Seismic design force level for precast concrete diaphragms

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- This paper summarizes the history of and recent updates to the U.S. codes and standards governing the seismic design of precast concrete diaphragms.
- Guidance for determining seismic design force level for topped precast concrete diaphragms is provided, as well as recommendations for details.

This paper provides guidance for determining seismic design force level for topped precast concrete diaphragms. This has been a controversial topic ever since ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*,[1] introduced a section titled "Alternative Design Provisions for Diaphragms" and mandated its use for precast concrete diaphragms in buildings assigned to seismic design category (SDC) C, D, E, or F.

Diaphragm seismic design force level

The seismic design force level for diaphragms given in section 12.10.1 of ASCE 7-16[1] has been used since before the first edition of the *International Building Code*[2] (IBC) was issued in 2000. It is applicable to diaphragms of all materials. **Table 1** shows that the origin of this section can be traced back to the 1979 edition of the *Uniform Building Code*[3] (UBC). The appendix contains details of the publication histories of standards and codes discussed in this paper.

ASCE 7-16[1] introduced section 12.10.3, "Alternative Design Provisions for Diaphragms Including Chords and Collectors." The section provides for an alternative determination of diaphragm design force level, which is mandatory for precast concrete diaphragms in buildings assigned to SDC C, D, E, or F. Section 12.10.3 can also be used for SDC B precast concrete diaphragms, cast-in-place concrete diaphragms, and wood diaphragms supported on wood light-framed con-

Table 1. Seismic design force for diaphragms in U.S. model codes

Model code	Seismic design force for diaphragms reference
1979 UBC	Section 2312(j)2D
1982 UBC	Section 2312(j)2C
1985 UBC	Section 2312(j)2C
1988 UBC	Section 2312(h)2I
1991 UBC	Section 2337(b)9
1994 UBC	Section 1631.2.9
1997 UBC	Section 1633.2.9
2000 IBC	Section 1620.3.3
2003 IBC	Section 1620.4.3
2006 IBC, 2009 IBC	ASCE 7-05 section 12.10.1
2012 IBC, 2015 IBC	ASCE 7-10 section 12.10.1
2018 IBC, 2021 IBC	ASCE 7-16 section 12.10.1; alternative: ASCE 7-16 section 12.10.3
2024 IBC	ASCE 7-22 section 12.10.1; alternative: ASCE 7-22 section 12.10.3

Note: ASCE 7 = American Society of Civil Engineers' *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*; IBC = *International Building Code*; UBC = *Uniform Building Code*.

struction, but it does not apply to steel deck diaphragms. All diaphragms other than precast concrete diaphragms in SDC C, D, E, or F buildings may continue to be designed using the design force level in ASCE 7-16 section 12.10.1, which was carried over unchanged from ASCE 7-10.[4]

ASCE 7-16[1] section 12.10.3 presents an elastic diaphragm design force as the statistical sum of first mode effect and higher mode effects. The first mode effect is reduced by the *R* factor of the seismic-force-resisting system, but then amplified by the overstrength factor Ω_o because vertical element overstrength will generate higher first-mode forces in the diaphragm. The effect caused by higher mode response is not reduced by *R* or amplified by the overstrength factor. In recognition of the deformation capacity and overstrength of the diaphragm, the total elastic diaphragm design force is reduced by a diaphragm force reduction factor R_s. A detailed explanation of ASCE 7-16 section 12.10.3 appears in the commentary to ASCE 7-16 and is not repeated here. Additional information can also be found in National Earthquake Hazards Reduction Program (NEHRP) Seismic Design Technical Brief No. 13, *Seismic Design of Precast Concrete Diaphragms: A Guide for Practicing Engineers*,[5] appendix C in the eighth edition of the *PCI Design Handbook: Precast and Prestressed Concrete*,[6] and the Federal Emergency Management Agency publication *NEHRP Recommended Seismic Provisions: Design Examples* (FEMA P-1052).[7]

Since the introduction of section 12.10.3 in ASCE 7-16, engineers, designers, and code enforcers have repeatedly asked whether the seismic design force level of that section is applicable to *all* precast concrete diaphragms. This question is logical and relevant in view of the history of seismic design provisions for precast concrete diaphragms, as outlined in the next section.

According to NEHRP Seismic Design Technical Brief No. 13,[5] a precast concrete diaphragm is a diaphragm consisting of precast concrete components with optional cast-in-place pour strips along some or all boundaries and with or without cast-in-place concrete topping slabs. Beyond NEHRP Seismic Design Technical Brief No. 13, no complete definition for a precast concrete diaphragm has been provided in any U.S. code or standard; this omission is finally addressed in ASCE 7-22,[8] as discussed later.

