NCSEA Structural Engineering Exam Review Course
Lateral Forces Review

Masonry

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Masonry Lateral Forces

Introduction and acknowledgments

- Many of the slides and handouts were originated by Sue Frey, who passed away in 2012.
- John M. Hochwalt, PE, SE (johnh@kpff.com)
  - Co-author of the 7th edition of the Reinforced Masonry Engineering Handbook
  - Voting member of MSJC subcommittees
  - Associate with KPFF in Seattle

Masonry Lateral Forces

Agenda

- **Overview and Review Material**
- General Requirements (MSJC Chapter 1)
- Allowable Stress Design (MSJC Chapter 2)
- Strength Design (MSJC Chapter 3)
- Wall Anchorage
- Handouts
- Close

2015 NCEES Exam

- Component 2 Lateral: AM (Breadth)
  - Lateral forces (wind/seismic)
  - Four hours on design, analysis, application, detailing
- Masonry specific
  - Flexural members
  - Compression members
  - Bearing walls/slender walls
  - Shear wall types: ordinary, intermediate, special
  - Anchorage of masonry walls (OOP)
  - Attachments of elements to masonry

2015 NCEES Exam

- Component 2: PM Buildings (Depth)
  - Four, one-hour essay design/analysis on
    - lateral forces and force distribution;
    - design, analysis, application, and detailing;
    - foundations and retaining structures;
    - two or more problems with SDC D or higher;
    - one or more problem with wind 110 mph or higher; and
    - may include a multi-story building or foundation design.
- Masonry specific
  - All above and masonry lateral load resisting system

2015 NCEES Exam

- Masonry
  - New in 2015—Exam may have questions on both
    - Allowable Stress Design (ASD)
    - Strength Design (SD)

Controlling Code Precedence

Order of precedence:

IBC

↓

ASCE 7 and MSJC

↓

ASTM and other Standards

IBC controls over all other IBC
all other codes/standards for:
loads, detailing, design

IBC Chapter 35 lists sections of other codes adopted/excluded by IBC so cannot be used on exam or in practice if not adopted.
Excluded:
ASCE-7 Chapter 14 and Appendix 11A

Controlling Code Precedence

- Masonry Design and Construction applicable and in general:
  - IBC Chapter 16, Structural Design, overrides ASCE 7 and MSJC load requirements
  - IBC Chapter 21, Masonry, overrides all MSJC masonry design and detailing requirements
  - IBC Chapter 17, Structural Tests and Inspections, overrides all ASCE 7 MSJC requirements tests and inspection and observation requirements

Important Code Information for Masonry Design

- IBC and ASCE 7
- IBC 1604.10
  - Lateral force resisting systems detailing requirements shall meet seismic detailing and limitations prescribed in IBC and ASCE-7 even when wind load effects are greater than seismic load effects
  - Meet MSJC 1.18 requirements even if wind controls building design based on wall type with its appropriate R value used to calculate seismic forces

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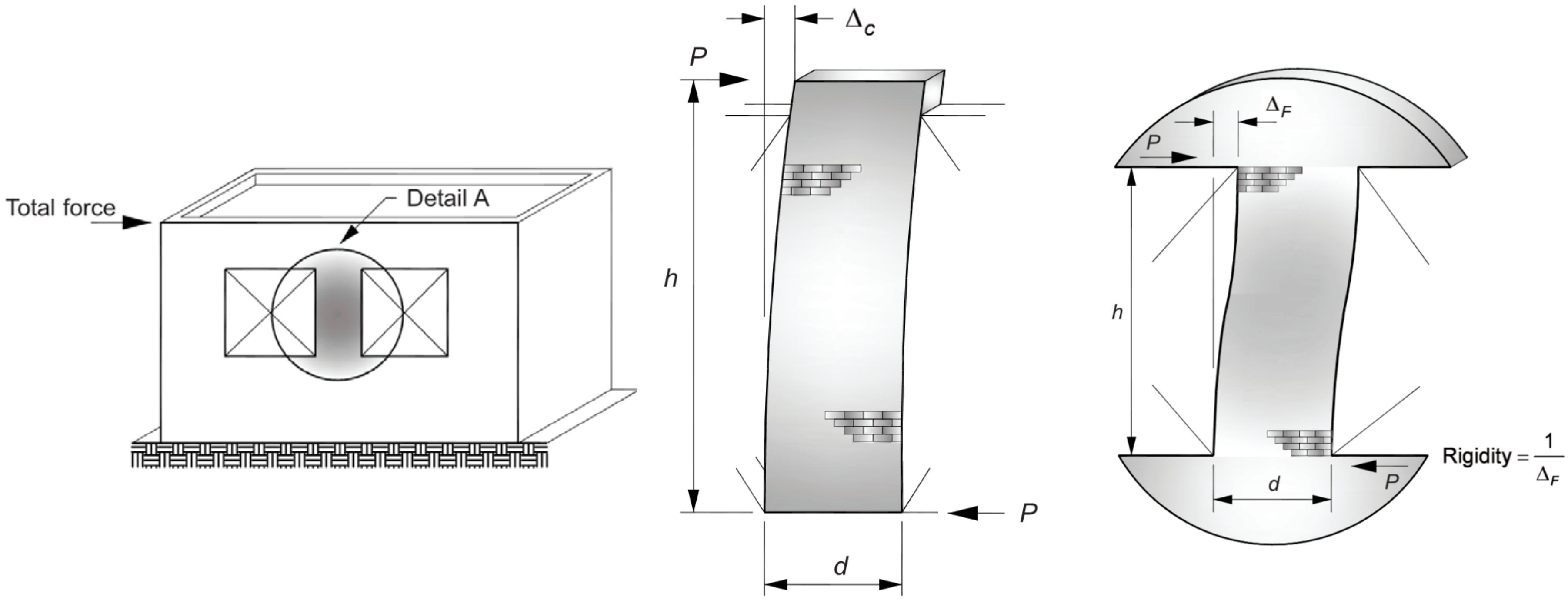
General Requirements

