Seismic Design of Diaphragms

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2009 NEHRP Provisions

NEHRP Recommended Seismic Provisions
for New Buildings and Other Structures
FEMA P-750 / 2009 Edition

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BSSC PUC IT-6 Scope

Reexamine and refine seismic design provisions for cast-in-place concrete, precast concrete (with or without topping), metal, and wood diaphragms, focusing on objectives with regards to performance in the design earthquake.
Multi-Part Resource Paper

- Global (ASCE 7) Issues
- Cast-in-Place Concrete Diaphragms
- Precast Concrete Diaphragms (topped and untopped)
- Steel Deck Diaphragms (topped and untopped)
- Wood Diaphragms

Global (ASCE 7) Issues
Diaphragms, Chords, and Collectors

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:

\[
0.2S_{DS}w_{px} \leq F_{px} \leq 0.4S_{DS}w_{px}
\]

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 \( x \)

\[
\sum_{i=x}^{n} F_i = \sum_{j=x}^{n} w_j
\]
Diaphragm Design Forces

Diaphragm Design Force

Recommendations in PCI’s *Seismic Design Manual*, based on results of research:

For structures assigned to SDC B or C, if every floor diaphragm is designed for the force at the uppermost level derived from the IBC, additional load factors are not required for elastic diaphragm response under the design earthquake.
Diaphragm Design Force

Recommendations in PCI’s *Seismic Design Manual*, based on results of research:

For structures assigned to SDC D, E, or F, if lateral forces are resisted entirely by special moment frames, additional load factors are not required if every floor diaphragm is designed for the force at the uppermost level derived from ASCE 7.

Diaphragm Design Force

Recommendations in PCI’s *Seismic Design Manual*, based on results of research:

For structures assigned to SDC D, E, or F, if shear walls are part of the lateral force-resisting system, it is sufficient to apply a diaphragm load factor of 2 to the force at the uppermost level derived from ASCE 7 and to design each floor for that force.
### Diaphragm IT Contributors

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</tbody>
</table>

### Diaphragm IT Products

  - Approved for inclusion in ASCE 7-16
- Design Force Level Proposal for Part 3 of the 2015 NEHRP *Provisions* – modifies ASCE 7-10 Section 12.10
- Precast Diaphragm Design Proposal for Part 1 of the 2015 NEHRP *Provisions* – modifies ASCE 7-10 Section 14.2
  - Approved for inclusion in ASCE 7-16
- Resource Paper for Part 3 of the 2015 NEHRP *Provisions*
Each mode’s contribution is reduced by $R$

$$F_j = \sum_{i=1}^{n} \left( \frac{f_i w_j}{g R} \right)^{S(T)}$$

For periods less than $T_o$, the design spectral response acceleration, $S$, shall be taken as given by Eq. 11.4-5:

$$S = S_{0.1} \left( 0.4 + 0.6 \frac{T}{T_o} \right)$$  (11.4-5)
Diaphragm Design

In 2001 Rodriguez et al. noted that inelastic response in multi-story buildings tended to cause an important reduction in floor accelerations contributed by the first mode of response but had a much lesser effect on those contributed by the higher modes of response.

They proposed the First Mode Reduced method, in which the roof acceleration could be determined by a square root sum of the squares combination in which the first mode contribution was reduced for inelasticity and the higher modes were left unreduced.
Diaphragm Design

\[ F_{px} = \frac{C_{px} w_{px}}{R_s} \geq 0.2 S_{DS} I_e w_{px} \]

\( C_{px} \) comes from \( C_{p0}, C_{pi}, \) and \( C_{pn} \)

Note: \( C_{pi} \) is not used in the 2015 NEHRP Provisions
Diaphragm Design

ASCE 7-16

\[
\frac{h_s}{h_n} = \frac{1}{\Gamma_m \Omega_0 C_S} + \frac{1}{\Gamma_m C_S^2} \geq C_{pi}
\]

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

\[ \Gamma_{m1} = 1 + 0.5z_S (1 - 1/n) \]
\[ \Gamma_{m2} = 0.9z_S (1 - 1/n)^2 \]
where \( z_S \) = modal contribution coefficient modifier dependent on seismic force-resisting system.

