Introduction to Strength Design of Masonry and Design Methodologies

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John M. Hochwalt, P.E., S.E.,
Director of Engineering,
KPFF Consulting Engineers-Seattle Structural Group

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Welcome to Night School

- Course Description
- Focus of Course
- Road Maps

Course Description

This 6-session course will introduce strength design of masonry, review code requirements, and examine designs of common masonry elements including, beams, walls, columns, and pilasters. Design methodology will be reviewed, as will design for flexure, axial loads, and in-plane loads. The course will conclude with a review of requirements for reinforcement and connectors and detailing masonry effectively. This course is an excellent way to learn strength design procedures. Those taking the course should have a basic familiarity with masonry (consistent with content presented in the Masonry 101).

Poll #1

Which best describes your experience with masonry design?

A. None
B. A little, using Allowable Stress Design
C. A little, using Strength Design
D. A fair amount, using Allowable Stress Design
E. A fair amount, using Strength Design
F. I should be teaching this class

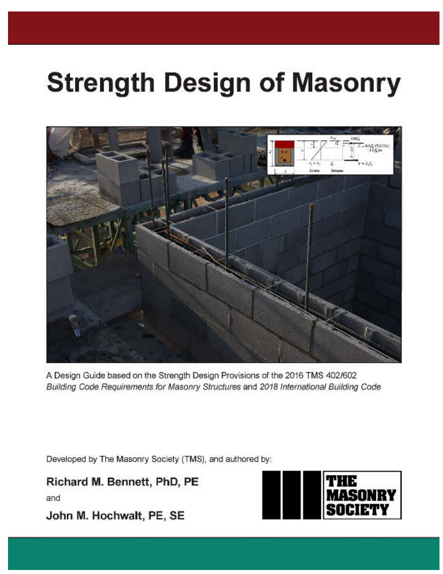
Focus of Course

Course Reference:

Strength Design of Masonry

By Bennett and Hochwalt

Available from The Masonry Society



Focus of Course

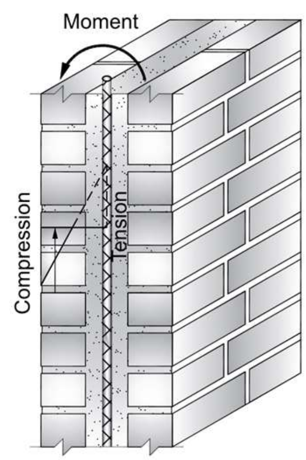
Included:

- 2018 IBC + TMS 402/602-16
- Concrete and Clay Hollow Masonry
- Reinforced Masonry

Focus of Course

Not Included:

- Multiwythe masonry
- AAC Masonry (TMS 402 Chapter 10)
- Unreinforced Masonry (TMS 402 Section 9.2)
- Masonry Veneer (TMS 402 Chapter 12)



Multiwythe Masonry

Poll #2

I currently design masonry as unreinforced, that is using Section 8.2 or 9.2 of TMS 402.

- **Never**
- **Rarely**
- **Some**
- **Frequently**

Course Road Map

Session 1 – Introduction to Strength Design of Masonry and Design Methodologies (Hochwalt)

Session 2 – Strength Design of Beams (Bennett)

Session 3 – Strength Design of Walls for Axial Load and Out-of-Plane Loads (Bennett)

Course Road Map

Session 4 – Strength Design of Walls for In-Plane Loads & Seismic Detailing (Hochwalt)

Session 5 – Strength Design of Columns and Pilasters & System Behavior (Hochwalt)

Session 6 – Strength Design Requirements for Reinforcement & Connectors (Bennett)

Tonight's Road Map

✓Introduction to Night School

- Introduction to Masonry
  - Materials
  - Assemblages
  - Elements
  - Systems
- Introduction to Strength Design
  - Strength
  - Serviceability

Course Description

This introductory session will review basic strength design concepts for masonry, noting key differences with procedures for concrete. Masonry assemblies and systems will be briefly reviewed noting their purposes and resistance to primary loads. Individual masonry elements of masonry buildings including walls, beams, columns, and pilasters will then be introduced, related to their roles in the overall structural system to orient attendees for further sessions where the design of these elements will be discussed.

