# Seismic/Limit States Design per TMS 402/602-22

TMS20221102

November 2, 2022

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

# Course Description

This session of the TMS 402/602-22 Night School will review the changes to the provisions in Chapter 7 and Appendix C that effect the seismic design of masonry structures.

This will include revisions to the requirements for special reinforced masonry shear walls, changes to the requirements based on the assigned Seismic Design Category, and changes made to the treatment of seismic displacements in the masonry code, including a new deformation compatibility provision.

The potential impacts of these changes will also be reviewed.



# Learning Objectives

- Review the changes made in TMS 402/602-22 that affect seismic design
- Understand the technical background for the revisions to the provisions for special reinforced masonry shear walls.
- Review the relationship between ASCE 7-22 seismic displacements and the TMS 402 provisions including the use of $MCE_R$ displacements.
- Understand the new deformation compatibility provision and its application.

# Overview

- Special Reinforced Masonry Shear Walls
- Seismic Design Category C+
- Displacements

5

# Special Shear Walls

- Hooks
- Joint Reinforcement
- Shear Capacity Design

6

# Hooks

## Origin

Public Comment on 2016 Code from a Building Official

## Motivations

Resolve ambiguity in the code

## Impact

Moderate



# Hooks

## Comment

*Section 7.3.2.6 (d) states that "shear reinforcement shall be anchored around vertical reinforcing bars with a standard hook" . . . This section is worded sufficiently ambiguous that it can be interpreted in various ways. . .*

1. *Only horizontal reinforcement designed to resist shear need be hooked and all other horizontal reinforcement need not be hooked. Furthermore, if the wall can resist all seismic loads in the masonry only, then none of the horizontal reinforcement need be hooked. . .*
2. *All horizontal steel is shear reinforcement and should be hooked, regardless of the demand on the wall. . .*

# Hooks

**TMS 402-16**

**7.3.2.6** *Special reinforced masonry shear walls* . . . shall comply . . . with the following:

(d) Shear reinforcement shall be anchored around vertical reinforcing bars with a standard hook.

**TMS 402-22**

**7.3.2.5** *Special reinforced masonry shear walls* . . . shall comply . . . with the following:

(i) When the ratio of $V/F_{vm}$ for masonry designed in accordance with Chapter 8 or when the ratio $V_u/\phi V_{nm}$ for masonry designed in accordance with Chapter 9, 10, or 11 exceeds 0.40, the termination of horizontal reinforcement embedded in grout shall meet one of the following:

9

# Hooks

**TMS 402-16**

**TMS 402-22**

1. Except at wall intersections, the ends of horizontal reinforcement shall be bent around the edge vertical reinforcement with a 180-degree standard hook.

10

# Hooks

## TMS 402-16

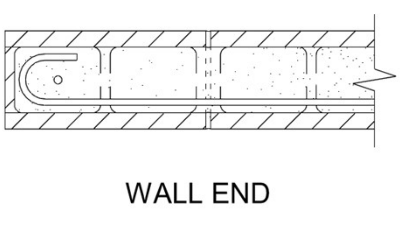
## TMS 402-22

2. At wall intersections, horizontal reinforcement shall be bent around the edge vertical reinforcement with a 90-degree standard hook and shall extend horizontally into the intersecting wall a minimum distance at least equal to the development length.

