Overview of Masonry Codes

Richard Bennett, PhD, PE
The University of Tennessee

Chair, 2016 TMS 402/602 Committee
2nd Vice-chair, 2022 TMS 402/602 Committee

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Description

This presentation will provide information on the TMS 402 Building Code Requirements for Masonry Construction and TMS 602 Specification for Masonry Construction. An overview of the code will be provided, recent changes will be discussed, and design methods using the code will be illustrated.

Keywords: masonry, building codes, structural design
Learning Objectives

1. Understand the organization of TMS 402/602
2. Be informed on recent changes in the code
3. Understand the basic provisions of the TMS 402 Building Code Requirements for Masonry Construction
4. Understand structural masonry design using the TMS 402 code

Masonry Codes and Standards

- Almost the entire US now uses the IBC. We will focus on the 2018 IBC.

- The IBC extensively references “Consensus” Design and Material Standards:
  - ASTM Standards for Materials
  - ASCE 7 for Loads
  - ACI 318 for Concrete
  - TMS 402/602 for Masonry
Masonry Introduction

IBC Masonry Requirements

- Chapter 7 – Fire Ratings
- Chapter 14 – Veneer
- Chapter 17 – Quality Assurance
- Chapter 18 – Foundation Walls (includes prescriptive requirements based on TMS 402 Strength Design Procedures)
- Chapter 21 – Masonry

IBC Chapter 21

Section 2101 General
Section 2102 Definitions and Notations
Section 2103 Masonry Construction Materials
Section 2104 Construction
Section 2105 Quality Assurance
Section 2106 Seismic Design
Section 2107 Allowable Stress Design
Section 2108 Strength Design of Masonry
Section 2109 Empirical Design of Masonry
Section 2110 Glass Unit Masonry
Section 2111 Masonry Fireplaces
Section 2112 Masonry Heaters
Section 2113 Masonry Chimneys
IBC Section 2107: ASD

IBC Section 2107 requires compliance with TMS 402 Chapter 8, except for:

- Modifies splice lengths
  - $l_d = 0.002 d_b f_s \geq 12$ in.
  - $f_s = \text{computed stress in reinforcement due to design loads}$
  - Increase lap length by 50% when $f_s > 0.80 f_y$
  - Some cases is more conservative and in some cases less conservative than the TMS 402

- Has additional requirements for mechanical and welded splices
  - ASTM A706 steel required for welded lap splices.
  - Mechanical splices required for bars > No. 9

IBC Section 2108: SD

IBC Section 2108 requires compliance with TMS 402 Chapter 9, except:

- Development lengths capped at $72 d_b$
  - for No. 7 and larger bars, the $72 d_b$ cap governs, and the IBC gives a shorter development lengths than the TMS 402 for centered bars.

- Has additional requirements for mechanical and welded splices
  - ASTM A706 steel required for welded lap splices. Welded splices not permitted in plastic hinge zones of intermediate or special shear walls.
  - ACI 318 Type 1 mechanical splices required in plastic hinge zones of intermediate and special shear walls.
TMS 402/602

- **TMS 402 “Code”**
  - Design provisions are given in Chapters 1 - 14 and Appendices A, B and C
  - Sections 1.2.4 and Chapter 3 require a QA program in accordance with the Specification
  - Section 1.4 invokes the Specification by reference.

- **TMS 602 “Specification”**
  - verify compliance with specified $f'_m$
  - comply with required level of quality assurance
  - comply with specified products and execution

History of TMS 402/602

1988: First edition
1995: Seismic requirements moved from Appendix to main body of code; chapter on veneers added; chapter on glass block added
1998: Major reorganization of code; prestressed masonry chapter added
2002: Strength design chapter added; definitions of shear walls added to correspond to IBC definitions; code moved to a three year revision cycle
2005: Changed lap splice requirements, requiring much longer lap lengths
2008: Major reorganization of seismic requirements; added AAC masonry in Appendix
2011: Eliminated one-third stress increase and recalibrated allowable stresses; added infill provisions in Appendix
2013: Changes for partially grouted shear walls; updated unit strength table; limit states appendix
2016: Add shear friction provisions; increase cavity width; update anchor bolts
2022: Go to a six-year cycle
TMS 402 Part 1 General Requirements

- Ch. 1: Scope, Contract documents and calculations, Special Systems, Reference Standards
- Ch. 2: Notation, Definitions
- Ch. 3 Quality & Construction
  - Requires a quality assurance program in accordance with the Specification
  - Three levels of quality assurance (1, 2, 3)
  - Increasing levels of quality assurance require increasingly strict requirements for inspection, and for compliance with specified products and execution
Masonry Introduction

TMS 602 Verification Requirements

Table 3 — Minimum Verification Requirements

<table>
<thead>
<tr>
<th>Minimum Verification</th>
<th>Required for Quality Assurance</th>
<th>Reference for Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to construction, verification of compliance of submittals.</td>
<td>R</td>
<td>Art. 1.5</td>
</tr>
<tr>
<td>Prior to construction, verification of $f'<em>{wa}$ and $f'</em>{wrc}$ except where specified in the Code.</td>
<td>NR</td>
<td>Art. 1.4 B</td>
</tr>
<tr>
<td>During construction, verification of slump flow and Visual Stability Index (VSI) when self-consolidating grout is delivered to the project site.</td>
<td>NR</td>
<td>Art. 1.5 &amp; 1.6.3</td>
</tr>
<tr>
<td>During construction, verification of $f'<em>{wa}$ and $f'</em>{wrc}$ for every 5,000 sq. ft. (465 sq. m.).</td>
<td>NR</td>
<td>Art. 1.4 B</td>
</tr>
<tr>
<td>During construction, verification of proportions of materials as delivered to the project site for grouted or prebushed concrete, prestressing grout, and grout other than self-consolidating grout.</td>
<td>NR</td>
<td>Art. 1.4 B</td>
</tr>
</tbody>
</table>

(a) R=Required, NR=Not Required

TMS 602 ( & IBC) QA Requirements

Table 4 — Minimum Special Inspection Requirements

<table>
<thead>
<tr>
<th>Inspection Task</th>
<th>Frequency</th>
<th>Reference for Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. As masonry construction begins, verify that the following are in compliance.</td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>a. Proportions of sand-cement mortar</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>c. Grade and size of prestressing tendons and anchors</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>e. Grade, type and size of reinforcement, connectors, anchor bolts, and prestressing tendons and anchors</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>d. Prestressing technique</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>f. Properties of finished mortar for A&amp;C masonry</td>
<td>NR</td>
<td>C</td>
</tr>
<tr>
<td>f. Sample panel construction</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>2. Prior to grouting, verify that the following are in compliance.</td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>a. Guest space</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>b. Placement of prestressing tendons and anchors</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>e. Placement of reinforcement, connectors, and anchor bolts</td>
<td>NR</td>
<td>P</td>
</tr>
<tr>
<td>d. Proportions of sand-cement mortar and prestressing grout for bundled tendons</td>
<td>NR</td>
<td>P</td>
</tr>
</tbody>
</table>
TMS 402 Section 3.2: Construction

- Grout space requirements in Table 3.2.1 are intended to provide adequate room for placement of grout.
- Restricts pour height based on width/space minus horizontal reinforcement which restricts the space.

