Precast Concrete Diaphragm Design – New Provisions

October 8, 2019
ASCE 7-16 Seismic Design Methodology

• A new alternative design method is included in ASCE 7-16
• The method is optional for reinforced concrete, timber construction, and precast concrete in SDC B.
• The method is mandatory for precast concrete in SDC C, D, E an F.
• The method does not apply the steel deck
Current Precast Diaphragm Seismic Design

- ACI 318 11 and before
  - 21.11 Structural diaphragms and trusses
    - Structures assigned to SDC D, E & F
    - 21.11.4 Cast-in-place composite topping slab diaphragms
    - 21.11.5 Cast-in-place topping slab diaphragms (non-composite)
History of Precast Diaphragm Seismic Design

• ACI 318 14
  – Chapter 12 Diaphragms
    • (a) Diaphragms that are cast-in-place slabs
    • (b) Diaphragms that comprise a cast-in-place topping slab on precast elements
    • (c) Diaphragms that comprise precast elements with end strips formed by either a cast-in-place concrete topping slab or edge beams
    • (d) Diaphragms of interconnected precast elements without cast-in-place concrete topping

• No Seismic Provisions
Current Precast Diaphragm Seismic Design

- ACI 318 14
  - Section 18.12 Diaphragms and trusses
  - 18.12.4 Cast-in-place composite topping
  - 18.12.5 Cast-in-place non-composite topping slab diaphragms
Brief History

• 1994 Northridge Earthquake
  – Northridge Fashion Center
Brief History

- 1994 Northridge Earthquake
  - CSU Northridge
Brief History

- 1994 Northridge Earthquake
  - Kaiser Permanente Garage (CIP-PT)
Brief History

• ACI 318-99
  – 21.7.1 Structural diaphragms and trusses changed
  – 21.7.5.1 “Where welded wire fabric is used as the distributed reinforcement in topping slabs placed of precast floor and roof elements, the wires parallel to the span of the precast elements shall be spaced not less than 10 in. on center.”
Brief History

- PCI Diaphragm Seismic Design Methodology DSDM
  - 2003 to 2012
  - Lehigh University: connection qualification
  - UCSD: shake table testing
  - University of Arizona: analysis and lead
Shake Table Test
Seismic Design Methodology for Precast Concrete Floor Diaphragms

2012 PCI National Convention

Dr. Robert B. Fleischman
University of Arizona
Brief History

- Building Seismic Safety Council (BSSC) Issue Team 6 on diaphragms formed in 2011
- Included all diaphragm materials
- Intent to write a Part 3 resource paper on diaphragm design
- Changed to include a Part 1 code change proposal
Brief History

• 2014 BSSC IT 6 completes report with code change proposal
• 2014 DSDM Report updated
• Code change submitted to ASCE 7
Brief History

- Code change adopted into ASCE 7 as voluntary option for cast-in-place concrete, non-composite topping on precast, and wood.
- Alternative is mandatory for precast concrete diaphragms in SDC C, D, E, and F
- ASCE 7 adopted by reference into IBC 2018
ASCE 7-16

- Chapter 12
  - 12.10.3 alternative Design Provisions for Diaphragms Including Chords and Collectors: Adopted into IBC 2018

- Chapter 14
  - 14.2.4 Additional Design and Detailing Requirements for Precast concrete Diaphragms: Not Adopted into Sec. 1905
• 18.12.1.2 for precast diaphragms
• 18.12.11 Precast concrete diaphragms
  – ACI 550.5-18: Code Requirements for the Design of Precast Concrete Diaphragms for Earthquake Motions
  – ACI 550.4-18: Qualification of Precast Prestressed Concrete Diaphragm Connector and Reinforcement at Joints for Earthquake Loading
Global (ASCE 7) Issues
12.10.1.1 Diaphragm Design Forces. Floor and roof diaphragms shall be designed to resist design seismic forces from the structural analysis, but not less than the following forces:

\[
0.2S_{DS}I_w p_x \leq F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_{px}} \leq 0.4S_{DS}I_w p_x
\]

