NEHRP Seismic Design Technical Brief No. 9

Seismic Design of Special Reinforced Masonry Shear Walls

A Guide for Practicing Engineers

NEHRP Seismic Design Technical Brief No. 9

presented by

Greg Kingsley, PE, PhD
President and CEO, KL&A Inc.

KL&A, Inc.
Structural Engineers and Builders

NCSEA
National Council of Structural Engineers Associations

NEHERP Seismic Technical Briefs

- http://www.nehrp.gov/library/techbriefs.htm
- No 1: Reinforced Concrete Special Moment Frames
- No 2: Steel Special Moment Frames
- No 3: Cast-in-Place Concrete Diaphragms, Chords, and Collectors
- No 4: Nonlinear Structural Analysis for Seismic Design
- No 5: Composite Steel Deck and Concrete-filled Diaphragms
- No 6: Cast-in-Place Concrete Special Structural Walls and Coupling Beams
- No 7: Reinforced Concrete Mat Foundations
- No 8: Steel Special Concentrically Braced Frame Systems
- No 9: Special Reinforce Masonry Shear Walls
- No 10: Wood Light-Frame Structural Diaphragm Systems

Acknowledgements

Tech Brief 9 was prepared under the
- National Earthquake Hazards Reduction Program (NEHRP)

By
- National Institute of Standards and Technology (NIST)
  - Dr. Steven L. McCabe
- Applied Technology Council (ATC)
  - Jon Heintz, Bernadette Hadnagy
- Consortium of Universities for Research in Earthquake Engineering (CUREE)
  - Robert Reitherman, Reed Helgens, Darryl Wong

Acknowledgements

The authors of Tech Brief 9 were:

- Authors
  - Greg Kingsley, KL&A Inc., Structural Engineers, Golden, CO
  - Thomas Gangel, Wallace Engineering, Tulsa, OK
  - P. Benson Shing, Professor of Structural Engineering, UC San Diego

- Review Panel
  - Richard Klingner, Professor Emeritus, University of Texas, Austin
  - Steve Dill, KPFF Consulting Engineers, Seattle, WA
  - David Biggs, Biggs Consulting Engineering, Saratoga Springs, NY

Learning Objectives

Participants will

1. Be familiar with the Special Reinforced Masonry Shear Wall **design process**
2. Be alert to **unique issues** that make design of Special Reinforced Masonry Shear Walls different from other materials
3. Know which **analysis techniques** are appropriate to special RM walls
4. Be aware of new **limit design procedures** in TMS 402

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

NEHRP Seismic Tech Brief 9

NEHRP Seismic Design Technical Brief No. 9

Seismic Design of Special Reinforced Masonry Shear Walls

A Guide for Practicing Engineers

Gregory R. Kingsley
P. Benson Shing
Thomas Gangel

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

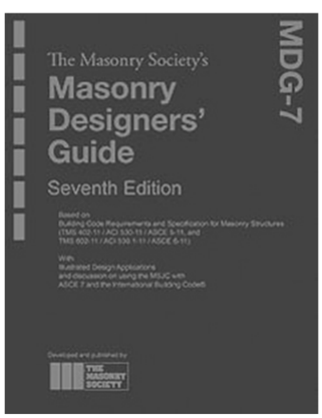
The Tech Brief is “brief” and general in nature

Draw some circles

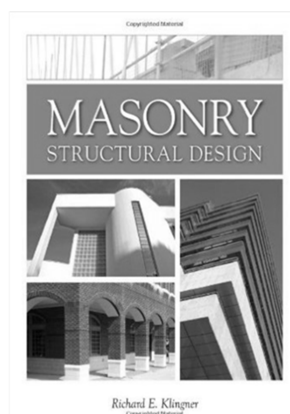
Draw the rest of the owl

The Tech Brief does not have design examples

MDG-7



Masonry Structural Design

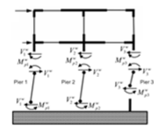


NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

NEHRP Seismic Tech Brief 9: Scope

- Only **<u>Special</u> Reinforced Masonry Shear Walls**
- With particular guidance for
  - Ductile walls that need strength
  - Strong walls that need ductility
  - Mixed combinations of walls in one line
  - Appropriate analysis to capture these effects



ATC CUREE *NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers* NIST nehrp

nehrp NEHRP Seismic Design Technical Brief No. 9

CHAPTER 1
INTRODUCTION

ATC CUREE *NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers* NIST nehrp

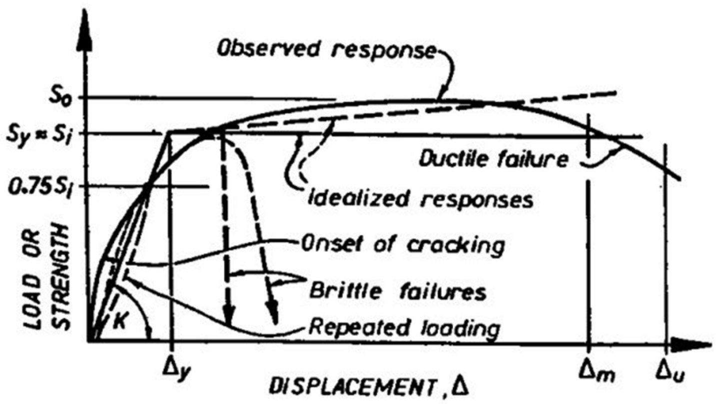
When are Masonry Walls "Special"?

- The IBC 2012 requires the use of special reinforced masonry walls in structural masonry buildings assigned to Seismic Design Category D, E, or F
- Design force levels are specified in ASCE 7-10
- Design procedures and detailing requirements are addressed in TMS 402, *Building Code Requirements for Masonry Structures*

When are Masonry Walls "Special"?

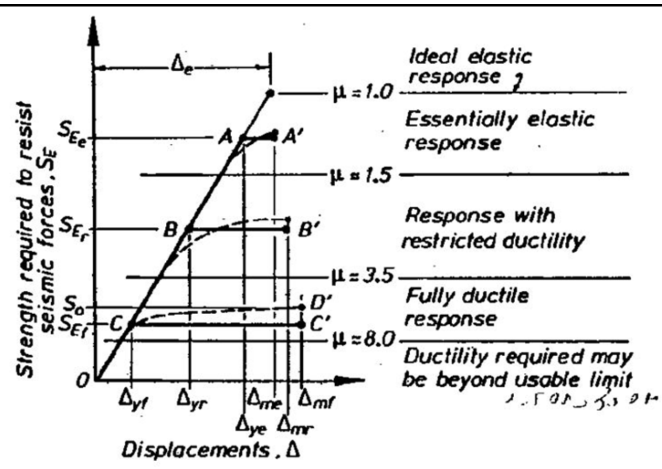
- ASCE 7 assigns the response modification factor:
  - R = 5 for bearing wall systems
  - R = 5.5 for building frame systems
- Inherent in the use of R=5 or more is the presumption of ductile behavior associated with the development of plastic hinges with stable, inelastic rotation capacity.

Code Intent for Special Walls: Ductility



Typical load-displacement relationship for reinforced masonry or concrete. (From Paulay and Priestley)

Code Intent for Special Walls: Ductility



The relationship between demand for strength and available ductility (From Paulay and Priestley)

ATC CUREE NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers NIST nehrp

Code Intent for Special Walls: Ductility

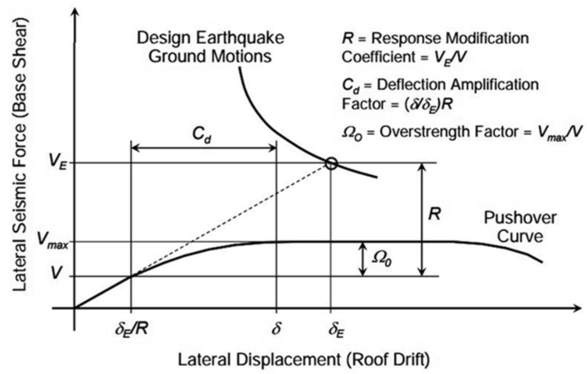


Figure 1-1 Illustration of seismic performance factors (R, Ω_O, and C_d) as defined in the Commentary to the *NEHRP Recommended Provisions* (FEMA, 2004b).

Where R-factors come from. (From FEMA p695)

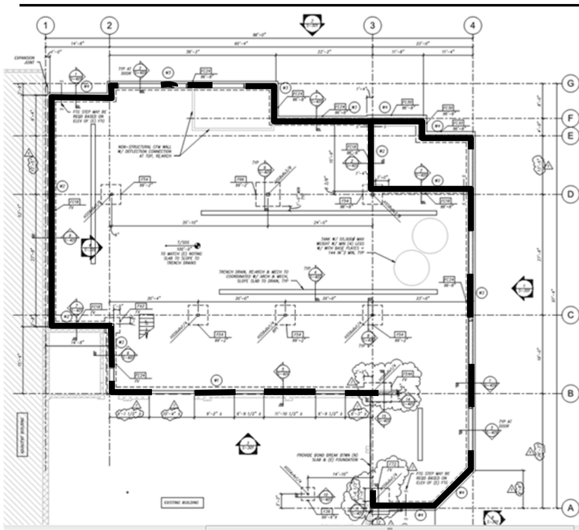
Masonry Buildings are Different

- Structural designers usually locate and size structural elements to achieve the desired behavior
- But masonry serves simultaneously as:
  - Architecture
  - Enclosure
  - Structure
- Structural design must respond first to constraints imposed by *architecture* and *enclosure*.