Seismic design provisions for precast concrete diaphragms in U.S. codes and standards

Table 2 traces the history of seismic design provisions for precast concrete diaphragms in the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318)[9] and, by extension, in different editions of the IBC[10] since the code's debut in 2000. The table shows that precast concrete diaphragms were not recognized in ACI 318 until its 1995 edition. ACI 318-95[11] was the first edition to recognize cast-in-place composite topping slab diaphragms, and ACI 318-99[12] was the first to also recognize cast-in-place noncomposite topping slab diaphragms. ACI 318 did not recognize the use of untopped precast concrete diaphragms in SDC D, E, or F buildings until ACI 318-19, as discussed later.

Table 2 should not be interpreted to suggest that precast concrete diaphragms could not be designed and constructed until local jurisdictions adopted the 2000 IBC.[2] In fact, the UBC,[13–16] which was the legacy model code of choice in the United States west of the Mississippi River and in significant jurisdictions elsewhere, recognized the use of topped precast concrete diaphragms in seismic zones 3 and 4 from its 1988 edition through its last edition in 1997 (**Table 3**). The 1997 UBC was in effect in California from July 1, 1999, through December 31, 2007. In all editions between 1988 and 1997, the UBC stated, "A cast-in-place topping on a precast floor system may serve as the diaphragm, provided the cast-in-place topping acting alone is proportioned and detailed to resist the design forces."

ACI 318 first labeled these diaphragms as cast-in place (noncomposite) topping slab diaphragms in its 1999 edition. From ACI 318-99[12] through ACI 318-19,[9] the relevant passage from section 18.12.5 in ACI 318-19 is as follows, "A cast-in-place noncomposite topping on a precast floor or roof is permitted as a structural diaphragm, provided the cast-in-place topping acting alone is designed and detailed to resist the design earthquake forces." This wording is obviously very similar to the UBC[13–16] language.

Table 2. History of seismic design provisions for precast concrete diaphragms in ACI 318

ACI 318 edition (model code)	Seismic design provisions for precast concrete diaphragms
ACI 318-71	"Appendix A: Special Provisions for Seismic Design" is added to ACI 318. It does not mention diaphragms.
ACI 318-77	No mention of diaphragms in appendix A.
ACI 318-83	Section A.5 is titled "Structural Walls, Diaphragms, and Trusses." Thus, diaphragms are lumped together with shear walls. Both are cast-in-place concrete.
ACI 318-89	Appendix A becomes chapter 21, "Special Provisions for Seismic Design." Section A.5 becomes section 21.5, "Structural Walls, Diaphragms, and Trusses." Diaphragms are still lumped together with shear walls. Both are cast-in-place concrete.
ACI 318-95 (1997 UBC)	In section 21.6, "Structural Walls, Diaphragms, and Trusses," there is, for the first time, a separate subsection 21.6.4, "Diaphragms." In that subsection, ACI 318 introduces cast-in-place composite topping slab diaphragms. This is the first mention of topped precast concrete diaphragms in ACI 318.
ACI 318-99 (2000 IBC)	For the first time, ACI 318 addresses diaphragms in a separate section, section 21.7, "Structural Diaphragms and Trusses." Cast-in-place (noncomposite) topping slab diaphragms are introduced in addition to cast-in-place composite topping slab diaphragms.
ACI 318-02 (2003 IBC)	ACI 318 section 21.7 becomes section 21.9, "Structural Diaphragms and Trusses." The contents of the section do not change.
ACI 318-05 (2006 IBC)	No change from ACI 318-02.
ACI 318-08 (2009 IBC)	ACI 318 section 21.9 becomes section 21.11, "Structural Diaphragms and Trusses." The section is significantly expanded and reorganized. Two significant changes are made in the diaphragm design procedure itself. These are discussed in the text of this paper.
ACI 318-11 (2012 IBC)	No change from ACI 318-08.
ACI 318-14 (2015 IBC, 2018 IBC)	As part of the overall reorganization of ACI 318, section 21.11 becomes section 18.12, "Diaphragms and Trusses."
ACI 318-19 (2021 IBC, 2024 IBC)	Substantive changes are made in section 18.12, "Diaphragms and Trusses." The most important change is the addition of subsection 18.12.11, "Precast Concrete Diaphragms." (This change is discussed further in the text of this paper.) The applicability of section 18.12.11 extends down to SDC C, whereas the diaphragm seismic design provisions of ACI 318 have always been applicable only to SDC D, E, and F structures.

Note: ACI 318 = American Concrete Institute's *Building Code Requirements for Structural Concrete and Commentary*; IBC = *International Building Code*; SDC = seismic design category; UBC = *Uniform Building Code*.