Where

- \( F_{px} \) = the diaphragm design force
- \( F_i \) = the design force applied to Level \( i \)
- \( w_i \) = the weight tributary to Level \( i \)
- \( w_{px} \) = the weight tributary to the diaphragm at Level \( x \)
Diaphragm Design Forces

The diagram illustrates the relationship between floor level and force in kips. Two lines are shown:
- Fpx (blue line)
- Fx (red line)

The x-axis represents force in kips, ranging from 0 to 200. The y-axis represents floor level, ranging from 0 to 7. The graph shows how the forces change with increasing floor level.
The upper and lower limits in ASCE7 do not seem to be rational.
The computation of floor accelerations based on the assumption that all modes are equally reduced by plasticity does not seem rational either.
Diaphragm Design

ASCE 7-16

\[ h_x / h_n \]

For \( N \leq 2 \):
- \( h_x / h_n = 1 \)
- \( C_{p0} \) to \( C_{pn} \)

For \( N \geq 3 \):
- \( h_x / h_n > 0.8 \)
- \( C_{p0} \) to \( C_{pi} \) to \( C_{pn} \)

- \( h_x / h_n \leq 0.8 \)
- \( C_{p0} \) to \( C_{px} \)
Diaphragm Design

\[ C_{p0} = 0.4 \, S_{DS} I_e \]

\[ C_{pn} = \sqrt{ \left( \Gamma_m \Omega_0 C_S \right)^2 + \left( \Gamma_m C_{S2} \right)^2 } \geq C_{pi} \]

Note: The lower-bound limit on \( C_{pn} \) is in ASCE 7-16 only, not in the 2015 NEHRP Provisions.
Diaphragm Design

\[
\begin{align*}
\Gamma_{m1} &= 1 + 0.5z_s (1 - 1/N) \\
\Gamma_{m2} &= 0.9z_s (1 - 1/N)^2
\end{align*}
\]

where \( z_s \) = modal contribution coefficient modifier dependent on seismic force-resisting system.
Diaphragm Design

\[ \Gamma_{m1} = \text{Eq. 3.1} \]

\[ z_s = 1 \]

\[ z_s = 0.7 \]

Number of levels, \( n \)

Graph showing the relationship between the number of levels and \( \Gamma_{m1} \) for different building types.
Diaphragm Design

\[ \Gamma_{m2} = \begin{cases} 1 & \text{Eq. 3.1 } z_s = 1 \\ 0.7 & \text{Eq. 3.1 } z_s = 0.7 \end{cases} \]

- **Wall buildings**
- **Frame buildings**

Number of levels, \( n \)
$C_{pi}$ is the greater of values given by:

\[ C_{pi} = C_{p0} \]

\[ C_{pi} = 0.9 \Gamma_{m1} \Omega_{0} C_{S} \]
Diaphragm Design

\[ C_S = \frac{V}{W} \text{ or } \frac{V_t}{W} \]

\[ C_{S2} = \text{minimum of:} \]

\[ (0.15N + 0.25) \ I_e \ S_{DS} \]

\[ I_e \ S_{DS} \]

\[ I_e \ S_{D1}/[0.03(N-1)] \text{ for } N \geq 2 \text{ or } 0 \text{ for } N = 1 \]
Why are we not seeing inadequate performance of diaphragms in seismic events?
Inertial Forces in Diaphragms

Existing diaphragms may carry seismic inertial forces through:

(a) inherent overstrength in the floor system, including the floor plate and framing elements, that permit the transfer of higher than code design forces,
Inertial Forces in Diaphragms

or

(b) inherent ductility or plastic redistribution qualities within the diaphragm (or at the boundaries of the diaphragm) that limit the amount of inertial forces that can develop, without significant damage or failure.
Step-by-Step Determination of Alternative Diaphragm Seismic Design Force
Alternative– Step 1

Determine \( w_{px} \). (Same as Traditional – Step 1)

- ASCE 7-16 Section 12.7.2 defines effective seismic weight, \( W \).
- \( w_x \) is the portion of \( W \) that is tributary to level \( x \).
- \( w_{px} \) is different from \( w_x \) only in that the weights of the walls parallel to the earthquake forces may be excluded from \( w_{px} \).
Determine $R_s$, Diaphragm Design Force Reduction Factor (ASCE 7-16 Table 12.10.3.5-1)

