Reinforced Concrete

By Peter W. Somers, S.E.

Originally developed by Finley A. Charney, PhD, P.E.
Topic Overview

• Concrete and reinforcement behavior
• Reference standards
• Requirements by Seismic Design Category
  – Moment resisting frames
  – Shear walls
• Other topics
• Design Examples
Topic Overview

• Concrete and reinforcement behavior

• Reference standards

• Requirements by Seismic Design Category
  – Moment resisting frames
  – Shear walls

• Other topics

• Design Examples
Summary of Concrete Behavior

• Compressive Ductility
  — Strong in compression but brittle
  — Confinement improves ductility by
    • Maintaining concrete core integrity
    • Preventing longitudinal bar buckling

• Flexural Ductility
  — Longitudinal steel provides monotonic ductility at low
    reinforcement ratios
  — Transverse steel needed to maintain ductility through
    reverse cycles and at very high strains (hinge
    development)
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Reference Standards

Minimum Design Loads for Buildings and Other Structures

An ACI Standard and Report

Building Code Requirements for Structural Concrete (ACI 318-14)

Commentary on Building Code Requirements for Structural Concrete (ACI 318R-14)

Reported by ACI Committee 318
CHAPTER 14, MATERIAL SPECIFIC SEISMIC DESIGN AND DETAILING REQUIREMENTS
(Modifications)

SECTION 14.2.2.1
Replace Section 14.2.2.1 with the following:

14.2.2.1 Definitions
Add the following definitions to Section 2.2

CONNECTION: A region that joins two or more members. For precast concrete diaphragm design, a connection also refers to an assembly of connectors with the linking parts, welds and anchorage to concrete which forms a load path across a joint between members, at least one of which is a precast concrete member.

CONNECTOR: fabricated part embedded in concrete for anchorage and intended to provide a load path across a precast joint.

DETAILED PLAIN CONCRETE STRUCTURAL WALL: A wall complying with the requirements of Chapter 22 of ACI 318.

ORDINARY PRECAST STRUCTURAL WALL: A precast wall complying with the requirements of Chapter 18 of ACI 318.

PRECAST CONCRETE DIAPHRAGM DESIGN OPTIONS: (a) Basic Design Option (BDO) targets elastic diaphragm response in the design earthquake, (b) Elastic Design Option (EDO) targets elastic diaphragm response in the maximum considered earthquake, and (c) Reduced Design Option (RDO) permits limited diaphragm yielding in the design earthquake. These options are implemented in precast diaphragm design in accordance with Section 14.2.4.

SECTION 14.2.4
Add Section 14.2.4 as follows:

14.2.4 Additional Design and Detailing Requirements for Precast Concrete Diaphragms
In addition to the requirements for reinforced concrete set forth in this standard and Section 21.11 of ACI 318, design, detailing and construction of diaphragms constructed with precast concrete components in Seismic Design Categories C, D, E, and F shall conform to the requirements of this section.

14.2.4.1 Diaphragm Seismic Demand Levels
A seismic demand level for each precast concrete diaphragm shall be determined in such direction, based on Seismic Design Category (SDC), number of stories, $u$, diaphragm span, $L$, as defined in Section 14.2.4.1.1, and diaphragm aspect ratio, $A_d$, as defined in Section 14.2.4.1.2. For structures assigned to SDC C, the seismic demand level is low. For structures assigned to SDC D, E or F, the seismic demand level shall be determined in accordance with Figure 14.2.4-1.
Context in NEHRP Recommended Provisions

Provisions ➔ ASCE 7-16 ➔ ACI 318-14

ASCE 7-16 for Concrete

Structural design criteria: Chap. 12
Structural analysis procedures: Chap. 12
Design of concrete structures: Sec. 14.2

Provisions modifications to ASCE 7-10
ASCE 7-16 modifications to ACI 318-14
Reference Standards

**ASCE 7-16:**
- Defines systems and classifications
- Provides design coefficients

**ACI 318-14:**
- Provides system design and detailing requirements consistent with ASCE 7-16 system criteria
- Modified by ASCE 7-16
Use of Reference Standards

