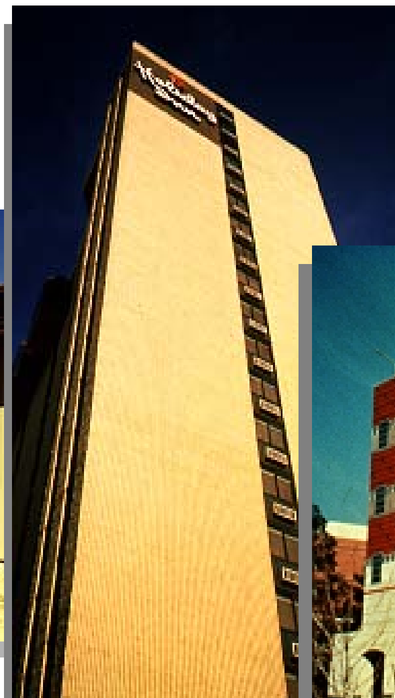
SEISMIC DESIGN OF MASONRY STRUCTURES



NEHRP Recommended Provisions Masonry Design

- Context in the *NEHRP Recommended Provisions*
- Masonry behavior
- Reference standards
- Seismic resisting systems
- Component design
- Quality assurance
- Summary

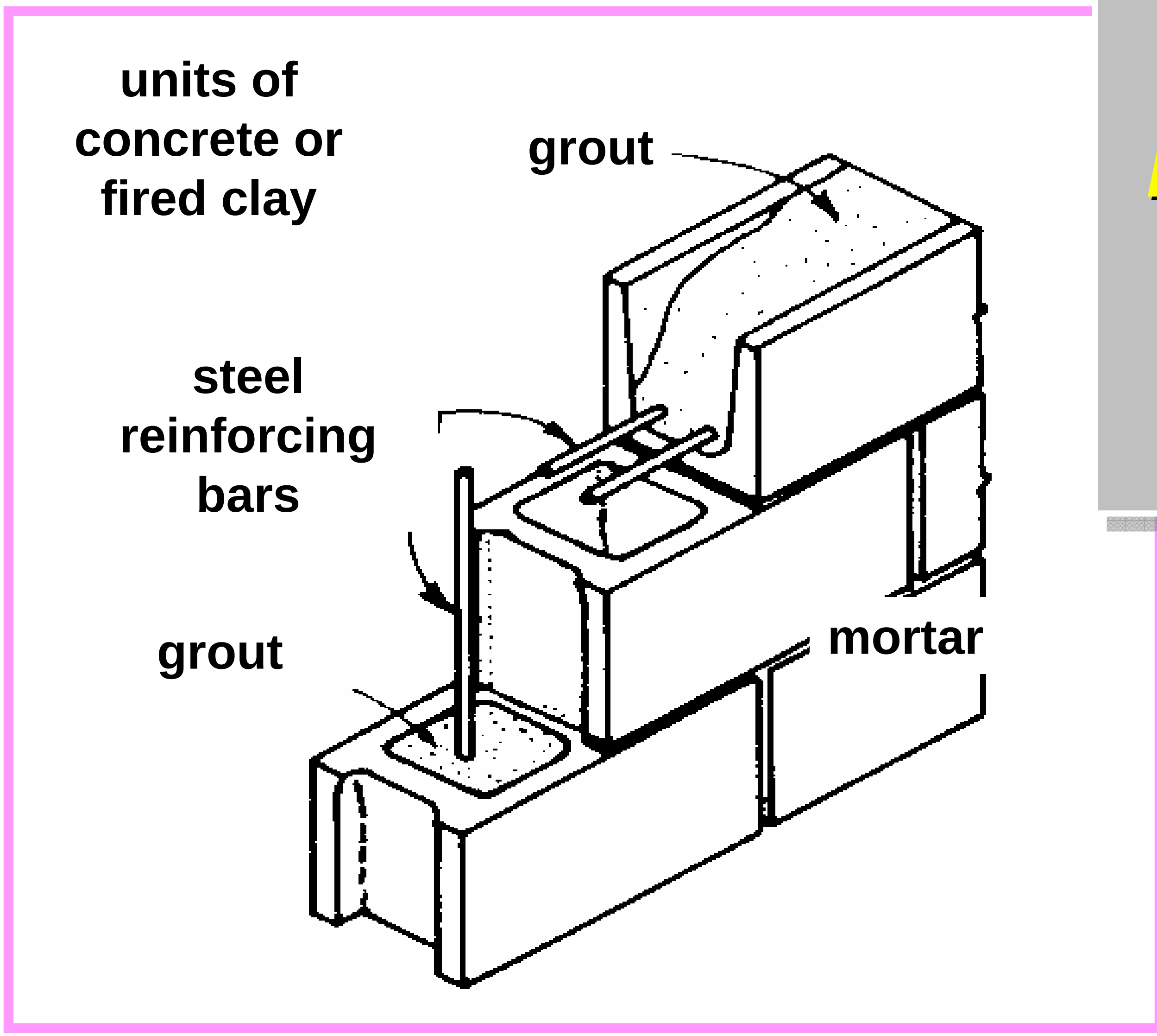
Objectives of Module

- Basics of masonry behavior
- Basics of masonry specification
- The MSJC code and specification and their relationship to the *NEHRP Recommended Provisions* documents
- Earthquake design of masonry structures and components using the 2005 MSJC code and specification
- Example of masonry shear wall design

Context in the *NEHRP Recommended Provisions*

- **Design seismic loads**
  - **Load combinations** — **Chap. 5**
  - **Loads on structures** — **Chap. 5**
  - **Loads on components & attachments** — **Chap. 6**
- **Design resistances** — **Chap. 11**
  - **Strength design (mostly references the 2002 MSJC)**

... typical materials in reinforced masonry



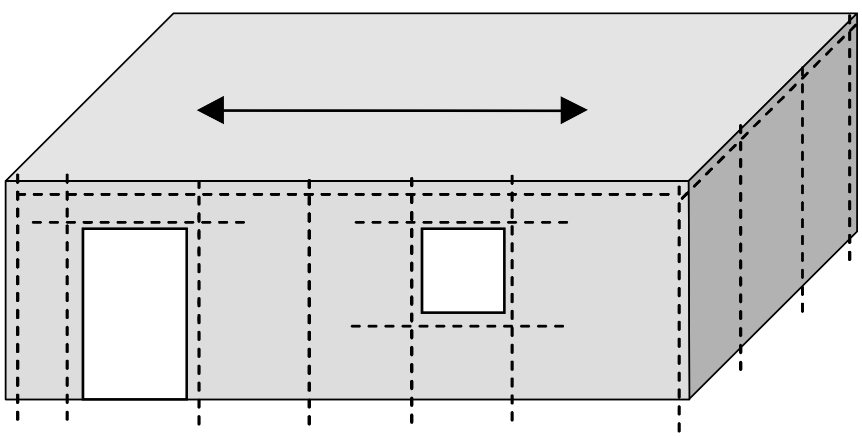
Essential Elements of Simplified Design for Wall-type Structures

- Starting point for design
- Design of vertical strips in walls perpendicular to lateral loads
- Design of walls parallel to lateral loads
- Design of lintels
- Simplified analysis for lateral loads
- Design of diaphragms
- Detailing

Starting Point for Wall-type Masonry Structures

No beams or columns

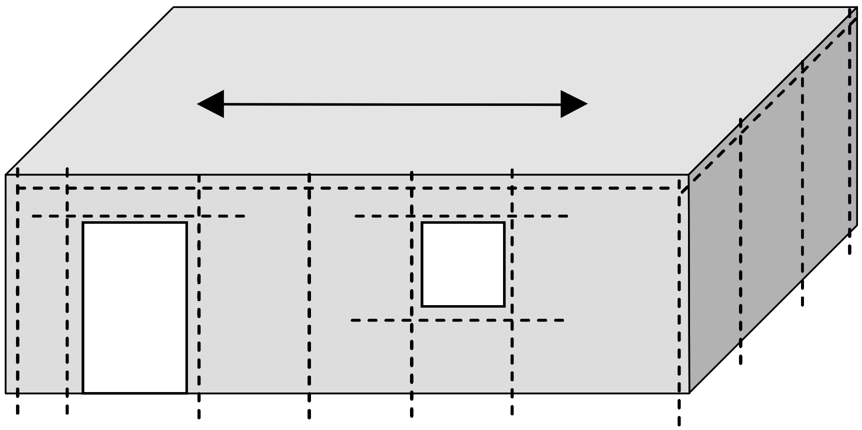
(Example of direction of span)



Vertical reinforcement of #4 bars at corners and jambs

Horizontal reinforcement of two #4 bars in bond beam at top of wall, and over and under openings (two #5 bars with span > 6 ft)

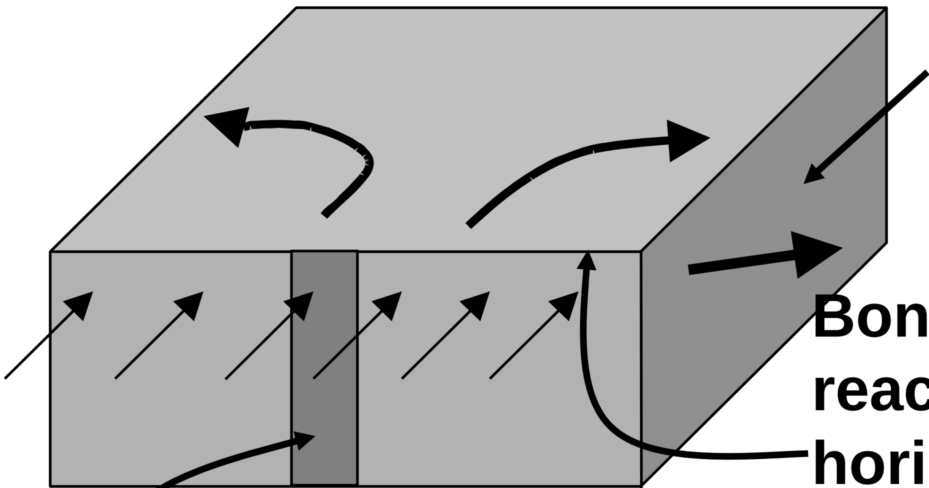
Essential Function of Walls in Resisting Gravity Loads



Bearing walls resist axial loads (concentric and eccentric) as vertical strips

Nonbearing walls resist concentric axial load as vertical strips

Essential Function of Walls in Resisting Lateral Forces

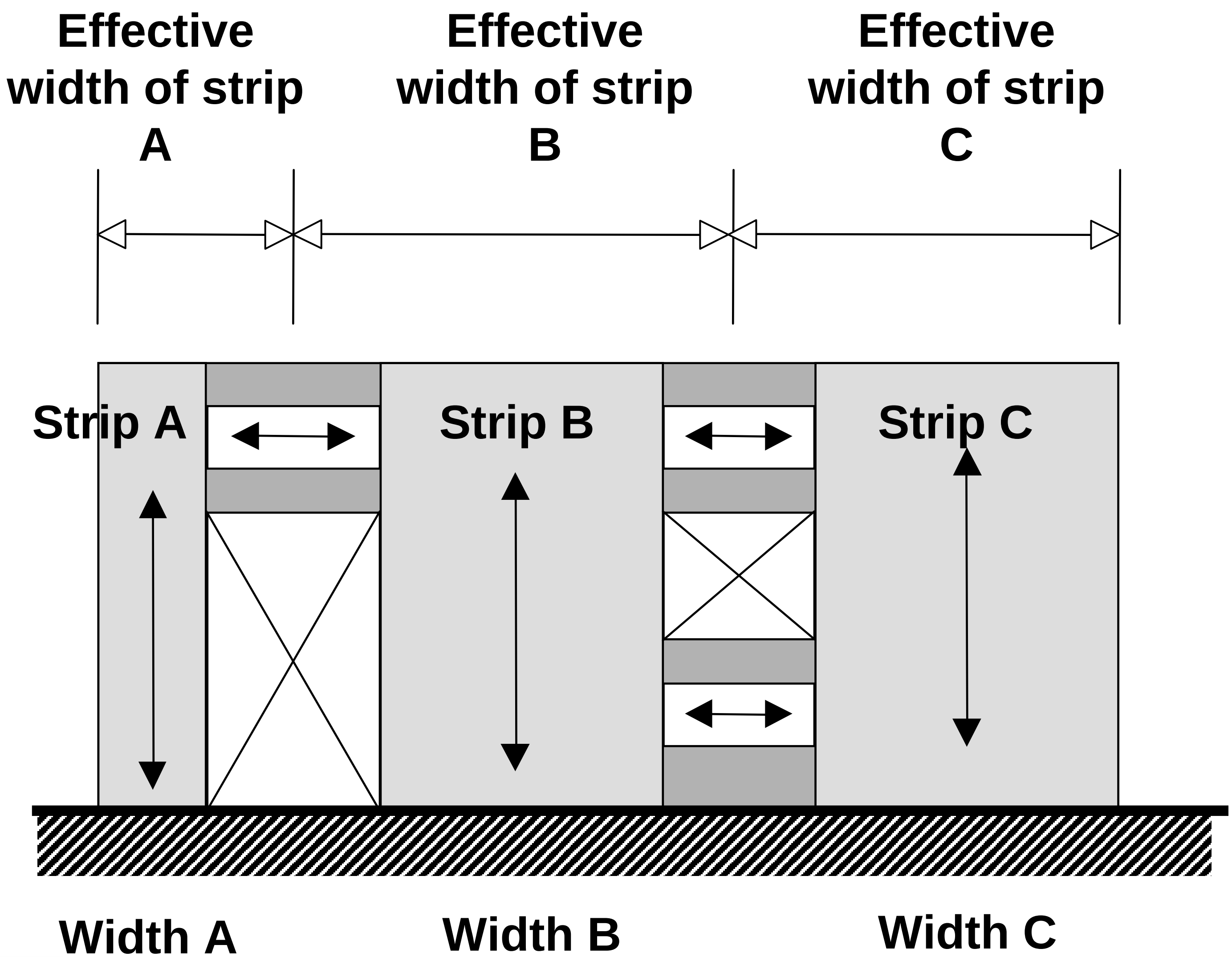


Walls parallel to lateral forces act as shear walls

Bond beams transfer reactions from walls to horizontal diaphragms and act as diaphragm chords

Vertical strips of walls perpendicular to lateral forces resist combinations of axial load and out-of-plane moments, and transfer their reactions to horizontal diaphragms

Effect of Openings



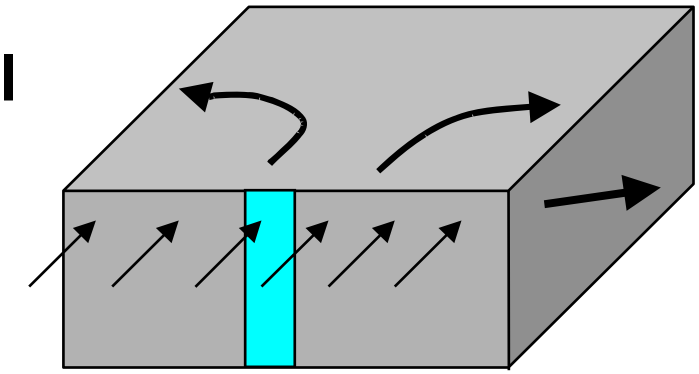
Effect of Openings

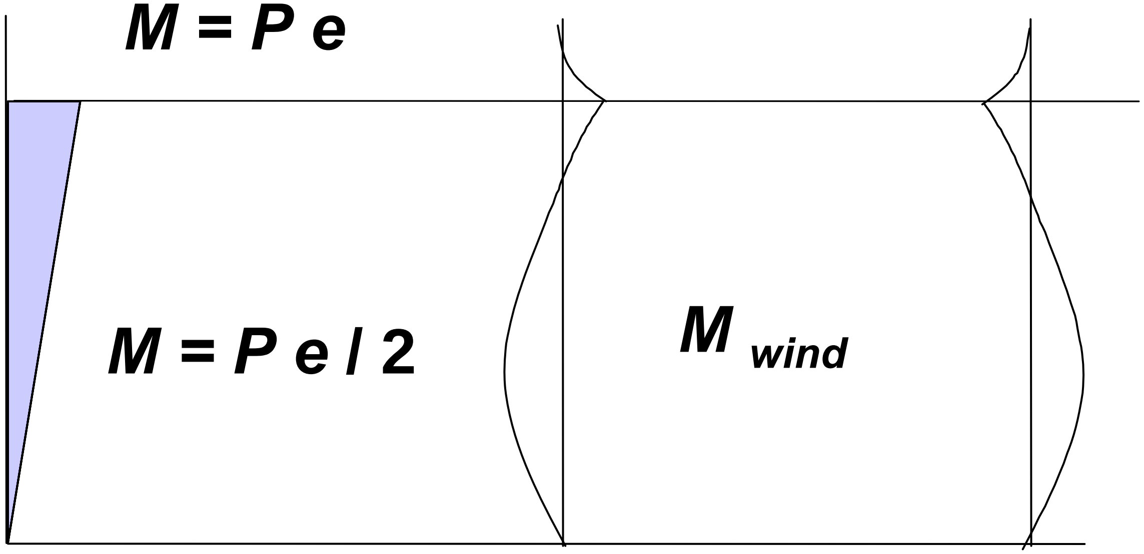
Openings increase original design actions on each strip by a factor equal to the ratio of the effective width of the strip divided by the actual width:

$$Actions\ in\ Strip\ B = Original\ \ Actions\left(\frac{Effective\ Width\ B}{Actual\ Width\ B}\right)$$