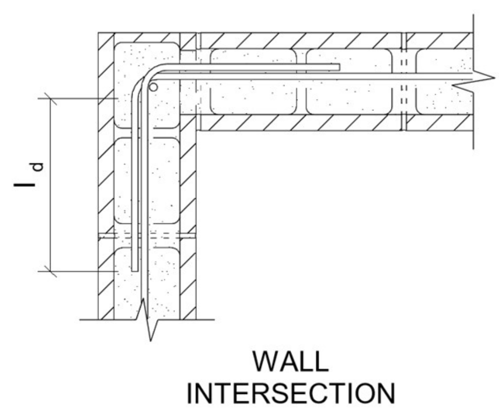


# Hooks

## Free End




## End at Intersection



# Hooks – Flashback to Last Session

TMS 402-16

**6.1.7.1** *Horizontal shear reinforcement*
**6.1.7.1.1** Except at wall intersections, the end of a horizontal reinforcing bar needed to satisfy shear strength requirements of Section 9.3.4.1.2 or Section 11.3.4.1.2 shall be bent around the edge vertical reinforcing bar with a 180-degree standard hook.
**6.1.7.1.2** At wall intersections, horizontal reinforcing bars needed to satisfy shear strength requirements of Section 9.3.4.1.2 or 11.3.4.1.2 shall be bent around the edge vertical reinforcing bar with a 90- degree standard hook and shall extend horizontally into the intersecting wall a minimum distance at least equal to the development length.

**TMS 402-16**

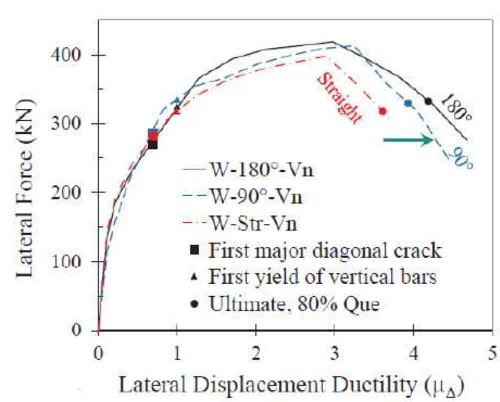
- Requirement deleted except for certain cases of special reinforced shear walls
- Research has shown that hooks provide little to no benefit.



# Hooks – Research Continued

**Seif ElDin, H.M., and Galal, K. (2017):**

It can be concluded . . . that the horizontal reinforcement anchorage end detail in RM shear walls has two main functions.
The first one is to provide a sufficient development length such that the horizontal bars can reach their yield strength



## Hooks – Research Continued

**Seif ElDin, H.M., and Galal, K. (2017):**

. . . the second is to improve the confinement of the extreme vertical bars and the grout in the end zones under compressive stress.

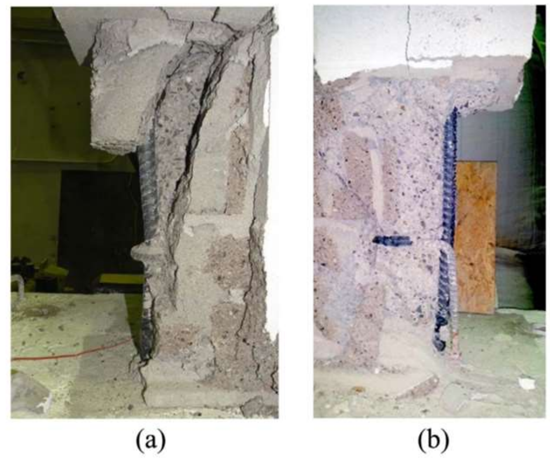


**Fig. 10.** In-plane lateral confinement of vertical reinforcement using: (a) 180° hook; (b) 90° hook anchorage end detail.



