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Changes to the Concrete Design Standard

Speaker

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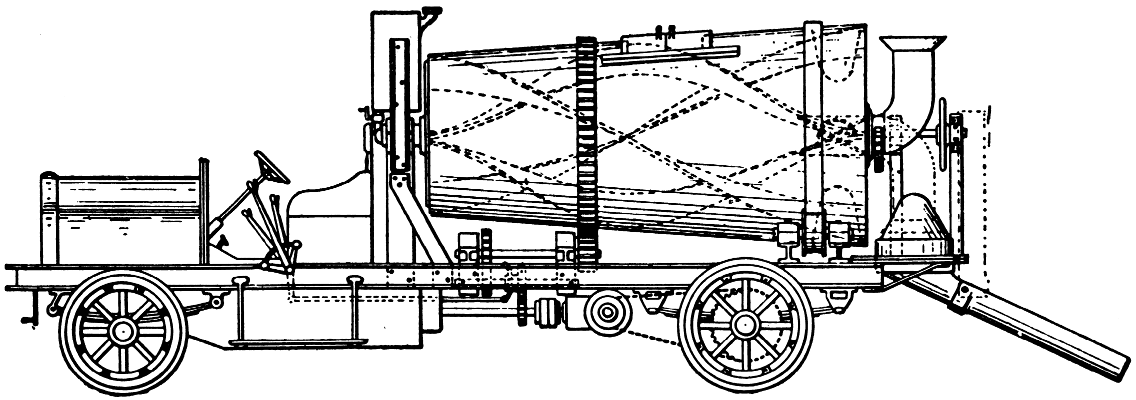
Introduction

History



Founded in 1904

- **1910**
  - First code
  - Working stress limit
- **1963**
  - Ultimate strength design
- **1971**
  - Emphasize USD
  - Behavior based with specialty chapters
- **2014**
  - Reorganized by member type

Organization

10 Parts and New Appendix

1. General
2. Loads & Analysis
3. Members
4. Joints/Connections/ Anchors
5. Earthquake Resistance
6. Materials & Durability
7. Strength & Serviceability
8. Reinforcement
9. Construction
10. Evaluation

App. A – Non-Linear Analysis

Organization – General

Ch. 1 – General

Ch. 2 – Notation and Terminology

Ch. 3 – Referenced Standards

Ch. 4 – Structural System Requirements

Chapter 1: Purpose of the Code

- The purpose is to provide for public health and safety
- The Code does not address all design considerations
- Construction means and methods are not addressed in the Code

Concrete designs governed by other ACI codes


216 - Fire


307 - Chimneys


313 - Silos


332 – Residential


349 – Nuclear Facilities


350 – Environmental


359 – Nuclear Contain.


369 – Seismic Retrofit

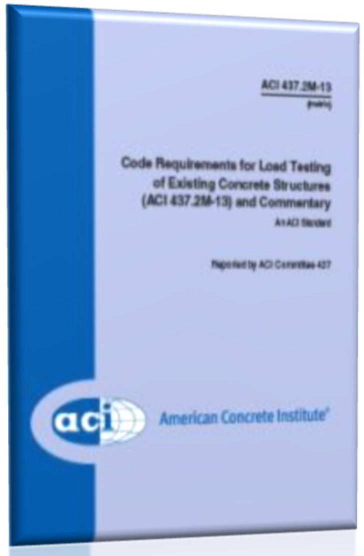

376 – RLG Containment


437 – Strength Evaluation


562 - Repair

Design recommendations provided in guides

- Slabs-on-ground (ACI 360R)
- Blast-resistant structures (ACI 370R)
- Wire Wrapped Tanks (ACI 372R)

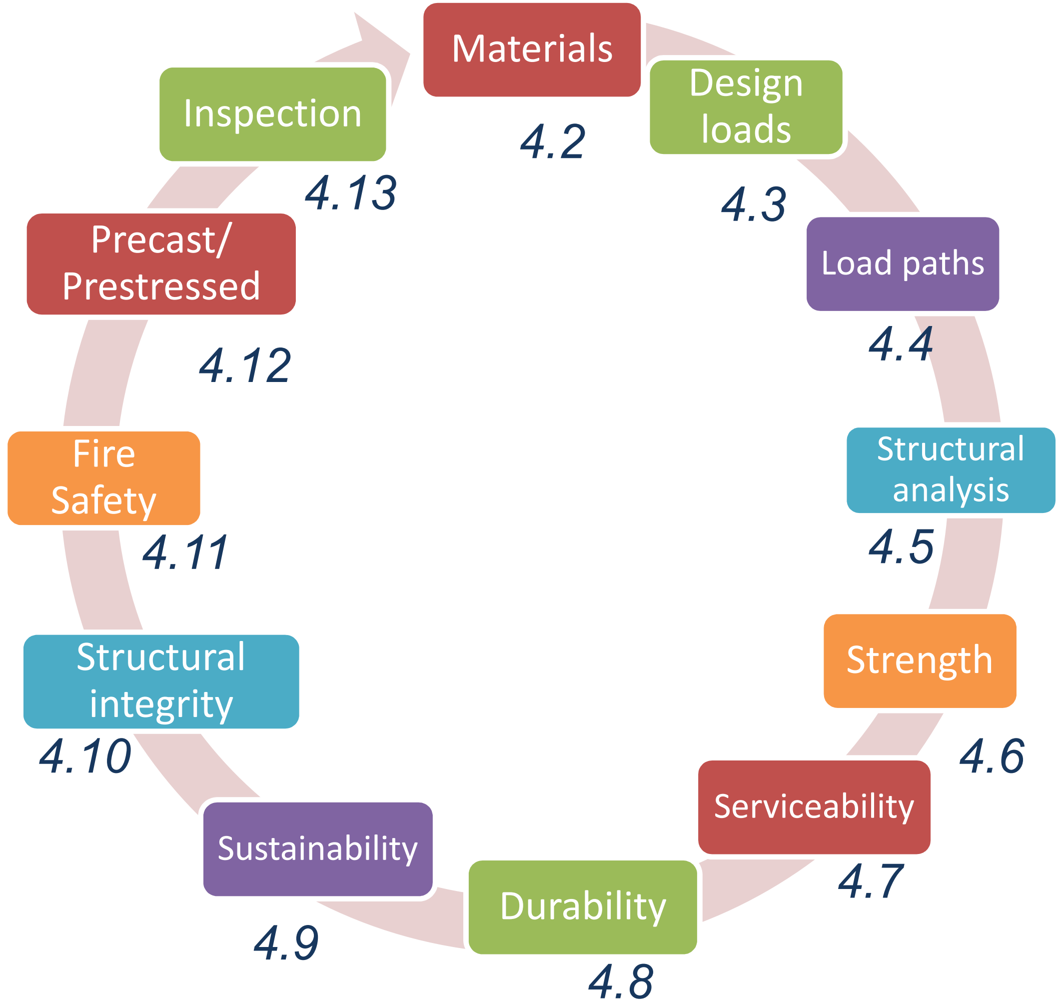


1.5 Code language – Interpretation

- Headings, footnotes, tables, figures, tables, footnotes to tables and figures, and referenced, etc. are all parts of the code
- Commentary provides contextual information, but is not part of the Code
- Specific provisions govern over general provisions
- Plain meaning of words and terms

Chapter 4: Structural System Requirements

- **Purpose**
  - Structure as a whole
  - Design roadmap
- **Layout**
  - Scope
  - 12 subsections



Organization – Loads & Analysis

Ch. 5 – Loads

- **ASCE 7**

Ch. 6 – Structural Analysis

- **Permitted analysis methods**
  - Simplified methods
  - Linear elastic, first–order
  - Linear elastic, second-order
  - Inelastic
  - Finite element analysis
  - Strut-and-tie models

Organization – Members

Ch. 7 – One-Way Slabs

Ch. 8 – Two-Way Slabs

Ch. 9 – Beams

Ch. 10 – Columns

Ch. 11 – Walls

Ch. 12 – Diaphragms

Ch. 13 – Foundations

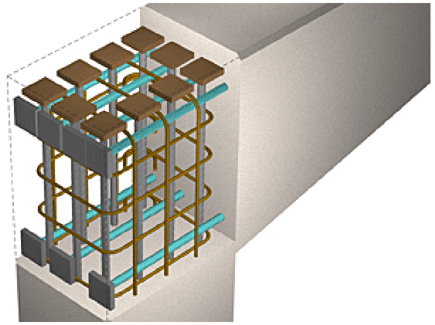
Ch. 14 – Plain Concrete

Organization

Typical member chapter sections

- X.1 Scope
- X.2 General
- X.3 Design Limits
- X.4 Required Strength
- X.5 Design Strength
- X.6 Reinforcement Limits
- X.7 Reinforcement Detailing
- X.?

Organization – Joints / Connections / Anchors



Ch.15 – Beam-column and slab-column joints

Ch. 16 – Connections between members

Ch. 17 – Anchoring to concrete

Organization – Seismic

Ch. 18 – Earthquake Resistant Structures

- Philosophy
- Changes described by member type

Organization – Materials & Durabilty

Ch. 19 – Concrete: Design and Durability Properties

Ch. 20. – Steel Reinforcement Properties, Durability, and Embedments

Organization – Strength & Serviceability

Ch. 21 – Strength Reduction Factors

Ch. 22 – Sectional Strength

Ch. 23 – Strut-and-Tie Models

Ch. 24 – Serviceability Requirements

Organization – How Toolbox Works

Member Chapter	Toolbox Chapter
9.5 — Design strength	
9.5.2 — Moment	
9.5.2.1 — If Pu < 0.10f’cAg, Mn shall be calculated in accordance with 22.3.	22.3 —Flexural strength…
9.5.2.2 — If Pu ≥ 0.10f’cAg, Mn shall be calculated in accordance with 22.4.	…End of section

Organization – Reinforcement

Chapter 25 – Reinforcement

- Reinforcement Details; standard hooks
- Development of reinforcement
- Splices
- Bundled bars
- PT anchorages

Organization – Construction

Ch. 26 – Construction Documents and Inspection

- 318M is written to the engineer, not the contractor.
- Construction requirements must be communicated on the construction documents.

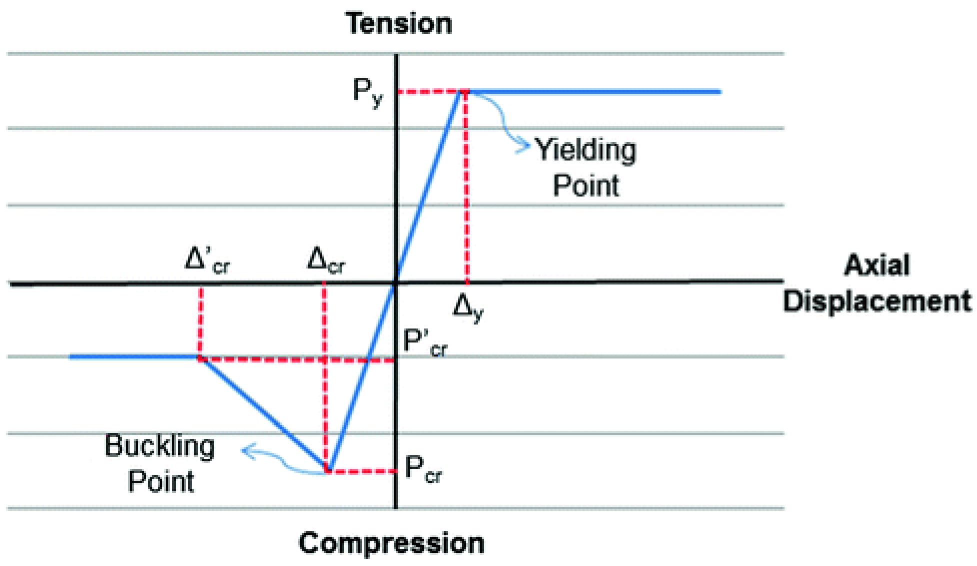
Organization – Evaluation

Ch. 27 – Strength Evaluation of Existing Structures

- **Applies when strength is in doubt**
- **Well understood – analytical evaluation**
- **Not well understood – load test**
  - Monotonic procedure, ACI 318M
  - Cyclic procedure, ACI 437.2M

