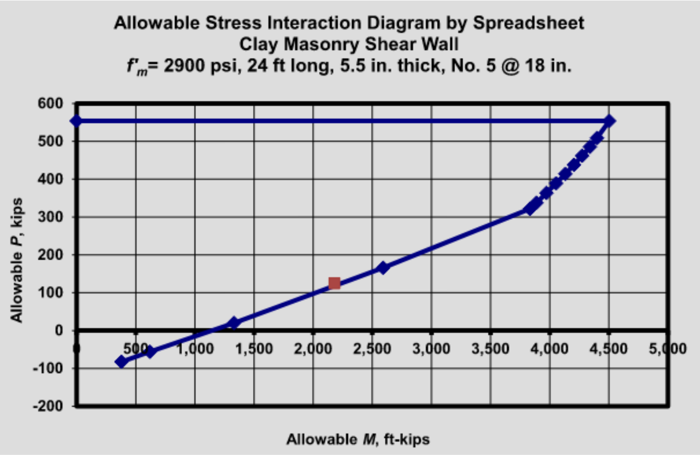
	k	kd	f_b	C	$f_s(1)$	...	$f_s(13)$	$f_s(14)$	$f_s(15)$	$f_s(16)$	$f_s(17)$	Moment	Axial Force
				kips	psi		psi	psi	psi	psi	psi	kip-ft	kips
pure axial compression load												0	554
Points controlled by masonry	0.560	159.5	1.305	572	0.00	...	6.26	8.36	10.47	12.57	14.68	4,504	554
	0.520	148.2	1.305	532	0.00	...	8.15	10.42	12.68	14.94	17.21	4,400	509
	0.500	142.5	1.305	511	0.00	...	9.22	11.58	13.93	16.29	18.64	4,340	486
	0.480	136.8	1.305	491	0.00	...	10.38	12.84	15.29	17.74	20.20	4,275	462
	0.460	131.1	1.305	470	0.00	...	11.65	14.21	16.77	19.33	21.89	4,206	438
	0.440	125.4	1.305	450	0.00	...	13.02	15.70	18.38	21.05	23.73	4,132	414
	0.420	119.7	1.305	430	0.00	...	14.53	17.33	20.14	22.94	25.74	4,054	389
	0.400	114.0	1.305	409	0.00	...	16.19	19.13	22.08	25.02	27.96	3,972	363
	0.380	108.3	1.305	389	0.00	...	18.02	21.12	24.22	27.32	30.42	3,887	338
	0.368	104.9	1.305	377	0.00	...	19.21	22.40	25.60	28.80	32.00	3,835	322
Points controlled by steel	0.368	104.9	1.305	377	0.00	...	19.21	22.40	25.60	28.80	32.00	3,835	322
	0.277	79.0	0.859	187	0.00	...	20.82	23.61	26.41	29.20	32.00	2,249	125
	0.200	57.0	0.560	88	0.00	...	21.89	24.42	26.95	29.47	32.00	1,330	20
	0.100	28.5	0.249	20	0.00	...	23.02	25.26	27.51	29.75	32.00	619	-56
	0.010	2.9	0.023	0	0.02	...	23.83	25.88	27.92	29.96	32.00	378	-83

Flexure + Axial Design - Example

Masonry Designers' Guide: Example 11.4-7

Distributed (Smeared) Reinforcement – Interaction Diagram

- $M_{applied} = 2180kip - ft.$
- At $P = 124.8kips$
  - $M_{allowed} = 2249kip - ft.$
- $\frac{M_{applied}}{M_{allowed}} = \frac{2180}{2249} = 0.97$ **OK**

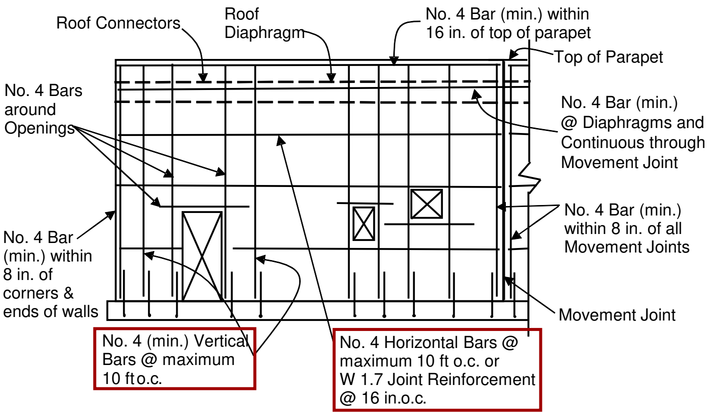


Flexure + Axial Design - Example

Distributed (Smeared) Reinforcement – Approximate Method

- Calculate allowable axial load:
  - $P_a = (0.25f'_m A_n + 0.65A_{st}F_s)(\frac{70r}{h})^2$
  - $P_a = (0.25(2900psi)(1584in.^2) + 0)(\frac{70}{100.8})^2 = 554kips$
- Compare to maximum factored axial load:
  - $P = D + L = 343kips$ **OK**