Chapter 1: Introduction

The engineer designing structural masonry must play the hand they are dealt.

Imposed PLAN configuration for RM walls



Some walls are very long, with more strength than demand

Some walls are short

Some walls have flanges

Some lines of resistance have multiple, flexure-dominated elements

Some lines of resistance have multiple, disparate elements

All walls carry both in and out-of-plane loads

… and so on

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Imposed ELEVATION Configuration

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

ATC CUREE NIST nehrp

Imposed ELEVATION Configuration

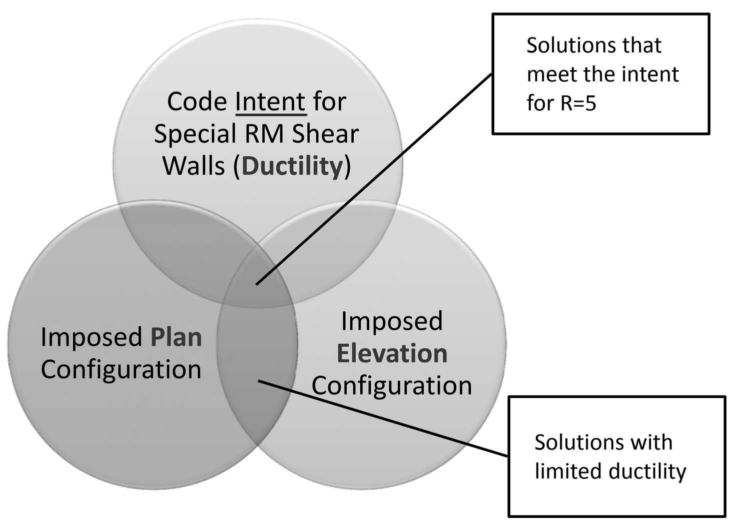
NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

ATC CUREE NIST nehrp

Imposed ELEVATION Configuration

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

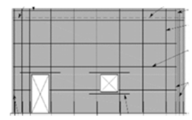
Chapter 1: Introduction



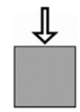
NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

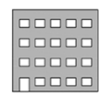
Chapter 1: Introduction

The Code encourages ductility by addressing:



- Minimum reinforcement requirements
- Maximum reinforcement requirements
- Axial load effects
- Plan geometry
- Elevation geometry



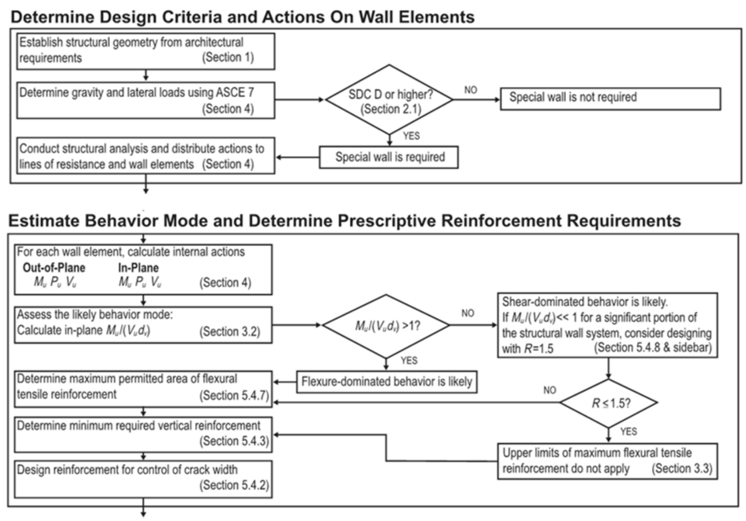


Chapter 1: Introduction

But meeting the Code does not *always* ensure a design that is consistent with the intention of ductility

ATC CUREE NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers NIST nehrp

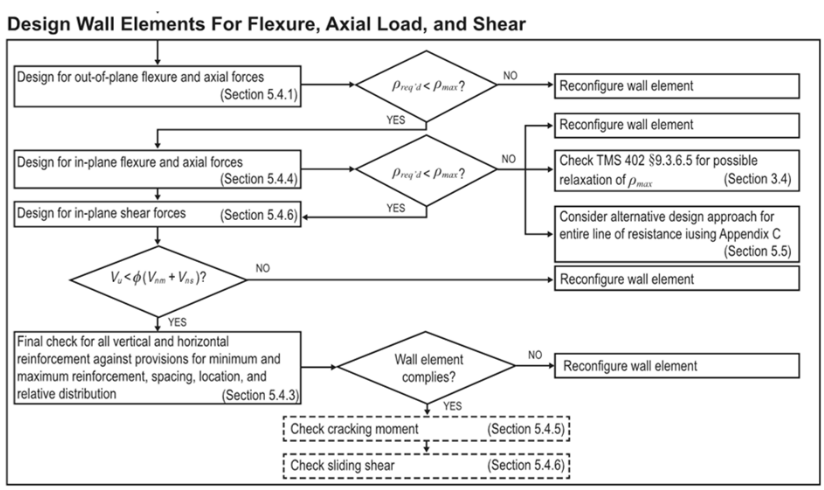
Chapter 1: Introduction



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

ATC CUREE NIST nehrp

Chapter 1: Introduction



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

ATC CUREE NIST nehrp

Chapter 1: Introduction

THE SIDEBARS

Sidebars in this Guide

Sidebars are used in this Guide to provide additional guidance on good practices and open issues in analysis, design, and construction.

Chapter 1: Introduction

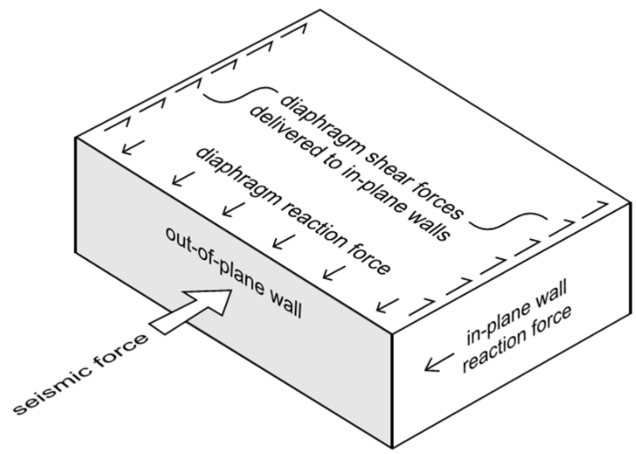
A note about the MSJC: the masonry code has traditionally been produced through the efforts of a joint committee sponsored by The Masonry Society (TMS), American Concrete Institute (ACI), and American Society of Civil Engineers (ASCE). In 2013, the ACI and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE) released their rights to future editions of the building code and commentary TMS 402/ ACI 530/ASCE 5 and the specifications TMS 602/ ACI 530.1/ASCE 6 (TMS 2013b). Going forward, the masonry code will be known as "TMS 402" and the specifications as "TMS 602." This Guide respects that change.

CHAPTER 2 THE USE OF REINFORCED MASONRY STRUCTURAL WALLS IN BUILDINGS

Chapter 2: The Use of RM Structural Walls in Buildings

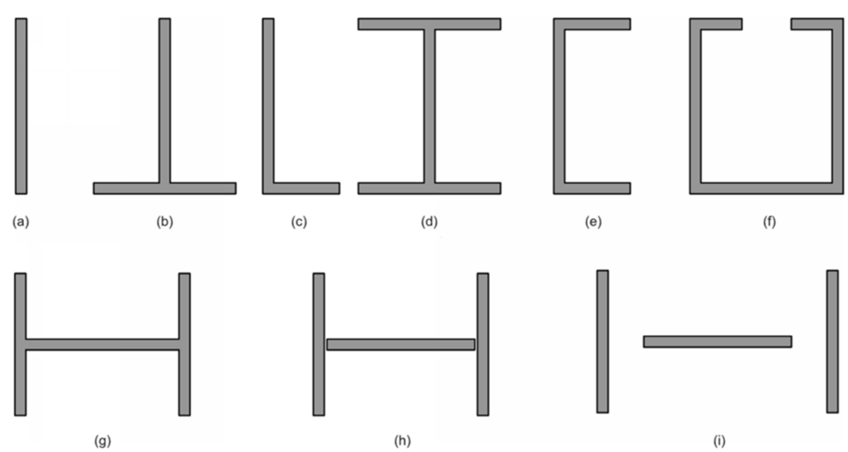
- Chapter 2 addresses
  - Typical load paths through masonry buildings
  - Typical plan configurations that affect behavior of shear walls
  - Typical elevation configurations that affect behavior of shear walls