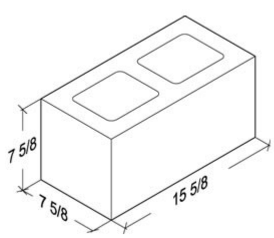
Learning Objectives

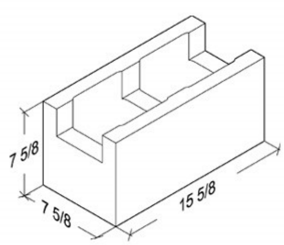
- Introduce strength design concepts for masonry
- Classify different types of masonry systems
- Review the role of various masonry elements
- Identify common loadings on typical masonry building systems and elements

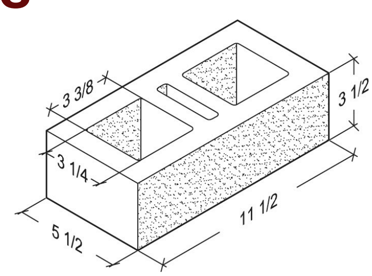
Introduction to Masonry

- Materials
- Assemblages
- Elements
- Systems

Materials – Masonry Units







Concrete Units:
- 8” (7-5/8”)
- 10” (9-5/8”)
- 12” (11-5/8”

Clay Units:
- 4” (3-1/2” or 3-5/8”)
- 6” (5-1/2” or 5-5/8”)
- 8” (7-1/2” or 7-5/8”)

Basic geometry is standardized
Uses 8” module

Geometry varies by supplier
Need to verify module

Figures from Mutual Materials

Poll #3

Which masonry unit types are you accustomed to using in design?

A. **None**
B. **Concrete masonry units**
C. **Clay masonry units**
D. **Both concrete and clay units**

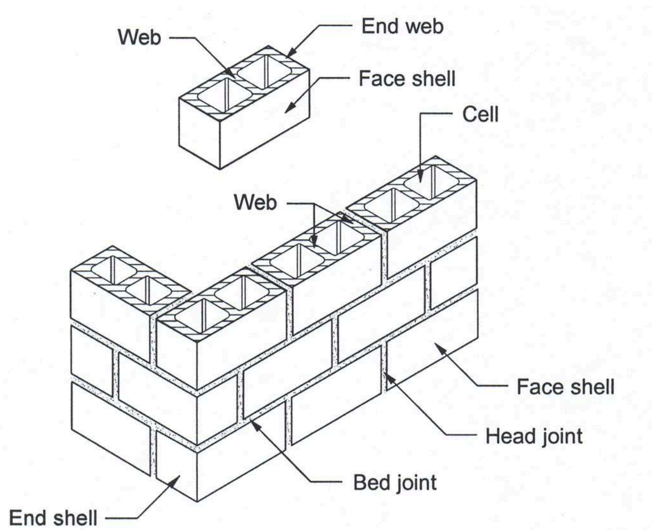
Materials – Masonry Units

- Selection of Unit Type – Usually not structural
  - Aesthetics
  - Economy
- Typical Assumptions for Night School
  - f'_m = 2,000 psi for concrete; 3,000 psi for clay
  - 8" module
- Most Code Provisions Are Independent of Unit Type