- 1.7.5—Refer to other presentations on lateral load distribution to shear walls based on stiffness due to length of wall and to amount of openings in wall. Loads transferred to top of wall or pier element by roof or floor diaphragm, by in-wall beam or by drag strut

General Requirements

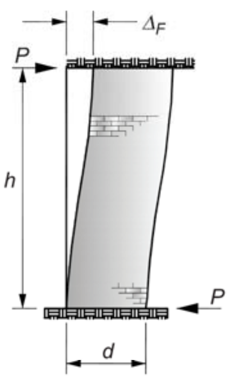


Illustrations from the Reinforced Masonry Engineering Handbook

General Requirements

TABLE GN-89a Coefficients for Deflection and Rigidity of Walls or Piers for Distribution of Horizontal Forces

Fixed Wall or Pier[1]



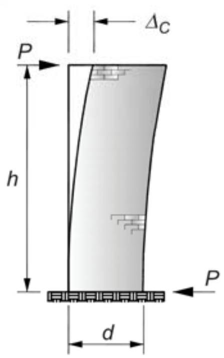
Δ_F = Deflection of wall or pier fixed top and bottom[2]

$$\Delta_F = \frac{P}{E_m t}\left[\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)\right]$$

$$\Delta_F = 0.1\left(\frac{h}{d}\right)^3 + 0.3\left(\frac{h}{d}\right)$$

$$R_F = \frac{1}{\Delta_F}$$ Rigidity of fixed wall or pier

Cantilever Wall or Pier[1]



Δ_C = Deflection of wall or pier fixed top and bottom[2]

$$\Delta_C = \frac{P}{E_m t}\left[4\left(\frac{h}{d}\right)^3 + 3\left(\frac{h}{d}\right)\right]$$

$$\Delta_C = 0.4\left(\frac{h}{d}\right)^3 + 0.3\left(\frac{h}{d}\right)$$

$$R_C = \frac{1}{\Delta_C}$$ Rigidity of cantilever wall or pier

$P = 100{,}000$ pounds; $t = 1"$; $E_m = 1{,}000{,}000$ psi

h/d	Δ_F	Δ_C	R_F	R_C	h/d	Δ_F	Δ_C	R_F	R_C	h/d	Δ_F	Δ_C	R_F	R_C
0.10	0.030	0.030	33.22	32.89	0.50	0.163	0.200	6.154	5.000	0.90	0.343	0.562	2.916	1.781
0.11	0.033	0.034	30.18	29.82	0.51	0.166	0.206	6.014	4.853	0.91	0.348	0.574	2.871	1.741
0.12	0.036	0.037	27.65	27.25	0.52	0.170	0.212	5.880	4.712	0.92	0.354	0.587	2.826	1.702
0.13	0.039	0.040	25.50	25.08	0.53	0.174	0.219	5.751	4.576	0.93	0.359	0.601	2.782	1.665
0.14	0.042	0.043	23.65	23.20	0.54	0.178	0.225	5.626	4.445	0.94	0.365	0.614	2.739	1.628

Illustrations from the Reinforced Masonry Engineering Handbook

General Requirements

- 1.8—Provides masonry material properties
- 1.9—Provides section properties including those relevant to lateral load design

General Requirements—Seismic

- 1.18 (referenced by IBC 2106.1): Know well
- 1.18.3.1 Non-Participating Elements
  - Not part of seismic force resisting system
  - Must be isolated from the seismic force resisting system
  - Detailed as required for Seismic Design Category

General Requirements—Seismic

- Participating Elements—Detailed for
  - Seismic Design Category
  - Shear Wall Type

- 1.18.3 Requirements for Shear Walls
  - 1.18.3.4 Ordinary
  - 1.18.3.5 Intermediate
  - 1.18.3.6 Special

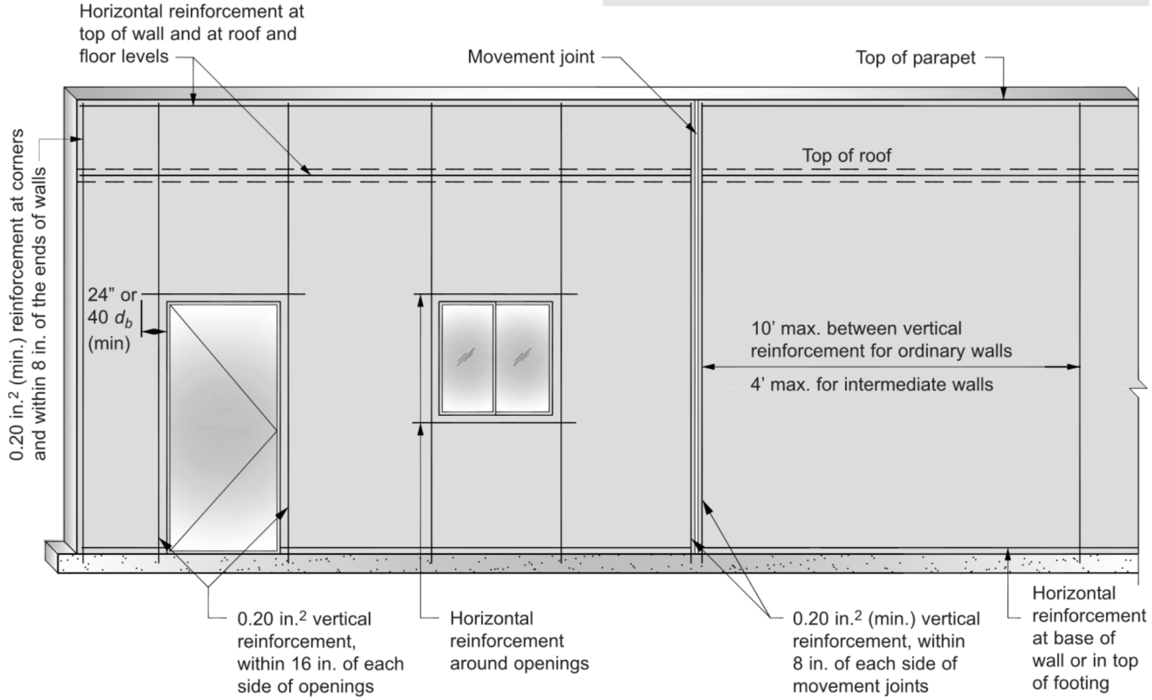
General Requirements—Shear Walls

More ductility is built into Special than Intermediate, and more into Intermediate than Ordinary.