## Hooks – Why 0.4 Ratio?

### The Wisdom of Crowds

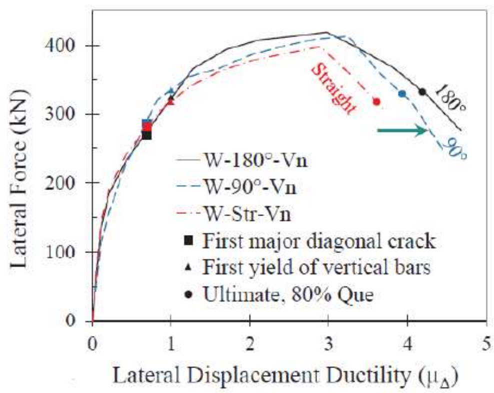
*By James Surowiecki*

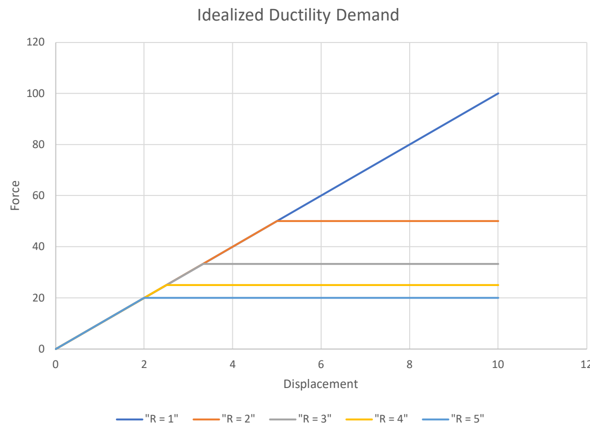
*"Diversity and independence are important because the best collective decisions are the product of disagreement and contest, not consensus or compromise."*

### What Makes a Wise Crowd?

- Diversity of Opinion
- Independence
- Decentralization
- Aggregation
- Trust

# Hooks – Why 0.4 Ratio?




17

# Hooks – Unfinished Business

For partially grouted walls, my recommendation would be to include $\gamma_g$

$V / F_{vm}\gamma_g$

$V_u / \phi V_{nm}\gamma_g$

Don't sweat reference to Chapters 10 and 11

You can't get here from there

18

## Hooks – Unfinished Business

### Confused about wall intersections

Me too!

. . . horizontal reinforcement shall be bent around the edge vertical reinforcement with a 90-degree standard ~~hook~~ bend and shall extend horizontally into the intersecting wall a minimum distance at least equal to the development length

19

## Shear Capacity Design

### Origin

Internal to Committee

### Motivations

Improve clarity and consistency of the Code

### Impact

Low

20

## Shear Capacity Design

### TMS 402-16

**7.3.2.6.1** *Shear capacity design*

**7.3.2.6.1.2** When designing special reinforced masonry shear walls in accordance with Section 8.3.5, the calculated shear stress, $f_v$, or diagonal tension stress resulting from in-plane seismic forces shall be increased by a factor of 1.5.

### TMS 402-22

**7.3.2.5.1** *Shear capacity design*

**7.3.2.5.1.1** When designing special reinforced masonry shear walls in accordance with Section 8.3.5, the calculated shear stress, $f_v$, or diagonal tension stress resulting from in-plane seismic forces shall be increased by a factor of 2.0.



## Shear Capacity Design

### TMS 402-16

**8.3.5.1.3** The allowable shear stress resisted by the masonry, $F_{vm}$, shall be calculated using Equation 8-25 for special reinforced masonry shear walls and using Equation 8-26 for other masonry:

$$F_{vm} = \frac{1}{4}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.20\frac{P}{A_n}$$

(Equation 8-25)

$$F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.20\frac{P}{A_n}$$

(Equation 8-25)

### TMS 402-22

**8.3.5.1.3** The allowable shear stress resisted by the masonry, $F_{vm}$, shall be calculated using Equation 8-23:

$$F_{vm} = \frac{1}{2}\left[\left(4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right)\sqrt{f'_m}\right] + 0.20\frac{P}{A_n}$$

(Equation 8-23)

# Shear Capacity Design

## Consequences

- Much more consistent designs between ASD and SD
- For ASD Designs
  - If $V < 2V_{nm}$ less reinforcement
  - If $V > 2V_{nm}$ more reinforcement



# Shear Capacity Design

## TMS 402-16

**7.3.2.6.1** *Shear capacity design*

**7.3.2.5.1.1** When designing special reinforced masonry shear walls to resist in-plane forces in accordance with Section 9.3, the design shear strength, $\phi V_n$, shall exceed the shear corresponding to the development of 1.25 times the nominal flexural strength, $M_n$, of the element, except that the nominal shear strength, $V_n$, need not exceed 2.5 times required shear strength, $V_u$.

## TMS 402-22

**7.3.2.5.1** *Shear capacity design*

**7.3.2.5.1.2** When designing special reinforced masonry shear walls to resist in-plane forces in accordance with Section 9.3, the design shear strength, $\phi V_n$, shall exceed the shear corresponding to the development of 1.25 times the nominal flexural strength, $M_n$, of the element, except that the design shear strength, $\phi V_n$, need not exceed 2.0 times required shear strength, $V_u$.

