Introduction to Allowable Strength Design of Masonry and Design Methodologies

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Welcome to Night School

- Course Description
- Focus of Course
- Road Maps

Course Description

This 6-session course will introduce allowable stress design (ASD) 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 6-sessions will also conclude with a review of requirements for reinforcement and connectors and detailing masonry effectively. This course is an excellent way to learn allowable stress design procedures. Those taking the course should have a basic familiarity with masonry (consistent with content presented in TMS's Masonry 101).

Focus of Course

Address the ASD Design procedures in:

- 2018 IBC + TMS 402/602-16

Look at both

- Concrete and Clay Hollow Masonry

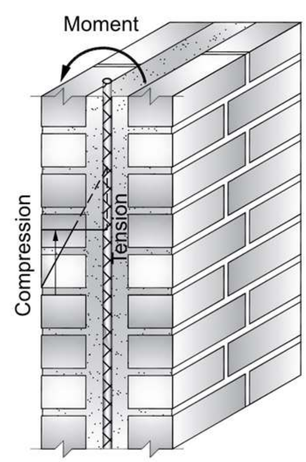
Restrict ourselves to:

- Reinforced Masonry

Focus of Course

Not Included are:

- Multiwythe masonry
- AAC Masonry (TMS 402 Chapter 10)
- Unreinforced Masonry (TMS 402 Section 8.2)
- Masonry Veneer (TMS 402 Chapter 12)



Multiwythe Masonry

Course Road Map

Session 1 – Introduction to Allowable Stress Design of Masonry and Design Methodologies (McGinley)

Session 2 – Design of Beams (Walkowicz)

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

Course Road Map

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

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

Session 6 –Design Requirements for Reinforcement & Connectors (Walkowicz)

Tonight's Road Map

✓Introduction to Night School

- Introduction to Masonry
  - Materials
  - Assemblages
  - Elements
  - Systems

- Introduction to Allowable Strength Design
  - Stress Limits
  - Serviceability

Course Description

This introductory session will quickly introduce the entire Allowable Stress Design (ASD) night school course, and then will review the basic Allowable Stress Design concepts for masonry. Key differences with strength design procedures will be presented. Masonry assemblies and systems will be briefly reviewed noting their purposes and resistance to primary loads. Typical masonry building elements will be introduced related to their roles in the overall structural system including walls, beams, columns, and pilasters, to ensure attendees understand their function for sessions where the design of these elements will be discussed. Loads and load combinations from ASCE-7 & and the IBC will be reviewed.

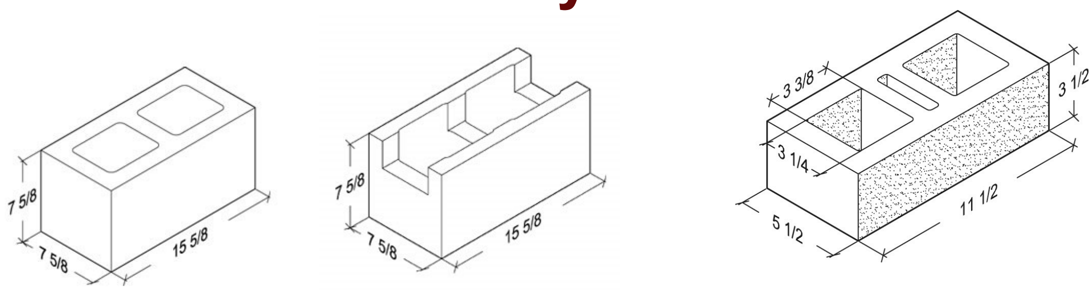
Learning Objectives

- Introduce Allowable Stress Design (ASD) 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

Be aware that ASTM standards have Changed

Starting with C90-11b – Equivalent web area replaces equivalent web thickness

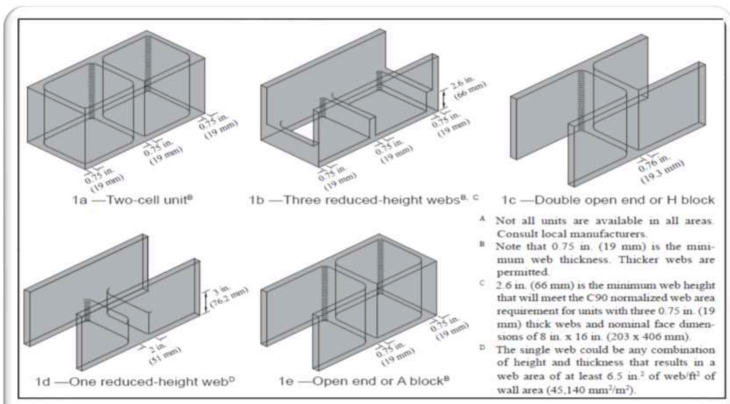


Figure 1—Examples of Web Configurations Permitted Under ASTM C90-11b[A]