Load paths in structural wall buildings



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

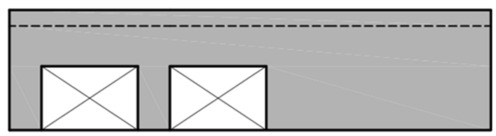
Plan configurations of shear walls



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

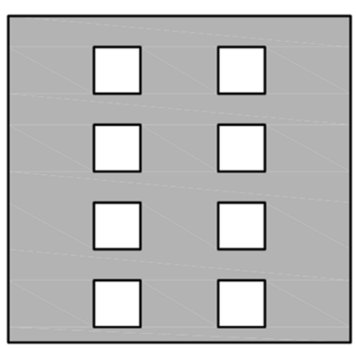
Elevation configurations of shear walls

(a) Squat, shear-dominated wall,
showing control joints

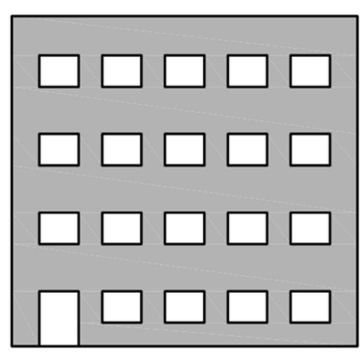


(b) Single line of resistance with
disparate wall element stiffnesses

Elevation configurations of shear walls

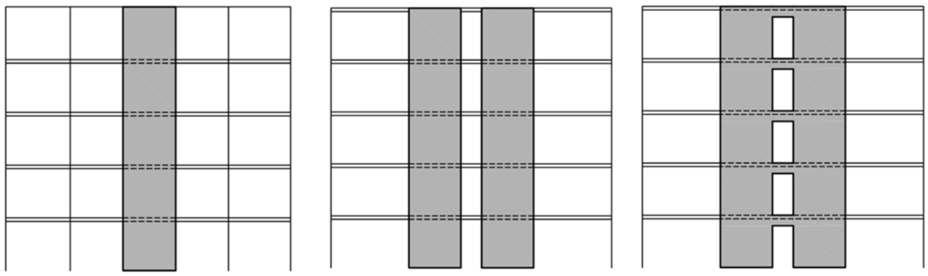


(c) Perforated wall: beam-governed



(d) Perforated wall: pier-governed

Elevation configurations of shear walls



(e) Cantilever wall (f) Slab-coupled wall (g) Beam-coupled wall

Elevation configurations of shear walls

Elevation configurations of shear walls

Elevation configurations of shear walls

Elevation configurations of shear walls

Elevation configurations of shear walls

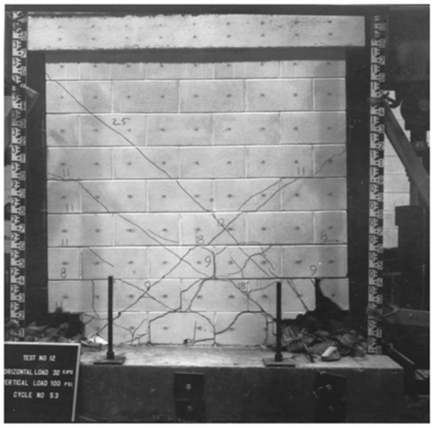
NEHRP Seismic Design Technical Brief No. 9

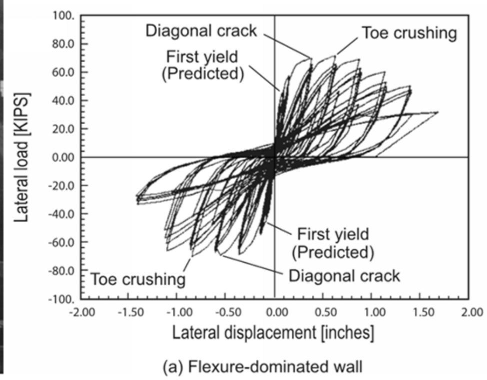
CHAPTER 3 DESIGN PRINCIPLES FOR SPECIAL MASONRY SHEAR WALLS

Chapter 3: Design Principles for Special Masonry Shear Walls

- Chapter 3 addresses
  - The concept of ductility
  - The concept of Flexure vs. Shear dominated walls
  - Options available to the designer to control the behavior mode of wall elements and lines of resistance

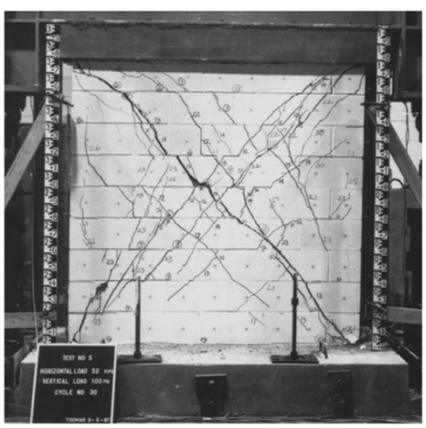
Flexure-Dominated Wall

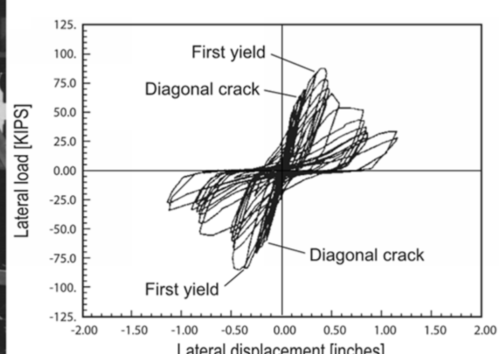




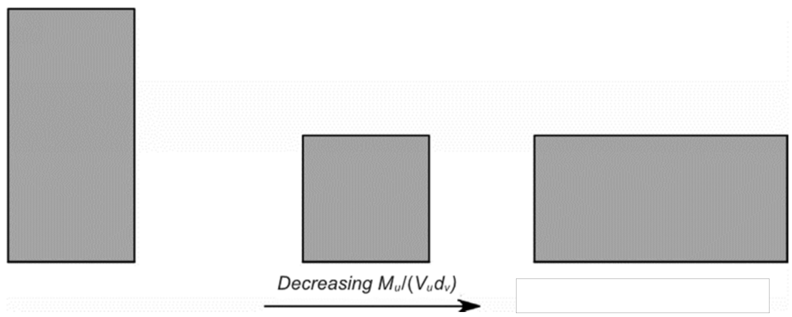
(a) Flexure-dominated wall

Shear-Dominated Wall





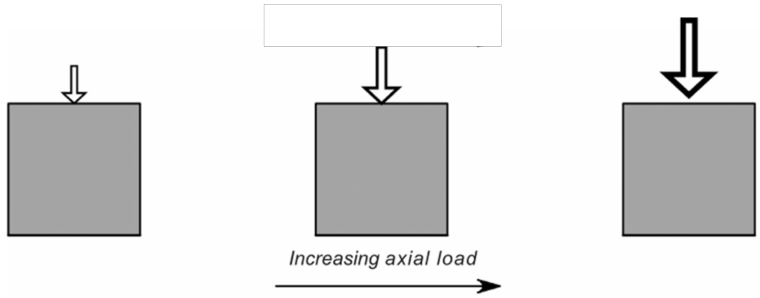
Shear-span-to-depth Ratio, Axial Load and Reinforcing Distribution affect ductility



FLEXURE-DOMINATED → SHEAR DOMINATED

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

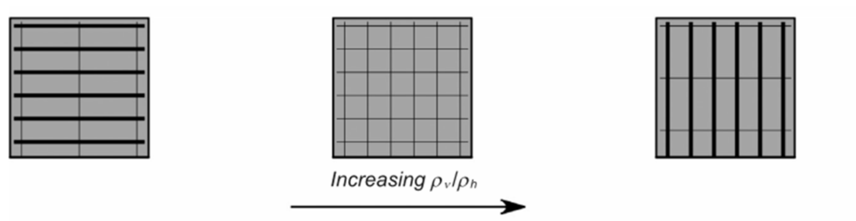
Shear-span-to-depth Ratio, Axial Load and Reinforcing Distribution affect ductility



FLEXURE-DOMINATED → SHEAR DOMINATED

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Shear-span-to-depth Ratio, Axial Load and Reinforcing Distribution affect ductility

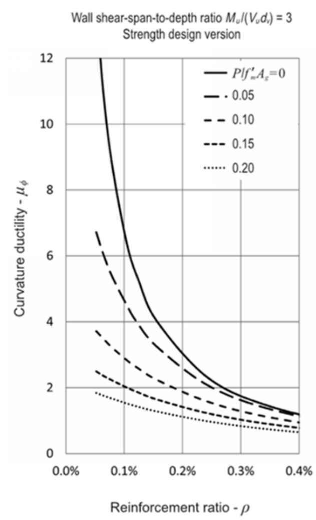


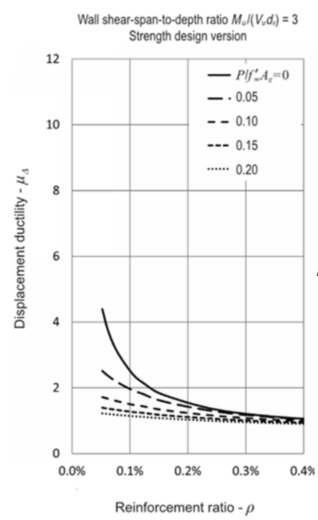
FLEXURE-DOMINATED → SHEAR DOMINATED

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Ductility in flexure-dominated walls