## Shear Capacity Design

### Consequences

- None



## Joint Reinforcement

### Origin

Two Public Comments on 2016 Code from a Building Official

### Motivations

Address ambiguities and inconsistencies in the Code

### Impact

Low

# Joint Reinforcement

## Comment

The commenter identified two issues with the code treatment of joint reinforcement used as shear reinforcement:

1. Ambiguity – was it permitted in special shear walls?
2. Inconsistency – why was it treated differently in Allowable Stress Design and in Strength Design?



# Joint Reinforcement

## TMS 402-16

**9.3.3.4** *Joint reinforcement used as shear reinforcement*

- Always: (2) 3/16 in. diameter longitudinal wires
- SDC A and B: spacing 16 in. maximum
- SDC C+:
  - Partially Grouted: Spacing 8 in. max
  - Fully Grouted: (4) 3/16 in. diameter longitudinal wires, max 8 in. spacing

## TMS 402-22

**7.4.1** *Seismic Design Category A*

**7.4.1.2.1** *Joint reinforcement used as shear reinforcement*

On face same as TMS 402-16, but:

- Applies to ASD
- Applies to participating elements only

# Joint Reinforcement

**TMS 402-16**

**TMS 402-22**

**7.4.3** *Seismic Design Category C+*

**7.4.3.2.6** *Joint reinforcement used as shear reinforcement*

On face same as TMS 402-16, but:

- Applies to ASD
- Applies to participating elements only

29

# Joint Reinforcement

**TMS 402-16**

**7.3.2.6** *Special reinforced masonry shear walls* . . . shall comply . . . with the following:

(b) The maximum spacing of horizontal reinforcement required to resist in-plane shear shall be uniformly distributed, shall be the smaller of one-third the length of the shear wall and one-third the height of the shear wall, and shall be embedded in grout.

**TMS 402-22**

**7.3.2.5** *Special reinforced masonry shear walls* . . . shall comply . . . with the following:

(e) Joint reinforcement and deformed wire placed in mortar required to resist in-plane shear shall be a single piece without splices for the length of the wall used for shear design, $d_v$.

30

# Joint Reinforcement

## TMS 402-16

## TMS 402-22

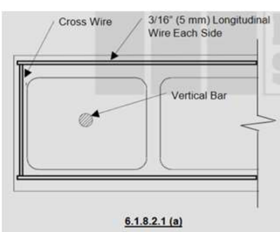
**7.3.2.5** *Special reinforced masonry shear walls* . . . shall comply . . . with the following:

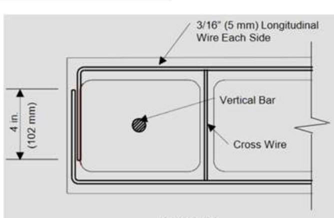
(g) Joint reinforcement used as shear reinforcement shall be anchored in accordance with Section 6.1.8.1.3.1 (a) or (c) when two longitudinal wires are used and Section 6.1.8.1.3.2 when four longitudinal wires are used .



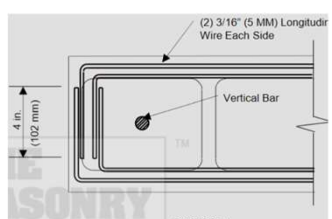
# Joint Reinforcement

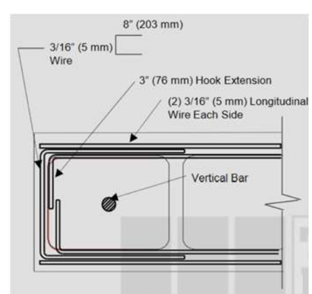
## (2) Wires




## (4) Wires



# Seismic Design Category C+

- Minimum Reinforcement in Nonstructural Walls
- Contribution of Masonry Columns to Lateral Stiffness



## Minimum Reinforcement in Nonstructural Walls

Origin

Public Comment on 2022 Code from me

Motivations

Safety

Align provisions of the Code with the intent

Impact

Low

## Minimum Reinforcement in Nonstructural Walls

**TMS 402-16**

**7.4.3** *Seismic Design Category C*

**7.4.3.1** *Design of nonparticipating elements* — Nonparticipating masonry elements . . . shall be reinforced in either the horizontal or vertical direction . . .