- V = SDSW/(R/I)

- R: Detailing
  - 1.5 to 2.0 Crack Control
  - 3.5 Trim Areas Reinforced
  - 5.0. More reinforcing each way

Ordinarv and Intermediate Shear Walls



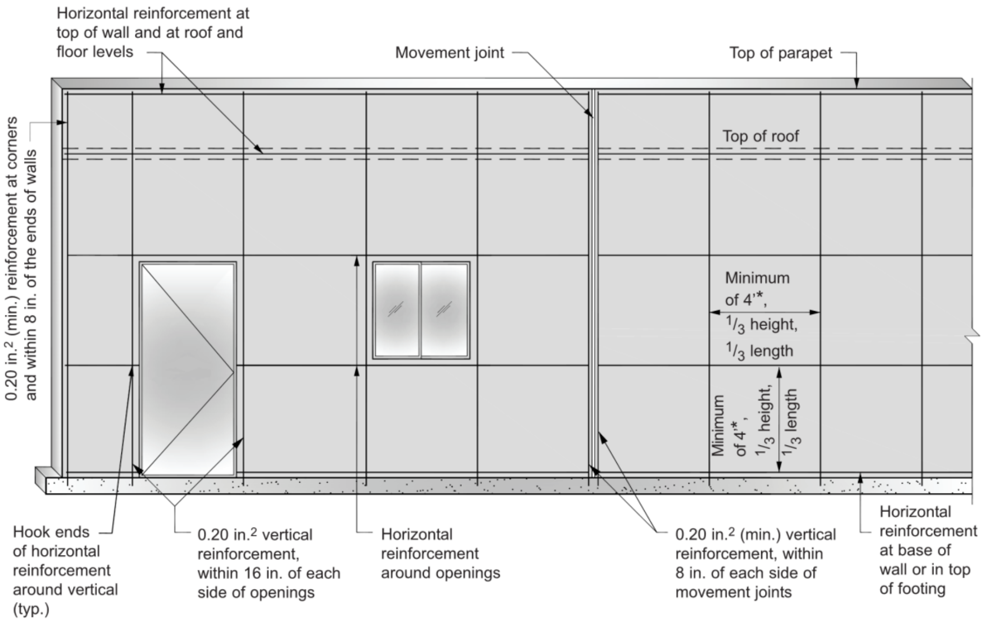
Note: Horizontal reinforcement shall consist of at least two longitudinal wires of W1.7 joint reinforcement spaced at 16 in. on center maximum or 0.2 in.^{2} of bond beam reinforcement spaced at 120 in. on center maximum.

Illustrations from the Reinforced Masonry Engineering Handbook

Special Shear Walls

- 1.18.3.2.6
- ⅓ of total (.0007 bt) in lesser OOP working direction and remainder of total (.002bt) in main direction is economically met by
  - #6 at 48 inches oc vertically and #5 at 48 inches oc horizontally, centered in an 8-inch wall
  - #6 at 48 inches oc vertically EF, and #5 at 48 inches oc horizontally EF, in a 12-inch wall
  - 10-inch walls: use reinforcing centered or each face depending on loads

Special Shear Walls



*Reduced to 24 in. for reinforcement not laid in running bond

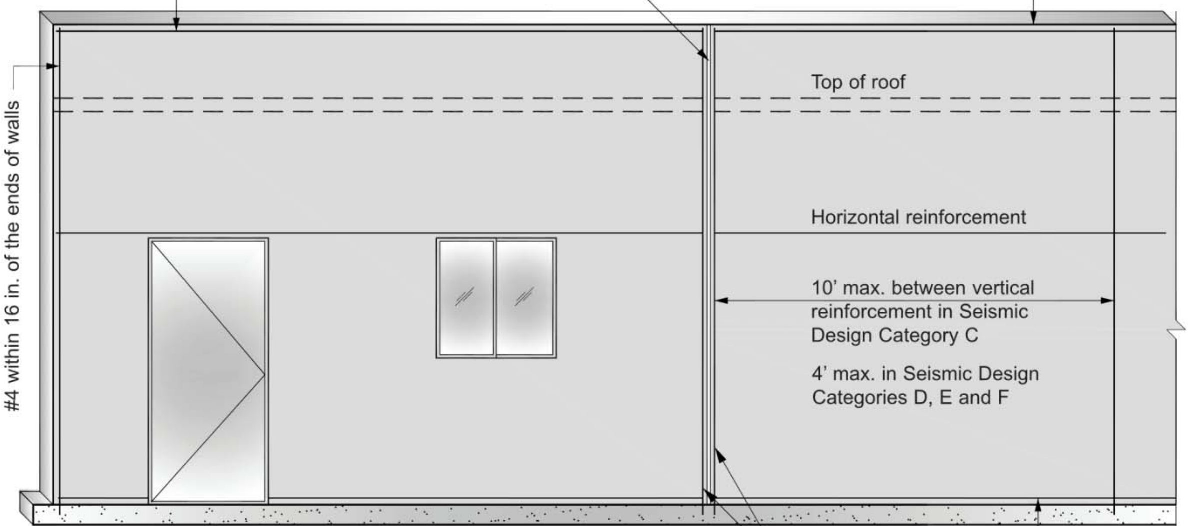
Note: Horizontal reinforcement shall consist of at least two longitudinal wires of W1.7 joint reinforcement spaced at 16 in. on center maximum or 0.2 in.^{2} of bond beam reinforcement spaced at 120 in. on center maximum.