Materials – Masonry Units

Terminology for Units

- Face Shell
- Web
- End Web
- Cell / Core

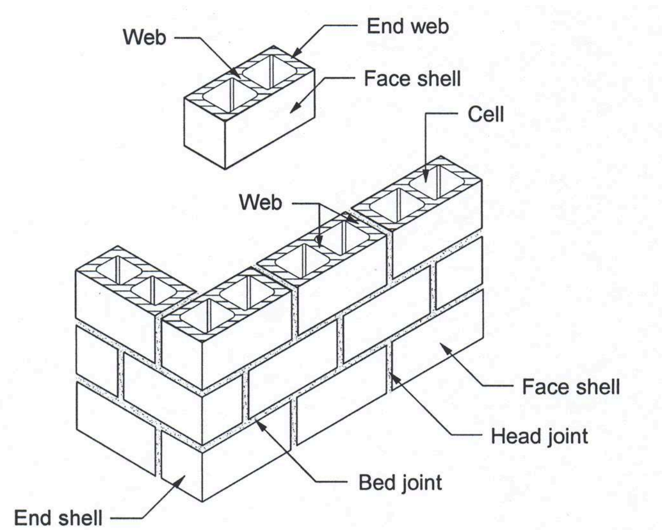


Materials – Mortar

- Function of Mortar
- Mortar Types – M, S, N
  - S is most common for structural masonry
- Mortar Type Has Limited Influence on Engineering

Materials – Mortar

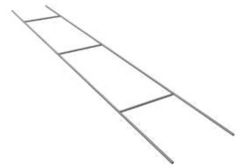
Terminology for Mortar
- Bed Joint
- Head Joint



Materials – Grout

- Function of Grout
- Grout Types
  - Fine
  - Coarse
  - Self-Consolidating
- Grout Type Has Limited Influence on Engineering
- Strength Matters

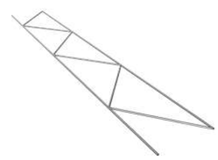
Materials – Reinforcing



- Function of Reinforcing
- Reinforcement Types
  - Reinforcing Bars
  - Joint Reinforcing
- Bar Reinforcement
  - Typical: F_y = 60 ksi
  - No Restrictions on Use

Figures from Wire-Bond

Materials – Joint Reinforcing



- Joint Reinforcing - Material
  - Cold worked wire, with limited deformations
  - 9 gauge or 3/16” longitudinal wires
  - Truss or ladder configuration
  - Typical: F_y = 70 ksi
- Uses:
  - Prescriptive / crack control
  - In-plane shear
  - Out of plane flexure (wall spans horizontal)
- Not permitted for in-plane flexure (beams) (TMS 9.1.9.3.1)

Figures from Wire-Bond

Assemblages – Strength (Clay)

Table 1 — Compressive strength of masonry based on the compressive strength of clay masonry units and type of mortar used in construction

Net area compressive strength of clay masonry, psi (MPa)	Net area compressive strength of clay masonry units, psi (MPa)	
	Type M or S mortar	Type N mortar
1,000 (6.90)	1,700 (11.72)	2,100 (14.48)
1,500 (10.34)	3,350 (23.10)	4,150 (28.61)
2,000 (13.79)	4,950 (34.13)	6,200 (42.75)
2,500 (17.24)	6,600 (45.51)	8,250 (56.88)
3,000 (20.69)	8,250 (56.88)	10,300 (71.02)
3,500 (24.13)	9,900 (68.26)	—
4,000 (27.58)	11,500 (79.29)	—

Assemblages – Strength (Concrete)

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

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

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

Assemblages – Strength (Grout)

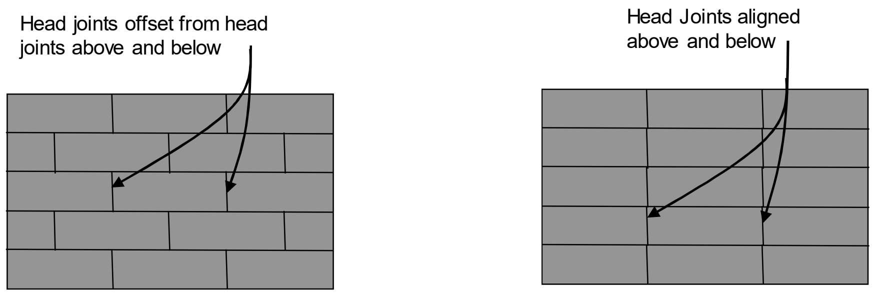
- What about grout? (TMS 602 Art. 2.2)
  - If $f'_m \leq 2{,}000$ psi
    - Comply ASTM C476
  - If $f'_m > 2{,}000$ psi
    - Comply ASTM C476
    - Grout strength ≥ f'_m when tested using ASTM C1019.