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear Control</th>
<th>Flexure Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDO</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>BDO</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>RDO</td>
<td>1.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Alternative— Step 3

Determine $C_{px}$, Diaphragm Design Acceleration (Force) Coefficient at Level $x$ (ASCE 7-16 Section 12.10.3.2)

• In order to determine $C_{px}$, $C_{p0}$, $C_{pi}$, and $C_{pn}$ need to first be determined.
Alternative – Step 3

Use Figure 12.10.3-1 to determine $C_{px}$
(ASCE 7-16 Section 12.10.3.2)
Determine $F_{px}$, Diaphragm Design Force at Level $x$ (Section 12.10.3.2)

$$F_{px} = C_{px} w_{px}/R_s \geq 0.2 S_{DS} I_e w_{px}$$
Diaphragm Design Force Level Comparisons
4-Story Perimeter Wall Precast Concrete Parking Structure (SDC C, Knoxville)
4-Story Perimeter Wall Precast Concrete Parking Structure (SDC C, Knoxville)
4-Story Interior Wall Precast Concrete Parking Structure (SDC D, Seattle)
4-Story Interior Wall Precast Concrete Parking Structure (SDC D, Seattle)
8-Story Precast Concrete Moment Frame Office Building

(a) SDC C

(b) SDC D

(c) SDC C

(d) SDC D
8-Story Precast Concrete Moment Frame Office Building

8-Story Moment Frame Office Building
Knoxville (SDC C)

8-Story Moment Frame Office Building
Seattle (SDC D)
ACI 550.5-18

Connection Considerations
Diaphragm 1 Plan View

F_{px} = w_{px} \ell

Shear Wall

VL = F_{px}/2
VR = F_{px}/2

M = F_{px}\ell/8

Beam Analogy

- Shear walls Supports
- Floor acts as beam

Earthquake Direction

DIAPHRAGM 1
Shear Forces
Resisted by WEB Connectors

Diaphragm Plan View

Joint Shear Forces

Web Connection

Field Topped

Pre-Topped

Panel-To-Panel Web Connection
Flexure Forces

Resisted by CHORD Connectors
Flexure Forces

Resisted by CHORD Connectors

“Wet Chord” Pour Strip Detail Concrete Placed On site
Response Under Earthquake Motion

(Fleischman – U. Arizona)
Connection Performance

- **Chord Connection**
  - Designed for Tension
  - Shear Neglected

- **Web Connection**
  - Designed for Shear
  - Tension Neglected
Earthquake Category

- **Maximum Considered Earthquake (MCE)**
  - Most severe earthquake ground motion considered at the site.
  - Eq. expected to occur once in 2500 years
  - 2% Probability of being exceeded in 50 years

- **Design Basis Earthquake (DBE)**
  - 2/3 that of the MCE
  - Eq. expected to occur once in 474 years
  - 10% Probability of being exceeded in 50 years
Diaphragm Seismic Design Concept

Design Method

1. Modify $F_{px}$ to develop defined yielding under:
   - Design Basis Earthquake
   - Max Considered Earthquake

2. Prevent Shear Failure

Shear Wall

F_{px}

Diaphragm 1 Plan View

Shear on Diaphragm

Moment on Diaphragm

Design Basis

Max Considered Earthquake
Diaphragm Seismic Design Concept

Diaphragm Design Force

- $C_{px}w_{px}$
- $0.7$
- $C_{px}w_{px}$
- $1.0$
- $C_{px}w_{px}$
- $1.4$

- Elastic Design Option (EDO)
- Shear Failure
- MCE - Max EQ.
- DBE - Design EQ.
- Yielding

- Basic Design Option (BDO)
- Reduced Design Option (RDO)

- LDE Limit
- MDE Limit
- HDE Limit
- Diaphragm Joint Deformation
Diaphragm Design Options

**Elastic Design Option (EDO)**
- Diaphragm remain elastic in DBE and MCE
- Highest diaphragm design force
- Connections can include LDE, MDE and HDE
- No shear overstrength needed since elastic design