Illustrations from the Reinforced Masonry Engineering Handbook

General Requirements—SDC

- **Remember:** Applies to both participating and non-participating
- Each wall detailing type for A to E/F builds on the lesser SDC type before it—so requirements are cumulative
- There are material restrictions, drift limitations, non-lateral load resisting masonry (e.g., partition walls) requirements, anchorage requirements, and so on in addition to rebar amount and detailing requirements
- If in SDC D, E, or F, select *Special* and move on

Non-Participating Walls—SDC C +



Note: Horizontal reinforcement shall consist of at least two longitudinal wires of W1.7 bed joint reinforcement spaced not more than 16 in. on center for walls greater than 4 in. width and at least one longitudinal W1.7 wire spaced not more than 16 in. on center for walls not exceeding 4 inches in width or at least one #4 bar spaced not more than 48 in. on center.

Illustrations from the Reinforced Masonry Engineering Handbook

Masonry Lateral Forces

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ASD Design

- Basics of ASD Design were discussed in previous review session
- This session focuses on issues unique to lateral design
- Special shear walls

ASD Special Shear Walls

- 1.18.3.2.6.1.2 Shear Capacity Design
  - Applicable only walls design by Section 2.3 (ASD)
  - Increase the seismic shear force by a factor of 1.5
  - Intended to reduce likelihood of shear failure, promote more ductile behavior

ASD Special Shear Walls

- 2.3.6.1.4 Reduced allowable shear stress
  - Applicable only to special reinforced masonry shear walls
  - Allowable shear stress due to strength of masonry is reduced by ½:

$$F_{vm} = \frac{1}{4}\left[\left(4.0 - 1.75\left(\frac{M}{Vd}\right)\right)\sqrt{f'_m}\right] + 0.25\frac{P}{A_n}$$

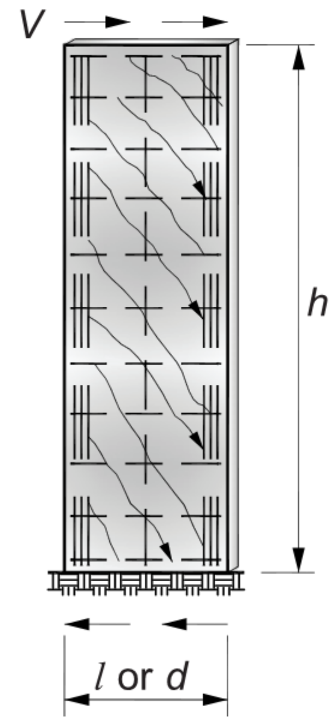
ASD Special Shear Walls

- 2.3.4 (ρ_{max}) Shear Walls
  - Applies when:
    - M/Vd > 1 (Flexural dominated behavior)
    - $F_a > 0.05\, f'_m A_n$

$$\rho_{max} = \frac{n f'_m}{2 f_y \left(n + \frac{f_y}{f'_m} \right)}$$

ASD Special Shear Walls

- 2.3.4 (ρ_{max}) Shear Walls
  - Intent is to ensure flexural behavior
  - Needs to consider all tension reinforcing



Illustrations from the Reinforced Masonry Engineering Handbook

ASD Shear Walls

- Design for flexure + axial load as discussed in previous review session
- 3 point interaction diagram
- May want to simplify design by concentrating steel at ends of the wall

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SD Design

- Basics of Strength Design were discussed in previous review session
- This session focuses on issues unique to lateral design

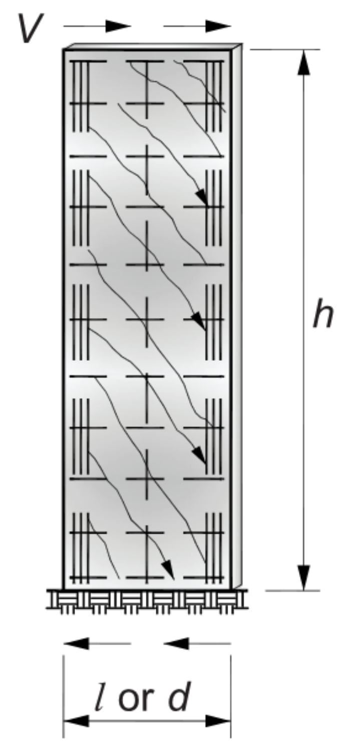
SD Special Shear Walls—Shear

- 1.18.3.2.6.1.1 Shear Capacity Design
  - Applicable only walls design by Section 3.3 (SD)
  - Either:
    - Design for a seismic shear force equal to 2.5V_u, or
    - Design for the shear associated with the wall reaching 1.25 times its nominal yield strength.

$$\phi V_n \geq \min\left(1.25V_u\left(\frac{M_n}{M_u}\right), \phi 2.5V_u\right)$$

SD Special Shear Walls—Shear

- Intent is to achieve flexural behavior or ensure that the wall remains essentially elastic
- Note that M_n must consider all reinforcing that will contribute to flexural strength
- For exam, consider designing for 2.5Vu to avoid computing an exact M_n