Table 3. History of seismic design provisions for precast concrete diaphragms in the *Uniform Building Code*

Model code	ACI standard	UBC section	Text
1988 UBC (revised in 1986)	ACI 318-83	2625(f)7	A cast-in-place topping on a precast floor system may serve as the diaphragm, provided the cast-in-place topping acting alone is proportioned and detailed to resist the design forces.
1991 UBC	ACI 318-89	2625(f)7	Same as above.
1994 UBC (revised in 1992)	ACI 318-89	1921.6.10 "Floor Topping"	Same as above.
1997 UBC	ACI 318-95	1921.6.11 "Floor Topping"	Same as above.

Note: ACI 318 = American Concrete Institute's *Building Code Requirements for Structural Concrete and Commentary*; UBC = *Uniform Building Code*.

Because the UBC[13–16] only permitted one method to design a precast concrete diaphragm in seismic zone 3 or 4, all precast concrete diaphragms in SDC D, E, or F buildings have been—and continue to be—designed in that way in the areas where the UBC was in effect. As in the case of ACI 318,[9] the use of untopped precast concrete diaphragms in SDC D, E, or F buildings, was not recognized in the UBC.

ACI 318-95[11] states the following about cast-in-place composite-topping slab diaphragms:

> A composite-topping slab cast in place on a precast floor or roof shall be permitted to be used as a structural diaphragm provided the topping slab is reinforced and its connections are proportioned and detailed to provide for a complete transfer of forces to chords, collector elements, and the lateral-force-resisting system. The surface of the previously hardened concrete on which the topping slab is placed is clean, free of laitance, and intentionally roughened.

The ACI 318-95[11] commentary states the following:

> A bonded topping slab is required so that the floor or roof system can provide restraint against slab buckling. Reinforcement is required to ensure the continuity of the shear transfer across precast joints. The connection requirements are introduced to promote a complete system with necessary shear transfers.

Although the connection requirements were dropped in ACI 318-11[17] and subsequent editions, the commentary was never corrected to reflect that change. The language in ACI 318-95[11] section 21.6.4.2, which is now ACI 318-19[9] section 18.12.4, does not indicate that the diaphragm shear in a cast-in-place composite-topping precast concrete diaphragm is resisted partly by the topping and partly by the connections between precast concrete components; however, designers have sometimes interpreted the word *composite* to mean that it does. In fact, the commentary for ACI 318-19 section 18.12.9.3 specifically states, “It is assumed that connections between the precast elements do not contribute to the shear strength of the topping slab diaphragm.” ACI 318-19 section 18.12.9.3 applies to both composite and noncomposite topping slab diaphragms.

The design of high-SDC precast concrete diaphragms as cast-in-place composite-topping slab diaphragms has been practiced in high-seismic-hazard parts of the United States (such as Charleston, S.C.) where *The BOCA National Building Code*[18] or the *Standard Building Code*[19] have been used. The practice continues; however, the topping is designed to resist the entire diaphragm shear. The connectors between the precast concrete units are not called upon to resist any of it. Untopped diaphragms have also been designed following the principles outlined by Cleland and Ghosh.[20]

ACI made two significant changes in the seismic diaphragm design procedure in ACI 318-08.[21] First, a new approach replaced the previous assumption in design practice that design moments in structural diaphragms were resisted entirely by chord reinforcement at opposite edges of the diaphragm. In place of this idealization, which was implicit in earlier editions of ACI 318, the new approach in ACI 318-08 assumed that all longitudinal reinforcement contributes to the flexural strength of the diaphragm. This change reduced the required area of longitudinal reinforcement concentrated near the edge of the diaphragm. The commentary for ACI 318-08 warned that the change should not be interpreted as a requirement to eliminate all boundary reinforcement.

Second, because cast-in-place topping slabs on a precast concrete floor or roof system tend to have shrinkage cracks that are aligned with the joints between adjacent precast concrete units, ACI 318-08[21] section 18.12.9.3 introduced additional shear strength requirements for topping slab diaphragms. These requirements are based on a shear friction model, and the assumed crack plane corresponds to joints in the precast concrete system along the direction of the applied shear. The coefficient of friction μ in the shear friction model is taken to be equal to 1.0 for normalweight concrete. Both distributed and boundary reinforcement in the topping slab may be considered as contributing to the area of shear friction reinforcement A_{vf}. Although the boundary reinforcement also resists forces due to moment and axial force, the reduction in the shear friction resistance in the tension zone is offset by the increase in shear friction resistance in the compression zone. Therefore, the area of boundary reinforcement used to resist shear friction does not need to be added to the area of boundary reinforcement used to resist moment and axial force. The distributed topping slab reinforcement must contribute at least one-half of the nominal shear strength.