NCMA TEK 2-5B

Examples of unit configurations that comply with new ASTM C90 web area requirements

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

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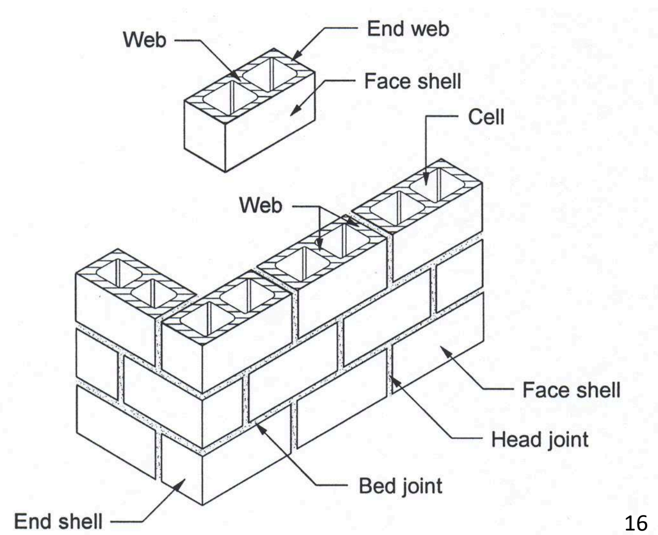
Materials – Masonry Units

Terminology for Units

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



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Materials – Mortar

- Function of Mortar
- Mortar Types – M, S, N
  - S is most common for structural masonry
  - 3 mortar systems- PCL, Masonry Cement, Mortar Cement
- Mortar Type Has Limited Influence on Engineering properties of reinforced masonry

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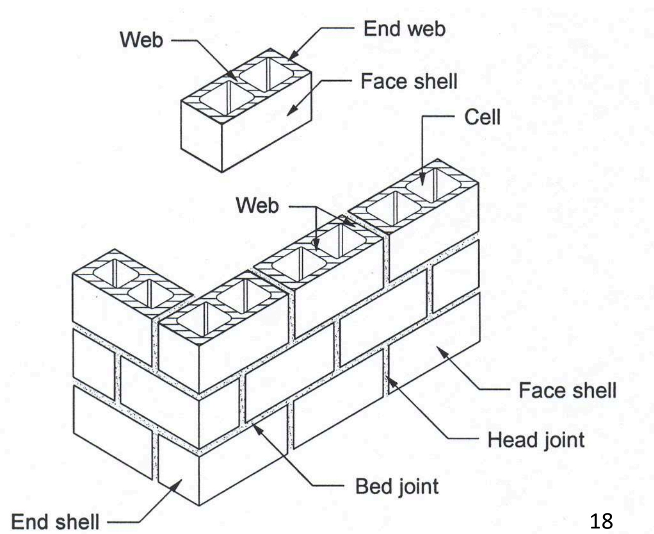
Materials – Mortar

Terminology for Mortar

- Bed Joint
- Head Joint



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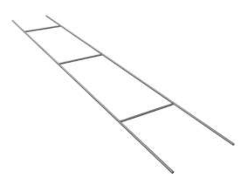
Materials – Grout

- Function of Grout
- Grout Types
  - Fine
  - Coarse
  - Self-Consolidating
- Grout Type Has Limited Influence on Engineering properties
- 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)
- Permitted for in-plane flexure (beams) - SD does not allow.

Figures from Wire-Bond

Details of Reinforcement: TMS 402 Section 6.1

- reinforcing bars must be embedded in grout; joint reinforcement can be embedded in mortar
- placement of reinforcement
- protection for reinforcement
- standard hooks
- See Session 6 Also Anchors

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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)	—

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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.

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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 $\geq f'_m$ when tested using ASTM C1019.