Assemblages – Stiffness

Table 4.2.2 Elastic Moduli

Material	Modulus of Elasticity	Modulus of Rigidity
Steel Reinforcement	E_s = 29,000,000 psi (200,000 MPa)	---
Prestressing Steel	E_{ps} shall be determined by tests or provided by manufacturer	---
Clay Masonry[a]	$E_m = 700\ f'_m$	$G = 0.4E_m$
Concrete Masonry[a]	$E_m = 900\ f'_m$	$G = 0.4E_m$
AAC Masonry	$E_{AAC} = 6500\ (f'_{AAC})^{0.6}$	$G = 0.4\ E_{AAC}$
Grout	$E_g = 500\ f'_g$	---

Assemblages – Bond Patterns



Running Bond

Stack Bond

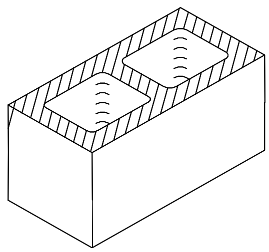
AKA
"Not Laid in Running Bond"

Bond Pattern does not affect reinforced masonry strength
Bond Pattern does affect prescriptive reinforcement and cracking moment

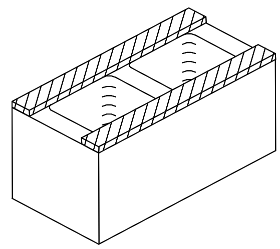
Assemblages – Grouting

- Fully Grouted
  - All void spaces are filled with grout
- Partial Grouting
  - Only spaces with reinforcing are grouted
  - Advantages
    - Reduces grout volume
    - Reduces dead and seismic loads
  - Disadvantages
    - Labor to block off grout
    - Reduced stiffness, axial and shear strength

Assemblages – Section Properties



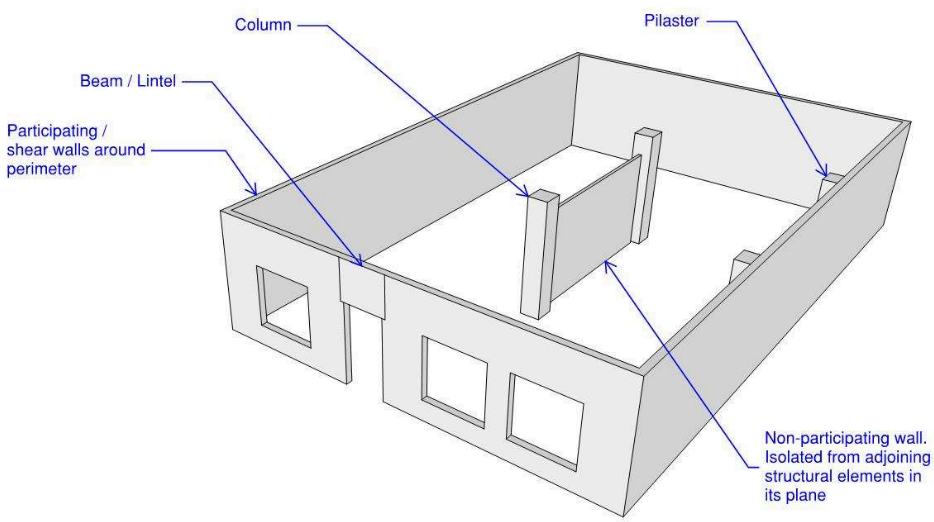
Fully Bedded



Face Shell Bedded

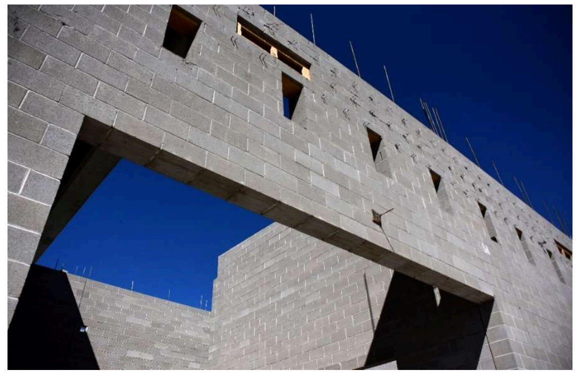
Typically assume this for design

Elements – Overview



Elements – Beams / Lintels

- TMS 402 Definition (TMS 2.2)
  - Beam - A member designed primarily to resist flexure and shear induced by loads perpendicular to its longitudinal axis.
  - Lintel = Beam
- Session 2!