An important question

Diaphragms that are now described in ACI 318-19[9] as cast-in-place (noncomposite) topping slab diaphragms have long been designed in UBC[12–15] seismic zones 3 and 4, and in buildings assigned to SDC D, E, or F for the seismic design force level in ASCE 7-16[1] section 12.10.1. Does that practice need to change following the introduction of section 12.10.3 in ASCE 7-16 and in view of the requirement that precast concrete diaphragms in buildings assigned to SDC C, D, E, or F be designed using the force level in section 12.10.3? A change in ACI 318-19 sheds some direct light on this, as discussed in the next section.

ACI 318-19 seismic design provisions for precast concrete diaphragms

To go hand-in-hand with the alternative diaphragm design force level in ACI 318-19[9] section 12.10.3, ASCE 7-16[1] included a precast concrete diaphragm design procedure in section 14.2.4 that is based on the Diaphragm Seismic Design Methodology (DSDM) Consortium research[22] and includes a connector qualification protocol. The requirements of ASCE 7-16 section 14.2.4 are in addition to the requirements set forth in ACI 318-14[23] section 18.12, "Diaphragms and Trusses."

The design procedure in ASCE 7-16[1] section 14.2.4 presents the designer with three diaphragm design options: elastic, basic, and reduced. The options concern the target performance of a diaphragm when subjected to earthquake excitation. The elastic design option (EDO) seeks to keep the diaphragm elastic in the maximum considered earthquake (MCE). The basic design option (BDO) seeks to keep the diaphragm elastic in the design earthquake while permitting controlled inelastic behavior in the MCE. The reduced design option (RDO) permits controlled inelastic behavior even in the design earthquake.

The choice of options is not unrestricted; rather, it depends on the diaphragm seismic design level, which is a function of the SDC, the number of stories, the diaphragm span, and the diaphragm aspect ratio. The EDO is permitted for low seismic demand level and moderate seismic demand level, provided the diaphragm design force is increased by 15%. The BDO is permitted for low seismic demand level, moderate seismic demand level, and high seismic demand level, provided the diaphragm design force is increased by 15%. The RDO is permitted to be used for all seismic demand levels.

The EDO permits any type of diaphragm connector to be used, including those classified as low deformability elements (LDEs). If the BDO is selected, connectors qualifying as moderate deformability elements (MDEs) need to be used as a minimum. Connectors qualifying as high deformability elements (HDEs) must be used exclusively if the RDO is chosen. A precast concrete diaphragm connector is assigned a deformability classification (LDE, MDE, or HDE) based on its measured deformation capacity in tension. The measurement requires testing, which is more generally required to establish the performance characteristics of strength, stiffness, and deformation capacity of the precast concrete diaphragm connectors under in-plane shear and in-plane tension. The testing must follow a protocol that is part of section 14.2.4 of ASCE 7-16.[1]

For precast concrete diaphragms designed using ASCE 7-16[1] section 14.2.4 and ACI 318-14,[23] R_s is 0.7 for EDO, 1.0 for BDO, and 1.4 for RDO. The required shear strength for a diaphragm must be amplified by the diaphragm shear overstrength factor Ω_v, which is taken to be equal to $1.4R_s$, so the shear amplification factors are 1.0, 1.4, and 2.0 for EDO, BDO, and RDO, respectively.

The joint ACI-ASCE Committee 550 (Precast Concrete Structures) has now processed two standards: *Qualification of Precast Concrete Diaphragm Connections and Reinforcement at Joints for Earthquake Loading (ACI 550.4) and Commentary (ACI 550.4R)*[24] and *Code Requirements for the Design of Precast Concrete Diaphragms for Earthquake Motions (ACI 550.5) and Commentary (ACI 550.5R).*[25] The two ACI 550 standards together have the same content as ASCE 7-16 section 14.2.4; however, changes—some of which are significant—have been made in response to comments from ACI-ASCE Committee 550 members and members of the ACI Technical Activities Committee. The two standards have been adopted by reference in ACI 318-19,[9] which, in turn, has been adopted by the 2021 IBC.[10] Notably, section 14.2.4 has been deleted from the newest edition of ASCE 7 (ASCE 7-22[8]). ACI 318-19 section 18.12 on diaphragms now contains two important subsections:

> **18.12.1.2** Section 18.12.11 shall apply to diaphragms constructed using precast concrete members and forming part of the seismic-force-resisting system for structures assigned to SDC C, D, E, or F.
>
> **18.12.11.1** Diaphragms and collectors constructed using precast concrete members with composite topping slab and not satisfying 18.12.4, and untopped precast concrete diaphragms, are permitted provided they satisfy the requirements of ACI 550.5. Cast-in-place noncomposite topping slab diaphragms shall satisfy 18.12.5 and 18.12.6.

It should be clear from ACI 318-19[9] section 18.12.11.1 that cast-in-place noncomposite topping slab diaphragms are to be designed as cast-in-place concrete diaphragms and, by implication, should use the seismic design force level in ASCE 7-16[1] section 12.10.1 (or 12.10.3 with the diaphragm defined as a cast-in-place concrete system).