Design of Vertical Strips in Perpendicular Walls

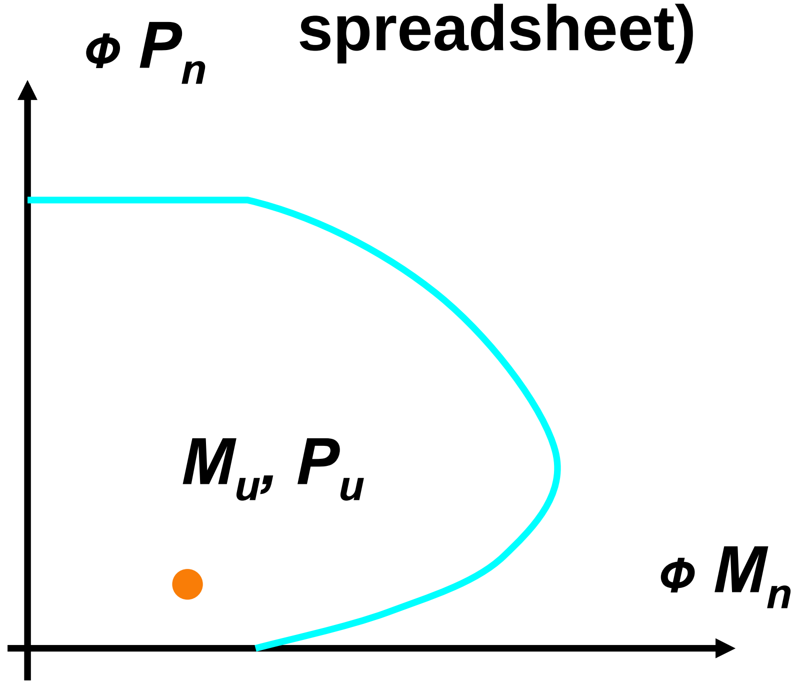
Moments and axial forces due to combinations of gravity and lateral load

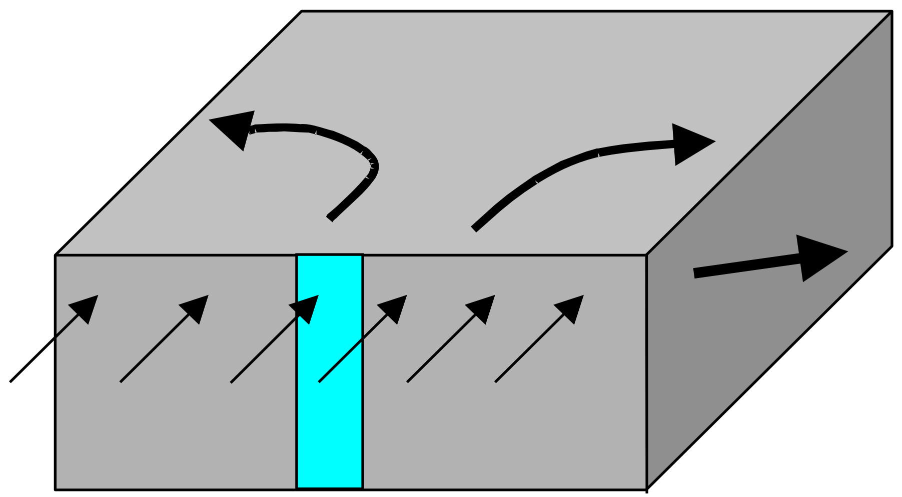




Design of Vertical Strips in Perpendicular Walls

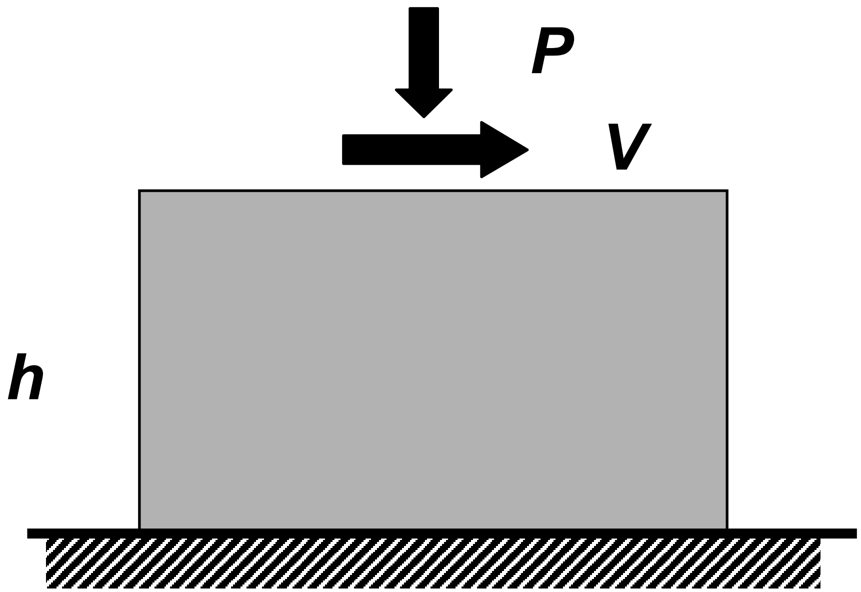
Moment-axial force interaction diagram (with the help of a spreadsheet)

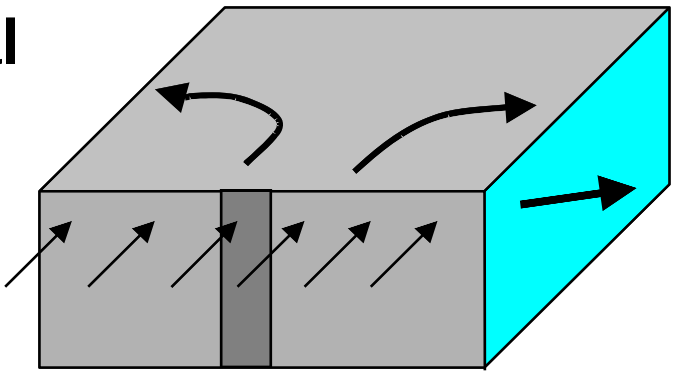




Design of Parallel Walls

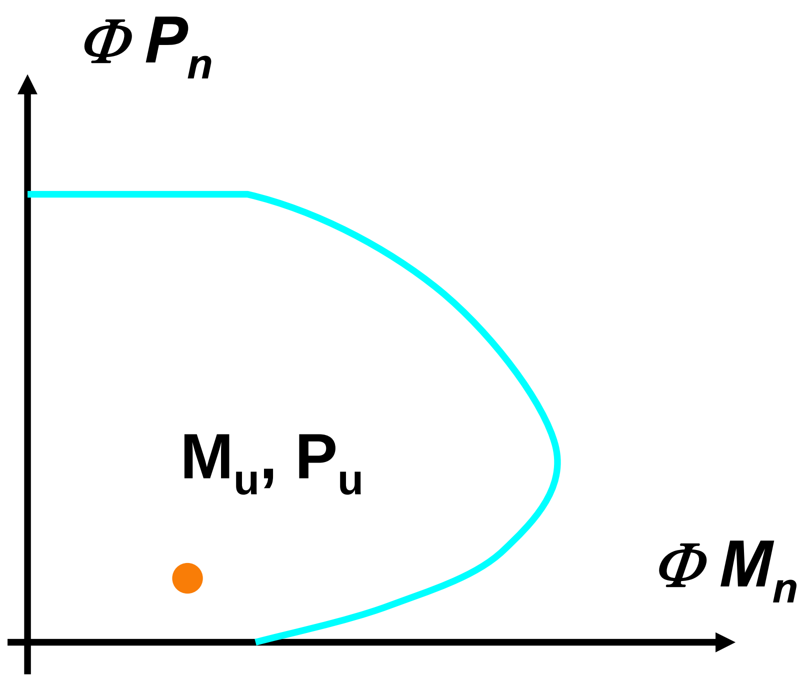
Moments, axial forces, and shears due to combinations of gravity and lateral loads



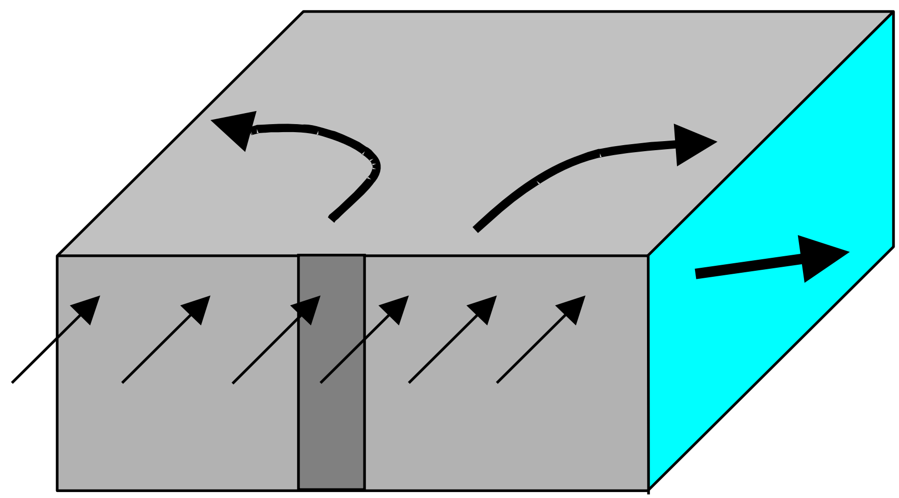


Design of Parallel Walls

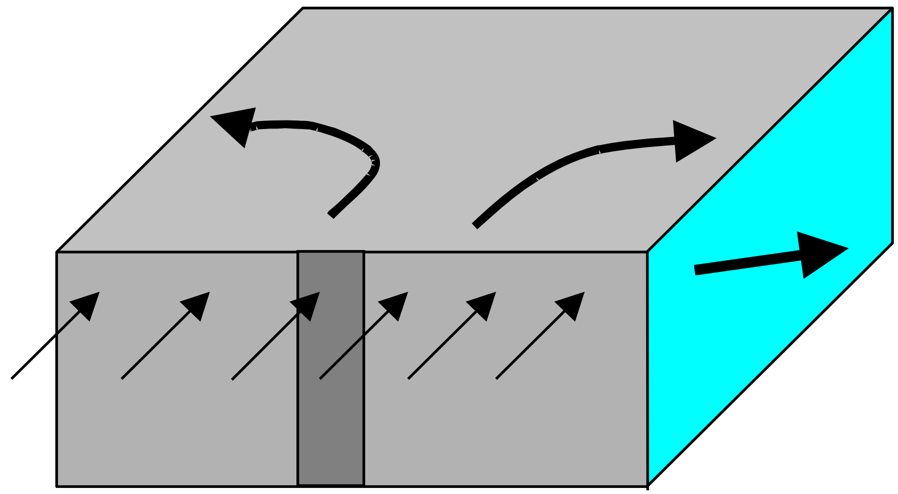
Moment-axial force interaction diagram (with the help of a spreadsheet)



Sufficient lateral capacity comes from wall density.



Design of Parallel Walls



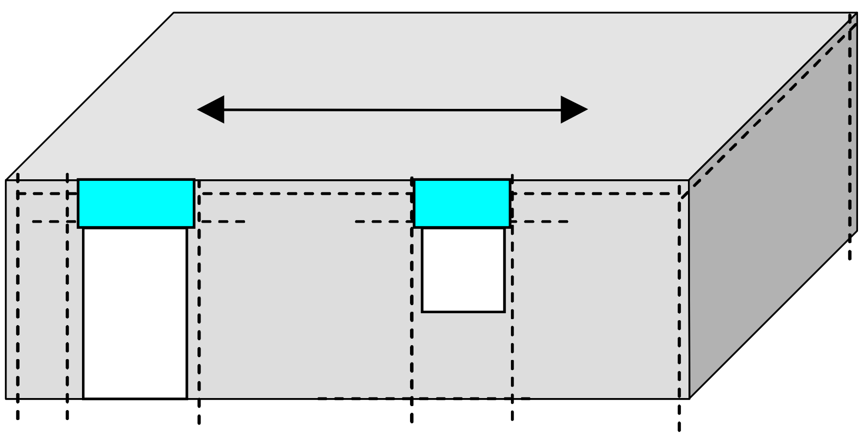
Shearing resistance:

$$V_n = V_m + V_s$$

$$V_m = \left[4.0 - 1.75 \left(\frac{M_u}{V_u \, d_v} \right) \right] A_n \sqrt{f'_m} + 0.25 \, P_u$$

Design of Lintels

(Example of direction of span)

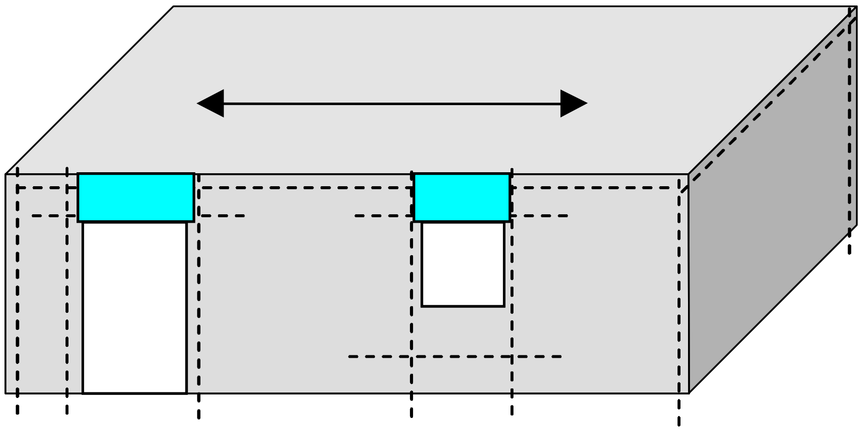


Moments and shears due to gravity loads:

$$M_u = \frac{w \ell^2}{8}$$

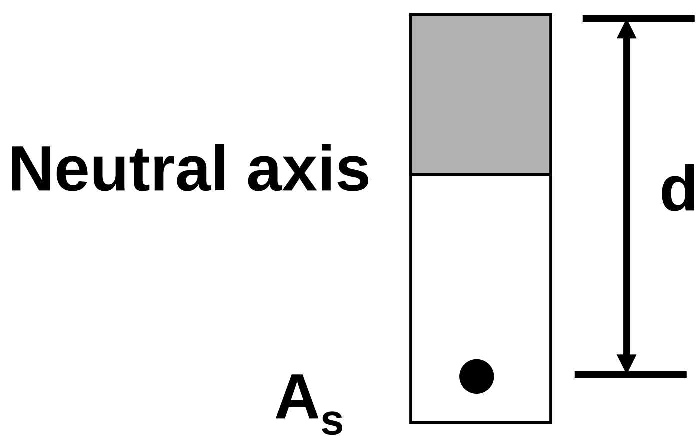
$$V_u = \frac{w \ell}{2}$$

Design of Lintels



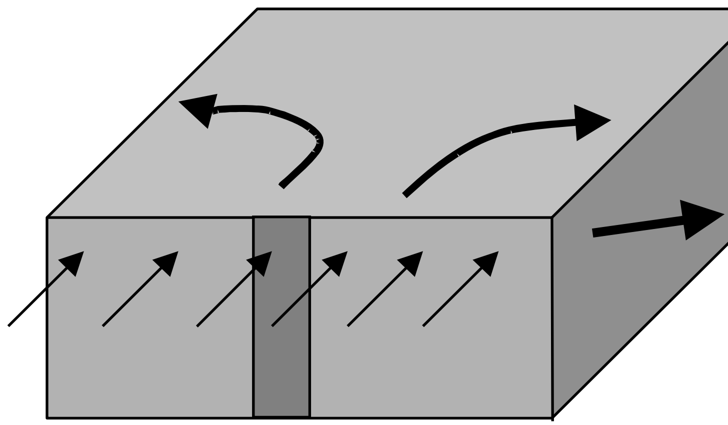
Shear design: Provide enough depth so that shear reinforcement is not needed.

Flexural design:



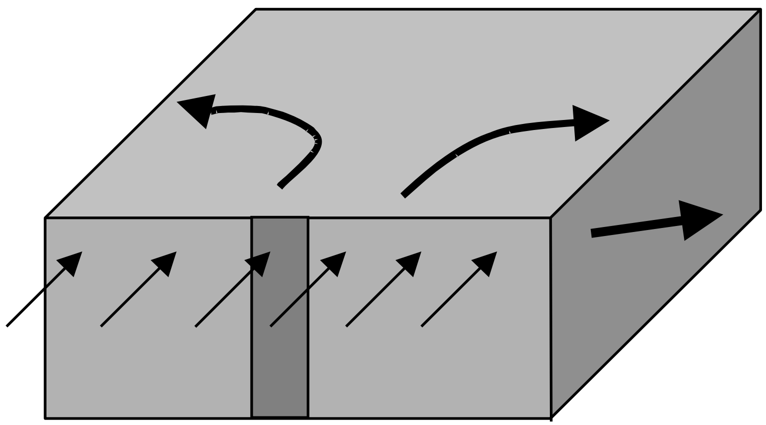
$$A_s \approx \frac{M_u}{\phi \times f_y \times 0.9\,d}$$

Distribution of Shears to Shear Walls



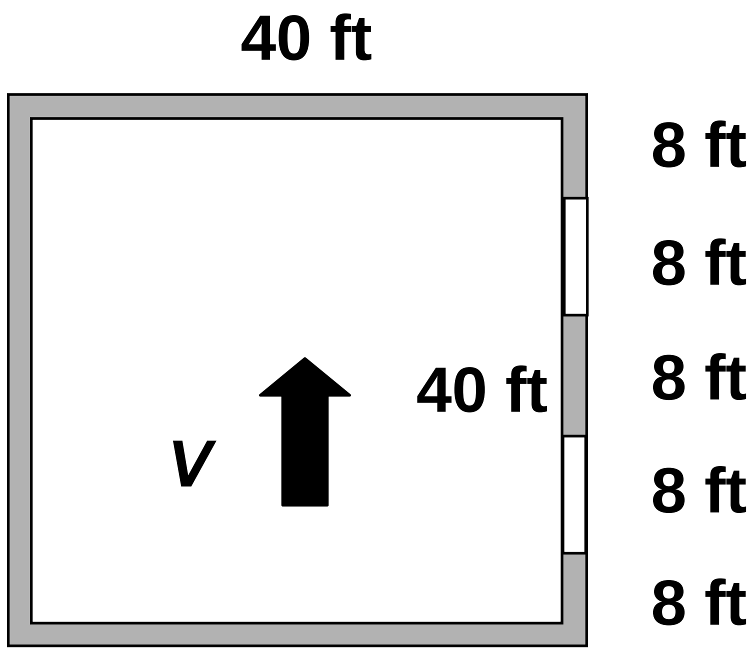
- Classical approach
  - Determine whether the diaphragm is “rigid” or “flexible”
  - Carry out an appropriate analysis for shears