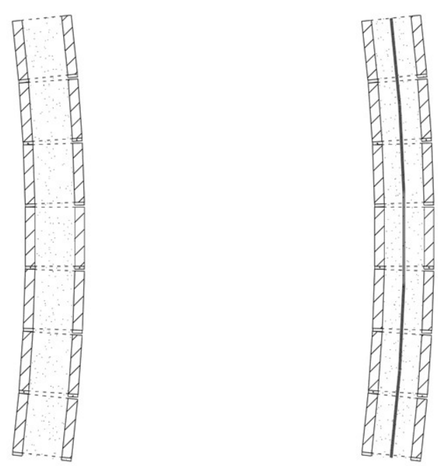
**TMS 402-22**

**7.4.3** *Seismic Design Category C*

**7.4.3.1** *Design of nonparticipating elements* — Nonparticipating masonry elements . . . shall be reinforced in the direction of span . . .

35

## Minimum Reinforcement in Nonstructural Walls



36

# Masonry Columns

## Origin

Public Comment on 2022 Code from a Building Official

## Motivations

Remove ambiguity from the code

## Impact

Low



# Masonry Columns

### TMS 402-16

**7.4.3** *Seismic Design Category C*

**7.4.3.2.4** *Lateral stiffness* —Along each line of lateral resistance at each story, at least 80 percent of the lateral stiffness shall be provided by seismic-force-resisting walls. Where seismic loads are determined based on a seismic response modification factor, R, not greater than 1.5, columns shall be permitted to be used to provide seismic load resistance.

### TMS 402-22

**7.4.3** *Seismic Design Category C*

**7.4.3.2.4** *Lateral stiffness* —Along each line of lateral resistance at each story, not more than 20 percent of the lateral stiffness may be provided by masonry columns.

# Masonry Columns

## TMS 402-16

**7.4.3** *Seismic Design Category C*

**7.4.3.2.4** *Lateral stiffness* —Along each line of lateral resistance at each story, at least 80 percent of the lateral stiffness shall be provided by seismic-force-resisting walls. Where seismic loads are determined based on a seismic response modification factor, R, not greater than 1.5, columns shall be permitted to be used to provide seismic load resistance.

## TMS 402-22

Exception: Where seismic loads are determined based on a seismic response modification factor, $R$, not greater than 1.5, columns shall be permitted to contribute more than 20 percent of the lateral stiffness along any line of resistance and may be used to provide seismic load resistance.

39

# Masonry Columns

## TMS 402-22 Commentary

A line of lateral resistance refers to the plan view of participating members within a vertical plane that provide resistance to seismic forces, including torsional effects. Potential lines of lateral resistance that do not include walls should be considered in determining whether compliance with this section has been achieved.

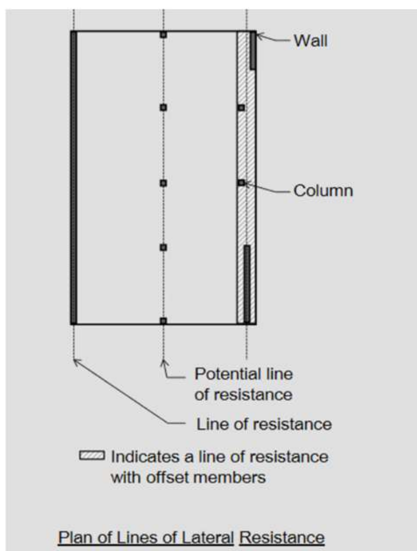



Figure CC-7.4-1 —Lines of Lateral Resistance

40

# Displacements

- ASCE 7-22 Displacements
- Use of $MCE_R$ Displacements
- Deformation Compatibility