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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	$E_g = 500 f'_g$	---

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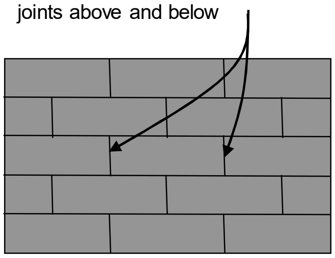
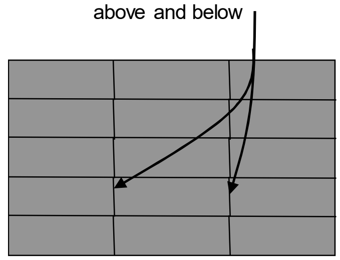
Assemblages – Bond Patterns

Head joints offset from head joints above and below



Running Bond

Head Joints aligned above and below



Stack Bond

AKA
“Not Laid in Running Bond”

Type of Running Bond Pattern will not affect reinforced masonry strength
Other than Running Bond Pattern does affect prescriptive reinforcement and must be reinforced to provide continuity

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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

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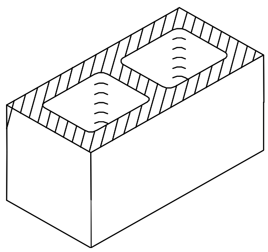
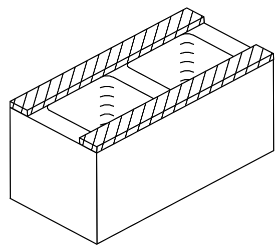
Assemblages – Section Properties



Fully Bedded



Face Shell Bedded

Typically assume this for design

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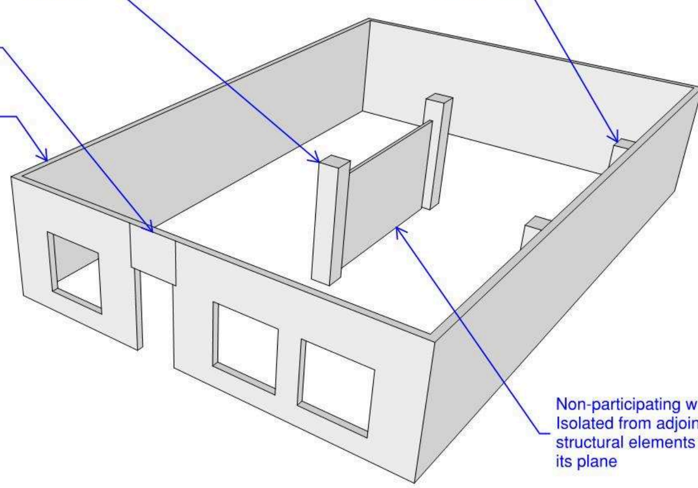
Elements – Overview



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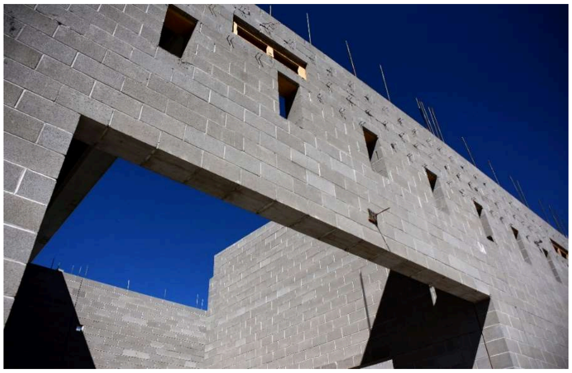
Elements – Beams / Lintels

- 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
- more in Session 2!



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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!

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Elements – Walls and Pilasters

- TMS 402 Definition (TMS 2.2)
  - Wall — A member, usually vertical, used to enclose or separate spaces or uses.
- 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.
  - Essentially a T beam wall element.
- Uses -
  - Out-of-plane support for wall spanning horizontally
  - Support concentrated loads
- Session 5!

