SEISMIC DESIGN OF MASONRY STRUCTURES
NEHRP Recommended Provisions
Masonry Structures:

- Reference standards
- Masonry basics
- Masonry behavior
- Organization of TMS 402 Code
- Types of shear walls
- Ductility provisions
- Masonry walls out-of-plane
- Shear wall in-plane design
- Simplified design for wall-type structures
- Shear wall design example
NEHRP Recommended Provisions
Masonry Design

Basic Documents

- NEHRP Recommended Provisions
- ASCE 7-16, Minimum Design Loads for Buildings and Other Structures
- TMS 402-13, Building Code Requirements for Masonry Structures
- TMS 602-13, Specification for Masonry Structures
- IBC 2015, International Building code
NEHRP Recommended Provisions
Masonry Design
Masonry Basics
Review Masonry Basics

- Basic terms
- Units
- Mortar
- Grout
- Accessory materials
  - Reinforcement, connectors, flashing, sealants
Basic Terms

- Bond patterns (looking at wall):

  - **Running bond**
  - **Stack bond**
  - **1/3 Running bond**
  - **Flemish bond**

   - bed joints
   - head joints
Masonry Units

- Concrete masonry units (CMU):
  - Specified by ASTM C 90
  - Minimum strength (net area) of 2000 psi (average)
  - Net area 55% of gross area
  - Nominal vs specified vs actual dimensions
  - Type I and Type II designations no longer exist
Masonry Units

- Clay masonry units:
  - Specified by ASTM C 62 or C 216
  - Usually solid, with small core holes
  - If cores $\leq 25\%$ net area, considered 100% solid
  - Hollow units are similar to CMU - can be reinforced
Masonry Mortar

- Mortar specified by ASTM C 270
- Three cementitious systems
  - Portland cement + lime + sand (“traditional”)
  - Masonry cement mortar (lime is included in cement)
  - Mortar cement mortar (lime is included in cement, higher air contents)
Masonry Mortar

- Within each cementitious system, mortar is specified by type (M a S o N w O r K):
  - Type K to Type M, increasing volume of portland cement.
  - As the volume proportion of portland cement increases,
    - sets up faster
    - higher compressive and tensile bond strengths.
    - mortar is less able to deform when hardened.
  - Types M and S are specified for modern structural masonry construction.
  - Type N for non-loadbearing and for brick veneer
  - Type O or K for historic masonry repairs
  - Specify by Proportion (preferred) or Property
    - Onsite testing is not required
Masonry Mortar

- **Plastic mortar properties**
  - Workability
  - Water retentivity
  - Rate of hardening
  
  Important for good bond

- **Hardened mortar properties**
  - Bond
  - Compressive strength
  - Volume stability
  - Durability
  
  Important, seldom specified
Grout

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

- Proportion of water not specified
- The slump should be 8 to 11 in.
- Masonry units absorb water from the grout
  - High-slump grout will still be strong enough
Role of $f_m'$

- **Concrete:**
  - Designer specifies value of $f'_c$
  - Compression tests on cylinders cast in field

- **Masonry**
  - Designer specifies value of $f'_m$
  - “Unit Strength Method” or “Prism Test Method”
Application of Unit Strength Method
(Specification Tables 1, 2)

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

Masonry Behavior
Masonry Behavior

- Locally, masonry is nonisotropic, nonhomogeneous, and nonlinear.
- Globally, can be idealized as isotropic and homogeneous.
- Equivalent rectangular stress block.
Summary of Masonry Behavior

4-Way Composite Action
● Units, mortar, reinforcement, grout

Compression
● High strength
● Brittle - low ductility
● Confinement difficult to achieve

Tension
● Good strength when reinf. takes tension
● Very little strength without reinf.
● (continuous joints are a plane of weakness)
Design Implications from Masonry Behavior

Unreinforced

● Design as elastic / brittle material
● $R$ factors very low
● Design force = EQ force

Reinforced

● Design similar to reinforced concrete
● Confinement, ductility difficult to achieve
● $R$ factors lower than concrete
Masonry Behavior

Head joint weakness

Stacked bond
- only mortar

Running bond
- half units
Masonry Behavior

Crowded cells make grout flow difficult
Masonry Behavior: out-of-plane

flexural strength

anchorage
NEHRP Recommended Provisions
Masonry Design

Organization of TMS 402 Code
Organization of 2013 TMS 602 Specification

TMS 402 Code → TMS 602 Specification

Part 1 General

1.6 Quality assurance

Part 2 Products

2.1 - Mortar
2.2 - Grout
2.3 - Masonry Units
2.4 - Reinforcement
2.5 - Accessories
2.6 - Mixing
2.7 - Fabrication