41

## ASCE 7-22 Displacements

Origin

Public Comment on 2022 Code from me

Motivations

Improve coordination of ASCE 7-22 and TMS 402-22

Impact

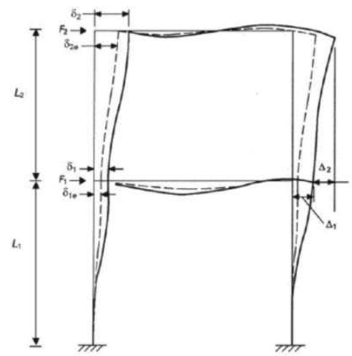
Buildings with large diaphragm displacements

42

# ASCE 7-22 Displacements

## ASCE 7-22

- ASCE 7 Defines how building displacements are calculated and what limits they must meet
- Δ denotes a story displacement
- $\delta$ denotes a displacement relative to the seismic base
- $MCE_R$ denotes the risk-targeted maximum considered earthquake
- Design earthquake is two-thirds of $MCE_R$




ASCE 7-22 Figure 12.8-2



# ASCE 7-22 Displacements

## ASCE 7-22

Design earthquake displacement:

$$\delta_{DE} = \frac{C_d \delta_e}{I_e} + \delta_{di} \qquad (12.8\text{-}16)$$

(New! Now with diaphragm displacements!)

Maximum conserved earthquake displacement:

$$\delta_{MCE} = 1.5\left[\frac{R\delta_e}{I_e} + \delta_{di}\right] \qquad (12.8\text{-}17)$$

(New!)

## ASCE 7-22 Displacements

**TMS 402-22**

$\Delta$ = design story drift, in.

$\delta_{MCE}$ = displacement due to Maximum Considered Earthquake, in.

*Design story drift* — The difference of deflections at the top and bottom of the story under consideration, taking into account the possibility of inelastic deformations as defined in ASCE/SEI 7.



## Use of $MCE_R$ Displacements

Origin

- Internal to Committee

Motivations

- Safety

Impact

- Limited – Provisions infrequently used

## Use of $MCE_R$ Displacements

**TMS 402-16**

**9.3.3.6.3**

. . . Special boundary elements shall be provided over portions of compression zones where:

$$c \geq \frac{l_w}{600(C_d \delta_{ne}/h_w)}$$

**TMS 402-22**

**9.3.5.6.2** *Alternate Approaches to Wall Ductility*

**9.3.5.6.2.3**

. . . Special boundary elements shall be provided over portions of compression zones where:

$$c \geq \frac{l_w}{600(\delta_{MCE}/h_w)}$$

(Note: Errata!)

47

## Use of $MCE_R$ Displacements

**ACI 318-14 Code**

**18.10.6.2**

. . . Compression zones shall be reinforced with special boundary elements where:

$$c \geq \frac{l_w}{600(1.5\delta_u/h_w)}$$

**ACI 318-14 Commentary**

**R18.10.6.2**

The multiplier of 1.5 on the design displacement was added . . . In the 2014 version of the Code to produce detailing requirements more consistent with the building code intent of a low probability of collapse in Maximum Considered Earthquake level shaking.

48

## Deformation Compatibility

Origin

- Technical Activities Committee comment

Motivations

- Provide flexibility to designers

Impact

- Limited – May be hard to advantage of



## Deformation Compatibility

**TMS 402-16**

**7.3.1** *Nonparticipating elements* — Masonry elements that are not part of the seismic-force-resisting system shall be classified as nonparticipating elements and shall be isolated in their own plane from the seismic-force-resisting system except as required for gravity support. Isolation joints and connectors shall be designed to accommodate the design story drift.

**TMS 402-22**

**7.3.1** *Nonparticipating elements* — Masonry elements that are not part of the seismic-force-resisting system shall be classified as nonparticipating elements and shall be isolated in their own plane from the seismic-force-resisting system. Isolation joints and connectors shall be designed to accommodate the design story drift.