Organization – Nonlinear Analysis

APPENDIX A—A DESIGN VERIFICATION USING NONLINEAR RESPONSE HISTORY ANALYSIS



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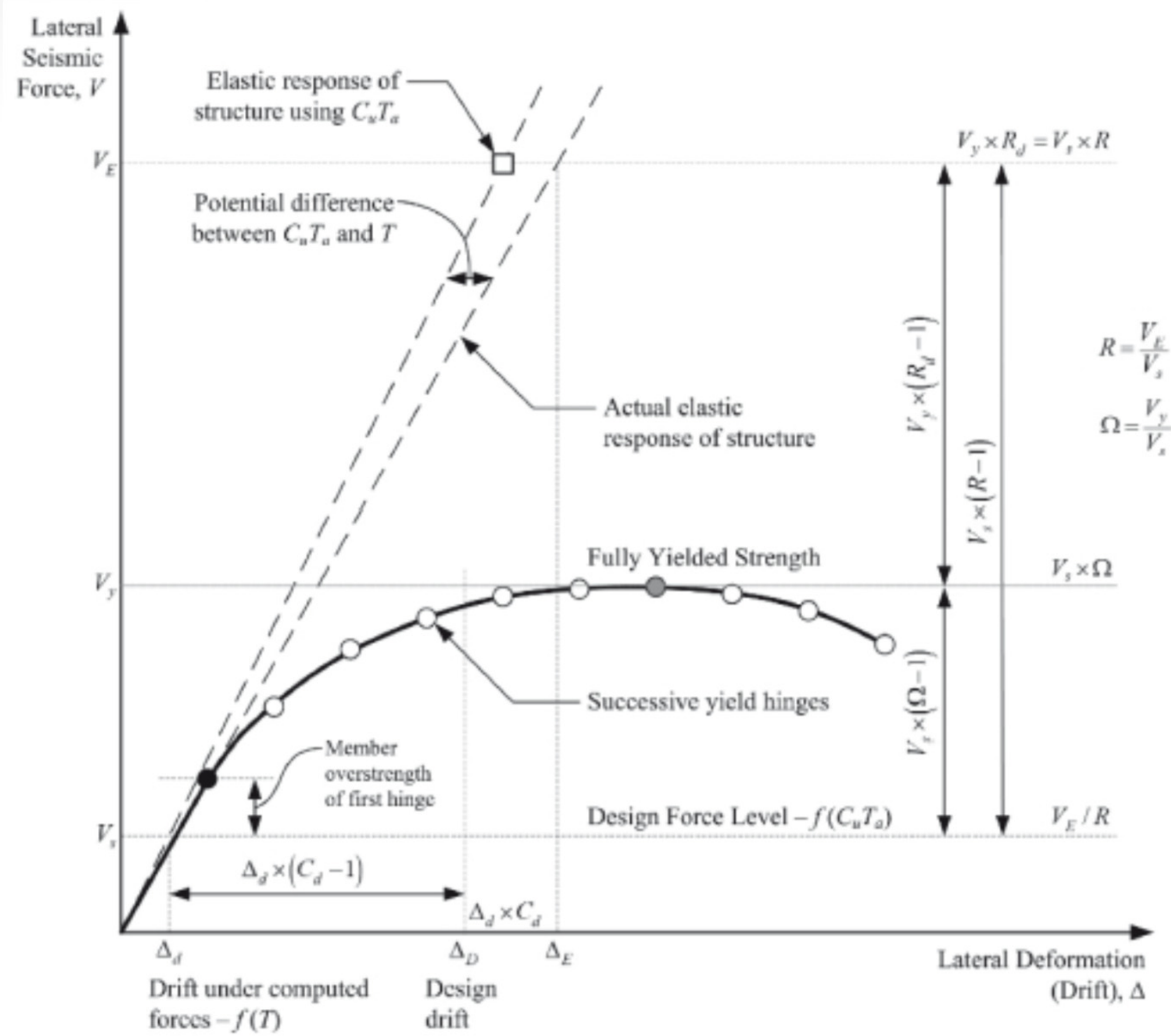
Seismic Design Philosophy

Seismic

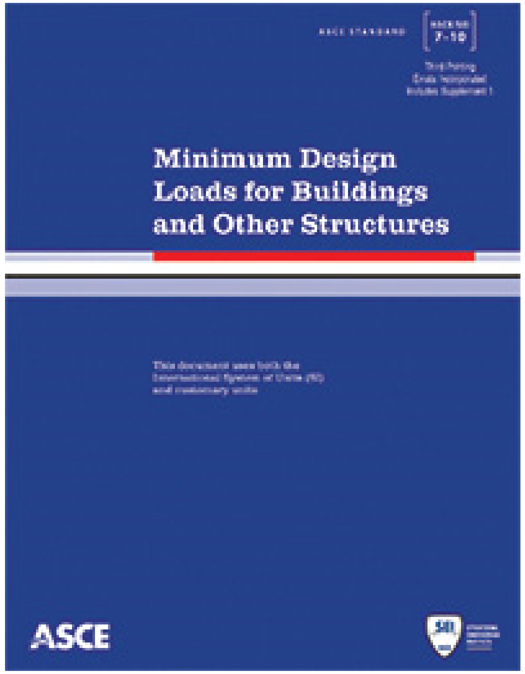
- Both concrete and reinforcement are permitted to respond in the inelastic range
- This is consistent with the strength design approach adopted throughout the Code

Seismic – Ω, C_d, and R Factors (ASCE 7)



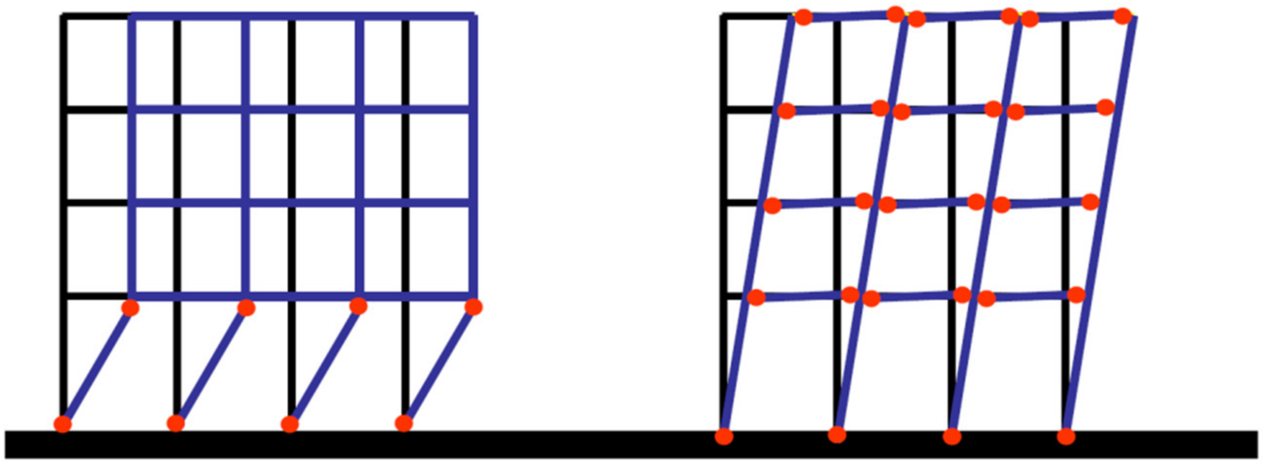
Seismic – Parameters

Parameter in ASCE 7-10 Table 12.2-1	Example
Seismic Force Resisting System	Special reinforced concrete shear walls (building frame system)
ASCE 7 Section Where Detailing Requirements Are Specified	ASCE 7 Section 14.2 "Concrete"
Response Modification Coefficient, $\boldsymbol{R}$	6
Overstrength Factor, $\boldsymbol{\Omega_0}$	2.5
Deflection Amplification Factor, $\boldsymbol{C_d}$	5
Structural System Limitations, Including Structural Height Limits	SDC B No limit SDC C No limit SDC D 48.8 m SDC E 48.8 m SDC F 30.5 m



Seismic

- Controlled inelastic action is permitted at pre-determined locations, called plastic hinges
- Typical plastic hinge locations are at the ends of beams in moment frames, and at the bases of shear walls



Seismic

- Prescriptive rules for detailing of reinforcement are enforced, creating robust plastic hinges
- Plastic hinging reduces the stiffness of the structure, which lengthens the period; and plastic hinges dissipate earthquake energy

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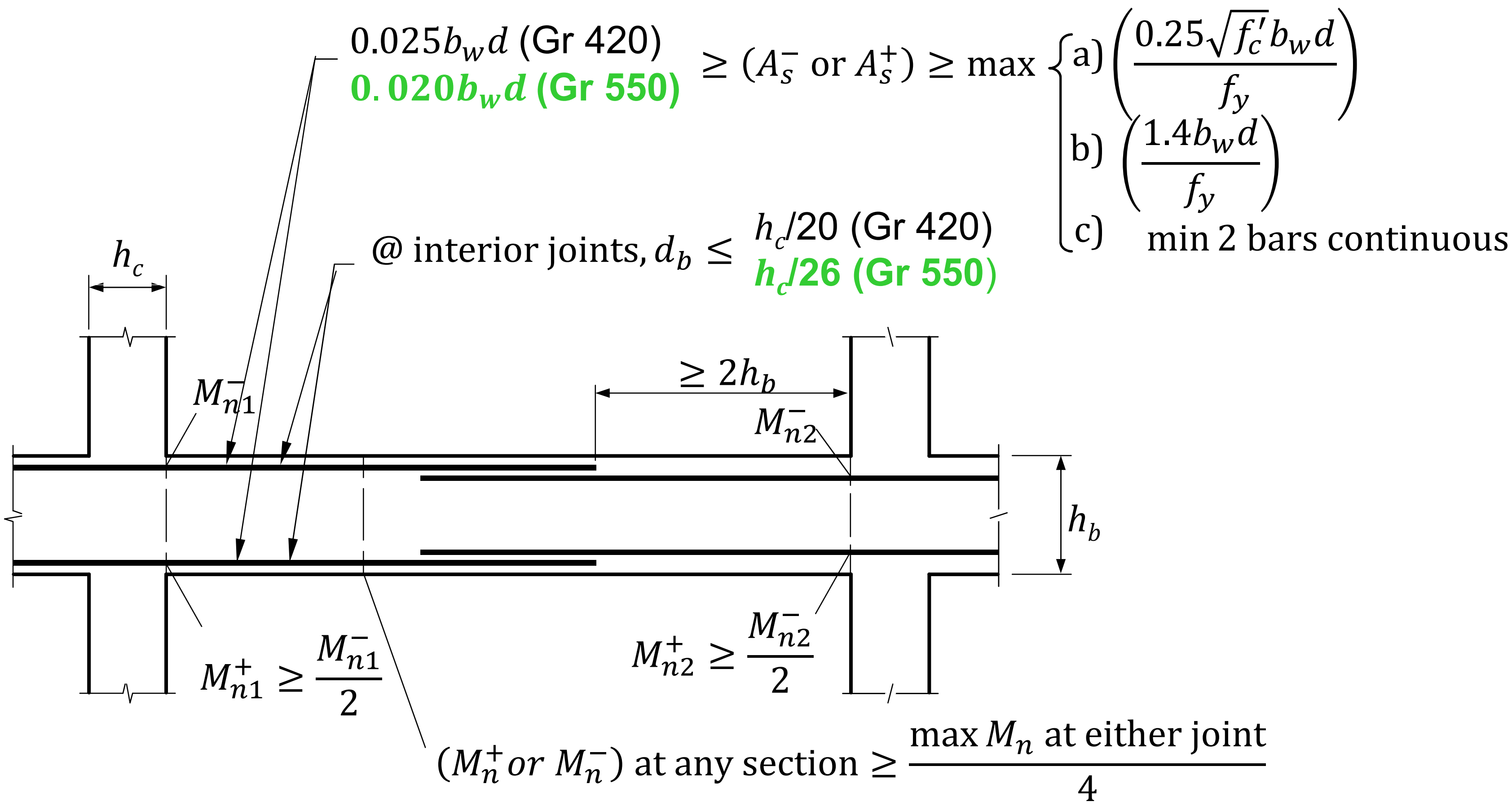
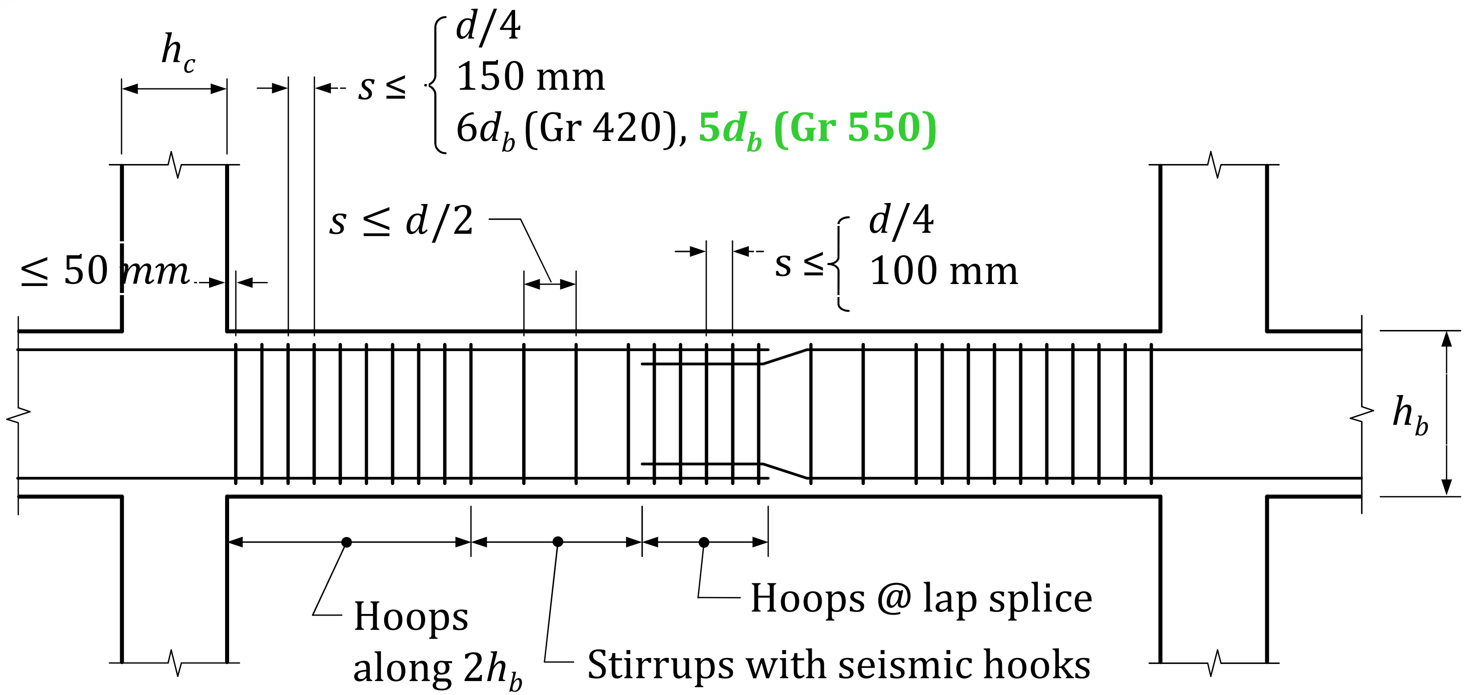
Special Moment Frames