Classical Analysis of Structures with Rigid Diaphragms



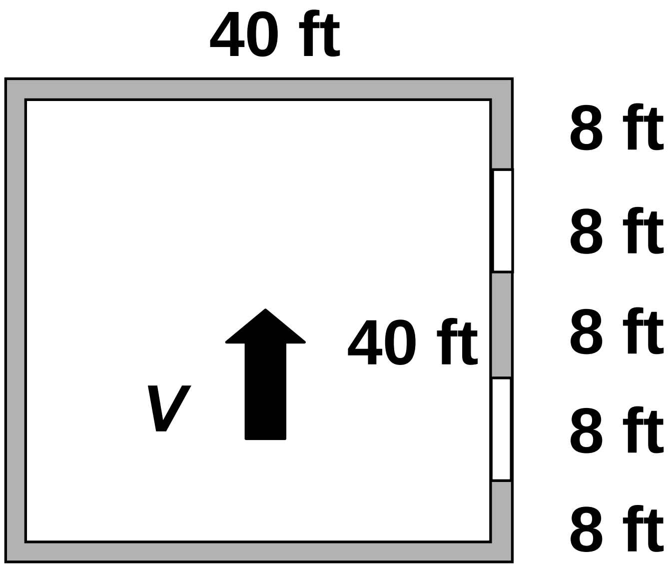
- Locate center of rigidity
- Treat the lateral load as the superposition of a load acting through the center of rigidity and a torsional moment about that center of rigidity

Simplified Analysis of Structures with Rigid Diaphragms



- **Consider only the shearing stiffness, which is proportional to plan length**
- **Neglect plan torsion**

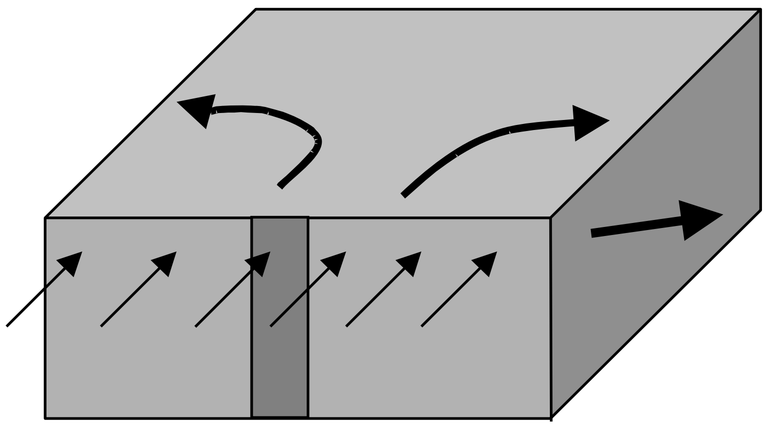
Simplified Analysis of Structures with Rigid Diaphragms



$$V_{left} = \frac{40\ ft}{(40+8+8+8)\ ft} \times V_{total} = \frac{5}{8} V_{total}$$

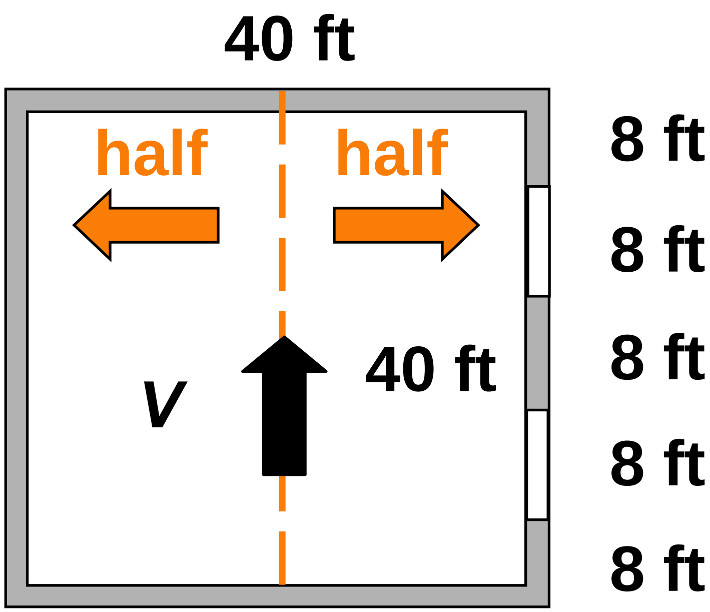
$$V_{right} = \frac{(8+8+8)\ ft}{(40+8+8+8)\ ft} \times V_{total} = \frac{3}{8} V_{total}$$

Classical Analysis of Structures with Flexible Diaphragms



- **Distribute shears according to tributary areas of the diaphragm independent of the relative stiffnesses of the shear walls**

Classical Analysis of Structures with Flexible Diaphragms

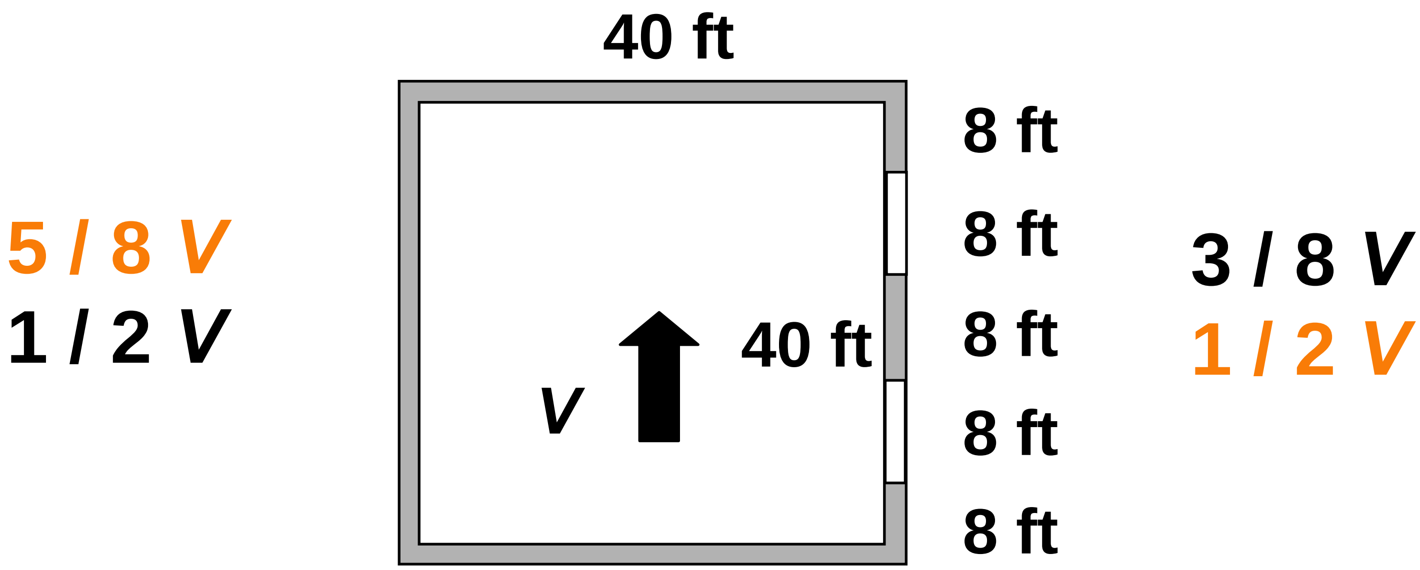


$$V_{left} = \frac{1}{2} V_{total}$$

$$V_{right} = \frac{1}{2} V_{total}$$

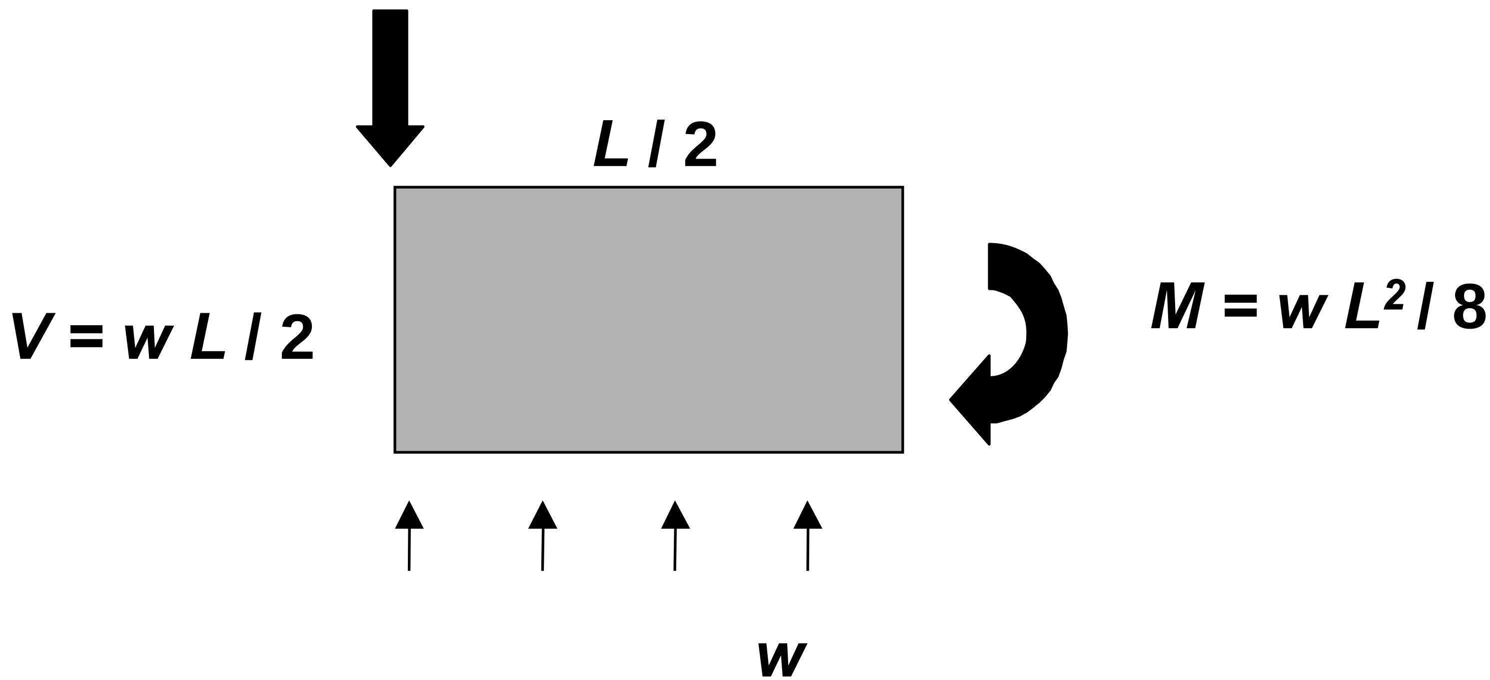
Simplified Diaphragm Analysis

Design for the worse of the two cases:



Diaphragm Design

- Diaphragm shears are resisted by total depth or by cover (for plank diaphragms). Diaphragm moments are resisted by diaphragm chords in bond beams.



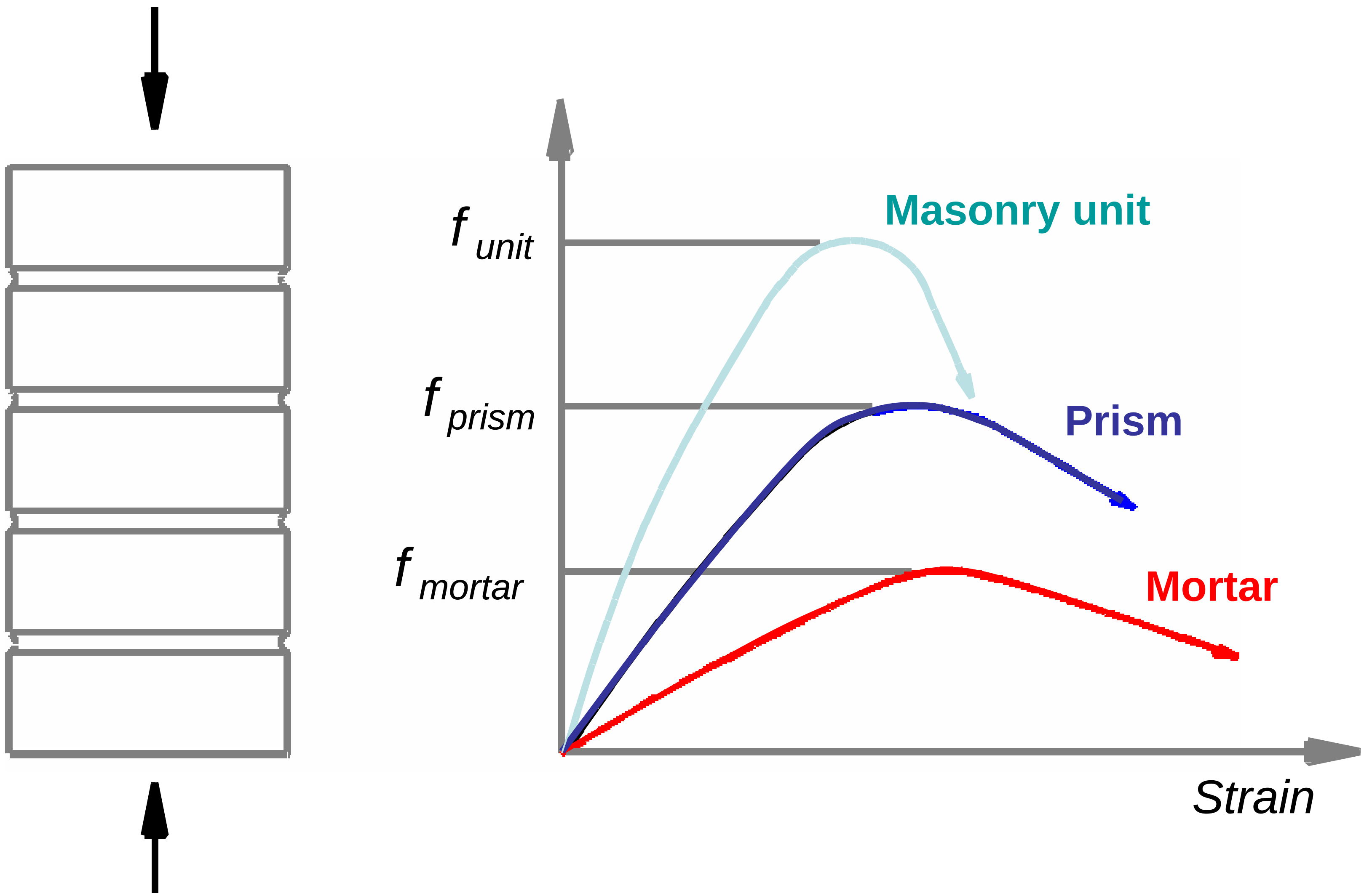
Details

- Wall-diaphragm connections
- Design of lintels for out-of-plane loads between wall-diaphragm connections
- Connections between bond beam and walls
- Connections between walls and foundation

Masonry Behavior

- On a local level, masonry behavior is nonisotropic, nonhomogeneous, and nonlinear.
- On a global level, however, masonry behavior can be idealized as isotropic and homogeneous. Nonlinearity in compression is handled using an equivalent rectangular stress block as in reinforced concrete design.
- A starting point for masonry behavior is to visualize it as very similar to reinforced concrete. Masonry capacity is expressed in terms of a specified compressive strength, f_m', which is analogous to f_c'.

Masonry Behavior Stress-Strain Curve for Prism Under Compression

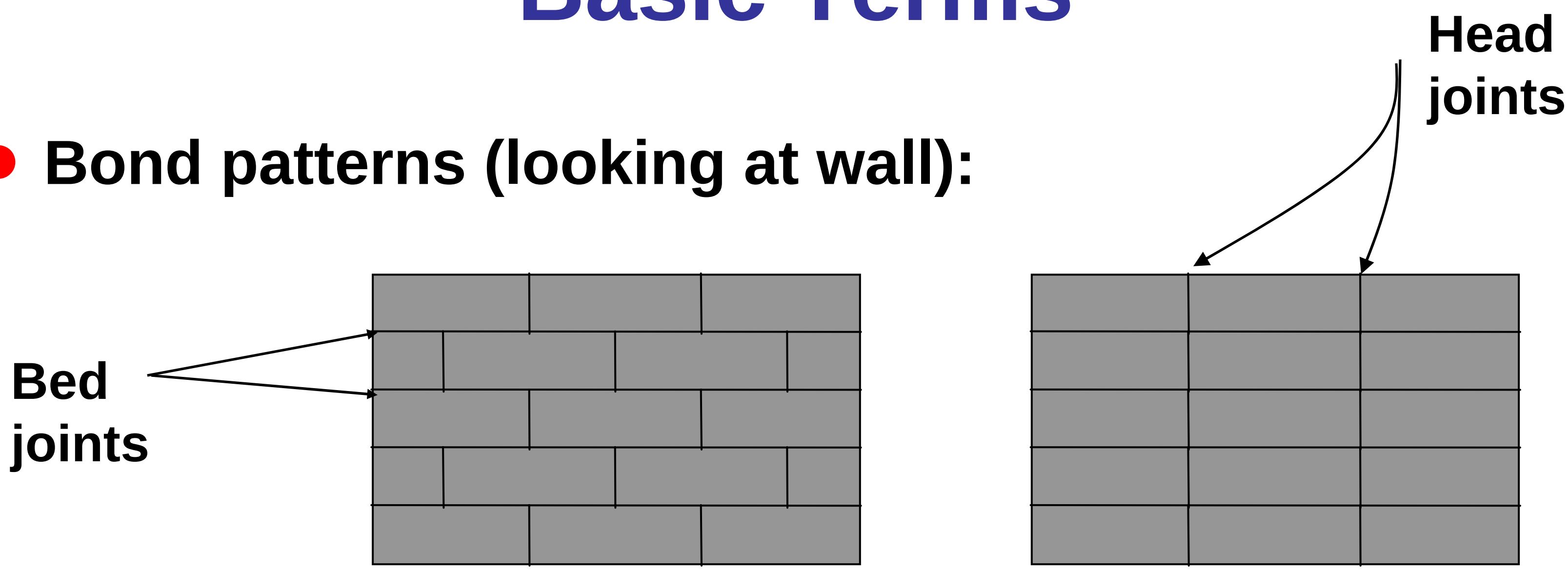


Review Masonry Basics

- Basic terms
- Units
- Mortar
- Grout
- Accessory materials
  - Reinforcement (may or may not be present)
  - Connectors
  - Flashing
  - Sealants
- Typical details