Elements – Columns

- TMS 402 Definition (TMS 2.2)
  - Column — A structural member, not built integrally into a wall, designed primarily to resist compressive loads parallel to its longitudinal axis and subject to dimensional limitations.
- Session 5!

Elements – Pilasters

- TMS 402 Definition (TMS 2.2)
  - Pilaster - A vertical member, built integrally with a wall, with a portion of its cross section typically projecting from one or both faces of the wall.
- Uses
  - Out-of-plane support for wall spanning horizontally
  - Support concentrated loads
- Session 5!

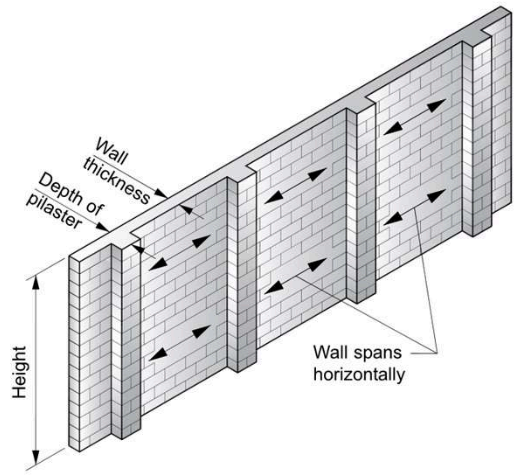
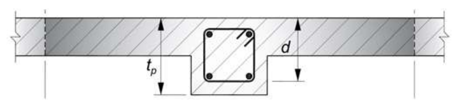


Figure from RMEH

Elements – Pilasters

- Types
  - Projecting
  - Flush
- Ties only required if:
  - Longitudinal bars used to resist compression
- Session 5!



Figures from RMEH

Elements – Walls

- TMS 402 Definition (TMS 2.2)
  - Wall — A member, usually vertical, used to enclose or separate spaces or uses.
- Types (TMS 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.

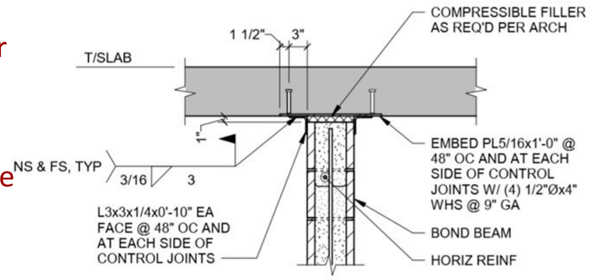


Figure from KPFF

Elements – Shear Walls

- Shear Walls Are The Only Code Recognized Type of Masonry Lateral Force Resisting System
- Types
  - ASCE 7 Chapter 12 defines which types can be used based on Seismic Design Category
  - TMS 402 Section 7.3 defines requirements for design and detailing of shear wall types

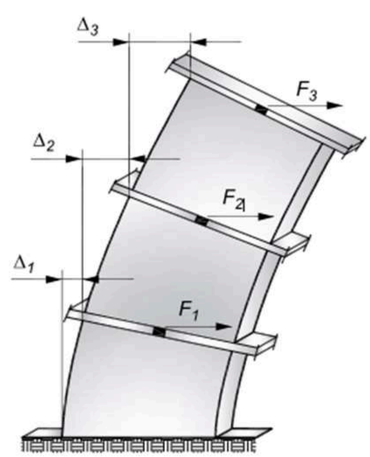


Figure from RMEH

Elements – Shear Walls

- TMS 402 Definition (TMS 2.2)
  - Wall, Load-Bearing — Wall supporting vertical loads greater than 200 lb/linear ft in addition to its own weight.
- Whether Wall is Load-Bearing Does Not Effect Design