TMS 402 Part 2: Design Requirements

- Ch. 4: General Analysis & Design Considerations
  - 4.1 Loading
  - 4.2 Material properties
  - 4.3 Section properties
  - 4.4 Connections to structural frames
  - 4.5 Masonry not laid in running bond
- Ch. 5: Structural Elements
- Ch. 6: Details of reinforcement, metal accessories & anchor bolts
- Ch. 7 Seismic design requirements
Masonry Introduction

TMS 4.2 Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>CMU</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>$900f'_m$</td>
<td>$700f'_m$</td>
</tr>
<tr>
<td>Modulus of rigidity (shear modulus)</td>
<td>$0.4E_m$</td>
<td>$0.4E_m$</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>$4.5 \times 10^{-6}$ in./in./°F</td>
<td>$4.0 \times 10^{-6}$ in./in./°F</td>
</tr>
<tr>
<td>Coefficient of moisture expansion</td>
<td>N/A</td>
<td>$3 \times 10^{-4}$ in./in.</td>
</tr>
<tr>
<td>Coefficient of shrinkage</td>
<td>$k_m = 0.5\delta_t$ C90 limits shrinkage to 0.065%</td>
<td>N/A</td>
</tr>
<tr>
<td>Coefficient of creep</td>
<td>$2.5 \times 10^{-7}$ /psi</td>
<td>$0.7 \times 10^{-7}$ /psi</td>
</tr>
</tbody>
</table>

TMS 402 Section 4.3: Section Properties

- Use minimum (critical) net area for computing member stresses or capacities.
- Radius of gyration and member slenderness are better represented by the average section

TEK 14-01B: Section Properties of Concrete Masonry Walls
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

TMS 402 5.1.1: Wall Intersections

\[ L = 6t \text{ for compression or unreinforced masonry in tension} \]
\[ L = \frac{3}{4} \text{ floor-to-floor wall height for reinforced masonry in tension} \]

Either:
- 50% interlocking units
- bond beams
- connectors

nominal flange thickness, \( t \)

effective flange length, \( L \)

wall to the right of movement joint not part of flange of web wall

movement joint
TMS 402 5.1.2: Effective Comp. Width

For running-bond masonry, or masonry with bond beams spaced no more than 48 in. center-to-center:

- Center-to-center bar spacing
- Six times the wall thickness (nominal)
- 72 in.

![Diagram of Effective Comp. Width]

TMS 402 5.1.3: Concentrated Load Dist.

Effective Length

![Diagram of Concentrated Load Dist.]

Effective Length
TMS 402 5.1.3: Concentrated Load Dist.

Span length equals clear span plus depth, but not more than distance between support centers

- Minimum bearing distance = 4 in.
- Lateral support on compression face required
  - $32b$ (b = nominal beam thickness)
  - $120b^2/d$
- Deflection < L/600 when supporting unreinforced masonry
  - Deflections need not be checked when the span length does not exceed 8 multiplied by the effective depth to the reinforcement, d, in the masonry beam.
TMS 402 5.3: Columns

- ISOLATED member that primarily resists compressive loads
- \( h / r \leq 99 \)
- Minimum side dimension: 8 in.
- \( 0.25\% \leq \rho_g \leq 4.0\% \)
- At least 4 longitudinal bars, laterally tied, except for lightly loaded columns

TMS 402 Part 2: Design Requirements

- Ch. 4: General Analysis & Design Considerations
- Ch. 5: Structural Elements
- Ch. 6: Details of reinforcement, metal accessories & anchor bolts
  - 6.1 Reinforcement
  - 6.2 Metal accessories
  - 6.3 Anchor bolts
- Ch. 7 Seismic design requirements
### TMS 402 6.1: Reinforcement

<table>
<thead>
<tr>
<th>2013 TMS 402</th>
<th>2016 TMS 402</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>6.1 Details of reinforcement and metal accessories</strong></td>
<td><strong>6.1 Reinforcement</strong></td>
</tr>
<tr>
<td>6.1.1 Embedment</td>
<td>6.1.1 Embedment</td>
</tr>
<tr>
<td>6.1.2 Size of reinforcement</td>
<td>6.1.2 Size of reinforcement</td>
</tr>
<tr>
<td>6.1.3 Placement of reinforcement</td>
<td>6.1.3 Placement or reinforcement</td>
</tr>
<tr>
<td>6.1.4 Protection of reinforcement and metal accessories</td>
<td>6.1.4 Protection of reinforcement</td>
</tr>
<tr>
<td>6.1.5 Standard hooks</td>
<td>6.1.5 Development</td>
</tr>
<tr>
<td>6.1.6 Minimum bend diameter for reinforcing bars</td>
<td>6.1.5.1 Development of bar reinforcement in tension or compression</td>
</tr>
<tr>
<td></td>
<td>6.1.5.2 Development of wires in tension</td>
</tr>
<tr>
<td></td>
<td>6.1.6 Splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.1 Splices of bar reinforcement</td>
</tr>
<tr>
<td></td>
<td>6.1.6.1.1 Lap splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.1.2 Welded splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.1.3 Mechanical splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.1.4 End-bearing splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.2 Splices of wires in tension</td>
</tr>
<tr>
<td></td>
<td>6.1.6.2.1 Lap splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.2.2 Welded splices</td>
</tr>
<tr>
<td></td>
<td>6.1.6.2.3 Mechanical splices</td>
</tr>
<tr>
<td><strong>6.1.7 Shear reinforcement</strong></td>
<td><strong>6.2 Metal accessories</strong></td>
</tr>
<tr>
<td>6.1.7.1 Horizontal shear reinforcement</td>
<td>6.2.1 Protection of metal accessories</td>
</tr>
<tr>
<td>6.1.7.2 Stirrups</td>
<td></td>
</tr>
<tr>
<td>6.1.7.3 Welded wire reinforcement</td>
<td></td>
</tr>
<tr>
<td><strong>6.2 Anchor bolts</strong></td>
<td><strong>6.3 Anchor bolts</strong></td>
</tr>
</tbody>
</table>
## TMS 402 6.1: Reinforcement

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Provision</th>
<th>TMS 402 Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size of reinforcement</strong></td>
<td>Maximum size: No. 11 Maximum size, Strength design: No. 9 ( d_b \leq \frac{1}{2} ) of least clear dimension Strength design: ( d_b \leq \frac{1}{4} ) of least clear dimension Area of vertical reinforcement ( \leq 6% ) grout space Strength design: Area of vertical and horizontal reinforcement ( \leq 4% ) grout space ( d_b \leq \frac{1}{8} ) least nominal dimension</td>
<td>6.1.2.1 9.3.3.1 6.1.2.2 9.3.3.1 6.1.2.4 9.3.3.1 6.1.2.5</td>
</tr>
<tr>
<td><strong>Placement of reinforcement</strong></td>
<td>Clear distance between bars ( \geq \max { d_b, 1 \text{ in. (25.4 mm)} } ) Columns and pilasters: Clear distance between bars ( \geq \max { 1.5d_b, 1.5 \text{ in. (38.1 mm)} } ) Thickness of grout between reinforcement and masonry unit Coarse grout: ( \frac{1}{8} ) in. (12.7 mm) Fine grout: ( \frac{1}{4} ) in. (6.35 mm)</td>
<td>6.1.3.1 6.1.3.2 6.1.3.5</td>
</tr>
<tr>
<td><strong>Protection of reinforcement</strong></td>
<td>Masonry exposed to earth or weather: No. 5 and smaller: ( 1\frac{1}{2} ) in. cover (38.1 mm) larger than No. 5: 2 in. cover (50.8 mm) Masonry not exposed to earth or weather: 1.5 in. cover (38.1 mm)</td>
<td>6.1.4.1</td>
</tr>
</tbody>
</table>