18.6.3.1 and 18.8.2.3—Special moment beams



18.6.4.4—Special moment beams



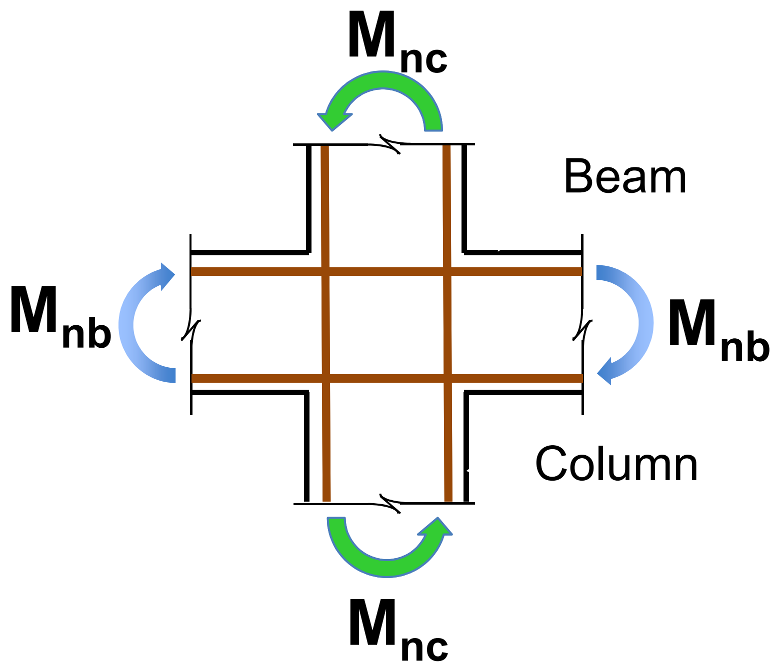
18.7.3.1—Columns of SMF

Strong Column/Weak Beam

- **Dimensional limits**
  - Smallest dimension ≥ 300 mm
  - Short side/long side ≥ 0.4
- **Min. flexural strength**
  - ∑Mnc ≥ (6/5)∑Mnb,

Except at

- **Roof or mezzanine levels where $P_u \leq 0.1 A_g f'_c$**

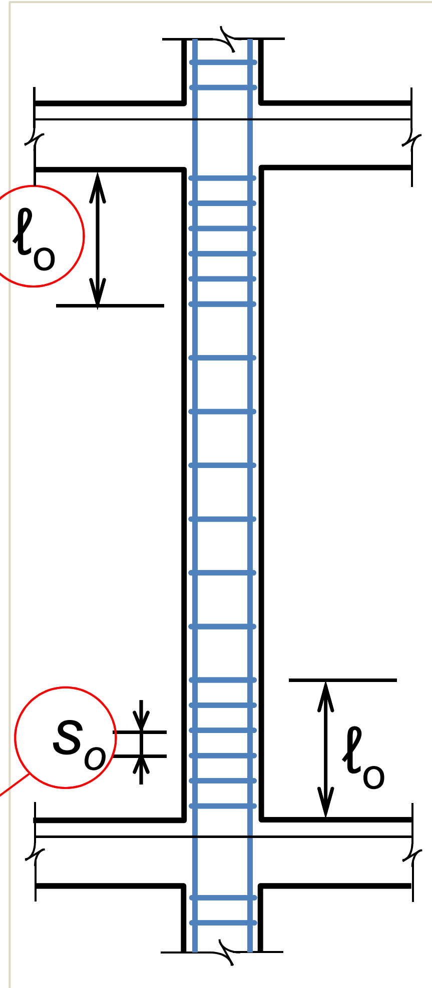


18.4.3.3—Columns in intermediate moment frames

- Hoops or spirals required
- First hoop at so/2 from the joint face

$$l_o \geq \begin{cases} l_u/6 \text{ clear span} \\ [c_1, c_2]_{max} \\ 450 \text{ mm} \end{cases}$$

$$s_o \leq \begin{cases} 8d_b \text{ (Gr 420) and 200 mm} \\ 6d_b \text{ (Gr 550) and 150 mm} \\ 1/2[c_1, c_2]_{min} \end{cases}$$



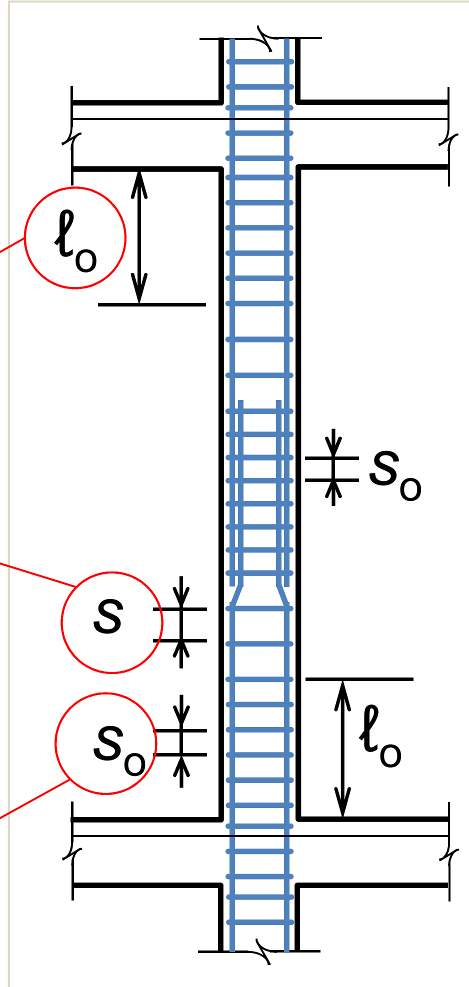
18.7.5.3—Columns in special moment frames

- First hoop at $s_o/2$ from the joint face

$$l_o \geq \begin{cases} l_u/6 \text{ clear span} \\ [c_1, c_2]_{max} \\ 450 \text{ mm} \end{cases}$$

$$s \leq \begin{cases} 6d_{b,min} \text{ (Gr 420)}, 5d_{b,min} \text{ (Gr 550)} \\ 150 \text{ mm} \end{cases}$$

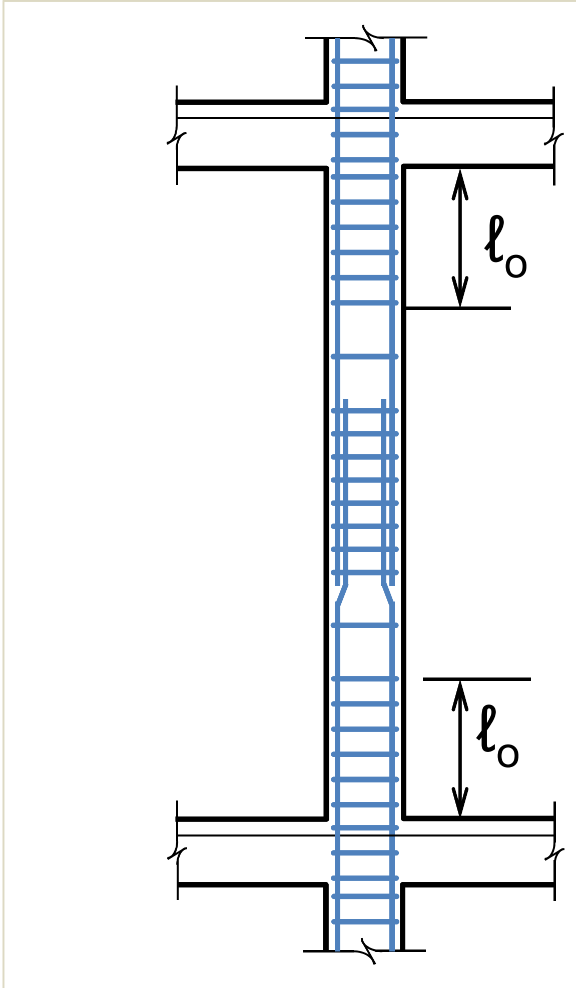
$$s_o \leq \begin{cases} 6d_{b,min} \text{ (Gr 420)}, 5d_{b,min} \text{ (Gr 550)} \\ \tfrac{1}{4}[c_1, c_2]_{min} \\ 100 + \left(\frac{350 - h_x}{3}\right), \leq 150 \text{ mm}; \geq 100 \text{ mm} \end{cases}$$



18.14.3.2—Nonparticipating columns

Clarification

- **Typical transverse spacing is the lesser of**
  - – $6d_b$ of the smallest long. Bar
  - – 150 mm
- **Transverse spacing along ℓ_o is according to 18.7.5.2 (a) through (e)**
  - – 18.7.5.2(f) is no longer required



