ICC-ES Evaluation Report

ESR-3010

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DIVISION: 03 00 00—CONCRETE
Section: 03 41 10—Precast Concrete Design

REPORT HOLDER:

PRECAST/PRESTRESSED CONCRETE INSTITUTE (PCI)

EVALUATION SUBJECT:

PRECAST CONCRETE DIAPHRAGMS

1.0 EVALUATION SCOPE

Compliance with the following codes:

- 2015 and 2012 *International Building Code®* (IBC)

Property evaluated:

Structural

2.0 USES

Precast concrete used as horizontal diaphragms in buildings assigned to Seismic Design Category (SDC) C, D, E or F, and optional in SDC B.

3.0 DESCRIPTION

3.1 General:

The general purpose of this evaluation report is to provide an alternative seismic design procedure for precast diaphragms under the IBC.

Precast concrete diaphragms designed under the 2015 IBC must comply with the requirements of ACI 318-14 including Chapter 12. If the precast concrete diaphragm design is under the 2012 IBC, the diaphragm must comply with the requirements of ACI 318-11.

If the precast concrete diaphragm is in a building assigned to SDC D, E, or F, it must also comply with the requirements of ACI 318-14 Section 18.12, or ACI 318-11 Section 21.11.

The design must include basic information on the diaphragm components including precast units, topping, chords, shear reinforcement, connectors and generic deformed bar joint reinforcement, as applicable.

3.2 Materials:

Precast concrete must comply with ACI 318. Deformed bar reinforcement must comply with ASTM A615 or ASTM A706.

4.0 DESIGN AND INSTALLATION

Where equations are not given to determine variables, those variables must be determined in accordance with ASCE 7.

Definitions (for other definitions, see ASCE 7):

Diaphragm: Roof, floor, or other membrane or bracing system acting to transfer the lateral forces to the vertical resisting elements.

Diaphragm Chord: A diaphragm boundary element perpendicular to the applied load that is assumed to take axial stresses due to the diaphragm moment.

Diaphragm Collector: A diaphragm element parallel to the applied load that collects and transfers diaphragm shear forces to the vertical seismic force-resisting elements or distributes forces within the diaphragm.

Diaphragm Connection: A region that joins two or more members of a diaphragm. For precast concrete diaphragm design, a diaphragm 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.

Diaphragm Connector: A proprietary product or deformed bar reinforcement embedded in the precast concrete diaphragm for anchorage to the supporting structure or to provide a load path across a precast concrete diaphragm joint.

Deformability Classification: The performance classification of precast concrete diaphragm connectors must be included in a separate ICC-ES evaluation report except for deformed bar reinforcement used as connectors (See Section 4.6.7.1).

Low-Deformability Element (LDE): Connectors used in precast concrete diaphragms with tension deformation capacity less than 0.3 in. (7.5mm) are classified as low-deformability elements.

Moderate-Deformability Element (MDE): Connectors used in precast concrete diaphragms with tension deformation capacity greater than or equal to 0.3 in. (7.5mm) but less than 0.6 in. (15 mm) are classified as moderate-deformability elements.

High-Deformability Element (HDE): Connectors used in precast concrete diaphragms with tension deformation capacity greater than or equal to 0.6 in. (15 mm) are classified as high-deformability elements.

Flexure-Controlled Diaphragm: Diaphragm with a flexural yielding mechanism, which limits the maximum forces that develop in the diaphragm, and having a design shear strength greater than the shear corresponding to the nominal flexural strength.

Performance Characteristics: Characteristics such as effective yield (reference) deformation, tension deformation capacity, tensile strength, and shear strength.

Precast Concrete Diaphragm Design Options:

Basic Design Option (BDO): An option where elastic diaphragm response in the design earthquake is targeted.

Elastic Design Option (EDO): An option where elastic diaphragm response in the maximum considered earthquake is targeted.

Reduced Design Option (RDO): An option that permits limited diaphragm yielding in the design earthquake.