**Basic Design Option (BDO)**
- Diaphragm remain elastic in DBE but *Not Necessarily in MCE*
- Lower diaphragm design force than EDO
- Connections can include MDE and HDE
- Shear overstrength factor is needed

**Reduced Design Option (RDO)**
- Some Diaphragm yielding in DBE, significant in MCE
- Lowest diaphragm design force
- Connections must be High Deformation Elements (HDE)
- Shear overstrength factor is needed
Diaphragm Seismic Design Level (DSDL)

Determine Diaphragm Seismic Design Level (DSDL)

- **Diaphragm Seismic Design Level: LOW**
  - B or C
  - Seismic Design Category
  - DSDL: LOW & AR>2.5
    - YES
    - Diaphragm Seismic Design Level: MODERATE
  - NO

- **Diaphragm Seismic Design Level: MODERATE**
  - IF DSDL Moderate
    - YES
    - Diaphragm Seismic Design Level: HIGH
  - NO

- **Diaphragm Seismic Design Level: HIGH**
  - IF DSDL HIGH & AR<1.5
    - YES
    - DSDL: High
  - NO

![Graph showing the Diaphragm Seismic Design Level (DSDL) determination process.](image)
Seismic Design Option

Determine Diaphragm Design Option

Diaphragm Seismic Design Level: LOW

Diaphragm Seismic Design Level: MODERATE

Diaphragm Seismic Design Level: HIGH

Design Option | Diaphragm Seismic Demand level
--- | ---
Elastic | Recommended / With Penalty* / Not Allowed
Basic | Alternative / Recommended / With Penalty*
Reduced | Alternative / Alternative / Recommended

Penalty* = Diaphragm design force shall be increased by 15%.

Choose Design Option: Elastic / Basic / Reduced
### Connection Element

#### Recommended Factors

<table>
<thead>
<tr>
<th>Diaphragm Seismic Design Level (DSDL)</th>
<th>Diaphragm Force Reduction Factor, $R_s$</th>
<th>Diaphragm Reinforcement Classification</th>
<th>Reliable And Stable Maximum Joint Opening Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic (EDO)</td>
<td>0.7</td>
<td>Low Deformability Element</td>
<td>&lt; 0.3 in.</td>
</tr>
<tr>
<td>Basic (BDO)</td>
<td>1.0</td>
<td>Moderate Deformability Element</td>
<td>0.3 to 0.6 in.</td>
</tr>
<tr>
<td>Reduced (RDO)</td>
<td>1.4</td>
<td>High Deformability Element</td>
<td>&gt; 0.6 in.</td>
</tr>
</tbody>
</table>
Determine Shear Force

- The required shear strength for diaphragm shall be amplified by the diaphragm shear overstrength factor, $\Omega_v$

$$\Omega_v = 1.4 \cdot R_s$$

<table>
<thead>
<tr>
<th>Diaphragm Seismic Design Level (DSDL)</th>
<th>Diaphragm Force Reduction Factor, $R_s$ $(1/R_s)$</th>
<th>Diaphragm Reinforcement Classification</th>
<th>Shear Overstrength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic (EDO)</td>
<td>0.7 (1.4)</td>
<td>Low Deformability Element</td>
<td>1.0</td>
</tr>
<tr>
<td>Basic (BDO)</td>
<td>1.0 (1.0)</td>
<td>Moderate Deformability Element</td>
<td>1.4</td>
</tr>
<tr>
<td>Reduced (RDO)</td>
<td>1.4 (0.7)</td>
<td>High Deformability Element</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Connection Qualification Protocol
ACI 550.4 -18
ACI 550.4: Definitions

- **CONNECTION:**

- **CONNECTOR:**
7.4 Classification of deformability

- 7.4.2 Low-Deformability Element (LDE) shall be connections with tension deformation less than 0.3 in.

- 7.4.3 Moderate-Deformability Element (MDE) shall be connections with tension deformation capacity greater than or equal to 0.3 in. but less than 0.6 in.