## TMS 402 6.1: Development Length

<table>
<thead>
<tr>
<th>Condition</th>
<th>Provision</th>
<th>TMS 402 Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bars in grouted clay masonry and concrete masonry</td>
<td>( \max \left{ \frac{0.13d_b f_y}{K \sqrt{f_m}}, 12 \text{ in.} \right} ) ( K = \min {\text{masonry cover, clear spacing between adjacent splices, } 9d_b } ) ( \gamma = \begin{cases} 1.0 &amp; \text{for No. 3 through No. 5} \ 1.3 &amp; \text{for No. 6 and No. 7} \ 1.5 &amp; \text{for No. 8 and larger} \end{cases} )</td>
<td>6.1.5.1.1 6.1.5.1.3 6.1.5.2</td>
</tr>
<tr>
<td>Hooks in tension</td>
<td>Equivalent embedment length: 13( d_b )</td>
<td>6.1.5.1.1 and 6.1.5.2</td>
</tr>
<tr>
<td>Wires in tension</td>
<td>( l_d = 48d_b )</td>
<td>6.1.5.1.3</td>
</tr>
<tr>
<td>Epoxy-coated wires and bars</td>
<td>Development length increased by 150%</td>
<td>6.1.5.1.1 and 6.1.5.2</td>
</tr>
</tbody>
</table>
TMS 402 6.1: Splice Length

<table>
<thead>
<tr>
<th>Condition</th>
<th>Provision</th>
<th>TMS 402 Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lap splices of bar reinforcement</td>
<td>( \text{max} \left{ \frac{0.13d^2f_y}{K_f^2}, 12\text{in.} \right} )</td>
<td>6.1.6.1.1.1</td>
</tr>
<tr>
<td>Noncontact lap splices</td>
<td>Transverse spacing ( \leq \min{1/5 \text{ lap length, 8 in.} } )</td>
<td>6.1.6.1.1.3</td>
</tr>
<tr>
<td>Welded splices of bar reinforcement</td>
<td>Develop ( 1.25f_y )</td>
<td>6.1.6.1.2</td>
</tr>
<tr>
<td></td>
<td>Welding conforms to AWS 1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASTM A706 bars or chemical analysis and carbon equivalent</td>
<td></td>
</tr>
<tr>
<td>Mechanical splices of bar reinforcement</td>
<td>Develop ( 1.25f_y )</td>
<td>6.1.6.1.3</td>
</tr>
<tr>
<td>End-bearing splices (compression)</td>
<td>Bar ends within 1.5° to right angle of axis</td>
<td>6.1.6.1.4</td>
</tr>
<tr>
<td></td>
<td>Fitted to within 3° after assembly</td>
<td></td>
</tr>
</tbody>
</table>

TMS 402 6.3: Anchor Bolts

- Tensile capacity governed by
  - tensile breakout
  - tensile pullout
  - yield of anchor in tension
- Shear capacity governed by
  - shear breakout
  - masonry crushing
  - shear pryout
  - yield of anchor in shear

- Headed bolts, J - bolts or L - bolts
- Must be embedded in grout
# TMS 402 6.3: Anchor Bolts - Tension

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Allowable Stress Design (8.1.3.3.1)</th>
<th>Strength Design (9.1.6.3.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry breakout</td>
<td>[ B_{ab} = 1.25A_{pt} \sqrt{f_m^r} ]</td>
<td>[ B_{anb} = 4A_{pt} \sqrt{f_m^r} \phi = 0.5 ]</td>
</tr>
<tr>
<td>Steel yielding</td>
<td>[ B_{as} = 0.6A_b f_y ]</td>
<td>[ B_{ans} = A_b f_y \phi = 0.9 ]</td>
</tr>
<tr>
<td>Anchor pullout (Only bent bar)</td>
<td>[ B_{ap} = 0.6f_m^s e_b d_b + 120 \pi (l_b + e_b + d_b) d_b ]</td>
<td>[ B_{anp} = 1.5f_m^s e_b d_b + 300 \pi (l_b + e_b + d_b) d_b \phi = 0.65 ]</td>
</tr>
</tbody>
</table>

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# TMS 402 6.3: Anchor Bolts - Shear

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Allowable Stress (8.1.3.3.2)</th>
<th>Strength (9.1.6.3.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry breakout</td>
<td>[ B_{vb} = 1.25A_{pv} \sqrt{f_m^r} ]</td>
<td>[ B_{vnb} = 4A_{pv} \sqrt{f_m^r} \phi = 0.5 ]</td>
</tr>
<tr>
<td></td>
<td>Errata: Listed as [ b_{vb} ] in 2016 TMS 402</td>
<td></td>
</tr>
<tr>
<td>Masonry crushing (changed in 2016)</td>
<td>[ B_{vc} = 580 \sqrt{f_m^r A_b} ]</td>
<td>[ B_{vnc} = 1750 \sqrt{f_m^r A_b} \phi = 0.5 ]</td>
</tr>
<tr>
<td>Anchor bolt pryout</td>
<td>[ B_{vpry} = 2B_{ab} = 2.5A_{pv} \sqrt{f_m^r} ]</td>
<td>[ B_{vmpry} = 8A_{pv} \sqrt{f_m^r} \phi = 0.5 ]</td>
</tr>
<tr>
<td>Steel yielding</td>
<td>[ B_{vs} = 0.36A_b f_y ]</td>
<td>[ B_{vns} = 0.6A_b f_y \phi = 0.9 ]</td>
</tr>
</tbody>
</table>
**Masonry Introduction**

**TMS 402 6.3: Anchor Bolts**

<table>
<thead>
<tr>
<th>Masonry Crushing</th>
<th>Allowable Stress Design</th>
<th>Strength Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{vc} ) = ( 350 \frac{4}{f_m A_B} )</td>
<td>( B_{vnc} = 1050 \frac{4}{f_m A_B} )</td>
<td></td>
</tr>
<tr>
<td>( B_{vc} = 580 \frac{4}{f_m A_B} )</td>
<td>( B_{vnc} = 1750 \frac{4}{f_m A_B} )</td>
<td></td>
</tr>
</tbody>
</table>

\[ \frac{b_u}{B_a} + \frac{b_v}{B_v} \leq 1 \]

**Interaction**

\[ \left( \frac{b_u}{\phi B_{an}} \right)^{\frac{5}{3}} + \left( \frac{b_v}{\phi B_{vn}} \right)^{\frac{5}{3}} \leq 1 \]
TMS 402 Part 2: Design Requirements

- Ch. 4: General Analysis & Design Considerations
- Ch. 5: Structural Elements
- Ch. 6: Details of reinforcement, metal accessories & anchor bolts
- Ch. 7 Seismic design requirements
  - 7.1 Scope
  - 7.2 General analysis
  - 7.3 Element classification
  - 7.4 Seismic Design Category Requirements