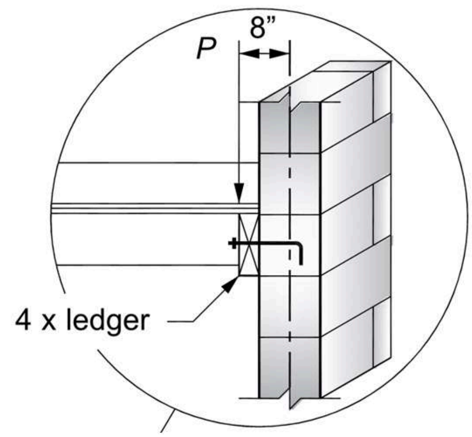
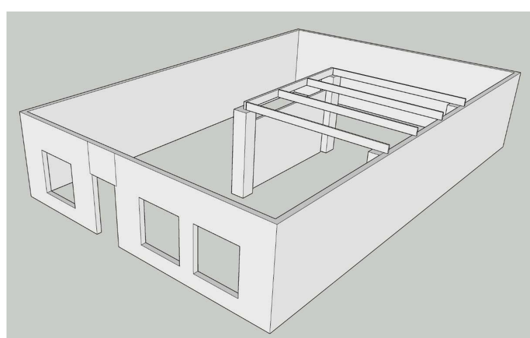


Figure from RMEH

System – Overview

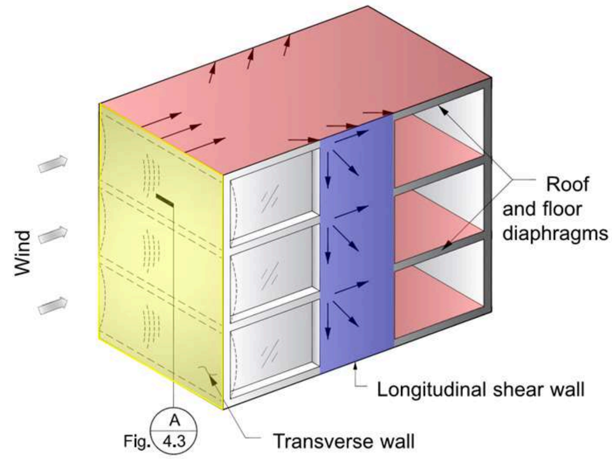
- Structural Functions
  - Bearing Walls – Support gravity loads
  - Shear Walls – Resist lateral loads
- Architectural Functions
  - Enclosure – Resist weather
  - Life Safety – Fire separation
  - Acoustics
  - Durability



- Often Architectural Functionality Determines Location and Extent of Masonry Walls

System – Load Path

- Wall Out-of-Plane Loads
  - Wind or Seismic
  - Session 3!
- Diaphragm
  - Wind / Seismic from out-of-plane
  - Seismic from floor / roof mass
  - Not covered in Night School
- Wall In-Plane Loads
  - Loads from diaphragm
  - Session 4!
- Foundations (not shown)



Introduction to Strength Design

- Strength
- Serviceability

Strength – Philosophy

- Similar to SD of Concrete and Steel
- TMS 402 Section 9.1.3

Masonry members shall be proportioned so that the design strength equals or exceeds required strength.

Design strength is the nominal strength multiplied by the strength-reduction factor.

Strength – Philosophy

$$\phi C_n \geq D_u$$

ϕC_n Design Strength (Capacity)

D_u Required Strength = Factored Load (Demand)

Strength – Philosophy

$$\phi C_n$$

ϕ Strength Reduction Factor

C_n Nominal Strength

Strength – Philosophy

$$C_n$$

- Nominal Strength
  - Estimate of strength (limit state), based on code prescribed equations.