- 7.4.4 High Deformability Element (HDE) shall be connections with tension deformation capacity greater than or equal to 0.6 in.
Connectors

- What connections are qualified in each category?
- Qualification testing is needed...
Qualification Procedure

- **Goal:** Determine the tension deformation capacity of the connector
  
- Chapter 4 – Test modules and test set-up
- Chapter 5 – Test methods
- Chapter 6 – Test report
- Chapter 7 – Interpretation of test results
  - Backbone curve
  - Classification of deformability
Subassembly Requirements 4.2

Figure C14.2.4-3 Possible test set-up.
Subassembly Requirements 4.2

- Panels installed in testing fixture

- Goal Measure Forces on Panel
- Displacements at connector.
- Tension/Compression
- Shear
5.3 Loading Protocols - Monotonic

- Monotonic Test – Determine the reference deformation for the connection.

Determine an effective yield for the connection.
5.2 Loading Protocols - Monotonic

Reference Deformation, $\Delta$

Monotonic response

$T_{\text{max}}$ or $V_{\text{max}}$

$0.75(T_{\text{max}}$ or $V_{\text{max}})$
5.2 Loading Protocols – Cyclic Shear

- Monotonically increasing displacement
- Increase in increments of 20Δ
- System Verification
- Applied shear displacement
- Tension displacement compensation to provide constant panel spacing
- 3 at 2Δ
- 3 at 3Δ
- 3 at 4Δ
- 3 at 6Δ
- 3at.25Δ
- 3at.75Δ
- 3 at Δ
- 3at0.5Δ
- 3at1.5Δ
- 0 10 20 30 Cycle #
5.3 Loading Protocols – Cyclic Tension

- **System Verification**: 3 at 0.5\(\Delta\)
- **3 at 2.5\(\Delta\)**
- **3 at 7.5\(\Delta\)**
- **3 at \(\Delta\)**
- **3 at 1.5\(\Delta\)**
- **3 at 2\(\Delta\)**
- **3 at 3\(\Delta\)**
- **3 at 4\(\Delta\)**
- **3 at 6\(\Delta\)**
- **Increase in increments of 2.0\(\Delta\)**

**Deform in compression until force equals preceding cycle tension force**

**Tension only**

**Tension displacement**

**Compression Force**

**Cycle #**
Ductile Joint Ladder Connection

- 50 mm Lap Joint
- 1018 Steel no cold rolling
- Tension Capacity ~ 133kN
- High Deformation Connection ~ 50 mm.
Sample Results
Determine Envelope of Cyclic Results

Section 7.2
Force corresponding to the peak displacement applied during the first cycle of each increment of deformation.
Backbone Development from Envelope

![Graph showing force vs. Delta with points P1, P2, P2a, and 15%P2 marked at different Delta values.]

- Force
- P2
- P1
- P2a
- 15%P2
- Δ1
- Δ2
- Δ2a
- Δ3
Backbone Development from Envelope

![Diagram showing backbone development from experimental envelope. The graph plots force against displacement, with points marked at various stages: P₁, P₂, P₂a, and Kₑ. The backbone envelope is represented by a solid line, while the experimental envelope is dashed.](image-url)
Deformation Classification

LDE – Low Deformability Element
MDE – Moderate Deformability Element
HDE – High Deformability Element
High Deformability Elements

- 14.2.4.3.5 Deformed Bar Reinforcement. Deformed bar reinforcement (ASTM A615 or ASTM A706) placed in cast-in-place concrete topping or cast-in-place concrete pour strips and satisfying the cover, lap, and development requirements of ACI 318 shall be deemed to qualify as High Deformability Elements (HDE).
High Deformability Elements

• 14.2.4.3.6 Special Inspection. For precast concrete joint reinforcement or connector classified as a High Deformability Element (HDE), installation of the embedded parts and completion of the reinforcement or connection in the field shall be subject to continuous special inspection performed by qualified inspectors under the supervision of a licensed design professional.

HDE Requires Special Inspection
Precast Concrete Diaphragm Design

- Deficiencies revealed
- Research conducted
- Code changed
- Connections qualified
- Design procedures updated