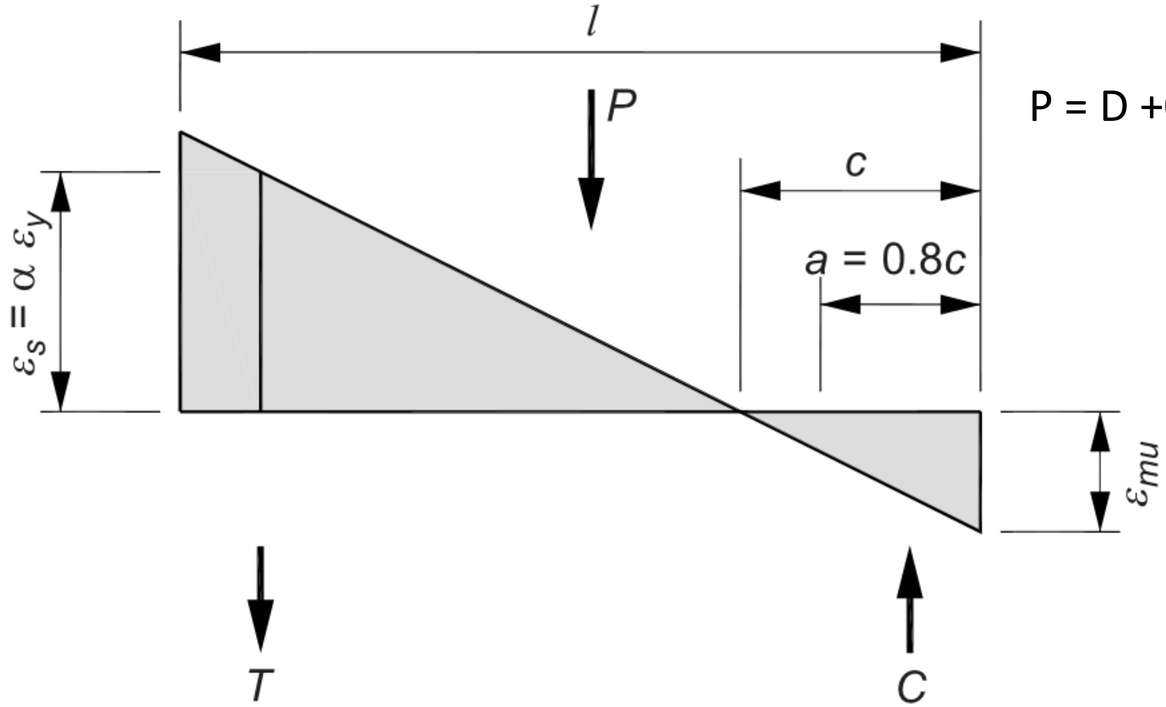
SD Shear Walls—Ductility

- Three ways to demonstrate sufficient ductility in shear walls:
  - **ρ_{max} per Section 3.3.3.5**
  - Provide boundary zones per Section 3.3.6.5
  - Demonstrate boundary zones are not required using Section 3.3.6.5.1, 3.3.6.5.3, or 3.3.6.5.4.

SD Shear Walls—Ductility

- **Last Session**
  - **3.3.3.5** If $M_u/V_ud \geq 1.0$, no more reinforcing is permitted than that which can develop 1.5 times the yield strain when the maximum compression strain in the masonry is reached.
- Intermediate Shear Walls must develop $3\varepsilon_y$
- Special Shear Walls must develop $4\varepsilon_y$

SD Shear Walls—Ductility



P = D +0.75L + 0.525 Q_E

Illustrations from the Reinforced Masonry Engineering Handbook

SD Shear Walls—Ductility

	$\rho_{max,P=0}$			
	α = 1.0	α = 1.5	α = 3.0	α = 4.0
	Balanced	$M_u/V_u d_v \geq 1$, and Ordinary Shear Walls	**Intermediate Shear Walls**	**Special Shear Walls**
Concrete				
1,500	0.0088	0.0071	0.0046	0.0037
2,000	0.0117	0.0095	0.0061	0.0049
2,500	0.0146	0.0119	0.0077	0.0062
3,000	0.0175	0.0143	0.0092	0.0074
3,500	0.0204	0.0167	0.0107	0.0087
4,000	0.0233	0.0190	0.0123	0.0099

SD Shear Walls

- Design for flexure + axial load as discussed in previous review session
- 3 point interaction diagram
- May want to simplify design by concentrating steel at ends of the wall

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Attachments: OOP Walls to Diaphragms

- OOP load to wall
  - React wind and seismic forces at floor and roof diaphragms to support wall reaction into or away from diaphragm (compression, tension, shear)
- 90-degree wind/seismic event
  - Same or additional connections will need to transfer diaphragm reactions into wall to receive in-plane shear loads (shear)

Attachments: OOP Walls to Diaphragms

- Design of Wall
  - Exterior Walls: Design for wind loads in addition to seismic loads
  - Interior Walls: Design for 5 psf minimum live load (IBC 1607.14)
  - Seismic Design Category > A (ASCE 7 12.11.1)

$$0.4S_{DS}I_eW_p$$

$$\geq 0.10W_p$$

Attachments: OOP Walls to Diaphragms

- Design of Wall Anchors
  - Seismic Design Category A: (ASCE 7 1.4.5)

$$0.2W_p$$

$$\geq 5\ psf$$

Attachments: OOP Walls to Diaphragms

- Design of Wall Anchors
  - Seismic Design Category A: (ASCE 7 12.11.2.1)

$$0.4S_{DS}k_aI_eW_p$$

$$\geq 0.20k_aI_eW_p$$

- k_a is an amplification factor for diaphragm flexibility
  - 1.0 for rigid diaphragms
  - For flexible diaphragms

$$k_a = 1.0 + \frac{L_f}{100}$$

Attachments: OOP Walls to Diaphragms

- Design of Wall Anchors
  - Structural Walls: Increase force 1.4 for the design of steel elements other than reinforcing steel and anchor bolts
  - Non-Structural Walls:
    - Compute forces by ASCE 7 Chapter 13.
    - Anchors in masonry shall be designed to be governed by tensile or shear strength of a ductile steel element or design for 2.5 times the factored load.