Shear Walls: Minimum Reinforcement

<table>
<thead>
<tr>
<th>SW Type</th>
<th>Minimum Reinforcement</th>
<th>SDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirically Designed</td>
<td>none</td>
<td>A</td>
</tr>
<tr>
<td>Ordinary Plain</td>
<td>none</td>
<td>A, B</td>
</tr>
<tr>
<td>Detailed Plain</td>
<td>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</td>
<td>A, B</td>
</tr>
<tr>
<td>Ordinary Reinforced</td>
<td>same as above</td>
<td>A, B, C</td>
</tr>
<tr>
<td>Intermediate Reinforced</td>
<td>same as above, but vertical reinforcement @ 4 ft</td>
<td>A, B, C</td>
</tr>
<tr>
<td>Special Reinforced</td>
<td>same as above, but horizontal reinforcement @ 4 ft, and $\rho_v + \rho_h \geq 0.002$, and $\rho_v \geq 0.0007$</td>
<td>any</td>
</tr>
</tbody>
</table>
TMS 402: Ordinary Reinforced Walls

- Reinforcement of at least 0.2 in²
- Within 16 in. of top of wall
- Structurally connected floor and roof levels
- ≤ 8 in.
  - Corners and end of walls
- ≤ 8 in.
  - Control joint
- ≤ 16 in.
- Joint reinforcement at 16 in. o.c. or bond beams at 10 ft.
- Reinforcement not required at openings smaller than 16 in. in either vertical or horizontal direction

TMS 402: Special Reinforced Walls

- Maximum spacing of vertical and horizontal shear reinforcement smallest of:
  - one-third length of wall
  - one-third height of wall
  - 48 in. for running bond; 24 in. not laid in running bond
- Shear reinforcing anchored around vertical bars with a standard hook
- Type S or Type M cement-lime mortar or mortar cement mortar
  - 2013: Masonry cement mortar permitted for fully grouted members
Shear Capacity Design

- Allowable Stress Design
  - Calculated shear stress increased by 1.5
  - Allowable shear stress due to masonry approximately 1/2

- Strength Design
  - Design shear strength, $\phi V_n$, greater than shear corresponding to 1.25 times nominal flexural strength, $M_n$
  - Except $V_n$ need not be greater than $2.5V_n$.
  - Normal design: $\phi V_n$ has to be greater than $V_u$. Thus, $V_n$ has to be greater than $V_u/\phi = V_u/0.8 = 1.25V_u$. This requirement doubles the shear.

Chapter 8 and 9

- Chapter 8: Allowable Stress Design
- Chapter 9: Strength Design
- Will cover later
Masonry Introduction

TMS 402 Chapter 10: Prestressed

- Prestressed masonry provisions were introduced in the 1999 TMS 402, and extensively updated in the 2005 TMS 402
- Provisions address bonded and unbonded tendons
- Provisions address laterally restrained and laterally unrestrained tendons

TMS 402 Chapter 11: AAC Masonry

- Autoclaved Aerated Concrete (AAC) is a lightweight, concrete-like material
  - density from 25 to 50 pcf
  - compressive strength from 290 to 1100 psi
- Strength is specified by strength class of the AAC material alone (no prisms)
  - strength class is the specified compressive strength in MPa (for example, Strength Class 4 has a specified compressive strength of 4 MPa, or 580 psi)
- AAC masonry units are laid using thin-bed, polymer-modified mortar, which is stronger than the AAC material itself
TMS 402 Chapter 12: Veneer

- **12.1 General**
  - 12.1.1 to 12.1.6 Scope & General design requirements

- **12.2 Anchored Veneer**
  - 12.2.1 Alternate design method
  - 12.2.2 Prescriptive requirements

- **12.3 Adhered Veneer**
  - 12.3.1 Alternate design method
  - 12.3.2 Prescriptive requirements

TMS 402 Chapter 12: Anchored Veneer

- Prescriptive requirements of TMS 402 Section 12.2.2
  - Vertical support to meet TMS 402 Section 12.2.2.3
  - Thickness ≥ 2 – 5 / 8 in.
  - Anchor requirements in TMS 402 Section 12.2.2.5
    - Corrugated sheet metal anchors
    - Sheet metal anchors
    - Wire anchors
    - Joint reinforcement
    - Adjustable anchors and spacings
TMS 402 Chapter 12: Anchored Veneer

Increased allowed cavity width for prescriptive design to 6-5/8 in. under certain conditions
- 4 in. to 6 in. to accommodate increased insulation thicknesses
- 1/2 in to 5/8 in. to accommodate 5/8 in. sheathing
- Part attached to backing either 1/4 in. barrel anchor, a plate or prong anchor at least 0.074 in. thick and 1-1/4 in. wide; or a tab or two eyes formed of minimum size W2.8 wire welded to joint reinforcement.

TMS 402 Chap. 13: Glass Unit Masonry

- Prescriptive requirements for
  - interior and exterior panels
  - isolated panels and continuous bands
  - standard (3 7/8 in.) or thin (3 7/8 in.) units
  - $f'_{m}$ not required for glass unit masonry designed by Chapter 13
- Figure 13.2-1 sets maximum panel areas for different design wind pressures
TMS 402 Chap. 14: Partition Walls

- New in 2013 TMS 402
- Rationally based using engineering analysis

Table 14.3.1 – Maximum J/t or h/t for partition walls of ungrouted or partially grouted hollow units

<table>
<thead>
<tr>
<th>Maximum combined allowable stress level out of plane load acting on simple span partition wall</th>
<th>Mortar type</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Portland cement</td>
<td>or air-entrained portland cement</td>
<td>Masonry cement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M or S</td>
<td>N</td>
<td>M or S</td>
</tr>
<tr>
<td>5 psf (0.225 kPa)</td>
<td>26</td>
<td>24</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>10 psf (0.479 kPa)</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>15 psf (0.711 kPa)</td>
<td>15</td>
<td>13</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>20 psf (0.958 kPa)</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>30 psf (1.435 kPa)</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>40 psf (1.915 kPa)</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>50 psf (2.304 kPa)</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

Appendix A: Empirical Design

- Almost deleted in 2016, but retained as IBC referenced provisions for adobe construction
- Will be deleted in 2022 TMS 402
Appendix B: Infills

- Participating and Non-participating infills
- In-plane loading
  - Equivalent diagonal strut for stiffness
  - Strength based on shear, limiting deformation, or crushing
- Out-of-plane loading
  - Arching

Appendix C: Limit Design Method

- Alternative for Special Reinforced Shear Walls
  - Avoids maximum reinforcement requirements
- Useful for design of complex, perforated wall configurations
  - Performance-based option
  - Global look at the wall rather than just the segments
  - Distribute shear according to the plastic capacities, rather than according to elastic stiffness
  - Code and Commentary is two pages
TMS 602: Verification of $f_m'$

- Prism test
- Unit strength table

<table>
<thead>
<tr>
<th>Net area compressive strength of concrete masonry, psi</th>
<th>Net area compressive strength of ASTM C90 concrete masonry units, psi (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type M or S Mortar</td>
</tr>
<tr>
<td>1,700</td>
<td>---</td>
</tr>
<tr>
<td>1,900</td>
<td>1,900</td>
</tr>
<tr>
<td><strong>2,000</strong></td>
<td><strong>2,000</strong></td>
</tr>
<tr>
<td>2,250</td>
<td>2,600</td>
</tr>
<tr>
<td>2,500</td>
<td>3,250</td>
</tr>
<tr>
<td>2,750</td>
<td>3,900</td>
</tr>
</tbody>
</table>