Shear-Controlled Diaphragm: Diaphragm that does not meet the requirements of a flexure-controlled diaphragm.

Transfer Forces: Forces that occur in a diaphragm due to transfer of seismic forces from the vertical seismic force-resisting elements above the diaphragm to other vertical seismic force-resisting elements below the diaphragm.

Notation (for other notation, see ASCE 7)

C_{p0} = diaphragm design acceleration coefficient at the structure base.

C_{pi} = diaphragm design acceleration coefficient at 80 percent of the structural height above the base, h_n.

C_{pn} = diaphragm design acceleration coefficient at the structural height, h_n.

C_{px} = diaphragm design acceleration coefficient at Level x.

C_s = seismic response coefficient.

C_{s2} = higher mode seismic response coefficient.

F_{px} = diaphragm seismic design force at Level x.

I_e = the importance factor.

K_e = initial elastic stiffness.

R_s = diaphragm design force reduction factor from Table 2.

S_{DS} = design, 5 percent damped, spectral response acceleration parameter at short periods.

w_{px} = the weight tributary to the diaphragm at Level x.

z_s = mode shape factor from Table 1.

Γ_{m1}, Γ_{m2} = first and higher modal contribution factors.

Ω_0 = overstrength factor as defined in ASCE 7.

Ω_v = diaphragm shear overstrength factor from Section 4.6.5.

4.1 Diaphragms, Chords, and Collectors

4.1.1 Design: Diaphragms, chords, and collectors must be designed in accordance with ASCE 7 Sections 12.10.1 and 12.10.2.

Exceptions:

1. Precast concrete diaphragms including chords and collectors in structures assigned to SDC C, D, E or F must be designed in accordance with Section 4.
2. Precast concrete diaphragms in SDC B may be designed in accordance with Section 4.
3. Design for transfer forces in diaphragms must be in accordance with Section 4.3.

4.2 Alternative Design Provisions for Diaphragms Including Chords and Collectors

4.2.1 General: Diaphragm connectors, chords and collectors must be designed using the provisions in Sections 4.2 through 4.6 with the following exceptions:

1. Footnote g to ASCE 7 Table 12.2-1 is not applicable.
2. ASCE 7 Section 12.3.3.4 is not applicable.
3. Replace ASCE 7 Section 12.3.4.1 Item 5 with the following: "Design of diaphragms including chords, collectors, and their connections to the vertical elements."
4. ASCE 7 Section 12.3.4.1, Item 7 is not applicable.

4.2.2 Design: Diaphragms including chords, collectors and their connections to the vertical elements must be designed in two orthogonal directions to resist the in-plane design seismic forces determined in Section 4.2.3. Collectors must be provided that are capable of transferring the seismic forces originating in other portions of the structure to the vertical elements providing the resistance to those forces. Design must provide for transfer of forces at diaphragm discontinuities, such as openings and reentrant corners.

4.2.3 Seismic Design Forces for Diaphragms including Chords and Collectors: Diaphragms including chords, collectors and their connections to the vertical elements must be designed to resist in-plane seismic design forces given by Eq. 4-1.

$$F_{px} = \frac{C_{px}}{R_s} w_{px} \qquad \text{(Eq. 4-1)}$$

The force F_{px} determined from Eq. 4-1 must not be less than:

$$F_{px} = 0.2 S_{DS} I_e w_{px} \qquad \text{(Eq. 4-2)}$$

C_{px} must be determined as illustrated in Figure 1.

4.2.3.1 Design acceleration coefficients C_{p0} and C_{pn} must be calculated by Eqs. 4-3 and 4-4.

$$C_{p0} = 0.4 S_{DS} I_e \qquad \text{(Eq. 4-3)}$$

and

$$C_{pn} = \sqrt{\left(\Gamma_{m1}\Omega_0 C_s\right)^2 + \left(\Gamma_{m2} C_{s2}\right)^2} \geq C_{pi} \qquad \text{(Eq. 4-4)}$$

where Ω_0 is the overstrength factor given in ASCE 7 Table 12.2-1.