$$\mu_\varphi = \frac{\varphi_m}{\varphi_y}$$

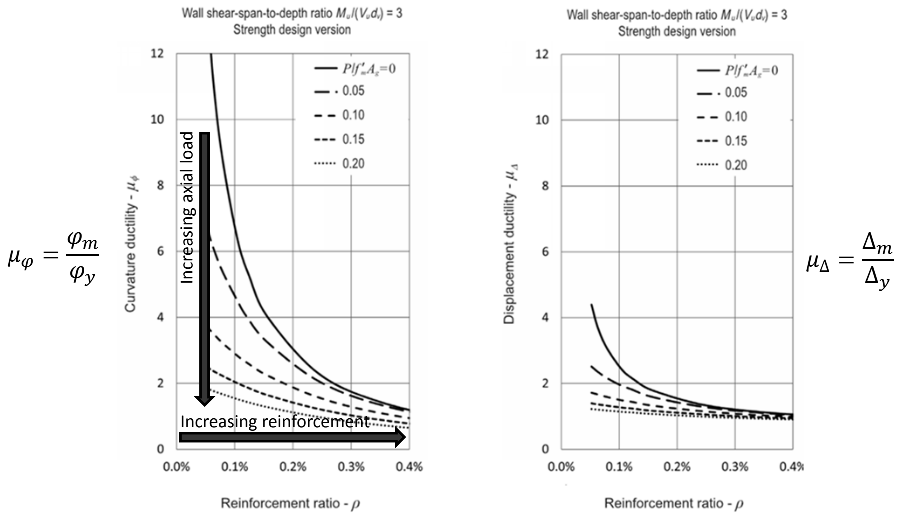




$$\mu_\Delta = \frac{\Delta_m}{\Delta_y}$$

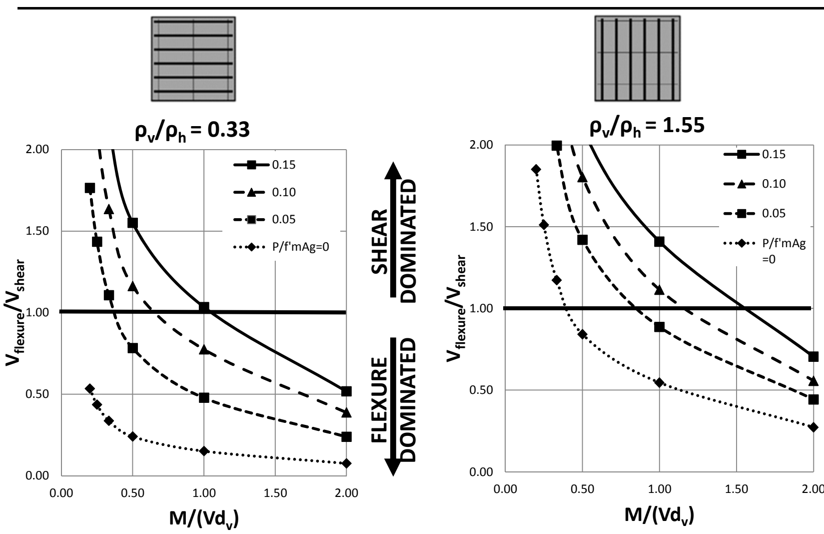
NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Ductility in flexure-dominated walls



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Aspect Ratio, Axial Load and Reinforcing Distribution affect ductility



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Maximum Reinforcement Limits

- To encourage ductile behavior, TMS 402 applies strict limits to the amount of flexural reinforcement allowed in special walls
- These limits can occasionally be a barrier to achieving the required flexural strength for flexure-dominated elements

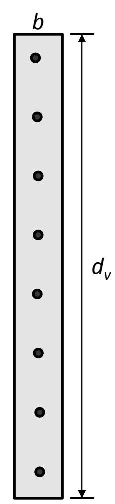
Maximum Reinforcement Ratio – Distributed Reinforcement

Maximum Reinforcement per TMS 402 §9.3.3.5.3

- *In-plane loads*
- *Uniformly distributed reinforcement*

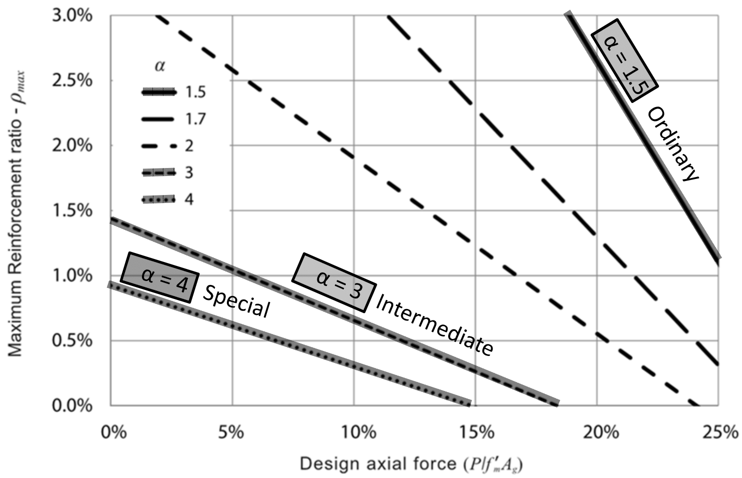
$$\frac{A_s}{d_v} = \frac{0.64 f'_m b \left(\frac{\varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right) - \frac{P}{d_v}}{f_y \left(\frac{\alpha\varepsilon_y - \varepsilon_{mu}}{\varepsilon_{mu} + \alpha\varepsilon_y}\right)}$$

α = 1.5 Ordinary α = 3 Intermediate α = 4 Special



α = ratio of maximum strain in tensile reinforcement to yield strain
ε_{mu} = maximum usable compressive strain of masonry
ε_y = yield strain of reinforcing steel
f_y = yield stress of reinforcing steel
f'_m = specified compressive strength of masonry
P = expected axial force at the time of the design earthquake

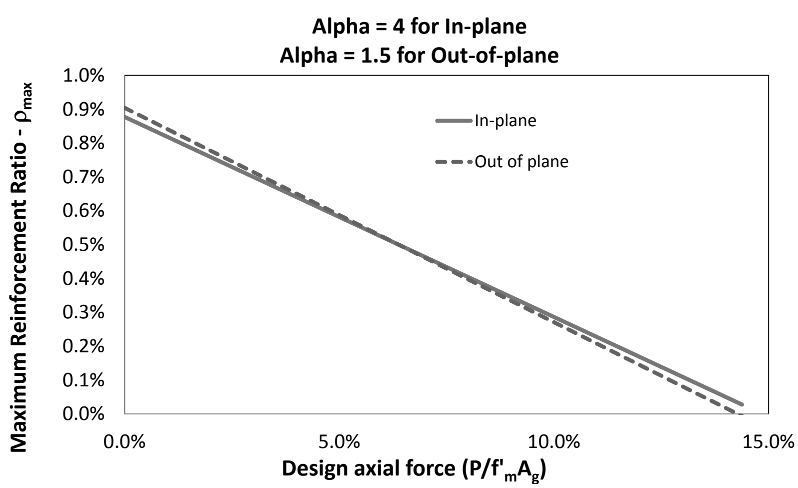
Maximum Reinforcement Ratio



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

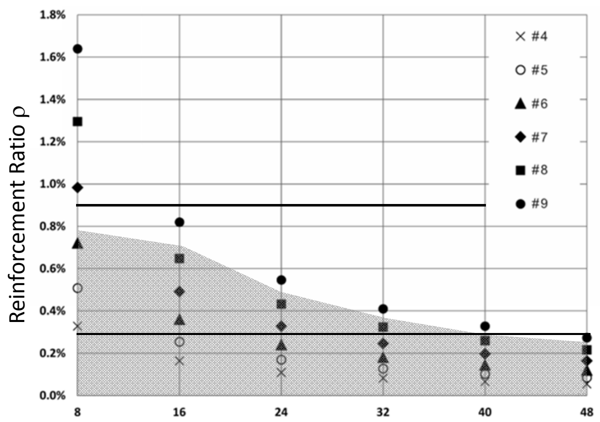
Maximum Reinforcement Ratio

Maximum reinforcement ratio for Special Walls: In-plane an Out-of-plane conditions



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

Reinforcement ratios for uniformly distributed reinforcement – 8” wall



ρ_{max}=.92 when $P/(f'_m A_g)=0$

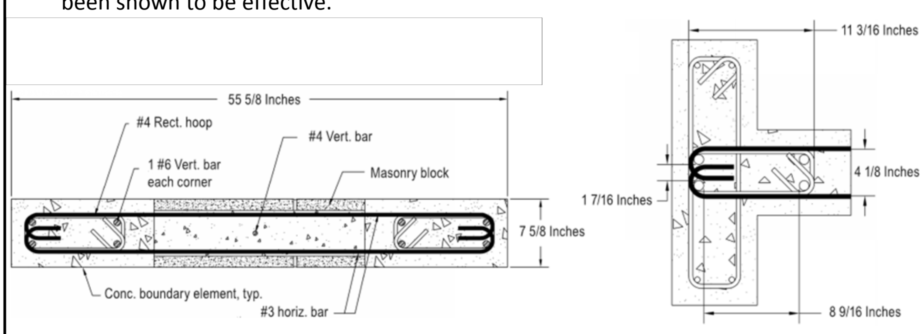
ρ_{max}=.3 when $(P/f'_m A_g)=0.1$

Shaded area:
Bar size limit for 8” block

3.4 Shear Walls with Boundary Elements

Effective boundary elements are hard to achieve in masonry, and require special testing (TMS 402 §9.3.6.5.5)

Supplemental reinforced concrete boundary elements have been shown to be effective.