Part 3 Execution

3.1 - Inspection
3.2 - Preparation
3.3 - Masonry erection
3.4 - Reinforcement
3.5 - Grout placement
3.6 - Prestressing
3.7 - Field quality control
3.8 - Cleaning

TMS 602 Specification
Organization of TMS 402 Code
Part 1 – General

Chapter 1
1.1 Scope
1.2 Contract documents and calculations
1.3 Special systems
1.4 Reference standards

Chapter 2
2.1 Notation
2.2 Definitions

Chapter 3
3.1 Quality assurance program
3.2 Construction
Organization of TMS 402 Code
Part 2 – Design Requirements

Chapter 4
4.1 Loading
4.2 Material properties
4.3 Section properties
4.4 Connections to structural frames
4.5 Stack bond masonry

Chapter 6
6.1 Details of reinforcement
6.2 Anchor bolts

Chapter 5
5.1 Masonry assemblies
5.2 Beams
5.3 Columns
5.4 Pilasters
5.5 Corbels

Chapter 7
Seismic design requirements
Code 4.2, Material Properties

- Prescriptive modulus of elasticity:
  \[ E_m = 700 \text{ f'}_m \text{ for clay masonry} \]
  \[ E_m = 900 \text{ f'}_m \text{ for concrete masonry} \]
  or
  Chord modulus of elasticity from tests

- Shear modulus, thermal expansion coefficients, and creep coefficients for clay, concrete, and AAC masonry

- Moisture expansion coefficient for clay masonry

- Shrinkage coefficients for concrete and AAC masonry
Code 4.3, Section Properties

- Use minimum (critical) area for computing member stresses or capacities
  - Capacity is governed by the weakest section; for example, the bed joints of face-shell bedded hollow masonry
Chapter 7, Seismic Design

- ASCE 7-16 General Structural Integrity:
  - Load path connections
  - Notional lateral forces
  - Connection to supports
  - Anchorage of walls
Chapter 7, Seismic Design

• General analysis
  – Drift limits: Use legally adopted building code or ASCE7
  – Drift limits assumed satisfied for many wall types
    – Special Reinforced Masonry walls are the exception to this rule
Chapter 7, Seismic Design

- Seismic Design Category C:
  - Empirical and plain not permitted
  - All other types of shear walls permitted:
    - Ordinary reinforced
    - Intermediate reinforced
    - Special reinforced
  - Participating walls shall be reinforced
  - Non-participating walls - minimum prescriptive reinforcement
  - At least 80% lateral resistance in a line from shear walls
Chapter 7, Seismic Design

- Seismic Design Category D:
  - Only special reinforced shear wall permitted
  - Minimum prescriptive requirements for reinforcement and connections
  - Type N mortar and masonry cement mortars are prohibited in the lateral force-resisting system
  - Non-participating walls - minimum prescriptive reinforcement
Chapter 7, Seismic Design

Seismic Design Category D:

● Extra caution against brittle shear failure for Special Reinforced Masonry Shear Walls (7.3.2.6.1.1):

- $\phi V_n > 1.25 M_n$ or
- $\phi V_n > 2.5 V_u$
Chapter 7, Seismic Design

• Seismic Design Categories E and F:
  – Additional reinforcement requirements for non-participating stack-bond masonry
Minimum Reinforcement for Special Reinforced Shear Walls

- Roof connectors @ 48 in. max oc
- Roof diaphragm
- #4 bar (min) within 16 in. of top of parapet
- Top of Parapet
- #4 bar (min) @ diaphragms continuous through control joint
- #4 bar (min) within 8 in. of all control joints
- #4 bars around openings 24 in. or 40 db past opening
- #4 bar (min) within 16 in. of corners & ends of walls
- Min. #4 bars @ 4 ft oc max. or W1.7 @ 16 in oc
- Min. #4 bars @ 4 ft oc max.
- \( \rho \) total both ways = 0.002

Instructional Material Complementing FEMA P-1051, Design Examples
## Minimum Reinforcement, SW Types

<table>
<thead>
<tr>
<th>SW Type</th>
<th>Minimum Reinforcement</th>
<th>Permitted in 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 = #4 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 $\rho \geq 0.002$ (sum of horiz + vert)</td>
<td>A, B, C, D, E, F</td>
</tr>
</tbody>
</table>
Organization of TMS 402 Code
Chapter 9, Strength Design