• **ACI 318**
  – Chapter 18, Earthquake-Resistant Structures

• **ASCE 7-16 and Provisions Section 14.2**
  – Modifications to ACI 318
  – Detailing requirements for concrete piles

• *Provisions* supersede ASCE 7-10 modifications
Detailed Modifications to ACI 318

• Wall piers and wall segments
• Members not designated as part of the LRFS
• Columns supporting discontinuous walls
• Intermediate precast walls
• Plain concrete structures
• Anchoring to concrete
• Foundations
• Acceptance criteria for validation testing of special precast walls
Topic Overview

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## Design Coefficients Moment Resisting Frames

<table>
<thead>
<tr>
<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Deflection Amplification Factor, $C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special R/C Moment Frame</td>
<td>8</td>
<td>5.5</td>
</tr>
<tr>
<td>Intermediate R/C Moment Frame</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>Ordinary R/C Moment Frame</td>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Performance Objectives

• Special Moment Frames
  – Strong column
    • Avoid story mechanism
  – Hinge development
    • Confined concrete core
    • Prevent rebar buckling
    • Prevent shear failure
  – Member shear strength
  – Joint shear strength
  – Rebar development and splices (confined)
Performance Objectives

• **Intermediate Moment Frames**
  – Avoid shear failures in beams and columns
  – Plastic hinge development in beams and columns
  – Toughness requirements for two-way slabs without beams

• **Ordinary Moment Frames**
  – Minimum ductility and toughness
  – Continuous top and bottom beam reinforcement
  – Minimum column shear failure protection
# Summary of Seismic Detailing for Frames

<table>
<thead>
<tr>
<th>Issue</th>
<th>Ordinary</th>
<th>Intermediate</th>
<th>Special</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinge development and confinement</td>
<td>minor</td>
<td></td>
<td>full</td>
</tr>
<tr>
<td>Bar buckling</td>
<td>lesser</td>
<td></td>
<td>full</td>
</tr>
<tr>
<td>Member shear</td>
<td>lesser</td>
<td></td>
<td>full</td>
</tr>
<tr>
<td>Joint shear</td>
<td>minor</td>
<td>minor</td>
<td>full</td>
</tr>
<tr>
<td>Strong column</td>
<td></td>
<td></td>
<td>full</td>
</tr>
<tr>
<td>Rebar development</td>
<td>lesser</td>
<td>lesser</td>
<td>full</td>
</tr>
<tr>
<td>Load reversal</td>
<td>minor</td>
<td>lesser</td>
<td>full</td>
</tr>
</tbody>
</table>
Special Moment Frames

- General detailing requirements
- Beams
- Joints
- Columns
- Example problem
Frame Mechanisms
“strong column – weak beam”

Story mechanism

Sway mechanism
Required Column Strength

\[ \sum M_{nc} \geq 1.2 \sum M_{nb} \]
Hinge Development

- **Tightly Spaced Hoops**
  - Provide confinement to increase concrete strength and usable compressive strain
  - Provide lateral support to compression bars to prevent buckling
  - Act as shear reinforcement and preclude shear failures
  - Control splitting cracks from high bar bond stresses
ACI 318, Overview of SMF: Beam Longitudinal Reinforcement

\[ \frac{200}{f_y} \leq \rho \leq 0.025 \]

At least 2 bars continuous top & bottom

Joint face \( M_n^+ \) not less than 50% \( M_n^- \)

Min. \( M_n^+ \) or \( M_n^- \) not less than 25% max. \( M_n \) at joint face

Splice away from hinges and enclose within hoops or spirals
ACI 318, Overview of SMF:
Beam Transverse Reinforcement

Closed hoops at hinging regions with “seismic” hook

135° hook, $6d_h \geq 3”$ extension

Maximum spacing of hoops:

$$d/4 \quad 6d_b \quad 6”$$

Longitudinal bars on perimeter tied as if column bars

Stirrups elsewhere, $s \leq d/2$
ACI 318, Overview of SMF: Beam Shear Strength

\[ V_e = \frac{M_{pr1} + M_{pr2}}{\ell_n} \pm \frac{w_u \ell_n}{2} \geq V_e \text{ by analysis} \]