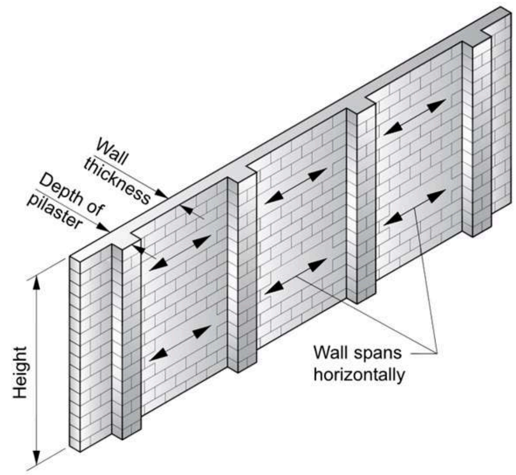

Figure from RMEH

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Elements – Walls lateral load resisting

- In-plane loading - 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.

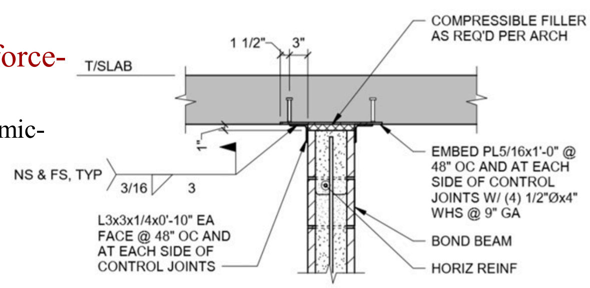

Figure from KPFF

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Elements – Shear Walls

- Shear Walls Are The Only Code Recognized Type of Lateral Force Resisting System for Masonry
- 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
- 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.

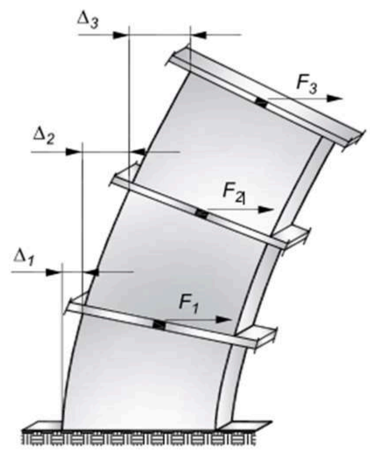

Figure from RMEH

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Masonry Design

- For ASD, IBC 2018 Section 2107 requires compliance with TMS 402 Chapters 1-8, except for:
  - It allows alternate splice & development lengths
  - it has additional requirements for mechanical and welded splices
- Since the IBC it requires compliance in accordance with TMS 402, this standard will be the focus of the next five sessions.
-
- Splices are discussed more in Session 6

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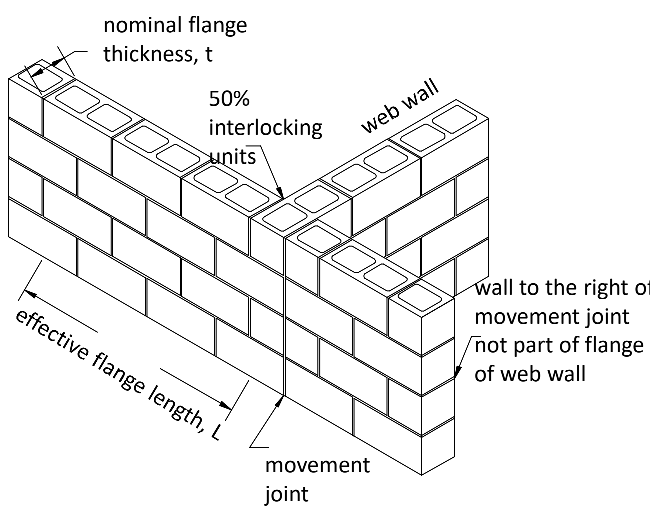
TMS 402 Part 2 Design Requirements

- Ch. 4: General Analysis & Design Considerations
- Ch. 5: Structural Elements
  - 5.1 Masonry assemblies
  - 5,2 Beams
  - 5.3 Columns
  - 5.4 Pilasters
  - 5.5 Corbels
- Ch. 6: Details of reinforcement, metal accessories & anchor bolts
- Ch. 7 Seismic design requirements

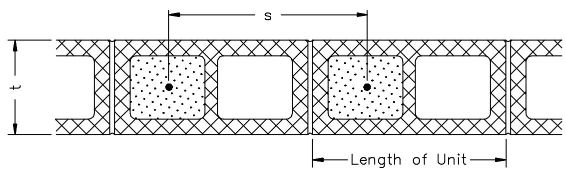
Wall intersections: TMS 402 Section 5.1.1

L = 6 t for compression or unreinforced masonry in tension
L = 3/4 floor - to - floor wall height for reinforced masonry in tension



Effective compression width per bar: TMS 402 Section 5.1.2

- For running - bond masonry, or masonry with bond beams spaced no more than 48 in. center – to – center, the width of compression area per bar for stress calculations shall not exceed the least of:
  - Center - to - center bar spacing
  - Six times the wall thickness (nominal)
  - 72 in.