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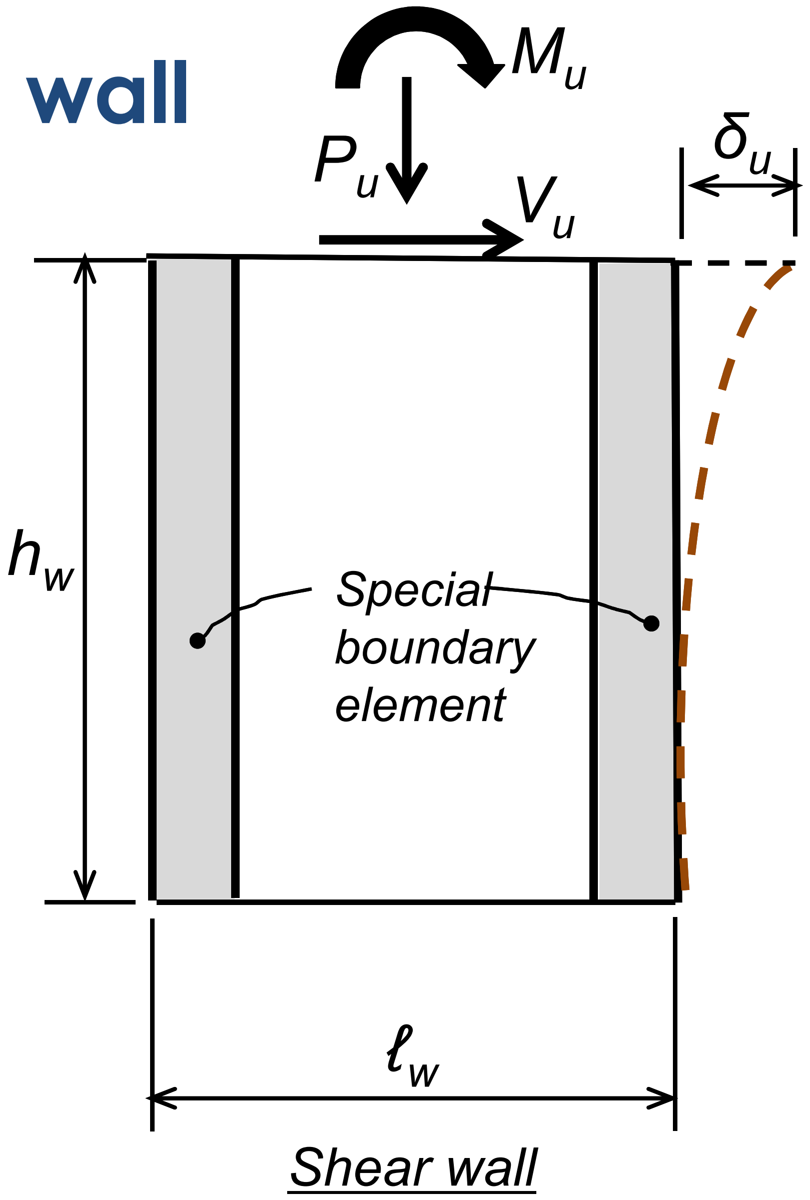
Standard

Special Structural Walls

Ch. 18—Special structural wall

- Cutoff of longitudinal bars in special boundary elements
- Reinforcement ratios at ends of walls
- Shear demand
- Drift capacity check
- Detailing in special boundary elements
- Ductile coupled walls



18.10.2.3(a)—Longitudinal bars

- **Previously,**
  - tension (vertical boundary) reinforcement in special structural walls to extend $0.8\ell_w$ beyond the point at which it is no longer required to resist flexure
- **Overly conservative**
  - This was an approximation of *d*
  - Similar to beams which extend *d*, $12d_b$ and $\ell_n/16$
  - Actual behavior is different

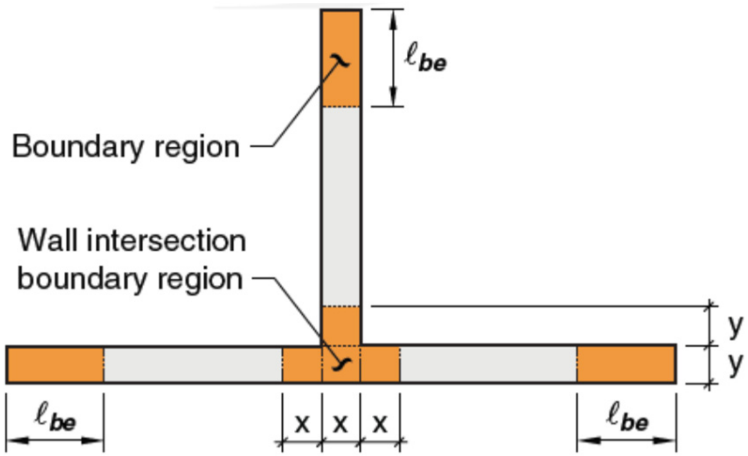
18.10.2.3(a)—Longitudinal bars

- **Change**
  - Except at the top of a wall, longitudinal reinforcement shall extend at least 3.6m above the point at which it is no longer required to resist flexure but need not extend more than ℓ_d above the next floor level.

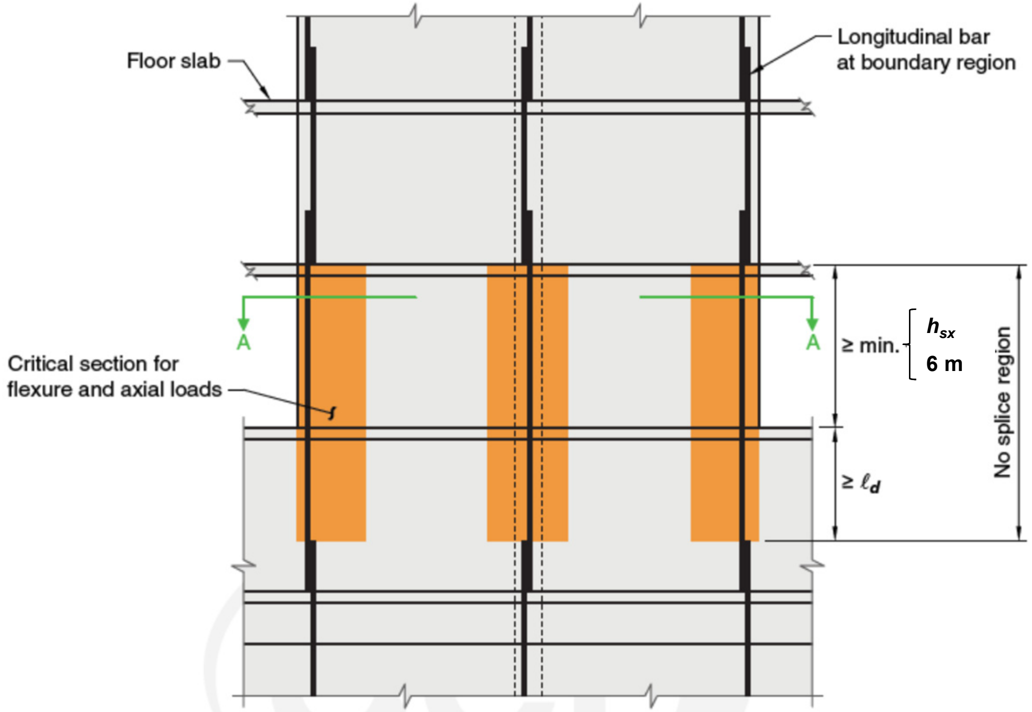
- **In practice**
  - Extend ℓ_d or 3.6m starting at floor above

18.10.2.3(c)—Longitudinal bars

- Lap splices not permitted over h_{sx} above (6 m, max) and ℓ_d below critical sections



(b) Section A-A

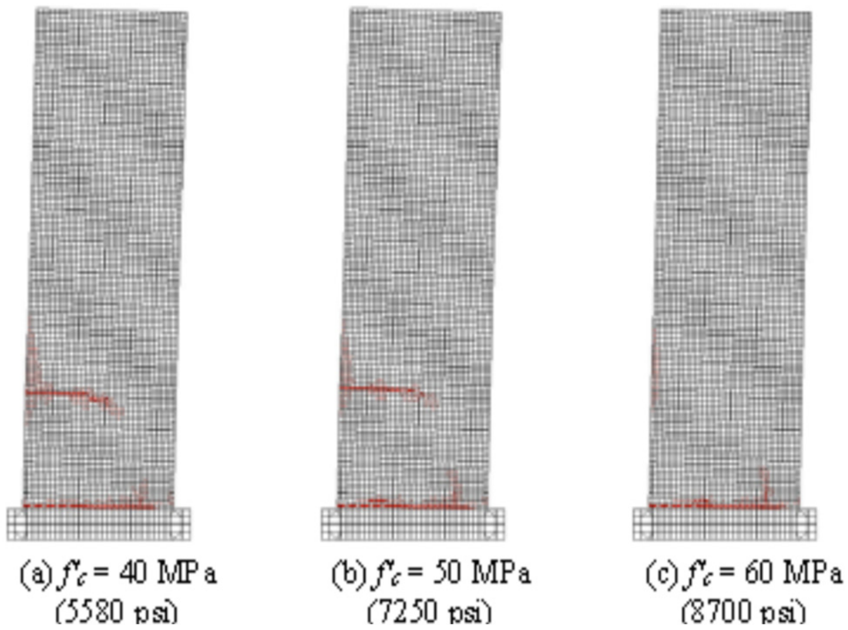


Note: For clarity, only part of the required reinforcement is shown.

18.10.2.4—Longitudinal reinforcement ratio at ends of walls

$h_w/\ell_w \geq 2.0$

- Failures in Chile and New Zealand
- 1 or 2 large cracks
- Minor secondary cracks



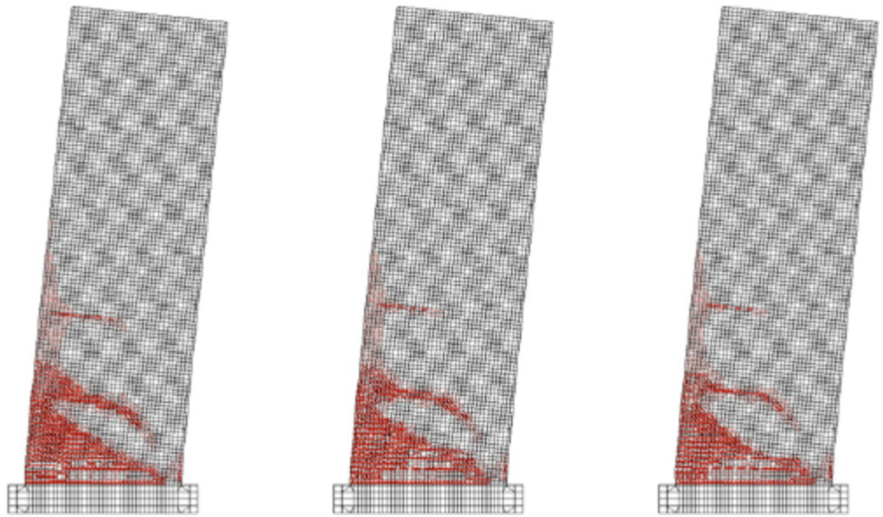
Crack patterns for walls with fixed minimum longitudinal reinforcement content of 0.25% (Lu et al. 2017)