4.2.3.2 Design acceleration coefficient C_{pi} must be the greater of values given by Equations 4-5 and 4-6. The higher mode seismic response coefficient C_{s2} is the smallest of values calculated from Equations 4-7, 4-8 and 4-9.

$$C_{pi} = 0.8 C_{p0} \qquad \text{(Eq. 4-5)}$$

$$C_{pi} = 0.9 \Gamma_{m1} \Omega_0 C_s \qquad \text{(Eq. 4-6)}$$

$$C_{s2} = \left(0.15 N + 0.25\right) I_e S_{DS} \qquad \text{(Eq. 4-7)}$$

$$C_{s2} = I_e S_{DS} \qquad \text{(Eq. 4-8)}$$

$$C_{s2} = \frac{I_e S_{D1}}{0.03(N-1)} \quad \text{For } N \geq 2 \qquad \text{(Eq. 4-9a)}$$

$$C_{s2} = 0 \quad \text{For } N = 1 \qquad \text{(Eq. 4-9b)}$$

where N = number of stories above the base.

4.2.3.3 The modal contribution factors Γ_{m1} and Γ_{m2} in Eq. 4-4 must be calculated from Equations 4-10 and 4-11:

$$\Gamma_{m1} = 1 + \frac{z_s}{2}\left(1 - \frac{1}{N}\right) \qquad \text{(Eq. 4-10)}$$

$$\Gamma_{m2} = 0.9\, z_s \left(1 - \frac{1}{N}\right)^2 \qquad \text{(Eq. 4-11)}$$

where z_s is the mode shape factor from Table 1.

TABLE 1—MODE SHAPE FACTOR VALUES, z_s

Description	z_s value
Buildings designed with Buckling Restrained Braced Frame systems defined in ASCE 7 Table 12.2-1	0.30
Buildings designed with Moment-Resisting Frame systems defined in ASCE 7 Table 12.2-1	0.70
Buildings designed with Dual Systems defined in ASCE 7 Table 12.2-1 with Special or Intermediate Moment Frames capable of resisting at least 25 percent of the prescribed seismic forces	0.85
Buildings designed with all other seismic force-resisting systems	1.00

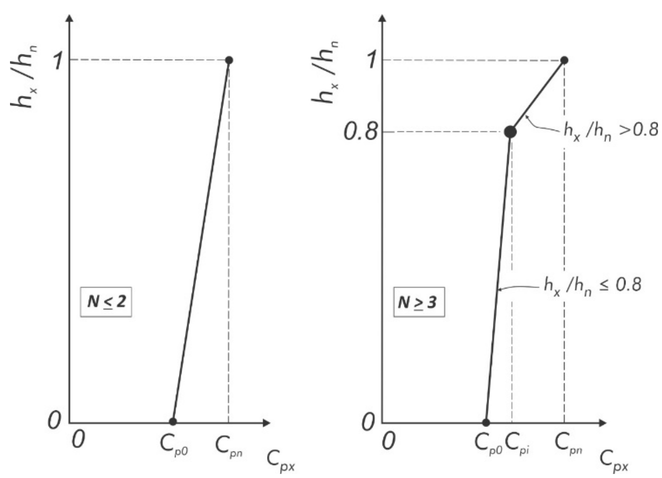

FIGURE 1—CALCULATING THE DESIGN ACCELERATION COEFFICIENT C_{PX} IN BUILDINGS WITH $N \leq 2$ AND IN BUILDINGS WITH $N \geq 3$

4.3 Transfer Forces in Diaphragms

All diaphragms must be designed for the inertial forces determined from Equations 4-1 and 4-2 and for all applicable transfer forces. For structures having a horizontal structural irregularity of Type 4 in ASCE 7 Table 12.3-1, the transfer forces from the vertical seismic force-resisting elements above the diaphragm to other vertical seismic force-resisting elements below the diaphragm must be multiplied by the overstrength factor of ASCE 7 Section 12.4.3 prior to being added to the diaphragm inertial forces. For structures having other horizontal or vertical structural irregularities of the types indicated in ASCE 7 Section 12.3.3.4, the requirements of that section apply.