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Distribution of concentrated loads, running bond: TMS 402 Section 5.1.3.1

- The critical area for walls laid in running bond shall not exceed the wall thickness times the smaller of:
  - Length of bearing area plus a length determined by a dispersion of 2 vertical: 1 horizontal. That dispersion is limited by the smallest of one - half the wall height, a movement joint, the end of the wall, or an opening.
  - Center – to – center distance between concentrated loads

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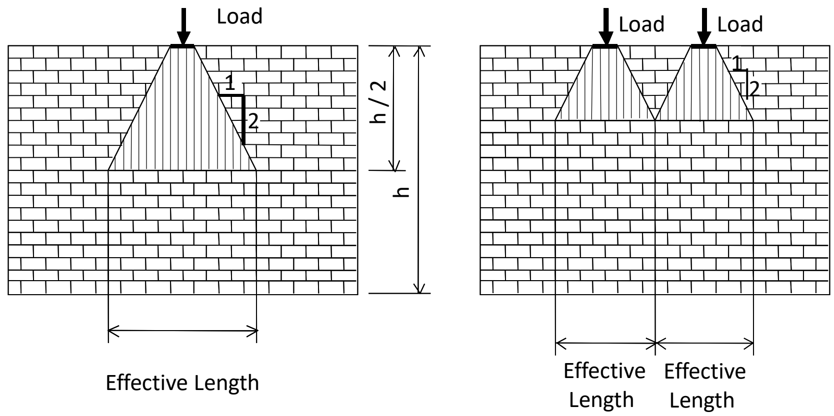
(5.1.3.1) Distribution of concentrated loads



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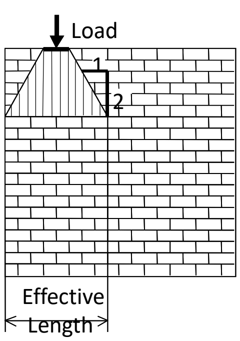
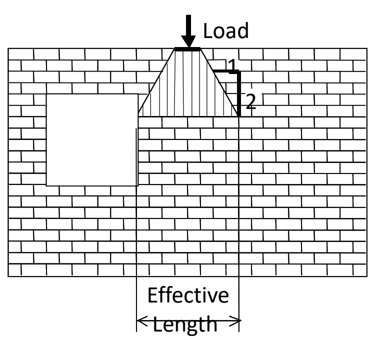
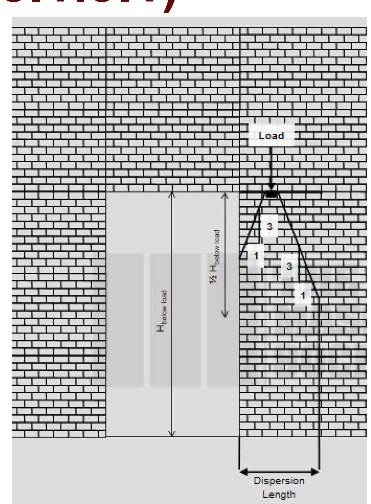
- Center – to – center distance between concentrated loads

Near Openings and Joints (5.1.3.1)







Composite versus noncomposite construction: (Section 5.1.4)

- Multiwythe walls have more than one wythe of masonry
- Multiwythe walls may be designed for:
  - composite action, or noncomposite action
- Composite action requires that collar joints be:
  - crossed by connecting headers, or filled with mortar or grouted and connected by ties
  - Composite action permits use of composite section properties in analysis and design
  - Composite action is assumed to transfer loads and provide continuity of deformations, without slip, across collar joints
  - TMS 402 Section limits shear stresses on collar joints or headers