18.10.2.4—Longitudinal reinforcement ratio at ends of walls

New ratio

$$\rho = \frac{0.5\sqrt{f_c'}}{f_y}$$

- Many well distributed cracks
- Flexure yielding over length



(a) $f_c' = 40$ MPa (5583 psi) $\rho_{le} = 0.64\%$

(b) $f_c' = 50$ MPa (7250 psi) $\rho_{le} = 0.71\%$

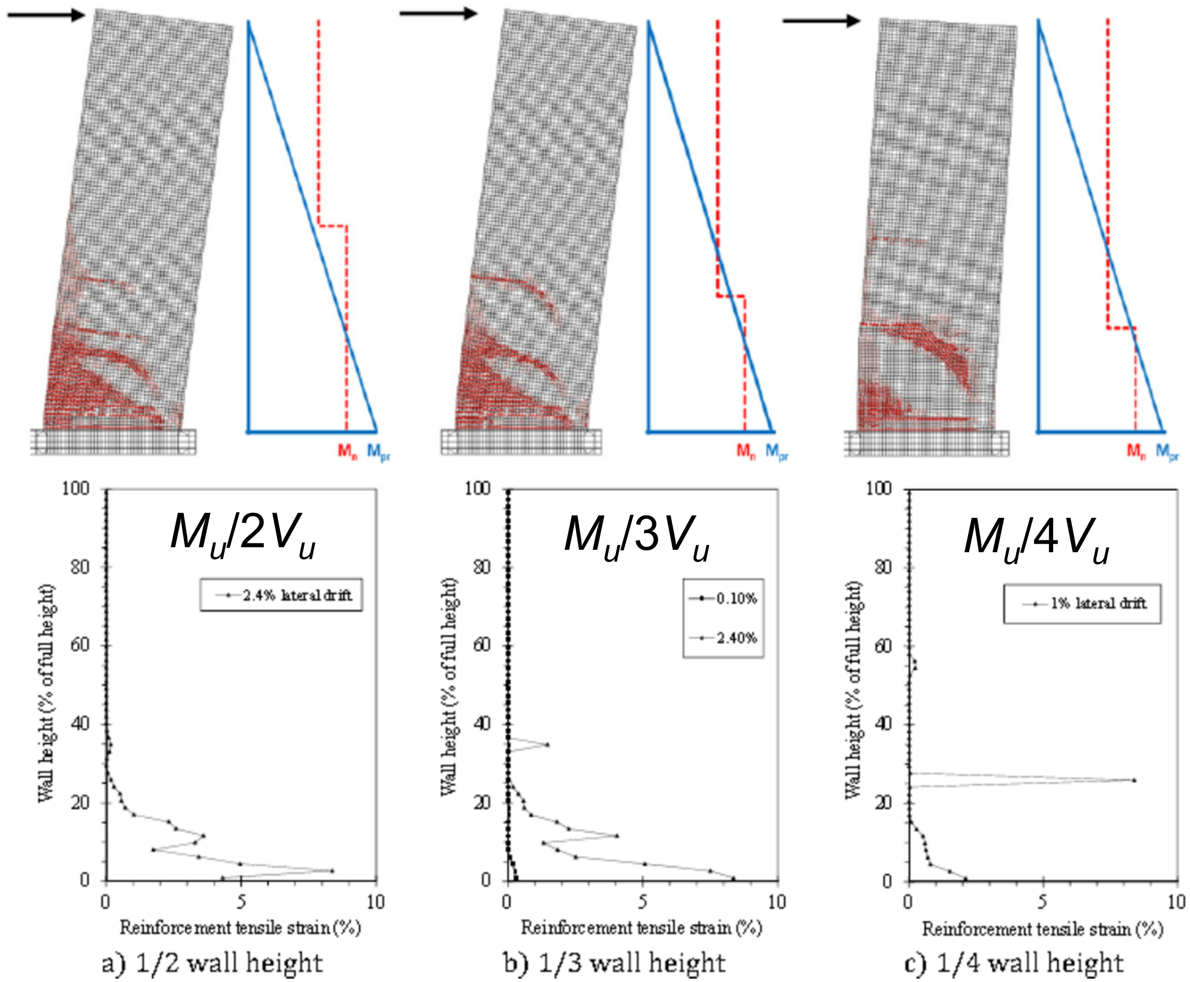
(c) $f_c' = 60$ MPa (8700 psi) $\rho_{le} = 0.78\%$

Crack patterns for walls according to equation (Lu et al. 2017)

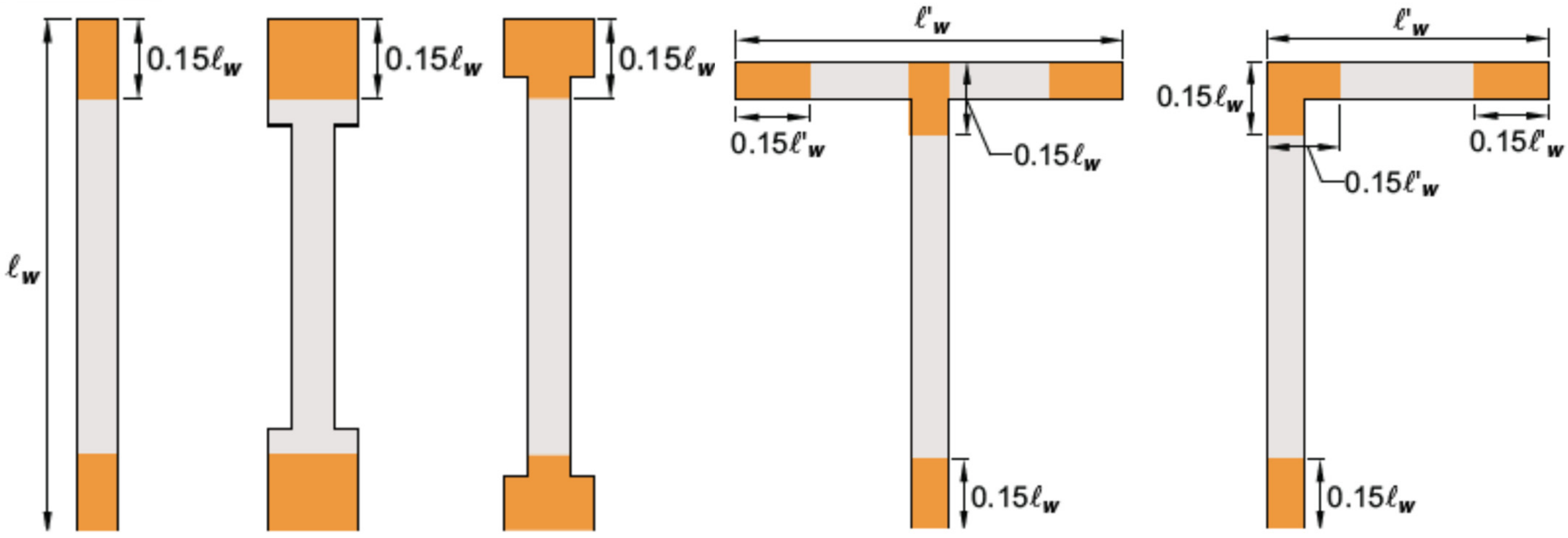
18.10.2.4—Longitudinal reinforcement ratio at ends of walls

Bar Cutoff

- $M_u/2V_u$ similar to wall with full reinforcement
- $M_u/3V_u$ good distribution
- $M_u/4V_u$ significant strain above cut off



18.10.2.4—Longitudinal reinforcement ratio at ends of walls



18.10.2.4—Longitudinal reinforcement ratio at ends of walls

Walls or wall piers with $h_w/\ell_w \geq 2.0$ must satisfy:

a) Long. reinf. ratio within 0.15 ℓ_w and minimum

$$\rho = \frac{0.5\sqrt{f_c'}}{f_y}$$

b) Long. reinf. extends above and below critical section the greater of ℓ_w and $M_u/3V_u$

c) Max. 50% of reinf. terminated at one section

18.10.3—Dynamic shear amplification

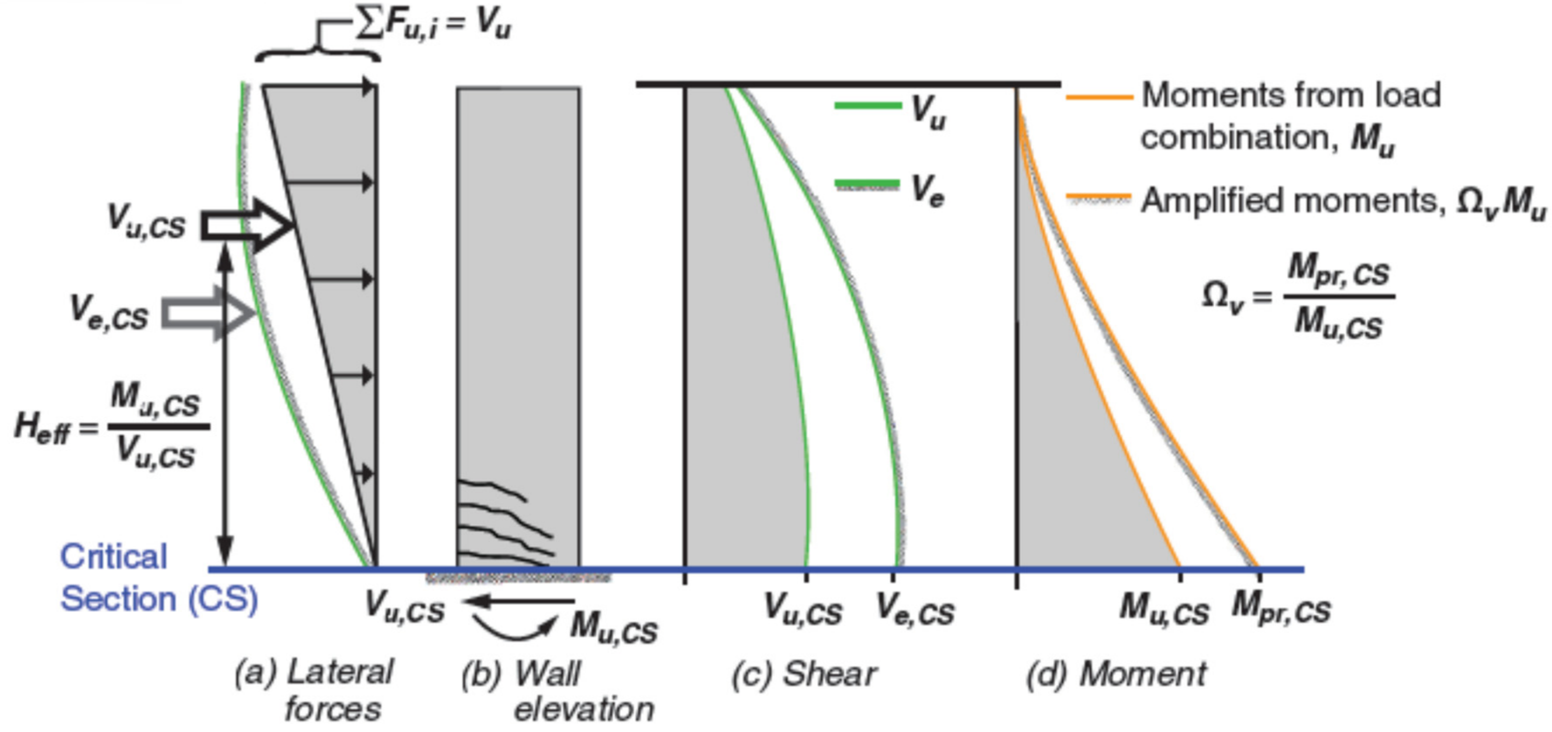


Fig. R18.10.3.1—Determination of shear demand for walls with $h_w/\ell_w \geq 2.0$ *(Moehle et al 2011).*

- **Similar to approach in New Zealand Standard, NZS 3101**

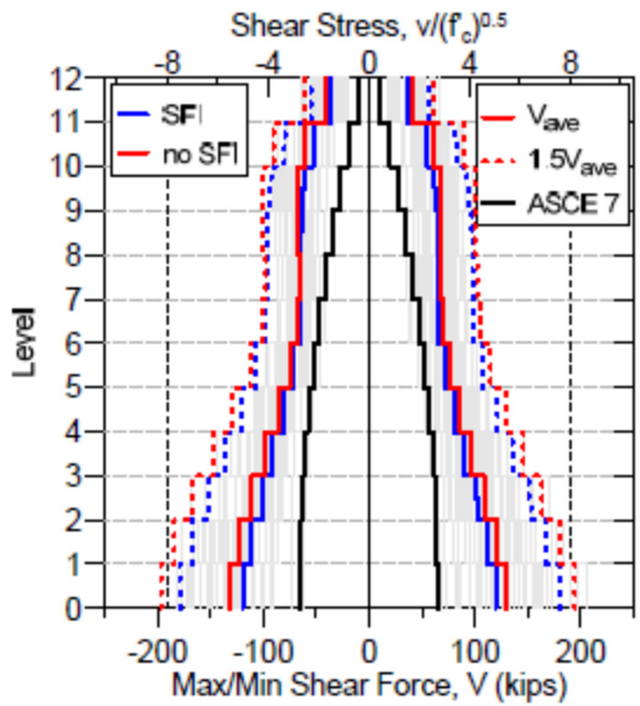
18.10.3—Dynamic shear amplification

18.10.3.1 The design shear force V_e shall be calculated by: $V_e = \Omega_v \omega_v V_u \leq 3V_u$

V_u = the shear force obtained from code lateral load analysis with factored load combinations

Ω_v = overstrength factor equal to the ratio of M_{pr}/M_u at the wall critical section.