Allowable Stress Design:
Chapter 8
TMS 402 Chapter 8: ASD

- 8.1.1 Scope
- 8.1.2 Design strength
- 8.1.3 Anchor bolts embedded in grout
- 8.1.4 Shear stress in multiwythe masonry elements
- 8.1.5 Bearing stress
  - 0.33$f_m'$

TMS 402 8.2: ASD Unreinforced Masonry

- 8.2.1 Scope
- 8.2.2 Design criteria
- 8.2.3 Design assumptions
- 8.2.4 Axial compression and flexure
- 8.2.5 Axial tension
- 8.2.6 Shear

Key design equation:

$$f_t = \frac{Mc}{I} - \frac{P}{A}$$
Masonry Introduction

TMS 402 8.3: ASD Reinforced

- 8.3.1 Scope
- 8.3.2 Design assumptions
- 8.3.3 Steel reinforcement
- 8.3.4 Axial compression and flexure
- 8.3.5 Shear

TMS 402 8.3: Allowable Stresses

- Tension
  - Grade 60 32,000 psi
  - Wire joint reinforcement 30,000 psi
- Stress in masonry from axial load plus bending:
  - $0.45 \frac{f_m'}{f_m}$ (if allowable masonry stress controls, reinforcement is not being used efficiently)
- Axial
  - $P_a = (0.25 f_m' A_n + 0.65 A_{st} F_y) \left( 1 - \left( \frac{h}{140r} \right)^2 \right)$ for $\frac{h}{r} \leq 99$
  - $P_a = (0.25 f_m' A_n + 0.65 A_{st} F_y) \left( \frac{70r}{h} \right)^2$ for $\frac{h}{r} > 99$
Masonry Introduction

TMS 402 8.3: Shear

Shear stress is computed as:

\[ f_v = \frac{v}{A_{nv}} \]

Allowable shear stress

\[ F_v = (F_{vm} + F_{vs}) \gamma_g \]

\[ \gamma_g = 0.75 \text{ for partially grouted shear walls, 1.0 otherwise} \]

<table>
<thead>
<tr>
<th>V_{experimental}</th>
<th>V_{nominal}</th>
<th>Mean</th>
<th>St Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully grouted</td>
<td></td>
<td>1.16</td>
<td>0.17</td>
</tr>
<tr>
<td>(Davis et al, 2010)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially grouted</td>
<td></td>
<td>0.90</td>
<td>0.26</td>
</tr>
<tr>
<td>(Minaie et al, 2010)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ 0.90 \frac{1.16}{1.16} = 0.776 \]

TMS 402 8.3: Shear

Allowable stress limit

\[ M/(V d_v) \leq 0.25 \]

\[ F_v = \left( 3 \sqrt{f_m^r} \right) \gamma_g \]

\[ M/(V d_v) \geq 1.0 \]

\[ F_v = \left( 2 \sqrt{f_m^r} \right) \gamma_g \]

\[ 0.25 < M/(V d_v) < 1.0 \]

\[ F_v = \left( \frac{2}{3} \left( 5 - 2 \frac{M}{V d_p} \right) \right) \gamma_g \]

Allowable masonry shear stress

\[ F_{vm} = \frac{1}{2} \left[ 4 - 1.75 \left( \frac{M}{V d_v} \right) \right] \sqrt{f_m^r} + 0.25 \frac{P}{A_n} \]

Special reinforced walls:

\[ F_{vm} = \frac{1}{4} \left[ 4 - 1.75 \left( \frac{M}{V d_p} \right) \right] \sqrt{f_m^r} + 0.25 \frac{P}{A_n} \]

\[ M/(V d_v) \text{ is positive and need not exceed 1.0.} \]
TMS 402 8.3: Shear

- Allowable reinforcement shear stress
  
  \[ F_{vS} = 0.5 \left( \frac{A_v F_z d_v}{A_{nv} s} \right) \]

- Shear reinforcement is placed parallel the direction of the applied force at a maximum spacing of \( d/2 \) or 48 in.
- One-third of \( A_v \) is required perpendicular to the applied force at a spacing of no more than 8 ft.

TMS 402 8.3.6: Shear Friction

<table>
<thead>
<tr>
<th>Shear Span Ratio</th>
<th>Allowable Shear Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{M}{Vd_v} \leq 0.5 )</td>
<td>( F_f = \frac{\mu (A_{sp} F_z + P)}{A_{nv}} )</td>
</tr>
<tr>
<td>( 0.5 &lt; \frac{M}{Vd_v} &lt; 1.0 ) Linear interpolation</td>
<td>( F_f = \left( 0.39 + \frac{\mu - 0.39}{0.5} \left( 1 - \frac{M}{Vd_v} \right) \right) A_{sp} F_z + \left( 0.65 + \frac{\mu - 0.65}{0.5} \left( 1 - \frac{M}{Vd_v} \right) \right) P )</td>
</tr>
<tr>
<td>( \frac{M}{Vd_v} \geq 1.0 )</td>
<td>( F_f = \frac{0.65 (0.6 A_{sp} F_z + P)}{A_{nv}} )</td>
</tr>
</tbody>
</table>

\( A_{sp} \) = cross-sectional area of reinforcement within the net shear area, perpendicular to and crossing the horizontal shear plane
**TMS 402 8.3.6: Shear Friction**

- \( \mu = 1.0 \) for masonry on concrete with unfinished surface, or concrete with a surface that has been intentionally roughened.
- \( \mu = 0.70 \) for all other conditions.

- UBC (1997) required concrete abutting structural masonry to be roughened to a full amplitude of 1/16 inch.
- For \( 0.5 < \frac{M}{Vd_p} < 1.0 \):
  - \( \mu = 1.0 \) \[ F_f = \frac{(0.39 + 1.22(1 - \frac{M}{Vd_p}))A_{np}F_s + (0.65 + 0.70(1 - \frac{M}{Vd_p}))p}{A_{np}} \]
  - \( \mu = 0.7 \) \[ F_f = \frac{(0.39 + 0.62(1 - \frac{M}{Vd_p}))A_{np}F_s + (0.65 + 0.10(1 - \frac{M}{Vd_p}))p}{A_{np}} \]

Special reinforced shear walls: The 1.5 multiplier should not be applied to \( V \) when calculating the \( M/(Vd_p) \) ratio, or for shear friction design.

---

**ASD: Flexure Formulas**

- Distance to neutral axis, \( kd \)
  \[ k = \sqrt{(np)^2 + 2n \rho - n \rho} \]
- Internal lever arm, \( jd \)
  \[ j = 1 - k/3 \]
- Steel stress, \( f_s \)
  \[ f_s = \frac{M}{A_s jd} \]
- Masonry stress, \( f_m \)
  \[ f_m = \frac{2M}{b(kd)(jd)} \]
ASD Design: Flexure

- Assume value of $j$ (or $k$). Typically $0.85 < j < 0.95$.
- Determine a trial value of $A_{s,reqd}$.
  - $A_{s,reqd} = \frac{M}{(F_sj)d}$
  - Choose reinforcement.
- Determine $k$ and $j$; steel stress and masonry stress.
- Compare calculated stresses to allowable stresses.
- If masonry stress controls design, consider other options (such as change of member size, or change of $f'_m$). Reinforcement is not being used efficiently.