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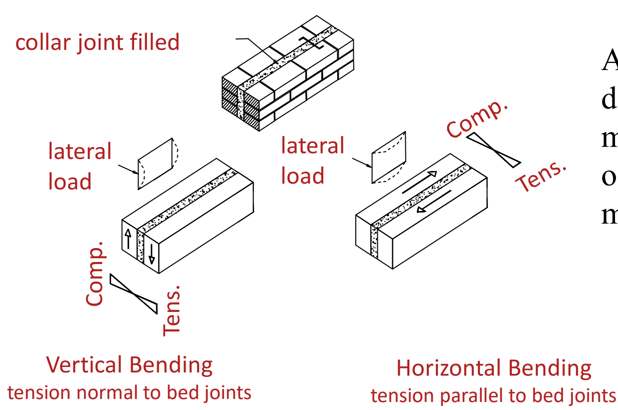
Stresses with **composite** action, Code Commentary - Fig. CC – 5.1-7



Assumed stress distribution in multiwythe walls of composite masonry

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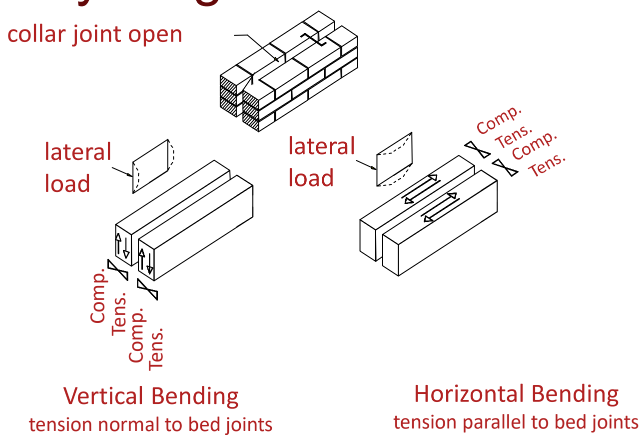
Stresses with **noncomposite** action, Code Commentary - Fig. 5.1-8

Assumed stress distribution in Multi-wythe noncomposite walls



Collar joints may not contain headers, grout, or mortar
Horizontal in-plane loads and gravity loads applied to one wythe are to be resisted by that wythe only

Weak–axis bending moments, however, are distributed to each wythe in proportion to its flexural stiffness

Seismic Design: TMS 402 Chapter 7

- Applies to all masonry except
  - glass unit masonry and veneer
- Walls must either be
  - isolated from the seismic force - resisting system
  - classified as shear walls
- Objective is to improve performance of masonry structures in earthquakes
  - improves ductility of masonry members
  - improves connectivity among masonry members
- Requirements for AAC masonry differ slightly

Seismic Design: TMS 402 Chapter 7

- Assign a structure's Seismic Design Category (SDC) according to ASCE 7
  - SDC depends on seismic risk (geographic location), risk category (importance), underlying soil.
- SDC determines
  - required types of shear walls (prescriptive reinforcement)
  - prescriptive reinforcement for other masonry elements
  - permitted design approaches for LFRS
  - Requirements are cumulative; requirements in each "higher" category are added to requirements in the previous category

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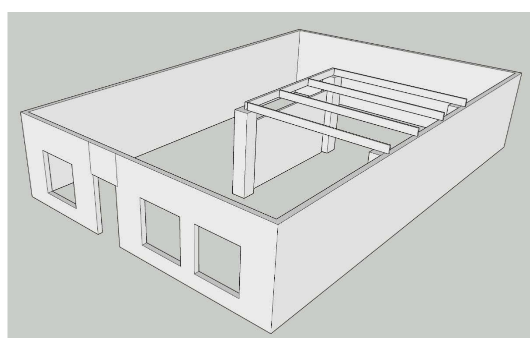
System – Overview

- 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

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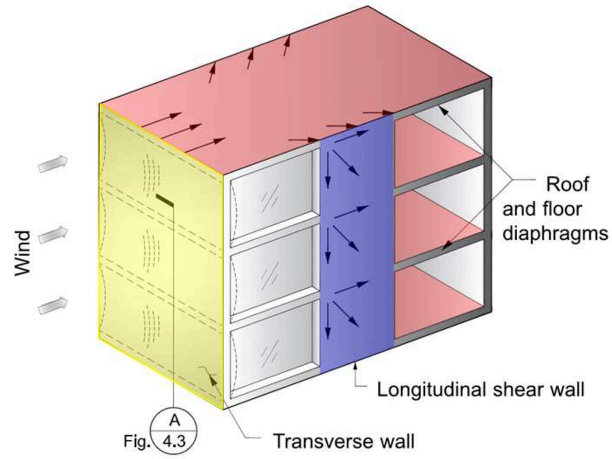
System – Load Path