(a) Rectangular boundary elements From Cyrier, (2012) (b) Boundary element with return

3.4 Shear Walls with Boundary Elements

BUT …

COMMENTARY

9.3.6.5.1 This subsection sets up some "screens" with the expectation that many, if not most, shear walls will go through the screens, in which case no special boundary elements would be required. This situation will be the case when a shear wall is lightly axially loaded and it is either short or is moderate in height and is subject to only moderate shear stresses.

In this case, the usual maximum reinforcement limits are waived.

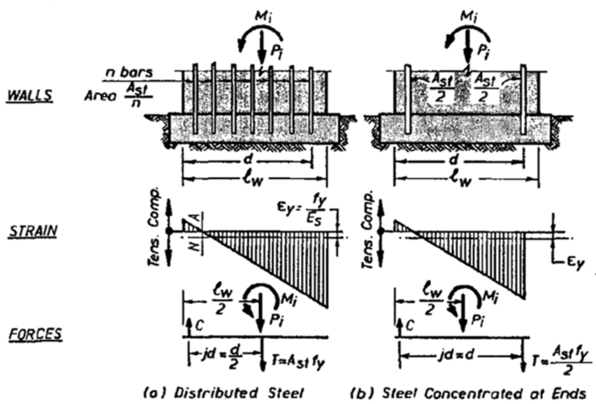
3.4 Shear Walls with Boundary Elements

Additional computations

1. A displacement based check intended to limit the ultimate curvature in the plastic hinge region of the wall, and
2. A stress based check

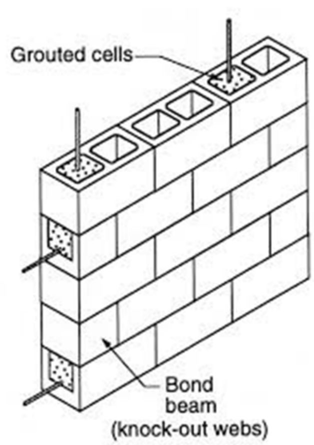
Satisfying these checks can allow reinforcement in excess of ρ_{max}, even if boundary elements are not required

3.5 Reinforcement Distribution



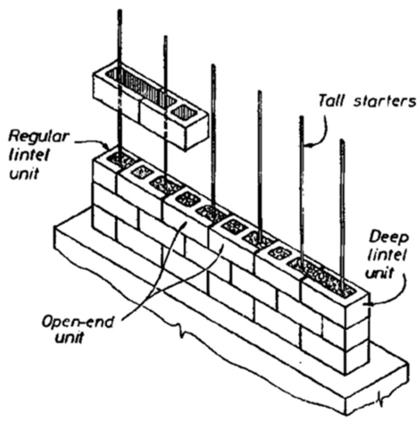
- For Strength Design, gain in strength with concentrated reinforcement typically less than 5%.
- Distributed reinforcement improves
  - Grout placement
  - Reinf congestion
  - Shear friction
  - Ductility

3.6 Grout Placement and Behavior



- Fully grouted walls
  - Appropriate for many flexure-dominated special walls
- Partially grouted walls
  - More economical
  - Appropriate for lightly loaded walls
  - Less ductile
  - Less shear strength

3.7 Lap Splices in Plastic Hinge Zones

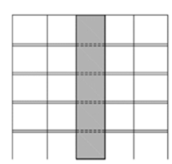


- Subject of debate!
- TMS 402 silent
- Prohibition in ASCE7 §14.4 negated by IBC
- In flexure-dominated walls, lap splices:
  - May cause flexural overstrength, and change a flexure-dominated wall to a shear dominated wall
  - May reduce plastic rotation capacity because splice reduces yield length
  - May not perform due to lack on confinement reinforcement
  - May slip

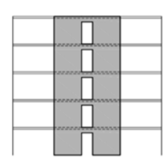
NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

3.8 Wall Configurations and Behavior

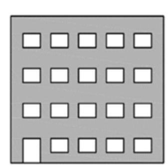
- Cantilevered walls



- Coupled walls



- Perforated walls

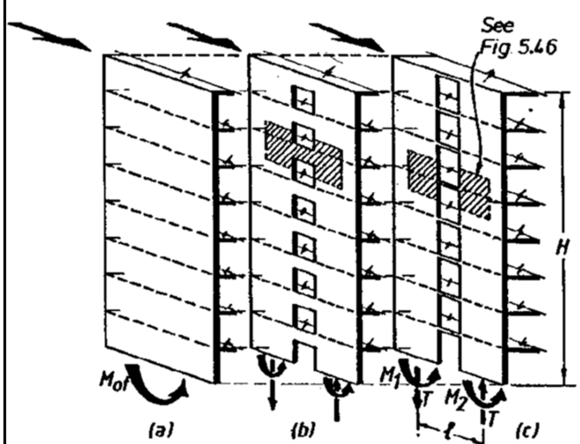


NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

3.8 Wall Configurations and Beahvior

- Designed as a coupled wall
- Performed like a perforated wall

3.9 Design of Coupled Walls



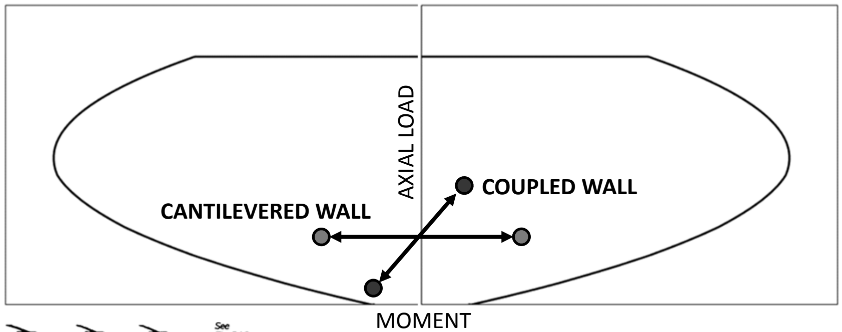
$$M_{ot} = M_1 + M_2 + \ell T$$

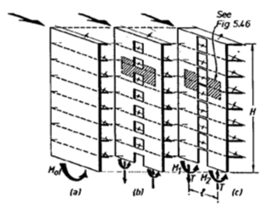
- Strong coupling from slabs alone can cause walls designed as cantilever walls to perform like coupled walls
- Strong coupling from beams and slabs can cause walls designed as coupled walls to perform like perforated walls

From Paulay and Priestley

ATC CUREE NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers NIST nehrp

3.9 Design of Coupled Walls



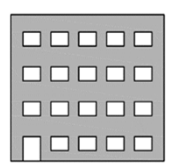


Coupling cantilevered walls:

- Reduces the moment demand on the wall
- Cycles the axial load demand on the wall
- Puts large ductility demand on coupling beams

3.10 Design of Perforated Walls

- Often very difficult to achieve ductility level intended for special walls
- Consider
  - Using lower R factor, or
  - Following TMS 402 Appendix C (Limit Design)



3.12 Stiffness and Drift Limits

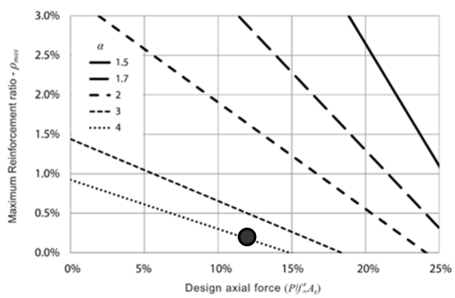
- Walls should provide at least 80% of stiffness on any level or along any line of resistance.
- Drift limits are per ASCE 7

  Not usually an issue for special walls in buildings of moderate height

3.13 Cracking Moment

- $M_{cr} < M_u$ required?
- Not in TMS 402, but some feel it is prudent
- The prevailing opinion is that this is not necessary for walls
  - Forces are transient
  - Result is not brittle failure as for beams
  - Already cracked from out-of-plane action

3.14 Building Frame Systems



- For walls with high axial load and thus low reinforcement limits and low ductility, detailing diaphragm connections to transmit only shear to the wall can be advantageous
- If consistent throughout the structure, then R can be increased from 5 to 5.5 for "building frame systems"

3.15 TMS, ASCE7, and IBC

ASCE 7-10

14.4.4 Modifications to Chapter 2 of TMS 402/ACI 530/ASCE 5

14.4.4.1 Stress Increase

If the increase in stress given in Section 2.1.2.3 of TMS 402/ACI 530/ASCE 5 is used, the restriction on load reduction in Section 2.4.1 of this standard shall be observed.

14.4.4.2 Reinforcement Requirements and Details

14.4.4.2.1 Reinforcing Bar Size Limitations Reinforcing bars used in masonry shall not be larger than No. 9 (M#29). The nominal bar diameter shall not exceed

… and so on.