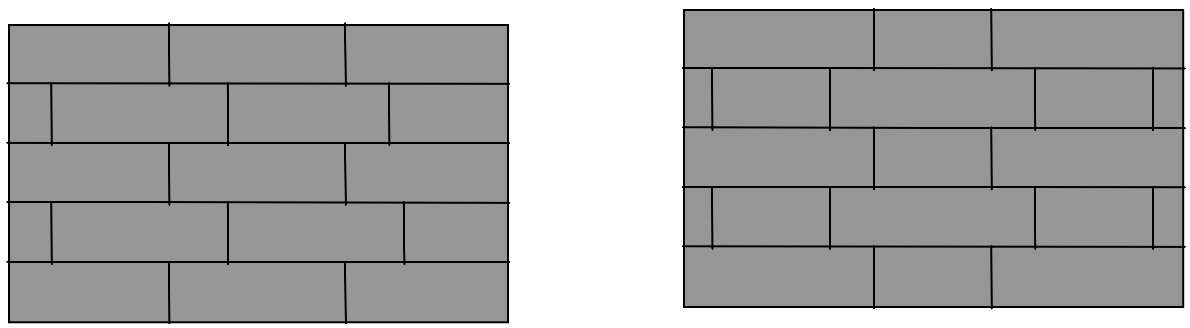
Basic Terms

- Bond patterns (looking at wall):



Running bond

Stack bond

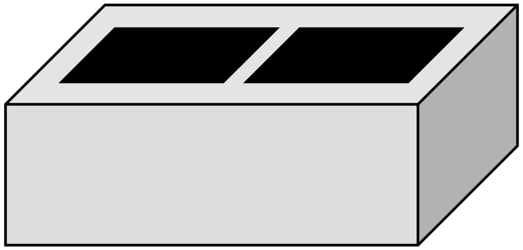


1/3 Running bond

Flemish bond

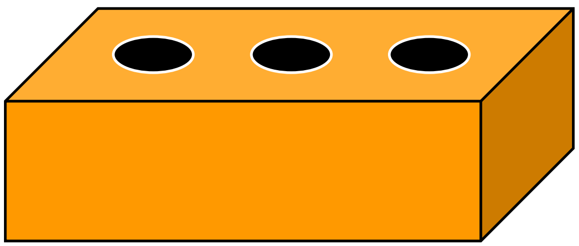
Masonry Units

- Concrete masonry units (CMU):
  - Specified by ASTM C 90
  - Minimum specified compressive strength (net area) of 1900 psi (average)
  - Net area is about 55% of gross area
  - Nominal versus specified versus actual dimensions
  - Type I and Type II designations no longer exist



Masonry Units

- **Clay masonry units:**
  - **Specified by ASTM C 62 or C 216**
  - **Usually solid, with small core holes for manufacturing purposes**
  - **If cores occupy ≤ 25% of net area, units can be considered 100% solid**



Masonry Mortar

- Mortar for unit masonry is specified by ASTM C 270
- Three cementitious systems
  - Portland cement – lime mortar
  - Masonry cement mortar
  - Mortar cement mortar

Masonry Mortar

- **Within each cementitious system, mortar is specified by type (M a S o N w O r K):**
  - **Going from Type K to Type M, mortar has an increasing volume proportion of portland cement. It sets up faster and has higher compressive and tensile bond strengths.**
  - **As the volume proportion of portland cement increases, mortar is less able to deform when hardened.**
  - **Types N and S are specified for modern masonry construction.**

Masonry Mortar

- Under ASTM C270, mortar can be specified by proportion or by property.
- If mortar is specified by proportion, compliance is verified only by verifying proportions. For example:
  - Type S PCL mortar has volume proportions of 1 part cement to about 0.5 parts hydrated mason's lime to about 4.5 parts mason's sand.
  - Type N masonry cement mortar (single-bag) has one part Type N masonry cement and 3 parts mason's sand.

Masonry Mortar

- **Under ASTM C270, mortar can be specified by proportion or by property:**
  - **Proportion specification is simpler -- verify in the field that volume proportions meet proportion limits.**
  - **Property specification is more complex: (1) establish the proportions necessary to produce a mortar that, tested at laboratory flow, will meet the required compressive strength, air content, and retentivity (ability to retain water) requirements and (2) verify in the field that volume proportions meet proportion limits.**

Masonry Mortar

- The proportion specification is the default. Unless the property specification is used, no mortar testing is necessary.
- The proportion of water is not specified. It is determined by the mason to achieve good productivity and workmanship.
- Masonry units absorb water from the mortar decreasing its water-cement ratio and increasing its compressive strength. Mortar need not have high compressive strength.

Grout

- Grout for unit masonry is specified by ASTM C 476
- Two kinds of grout:
  - Fine grout (cement, sand, water)
  - Coarse grout (cement, sand, pea gravel, water)
- ASTM C 476 permits a small amount of hydrated lime, but does not require any. Lime is usually not used in plant – batched grout.

Grout

- Under ASTM C476, grout can be specified by proportion or by compressive strength:
  - Proportion specification is simpler. It requires only that volume proportions of ingredients be verified.
  - Specification by compressive strength is more complex. It requires compression testing of grout in a permeable mold (ASTM C 1019).

Grout

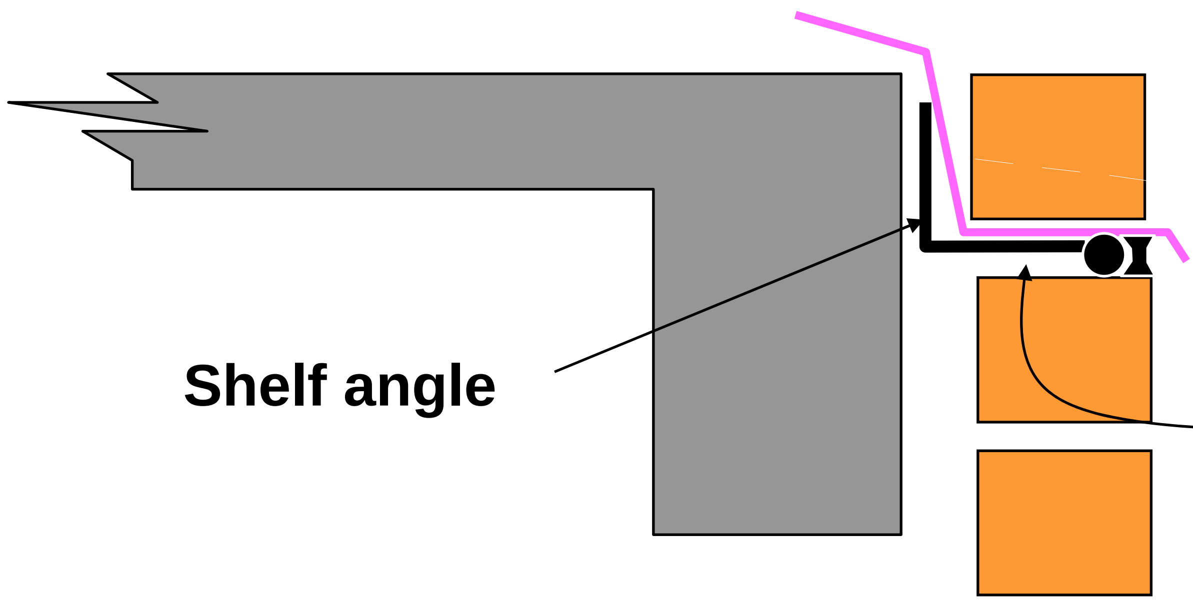
- If grout is specified by proportion, compliance is verified only by verifying proportions. For example:
  - Fine grout has volume proportions of 1 part cement to about 3 parts mason's sand.
  - Coarse grout has volume proportions of 1 part cement to about 3 parts mason's sand and about 2 parts pea gravel.
- Unless the compressive-strength specification is used, no grout testing is necessary.

Grout

- **The proportion of water is not specified. The slump should be 8 to 11 in.**
- **Masonry units absorb water from the grout decreasing its water-cement ratio and increasing its compressive strength. High-slump grout will still be strong enough.**

Accessory Materials

Horizontally oriented expansion joint under shelf angle:



MASONRY DESIGN CODES IN THE US

ANSI process (balance of interests, letter ballots, resolution of Negatives, public comment)

Technical Organizations

Industry Groups

MSJC develops provisions

MSJC Code

NEHRP

model codes reference those provisions

ICC (International Building Code)

Other Model Codes (NFPA)

local authorities adopt those model codes

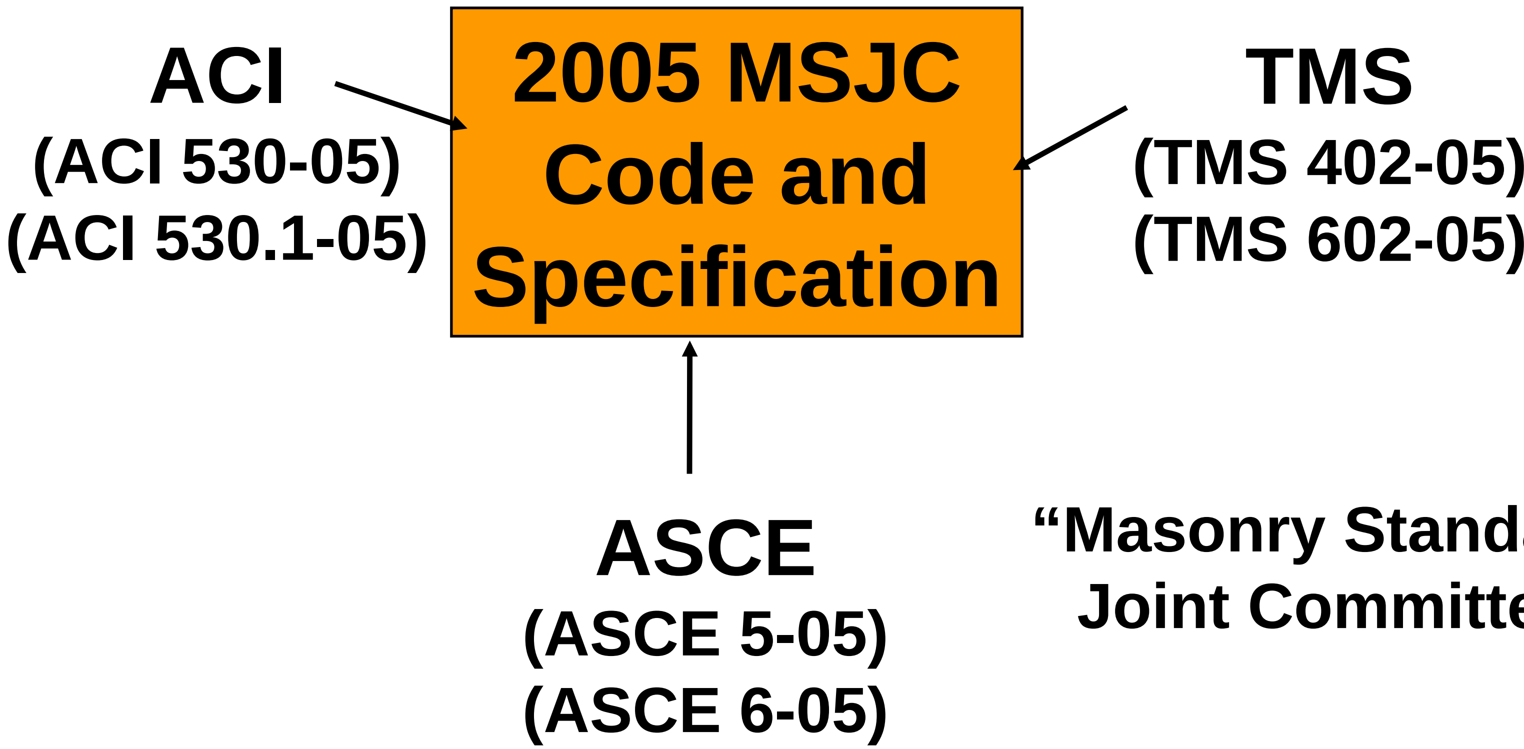
Building Code (legal standing) (contract between society and the designer)

ASTM (Material Specifications)

MSJC Specification (QA, materials, execution)

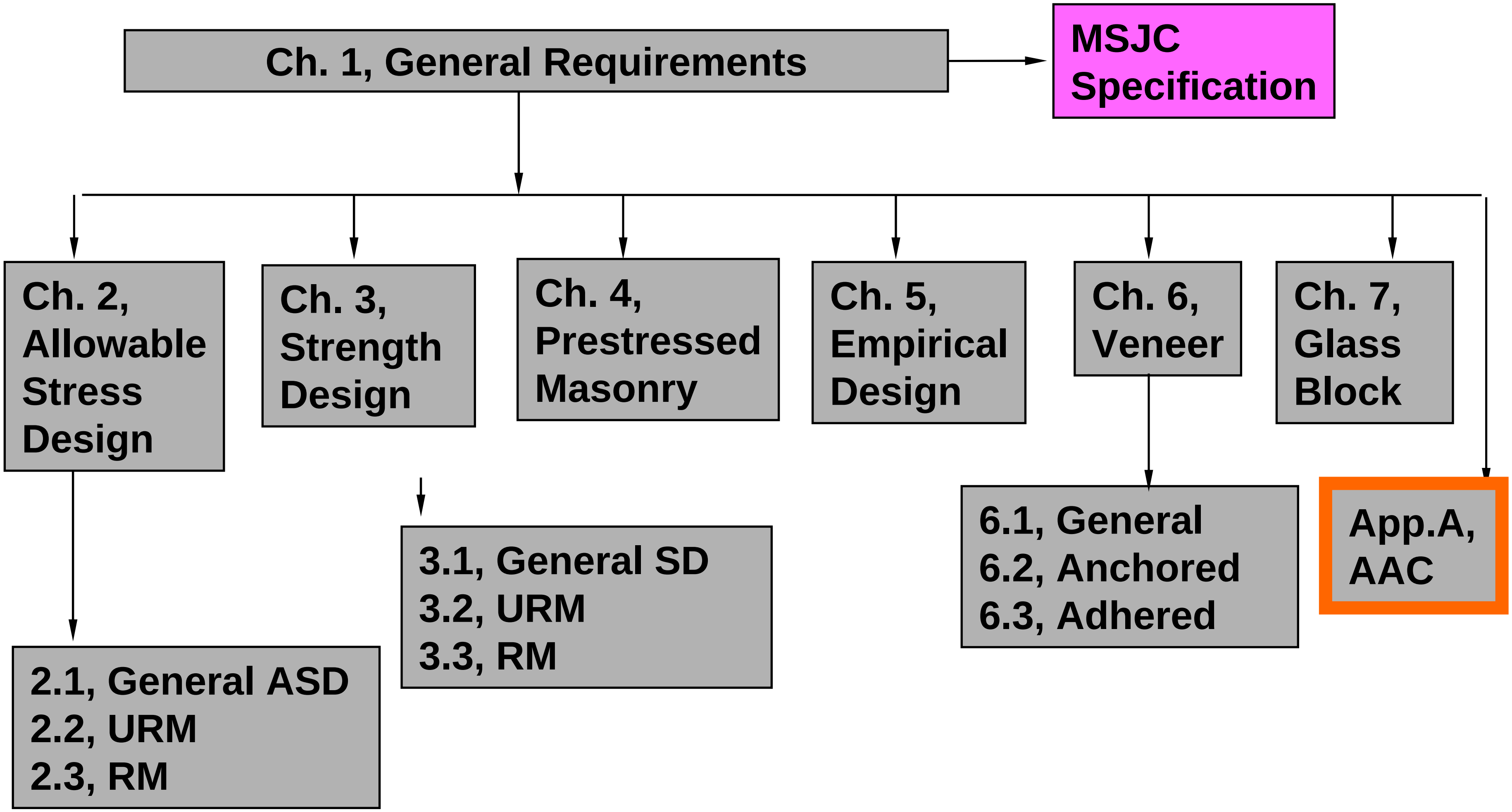
(part of a civil contract between owner and contractor)

What is the MSJC Code and Specification... ?