- Example – Nominal Tensile Strength of #5 Bar
  - $T_n = A_s f_y$
  - A_s = 0.31 in^2, average area of #5 bar
  - f_y= 60 ksi, specified yield strength
  - T_n= 18.6 kips

Strength – Philosophy

$$\phi$$

- Strength Reduction Factor
  - Variability in material strengths (f_y)
  - Variation in geometric properties (A_s)
  - Model error $(T_n = A_s f_y)$
  - Type of failure
    - Brittle versus ductile
    - Consequence of failure

Strength – Philosophy

$$\phi$$

Limit State for Reinforced Masonry Design	Strength-reduction factor, ϕ
Bearing	0.6
Combinations of flexure and axial load in unreinforced masonry	0.6
Combinations of flexure and axial load in reinforced masonry	0.9
Shear and shear-friction	0.8
Anchor bolts: For cases where the nominal strength is controlled by masonry breakout, by masonry crushing, or by anchor bolt pryout	0.50
Anchor bolts: For cases where the nominal strength is controlled by anchor bolt steel	0.90
Anchor bolts: For cases where the nominal strength is controlled by anchor pullout	0.65

Strength – Philosophy

$$D_u$$

- Nominal load x Load Factor (ASCE 7)
  - (1) $1.4D$
  - (2) $1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
  - (3) $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
  - (4) $1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$
  - **(5) $0.9D + 1.0W$**
  - (6) $1.2D + E_v + E_h + L + 0.2S$
  - **(7) $0.9D - E_v + E_h$**

Strength – Unreinforced

- Design Methodology - Same as ASD
  - Usually will have some prescriptive reinforcing
  - Reinforcing not relied upon for strength
- Uses
  - Non-participating – All Seismic Design Categories
  - Participating – Seismic Design Categories A and B
  - Projecting pilasters
- Not Permitted
  - Beams
  - Columns
  - Flush Pilasters

Strength – Unreinforced

$$-\frac{P_u}{A_n}+\frac{M_u}{S_n}\leq \phi f_r$$

- Flexural tension almost always controls design
- Strength reduction factor, ø
  - Flexure + Axial: 0.6
  - Shear: 0.8

Strength – Unreinforced

Table 9.1.9.2 — Modulus of rupture[1], f_r, psi (kPa)

Direction of flexural tensile stress and masonry type	Mortar types: Portland cement/lime or mortar cement, M or S	Portland cement/lime or mortar cement, N	Masonry cement or air entrained portland cement/lime, M or S	Masonry cement or air entrained portland cement/lime, N
Normal to bed joints				
Solid units	133 (919)	100 (690)	80 (552)	51 (349)
Hollow units[2]				
Ungrouted	84 (579)	64(441)	51 (349)	31 (211)
Fully grouted	163 (1124)	158 (1089)	153 (1055)	145 (1000)
Parallel to bed joints in running bond				
Solid units	267 (1839)	200 (1379)	160 (1103)	100 (689)
Hollow units				
Ungrouted and partially grouted	167 (1149)	127 (873)	100 (689)	64 (441)
Fully grouted	267 (1839)	200 (1379)	160 (1103)	100 (689)
Parallel to bed joints in masonry not laid in running bond				
Continuous grout section parallel to bed joints	335 (2310)	335 (2310)	335 (2310)	335 (2310)
Other	0 (0)	0 (0)	0 (0)	0 (0)

Strength – Unreinforced

Shear Strength

Masonry Bond Pattern	Construction	
	Fully Grouted	**Other than Fully Grouted**
Masonry Laid in Running Bond	$90\,A_{nv} + 0.45\,P_u$ $(0.620\,A_{nv} + 0.45\,P_u)$	$56\,A_{nv} + 0.45\,P_u$ $(0.386\,A_{nv} + 0.45\,P_u)$
Masonry Not Laid in Running Bond		
Open-Ended Units	$56\,A_{nv} + 0.45\,P_u$ $(0.386\,A_{nv} + 0.45\,P_u)$	$23\,A_{nv}$ $(0.159\,A_{nv})$
Other than Open-Ended Units	$23\,A_{nv}$ $(0.159\,A_{nv})$	$23\,A_{nv}$ $(0.159\,A_{nv})$

Summary of provisions in TMS 9.2.6.1

Poll #4

Which best describes your comfort with strength design?