4.4 Collectors - Seismic Design Categories C through F

In structures assigned to Seismic Design Category C, D, E, or F, collectors and their connections including connections to vertical elements must be designed to resist 1.5 times the diaphragm inertial forces from Section 4.2.3 in addition to 1.5 times the design transfer forces.

Exceptions:

1. Any transfer force increased by the overstrength factor of ASCE 7 Section 12.4.3 need not be further amplified by 1.5.
2. For moment frame and braced frame systems, collector forces need not exceed the lateral strength of the corresponding frame line below the collector, considering only the moment frames or braced frames. In addition, diaphragm design forces need not exceed the forces corresponding to the collector forces so determined.

4.5 Diaphragm Design Force Reduction Factor

The diaphragm design force reduction factor, R_s, must be determined in accordance with Table 2.

TABLE 2—DIAPHRAGM DESIGN FORCE REDUCTION FACTOR, R_s

Diaphragm System		Shear-Controlled	Flexure-Controlled
Precast concrete designed in accordance with Section 4 and ACI 318	EDO [1]	0.7	0.7
	BDO [2]	1.0	1.0
	RDO [3]	1.4	1.4

Notes:
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.

4.6 Additional Design and Detailing Requirements for Precast Concrete Diaphragms

4.6.1 General: In addition to the requirements set forth in Chapter 12 of ACI 318-14 and Section 21.11 of ACI 318-11 or Section 18.12 of ACI 318-14, design, detailing and construction of diaphragms constructed with precast concrete members in SDC C, D, E, and F, or in SDC B and using the requirements of Section 4.0, must conform to the requirements of this section.

4.6.2 Diaphragm Seismic Demand Levels: A diaphragm seismic demand level for each structure must be determined, based on Seismic Design Category (SDC), number of stories, N, diaphragm span, L, as defined in Section 4.6.3, and diaphragm aspect ratio, AR, as defined in Section 4.6.4. For structures assigned to SDC B or C, the seismic demand level shall be designated as *Low*. For structures assigned to SDC D, E or F, the seismic demand level must be determined in accordance with Figure 2 and the following:

4.6.2.1 If AR is greater than or equal to 2.5 and the diaphragm seismic demand is *Low* according to Figure 2, the diaphragm seismic demand level must be changed from *Low* to *Moderate*.

4.6.2.2 If AR is less than 1.5 and the diaphragm seismic demand is *High* according to Figure 2, the diaphragm seismic demand level may be changed from *High* to *Moderate*.

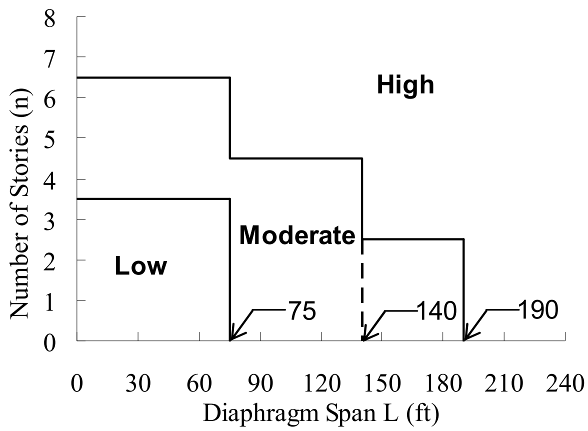

FIGURE 2—DIAPHRAGM SEISMIC DEMAND LEVEL

4.6.3 Diaphragm Span: Diaphragm span of a structure, *L*, must be the maximum diaphragm span on any floor in the structure in any direction. The diaphragm span in a particular direction on a particular floor level must be the larger of the maximum distance between two lateral force resisting system (LFRS) elements and twice the exterior distance between the outer LFRS element and the building free edge.