If earthquake-induced shear force \( > \frac{1}{2} V_e \)\), then \( V_c = 0 \)

and \( P_u < \frac{A_g f_c'}{20} \)
ACI 318, Overview of SMF: Beam-Column Joint

\[ V_j = T + C - V_{col} \]

\[ T = 1.25 f_y A_{s,top} \]

\[ C = 1.25 f_y A_{s,bottom} \]
ACI 318, Overview of SMF: Beam-column Joint

\[ V_n = \begin{cases} 
20 \\
15 \\
12 
\end{cases} \sqrt{f'_c A_j} \]

- \( V_n \) often controls size of columns
- Coefficient depends on joint confinement
- To reduce shear demand, increase beam depth
- Keep column stronger than beam
ACI 318, Overview of SMF: Column Transverse Reinforcement at Potential Hinging Region

Spacing shall not exceed the smallest of:

$\frac{b}{4}$ or $6d_b$ or $s_o$ (4” to 6”)

Distance between longitudinal bars supported by hoops or cross ties, $h_x \leq 14”$

$$s_o = 4 + \left(\frac{14 - h_x}{3}\right)$$
Topic Overview

• Concrete and reinforcement behavior
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## Design Coefficients
### Structural Walls (Bearing Systems)

<table>
<thead>
<tr>
<th>Seismic Force Resisting System</th>
<th>Response Modification Coefficient, R</th>
<th>Deflection Amplification Factor, $C_d$</th>
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<tbody>
<tr>
<td>Special R/C Structural Walls</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Ordinary R/C Structural Walls</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Intermediate Precast Structural Walls</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ordinary Precast Walls</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Performance Objectives

- **Special R/C structural walls**
  - Resist axial forces, flexure and shear
  - Boundary members
    - Where compression stress/strain is large, maintain capacity
  - Development of rebar in panel
  - Ductile coupling beams

- **Ordinary R/C structural walls**
  - No seismic requirements, Ch. 18 does not apply
Design Philosophy

- Flexural yielding will occur in predetermined flexural hinging regions
- Brittle failure mechanisms will be precluded
  - Diagonal tension
  - Sliding hinges
  - Local buckling
  - Shear failures in coupling beams
ACI 318, Overview of Special Walls: General Requirements

Shear plane, $A_{cv} = \text{web thickness } \times \text{length of wall}$

$\rho_t = \text{parallel to shear plane}$

$\rho_{\ell} = \text{perpendicular to shear plane}$
ACI 318, Overview of Special Walls: General Requirements

- $\rho_\ell$ and $\rho_t$ not less than 0.0025 unless

$$V_u < A_{cv} \sqrt{f'_c}$$

then per Sec.11.6

- Spacing not to exceed 18 in.

- Reinforcement contributing to $V_n$ shall be continuous and distributed across the shear plane
ACI 318, Overview of Special Walls: General Requirements

• Two curtains of reinforcing required if:

\[ V_u > 2A_{cv} \sqrt{f'c} \]

• Design shear force determined from lateral load analysis
ACI 318, Overview of Special Walls: General Requirements

• Shear strength:

\[ V_n = A_{cv} \left( \alpha_c \sqrt{f'_c} + \rho_t f_y \right) \]

\[ \alpha_c = 3.0 \text{ for } \frac{h_w}{l_w} \leq 1.5 \]
\[ \alpha_c = 2.0 \text{ for } \frac{h_w}{l_w} \geq 2.0 \]

Linear interpolation between

• Walls must have reinforcement in two orthogonal directions
ACI 318, Overview of Special Walls: General Requirements

- For axial load and flexure, design like a column to determine axial load – moment interaction
ACI 318, Overview of Special Walls: Boundary Elements

For walls with a high compression demand at the edges – special boundary elements are required

Widened end with confinement

Extra confinement and/or longitudinal bars at end
ACI 318: Overview of Special Walls
Boundary Elements

Two options for determining need for boundary elements

• **Strain-based**: Determined using wall deflection and associated wall curvature

• **Stress-based**: Determined using maximum extreme fiber compressive
ACI 318, Overview of Special Walls: Boundary Elements—Strain

• Boundary elements are required if:

\[ c \geq \frac{\ell_w}{600 \left( 1.5 \frac{\delta_u}{h_w} \right)} \]