ASD Design: Flexure and Axial

\[ kd = 3 \left[ \frac{d}{2} - \sqrt{\left(\frac{d'}{2}\right)^2 - 2\left(P(d - d_m/2) + M\right) \frac{3F_b t_{sp}}{2}} \right] \]

\[ k_{bal} = \frac{F_b}{F_b + F_s/n} \]

If $k \geq k_{bal}$?

For Grade 60 steel, CMU $k_{bal} = 0.312$

\[ A_{s,reqd} = \frac{F_b (kd) t_{sp}}{2nF_b \left( \frac{1}{K} - 1 \right)} - P \]

\[ M' = P \left( \frac{d_y - kd}{2} - \frac{M}{3} \right) \]

\[ \frac{A_{s,reqd}}{F_s d \left( 1 - \frac{k}{3} \right)} = \frac{M - M'}{F_s d \left( 1 - \frac{k}{3} \right)} \]

\[ \zeta = \frac{(P + A_{s,reqd} F_s) n}{F_s t_{sp}} \]

\[ (kd)_2 = \sqrt{\zeta^2 + 2\zeta d - \zeta} \]

Iterate. Use $(kd)_2$ as new guess and repeat.
If $k < k_{bat}$, tension controls; determine $kd$ from cubic equation.

$$\frac{t_{sp}F_s}{6n} [kd]^3 - \frac{t_{sp}dF_s}{2n} [kd]^2 - \left( P \left( d - \frac{d_y}{2} \right) + M \right) [kd] + \left( P \left( d - \frac{d_y}{2} \right) + M \right) d = 0$$

$$A_{s,reqd} = \frac{1}{2} (kd)t_{sp} \left( \frac{1}{n \left( d - kd \right)} - \frac{P}{F_s} \right)$$

**Determination of $k_{bat}$:**

$$k_{bat} = \frac{F_b}{F_b + \frac{F_s}{n}} = \frac{F_b}{F_b + \frac{E_s}{E_m}} = \frac{0.45f_{m}'}{0.45f_{m}'} + \frac{32 \text{ksi}}{29000 \text{ksi}} = \frac{0.45 + 32}{29000} = 0.312$$

For clay masonry, $E_m = 700f_{m}'$, $k_{bat} = 0.368$
ASD Design: Flexure and Axial

Method 2: \[ F'_b = F_b - f_a \]


ASD Design: Distributed Reinforcement

- Design method similar to single layer of reinforcement
  - Based on uniformly distributed reinforcement, \( A_s^* \)
  - Tends to overestimate reinforcement by 10-15% for wider spaced reinforcement
  - Use specified thickness, even for partial grout
- Interaction diagram to check capacity
- Spacing of intermediate reinforcing bars often controlled by out-of-plane loading
ASD Design: Distributed Reinforcement

Calculate

\[ k = \frac{M + P \frac{d_v}{6}}{\frac{5}{2} d_v^2 F_b t_{sp} - P \frac{d_v}{3}} \]

Is \( k \geq k_{bai} \)?

YES

\[ A_{s,reqd}^* = \frac{1}{2} k d_v F_b t_{sp} - P - \frac{1}{2} (1 - k)^2 \frac{d_v n F_b}{k} \]

Compression controls

NO

Determine \( kd \) from the quadratic equation

\[ \frac{1}{3} d_v^3 F_b \frac{t_{sp}}{n} + P \frac{d_v}{3} k^2 + \left[ M - P \frac{d_v}{6} \right] k - \left[ M + P \frac{d_v}{6} \right] = 0 \]

Solve for \( A_{s,reqd}^* \)

\[ A_{s,reqd}^* = \frac{1}{2} k d_v t_{sp} F_b \left( \frac{k}{1 - k} \right) \frac{1}{n} - P \]

Tension controls

ASD: Interaction Diagram

\[ P = C - \sum_{d_i > k_d} T_i \]

\[ M = C x_C + \sum_{d_i > k_d} T_i x_{T_i} \]
ASD: Interaction Diagram

<table>
<thead>
<tr>
<th>Stress</th>
<th>Force</th>
<th>Moment Arm</th>
</tr>
</thead>
</table>
| If $k > k_{ba1}$
$f_b = F_b$
$f_s = F_{bn} \frac{d - kd}{kd}$
| $C = \frac{1}{2} f_b (kd) t_{eq}$
$T_i = A_s f_{si}$
| $x_c = \frac{d_y}{2} - \frac{kd}{3}$
$x_{ri} = d_i - \frac{d_y}{2}$
| If $k \leq k_{ba1}$
$f_s = F_s$
$f_b = F_s \frac{kd}{n (d - kd)}$
$f_{si} = f_s \frac{d_i - kd}{d - kd}$

Strength Design:
Chapter 9
Masonry Introduction

TMS 402 9.1: General

- 9.1.1 Scope
- 9.1.2 Required strength
- 9.1.3 Design strength
- 9.1.4 Strength-reduction factors
- 9.1.5 Deformation requirements
- 9.1.6 Anchor bolts embedded in grout
- 9.1.7 Shear strength in multiwythe masonry elements
- 9.1.8 Nominal bearing strength
- 9.1.9 Material Properties

TMS 402 Chapter 9.1.4:

Strength-reduction factors

<table>
<thead>
<tr>
<th>Action</th>
<th>Reinforced Masonry</th>
<th>Unreinforced Masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>combinations of flexure and axial load</td>
<td>0.90</td>
<td>0.60</td>
</tr>
<tr>
<td>shear</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>bearing</td>
<td>0.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>
TMS 402 9.2: SD Unreinforced Masonry

- 9.2.1 Scope
- 9.2.2 Design criteria
- 9.2.3 Design assumptions
- 9.2.4 Nominal axial compression and flexure
- 9.2.5 Axial tension
- 9.2.6 Nominal shear strength

Key design equation: \[ f_t = \frac{Mc - P}{I} \]

TMS 402 9.3: Reinforced Masonry

- 9.3.1 Scope
- 9.3.2 Design assumptions
- 9.3.3 Reinforcement requirements and details, including maximum steel percentage
- 9.3.4 Design of beams and columns
  - nominal axial and flexural strength
  - nominal shear strength
- 9.3.5 Wall design for out – of – plane loads
- 9.3.6 Wall design for in – plane loads
TMS 402 9.3.2: Design assumptions

- continuity between reinforcement and grout
- equilibrium
- $\varepsilon_{mu} = 0.0035$ for clay masonry, $\varepsilon_{mu} = 0.0025$ 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 of stress $0.80f'_{cm}$ and depth of $0.80c$

TMS 402 9.3.3.2: Max. reinforcement

- No upper limit when $M_d/(V_u d_v) \leq 1$ and $R \leq 1.5$
- Other members, maximum area of flexural tensile reinforcement determined based on:
  - Strain in extreme tensile reinforcement = $1.5\varepsilon_y$
  - Axial forces determined from $D + 0.75L + 0.525Q_E$
  - Compression reinforcement, with or without lateral restraining reinforcement, permitted to be included.
- Intermediate shear walls with $M_d/(V_u d_v) \geq 1$, strain in extreme tensile reinforcement = $3\varepsilon_y$
- Special shear walls with $M_d/(V_u d_v) \geq 1$, strain in extreme tensile reinforcement = $4\varepsilon_y$
TMS 402 9.3.3.2: Max. reinforcement