"Masonry Standards Joint Committee"

2005 MSJC Code



Relation Between Code and Specification

- **Code:**
  - **Design provisions are given in Chapters 1-7 and Appendix A**
  - **Sections 1.2.4 and 1.14 require a QA program in accordance with the specification**
  - **Section 1.4 invokes the specification by reference.**
- **Specification:**
  - **Verify compliance with specified f_m'**
  - **Comply with required level of quality assurance**
  - **Comply with specified products and execution**

Role of f_m'

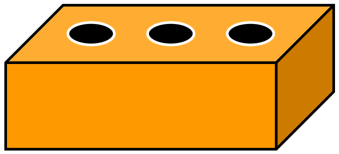
- **Concrete:**
  - **Designer states assumed value of f_c'**
  - **Compliance is verified by compression tests on cylinders cast in the field and cured under ideal conditions**
- **Masonry**
  - **Designer states assumed value of f_m'**
  - **Compliance is verified by "unit strength method" or by "prism test method"**

Verify Compliance with Specified f_m'

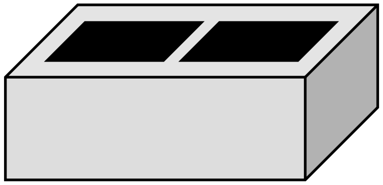
- Unit strength method (Spec 1.4 B 2):
  - Compressive strengths from unit manufacturer
  - ASTM C 270 mortar
  - Grout meeting ASTM C 476 or 2,000 psi
- Prism test method (Spec 1.4 B 3):
  - Pro -- can permit optimization of materials
  - Con -- require testing, qualified testing lab, and procedures in case of non-complying results

Example of Unit Strength Method (Specification Tables 1, 2)

- **Clay masonry units (Table 1):**
  - **Unit compressive strength ≥ 4150 psi**
  - **Type N mortar**
  - **Prism strength can be taken as 1500 psi**



- **Concrete masonry units (Table 2):**
  - **Unit compressive strength ≥ 1900 psi**
  - **Type S mortar**
  - **Prism strength can be taken as 1500 psi**



Application of Unit Strength Method (Spec Tables 1, 2)

- **Design determines required material specification:**
  - **Designer states assumed value of f_m'**
  - **Specifier specifies units, mortar and grout that will satisfy "unit strength method"**
- **Compliance with f_m' can be verified with no tests on mortar, grout, or prisms**

Comply with Specified Products and Execution

- Products -- Specification Article 2:
  - Units, mortar, grout, accessory materials
- Execution -- Specification Article 3
  - Inspection
  - Preparation
  - Installation of masonry, reinforcement, grout, prestressing tendons

Organization of MSJC Code Chapter 1

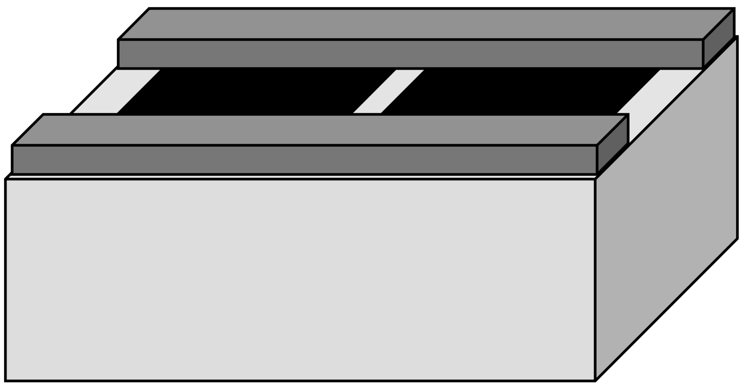
- 1.1 – 1.6 Scope, contract documents and calculations, special systems, reference standards, notation, definitions
- 1.7 Loading
- 1.8 Material properties
- 1.9 Section properties
- 1.10 Deflections
- 1.11 Stack bond masonry
- 1.12 Corbels
- 1.13 Details of reinforcement
- 1.14 Seismic design requirements
- 1.15 Quality assurance program
- 1.16 Construction

Code 1.8, Material Properties

- Chord modulus of elasticity, shear modulus, thermal expansion coefficients, and creep coefficients for clay, concrete, and AAC masonry
- Moisture expansion coefficient for clay masonry
- Shrinkage coefficients for concrete masonry

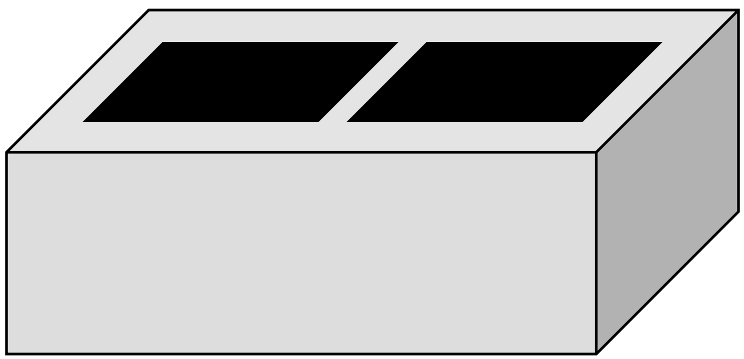
Code 1.9, Section Properties

- **Use minimum (critical) area for computing member stresses or capacities**
  - **Capacity is governed by the weakest section; for example, the bed joints of face-shell bedded hollow masonry**



Code 1.9, Section Properties

- **Radius of gyration and member slenderness are better represented by the average section; for example, the net area of units of face-shell bedded masonry**



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1.13 Details of reinforcement

1.14 Seismic design requirements

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1.16 Construction

Code 1.13, Details of Reinforcement

- **Reinforcing bars must be embedded in grout; joint reinforcement can be embedded in mortar**
- **Placement of reinforcement**
- **Protection for reinforcement**
- **Standard hooks**

Organization of MSJC Code Chapter 1

1.1 – 1.6 Scope, Contract documents and calculations, special systems, reference standards, notation, definitions

1.7 Loading

1.8 Material properties

1.9 Section properties

1.10 Deflections

1.11 Stack bond masonry

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1.13 Details of reinforcement

1.14 Seismic design requirements

1.15 Quality assurance program

1.16 Construction

Code 1.14, Seismic Design

- Applies to all masonry except
  - Glass unit masonry
  - Veneers
- Seeks to improve performance of masonry structures in earthquakes
  - Improves ductility of masonry members
  - Improves connectivity of masonry members
- Different requirements for AAC masonry

Code 1.14, Seismic Design

- Define a structure's Seismic Design Category (SDC) according to ASCE 7-02
  - SDC depends on seismic risk (geographic location), importance, underlying soil
- SDC determines
  - Required types of shear walls (prescriptive reinforcement)
  - Prescriptive reinforcement for other masonry elements
  - Permitted design approaches for LFRS (lateral force-resisting system)

Code 1.14, Seismic Design

- Seismic design requirements are keyed to ASCE 7-02 Seismic Design Categories (from A up to F).
- Requirements are cumulative; requirements in each "higher" category are added to requirements in the previous category.

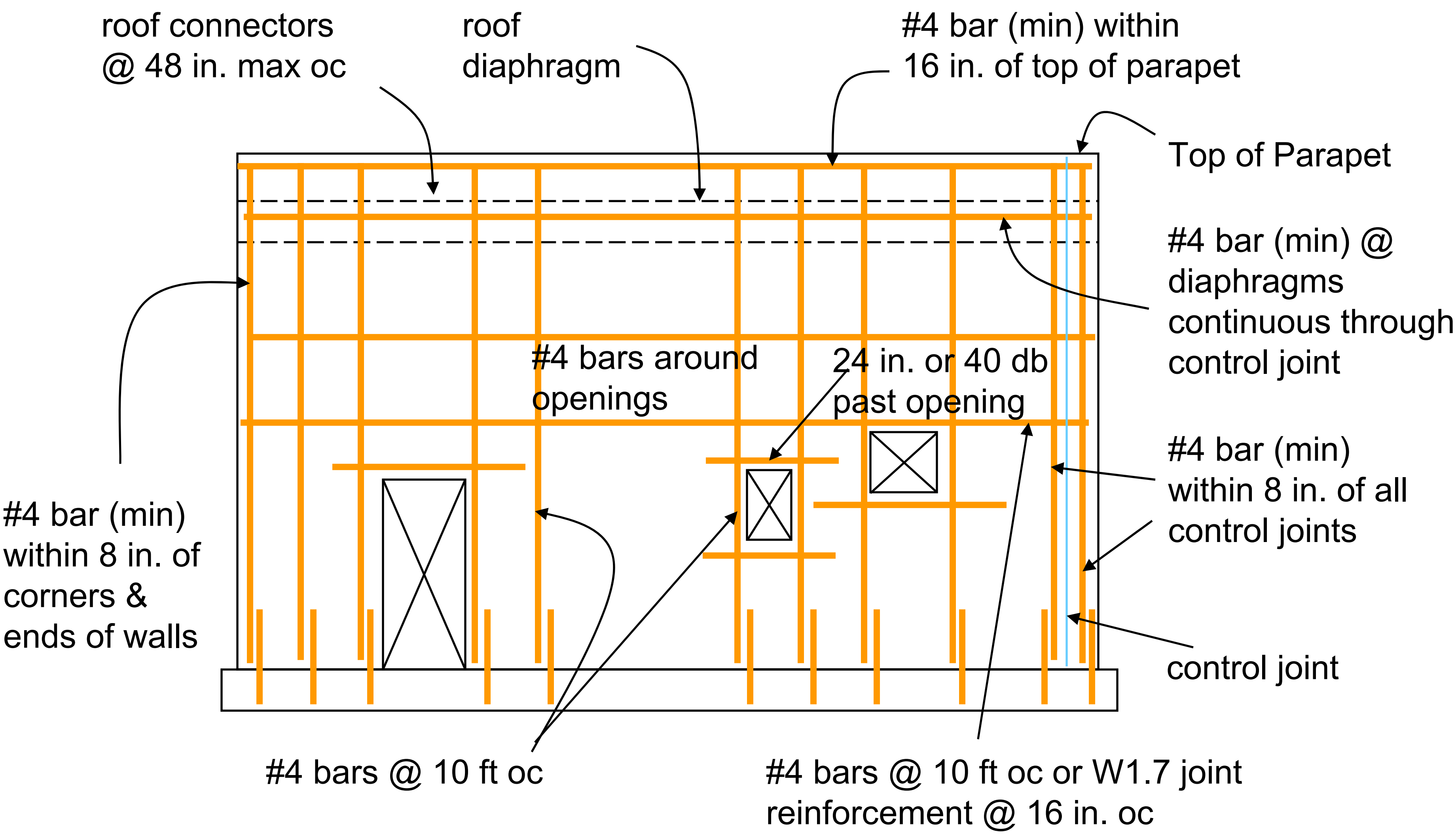
Code 1.14, Seismic Design

- **Seismic Design Category A:**
  - **Drift limit = 0.007**
  - **Minimum design connection force for wall-to roof and wall-to-floor connections**
- **Seismic Design Category B:**
  - **Lateral force resisting system cannot be designed empirically**

Code 1.14, Seismic Design

- Seismic Design Category C:
  - All walls must be considered shear walls unless isolated
  - Shear walls must meet minimum prescriptive requirements for reinforcement and connections (ordinary reinforced, intermediate reinforced, or special reinforced)
  - Other walls must meet minimum prescriptive requirements for horizontal or vertical reinforcement

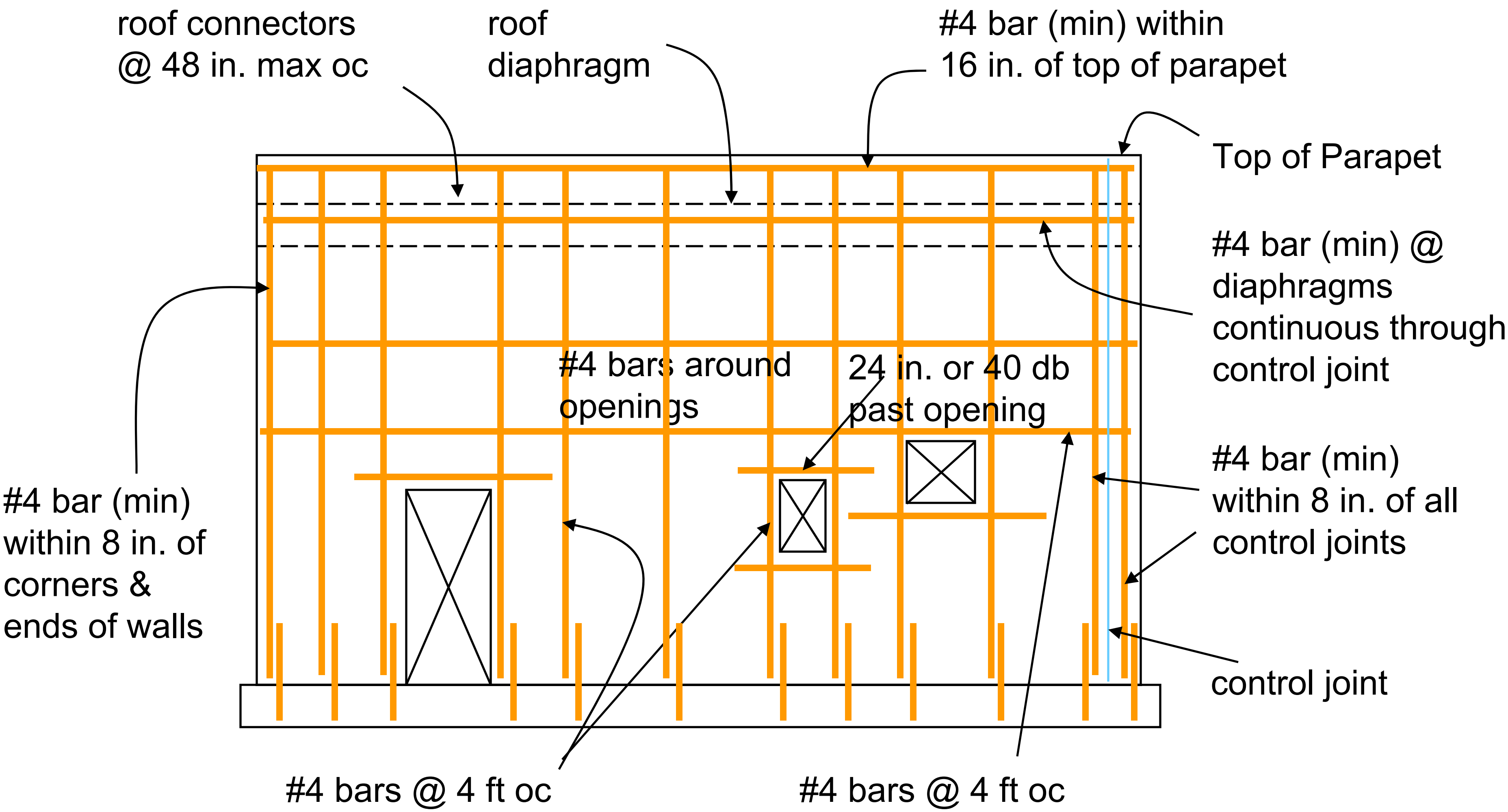
Minimum Reinforcement for Detailed Plain Shear Walls for SDC C



Code 1.14, Seismic Design

- **Seismic Design Category D:**
  - **Masonry that is part of the lateral force-resisting system must be reinforced so that $\rho_v + \rho_h \geq 0.002$, and ρ_v and $\rho_h \geq 0.0007$**
  - **Type N mortar and masonry cement mortars are prohibited in the lateral force-resisting system**
  - **Shear walls must meet minimum prescriptive requirements for reinforcement and connections (special reinforced)**
  - **Other walls must meet minimum prescriptive requirements for horizontal and vertical reinforcement**

Minimum Reinforcement for Special Reinforced Shear Walls



Code 1.14, Seismic Design

- **Seismic Design Categories E and F:**
  - **Additional reinforcement requirements for stack-bond masonry**

Minimum Reinforcement, SW Types

SW Type	Minimum Reinforcement	SDC
Empirically Designed	none	A
Ordinary Plain	none	A, B
Detailed Plain	Vertical reinforcement = 0.2 in.^{2} at corners, within 16 in. of openings, within 8 in. of movement joints, maximum spacing 10 ft; horizontal reinforcement W1.7 @ 16 in. or #4 in bond beams @ 10 ft	A, B
Ordinary Reinforced	same as above	A, B, C
Intermediate Reinforced	same as above, but vertical reinforcement @ 4 ft	A, B, C
Special Reinforced	same as above, but horizontal reinforcement @ 4 ft, and $\rho = 0.002$	any

Organization of MSJC Code Chapter 1

1.1 – 1.6 Scope, contract documents and calculations, special systems, reference standards, notation, definitions

1.7 Loading

1.8 Material properties

1.9 Section properties

1.10 Deflections

1.11 Stack bond masonry

1.12 Corbels

1.13 Details of reinforcement

1.14 Seismic design requirements

1.15 Quality assurance program

1.16 Construction

Code 1.15, Quality Assurance

- **Requires a quality assurance program in accordance with the MSJC Specification:**
  - **Three levels of quality assurance (A, B, C)**
  - **Compliance with specified f_m'**
  - **Increasing levels of quality assurance require increasingly strict requirements for inspection, and for compliance with specified products and execution**

Code 1.15, Quality Assurance

- **Minimum requirements for inspection, tests, and submittals:**
  - **Empirically designed masonry, veneers, or glass unit masonry**
    - Table 1.14.1.1 for nonessential facilities
    - Table 1.14.1.2 for essential facilities
  - **Other masonry**
    - Table 1.14.1.2 for nonessential facilities
    - Table 1.14.1.3 for essential facilities

Organization of MSJC Code Chapter 1

- 1.1 – 1.6 Scope, contract documents and calculations, special systems, reference standards, notation, definitions
- 1.7 Loading
- 1.8 Material properties
- 1.9 Section properties
- 1.10 Deflections
- 1.11 Stack bond masonry
- 1.12 Corbels
- 1.13 Details of reinforcement
- 1.14 Seismic design requirements
- 1.15 Quality assurance program
- 1.16 Construction

1.16, Construction

- **Minimum grout spacing (Table 1.16.2)**
- **Embedded conduits, pipes, and sleeves:**
  - **Consider effect of openings in design**
  - **Masonry alone resists loads**
- **Anchorage of masonry to structural members, frames, and other construction:**
  - **Show type, size, and location of connectors on drawings**

... Organization of MSJC Code Chapter 3, Strength Design (SD)

- Fundamental basis
- Loading combinations
- Design strength
- Deformation requirements
- *Φ*-factors
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Fundamental Basis for Strength Design

- Factored design actions must not exceed nominal capacities, reduced by Φ factors
- Quotient of load factor divided by the Φ factor is analogous to safety factor of allowable-stress design, and should be comparable to that safety factor.