ω_v = factor to account for dynamic shear amplification.



Gogus and Wallace, 2015

18.10.3—Dynamic shear amplification

18.10.3.1.2 – Calculation of Ω_v

Table 18.10.3.1.2—Overstrength factor Ω_v at critical section

Condition	Ω_v	
$h_{wcs}/\ell_w > 1.5$	Greater of	M_{pr}/M_u[1]
		1.5[2]
$h_{wcs}/\ell_w \leq 1.5$	1.0	

[1] For the load combination producing the largest value of Ω_v.

[2] Unless a more detailed analysis demonstrated a smaller value, but not less than 1.0.

18.10.3—Dynamic Shear Amplification

18.10.3.1.3 – Calculation of ω_v

$h_{wcs}/\ell_w < 2.0 \rightarrow \omega_v = 1.0$

$h_{wcs}/\ell_w \geq 2.0 \rightarrow \omega_v = 0.9 + n_s/10$ for $n_s \leq 6$

$\omega_v = 1.3 + n_s/30 \leq 1.8$ for $n_s > 6$

where $n_s \geq 0.00028h_{wcs}$

n_s = number of stories above the critical section.

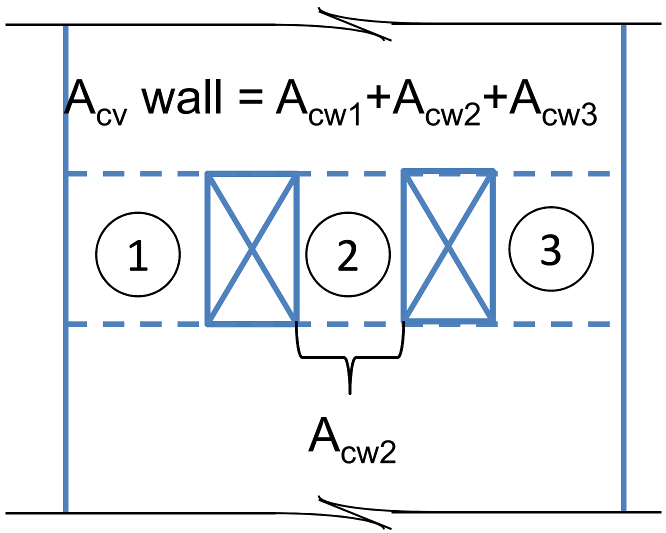
18.10.4.1—Shear strength, V_n

No Change

- The code shows change bars at this location; rewording only
- Shear calculations for Chapters 11 and 18 were harmonized
- 11.5.4.3 is now similar to 18.10.4.1

18.10.4.4—Clarification of A_{cv}

A_{cv} = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered in the case of walls, and gross area of concrete section in the case of diaphragms. Gross area is total area of the defined section minus area of any openings.

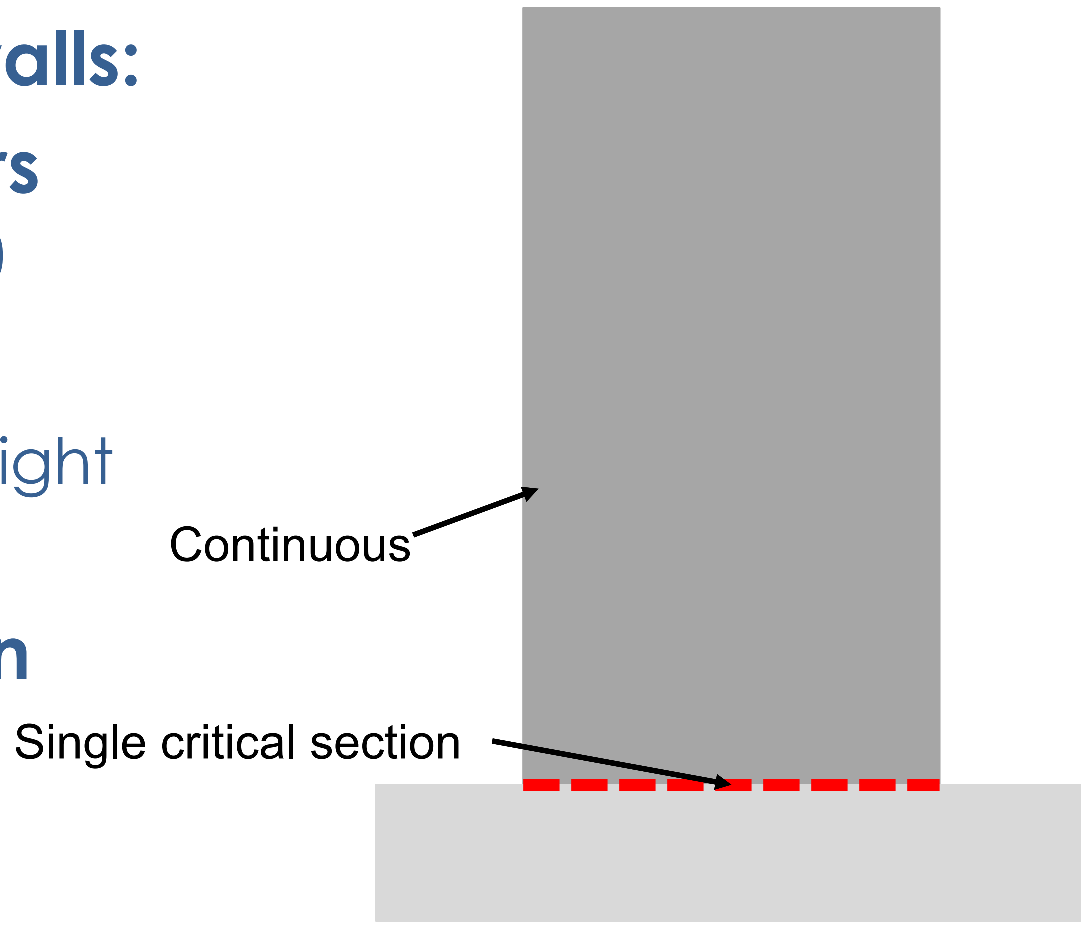


Vertical wall segments

18.10.6.2—Displacement based approach

Boundary elements of special structural walls:

- **Walls or wall piers with $h_{wcs}/\ell_w \geq 2.0$**
- **Continuous**
  - Uniform for full height
- **Single critical (yielding) section**
  - Plastic hinge

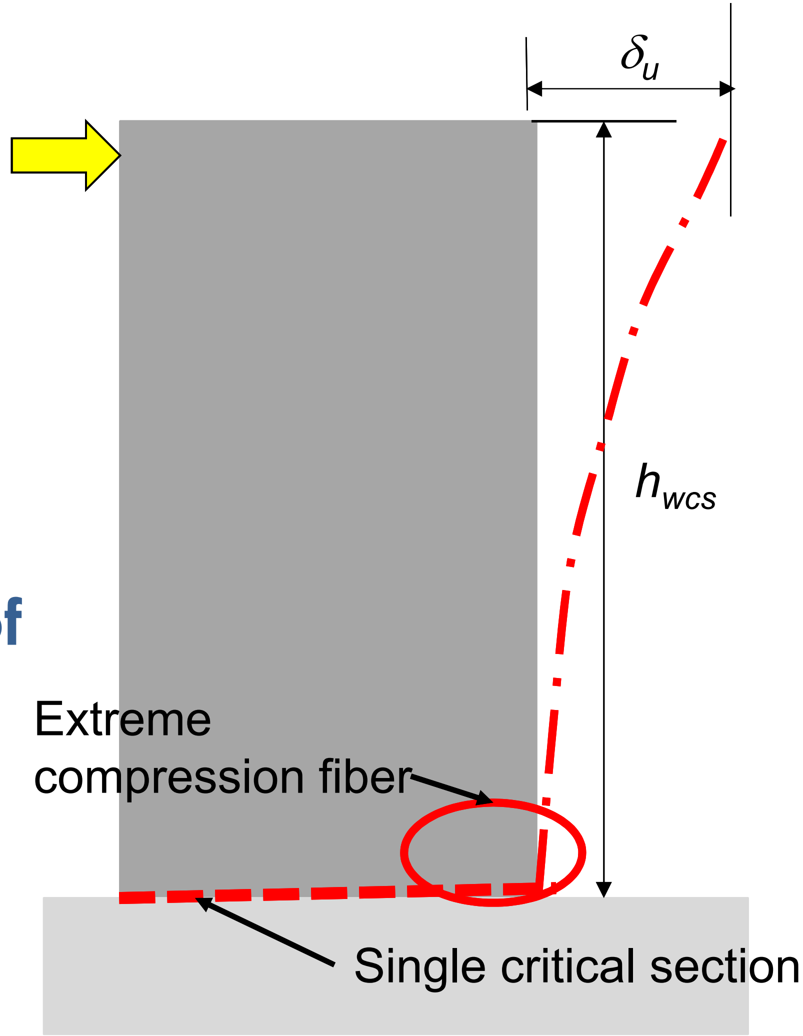


18.10.6.2—Displacement based approach

(a) Compression zone with special boundary elements required if:

$$\frac{1.5\delta_u}{h_{wcs}} \geq \frac{\ell_w}{600c}$$

- **$c = [P_u, \phi M_n]_{max}$ in direction of design displacement δ_u and**
- **$\delta_u/h_{wcs} \geq 0.005$**



18.10.6.2—Displacement based approach

(b) Boundary elements req'd, then (i) and either (ii) or (iii)

i. Transv. reinf. extends above and below critical section $[\ell_w, M_u/4V_u]_{max}$