IBC 2012

SECTION 1613
EARTHQUAKE LOADS

1613.1 Scope. Every structure, and portion thereof, including nonstructural components that are permanently attached to structures and their supports and attachments, shall be designed and constructed to resist the effects of earthquake motions in accordance with ASCE 7, excluding Chapter 14 and Appendix 11A. The *seismic design category* for a structure is permitted to be determined in accordance with Section 1613 or ASCE 7.

IBC Chapter 21 makes further modifications to TMS 402.

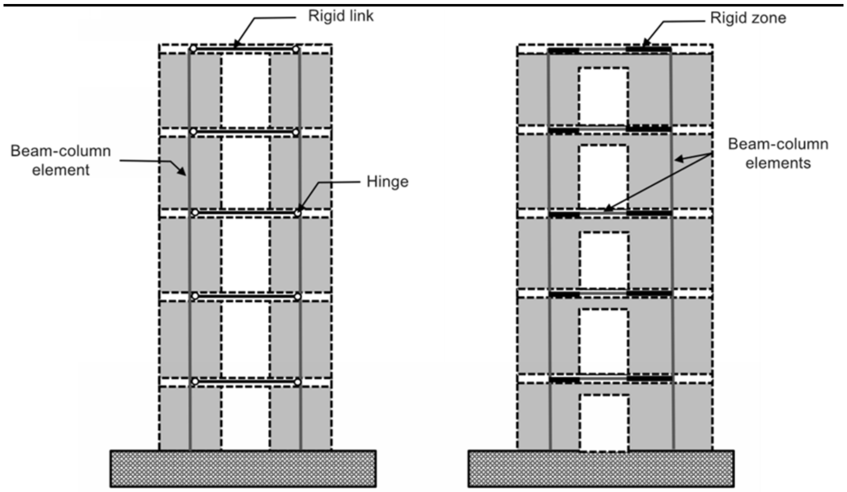
NEHRP Seismic Design Technical Brief No. 9

CHAPTER 4
BUILDING ANALYSIS GUIDANCE

4.1 Analysis Procedures

- ASCE 7 permits three analysis procedures:
  - Equivalent Lateral Force (ELF)
  - Modal Response Spectrum (MRS)
  - Seismic Response History (SRH)
- Most masonry structures can be analyzed with ELF using
  - Linear elastic analysis, or
  - Plastic limit analysis

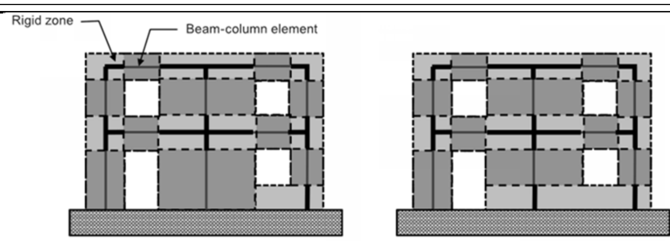
4.2 Structural Idealization



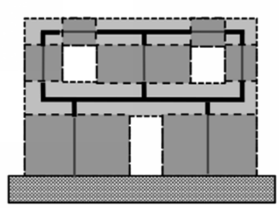
(a) Cantilever wall (weak slab coupling) (b) Coupled walls (slab and beam coupling)

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

4.2 Structural Idealization



(a) Regular arrangement of openings



(b) Irregular arrangement of openings

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

4.3 Elastic Analysis and Member Stiffness

Wall Configuration	Cracked Stiffness I_e
Reinforced concrete walls (in general) ACI 318 §8.8.2	50% I_g
Reinforced concrete walls (uncracked) ACI 318 §8.8.2	70% I_g
Reinforced concrete walls (cracked) ACI 318 §8.8.2	35% I_g
Reinforced masonry – Rectangular (cracked)	15% I_g
Reinforced masonry – T-shaped, (cracked) flange in tension	40% I_g
Reinforced masonry – T-shaped, (cracked) flange in comp.	15% I_g
Reinforced masonry – I-shaped, (cracked)	40% I_g
Reinforced masonry – (uncracked)	100% I_g
Reinforced masonry shear stiffness	35% GA_n *

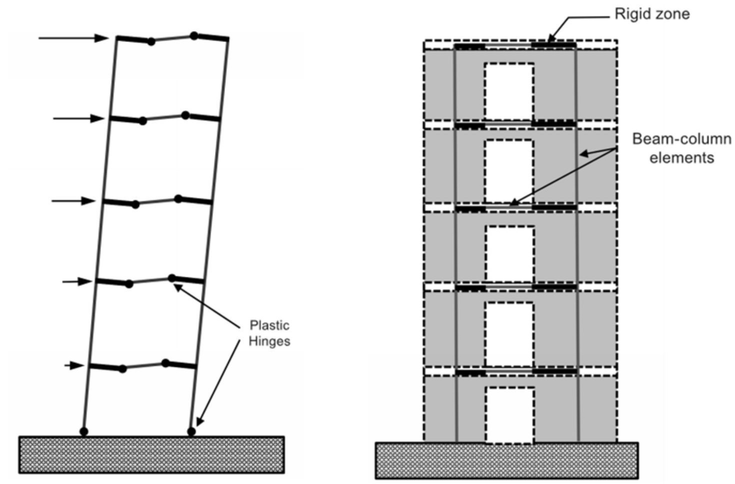
* For partially grouted masonry, A_n= area of face shells + area of grout

4.4 Effective Widths: T-Walls and Coupling Slabs

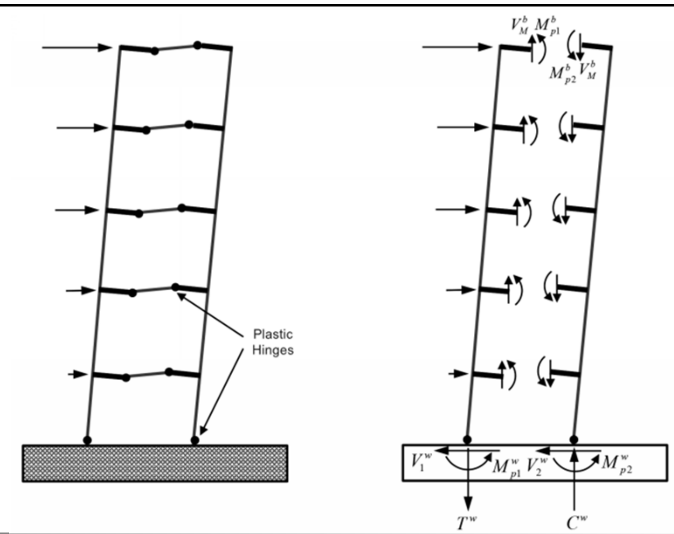
Element	Effective Width *
Flanged wall – Flange in tension	0.75 * Floor-to-floor height ≤ actual flange width
Flanged wall – Flange in compression	6 * nominal flange thickness
Flanged wall – Assume for analysis (conservative for strength)	0.75 * Floor-to-floor height ≤ actual flange width
Coupling slab – detailed for ductility	40 inches
Coupling slab – NOT detailed for ductility	Ignore
Coupling beam + slab –ductile	40 inches, not less than 6* slab thickness
Coupling beam + slab – NOT ductile	Ignore

* Increase by a factor of 1.5 for capacity design checks to avoid brittle shear failure in walls