Three methods for checking maximum reinforcement

- Commentary equations
  - only applicable for certain cases

- Determine location of neutral axis based on specified strain condition
  - Find axial capacity and check that axial force from $D + 0.75L + 0.525Q_e$ is less than axial capacity

- Determine location of neutral axis for given axial force, compute strain in extreme tension steel, and compare to minimum strain
  - Usually requires using trial and error to find the location of the neutral axis

TMS 402 Chapter 9.3.4.1.1: Axial

$$P_n = 0.80 \left[ 0.80 f_m'(A_n - A_{st}) + f_y A_{st} \right] \left[ 1 - \left( \frac{h}{140r} \right)^2 \right]$$ for $\frac{h}{r} \leq 99$

$$P_n = 0.80 \left[ 0.80 f_m'(A_n - A_{st}) + f_y A_{st} \right] \left( \frac{70r}{h} \right)^2$$ for $\frac{h}{r} > 99$
**Nominal shear strength**

\[ V_n = (V_{nm} + V_{ns})\gamma_g \]

\[ \gamma_g = 0.75 \text{ for partially grouted shear walls, } 1.0 \text{ otherwise} \]

**Nominal stress limit**

\[ \frac{M_u}{(V_u d_v)} \leq 0.25 \quad V_n = \left( 6A_{nv} \sqrt{f_m} \right) \gamma_g \]

\[ \frac{M_u}{(V_u d_v)} \geq 1.0 \quad V_n = \left( 4A_{nv} \sqrt{f_m} \right) \gamma_g \]

\[ 0.25 < \frac{M_u}{(V_u d_v)} < 1.0 \quad V_n = \left( \frac{4}{3} \left( 5 - 2 \frac{M_u}{V_u d_v} \right) A_{nv} \right) \gamma_g \]

**Nominal masonry shear strength**

\[ V_{nm} = \left[ 4 - 1.75 \left( \frac{M_u}{V_u d_v} \right) \right] A_{nv} \sqrt{f_m} + 0.25 P_u \]

\[ \frac{M_u}{(V_u d_v)} \text{ is positive and need not exceed } 1.0. \]

**Nominal reinforcement shear strength:**

\[ V_{ns} = 0.5 \left( \frac{d_v}{s} \right) f_y d_v \]

- Shear reinforcement bent around the edge vertical reinforcing bar with a 180° standard hook.
- Wall intersections: bent around the edge vertical bar with a 90° standard hook and extend horizontally into intersecting wall at least the development length.
TMS 402 Chapter 9.3.4.2: Beams

- $P_u \leq 0.05A_nf_m'$
- Fully grouted
- Minimum reinforcement $M_n \geq 1.3M_{cr}$
  - Unless $A_s$ provided is at least 1/3 greater than required
- Maximum reinforcement: $\varepsilon_s \geq 1.5\varepsilon_y$
  - Grade 60 steel, CMU, $f_m' = 2000$ psi, $\rho_{max} = 0.00952$
  - Grade 60 steel, Clay, $f_m' = 2000$ psi, $\rho_{max} = 0.01131$
- Specific requirements for transverse reinforcement

Beams: ASD vs. SD

![Graph showing ASD vs. SD for beams](image)
Design: Flexure plus Axial

Calculate

\[ a = d - \sqrt{d^2 - \frac{2[P(d - t/2) + M_u]}{\phi(0.8f_m'b)}} \]

\[ c = \frac{a}{0.8} \]

Is \( c \geq c_{bal} \)?
For Grade 60 steel
\( c_{bal} = \frac{\varepsilon_m - d}{\varepsilon_m + \varepsilon_y} \)

YES

Compression controls

\[ A_c = \frac{0.8f_m'b - P_u}{\varepsilon_m E_s \left( \frac{d - c}{c} \right)} \]

NO

Tension controls

\[ A_t = \frac{0.8f_m'b - P_u}{\frac{t_{sp} - a}{2} + A_s f_y \left( d - \frac{t_{sp}}{2} \right)} \]

TMS 402 Chapter 9.3.5: Out-of-Plane

- Capacity under combinations of flexure and axial load is based on the assumptions of TMS 402 Section 9.3.2 (interaction diagram)
- Single layer of steel, equivalent stress block in face shell or fully grouted.
  - \( a = \frac{A_sf_m + P_u}{0.80f_m'b} \)
  - \( M_n = (P_u/\phi + A_s f_y) \left( \frac{t_{sp} - a}{2} \right) + A_s f_y \left( d - \frac{t_{sp}}{2} \right) \)
- For centered flexural reinforcement
  - \( M_n = (P_u/\phi + A_s f_y) \left( d - \frac{a}{2} \right) \)
TMS 402 Chapter 9.3.5: Out-of-Plane

- Maximum reinforcement by 9.3.3.2
- Nominal shear strength by 9.3.4.1.2
- Three procedures for computing out–of–plane moments and deflections
  - Second – order analysis (new in 2013)
  - Moment magnification method (new in 2013)
  - Complementary moment method, or slender wall method; additional moment from P – δ effects

Slender Wall Procedure

- Assumes simple support conditions.
- Assumes midheight moment is approximately maximum moment
- Assumes uniform load over entire height
- Valid only for the following conditions:
  - \( \frac{P_u}{A_n} \leq 0.05 f'_{m} \) No height limit
  - \( \frac{P_u}{A_g} \leq 0.20 f'_{m} \) height limited by \( \frac{h}{r} \leq 30 \)

**Moment:**

\[
M_u = \frac{w_u h^2}{8} + P_{uf} \frac{\varepsilon_u}{2} + P_u \delta_u
\]

\( P_u = P_{uw} + P_{uf} \)

\( P_{uf} = \) factored floor load

\( P_{uw} = \) factored wall load

**Deflection:**

\[
\delta_u \leq M_{cr} \frac{5M_u h^2}{48E_m I_n}
\]

\[
\delta_u = \frac{5M_{cr} h^2}{48E_m I_n} + \frac{5(M_u - M_{cr}) h^2}{48E_m I_{cr}}
\]
Slender Wall Procedure

Solve simultaneous linear equations:

\[ M_u > M_{cr} \]

\[ M_u = \frac{w_u h^2}{8} + P u f_u \frac{e_u}{2} + \frac{5 M_{cr} P_u h^2}{48 E_m l_{cr}^2} \left( \frac{1}{l_n} - \frac{1}{l_{cr}} \right) \]

\[ \delta_u = \frac{5 h^2}{48 E_m l_{cr}} \left[ \frac{w_u h^2}{8} + P u f_u \frac{e_u}{2} + M_{cr} \left( \frac{l_{cr}}{l_n} - 1 \right) \right] \]

\[ M_u < M_{cr} \]

\[ M_u = \frac{w_u h^2}{8} + P u f_u \frac{e_u}{2} \frac{5 P_u h^2}{48 E_m l_{cr}^2} \left( 1 - \frac{1}{1 - \frac{M_{cr}}{M_{cr}}} \right) \]

\[ \delta_u = \frac{5 h^2}{48 E_m l_{cr}^2} \left[ \frac{w_u h^2}{8} + P u f_u \frac{e_u}{2} \right] \]

Slender Wall Procedure

Cracking Moment:  \[ M_{cr} = (P_u/A_n f_{fr}) l_n \frac{t_{sp}}{2} \]

Cracked moment of inertia:

\[ I_{cr} = n \left( A_s + \frac{P_u t_{sp}}{f_y} 2d \right) (d - c)^2 + \frac{bc^3}{3} \]

\[ c = \frac{A_s f_y + P_u}{0.64 f_m'} b \]

Centered bars:  \[ I_{cr} = n \left( A_s + \frac{P_u}{f_y} \right) (d - c)^2 + \frac{bc^3}{3} \]
9.3.5.4 P-delta effects

9.3.5.4.1 Members shall be designed for the strength level axial load, $P_u$, and the moment magnified for the effects of member curvature, $M_u$. The magnified moment shall be determined either by Section 9.3.5.4.2 (slender wall procedure) or Section 9.3.5.4.3.