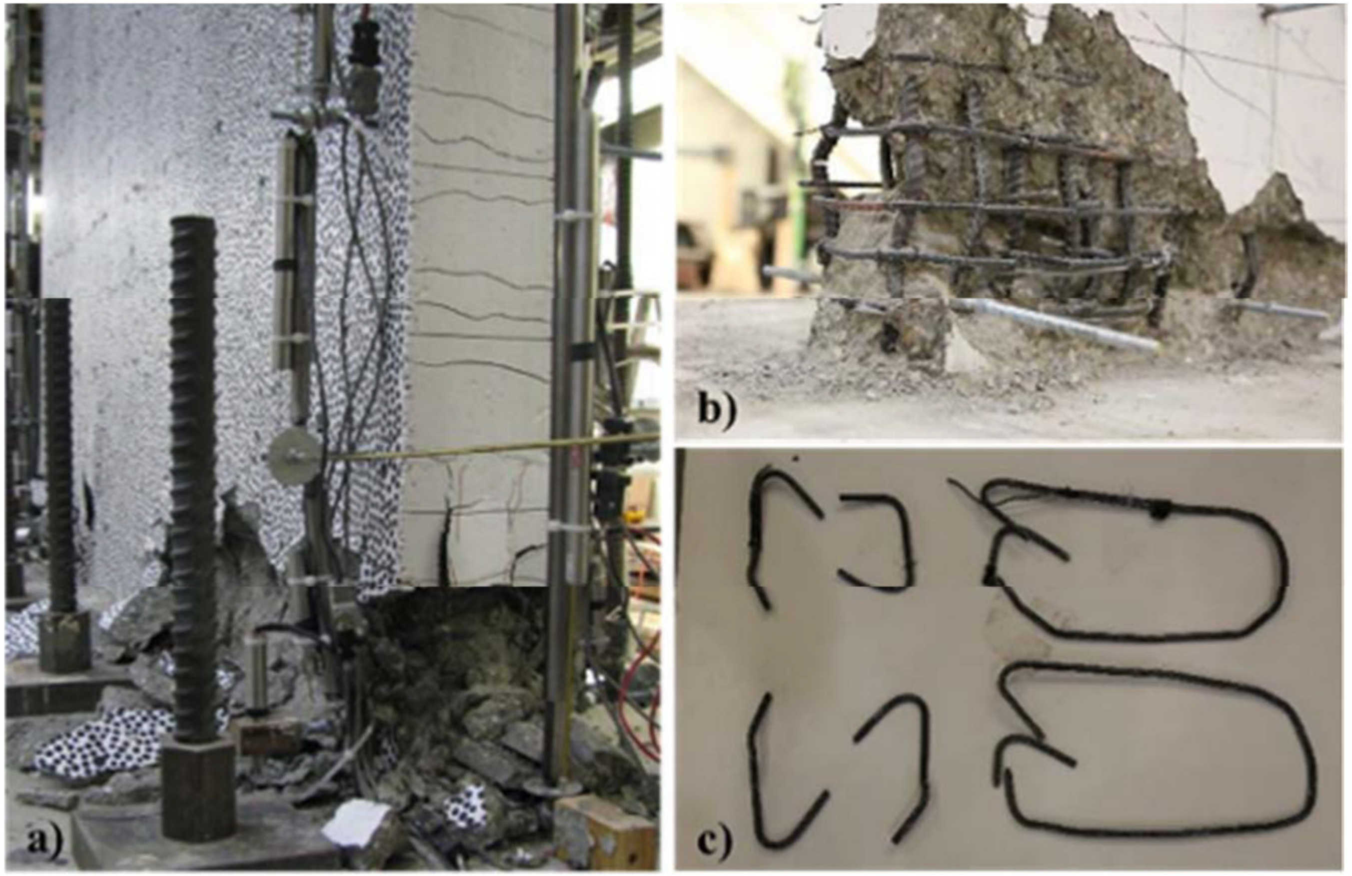
ii. $b \geq \sqrt{0.025 \ell c_w}$

iii. $\delta_c/h_{wcs} \geq 1.5\, \delta_u / h_{wcs}$, where

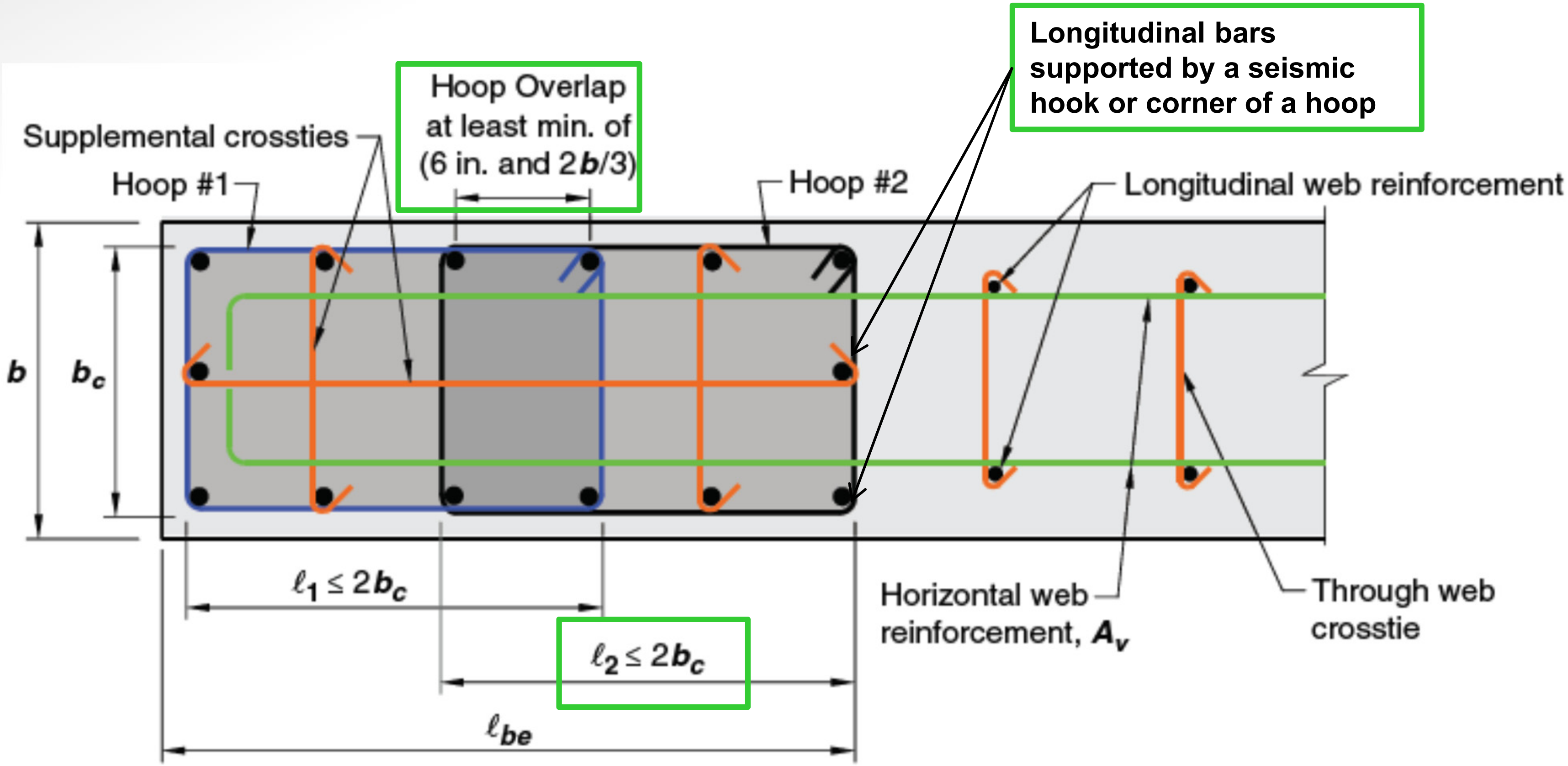
$$\frac{\delta_c}{h_{wcs}} = \frac{1}{100}\left(4 - \frac{1}{50}\left(\frac{\ell_w}{b}\right)\left(\frac{c}{b}\right) - \frac{V_e}{8\sqrt{f_c'}A_{cv}}\right) \geq 0.015$$

18.10.6.4—Special Boundary Elements

- Single perimeter hoops with 90-135 or 135-135 degree crossties, inadequate



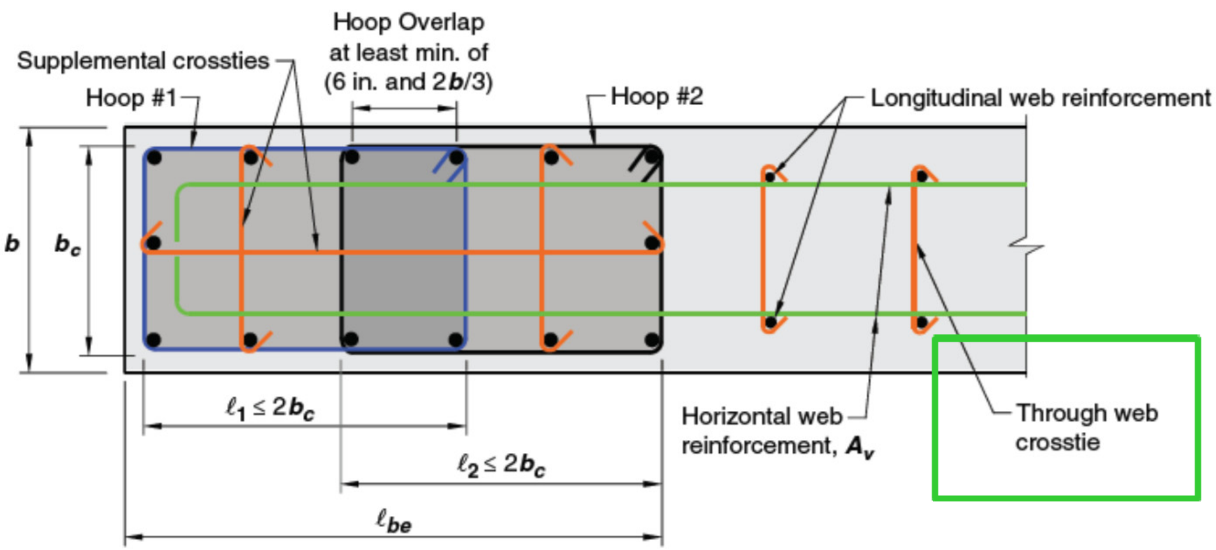
18.10.6.4(f)—Special Boundary Elements



(b) Overlapping hoops with supplemental 135-degree crossties and 135-degree crossties supporting distributed web longitudinal reinforcement

18.10.6.4(h)—Special Boundary Elements

- **18.10.6.4(i) – for a distance specified in 18.10.6.2(b) above and below the critical section, web vertical reinforcement shall have lateral support**
  - crossties vertical spacing, $s_v \leq 300$ mm



(b) Overlapping hoops with supplemental 135-degree crossties and 135-degree crossties supporting distributed web longitudinal reinforcement

18.10.6.5(b)—Maximum longitudinal ρ at the wall boundary exceeds $2.8/f_y$

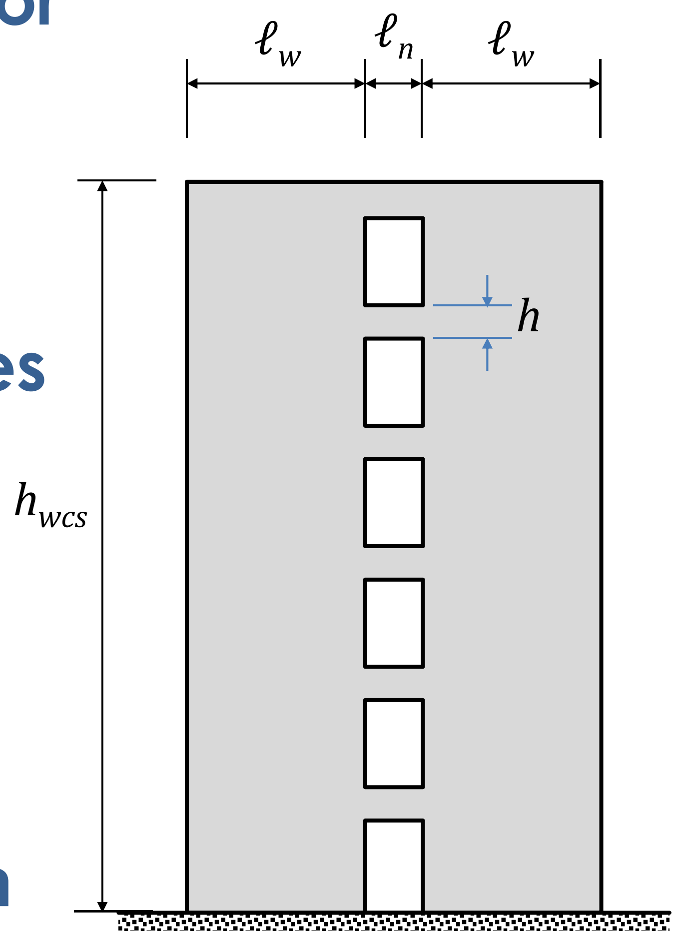
Table 18.10.6.5b—Vertical spacing of transverse reinforcement at wall boundary

Grade of primary flexural reinforcing bar	Transverse reinforcement required	Vertical spacing of transverse reinforcement[1]	
420	Within the greater of ℓ_w and $M_u/4V_u$ above and below critical sections[2]	Lesser of:	$6\ d_b$
			150 mm
	Other locations	Lesser of:	**$8\ d_b$**
			200 mm
550	Within the greater of ℓ_w and $M_u/4V_u$ above and below critical sections[2]	Lesser of:	$5\ d_b$
			150 mm
	Other locations	Lesser of:	**$6\ d_b$**
			150 mm
700	Within the greater of ℓ_w and $M_u/4V_u$ above and below critical sections[2]	Lesser of:	$4d_b$
			150 mm
	Other locations	Lesser of:	**$6d_b$**
			150 mm