Detailing – Detailed Plain Ordinary Reinforced



Vertical Bar Size: #5 > #4

Vertical Bar Spacing: 18” < 120”

Steel ratio: N/A

TMS MDG-2016 Table 10.4-1

Flexure + Axial Design - Example

Masonry Designers’ Guide: Example 11.4-7

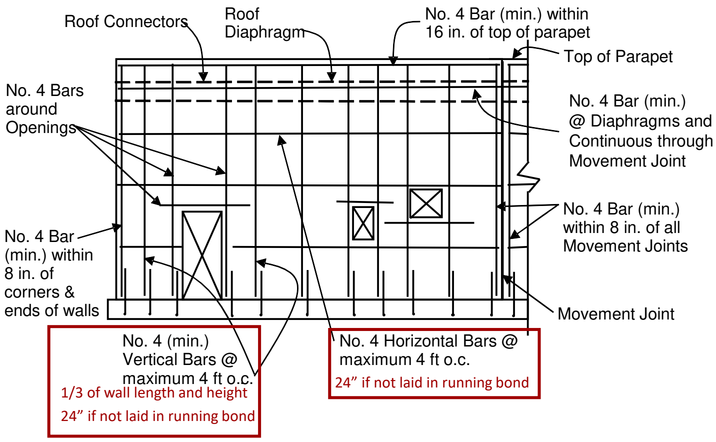
Rework as Special Reinforced Clay Masonry Shear Wall

- $S_{DS} = 2.5(0.24) = 0.6$ (SDC = D)
- $R = 5$ (with ORMSW $R = 2$)
- Lateral forces and moments would remain the same since ratio of S_{DS} values is the same as the ratio of the R values…
- Axial force changes: $P = 179.8 kips$
- Using interaction diagram:
  - $M_{allowable}$ increases to 2707kip-ft. and reinforcement could probably be reduced… retain #5’s at 18” o.c. per the example.

Detailing – Special Reinforced

Masonry Designers' Guide: Example 11.4-7

Special Reinforced Clay Masonry Shear Wall



Size: #5 > #4 **OK**

Spacing: 18" <

- 48"
- 1/3 height = 212"
- 1/3 length = 96"

Steel ratio:

$$\rho = \frac{A_S}{st} = \frac{0.31}{(18)(5.5)} = 0.0031 > 0.0007 \ \underline{\textbf{OK}}$$

Max Reinforcement:

$$\rho_{max} = \frac{nf_m'}{2f_y(n + \frac{f_y}{f_m'})}$$

$$\rho_{max} = \frac{14.3(2900psi)}{2(60{,}000psi)\ (14.3 + \frac{60}{29})} = 0.0098$$

$$\rho_{worst\ case} = \frac{A_s}{bd} = \frac{11((0.31in.^2))}{5.5in.(285in.)} = 0.00217$$

$0.00217 < 0.0098$ **OK**

Shear Design

Shear Design Process

- Design to Overall Shear Limits
- Utilize masonry shear capacity
- Add shear reinforcement if required

Special Considerations

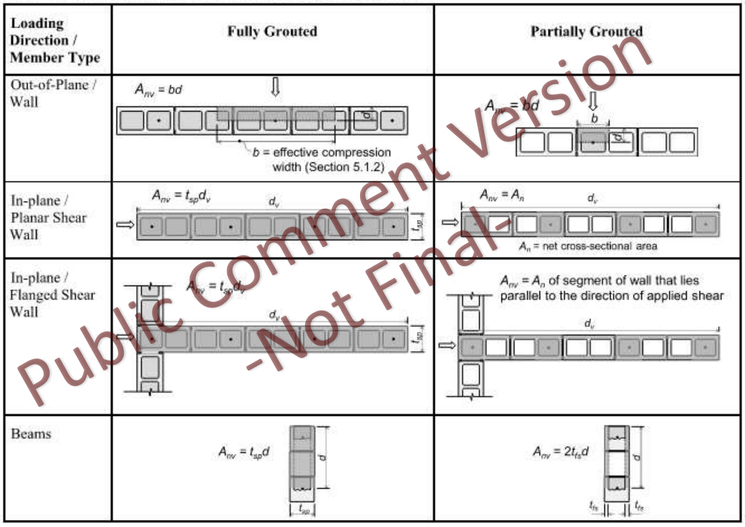
- Perforated Shear Walls
- Shear Walls with Flanges