Diaphragm Design

Values of mode shape factor \( z_S \)

- 0.3 for buildings designed with Buckling Restrained Braced Frame systems
- 0.7 for buildings designed with Moment-Resisting Frame systems
- 0.85 for buildings designed with Dual Systems with Special or Intermediate Moment Frames capable of resisting at least 25% of the prescribed seismic forces
- 1.0 for buildings designed with all other seismic force-resisting systems
Diaphragm Design

Eq. 3.1 $z_s = 1$
Eq. 3.1 $z_s = 0.7$

Wall buildings
Frame buildings

Number of levels, $n$

Diaphragm Design

Eq. 3.1 $z_s = 1$
Eq. 3.1 $z_s = 0.7$

Wall buildings
Frame buildings

Number of levels, $n$
Diaphragm Design

$C_{pi}$ is the greater of values given by:

$C_{pi} = C_{p0}$

$C_{pi} = 0.9 \Gamma m_1 \Omega_0 C_S$

Diaphragm Design

$C_S = V/W$ or $V_l/W$

$C_{S2} = \text{minimum of:}$

$(0.15n + 0.25) I_e S_{DS}$

$I_e S_{DS}$

$I_e S_{D1}/[0.03(n-1)]$ for $n \geq 2$ or $0$ for $n = 1$
Consistent Look into the Design Spectra $C_sR$

For the “Second mode”, $R = 1$

$C_s(T_2) = \min(0.15n+0.25, 1)I_eS_{DS}$

$\leq I_eS_{DS}/[0.03(n-1)]$

$n$: number of levels above ground, $n \geq 2$

Comparison of Results
(RR for ASCE7 and Measured)
7-story bearing wall building
Comparison of Results
(RR for ASCE7 and Measured)
5-story special MRF building

Comparison of Results
(RR for ASCE7 and Measured)
3-story PCI building
Comparison of Results
(RR for ASCE7 and Measured)
NEES Wood Capstone Building
(data Processed by R Hanson)

Comparison of Results
(RR for ASCE7 and Computed)
Steel BRB and special MRF buildings

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Comparison using Updated DSDM Equations

Diaphragm Capacity

Why are we not seeing inadequate performance of diaphragms in seismic events?

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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,

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.
Diaphragm Design

**Flexure-controlled diaphragm:** Diaphragm with a well-defined flexural yielding mechanism, which limits the force that develops in the diaphragm.

The factored shear resistance shall be greater than the shear corresponding to flexural yielding.

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Diaphragm Design

**Shear-controlled diaphragm:** Diaphragm that does not meet the requirements of a flexure-controlled diaphragm.
## Diaphragm Design (NEHRP Provisions)

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear Control</th>
<th>Flexure Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP Concrete</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Precast concrete</td>
<td>EDO</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>BDO</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>RDO</td>
<td>1.0</td>
</tr>
<tr>
<td>Untopped Steel Deck</td>
<td>Ductile</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Low ductility</td>
<td>2.0</td>
</tr>
<tr>
<td>Topped Steel Deck</td>
<td>Reinforced topped Steel Deck with shear stud connection to framing</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Other topped Steel Deck with structural concrete fill</td>
<td>1.5</td>
</tr>
<tr>
<td>Wood</td>
<td>Typical</td>
<td>3.0</td>
</tr>
</tbody>
</table>

When $R_s$ is greater than 1, such a diaphragm should have a well-defined, ductile shear yielding mechanism which limits the force that develops in the diaphragm.

\[
F_{px} = \frac{C_{px}}{R_s} W_{px}
\]

## Diaphragm Design (ASCE 7-16)

<table>
<thead>
<tr>
<th>Diaphragm System</th>
<th>Shear-Controlled</th>
<th>Flexure-Controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-in-place concrete designed in accordance with Section 14.2 and ACI 318</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Precast concrete designed in accordance with Section 14.2.4 and ACI 318</td>
<td>EDO</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>BDO</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>RDO</td>
<td>1.4</td>
</tr>
<tr>
<td>Wood sheathed designed in accordance with Section 14.5 and AF&amp;PA (now AWC)</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Special Design Provisions for Wind and Seismic</td>
<td></td>
<td>NA</td>
</tr>
</tbody>
</table>

1. EDO is precast concrete diaphragm Elastic Design Option.
2. BDO is precast concrete diaphragm Basic Design Option.
3. RDO is precast concrete diaphragm Reduced Design Option.
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
8-Story Precast Concrete Moment Frame Office Building

- 49 -

8-Story Precast Concrete Shear Wall Office Building

- 50 -

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8-Story Precast Concrete Shear Wall Office Building

Steel-Framed Assembly Structure in Southern California
Steel-Framed Office Structure in Seattle, WA

Cast-in-Place Concrete Framed Parking Structure in Southern California
Cast-in-Place Concrete Framed Residential Structure in Northern California

Cast-in-Place Concrete Framed Residential Structure in Seattle, WA
Cast-in-Place Concrete Framed Residential Structure in Hawaii

Steel Framed Office Structure in Southern California

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Thank You!!