Organization of MSJC Code Chapter 3, Strength Design

- Fundamental basis
- Loading combinations
- Design strength
- Φ factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.2, Loading Combinations for SD

- From governing building code
- From ASCE 7-02

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading
- Design strength
- *Φ* factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.3, Design Strength for SD

- Design strength must exceed required strength
- Extra caution against brittle shear failure:
  - Design shear strength shall exceed the shear corresponding to the development of 1.25 times the nominal flexural strength
  - Nominal shear strength need not exceed 2.5 times required shear strength

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- *Φ* factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.4, Strength-reduction Factors for SD

Action	Reinforced Masonry	Unreinforced Masonry
Combinations of flexure and axial load	0.90	0.60
Shear	0.80	0.80
Anchorage and splices of Reinforcement	0.80	---
Bearing	0.60	0.60

Code 3.1.4, Strength-reduction Factors for SD

Capacity of Anchor Bolts as Governed by	Strength-reduction Factor
Steel yield and fracture	0.90
Masonry breakout	0.50
Pullout of bent-bar anchors	0.65

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
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- *Φ* factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.5, Deformation Requirements

- Drift limits from ASCE 7-02
- Deflections of unreinforced masonry (URM) based on uncracked sections
- Deflections of reinforced masonry (RM) based on cracked sections

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- *Φ* factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.6, Anchor Bolts

- Tensile capacity governed by:
  - Tensile breakout
  - Yield of anchor in tension
  - Tensile pullout (bent-bar anchor bolts only)
- Shear capacity governed by:
  - Shear breakout
  - Yield of anchor in shear
- For combined tension and shear, use linear interaction

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- Deformation requirements
- *Φ* factors
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Reinforced masonry
- Unreinforced masonry

Code 3.1.7.1.1, Compressive Strength of Masonry

- For concrete masonry, 1,500 psi $\leq f_m' \leq$ 4,000 psi
- For clay masonry, 1,500 psi $\leq f_m' \leq$ 6,000 psi

Code 3.1.7.1.2, Compressive Strength of Grout

- **For concrete masonry, $f_m' \leq f_g' \leq$ 5,000 psi**
- **For clay masonry, $f_g' \leq$ 6,000 psi**

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- Deformation requirements
- *Φ* factors
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.8.2, Modulus of Rupture

- **In-plane and out-of-plane bending**
  - **Table 3.1.8.2.1**
  - **Lower values for masonry cement and air-entrained portland cement-lime mortar**
  - **Higher values for grouted masonry**
  - **For grouted stack-bond masonry, f_r = 250 psi parallel to bed joints for continuous horizontal grout section**

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- Deformation requirements
- Φ factors
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.1.8.3, Strength of Reinforcement

- $f_y \leq$ 60 ksi
- Actual yield strength shall not exceed 1.3 times the specified value
- Compressive strength of reinforcement shall be ignored unless the reinforcement is tied in compliance with Code 2.1.6.5

Organization of MSJC Code Chapter 3

- Fundamental basis
- Loading combinations
- Design strength
- Deformation requirements
- *Φ* factors
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry

Code 3.3, Reinforced Masonry

- **Masonry in flexural tension is cracked**
- **Reinforcing steel is needed to resist tension**
- **Similar to strength design of reinforced concrete**

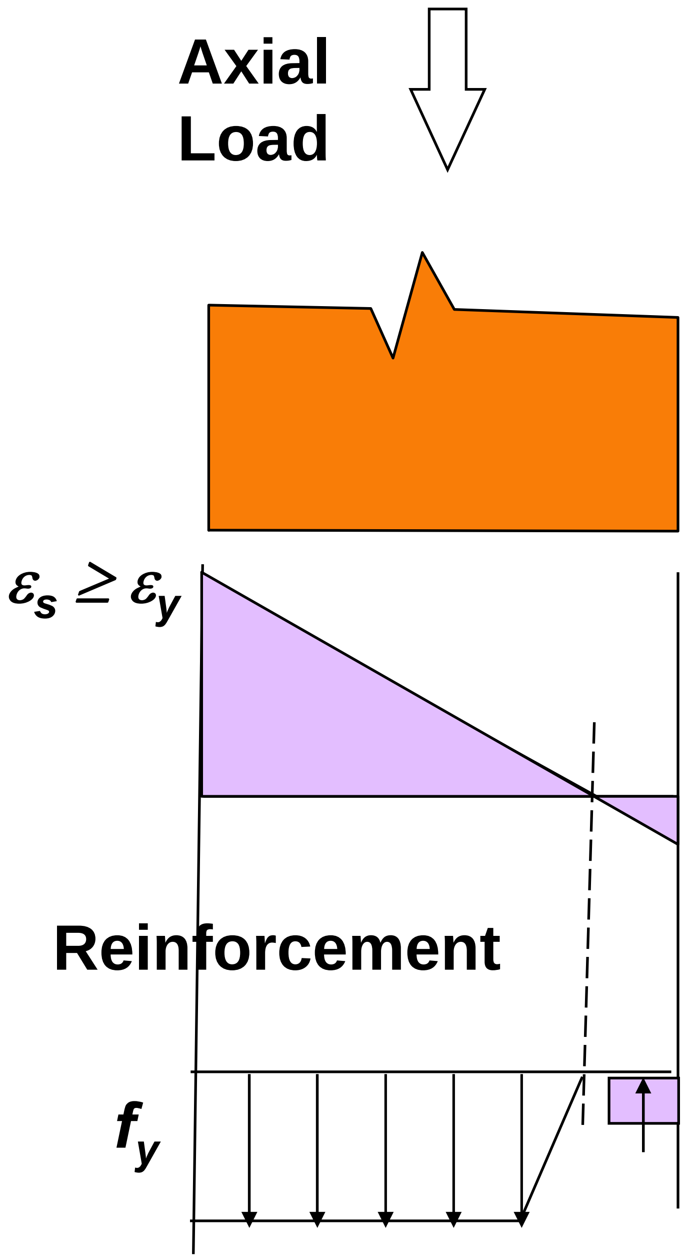
Code 3.3, Reinforced Masonry

- 3.3.2 Design assumptions
- 3.3.3 Reinforcement requirements and details, including maximum steel percentage
- 3.3.4 Design of piers, beams and columns:
  - Nominal axial and flexural strength
  - Nominal shear strength
- 3.3.5 Design of walls for out-of-plane loads
- 3.3.6 Design of walls for in-plane loads

Code 3.3.2, Design Assumptions

- **Continuity between reinforcement and grout**
- **Equilibrium**
- ε_{mu} **= 0.0035 for clay masonry, 0.0025 for concrete masonry**
- **Plane sections remain plane**
- **Elasto-plastic stress-strain curve for reinforcement**
- **Tensile strength of masonry is neglected**
- **Equivalent rectangular compressive stress block in masonry, with a height of 0.80** f_m' **and a depth of 0.80 c**

Flexural Assumptions



- Locate neutral axis based on extreme-fiber strains
- Calculate compressive force, *C*
- $P = C - T$
- $M = \sum F_i y_i$ (y_i from plastic centroid)

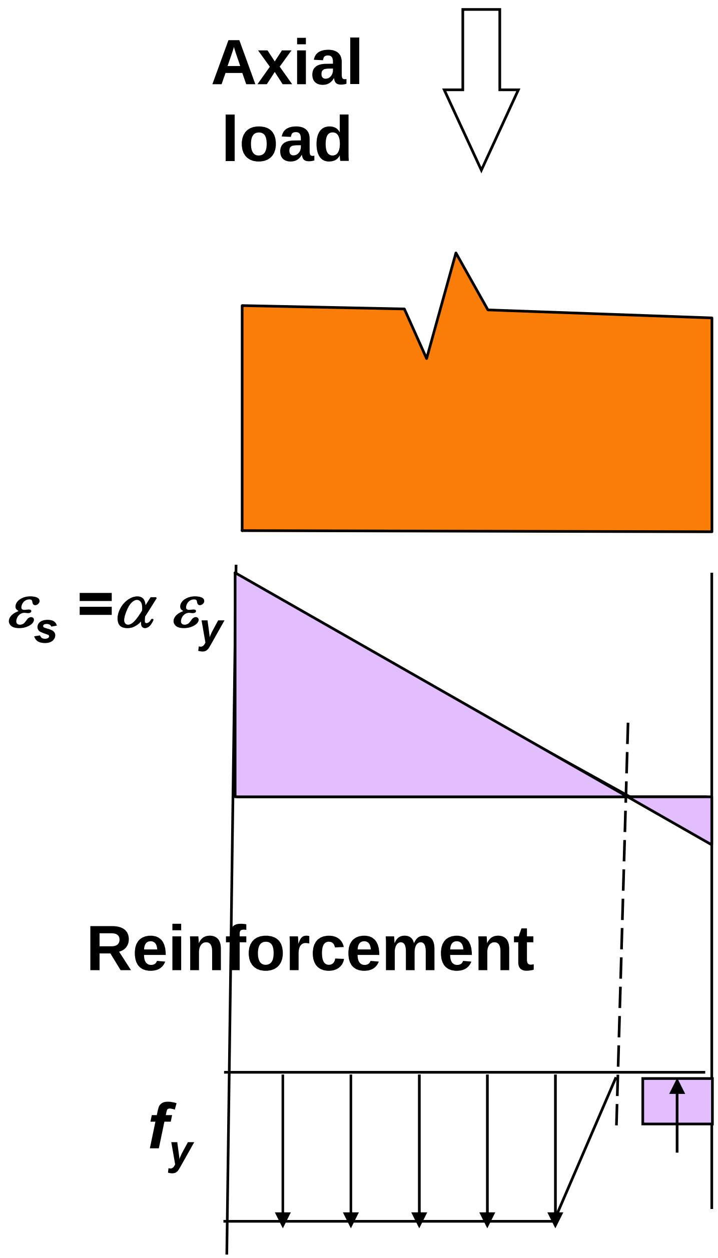
ε_{mu} = 0.0035 clay
0.0025 concrete

$0.80 f_m'$
$\beta_1 = 0.80$

Code 3.3.3, Reinforcement Requirements and Details

- Bar diameter ≤ 1 / 8 nominal wall thickness
- Standard hooks and development length:
  – Development length based on pullout and splitting
- In walls, shear reinforcement must be bent around extreme longitudinal bars
- Splices:
  – Lap splices based on required development length
  – Welded and lap splices must develop 1.25 f_y

Code 3.3.3.5, Maximum Reinforcement



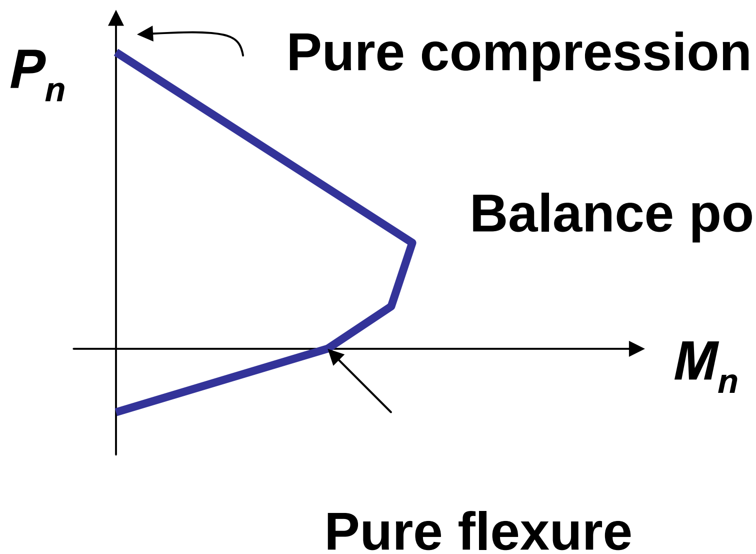
- **Locate neutral axis based on extreme-fiber strains**
- **Calculate compressive force, *C* (can include compressive reinforcement)**
- **Reinforcement + axial Load = C**

ε_{mu} = **0.0035 clay**
0.0025 concrete

0.80 f_m'
$\beta_1 = 0.80$

Code 3.3.4, Design of Beams, Piers, and Columns

- **Capacity under combinations of flexure and axial load is based on the assumptions of Code 3.3.2 (interaction diagram)**



Code 3.3.4, Design of Beams, Piers, and Columns

- **Slenderness is addressed by multiplying axial capacity by slenderness-dependent modification factors**

$$\left[1-\left(\frac{h}{140r}\right)^2\right] \quad \text{for } \frac{h}{r} \leq 99$$

$$\left(\frac{70r}{h}\right)^2 \quad \text{for } \frac{h}{r} > 99$$

Code 3.3.4, Nominal Shear Strength

- $V_n = V_m + V_s$
- V_n shall not exceed:
  - $M / V d_v \leq 0.25$ $\quad V_n \leq 6 A_n \sqrt{f_m'}$
  - $M / V d_v \geq 1.0$ $\quad V_n \leq 4 A_n \sqrt{f_m'}$
  - Linear interpolation between these extremes
  - Objective is to avoid crushing of diagonal strut

Code 3.3.4, Nominal Shear Strength

- V_m **and** V_s **are given by:**

$$V_m = \left[4.0 - 1.75 \left(\frac{M_u}{V_u d_v} \right) \right] A_n \sqrt{f'_m} + 0.25 P_u \qquad (3-21)$$

$$\left(\frac{M_u}{V_u d_v} \right) \leq 1.0$$

$$V_s = 0.5 \left(\frac{A_v}{s} \right) f_y d_v \qquad (3-22)$$

Code 3.3.4.2, Requirements for Beams

- $P_u \leq 0.05\, A_n\, f_m'$
- $M_n \geq 1.3\, M_{cr}$
- **Lateral bracing spaced at most 32 times beam width**
- **Nominal depth not less than 8 in.**

Code 3.3.4.3, Requirements for Piers

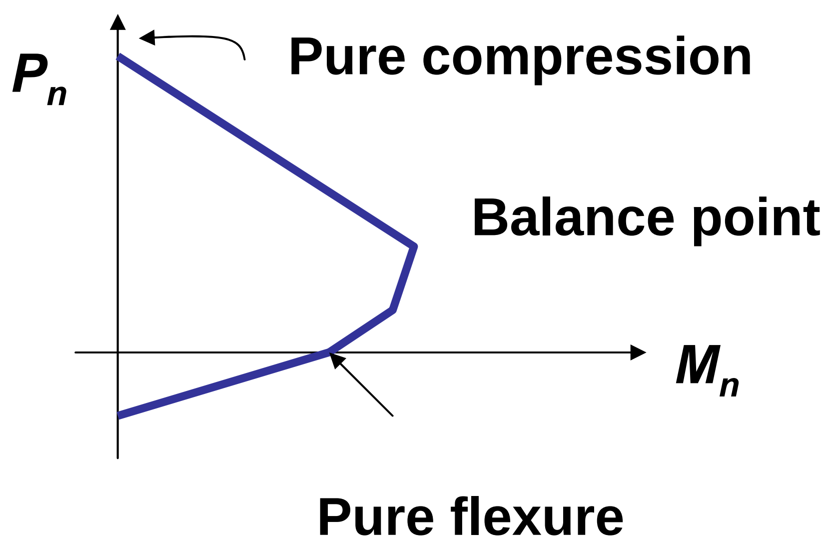
- **Isolated elements (wall segments are not piers)**
- $P_u \leq 0.3\, A_n\, f_m'$
- **Nominal thickness between 6 and 16 in.**
- **Nominal plan length between 3 and 6 times the nominal thickness**
- **Clear height not more than 5 times the nominal plan length**

Code 3.3.4.4, Requirements for Columns

- Isolated elements (wall segments are not columns)
- $\rho_g \geq 0.0025$
- $\rho_g \leq 0.04$, and also meet Code 3.3.3.5
- Lateral ties in accordance with Code 2.1.6.5
- Solid-grouted
- Least cross-section dimension $\geq$ 8 in.
- Nominal depth not greater than 3 times the nominal width

Code 3.3.5, Design of Walls for Out-of-plane Loads

- Capacity under combinations of flexure and axial load is based on the assumptions of Code 3.3.2 (interaction diagram)

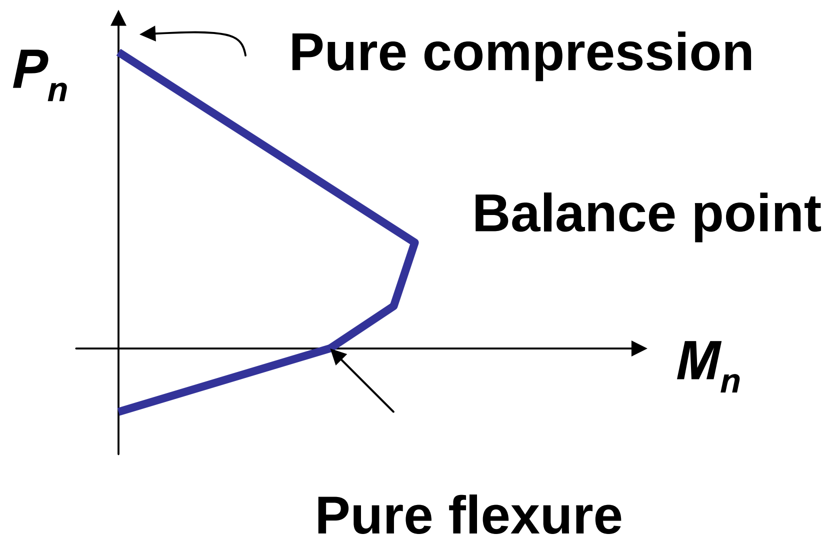


Code 3.3.5, Design of Walls for Out-of-plane Loads

- **Maximum reinforcement by Code 3.3.3.5**
- **Procedures for computing out-of-plane moments and deflections (moment magnifier, vary depending on axial load)**
- **Nominal shear strength by Code 3.3.4.1.2**

Code 3.3.6, Design of Walls for In-plane Loads

- **Capacity under combinations of flexure and axial load is based on the assumptions of Code 3.3.2 (interaction diagram)**