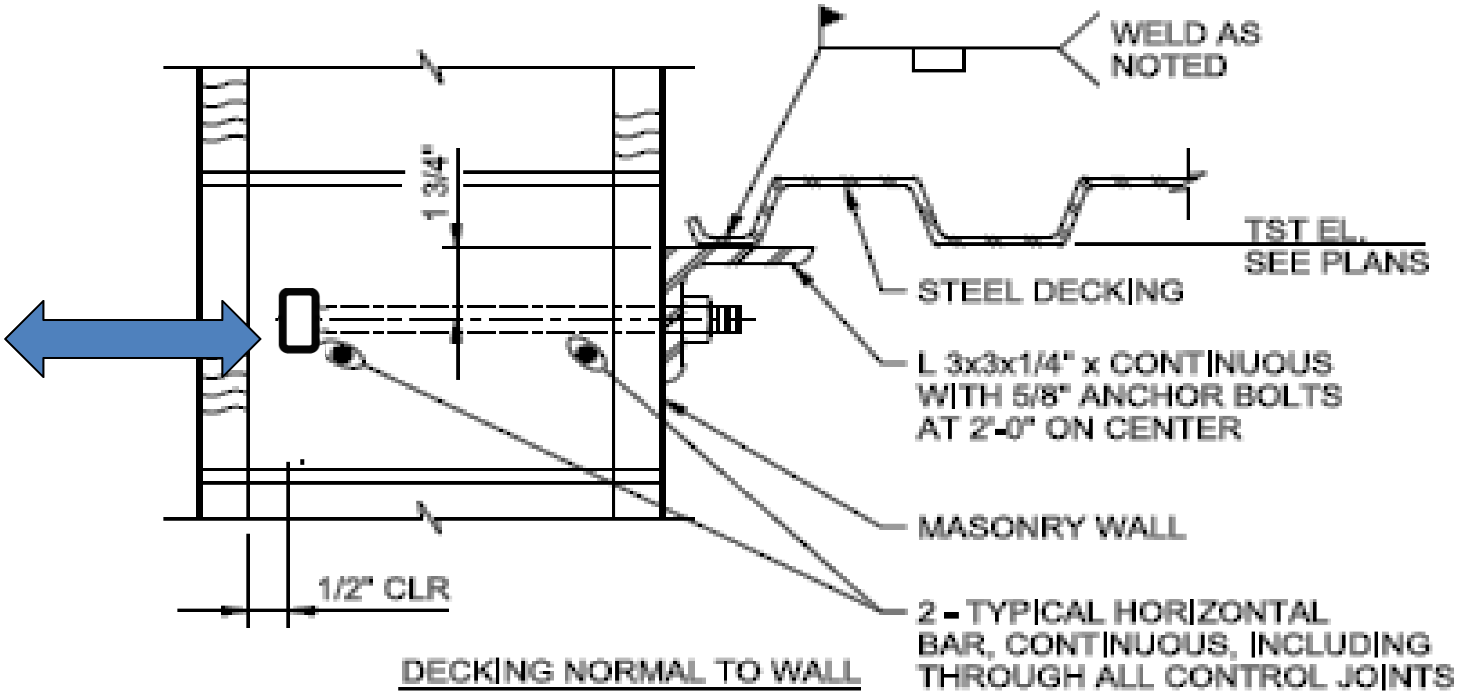
Attachments: OOP Walls to Diaphragms

- Design bolts per MSJC 2.1.4 ASD
- Account for
  - wall thickness,
  - embedment length,
  - combined tension and shear forces,
  - all load cases, and
  - in-plane load transfer

Attachments: OOP Walls to Diaphragms

- Design a top of masonry wall to roof connection to transfer 800 lbs/ft out-of-plane horizontal force per foot of wall from wall to diaphragm
- 8-inch CMU walls, f ’m = 2000 psi
- **Bolts**: ½-inch diameter, A307 headed
  A_b = 0.2 sq inches
  - Placed perpendicular to wall
  - J bolts not recommended
  - Bolt yield stress not defined by code. Use 36 ksi.
  - Embedment length = 4 inches = l_b

Attachments: OOP Walls to



Attachments: OOP Walls to Diaphragms

- T = 800 lbs/ft
- Breakout allowable load, B_{ab}
  - $B_{ab} = 1.25\ A_{pt}\ (f'_m)^{0.5}$
  - Where Apt = $\pi l_b^2 = \pi\ (4)^2 = 50.3 in^2$
  - $B_{ab} = 1.25$ (50.3 sq. in.) (2000 psi)$^{0.5}$ = 2800 lbs/bolt
- Bolt yielding allowable load
  - $B_{as} = 0.6\ A_b\ f_y$
  - 0.6 (0.2 sq. in.) (36,000 psi) = 4300 lbs/bolt
    Breakout controls
- Spacing required = 2800 lbs/800 lbs/foot
  = 3.5 ft   Use 40 inches o.c. = block module

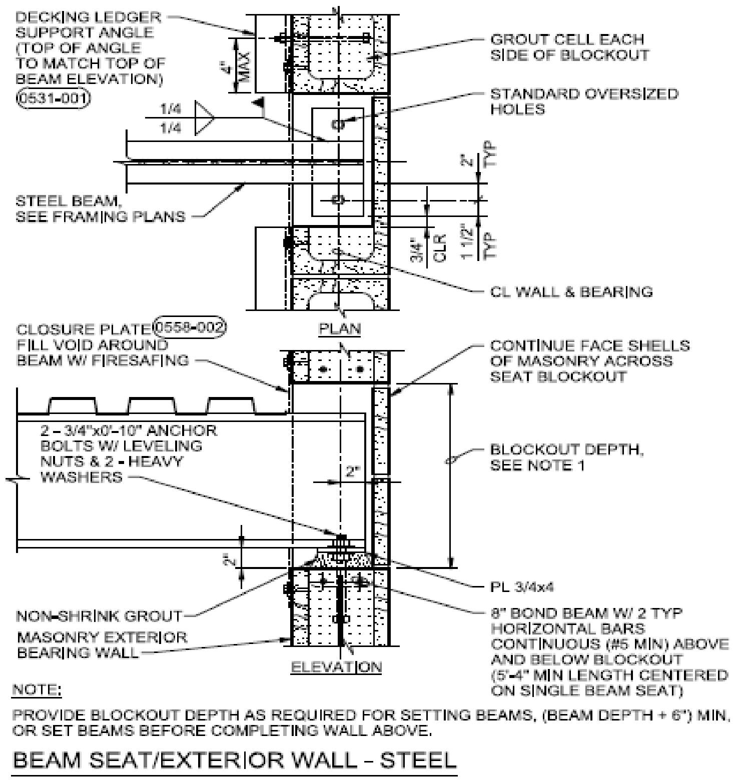
Attachments and Detailing

- Always provide a load path for flow of forces
- Account for construction requirements
- Indicate top and bottom of wall connections that can take vertical, shear, tension, and compression loads
- Top of wall bond beams or bond beams at diaphragm level may also serve as diaphragm chords—provide continuous, lapped reinforcing or provide alternative tension member
- Do not cut bond beam diaphragm chord steel at vertical wall control joints