# Deformation Compatibility

## TMS 402-16

## TMS 402-22

Exception: Isolation is not required if a deformation compatibility analysis demonstrates that the non-participating element can accommodate the inelastic displacement, Δ, of the structure in a manner complying with the requirements of this Code. Elements supporting gravity loads in addition their self-weight shall be evaluated for gravity load combinations of $(1.2D + 1.0L + 0.15S)$ or $0.9D$, whichever is critical, acting simultaneously with the inelastic displacement and shall have a ductility compatible with the ductility of the lateral force resisting system. The influence of any non-isolated nonparticipating elements on the lateral force resisting system shall be considered in design in accordance with Section 4.1.6 of this code.



# Deformation Compatibility

**Criteria to Meet Exception**

- Deformation Compatibility Analysis
  - Either
    - Elastic, with cracked properties
    - Inelastic, hinging per Appendix C
  - Must consider gravity loads
- Compatible Ductility
- Consider Influence on Lateral Force Resisting System

# Deformation Compatibility

## Sources of Cracked Properties

| Source | Section | %Ag | %Ig |
|---|---|---|---|
| TMS 402-22 | 9.1.5.2 | 50% | 50% |
| NEHRP Technical Brief No. 9 | NA | 35% | 15% |
| ASCE 41-17 Option A | 11.3.4.1 | 100% | 50% |
| ASCE 41-17 Option B | 11.3.4.1 | 100% | Cracked Section Analysis |



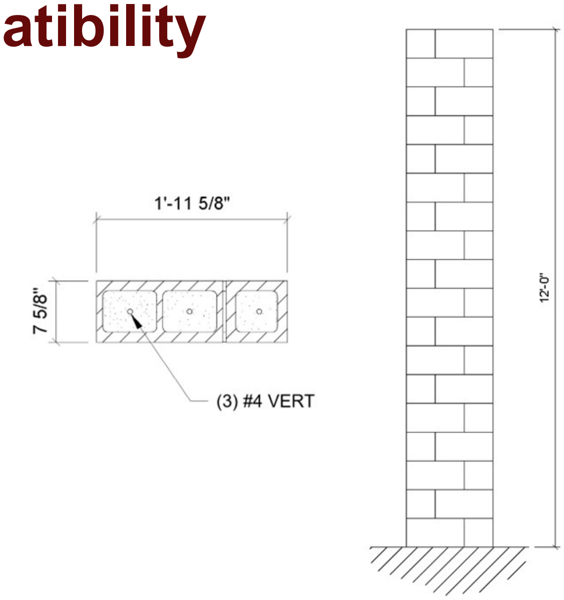
# Deformation Compatibility

**Example 1**

$f'_m = 2{,}000\ psi$
$F_y = 60{,}000\ psi$

$P_u = 0\ k$
$M_{u,max} = \phi M_n = 332\ k - in$
$V_{u,max} = \frac{M_{u,max}}{h_w} = 2.3\ \mathrm{k}$

No shear reinforcement required



# Deformation Compatibility

**Example 1**

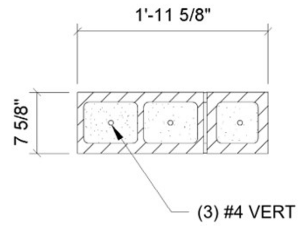
Elastic analysis with cracked properties, ASCE 41-17 “B”