\( \delta_u = \) Design displacement
\( c = \) Depth to neutral axis from strain compatibility analysis with loads causing \( \delta_u \)
ACI 318, Overview of Walls: Boundary Elements—Strain

- Where required, boundary elements must extend up the wall from the critical section a distance not less than the larger of:

\[ l_w \quad \text{or} \quad \frac{M_u}{4V_u} \]
ACI 318: Overview of Walls
Boundary Elements—Stress

• Boundary elements are required where the maximum extreme fiber compressive stress calculated based on factored load effects, linear elastic concrete behavior and gross section properties, exceeds $0.2f'_c$

• Boundary element can be discontinued where the compressive stress is less than $0.15f'_c$
ACI 318: Overview of Walls
Boundary Elements—Detailing

- Boundary elements must extend horizontally not less than the larger of \( c/2 \) or \( c-0.1\ell_w \)
- Width of boundary elements, \( b > h_u/16 \) or 12”
- In flanged walls, boundary element must include all of the effective flange width and at least 12 in. of the web
- Transverse reinforcement must extend into the foundation
- Horizontal reinforcement shall extend into the core of boundary and anchored to develop \( f_y \).
ACI 318: Overview of Walls Coupling Beams

Requirements based on aspect ratio and shear demand

\[ \ell_n / h \geq 4 \]

Design as Special Moment Frame beam

\[ \ell_n / h < 2 \text{ and } V_u > 4\sqrt{f'_c A_{cw}} \]

Reinforce with 2 intersecting groups of diagonal bars

Other cases

Standard or diagonal
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Members Not Part of LFRS

• In frame members not designated as part of the lateral-force-resisting system in regions of high seismic risk:
  — Must be able to support gravity loads while subjected to the design displacement
  — Transverse reinforcement increases depending on:
    Forces induced by drift
    Axial force in member
Precast Concrete: Performance Objectives

Field connections at points of low stress

Strong connections
- Configure system so that hinges occur in factory cast members away from field splices

Ductile connections
- Inelastic action at field splice

Field connections must yield
Topic Overview

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• Design Examples from FEMA P-751
Special Moment Frame Example

• Located in Berkeley, California
• 12-story concrete building
• N-S direction: SMF
• E-W direction: dual system
• Seismic Design Category D
• Modal Analysis Procedure
Update required.
Insung Kim, 8/4/2016
Frame Elevations

Grid Lines 3 to 6

Grid Lines 2 and 7
Story Shears: E-W Loading
Layout of Reinforcement

#4 stirrup

#8 bar, assumed

4

28.5” 29.5” 32”

24”

30”
### Design Strengths

<table>
<thead>
<tr>
<th>Design Aspect</th>
<th>Strength Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flexure</td>
<td>Design strength</td>
</tr>
<tr>
<td>Beam shear</td>
<td>Maximum probable strength</td>
</tr>
<tr>
<td>Beam-column joint</td>
<td>Maximum probable strength</td>
</tr>
<tr>
<td>Column flexure</td>
<td>1.2 times nominal beam strength</td>
</tr>
<tr>
<td>Column shear</td>
<td>Maximum probable strength</td>
</tr>
</tbody>
</table>
Bending Moment Envelopes: Frame 1 Beams, 7th Floor

(a) Span layout and loading

(b) Earthquake moment (in.-kips)

(c) Unfactored DL moment (in.-kips)

(d) Unfactored LL moment (in.-kips)

(e) Required strength envelopes (in.-kips)

- 1.46D + 0.5L + E
- 1.2D + 1.6L (midspan)
- 0.64D - E
Beam Reinforcement: Longitudinal

Design for Negative Moment at the Face of the Interior Support (Grid A’):

\[ \text{Mu} = 1.46(-602) + 0.5(-278) + 1.0(-3,973) = \text{-4,976 inch-kips} \]