Attachment of Elements to Masonry

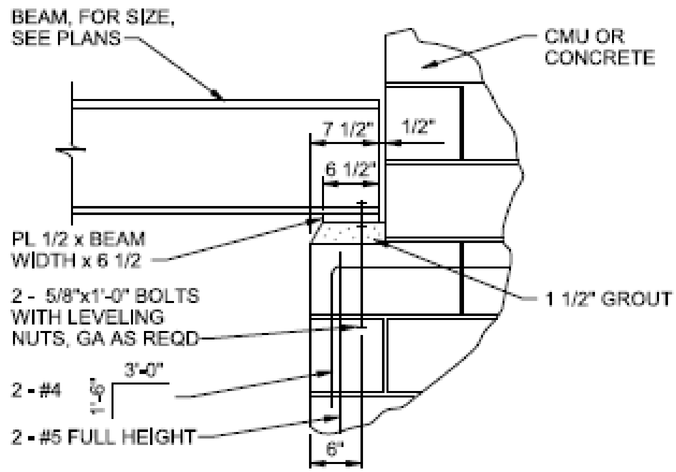
- Use MSJC 2.1.4 for set anchor bolts
- Face mounted embed plates are not common due to face shell lower strength
- Beam seats are preferred with vertical bolts
- Structural member connections must be carefully detailed
- Provide short slotted holes where steel members can undergo thermal movements but short slots will resist any seismic/wind movement

Attachment of Elements to Masonry



Attachment of Elements to Masonry

Lightly Loaded Drag Strut, Moderate SDC



For heavier drag strut tension forces, use channel on each side of wall and provide series of through bolts with additional wall horizontal tension steel in vicinity

NCSEA
National Council of Structural Engineers Associations

Attachment of Elements to Masonry

- Set horizontal anchor bolts are not preferred by Contactors—will request post installed anchors
- No code capacities for post installed anchors
  - Use ICC-ES reports for masonry anchors
  - Do not use mechanical anchors for seismic or vibratory loads unless stated as acceptable in an ICC-ES report or by building official
  - Adhesive anchors are commonly used where high temperatures are not expected
    - Pull test one anchor per cartridge per box

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Hints and Highlights: Handouts

Shortcut Resources

- From the Masonry Vertical Review Session, use the Handouts 01 to 09 for Lateral Design as well:
  - Masonry Formula Sheets
  - Geometry and Weight Tables
  - Wall Geometry Tables (both handouts)
  - Radius of Gyration Tables
  - Wall Design Requirement
  - Load/Moment Interaction Relationship

Hints and Highlights: Handouts

Shortcut Resource Attached: No. 10 Masonry Wall and Anchorage Loads

STRUCTURAL WALL LOADS AND ANCHORAGE

OUT-OF-PLANE WALL DESIGN LOADS ASCE7-10 REF UNO

Exterior Walls: Design for wind loads in addition to seismic loads

Interior Walls: Design for 5 psf minimum live load IBC 1607.14

Seismic Design Category > A

$F_{Pwall} \quad = 0.4 S_{DS} I_e W_p$

$\geq 0.10 W_p$

Design walls for bending between anchors when anchor
than 4 feet apart

OUT-OF-PLANE WALL DESIGN ANCHORAGE LOADS

NON-STRUCTURAL WALL LOADS AND ANCHORAGE

OUT-OF-PLANE WALL DESIGN LOADS ASCE 7-10 REF UNO

Exterior Walls: Design for wind loads in addition to seismic loads

Interior Walls: Design for 5 psf minimum live load IBC 1607.14

Seismic Design Category > A

F_{Pwall}	$= \frac{0.4 a_p S_{DS} I_e W_p}{\left(\frac{R_p}{I_p}\right)} \left(1 + 2\frac{z}{h}\right)$	13.3-1
	$\leq 1.6 S_{DS} I_P W_p$	13.3-2
	$\geq 0.3 S_{DS} I_P W_p$	13.3-3

where

a_p	1.0 walls supported top and bottom	Table 13.5-1
	2.5 cantilevered walls and parapets	
R_p	2.5	

OUT-OF-PLANE WALL DESIGN ANCHORAGE LOADS

Hints and Highlights: Handouts

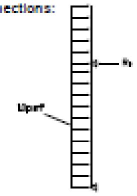
Shortcut Resource Attached: No. 11 Diaphragm Connection Forces

Service Level Connection Forces

Reaction per foot to diaphragm level for out-of-plane connections:

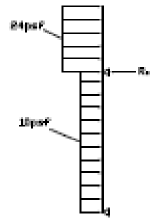
1 Seismic Load Case I - 10 psf to wall and parapet

$$R_D = \left(\frac{18}{2} + 2.5 + \frac{\frac{2.5^2}{2}}{18}\right)\cdot 10psf = 11.67\cdot 10psf = 116.7plf$$



2 Seismic Load Case II - wall and parapet load

$$R_D = \left(\frac{18}{2}\right)\cdot 10\cdot psf + \left(2.5 + \frac{\frac{2.5^2}{2}}{18}\right)\cdot 24psf = 154.2plf$$



Uses maximum parapet load with minimum wall design load on wall

3 $\frac{400\cdot S_{DS}\cdot I}{1.4} = \frac{(400)\cdot(0.28)\cdot(1.0)}{1.4} = 80plf$ 12.11.2

4 $\frac{280}{1.4} = 200plf$

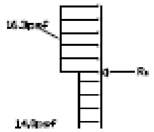
If diaphragm is flexible

6 $\frac{0.80\cdot S_{DS}\cdot I\cdot W_p}{1.4} = \frac{(0.80)\cdot(0.28)\cdot(1.0)\cdot(100psf)}{1.4} = 16plf$ 12.11.2.1

SEISMIC = 200plf

WIND

$$R_D = \left(\frac{18}{2}\right)\cdot(14.0psf) + \left(2.5 + \frac{\frac{2.5^2}{2}}{18}\right)\cdot(16.3psf) = 169.6plf$$