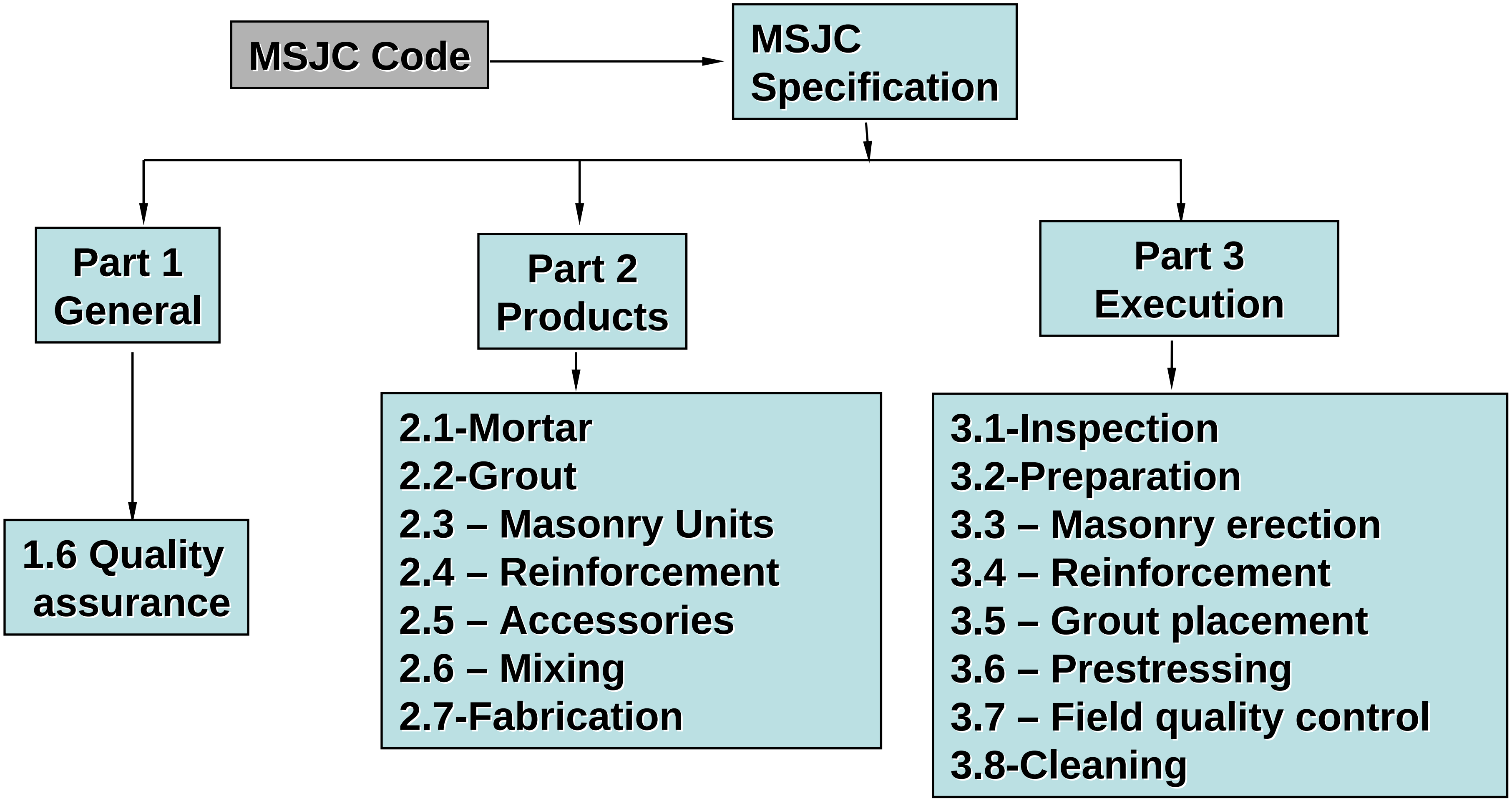
Code 3.3.6, Design of Walls for In-plane Loads

- **Maximum reinforcement by Code 3.3.3.5**
- **Vertical reinforcement not less than one-half the horizontal reinforcement**
- **Nominal shear strength by Code 3.3.4.1.2**

Code 3.3.6, Alternative Approach to Maximum Reinforcement

- **For walls expected to have flexural ductility in plane, provide confined boundary elements in hinging regions (this is another way of preventing toe crushing)**
- **Detailing requirements for boundary elements have yet to be developed**

Organization of MSJC Specification

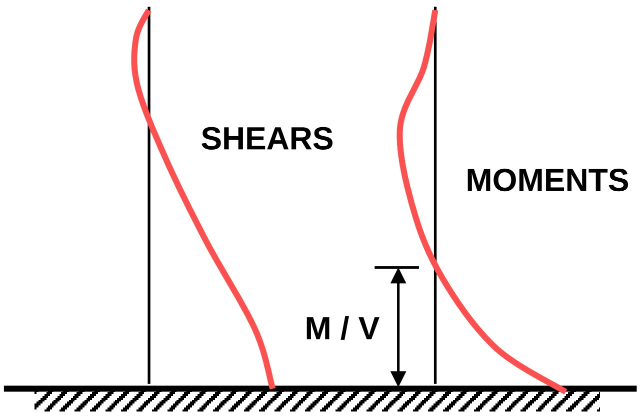


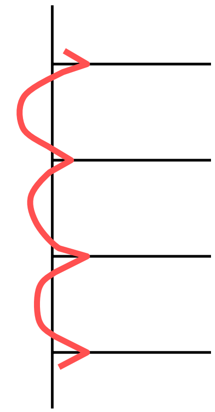
Strength Design of Reinforced Masonry Shear Walls

- **Compute factored design moments and shears for in- and out-of-plane loading.**
- **Given practical thickness for wall, design flexural reinforcement as governed by out-of-plane loading.**
- **Design flexural reinforcement as governed by in-plane loading and revise design as necessary.**
- **Check shear capacity using capacity design if required.**
- **Check detailing.**

Compute Factored Design Moments and Shears

- Factored design moments and shears for in-plane loading depend on actions transferred to shear walls by horizontal diaphragms at each floor level.
- Factored design moments and shears for out-of-plane loading depend on wind or earthquake forces acting between floor levels



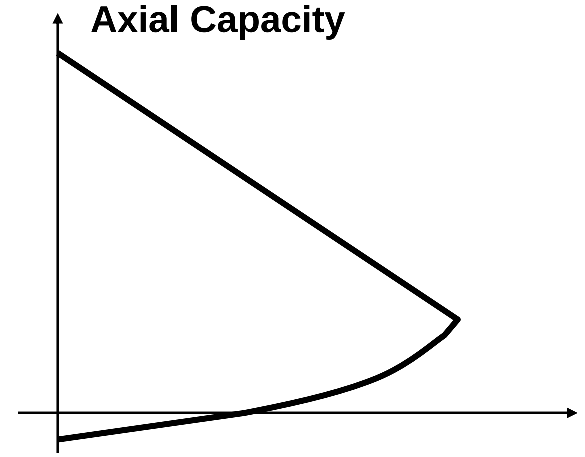


Design Flexural Reinforcement as Governed by Out-of-plane Loading

- Practical wall thickness is governed by available unit dimensions:
  - 8- by 8- by 16-in. nominal dimensions
  - Specified thickness = 7-5/8 in.
  - One curtain of bars, placed in center of grouted cells
- Practical wall thickness = 7-5/8 in.
- Proportion flexural reinforcement to resist out-of-plane wind or earthquake forces

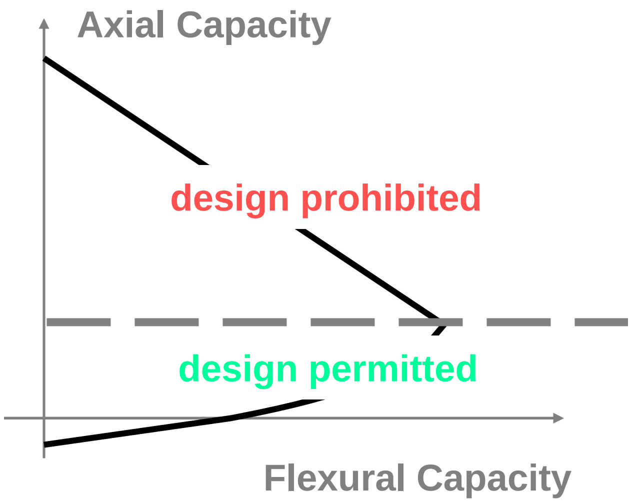
Design Flexural Reinforcement as Governed by In-plane Loading

- **Construct moment – axial force interaction diagram**
  - **Initial estimate (more later)**
  - **Computer programs**
  - **Spreadsheets**
  - **Tables**



Strict Limits on Maximum Flexural Reinforcement

- **Objective -- Keep compressive stress block from crushing:**
  - **Walls must be below balance point.**
  - **Maximum steel percentage decreases as axial load increases, so that design above balance point is impossible.**

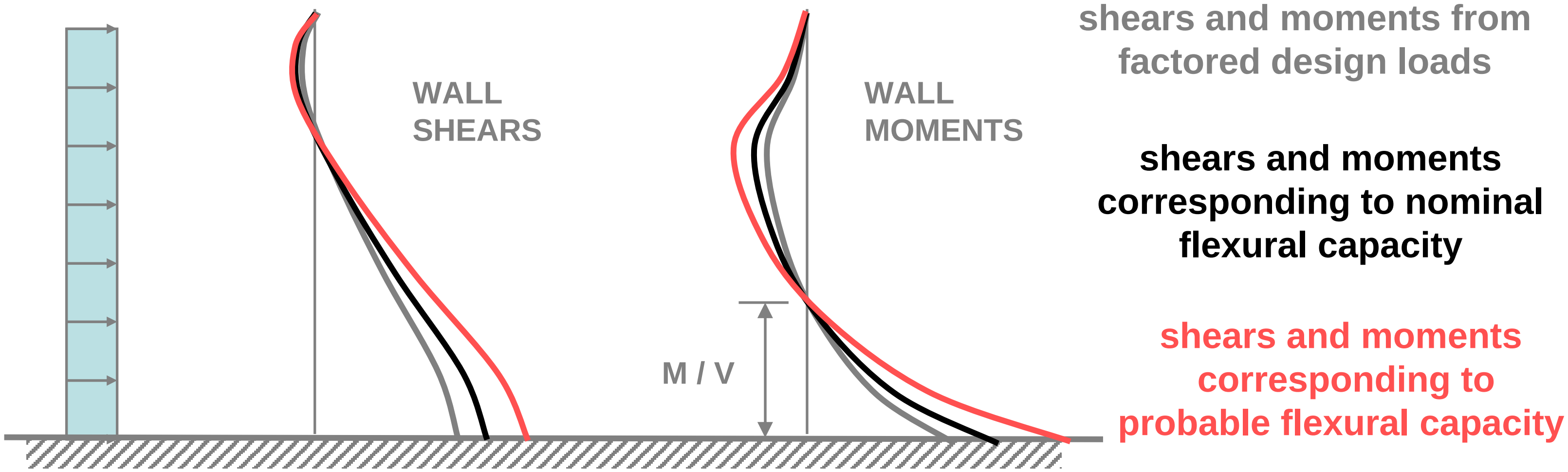


Revise Design as Necessary

- If flexural reinforcement required for out-of-plane moments is less than or equal to that required for in-plane moments, no adjustment is necessary. Use the larger amount.
- If flexural reinforcement required for out-of-plane moments exceeds that required for in-plane moments, consider making the wall thicker so that in-plane flexural capacity does not have to be increased. Excess in-plane capacity increases shear demand.

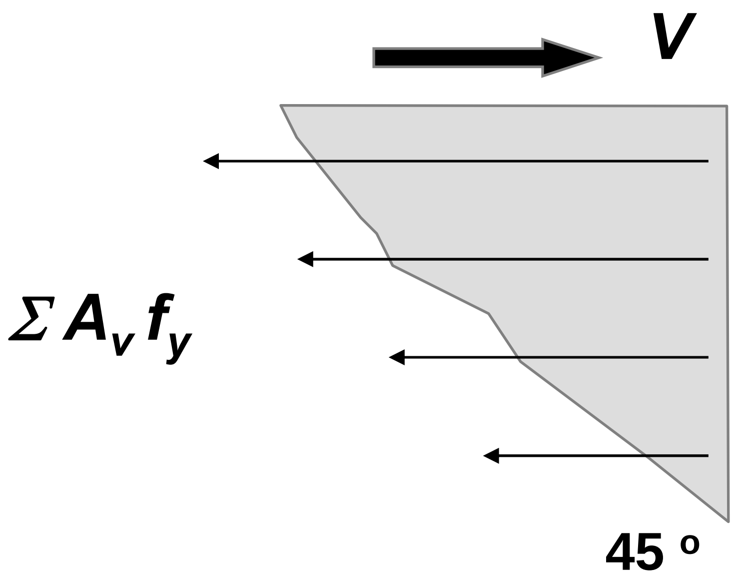
Check Shear Capacity (1)

- Elastic structures or those with considerable shear overstrength:
  - Compute factored design shears based on factored design actions.
- Inelastic structures:
  - Compute design shears based on flexural capacity



Check Shear Capacity (2)

- $V_n = V_m + V_s$
- V_m depends on $(M_u / V_u d_v)$ ratio
- $V_s = (0.5)\ A_v f_y$ (note efficiency factor)

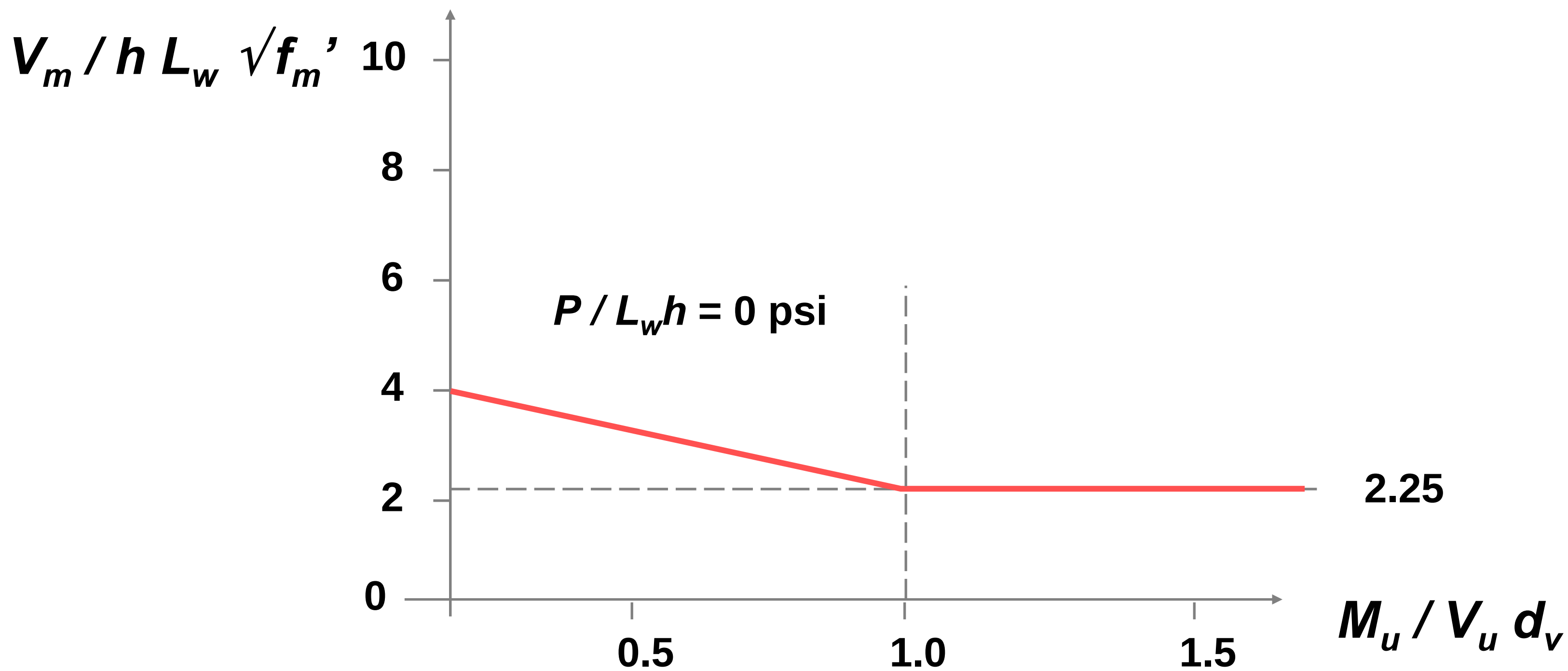


Shear Resistance from Masonry, V_m (1)

- V_m depends on ($M_u / V_u d_v$) ratio and axial force
- ($M_u / V_u d_v$) need not be taken greater than 1.0

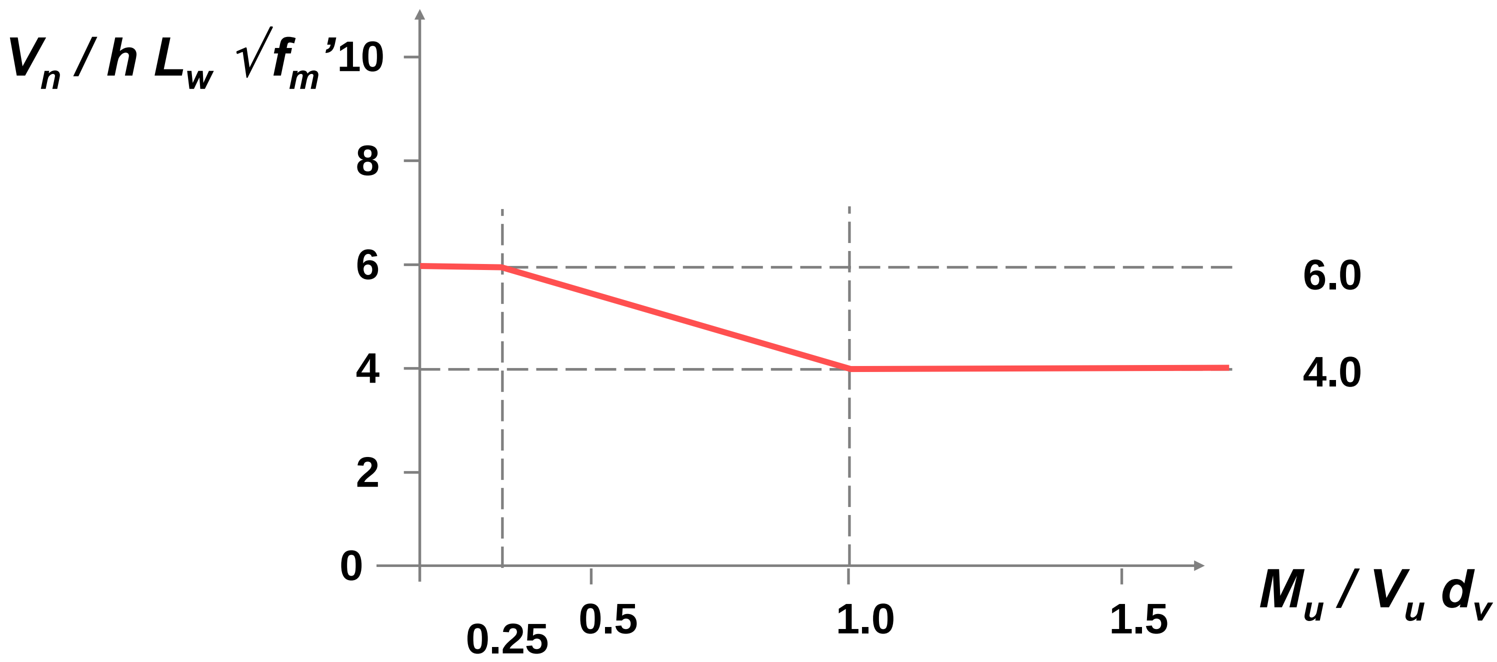
$$V_m = \left[4.0 - 1.75\left(\frac{M_u}{V_u\, d_v}\right)\right] A_n \sqrt{f'_m} + 0.25 P_u$$