4.6.4 Diaphragm Aspect Ratio: The diaphragm aspect ratio, *AR*, must be the diaphragm span-to-depth ratio using the diaphragm span, *L*, defined in Section 4.6.3. The diaphragm depth must be the diaphragm dimension perpendicular to the diaphragm span between the chord lines for the diaphragm or portion of diaphragm.

4.6.5 Diaphragm Shear Amplification Factor. The required shear strength for diaphragm must be amplified by the diaphragm shear overstrength factor, Ω_v, which must be taken equal to $1.4R_s$.

4.6.6 Diaphragm Design Options: A diaphragm design option (EDO, BDO, or RDO), as defined in Section 4.0, must be assigned based on the lowest classification of precast concrete diaphragm connector deformability used.

4.6.6.1 Elastic Design Option: Any classification of precast concrete diaphragm connector deformability is permitted to be used with the Elastic Design Option, which is permitted for:

1. Low Seismic Demand Level.
2. Moderate Seismic Demand Level, provided the diaphragm design force is increased by 15 percent.

4.6.6.2 Basic Design Option: MDE or HDE must be used with the Basic Design Option, which is permitted for:

1. Low Seismic Demand Level.
2. Moderate Seismic Demand Level.
3. High Seismic Demand Level, provided the diaphragm design force is increased by 15 percent.

4.6.6.3 Reduced Design Option: HDE must be used with the Reduced Design Option, which is permitted to be used for all Seismic Demand Levels.

4.6.7 Diaphragm Connector Deformability: Precast concrete diaphragm connectors must be classified as LDE, MDE or HDE, and be recognized in an ICC-ES Evaluation Report, except for deformed bar reinforcement used as diaphragm connectors.

Deformed Bar Reinforcement used as Diaphragm Connectors: Deformed bar reinforcement complying with 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 318-14 Sections 20.6.1, 25.5.2 and 25.4 respectively for 2015 IBC, and ACI 318-11 Sections 7.7, 12.15 and 12.2 respectively for 2012 IBC, are deemed to qualify as High Deformability Elements (HDE).

4.7 Installation:

Complete installation instructions for the precast concrete diaphragm connectors must be provided. Instructions must include requirements and limitations regarding installation of the precast concrete diaphragm connector products and description of the methods of field preparation and connector installation. Welding procedures must be defined by the precast concrete diaphragm connector manufacturer.

Special Inspection: For precast concrete diaphragm connectors classified as HDE, installation of the embedded elements and completion of the connection in the field by welding is subjected to continuous special inspection performed by qualified inspectors under the supervision of a registered design professional. Special inspection must also comply with Chapter 17 of the IBC.

5.0 CONDITIONS OF USE

The alternative seismic design of precast concrete diaphragms described in this report complies with, or is a suitable alternative to what is specified in, those codes listed in Section 1.0 of this report, subject to the following conditions:

5.1 Design of precast concrete diaphragms for wind resistance must be in accordance with ASCE 7 and ACI 318.

5.2 Special inspection requirements described in Section 4.7.1 and Chapter 17 of the IBC must be complied with.

5.3 Corrosion resistance of precast concrete diaphragm connectors is outside the scope of this report. Designers are responsible for addressing the corrosion resistance of the precast concrete diaphragm connectors.

6.0 EVIDENCE SUBMITTED

Acceptance Criteria for Alternative Seismic Design of Precast Concrete Diaphragms and Qualification of Precast Concrete Diaphragm Connectors (AC468), dated June 2016.

7.0 IDENTIFICATION

7.1 The identification of proprietary precast concrete diaphragm connectors must be included in a separate ICC-ES Evaluation Report.

7.2 The report holder's contact information is the following:

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