9.3.5.4.3 The strength level moment, $M_u$, shall be determined either by a second-order analysis, or by a first-order analysis and Equations 9-27 through 9-29 (moment magnification procedure).

No axial stress or $h/t$ limits

---

**Second-Order Procedure**

**Moment Magnification Procedure**

First Order Moment

\[
M_u = \frac{w_u h^2}{8} + P_u u_f \left( \frac{1}{4EB_h} \right) \left( \frac{5M_cr P_u h^2 (1 - \frac{1}{J_n})}{4EB_m l_{cr}} \right)
\]

Always Negative

\[
5 \frac{5P_h h^2}{4EB_m l_{cr}} = 0.104 \sim \frac{1}{\pi^2} = 0.101
\]

Magnified moment:

\[
M_u = \psi M_{u,0}
\]

Moment magnifier:

\[
\psi = \frac{1}{1 - \frac{P_n}{P_e}}
\]

Buckling load:

\[
P_e = \frac{\pi^2 E m_{eff}}{h^2}
\]

\[
M_u < M_{cr}: \quad I_{ef} = 0.75 I_n
\]

\[
M_u \geq M_{cr}: \quad I_{ef} = I_{cr}
\]
Moment Magnification Application

After 2015 NEHRP Recommended Seismic Provisions: Design Examples FEMA P-1051 / July 2016

Shear and Moment Diagrams for Pier: 0.9D + 1.0E

Pu = 0.614(8) = 4.91k

Shear

Moment

Conservatively use 0.972k/ft over entire height

M_o,0 = 95.3 k-ft; 23% higher
TMS 402 Chapter 9.3.5: Out-of-Plane

- Deflection limit: $\delta_s \leq 0.007h$
- $\delta_s$ calculated using ASD load combinations
- Effective moment of inertia for calculating deflections
  \[ I_e = \frac{I_{cr}}{1 - \frac{M_{cr}}{M} \left( 1 - \frac{I_{cr}}{I_m} \right)} \]


TMS 402 Chapter 9.3.6: In-Plane

Capacity under combinations of flexure and axial load is based on the assumptions of TMS 402 Section 9.3.2 (interaction diagram)
In-Plane: Design

- Modify design method for single layer of reinforcement
  - Use $d = 0.9d_y$
  - Determine distributed reinforcement, $A_s^* = A_s/0.65d_y$
  - Use specified thickness, even for partial grout
- Interaction diagram to check capacity
- Spacing of intermediate reinforcing bars often controlled by out-of-plane loading

Interaction Diagram

$$P_n = C - \sum_{d_i kd} T_i$$

$$M_n = Cx_C + \sum_{d_i kd} T_i x_i$$
### Interaction Diagram

<table>
<thead>
<tr>
<th>Stress</th>
<th>Force</th>
<th>Moment Arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_s = \varepsilon_{mu} \frac{d - c}{c} )</td>
<td>( C = 0.8f'<em>m(0.8c)t</em>{net} )</td>
<td>( x_C = \frac{d_c}{2} - \frac{0.8c}{2} )</td>
</tr>
<tr>
<td>( \varepsilon_{sl} = \varepsilon_s \frac{d_l - c}{d - c} )</td>
<td>( T_l = A_{sl}f_{sl} )</td>
<td>( x_{Tl} = d_l - \frac{d_c}{2} )</td>
</tr>
<tr>
<td>( f_{sl} = \min{E_s \varepsilon_{si}, f_y} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

### Shear Walls: ASD vs. SD

![Graph showing comparison between ASD and SD]
Maximum Reinforcement

Design with Boundary Elements?

Is \( \frac{M_u}{V_u d_v} \leq 1 \) OR \( \{V_u \leq 3A_{mv} \sqrt{f_m} \text{ AND } \frac{M_u}{V_u d_v} \leq 3\} \)

AND

\( P_u \leq 0.104 A_{pf}' \): Geometrically symmetrical walls

\( P_u \leq 0.05 A_{pf}' \): Geometrically unsymmetrical walls

No boundary elements required

Design boundary elements per TMS 402 Section 9.3.6.6.2

Yes

No

Design with TMS 402 Section 9.3.3.2.

Area of flexural tensile reinforcement ≤ area required to maintain axial equilibrium under the following conditions:

A strain gradient corresponding to \( \varepsilon_{mu} \) in masonry and \( \alpha e \) in tensile reinforcement

Axial forces from loading combination \( D + 0.75L + 0.525Q_e \).

Compression reinforcement, with or without lateral restraining reinforcement, can be included.

Yes

No

Ordinary reinforced walls: \( \alpha = 1.5 \)

Intermediate reinforced walls: \( \alpha = 3 \)

Special reinforced walls: \( \alpha = 4 \)

\( \alpha = 1.5 \)

TMS 402 9.3.6.5: Shear Friction

<table>
<thead>
<tr>
<th>Shear Span Ratio</th>
<th>Allowable Shear Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{M_u}{V_u d_v} \leq 0.5 )</td>
<td>( V_{nf} = \mu (A_{sp} f_y + P_u) \geq 0 )</td>
</tr>
<tr>
<td>( 0.5 &lt; \frac{M_u}{V_u d_v} &lt; 1.0 )</td>
<td>Linear interpolation</td>
</tr>
<tr>
<td>( \frac{M_u}{V_u d_v} \geq 1.0 )</td>
<td>( V_{nf} = 0.42f_m' A_{nc} )</td>
</tr>
</tbody>
</table>

\( A_{sp} \) = cross-sectional area of reinforcement within the net shear area, perpendicular to and crossing the horizontal shear plane.

\( A_{nc} \) = net cross-sectional area between the neutral axis of bending and the fiber of maximum compressive strain calculated at the nominal moment capacity of the section.
TMS 402 9.3.6.5: Shear Friction

- $\mu = 1.0$ for masonry on concrete with unfinished surface, or concrete with a surface that has been intentionally roughened
- $\mu = 0.70$ for all other conditions
- UBC (1997) required concrete abutting structural masonry to be roughened to a full amplitude of 1/16 inch.

Special reinforced shear walls: The shear capacity provisions only apply to the nominal shear strength, $V_n$, and not to the nominal shear friction strength, $V_{nf}$, or when calculating the $M_u/(V_u d_v)$ ratio.

Finally!!!

The End