One #7 bars in addition to the four #8 bars required for minimum steel:

\[ \text{As} = 4(0.79) + 1(0.60) = 3.76 \text{ in}^2 \]
\[ a = \frac{3.76 \text{ (60)}}{[0.85 (5) 24]} = 2.21 \text{ inches} \]
\[ F_{Mn} = 0.9(3.76)60(29.5 - 2.21/2) = 5,765 \text{ inch-kips} \]
\[ > 4,976 \text{ inch-kips} \]
**Beam Reinforcement: Longitudinal (continued)**

Check additional requirements:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum of two bars continuous top and bottom:</td>
<td>OK (three #8 bars continuous top OK (four #8 bars continuous top and bottom)</td>
</tr>
<tr>
<td>Positive moment strength greater than 50 percent negative moment strength at a joint:</td>
<td>OK (at all joints)</td>
</tr>
<tr>
<td>Minimum strength along member greater than 0.25 maximum strength:</td>
<td>OK ($A_s$ provided = four #8 bars is more than 25 percent of reinforcement provided at joints)</td>
</tr>
</tbody>
</table>
Beam Reinforcement: Layout

Note:
1. Drawing not to scale.
2. Splices not shown.
Determine Beam Design Shear

Probable moment strength, $M_{pr}$ (k-in)

$V_{u,grav} = 34.1$ kips

$$V_e = \frac{M_{pr1} + M_{pr2}}{\ell_n} + V_{u,grav} = \frac{7,929 + 6,841}{210} + 34.1 = 104.4 \text{ kips}$$
Beam Shear

Force

Hinge locations

Beam moments

Seismic shear

Factored gravity shear

Design shear
Beam Reinforcement: Transverse

\[V_{seismic} > 50\% \ V_u\] therefore take \(V_c = 0\)

Use 4 legged #4 stirrups

\[s_{max} = \frac{\phi A_v f_y d}{V_e} = \frac{0.75(0.8)(60)(29.5)}{104.4} = 10.2 \text{ in.}\]

At ends of beam \(s = 6 \text{ in.}\)
(near midspan, \(s = 6.0 \text{ in. w/ 2 legged stirrup}\))
Beam Reinforcement: Transverse

• Check maximum spacing of hoops within plastic hinge length (2h)
  – \( \frac{d}{4} = 7.4 \text{ in.} \)
  – \( 6d_b = 6.0 \text{ in.} \)
  – 6 in.

Therefore, 6.0 in. spacing at ends is adequate

At beam rebar splices, \( s = 4.0 \text{ in.} \)
Joint Shear Force

But how to compute $V_{col}$?

$$V_j = T + C - V_{col}$$

$$T = 1.25 f_y A_{s, \text{top}}$$

$$C = 1.25 f_y A_{s, \text{bottom}}$$
Joint Shear Force

\[ V_{col} = \frac{\left( M_{pr,L} + M_{pr,R} \right) + (V_R + V_L) \frac{h}{2}}{l_c} \]

At 7th Floor, Column C:

\[ V_{col} = \frac{\left( \left(7,929 + 6,841\right) + \left(70.3 + 70.3\right) \frac{30}{2} \right)}{156} = 108.2 \text{ kips} \]
Joint Shear Force

\[ T = 1.25 f_y A_{s, top} = 282 \text{ kips} \]
\[ C = 1.25 f_y A_{s, bot} = 237 \text{ kips} \]
\[ V_j = T + C - V_{col} = 411 \text{ kips} \]
\[ V_n = 15 \sqrt{f'_c A_j} = 15 \sqrt{5,000(30)^2} = 955 \]
\[ \phi V_n = 0.85 \cdot 955 = 811 \text{ kips} > 411 \text{ kips} \]
Frame 1 Column Design

Column: \[ P_u > \frac{f'_c A_g}{10} \]

then: \[ \sum M_{nc} > 1.2 \sum M_{nb} \]

Design column using standard P-M interaction curve
Column Design Moments

Design for strong column based on nominal beam moment strengths

Beam moments (Level 7)

\[ \sum M_{nc} = 1.2 \sum M_{nb} \]

\[ 1.2(5,498 + 6,406) = 14,285 \text{ k - ft} \]

Column moments (Level 7), assume uniform distribution top and bottom
## Column Transverse Reinforcement