- Fundamental basis
- Design strength
- \( \phi \) factors
- Deformation requirements
- Anchor bolts
- Bearing strength
- Compressive strength
- Modulus of rupture
- Strength of reinforcement
- Unreinforced masonry
- Reinforced masonry
Fundamental Basis for Strength Design

- $\phi Q_n > \gamma Q_u$
- Load factors come from ASCE 7
- Resistance factors ($\phi$) come from TMS 402
- $\gamma / \phi \approx$ F.S. from ASD
Code 9.1.4, Strength-reduction Factors ($\phi$) for Strength Design

<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>
Code 9.3, Reinforced Masonry

- Masonry in flexural tension is cracked
- Reinforcing steel is needed to resist tension
- Similar to strength design of reinforced concrete
- Compressive reinforcement ignored unless tied in compliance with 5.3.1.4
Code 9.3.2, Design Assumptions

- Continuity between reinforcement and grout
- Equilibrium
- $\varepsilon_{mu} = 0.0035$ for clay masonry, $0.0025$ for concrete masonry
- Plane sections remain plane
- Elasto-plastic stress-strain curve for reinforcement
- Tensile strength of masonry is neglected
- Stress block height of $0.80f_m'$ and depth of $a = 0.80c$
Code 9.3.3.5, Maximum Reinforcement (Flexural Ductility Check)

- Does not apply if $M_u / V_u d < 1.0$ and $R \leq 1.5$
- Locate neutral axis based on extreme-fiber strains
- Calculate compressive force, $C$ (may include compressive reinforcement)
- Tensile reinforcement + axial load = $C$

$\varepsilon_{mu} = 0.0035$ clay
$0.0025$ concrete

$\varepsilon_s = \alpha \varepsilon_y$

$0.80 f_m'$, $\alpha = 1.5$ Ordinary
3 Intermediate
4 Special
Code 9.3.4, Nominal Shear Strength

- \( V_n = (V_{nm} + V_{ns}) \gamma_g \)
- \( V_n \) shall not exceed:
  - \( \frac{M_u}{V_u} d_v \leq 0.25 \) \( V_n \leq 6 A_n \sqrt{f_{m'}} \)
  - \( \frac{M_u}{V_u} d_v \geq 1.0 \) \( V_n \leq 4 A_n \sqrt{f_{m'}} \)
  - Linear interpolation between these extremes
  - Objective is to avoid crushing of diagonal strut
  - Objective is to preclude critical (brittle) shear-related failures
- \( \gamma_g = 1.0 \) for fully grouted walls
  - \( = 0.75 \) for partially grouted walls
Code 9.3.4, Nominal Shear Strength

- \( V_m \) and \( V_s \) are given by:

\[
V_{nm} = \left[ 4 - 1.75 \left( \frac{M_u}{V_u d_v} \right) \right] A_n \sqrt{f_m'} + 0.25 P_u \quad (9-24)
\]

\[
V_{ns} = 0.5 \left( \frac{A_v}{s} \right) f_y d_v \quad (9-25)
\]

Empirical – from research
Code 9.3.5, Design of Walls for Out-of-Plane Loads

- Maximum reinforcement by Code 9.3.3.5
- Procedures for calculating $P - \delta$ effects using iteration or a moment magnifier
- **Note 9.3.5.4.2** – $M$ and $\Delta$ equations are based on simple supports top & bottom
Code 9.3.6, Design of Walls for In-plane Loads

- Design assumptions of Code 9.3.2 apply
- Interaction diagram:

![Interaction Diagram]

- $P_n$ max. per ductility requirement
- Pure compression
- Pure flexure
- Balance point
- Excluded portion non-ductile
NEHRP Recommended Provisions
Masonry Design

Simplified Design for Wall-type Structures
Essential Function of Walls in Resisting Lateral Forces

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

- Walls parallel to lateral forces act as shear walls.