A change in ASCE 7-22

To bring further clarity to the issue of a change to seismic design force level for precast concrete diaphragms, the diaphragm design provision of ASCE 7-16[1] was proposed and has been approved and included in ASCE 7-22.[8] The reason for the proposed code change is as follows:

> Because the broad term used in ASCE 7 Section 12.10 is "precast concrete diaphragms" some designers as well as code enforcers are attempting to apply the requirements of ASCE 7 12.10.3 to conventional noncomposite topping slab diaphragms. The addition of the two proposed definitions and the specific mention of cast-in-place concrete equivalent precast diaphragms in Section 12.10 Exception 2 will hopefully eliminate this misunderstanding in the future.

In the remainder of this section, the section numbers are ASCE 7-16[1] section numbers, which have not been changed in ASCE 7-22.[8] Underlining indicates language added in ASCE 7-22; crossed out text indicates deleted wording.

> **14.2 CONCRETE**
>
> **14.2.2.1 Definitions.** Add the following definitions to ACI 318, Section 2.3.

PRECAST CONCRETE DIAPHRAGM: A diaphragm constructed with precast concrete components, with or without a cast-in-place topping, that includes the use of discrete connectors or joint reinforcement to transmit diaphragm forces.

CAST-IN-PLACE CONCRETE EQUIVALENT PRECAST DIAPHRAGM: A cast-in-place noncomposite topping slab diaphragm, as defined in ACI 318, Section 18.12.5, or a diaphragm constructed with precast concrete components that uses closure strips between precast components with detailing that meets the requirements of ACI 318 for the Seismic Design Category of the structure.

12.10 DIAPHRAGMS, CHORDS, AND COLLECTORS

Modify Exception 2 as shown below:

EXCEPTIONS:

~~2.~~(b) Precast concrete diaphragms in Seismic Design Category B, cast-in-place concrete diaphragms, cast-in-place concrete equivalent precast diaphragms, and wood-sheathed diaphragms supported by wood diaphragm framing, bare steel deck diaphragms, and concrete-filled steel deck diaphragms are permitted to be designed in accordance with Section 12.10.3.

Modify Commentary Section C 12.10 as shown below:

C12.10 DIAPHRAGMS, CHORDS, AND COLLECTORS

This section permits choice of diaphragm design in accordance with either Sections 12.10.1 and 12.10.2 provisions or the new provisions of Section 12.10.3. Section 12.10.3 is mandatory for precast concrete diaphragms in buildings assigned to SDC C, D, E, or F and is optional for precast concrete diaphragms in SDC B buildings, cast-in-place concrete diaphragms, cast-in-place concrete equivalent precast diaphragms, and wood diaphragms. Precast concrete diaphragms and cast-in-place concrete equivalent precast diaphragms are defined in Section 14.2. [The remainder of the paragraph is unchanged.]

The changes incorporated into ASCE 7-22[8] define precast concrete diaphragms for the first time and clarify that some untopped diaphragms with pour strips and closure strips with the required details also qualify for the design force level of ASCE 7-16[1] or ASCE 7-22 section 12.10.1.

Cast-in-place concrete equivalent precast diaphragms as defined in ASCE 7-22[8] include diaphragms constructed using precast concrete components that use closure strips between precast concrete components with detailing that meets the requirements of ACI 318[9] for the SDC of the structure. Such detailing for SDC D, E, or F (also good for SDC C) is illustrated in **Fig. 1** and **2**. The details are based on research performed with rapid bridge construction in mind.[26]

Public comments

The noted changes in ASCE 7-22[8] drew public comments that are highly likely to be of interest to readers. The comments and the ASCE 7 Committee responses are presented in "Comment 1" and "Comment 2."

Comment 1

14.2.2.1 There is a new definition for "Cast-In-Place Concrete Equivalent Precast Diaphragm."

This new definition includes a cast-in-place noncomposite topping slab diaphragm, as defined in ACI 318, Section 18.12.5. This distinction is not necessary since ACI 318 Section 18.12.11.1 explicitly directs cast-in-place noncomposite topping slabs to satisfy 18.12.5 and 18.12.6 as opposed to the requirements of ACI 550.5, which apply only to precast concrete diaphragms.

Proposed resolution Cast-In-Place Concrete Equivalent Precast Diaphragm: A diaphragm constructed with precast concrete components that uses closure strips between precast components with detailing that meets the requirements of ACI 318 for the seismic design category of the structure.

Response Non-Persuasive. What the commenter points out about ACI 318-19 Section 18.12.11.1 is absolutely correct. However, TC-4 [Task Committee 4 on concrete of ASCE 7-22 Seismic Subcommittee] strongly feels that the exclusion of cast-in-place noncomposite precast concrete diaphragms would render the definition for Cast-in-Place Concrete Equivalent Precast Diaphragms incomplete. As it is, the proposed definition does not conflict in any way with anything said in ACI 318-19.