4.5 Plastic Limit Analysis

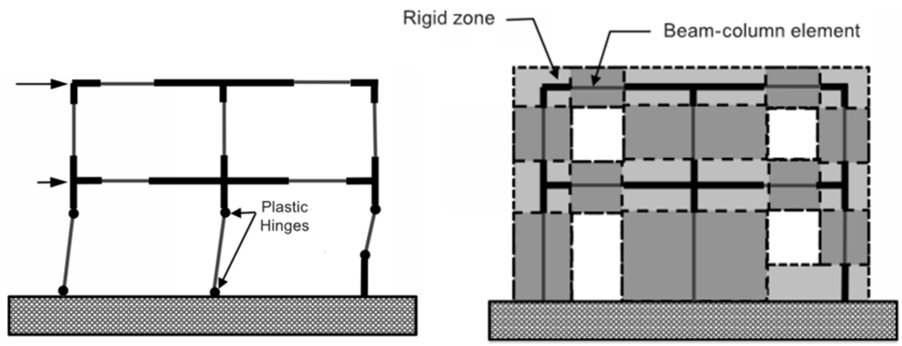


4.5 Plastic Limit Analysis

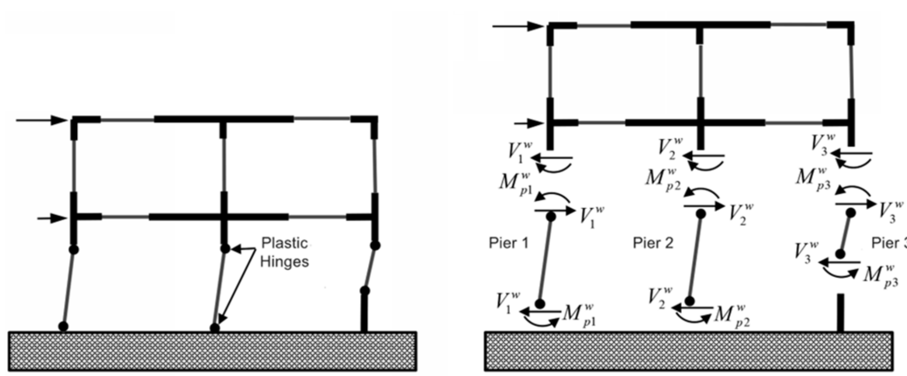


ATC CUREE
NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers
NIST nehrp

4.5 Plastic Limit Analysis



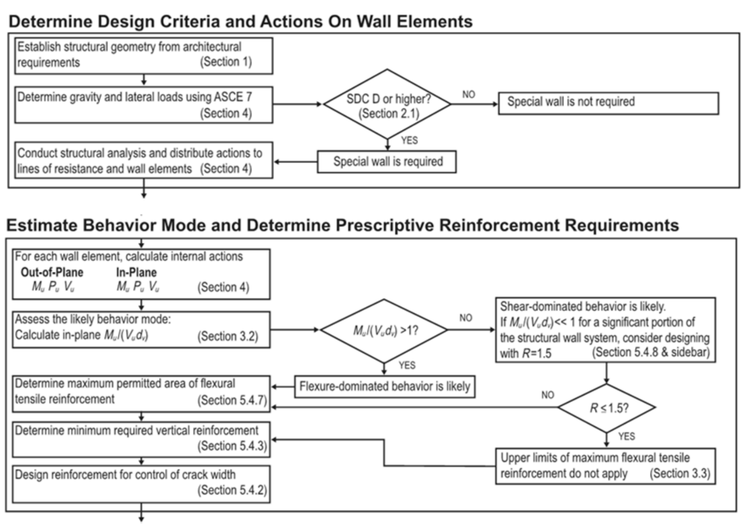
4.5 Plastic Limit Analysis



NEHRP Seismic Design Technical Brief No. 9

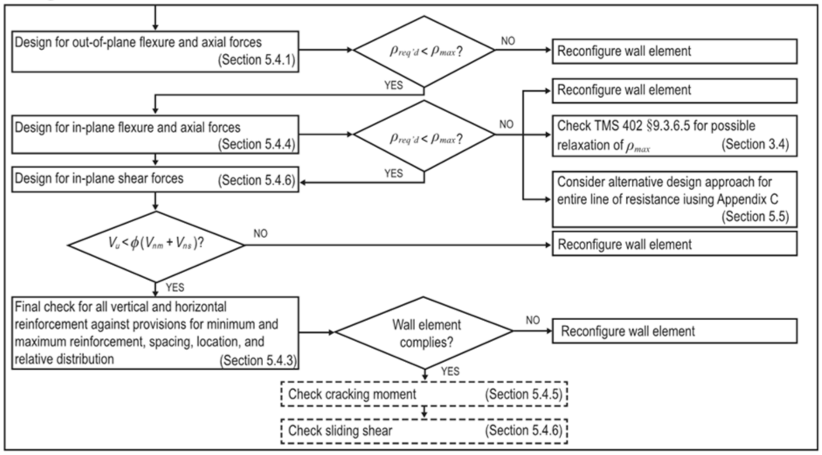
CHAPTER 5
DESIGN GUIDANCE

Chapter 5: Design Guidance



Chapter 5: Design Guidance

Design Wall Elements For Flexure, Axial Load, and Shear



5.4 General Approach to Design

Section 5.4 is organized as a design checklist:

5.4.1 Design the wall segment for the axial load and out-of-plane wind and seismic loads.

5.4.2 Design for shrinkage, permanent moisture expansion, and thermal movements.

5.4.3 Check prescriptive reinforcement requirements for special walls.

5.4.4 Design the wall segment for the axial and in-plane seismic loads.

5.4.5 Check cracking moment (optional).

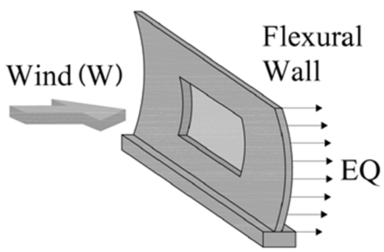
5.4.6 Check shear capacity.

Check sliding shear capacity (optional).

5.4.7 Check maximum reinforcement limits.

5.4.8 Check wall behavior mode, and, if necessary, check repercussions of shear-dominated behavior on other components.

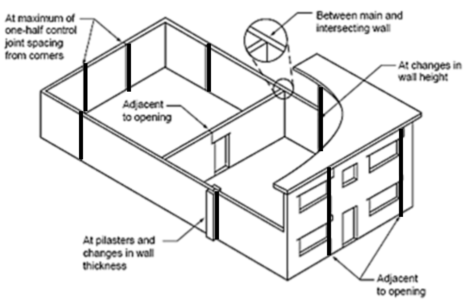
5.4.1 Design for Out-of-plane Forces



- Design for out-of-plane loads first
- The required reinforcement often exceeds that required for in-plane forces
- Reinforcement for out-of-plane forces may result in shear-dominated in-plane walls

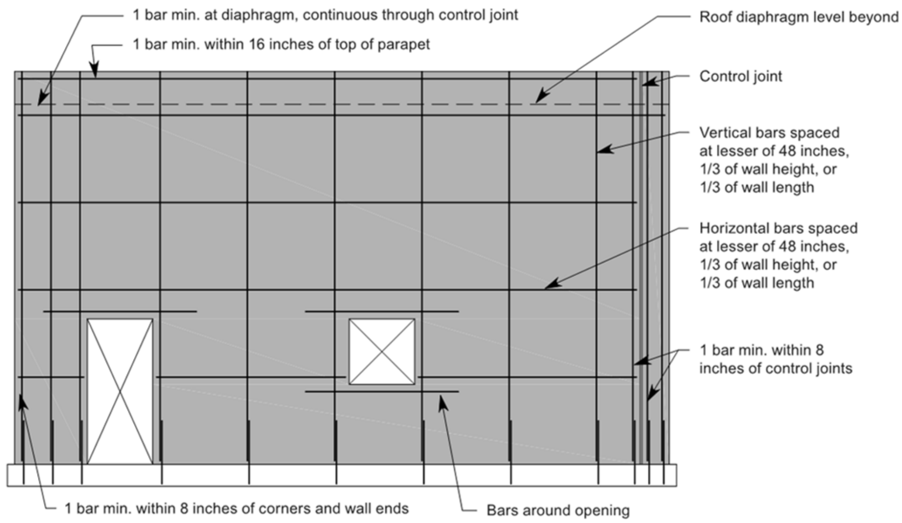
Figure courtesy of David Biggs

5.4.2 Design for masonry volume change



- Movement joints define structural wall segments
- They must precede design for in-plane forces

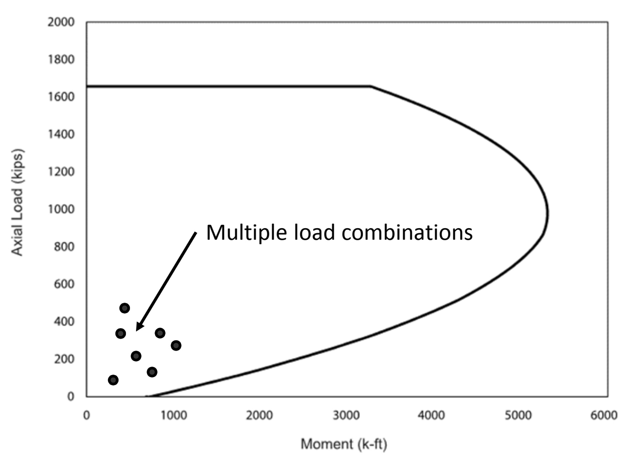
5.4.3 Check prescriptive requirements



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

5.4.4 Check Flexure Capacity

Design wall segments for flexural capacity in the presence of axial loads



NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

5.4.5 Check Cracking Moment (optional)

- Some designers may elect to provide sufficient reinforcement so that yield or ultimate moment exceeds cracking moment.
- Use modulus of rupture per TMS 402 §9.1.9.2

5.4.6 Check Shear Capacity

- TMS 402 §9.3.4.1.2
  - $V_n = (V_{nm} + V_{ns})\,\gamma_g$
  - V_n is capped at a limiting value, beyond which additional shear reinforcement is considered ineffective in increasing wall shear capacity.
  - γ_g reduces the shear capacity of partially grouted walls

5.4.6 Check Shear Capacity

- TMS 402 §9.3.3.7
  - Joint reinforcement can be used as shear reinforcement
- TMS 402 §7.3.2.6.1.1 for special walls
  - ϕV_n must be ≥ shear at 1.25 * M_n
  - V_n need not exceed 2.5 * V_u
    - If this provision is invoked, shear-dominated behavior is likely. Consider using R<5

5.4.6 Check Sliding Shear Capacity

- Not currently in TMS 402

Shear-Friction Strength

Shear friction is a limit state not addressed in TMS 402 but is under consideration. According to the current proposal, the nominal shear-friction strength, V_{nf}, at the sliding-critical interface of a wall can be calculated using the following formula:

$$V_{nf} = \mu(\gamma_f A_s f_y + P_u) \geq 0$$

5.4.7 Check Maximum Reinforcement

- TMS 402 §9.3.3.5 ρ_{max}
  - α = 4 for in-plane special walls
  - α = 1.5 for out-of-plane walls
- TMS 402 §9.3.6.5 Boundary Elements
  - If ρ_{max} is exceeded, check boundary element provisions for possible relaxation of limit (even without incorporating boundary elements)
- If ρ_{max} is still exceeded,
  - Consider Appendix C, Limit Design for line of resistance, or
  - Reconfigure element

5.4.8 Check Wall Behavior Mode

If the a wall element is shear dominated, some options available include:

1. Increase the shear reinforcement if possible.
2. Reduce the vertical (longitudinal) reinforcement to the minimum possible.
3. Increase shear strength by fully grouting the wall.
4. Reconfigure the wall element:
   a) Increase the thickness of the wall to increase its shear strength
   b) Adjust the wall height and/or plan length to increase its aspect ratio.