<table>
<thead>
<tr>
<th>Transverse reinforcement</th>
<th>Conditions</th>
<th>Applicable expressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{sh}/s_{bc}$ for rectilinear hoop</td>
<td>$P_u \leq 0.3A_g f'<em>{c}$ and $f'</em>{c} \leq 10,000$ psi</td>
<td>$0.3 \left( \frac{A_g}{A_{ch}} - 1 \right) \frac{f'}{f_{yt}}$ (a)</td>
</tr>
<tr>
<td></td>
<td>$P_u &gt; 0.3A_g f'<em>{c}$ or $f'</em>{c} &gt; 10,000$ psi</td>
<td>$0.09 \frac{f'}{f_{yt}}$ (b)</td>
</tr>
<tr>
<td></td>
<td>$P_u \leq 0.3A_g f'<em>{c}$ and $f'</em>{c} \leq 10,000$ psi</td>
<td>$0.2k_f k_n \frac{P_u}{f_{yt} A_{ch}}$ (c)</td>
</tr>
<tr>
<td>$\rho_{s}$ for spiral or circular hoop</td>
<td>$P_u &gt; 0.3A_g f'<em>{c}$ or $f'</em>{c} &gt; 10,000$ psi</td>
<td>$0.45 \left( \frac{A_g}{A_{ch}} - 1 \right) \frac{f'}{f_{yt}}$ (d)</td>
</tr>
<tr>
<td></td>
<td>$P_u \leq 0.3A_g f'<em>{c}$ and $f'</em>{c} \leq 10,000$ psi</td>
<td>$0.12 \frac{f'}{f_{yt}}$ (e)</td>
</tr>
<tr>
<td></td>
<td>$P_u &gt; 0.3A_g f'<em>{c}$ or $f'</em>{c} &gt; 10,000$ psi</td>
<td>$0.35k_f \frac{P_u}{f_{yt} A_{ch}}$ (f)</td>
</tr>
</tbody>
</table>

(a) $k_f = \frac{f'}{25,000} + 0.6 \geq 1.0$

(b) $k_n = \frac{n_i}{n_i - 2}$

$n_i$: number of longitudinal bars that are laterally supported by the corner of hoops or by seismic hooks.
Column Transverse Reinforcement

Maximum spacing is smallest of:
\[ h/4 = 30/4 = 7.5 \text{ in.} \]
\[ 6d_b = 6 \times 1.0 = 6.0 \text{ in. (}\#8\text{ bars)} \]
\[ s_o \text{ calculated as follows:} \]
\[ s_o = 4 + \frac{14 - h_x}{3} \]

for 12 \#8 vertical bars and \#4 hoops,
\[ h_x = 8.33 \text{ in. and } s_o = 5.72 \text{ in.} \]

Next, check confinement requirements……
Column Transverse Reinforcement

Assume 4 in. hoop spacing:

\( f_{c'} < 10,000 \text{ psi and } Pu < 0.3f_{c'}A_g \)  
Equation (c) was not required.

\[
A_{sh} = 0.3 \left( sbc \frac{f'c}{fyt} \right) \left[ \left( \frac{A_g}{A_{ch}} \right) - 1 \right] = 0.3 \left( 4 \times 27 \right) \left( \frac{5}{60} \right) \left( \frac{900}{729} - 1 \right) = 0.63 \text{ in}^2
\]

and

\[
A_{sh} = 0.09 sbc \frac{f'c}{fyt} = 0.09 \times 4 \times 27 \left( \frac{5}{60} \right) = 0.81 \text{ in}^2
\]

Therefore, use #4 bar hoops with 4 legs  
\( A_{sh} = 0.80 \text{ in}^2 \)
Determine Column Shear

Based on probable moment strength of columns and can be limited by probable moment strength of beams.

\[ M_{pr,1}, M_{pr,2}, M_{pr,3}, M_{pr,4} \]

\[ V_{seismic} \]

\[ M_{pr,top}, M_{pr,bottom} \]
Column Shear Design

Based on column moments:

\[ M_{pr,\text{col}} = 14,940 \text{ k-in} \quad (12 \#8 \text{ vert and } P_{max}) \]

\[ V_e = \frac{2(14,940)}{(124)} = 241 \text{ kips} \]