Shear Design

Calculated Shear Stress

- $f_v = \dfrac{V}{A_{nv}}$

Table 4.3.5: Net Shear Area for Reinforced Masonry Members



Loading Direction / Member Type	Fully Grouted	Partially Grouted
Out-of-Plane / Wall	$A_{nv} = bd$ b = effective compression width (Section 5.1.2)	$A_{nv} = bd$
In-plane / Planar Shear Wall	$A_{nv} = t_{sp}d_v$	$A_{nv} = A_n$ A_n = net cross-sectional area
In-plane / Flanged Shear Wall	$A_{nv} = t_{sp}d_v$	$A_{nv} = A_n$ of segment of wall that lies parallel to the direction of applied shear
Beams	$A_{nv} = t_{sp}d$	$A_{nv} = 2t_{fs}d$

Shear Design

Calculated Shear Stress

- $f_v = \dfrac{V}{A_{nv}}$

Overall Shear Stress Limits

  - $F_v = (F_{vm} + F_{vs})\gamma_g$
- If $\dfrac{M}{Vd_v} \leq 0.25$ Then:
  - $F_v \leq 3(\sqrt{f'_m})\gamma_g$
- If $\dfrac{M}{Vd_v} \geq 1.0$ Then:
  - $F_v \leq 2(\sqrt{f'_m})\gamma_g$

$\gamma_g = 0.75$ for partially grouted shear walls
$\gamma_g = 1.0$ otherwise….

Maximum value of F_v may be interpolated for $\frac{M}{Vd_v}$ between 0.25 and 1.0

Shear Design

Masonry Allowable Shear Stress

- For Special Masonry Shear Walls
  - $F_{vm} = \frac{1}{4}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.25\frac{P}{A_n} \geq 0$
- For Other Masonry
  - $F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.25\frac{P}{A_n} \geq 0$

$\frac{M}{Vd_v}$:

- Always positive
- Need not exceed 1.0
- Conservatively simplify by setting to 1.0

P:

- Positive for net compressive axial loads
- Negative for net tensile axial loads

Shear Design

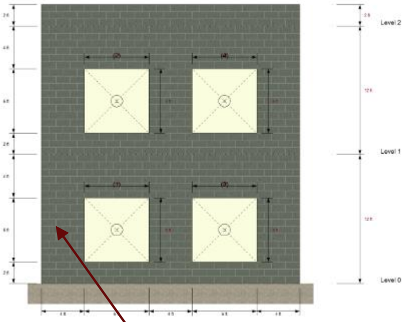
Steel Reinforcement Allowable Shear Stress

- $F_{vs} = 0.5(\frac{A_s F_s d_v}{A_{nv} s})$

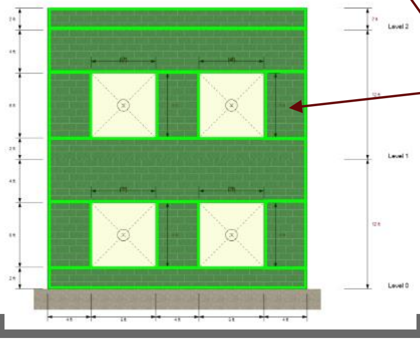
Shear Design

Perforated Shear Walls

- Utilize FEA software, or



- Analyze by wall segments
  - Flexure and axial
  - Shear
  - Distribute force by stiffness



NOT columns or even 'piers'… just wall segments!

Shear Design - Example

Ordinary Reinforced Clay Masonry Shear Wall

- Net Shear Area: $A_{nv} = bd_v = 5.5in.(288in.) = 1584in.^2$
- Shear Stress: $f_v = \frac{V}{A_{nv}} = \frac{56{,}000lbs.}{1584in.^2} = 35.4psi$
- Shear Span Ratio: $\frac{M}{Vd_v} = \frac{2{,}180{,}000lb.-ft.}{56{,}000lbs.(24ft.)} = 1.62 > 1.0$ **Use 1.0**
- Max Shear Stress: $F_v \leq 2\left(\sqrt{f'_m}\right)\gamma_g = 2\sqrt{2900psi}(1.0) = 107.7\ psi$
  - 107.7>35.4 **OK**

Shear Design - Example

Ordinary Reinforced Clay Masonry Shear Wall

- Masonry Allowable Shear Stress
  - $F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.25\frac{P}{A_n} \geq 0$
  - $F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75(1.0)\right)\sqrt{2900psi}\right] + 0.25\frac{124{,}800lbs.}{1584in.^2} = 80.3psi$
  - 80.3>35.4 – Masonry Appears to have sufficient strength… check final limit:
- Allowable Shear Stress
  - $F_v = (F_{vm} + F_{vs})\gamma_g$
  - $F_v = (80.3psi + 0psi)(1.0) = 80.3$ **OK – no shear reinforcement required**
  - Would be different, but still 'OK' if SRMSW and $\gamma_g = 0.75$