18.10.9—Ductile Coupled Walls

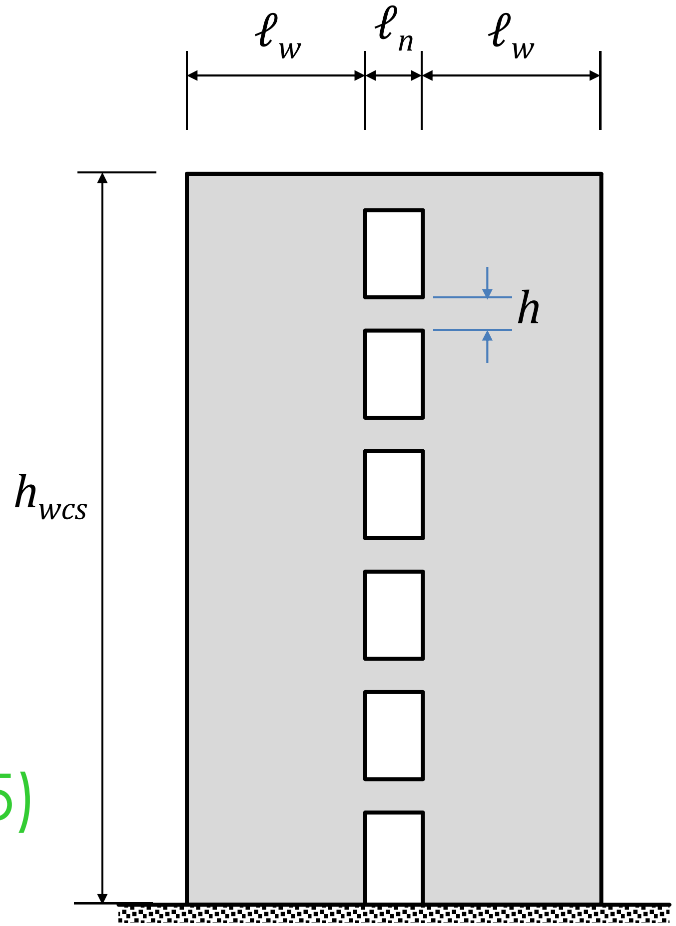
Issues preventing ductile behavior

- Inadequate quantity or distribution of qualifying coupling beams
- Presence of squat walls causes the primary mechanism to be shear and/or strut-and-tie failure in walls
- Coupling beams are inadequately developed to provide full energy dissipation



18.10.9—Ductile Coupled Walls

- **Individual walls satisfy**
  - $h_{wcs}/\ell_w \geq 2$
- **All coupling beams must satisfy:**
  - $\ell_n/h \geq 2$ at all levels
  - $\ell_n/h \leq 5$ at a floor level in at least 90% of the levels of the building
  - Development into adjacent wall segments, $1.25f_y$ (18.10.2.5)



ACI 318-19

American Concrete Institute
Always advancing

Changes to the Concrete Design Standard

High-Strength Reinforcement

High-Strength Reinforcement

Committee reviewed 550 and 700 MPa reinforcement for more thorough integration into code

- Impact on seismic design shown on earlier slides
- Next slides provide further information

Chapter 20—Several tables created

Table 20.2.2.4a—Nonprestressed deformed reinforcement

Usage	Application	Maximum value of f_y or f_{yt} permitted for design calculations, MPa	Applicable ASTM specification			
			Deformed bars	Deformed wires	Welded wire reinforcement	Welded deformed bar mats
Flexure; axial force; and shrinkage and temperature	Special seismic systems	420	Refer to 20.2.2.5	Not permitted	Not permitted	Not permitted
	Other	550	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M, A1022M	A184M[1]
Lateral support of longitudinal bars; or concrete confinement	Special seismic systems	700	A615M, A706M, A955M, A996M, A1035M	A1064M, A1022M	A1064M[2], A1022M[2]	Not permitted
	Spirals	700	A615M, A706M, A955M, A996M, A1035M	A1064M, A1022M	Not permitted	Not permitted
	Other	550	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M, A1022M	Not permitted
Shear	Special seismic systems	420	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M[2], A1022M[2]	Not permitted
	Spirals	420	A615M, A706M, A955M, A996M	A1064M, A1022M	Not permitted	Not permitted
	Shear friction	420	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M, A1022M	Not permitted
	Stirrups, ties, hoops	420	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M and A1022M welded plain wire	Not permitted
		550	Not permitted	Not permitted	A1064M and A1022M welded deformed wire	Not permitted
Torsion	Longitudinal and transverse	420	A615M, A706M, A955M, A996M	A1064M, A1022M	A1064M, A1022M	Not permitted

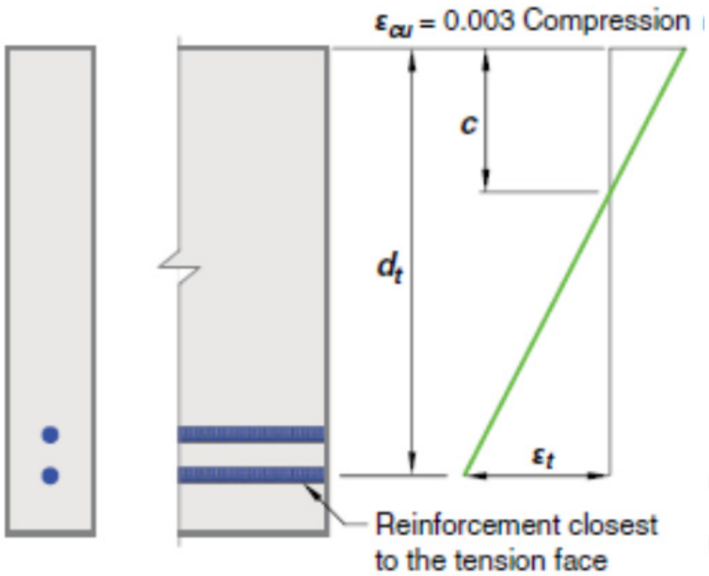
[1]Welded deformed bar mats shall be permitted to be assembled using A615M or A706M deformed bars.

[2] ASTM A1064M and A1022M are not permitted in special seismic systems where the weld is required to resist stresses in response to confinement, lateral support of longitudinal bars, shear, or other actions.

<table>
<tr><th rowspan="2">Usage</th><th rowspan="2" colspan="2">Application</th><th rowspan="2">Maximum value of f_y or f_{yt} permitted for design calc., Mpa</th><th>Applicable ASTM Specification</th></tr>
<tr><th>Deformed bars</th></tr>
<tr><td rowspan="3">Flexural, axial force, and shrinkage and temperature</td><td rowspan="2">Special seismic systems</td><td>Special moment frames</td><td>550</td><td rowspan="2">A706</td></tr>
<tr><td>Special structural walls</td><td>700</td></tr>
<tr><td colspan="2">Other</td><td>550</td><td>A615M, A706M, A955M, A966M, A1035M</td></tr>
<tr><td rowspan="3">Lateral support of longitudinal bars; or concrete confinement</td><td colspan="2">Special seismic systems</td><td>700</td><td>A615M, A706M, A955M, A966M, A1035M</td></tr>
<tr><td colspan="2">Spirals</td><td>700</td><td>A615M, A706M, A955M, A966M, A1035M</td></tr>
<tr><td colspan="2">Other</td><td>550</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td rowspan="6">Shear</td><td rowspan="2">Special seismic systems</td><td>Special moment frames</td><td>550</td><td rowspan="2">A615M, A706M, A955M, A966M</td></tr>
<tr><td>Special structural walls</td><td>700</td></tr>
<tr><td colspan="2">Spirals</td><td>420</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td colspan="2">Shear friction</td><td>420</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td colspan="2" rowspan="2">Stirrups, ties, hoops</td><td>420</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td>550</td><td>Not permitted</td></tr>
<tr><td>Torsion</td><td colspan="2">Longitudinal and transverse</td><td>420</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td rowspan="2">Anchor reinforcement</td><td colspan="2">Special seismic systems</td><td>550</td><td>A706</td></tr>
<tr><td colspan="2">Other</td><td>550</td><td>A615M, A706M, A955M, A966M</td></tr>
<tr><td rowspan="2">Regions designed using STM</td><td colspan="2">Longitudinal ties</td><td>550</td><td rowspan="2">A615M, A706M, A955M, A966M</td></tr>
<tr><td colspan="2">Other</td><td>420</td></tr>
</table>

Table 21.2.2—Strength reduction factor

- **ACI 318-14, Tension controlled limit**
  - $\varepsilon_t = 0.005$
- **ACI 318-19, Tension controlled limit**
  - $\varepsilon_t = \varepsilon_{ty} + 0.003$



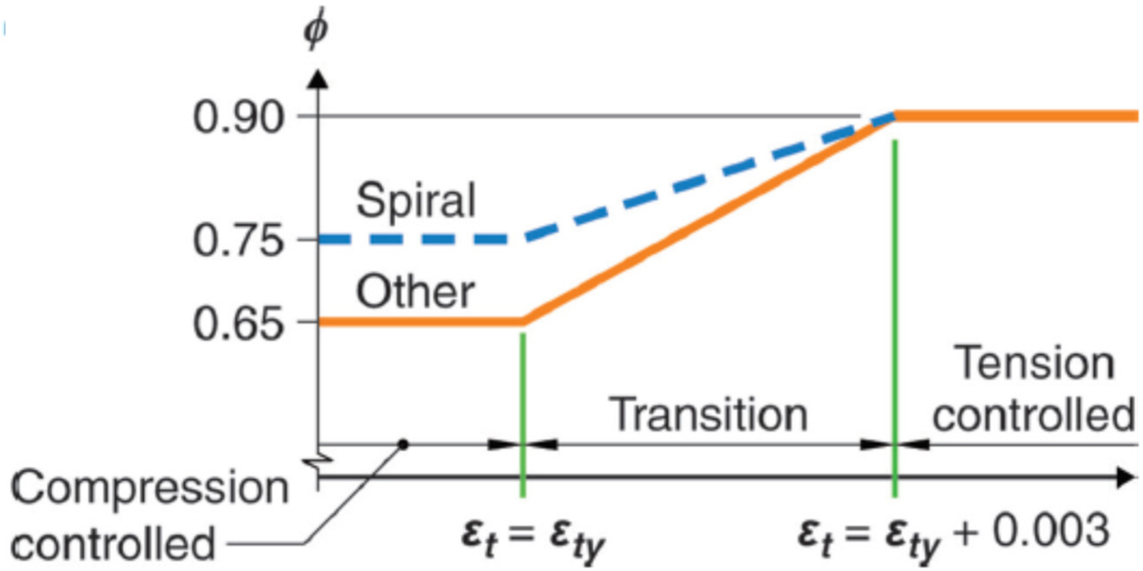


Table 21.2.2—Strength reduction factor

Table 21.2.2—Strength reduction factor ϕ for moment, axial force, or combined moment and axial force

Net tensile stain ε_t	Classification	ϕ — Type of transverse reinforcement — Spirals conforming to 25.7.3		ϕ — Type of transverse reinforcement — Other	
$\varepsilon_t \leq \varepsilon_{ty}$	Compression-controlled	0.75	(a)	0.65	(b)
$\varepsilon_{ty} < \varepsilon_t < \varepsilon_{ty} + 0.003$	Transition[1]	$0.75 + 0.15\dfrac{(\varepsilon_t - \varepsilon_{ty})}{(0.003)}$	(c)	$0.65 + 0.25\dfrac{(\varepsilon_t - \varepsilon_{ty})}{(0.003)}$	(d)
$\varepsilon_t \geq \varepsilon_{ty} + 0.003$	Tension-controlled	0.90	(e)	0.90	(f)

[1]For sections classified as transition, it shall be permitted to use ϕ corresponding to compression-controlled sections.

Overview of changes to ACI 318M-19

- Remove steel-concrete composite provisions
- Size effect; new one- & two-way shear eqns
- Joint shear and detailing
- STM updates (including seismic)
- Screw anchors

  Shear lugs
- Included Grades 80 and 100
- Development of headed and hooked bars
- Bi-directional shear
- Seismic design changes
- Deep foundation in EQ-resistant buildings
- Shotcrete
- Nonlinear response history analysis

ACI 318 Committee