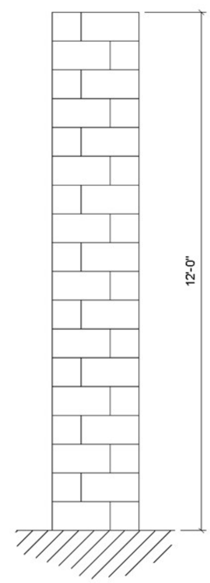
$A_e = A_g$

$I_e = 0.22 I_g$

$\Delta_{max} = 0.81\ in. = 0.56\%$

If $P_u = 15\ k$, $\Delta_{max} = 0.94\ in. = 0.65\%$





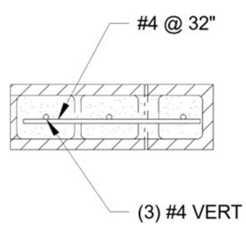

# Deformation Compatibility

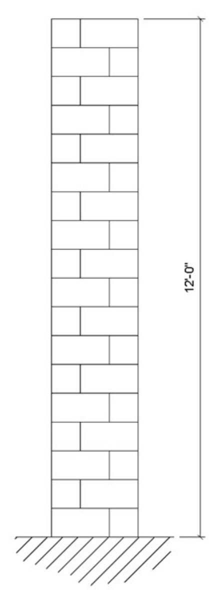
**Example 1**

Inelastic per Appendix C

$\theta_{max} = 1.0\%$

If $P_u = 15\ k$, $\theta_{max} = 0.74\%$

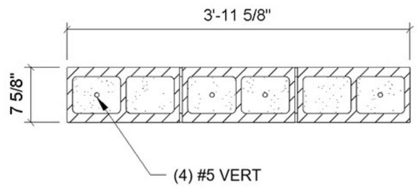


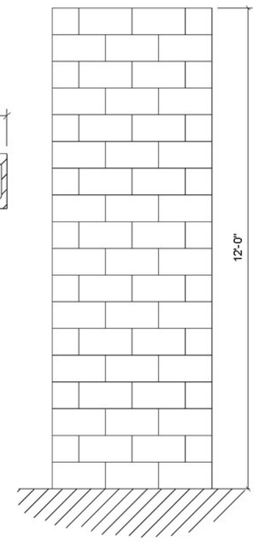



# Deformation Compatibility

**Example 2**
$f'_m = 2{,}000\ psi$
$F_y = 60{,}000\ psi$

$P_u = 0\ k$
$M_{u,max} = \phi M_n = 1426\ k - in$
$V_{u,max} = \frac{M_{u,max}}{h_w} = 9.9\ \text{k}$
No shear reinforcement required



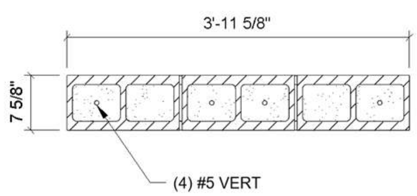

57

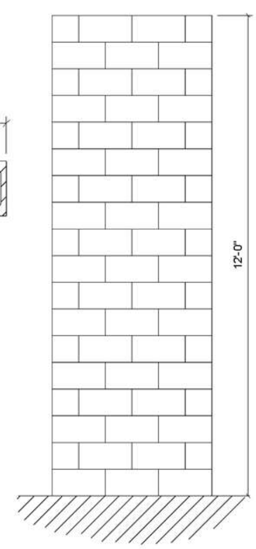
# Deformation Compatibility

**Example 2**
Elastic analysis with cracked properties, ASCE 41-17 “B”
$A_e = A_g$
$I_e = 0.19 I_g$

$\Delta_{max} = 0.42\ in. = 0.29\%$

If $P_u = 15\ k$, $\Delta_{max} = 0.46\ in. = 0.32\%$




58

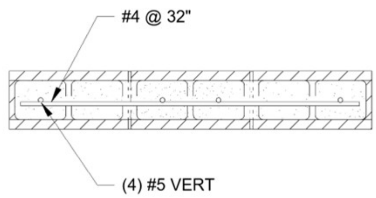
# Deformation Compatibility

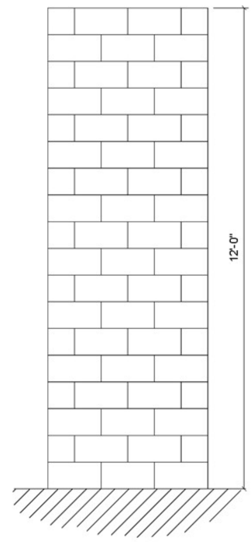
**Example 2**

Inelastic per Appendix C

$\theta_{max} = 1.0\%$

If $P_u = 15\ k$, $\theta_{max} = 0.82\%$




59

This concludes The American Institute of Architects Continuing Education Systems Course

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