Comment 2

14.2.2.1 There is a new definition for "Precast Concrete Diaphragm."

The definition is not sufficient in detail to be consistent with ACI 318 & 550.5. ACI 318, Section 18.12.11.1 directs designers of precast concrete diaphragms to ACI 550.5 and Section 1.2.2 of

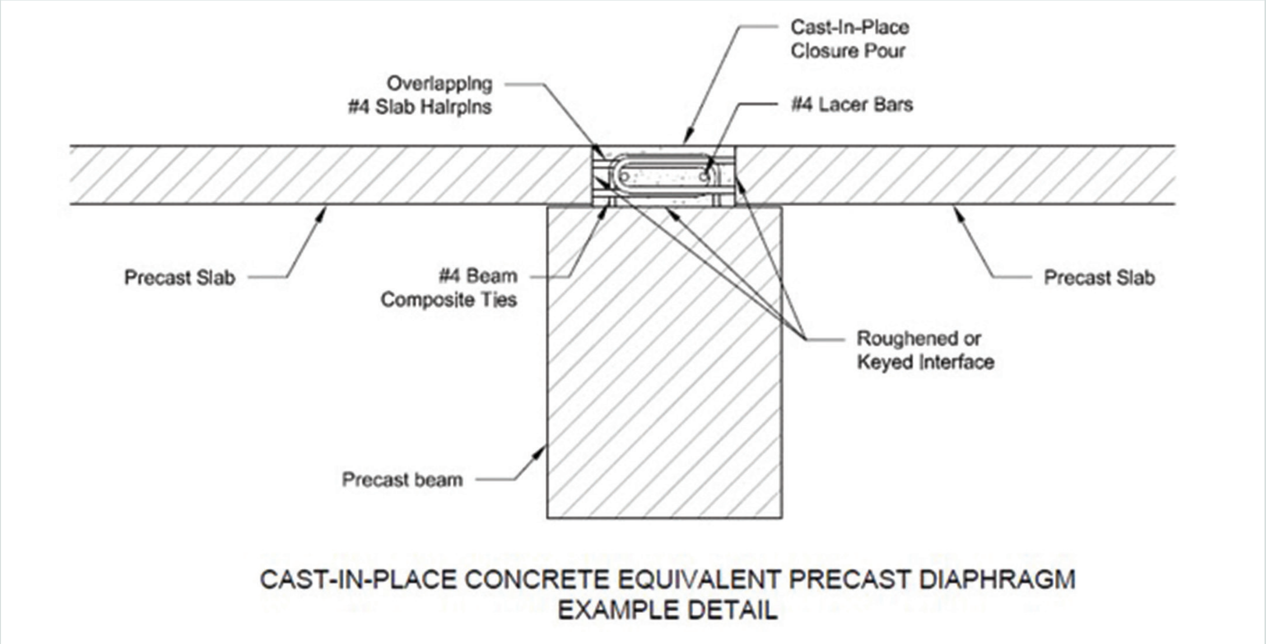

Figure 1. Closure strip between precast concrete units over a beam. Note: no. 4 = 13M. Courtesy of Jon Mohle, Clark Pacific.