- 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)



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Design

- Almost all reinforced masonry is designed by:

  A. Allowable Stress Design per TMS 402 Parts 1 & 2 and Chapter 8

  B. Strength Design per TMS 402 Parts 1 & 2 and Chapter 9

- Design is based on f'_m – *Specified compressive strength of masonry*

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Allowable Stress Design TMS 402 Ch8

- Stress limits
- Serviceability

ASD – applied stresses under ASD loads ≤ allowed stresses

$f \leq F$

Allowable–Stress Design: TMS 402 Chapter 8

Section 8.1

- fundamental basis
- Anchor bolts
- Shear stress limits on multi-wythe walls
- development and splices of reinforcement

Section 8.2 -

- Unreinforced masonry

Section 8.3

- Reinforced Masonry

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ASD Load Combinations – ASCE 7-16

- $D + F$
- $D + H + F + L$
- $D + H + F + (L_r \text{ or } S \text{ or } R)$
- $D + H + F + 0.75(L) + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + H + F + (0.6W \text{ or } 0.7E)$
- $D + H + F + 0.75(0.6W) + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
- $D + H + F + 0.75(0.7E) + 0.75L + 0.75(S)$
- $0.6D + 0.6W + H$
- $0.6(D + F) + H + 0.7E$
- No increase for E or W any more with Stress Recalibration – even with alternative load cases

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General Analysis Considerations

- Load distribution and deformation – elastic analysis based on uncracked sections, except beam defl. (I_{eff} was in Commentary now in Section 5.2 for beams)
- Member stresses and actions – calculated on minimum critical sections (reinforced – cracked). Section 4.3
- Member stiffness calculated based on average sections.
- For CMU – See Tek Note 14-1B Section Properties (www.ncma.org)

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Ch. 8.2 in MSJC-ASD URM Masonry

Assumptions (Stresses on net section) – $f_a = \frac{P}{A_n}$, $f_b = \frac{M}{S_n}$

- Net flexural tension stress limited - Table 8.2.1.4 $f_t \le F_t$

Table 8.2.4.2 — Allowable flexural tensile stresses for clay and concrete masonry, psi (kPa)

Direction of flexural tensile stress and masonry type	Mortar types			
	Portland cement/lime or mortar cement		Masonry cement or air entrained portland cement/lime	
	M or S	N	M or S	N
Normal to bed joints				
Solid units	53 (366)	40 (276)	32 (221)	20 (138)
Hollow units[1]				
Ungrouted	33 (228)	25 (172)	20 (138)	12 (83)
Fully grouted	65 (448)	63 (434)	61 (420)	58 (400)
Parallel to bed joints in running bond				
Solid units	106 (731)	80 (552)	64 (441)	40 (276)
Hollow units				
Ungrouted and partially grouted	66 (455)	50 (345)	40 (276)	25 (172)
Fully grouted	106 (731)	80 (552)	64 (441)	40 (276)
Parallel to bed joints in masonry not laid in running bond				
Continuous grout section parallel to bed joints	133 (917)	133 (917)	133 (917)	133 (917)
Other	0 (0)	0 (0)	0 (0)	0 (0)

Ch. 8.2 in MSJC-ASD URM Masonry

- Compression stress limited $f_a \le F_a$, $f_b \le 1/3 f_m$

$$F_a = (0.25f'_m)\left[1 - \left(\frac{h}{140r}\right)^2\right] \text{ for } \frac{h}{r} \le 99$$

$$F_a = (0.25f'_m)\left(\frac{70r}{h}\right)^2 \text{ for } \frac{h}{r} > 99 \text{ and}$$

$$P \le P_e = \left[\frac{\pi^2 E_m I_n}{h^2}\left(1 - 0.577\frac{e}{r}\right)^3\right]$$

- Force unity equation $\frac{f_a}{F_a} + \frac{f_b}{F_b} \le 1$

- Shear , $f_v = \frac{VQ}{I_n b} \le 1.5\sqrt{f'_m}$, 120 psi, or 37 psi +0.45 $\frac{N_v}{A_n}$, or 60 psi +0.45 $\frac{N_v}{A_n}$, or 15 psi

Ch. 8.3 in MSJC-ASD Reinforced Masonry

Assumptions

- Masonry in flexural tension is cracked
- Reinforcing steel is needed to resist tension
- Linear elastic theory
- No min. required steel area except columns
- Wire joint reinforcement can be used as flexural reinforcement
- No unity or interaction equation – use interaction curves

ASD- OOP (IP similar)

Look at internal Equil.