Shear Resistance from Masonry, V_m (2)



Total Shear Resistance, V_n (1)

- Resistance from masonry (V_m) plus resistance from reinforcement (V_s)
- Upper limit on V_m depends on ($M_u / V_u d_v$) ratio



Check Detailing

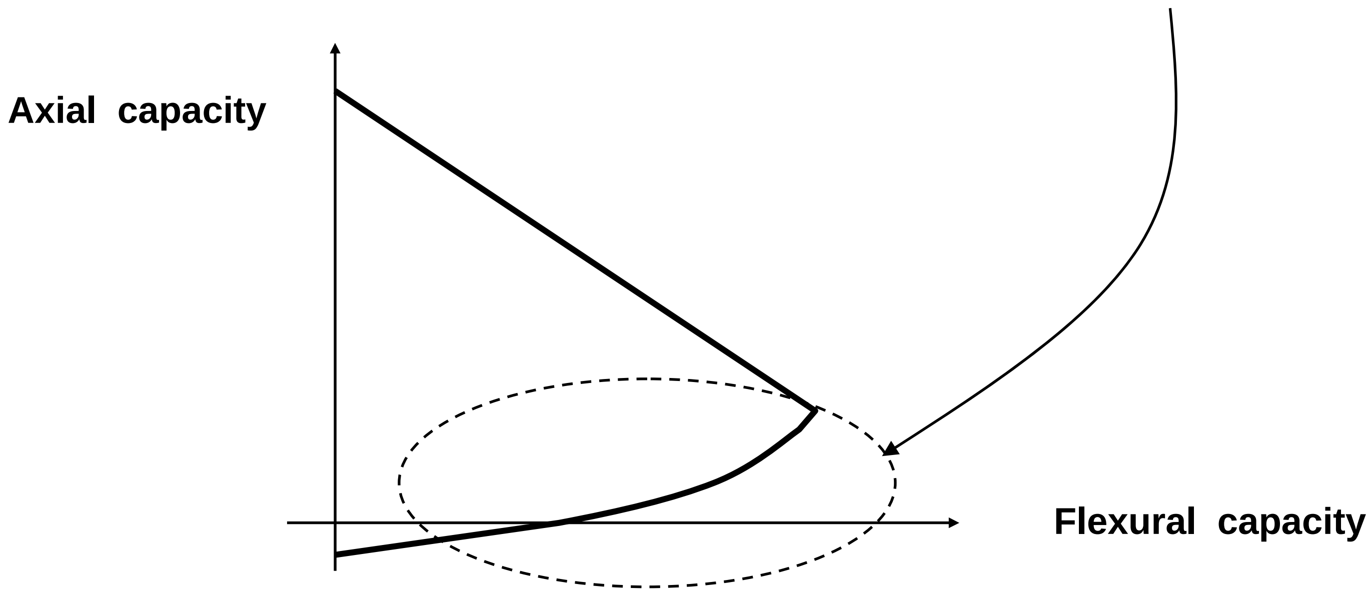
- Cover
- Placement of flexural and shear reinforcement
- Boundary elements not required:
  - Ductility demand is low
  - Maximum flexural reinforcement is closely controlled

Detailing (1)

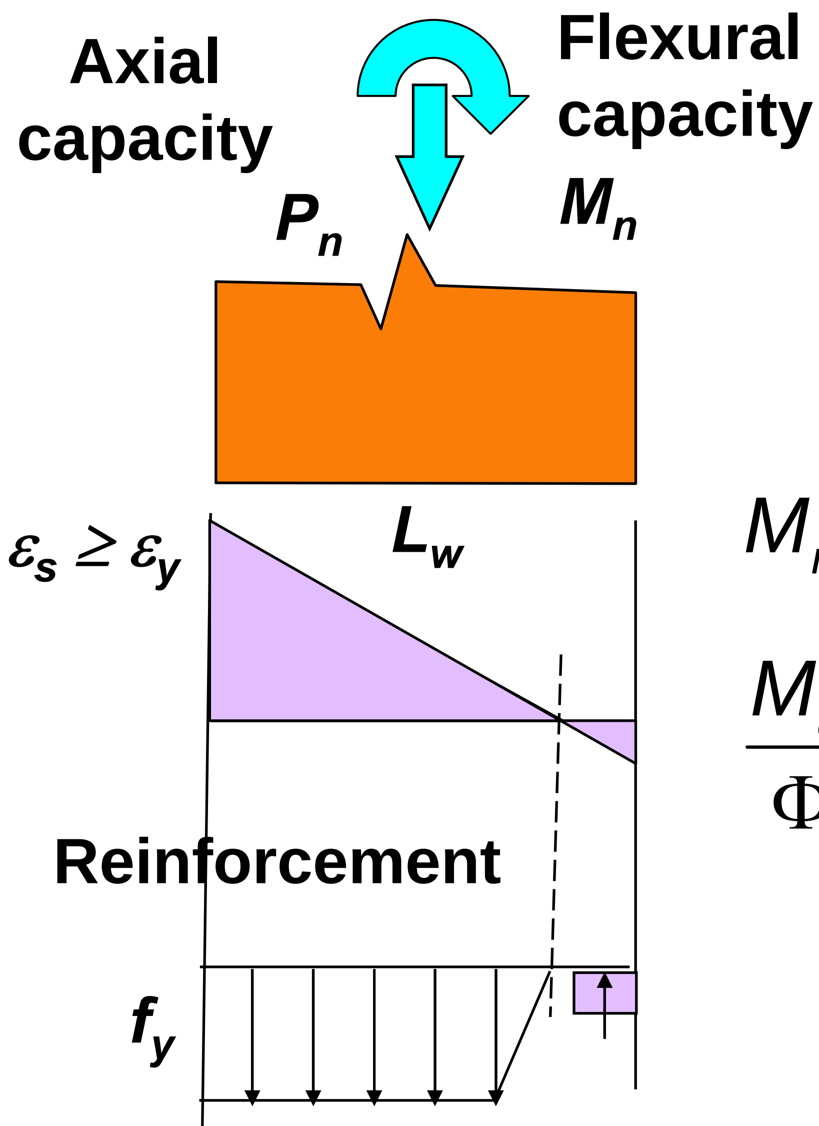
- **Cover:**
  - Automatically satisfied by putting reinforcement in grouted cells
- **Placement of flexural and shear reinforcement:**
  - Minimum flexural reinforcement and spacing dictated by Seismic Design Category
  - Flexural reinforcement placed in single curtain. Typical reinforcement would be at least #4 bars @ 48 in.
  - Place horizontal reinforcement in single curtain. Typical reinforcement would be at least #4 bars @ 48 in.
  - Add more flexural reinforcement if required, usually uniformly distributed.

Flexural Strength of Lineal Walls (1)

- **Approximation to moment-axial force interaction diagram for low axial load**



Flexural Strength of Lineal Walls (2)



- **Sum moments about centroid of compressive stress block**

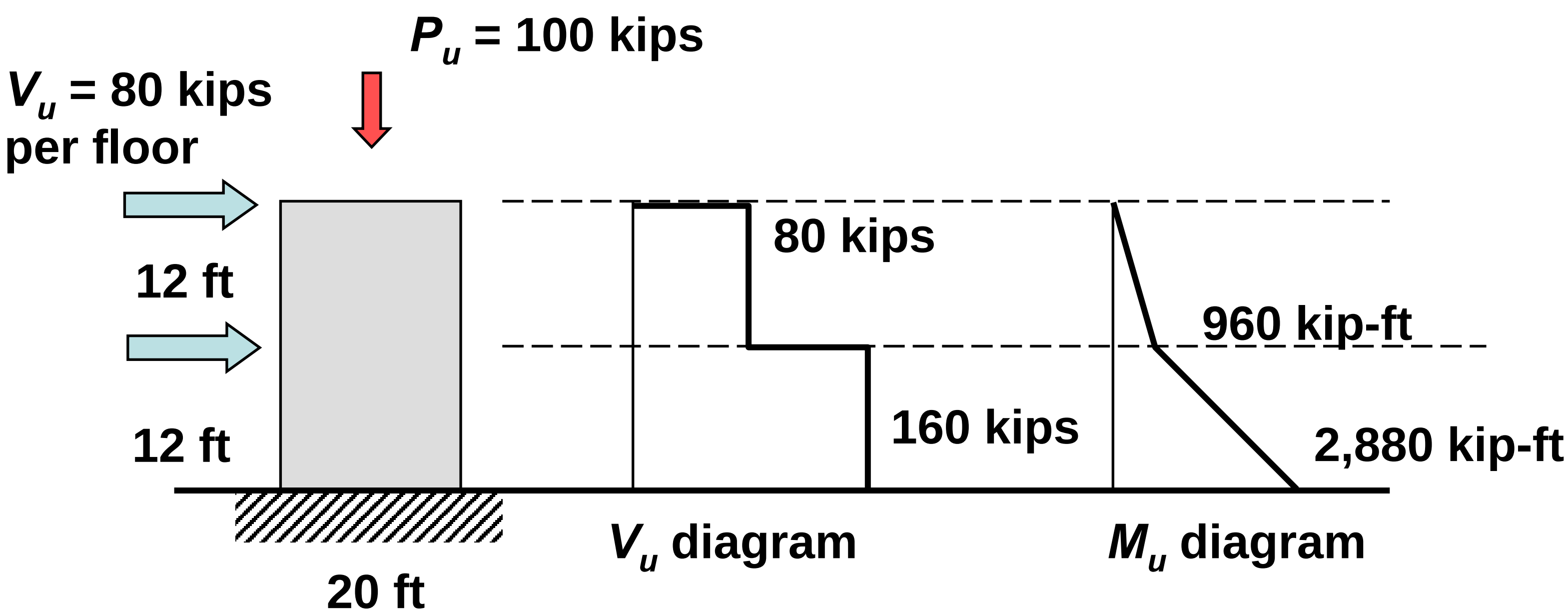
$$M_n \approx 0.9 A_s f_y \frac{0.9 L_w}{2} + P_n \frac{0.9 L_w}{2}$$

$$\frac{M_u}{\Phi} \approx 0.41 A_s f_y L_w + 0.45 \frac{P_u}{\Phi} L_w$$

- **Given M_u and P_u, solve for A_s**

Design Example (1)

- **Carry out the preliminary design of the masonry shear wall shown below. Use f_m' = 1500 psi.**



Design Example (2)

- **Assume out-of-plane flexure is OK.**
- **Check in-plane flexure using initial estimate.**

$$\frac{M_u}{\Phi} \approx 0.41\, A_s\, f_y\, L_w + 0.45\, \frac{P_u}{\Phi}\, L_w$$

$$\frac{2880\ kip-ft \times 12\ in./ft}{0.90} \approx 0.41\, A_s \times 60\ ksi \times 240\ in. + 0.45\, \frac{100\ kips}{0.9} \times 240\ in.$$

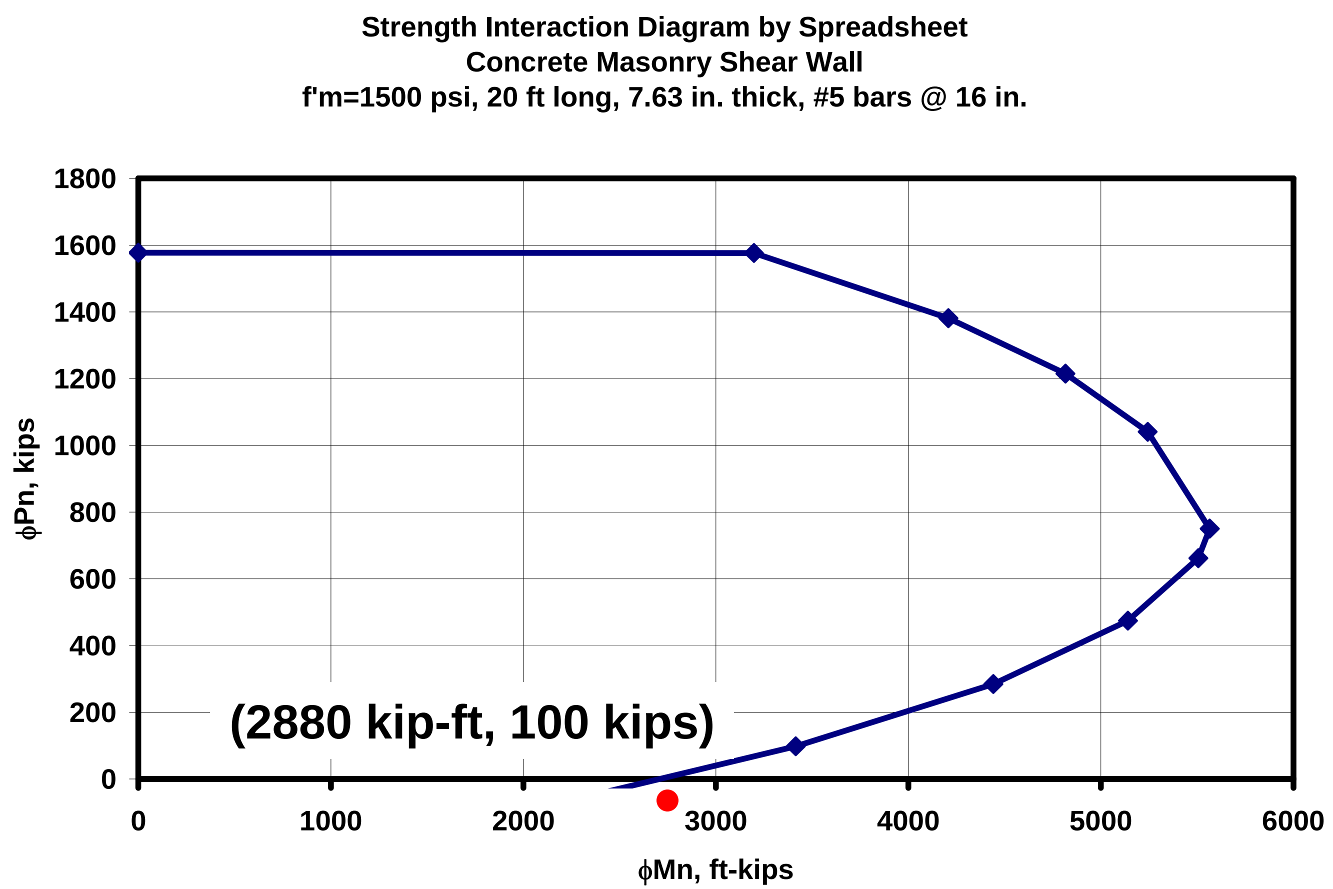
$$38,400 \approx 5,900\ A_s + 12,000$$

$$A_s \approx 4.47\ in.^2$$

- **This is equivalent to #5 bars @ 12 in.**

Design Example (3)

- **Refine flexural reinforcement using spreadsheet-based interaction diagram -- use #5 bars @ 16 in.**



Design Example (4)

- **Now check shear:**

$$\frac{M_u}{V_u\ d} = \frac{2{,}880\ kip - ft}{160\ kips \cdot 20 \cdot 0.8\ ft} = 1.13$$

$$V_m = 2.25\sqrt{f_m^{'}}\ h\ L_w + 0.25P$$

$$V_m = 2.25\sqrt{1500} \cdot 7.63\ in. \cdot 240\ in. + 0.25 \cdot 100\ kips$$

$$V_m = 159.6\ kips + 25.0\ kips = 184.6\ kips$$

Design Example (5)

- **Compute required shear reinforcement, including capacity design:**

$$V_u = 160\ kips \left(\frac{1.25\, M_n}{M_u} \right)$$

$$V_u = 160\ kips \left[\frac{1.25 \times 3427\ kip-ft \times \left(\frac{1}{0.9} \right)}{2880\ kip-ft} \right] = 160\ kips \times 1.65$$

$$V_n^{required} = \frac{V_u}{\Phi} = \frac{V_u}{0.8} = \frac{160\ kips \times 1.65}{0.8} = 2.07\, V_u \leq 2.5\, V_u$$

Design Example (6)

- **Compute required shear reinforcement including capacity design:**

$$V_s^{required} \geq \frac{V_u}{\Phi} - V_m = \frac{160 \times 1.65}{0.8} - 184.6 = 145.4\ kips$$

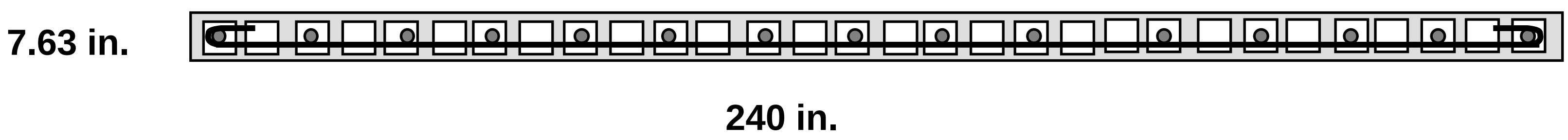
$$V_s^{required} = 2 \times A_v f_y \frac{d}{s}$$

$$A_v^{required} = \frac{V_s^{required} s}{d\ f_y} = \frac{145.4\ kips \cdot 16\ in.}{0.8 \cdot 240\ in. \cdot 60\ ksi} = 0.202\ in.^2$$

- **Use #4 bars every 16 in.**

Design Example (7)

- **Now finish detailing:**
  - **Use #5 bars @ 16 in. vertically**
  - **Use #4 bars @ 16 in. horizontally**
  - **Hook #4 horizontal bars around end #5 vertical bars**



Web sites for more information

- BSSC = www.bssconline.org
- TMS = www.masonrysociety.org
- ACI = www.aci-int.org
- ASCE / SEI = www.seinstitute.org
- MSJC = www.masonrystandards.org

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