For \( P_{\text{min}} > \frac{f'_c A_g}{20} = \frac{5(30)(3)}{20} = 225 \text{ kips,} \)

\( V_c \) can be included in shear calculation
Column Shear Design

Assume 6 in. max hoop spacing at mid-height of column

\[ V_c = 2\sqrt{f'_c bd} = 2\sqrt{5,000(30)(27.5)} = 117 \text{ kips} \]

\[ V_s = \frac{A_v f_y d}{s} = \frac{0.8(60)(27.5)}{6} = 220 \text{ kips} \]

\[ \phi V_n = \phi (V_c + V_s) = 0.75(117 + 220) = 252 \text{ kips} > 241 \text{ kips OK} \]

Hoops: 4 legs #4

s = 6 in. max
**Column Reinforcement**

- **Confinement length, \( l_o \), greater of:**
  - \( h = 30 \) in.
  - \( H_c/6 = (156-32)/6 = 20.7 \) in.
  - 18 in.

  Therefore, use 30 in.
Structural Wall Example

- Same building as moment frame example
- 12-story concrete building
- N-S direction: SMF
- E-W direction: dual system
- Seismic Design Category D
- Modal Analysis Procedure

Shear wall @ grid 3-6

Typical Floor Plan
Shear wall cross section

\[ A_g = (16)(210)+2(30)(30) = 5,160 \text{ sq in} \]

\[ A_{cv} = 16[(210)+2(30)] = 4,320 \text{ sq in} \]
Shear Panel Reinforcement

\[ \phi V_n = \phi A_{cv} \left( \alpha \sqrt{f'_c} + \rho_t f_y \right) \]

- \( V_u = 769 \) kips (below level 2)
- \( f'_c = 5,000 \text{ psi}, f_y = 60 \text{ ksi} \)
- \( \alpha = 2.0 \)
- \( \phi = 0.6 \) (per ACI 9.3.4(a))

Req’d \( \rho_t = 0.0019 \)
Min \( \rho_l \) (and \( \rho_t \)) = 0.0025

Use #5 @ 12” o.c. each face:
- \( \rho_t = 0.0032 \) and \( \phi V_n = 869 \) kips
Axial-Flexural Design

At ground floor: shear and moment determined from the lateral analysis and axial load from gravity load run down.

All are factored forces.

- \( M_u = 30,641 \text{ kip-ft} \)
- \( P_{u,\text{max}} = 6,044 \text{ kips} \)
- \( P_{u,\text{min}} = 2,460 \text{ kips} \)
Axial and Flexural Design

P-M interaction

Wall reinforcement:  #5 @12” o.c.
Boundary reinforcement:  12 #9 each end
Boundary Element Check

Use stress-based procedure (ACI 18.10.6.3).

Boundary Elements required if max stress > 0.2$f'_{c}$

Ground level axial load and moment are determined based on factored forces.

\[
\frac{P_u}{A_g} + \frac{M_u}{S} = \frac{6,044}{5,160} + \frac{30,641(12)}{284,444} = 2.46\text{ksi} = 0.49f'_{c}
\]

\[\therefore \text{Need confined boundary element}\]

(extend up to below 9th floor where max stress < 0.15$f'_{c}$)
Boundary Element Length

Length = larger of $c/2$ or $c - 0.1L_w$

From P-M interaction, max $c = 72.6$ in.
So, $c/2 = 38.8$ and $c - 0.1L_w = 50.6$ in

Since length > column dimension, either
• Extend boundary into wall panel
• Increase $f'_c = reduce boundary element length$

For this example, assume $f'_c = 7,000$ psi,
Then req’d boundary element length is 28.7 in.
Boundary Element Confinement

Transverse reinforcement in boundary elements is to be designed essentially like column transverse reinforcement.

Assume #5 ties and 4 in. spacing

\[
A_{sh} = 0.09 \, sb_c \, \frac{f'_c}{f_y} = 0.09 \, (4)(27)\left(\frac{7}{60}\right) = 1.13 \text{ in}^2
\]

#5 with 4 legs, \( A_{sh} = 1.24 \text{ in}^2 \)

Width of the flexural compression zone, \( b > 12 \text{in. or } h_u/16 \)
Questions
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