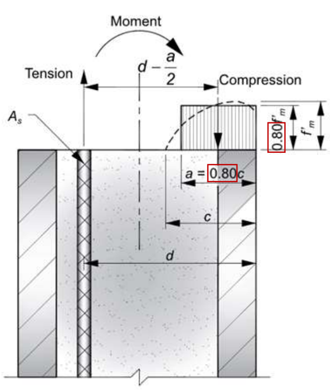
A. I am not comfortable with strength design
B. I am comfortable with strength design of concrete
C. I am comfortable with strength design of masonry
D. I am comfortable with strength design of concrete and masonry

Strength – Reinforced

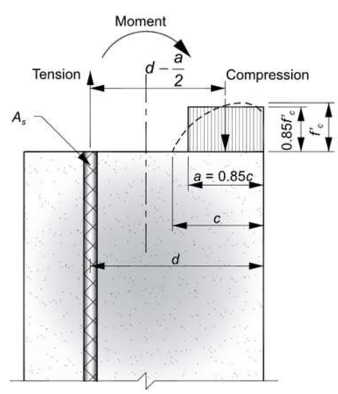
- Design Assumptions
  - Equilibrium
  - Strain compatibility
  - Strain proportional to distance from neutral axis
  - Maximum usable strain in masonry, ε_{mu}
    - Clay Masonry: 0.0035
    - Concrete Masonry: 0.0025
    - <Concrete: 0.0030
  - Stress is proportional to strain (Elastic Modulus)
  - Reinforcing can only resist compression if confined
  - Masonry does not resist tension induced by flexure or axial loads
  - Rectangular stress block

Strength – Reinforced

- Rectangular Stress Block



Masonry



Concrete

Figures from RMEH

Strength – Reinforced

- Many Similarities to Reinforced Concrete Design
- Flexure
  - Concrete: $\phi M_n = \phi\rho f_y b d^2 \left(1 - 0.59\rho \frac{f'_c}{f_y}\right)$
  - Masonry: $\phi M_n = \phi\rho f_y b d^2 \left(1 - 0.625\rho \frac{f'_m}{f_y}\right)$

Strength – Reinforced

- Axial
  - Concrete: $\phi P_{n,max} = \phi(0.80)\left[0.85 f'_c\left(A_g - A_{st}\right) + f_y A_{st}\right]$
  - Masonry: $\phi P_{n,max} = \phi(0.80)\left[0.80 f'_m(A_n - A_{st}) + f_y A_{st}\right]$
- Differences
  - Slenderness handled very differently

Strength – Reinforced

- Flexure + Axial
  - Approach to considering interaction is identical
- Differences
  - ϕ varies for concrete, 0.9 for masonry
- Shear
  - Both use √ of material strength
  - Otherwise quite a few differences.

Serviceability – Walls Out-of-Plane

- Deflection Limits
  - IBC Table 1604.3
    - Exterior walls, under 10 year wind load
      - With plaster or stucco finishes: $l/360$
      - With other brittle finishes: $l/240$
      - With flexible finishes: $l/120$
    - Interior partitions, under 5 psf interior live load
      - With plaster or stucco finishes: $l/360$
      - With other brittle finishes: $l/240$
      - With flexible finishes: $l/120$
  - TMS 402 9.3.5.5
    - Under 50 year wind load = 0.007h~$l/140$ ($l/200$ under 10 year wind load)

Serviceability - Beams

- Deflection Limits
  - IBC Table 1604.3
    - Roofs – depends on ceiling construction and loading condition
    - Floors – depends on loading condition
  - TMS 402 5.2.1.4
    - Deflections — Masonry beams shall be designed to have adequate stiffness to limit deflections that adversely affect strength or serviceability.
    - If supporting masonry designed using unreinforced provisions, or non-engineered methods (Chapter 14. Appendix A):
      - $l/600$ under dead + live

This concludes The American Institute of Architects Continuing Education Systems Course

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John Hochwalt
john.hochwalt@kpff.com

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