5.4.8 Check Wall Behavior Mode

If the a wall elements are still shear dominated, the designer must use judgment: code provisions may be explicitly met, but the code intent may not be met.

Often, this condition is associated with walls with significant overstrength.

The designer may choose to consider designing for R≤1.5, even while meeting special wall provisions

5.5 Limit Design Method

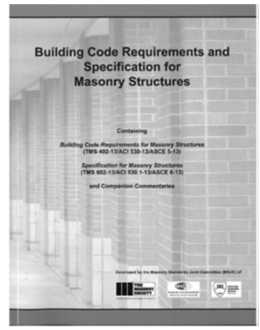
- TMS 402 Appendix C Limit Design
  - New to TMS 402 2013
  - Force based Limit Design procedure is an intermediate step toward displacement based design.
  - Shear distributed along a line of resistance according to plastic capacity, not elastic stiffness
  - Explicit consideration of flexure-dominated and shear-dominated behavior
  - Maximum permissible reinforcement and boundary element provisions do not apply

5.5 Limit Design Method

How is Limit Design Used?

Conventional
Seismic Analysis

THEN



Limit Design for
Selected Walls

From: Dill, Lepage, Frederick, Hochwalt, SEI Structures Congress, Portland, OR, April 2015

ATC CUREE *NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers* NIST nehrp

5.5 Limit Design Method

How is Limit Design Used?

First: Conventional Seismic Analysis

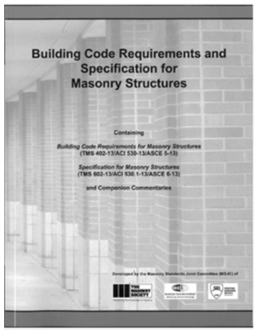
1) Determine design base shear
2) Distribute base shear to lines of resistance
3) Compute demands on wall segments

From: Dill, Lepage, Frederick, Hochwalt, SEI Structures Congress, Portland, OR, April 2015

ATC CUREE *NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers* NIST nehrp

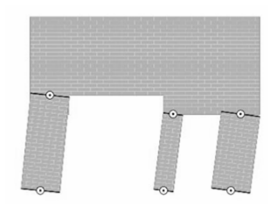
5.5 Limit Design Method

How is Limit Design Used?



Then: Invoke Limit Design for Selected Lines of Resistance

1) Select reinforcement (preferably minimum)
2) Determine controlling yield mechanism



Virtual Work:

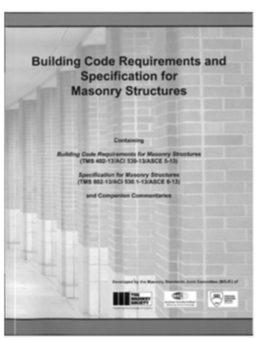
Internal Work: Internal plastic hinges undergoing rotations.

External Work: External force moving with building.

From: Dill, Lepage, Frederick, Hochwalt, SEI Structures Congress, Portland, OR, April 2015

5.5 Limit Design Method

How is Limit Design Used?



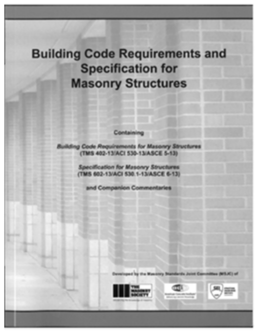
Then: Invoke Limit Design for Selected Lines of Resistance

3) Determine whether any elements are shear dominated
   a) If V_n < 2* shear at M_n, then shear dominated per Limit Design
   b) Reduce hinge capacity or increase shear strength
   c) At minimum, reduce plastic hinge strength to moment associated with half the nominal shear strength V_n

From: Dill, Lepage, Frederick, Hochwalt, SEI Structures Congress, Portland, OR, April 2015

5.5 Limit Design Method

How is Limit Design Used?



Then: Invoke Limit Design for Selected Lines of Resistance

4) Confirm mechanism strength, reduced by ϕ=0.8, is greater than demand per ASCE 7

5) Confirm deformation capacities

6) Design non-yielding components to make sure they remain elastic

From: Dill, Lepage, Frederick, Hochwalt, SEI Structures Congress, Portland, OR, April 2015

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

5.6 Allowable Stress Design

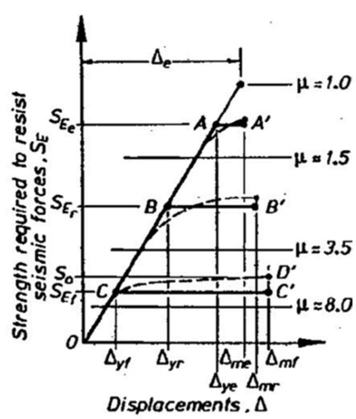
- ASD has been used for decades, and is an effective design method
- For special walls, especially those with larger percentages of longitudinal reinforcement than permitted by SD, the designer may want to consider the implications on inelastic capacity

NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

CHAPTER 6
ADDITIONAL REQUIREMENTS

6.3 Diaphragms

- TECH BRIEFS ON DIAPHRAGMS:
  - No 3: Cast-in-Place Concrete Diaphragms, Chords, and Collectors
  - No 5: Composite Steel Deck and Concrete-filled Diaphragms
  - No 10: Wood Light-Frame Structural Diaphragm Systems
- When shear-dominated walls attract forces larger than those consistent with R=5, diaphragms and their connections are subjected to those larger forces as well.



NIST Technical Brief No. 9: Seismic Design of Special
Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

NEHRP Seismic Design Technical Brief No. 9

CHAPTER 7 DETAILING AND CONSTRUCTABILITY ISSUES

7.1 Masonry Units

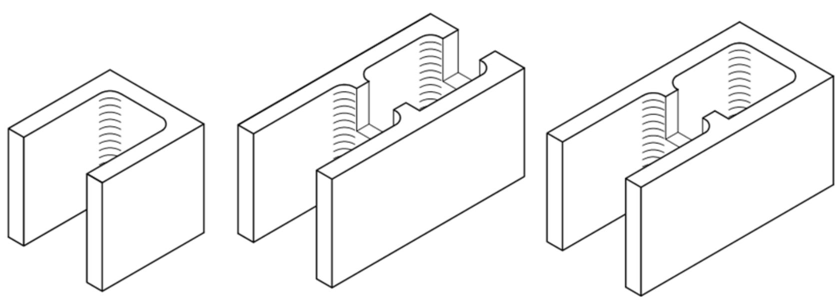


Figure 7-1. Special open-end shapes of hollow masonry units.

7.1 Masonry Units

Grout flow is facilitated by open-end masonry units

7.2 Details of Reinforcement

Shear reinforcement in special walls must be anchored around end vertical bars with a hook
TMS 402 §7.3.2.6(f)

7.4 Grouting

Special walls designed according to TMS 402 and constructed according to TMS 602 require proper placement and consolidation of grout

Consider
- Self-consolidating grout
- Open end units
- Grouting admixtures
- Vibration and reconsolidation
- Reinforcement design that does not inhibit grout placement

Summary and Conclusion

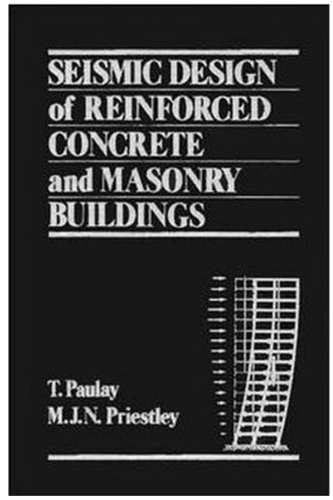
- Tech Brief 9, *Seismic Design of Special Reinforced Masonry Shear Walls* provides:
  - Guidance to meet *both* the letter *and* intent of the building code for Special Reinforced Masonry Walls
  - Guidance for flexure-dominated walls with high demand
  - Guidance for shear-dominated walls with limited ductility
  - A glimpse at some future directions for masonry design

ATC CUREE NIST Technical Brief No. 9: Seismic Design of Special Reinforced Masonry Shear Walls: A Guide for Practicing Engineers NIST nehrp

Dedication

Tom Paulay

Nigel Priestley



NIST Technical Brief No. 9: Seismic Design of Special
Reinforced Masonry Shear Walls: A Guide for Practicing Engineers

QUESTIONS?

NEHRP Seismic Design Technical Brief No. 9

Seismic Design of Special
Reinforced Masonry Shear Walls
A Guide for Practicing Engineers

Gregory R. Kingsley
P. Benson Shing
Thomas Gangel

NCSEA
National Council of Structural Engineers Associations

NIST Technical Brief No. 9: Seismic Design of Special
Reinforced Masonry Shear Walls: A Guide for Practicing Engineers