Non Load bearing $\Sigma F_{vert} = 0$, $P = 0$ so $C = T$

Load Bearing ΣF_{vert} so $P = C - T$

$C = ½ \times b \times f_m \times kd$

$T = A_s x f_s = C$

For Flexure only

ΣM about $C =$ $T \times d - 1/3kd$

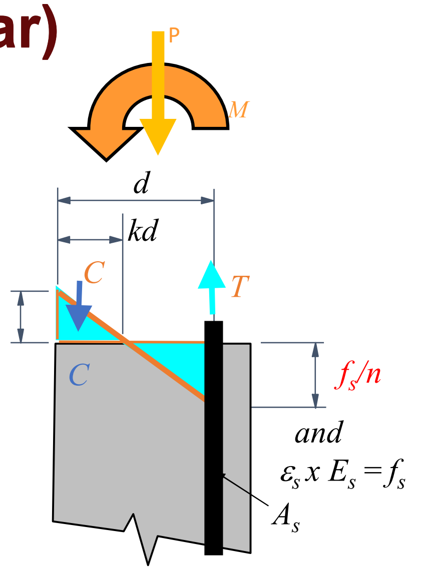
Let $d-1/3kd = d\,j$ where $j = 1-k/3$

$M_s = A_s \, x \, f_s \, x \, j \, d$

$M_m = ½ \, f_m \, x \, b \, x \, k \, x \, j \, x \, d^2$

At the limit $f_s = F_s$ or $f_m = F_b$

$\varepsilon_m \, x \, E_m = f_m$



f_b = is the f_m due to just flexure

Allowable Stresses Steel

Tension

Grade 40 or 50	20,000 psi
Grade 60	32,000 psi
Wire joint reinforcement	30,000 psi

Compression

- Only reinforcement that is laterally tied (Section 5.3.1.4) can be used to resist compression
- Allowable compressive stress = allowable tension stress if tied.

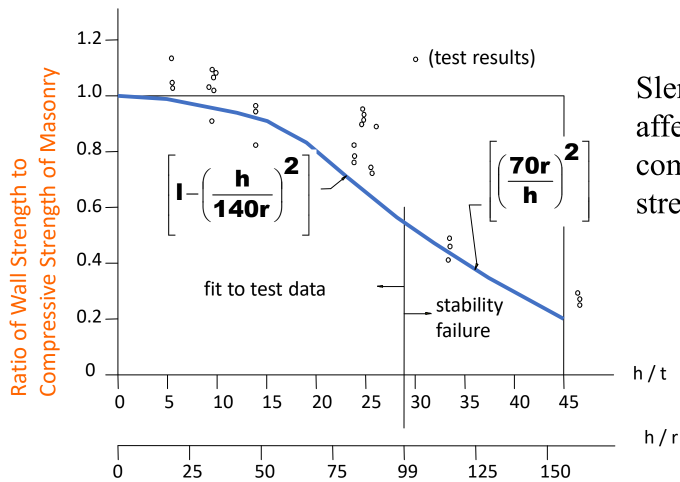
Allowable Axial Compression

- ASD reinforced allowable compressive capacity is expressed in terms of force rather than stress – 8-18, 8-19
- Allowable capacity Σ(masonry + tied compressive reinforcement)
- Max. compressive stress in masonry from axial load & bending ≤ (0.45)f'_m
- Axial compressive stress must not exceed allowable axial stress from Code 8.2.4.1

$$P_a = (0.25f'_m A_n + 0.65A_{st}F_s)\left[1 - \left(\frac{h}{140r}\right)^2\right] \text{ for } \frac{h}{r} \leq 99 \quad \text{Eq. 8-18}$$

$$P_a = (0.25f'_m A_n + 0.65A_{st}F_s)\left(\frac{70r}{h}\right)^2 \text{ for } \frac{h}{r} > 99 \quad \text{Eq. 8-19}$$

Code Commentary Fig. CC - 8.2-1



Slenderness affects axial compressive strength

Slide 61

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: $l/120$

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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