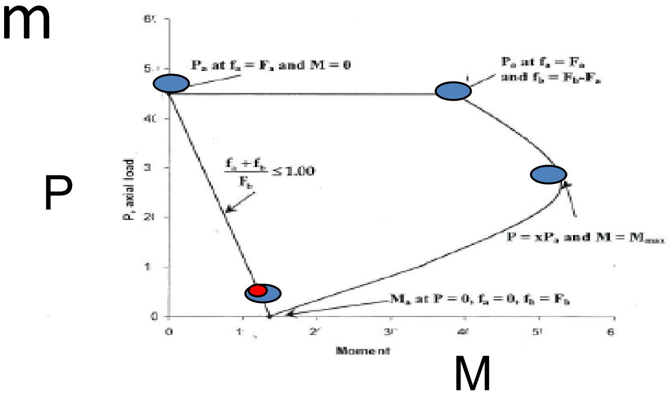
Shear Wall Design Examples

- Examples 8, 9, and 10
  - Look at loads and take appropriate short cuts
  - Determine if:
    - large M, small P—beam like, design similar to beam;
      - Example 8
    - large P, moderate to small M—not cracked; or
      - Example 9
    - moderate P and M, large P and M, and so on.
      - Longer analysis to determine correct steel amount
      - Example 10

Example 8—Shear Wall with Large M, Small P

- Large shear load applied at top of wall
- Only axial load from walls self-weight and vertical seismic acceleration up or down
- Check e = M/P and it is outside the middle kern by a large amount so basically a flexural problem

Red dot is location of load case



Example 8—Shear Wall with Large M, Small P

- Determine vertical acceleration and apply in direction (up or down) critical to load case being checked
- Verify capacity for axial
- Determine *d* by chord/jamb reinforcing pattern
  - Usually length minus 16 inches is adequate guess

Example 8—Shear Wall with Large M, Small P

- Estimate reinforcing as flexural member
- Can take advantage of axial load that is present to reduce required amount of reinforcing, as discussed last session
- Verify that estimated reinforcing does not exceed reinforcing limits

Example 8—Shear Wall with Large M, Small P

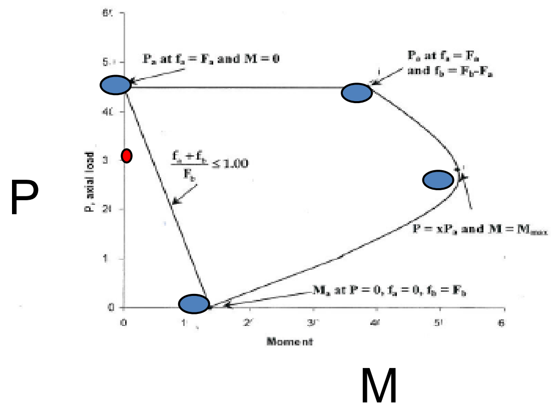
- Compute flexure only strength
- Compute strength at balanced condition
- Verify that applied loads fall with this two point interaction diagram

Example 8—Shear Wall with Large M, Small P

- Check in-plane shear
- Special Wall – Consider shear capacity design per 1.18.3.2.6.1 (Special Reinforced Shear Walls)
- Often missed

Example 9—Shear Wall with Large P, Small M

- Large axial load applied at top of wall plus wall D
- Small shear load applied at top of wall
- Apply vertical accelerations
- Check e = M/P and it is inside the middle kern so wall is uncracked



Red dot is location of load case

Example 9—Shear Wall with Large P, Small M

- Verify capacity for axial
- Detail per Section 1.18 requirements
- For completeness, compute strength at balanced condition

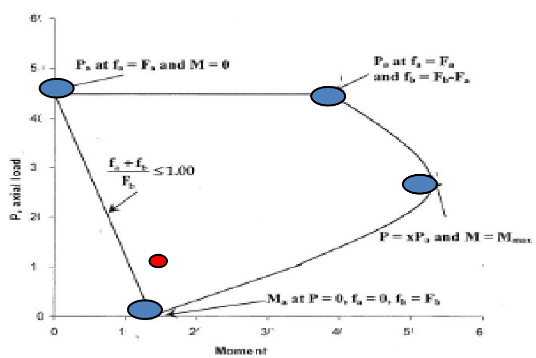
Example 9—Shear Wall with Large P, Small M

- Check shear. If special wall,
  - ASD—Design for 1.5 V
  - SD—Design for $2.5V_u$

Example 10—Shear Wall with Moderate/Large M and P

- Moderate/large shear load applied at top of wall
- Moderate axial load applied at top of wall plus wall D
- Apply vertical accelerations
- Check e = M/P: on wall but outside middle third. Wall is cracked. Tension reinforcing required but reduced by axial load.

P



Red dot is location of load case

M

Example 10—Shear Wall with Moderate/Large M and P

- Still on lower half of interaction diagram
- Procedure same as Example 9

Masonry Lateral Forces

Agenda

- Overview and Review Material
- General Requirements (MSJC Chapter 1)
- Allowable Stress Design (MSJC Chapter 2)
- Strength Design (MSJC Chapter 3)
- Wall Anchorage
- Handouts
- **Close**

Vertical Earthquake Effects

- Overview
  - Always calculate vertical accelerations for applied loads and for wall self-weight
  - Apply downward when checking maximum compressive effects
  - Apply upward when checking overturning or tension effects

Hints and Highlights

- Quickly Determine Detailing Requirements
  - Check chapters 1 and 2, minimum and maximum reinforcing requirements, prior to checking amount required by load for flexural or compression
- Quickly Determine Axial Load, h/t and h/r Requirements (Slenderness)
  - Design of columns and walls (including 3.3.5 slender walls) are often dependent on maximum axial load applied and on geometry. Check first to see if material or geometry needs to be modified.

Hints and Highlights

- Quickly Determine Flexural Reinforcing Requirements
  - Never do trial and error reinforcing checks
  - Use the following methods to quickly determine reasonable reinforcing amount and design once
  - Calculate trial steel based on known code requirements and minimums, then determine if stresses are less than allowable code levels

Questions?

Thanks to the Brick Industry Association, National Concrete Masonry Association, The North West Concrete Masonry Association, The Masonry Society, and Masonry Institute of America.

Thank you and good luck.