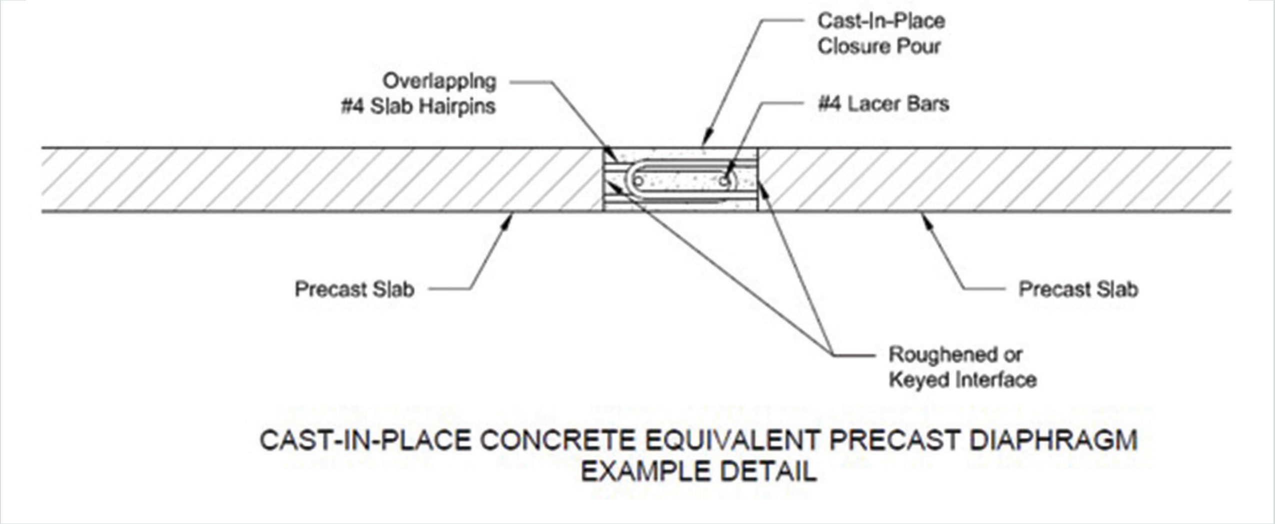

Figure 2. Closure strip between two slabs or untopped double-tee flanges. Note: no. 4 = 13M.

that standard provides a comprehensive scope statement that clearly defines a precast concrete diaphragm.

Proposed resolution Precast Concrete Diaphragm: A diaphragm that consists of a cast-in-place composite topping slab with a thickness of less than 3 in. [75 mm] on precast concrete components, a diaphragm that is comprised of precast concrete components with end strips formed by either a cast-in-place composite topping or edge beams, a diaphragm that consists of interconnected precast concrete components without cast-in-place concrete topping.

Response Non-Persuasive. The definition proposed for ASCE 7-22 is general, but not insufficient in detail. There is no inconsistency with ACI 318 or ACI 550.5.

ACI 318-19 Section 1.2.2 reads in its entirety: “In this Code, the general building code refers to the building code adopted in a jurisdiction. When adopted, this Code becomes part of the general building code." Thus, Section 1.2.2 of ACI 318 does not contain a definition. The commenter apparently means section 1.2.2 of ACI 550.5. That is indeed the scope section of that document and is discussed next.

The "Scope" section of ACI 550.5 states the following:

"**1.2.2** This standard shall apply to precast concrete diaphragms including a) through c):

a) Diaphragms that consist of a cast-in-place topping slab with a thickness of less than 3 in. [75 mm] on precast concrete members."

The implication clearly is that a topping thickness of 3 in. (75 mm) or more will make the diaphragms eligible to be designed as cast-in-place concrete equivalent precast diaphragms. But those are precast concrete diaphragms as well. The commenter essentially wants a subset of precast concrete diaphragms to be defined as precast concrete diaphragms. What is proposed for ASCE 7-22 is a broad, general definition. [Note: What the first sentence of this paragraph conveys is later refined in **Table 4**.]

Questions from a practitioner

A number of relevant questions on the subject of this paper were recently received from a practitioner. Following are the questions and the author's answers:

Question 1 As far as I understand, the DSDM method (ASCE 7-16, Section 12.10.3) is mandatory for precast [concrete] structures in SDC C and above, regardless of whether there is CIP [cast-in-place] topping or not. Can you confirm that?

Answer 1 That is not necessarily the case. Please see the response to Question 2 below.

Question 2 Is there a way to consider the topping on top of double tees as CIP and use ASCE 7-16 Sections 12.10.1 and 12.10.2 (old conventional approach) rather than Section 12.10.3 (new approach)?

Answer 2 ACI 318-19 Section 18.12.11.1 tells you: "Cast-in-place noncomposite topping slab diaphragms shall satisfy 18.12.5 and 18.12.6." In other words, if the topping slab acting alone is designed to act as the diaphragm, it is permitted to be designed as a cast-in-place concrete diaphragm, with design force level given by Sections 12.10.1 and 12.10.2.

Question 3 A similar question arises for precast double tees with pour strips all around the perimeter for chord reinforcement; in such a case, can we use the Section 12.10.1 and 12.10.2 (old conventional approach) for chord reinforcement (with F_{px} [diaphragm seismic design force]) and collector design (with $\Omega_o F_{px}$) and Section 12.10.3 for the connection and shear design since those are part of the "dry-system"?

Answer 3 An ASCE 7-16 change has now been included in ASCE 7-22. It defines a cast-in-place concrete equivalent precast diaphragm. The described precast diaphragm with pour strips will likely not meet the definition for a cast-in-place concrete equivalent precast diaphragm, because it has connectors between precast units instead of closure strips with the required detailing. Thus, the modified Exception 2 to Section 12.10 will not permit your diaphragm to be designed by Sections 12.10.1 and 12.10.2. There is no provision for designing the cast-in-place portions of the diaphragm by

Table 4. Design choices for topped precast concrete diaphragms according to ACI 318-19 section 18.12

Topping thickness, in.	Design*
<2	As untopped† (ACI 550.5)
≥2 to <2½	As composite (18.12.4) or untopped† (ACI 550.5)
≥2½ to <3	As composite (18.12.4), noncomposite (18.12.5), or untopped† (ACI 550.5)
≥3	As composite (18.12.4) or noncomposite (18.12.5)

Note: ACI 318-19 = American Concrete Institute's *Building Code Requirements for Structural Concrete and Commentary*; ACI 550.5 = *Code Requirements for the Design of Precast Concrete Diaphragms for Earthquake Motions*. 1 in. = 25.4 mm.