Shear Design - Example

Special Reinforced Clay Masonry Shear Wall

- TMS 402 Section 7.3.2.6.1.2 requires a 50% increase for in-plane seismic forces when determining shear stress
  - $f_v = \frac{1.5V}{A_{nv}} = \frac{1.5(56{,}000lbs.)}{1584in.^2} = 53.0psi$
- The Shear Span Ratio stays the same – do not apply the 50% increase
- The axial load increases to 179.8kips, use ASCE 7 exception for Dead Load
  - $F_{vm} = \frac{1}{4}\left[\left(4.0 - 1.75(1.0)\right)\sqrt{2900psi}\right] + 0.25\frac{179{,}800lbs.}{1584in.^2} = 58.7psi$
  - With $\gamma_g = 1.0$ 58.7>50.3 - **Still OK**

Shear Design - Example

Special Reinforced Clay Masonry Shear Wall

- Check Max Reinforcement?
- Already know Shear Span Ratio > 1.0
- Check Axial Force Limit:
  - $P_{max} = 0.05f'_m A_n = 0.05(2900psi)(1584in.^2) = 229.7kips$
  - Critical Axial Loads (ASCE 7 Combinations 8 and 9): 238.9kips and 326.5kips
  - Both are greater than P_{max} - **Must limit maximum reinforcement…**

Shear Design - Example

Special Reinforced Clay Masonry Shear Wall

- Check Max Reinforcement
  - $\rho_{max} = \frac{nf'_m}{2f_y(n+\frac{f_y}{f'_m})} = \frac{14.3(2900psi)}{2(60,000psi)(14.3+\frac{60,000psi}{2900psi})} = 0.00988$
  - Quick Check – use all 17 bars:
    - $\rho = \frac{A_{st}}{bd} = \frac{5.27in.^2}{5.5in.(285in.)} = 0.00336 < 0.00988$ **OK**
  - If that didn't work, then must identify bars in tension and use those… 11 bars
    - $\rho = \frac{11(0.31in.^2)}{5.5in.(285in.)} = 0.0.00217 < 0.00988$ **OK**

Shear Design - Example

Special Reinforced Clay Masonry Shear Wall

- Prescriptive reinforcement requirements
- Max spacing = 1/3 wall length or height, or 48” max.
  - $s \leq \frac{288in.}{3} = 96in;\ \frac{148in.}{3} = 49.3in.;\ or, 48in.$ USE 48in.
- Min. Reinforcement Ratio:
  - $\rho_{min} = 0.0007$
  - $\rho_v = 0.00336$ **OK**
  - For horizontal steel, determine minimum required
  - $A_s = \rho_{h,min} b = 0.0007(5.5in.) = 0.00385\frac{in.^2}{in.}$ **USE #4 bars @ 48in. o.c.**

Shear Friction Design - Design

- Shear Friction Design (TMS 8.3.6)
  - Check at interfaces (e.g. foundation)

Calculated Shear Stress

- $f_v = \frac{V}{A_{nv}}$

Calculate Allowable Shear Friction Stress

- If $\frac{M}{Vd_v} \leq 0.5$ Then:
  - $F_f \leq \frac{\mu(A_{sp}F_s+P)}{A_{nv}} \geq 0$
- If $\frac{M}{Vd_v} \geq 1.0$ Then:
  - $F_f \leq \frac{0.65(0.6A_{sp}F_s+P)}{A_{nv}} \geq 0$

- $\mu =$ coefficient of friction
  - 1.0 unfinished concrete
  - 1.0 intentionally roughened concrete
  - 0.7 all other conditions
- A_{sp} = shear friction reinforcement
  - Not additive
- Interpolate as required
- Reinforcement must be adequately developed for yield strength

Shear Friction Design - Example

Allowable Shear Friction Stress:

- Calculate A_{sp}: With (17) #5 bars crossing the shear plane
  - $A_{sp} = 17(0.31 in.^2) = 5.27 in.^2$
- Since $\frac{M}{Vd_v} \geq 1.0$ Then:
  - $F_f \leq \frac{0.65(0.6A_{sp}F_s+P)}{A_{nv}} = \frac{0.65(0.6(5.27in.^2)(32{,}000psi)+124{,}800lbs.)}{1584in.^2} = 92.7psi$
  - 92.7>35.4 **OK**

This concludes The American Institute of Architects Continuing Education Systems Course

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The Masonry Society