- Bond beams transfer reactions from walls to horizontal diaphragms and act as diaphragm chords.
Moments and axial forces due to combinations of gravity and lateral load

\[ M = P e \]

\[ M \approx P e / 2 \]

\[ M_{\text{wind, eq}} \]
Component Design: Design of walls

Out-of-plane forces, $F_p$

Out-of-plane bending and shear
Component Design basics

beff = 6t ≤ s ≤ 72”

T - beam section assumed to resist out-of-plane flexure
(Masonry laid in running bond)
Design Flexural Reinforcement as Governed by Out-of-plane Loading

- Practical wall thickness is governed by available unit dimensions:
  - 8- by 8- by 16-in. nominal dimensions is most common
  - Specified thickness = 7-5/8 in.
  - One curtain of bars, placed in center of grouted cells
- Can have nominal 6” through 12”
- Proportion flexural reinforcement to resist out-of-plane wind or earthquake forces
Distribution of Shears to Shear Walls

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

In-plane force

Force distributed according to relative stiffness
Design Flexural Reinforcement as Governed by In-plane Loading

- Construct moment – axial force interaction diagram
  - Initial estimate
  - Computer programs
  - Spreadsheets
  - Tables
Check Shear Capacity

- \( V_n = (V_{nm} + V_{ns})\gamma_g \)
- \( V_{nm} \) depends on \( (M_u / V_u d_v) \) ratio
- \( V_{ns} = (0.5) A_v f_y \) (note efficiency factor when combining \( V_{nm} \) and \( V_{ns} \))
- \( \gamma_g = 1.0 \) for fully grouted walls

\[ \Sigma A_v f_y \]
Procedure for Strength Design of Reinforced Masonry Shear Walls

- Select trial design
- Compute $M_u$ and $V_u$ for in- and out-of-plane loading
  - Include p-δ for out-of-plane moment
- Design reinforcement for out-of-plane loading
- Design reinforcement as controlled by in-plane loading
  - Revise design as necessary
- Check to ensure ductility
- Check shear capacity and revise if required
- Check detailing
Refer to NEHRP Design Examples (FEMA P-751) Ch. 13, Masonry

Shear Wall: Next slide
Design Example

Refer to NEHRP Ch. 13, Masonry
Design Example

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Trial design: (6) cells w/ (2) #6

Refer to NEHRP Ch. 13, Masonry
Design Example

Ductility Check

Refer to NEHRP Ch. 13, Masonry

Note: $\alpha = 4$ for Special Reinforced Masonry Shear Wall

$\varepsilon_x = 4\varepsilon_y = 0.0083$
Design Example

Ductility Check (cont.)

Refer to NEHRP Ch. 13, Masonry
Design Example

Ductility Check (continued)

\[ \Sigma C > \Sigma T + P \]

\[ Cm + Cs1 + Cs2 > Ts1 + Ts2 + Ts3 + Ts4 + P \]

\[ 315.5 + 53.6 + 28.1 > 52.8 + 52.8 + 52.8 + 43.4 + 45.1 \]

\[ 397 \text{ kips} > 247 \text{ kips} \quad \text{OK} \]

OK because comp capacity > tension capacity

Refer to NEHRP Ch. 13, Masonry
Refer to NEHRP Ch. 13, Masonry

\[ P = 0 \text{ Case} \]
Design Example

Refer to NEHRP Ch. 13, Masonry

Balanced Case

\[
\begin{align*}
C_{m1} & \quad C_{m2} & \quad C_{m3} \\
\varepsilon_m = 0.0025 & \quad \varepsilon_Y = 0.00207 & \\
0.8 f'_m & \quad C_{s2} & \quad C_{s1} \\
\varepsilon = 0.0019 & \quad \alpha = 40.3'' & \\
\end{align*}
\]

\[
\begin{align*}
16'' & \quad 16'' & \quad 8.3'' & \quad 7.7'' & \quad 2.3'' & \quad \varepsilon = 0.0017 \\
48'' & \quad 44'' & \quad 4'' & \quad \text{Center Line} & \quad \text{N.A.} & \quad 44'' \\
\end{align*}
\]
Design Example

Refer to NEHRP Ch. 13, Masonry

\[ Pn = \Sigma C - \Sigma T = 534 \text{ kips} \]
\[ \phi Pn = (0.9)(534) = 481 \text{ kips} \]
\[ \Sigma McI = 0: \]
\[ Mn = 23,540 \text{ in.-kips} \]
\[ \phi Mn = (0.9)(23,540) = 1,765 \text{ ft-kips} \]
Refer to NEHRP Ch. 13, Masonry
Web sites for more information

- BSSC = https://www.nibs.org/?page=bssc
- TMS = www.masonrysociety.org
- ACI = www.concrete.org
- ASCE / SEI = www.seinstitute.org
- NCMA = www.ncma.org
- BIA = www.bia.org
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● The material originally prepared by Dr. Harris was for FEMA, The Building Seismic Safety Council, and the American Society of Civil Engineers.
Questions?

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