* When designing by ACI 318-19 section 18.12.4 or 18.12.5, a designer must comply with the applicable provisions of section 18.12.

† "Untopped" in this table indicates that diaphragm reinforcement may include discrete connections between precast concrete components, reinforcement at cast-in-place joints between precast concrete components, or reinforcement in cast-in-place end strips or beams; however, reinforcement in the form of distributed reinforcement is not used in the topping.

12.10.1, 12.10.2 and the precast portions of the diaphragm by 12.10.3.

Question 4 I am assuming your answers to 2 and 3 above are "No"; and, if we have CIP topping or pour strips, as per ASCE 7-16, we can benefit from them with the use of mild reinforcement within them (as high deformability element, HDE); thus, we can apply reduced design approach (RDO), which would lower diaphragm demands significantly. Is there any other benefit of CIP topping or pour-strips?

Answer 4 My answer to Question 2 is obviously not "No." If you are designing a topped precast diaphragm that is not a cast-in-place equivalent precast diaphragm, the benefit you mentioned comes into play. However, be aware that the benefit only extends to the chords and collectors as the Ω_v contains R_s, negating this benefit when considering diaphragm shear.

Question 5 I remember you mentioning a few years ago about "CIP Analogy" considering the topping as the CIP diaphragm so that we can use Sections 12.10.1 and 12.10.2 methodology rather than precast Section 12.10.3 methodology. Is there any progress on that idea?

Answer 5 See response to Question 2.

Question 6 I see that design acceleration coefficient in ASCE 7-16 is defined as C_{pi} = max $(0.8\ C_{p0}, 0.9\ \Gamma m_1\ \Omega_o\ C_s)$ in equations 12.10-8 and 12.10-9 for 0.8th level of the building, which can result in a situation that $C_{pi} < C_{p0}$ and create a negative slope to diaphragm acceleration profile as opposed to what's shown in ASCE 7-16 Fig. 12.10-2. [Note: C_{pi} = diaphragm design acceleration force coefficient at 80% structure roof height; C_{p0} = diaphragm design acceleration force coefficient at structure base; Γm_1 = first mode contribution factor; C_s = seismic response coefficient.] I see that Dichuan (Dr. Zhang) used 1.0 C_{p0} factor in their reports and spreadsheet calculations. I don't think there would be error in such a code as ASCE 7, but I wonder if there is an error on the 0.8 C_{p0} or if the intent of the 0.8 C_{p0} [is] that it can create larger accelerations at lower levels compared to 0.8th level? This is not something bad in my opinion because I remember observing higher first-floor accelerations compared to midheight floor levels during my PhD research. Similarly, if I am not wrong, Dr. Restrepo's 2002 and 2007 papers mention high accelerations on the first floor. Actually, this floor acceleration profile occurs if we apply the [ASCE] 7-16 procedure to PCI Manual [*PCI Design Handbook*[6]], 8th ed., Example 4.8.3.1. C_{px} [diaphragm design acceleration force coefficient at level x] profile turns out to have a negative slope below 0.8th level; please see figures below for EW and NS direction acceleration profiles. [These figures are not included here.] If the intent is that the floor acceleration profile can have a negative slope, it should probably be mentioned in the code not to cause any confusion with Fig. 12.10-2. I would appreciate if you could give your insights.

Answer 6 There is no mistake in Eq. (12.10-8). 0.8 C_{p0} is what is intended. In the 2015 NEHRP Provisions (FEMA P-1050),[27] C_{pi} was equal to C_{p0}, and C_{pn} [diaphragm design acceleration force coefficient at structure roof height] given by Eq. (12.10-7) did not have a lower bound on it ($C_{pn} \geq C_{p0}$ was not there). Both changes were made by the Seismic Subcommittee of ASCE 7-16 in the process of adopting Section 12.10.3 from the 2015 NEHRP Provisions. Equation (12.10-9) is explained in Commentary Section C12.10.3.2. The use of $0.8C_{p0}$ should be looked upon as a lower bound on C_{pi} values given by Eq. (12.10-9). You are right about the negative slope of the line between C_{p0} and C_{pi} in Fig. 12.10-2. However, that should be obvious from the fact that C_{pi} can be $0.8C_{p0}$. A code or standard typically does not explain things like this. Explanation, if required, belongs in the commentary. In this case, such an explanation was not felt to be necessary.

Simplified diaphragm design force level

Another issue needs to be clarified before this paper is concluded. ASCE 7-16[1] contains section 12.14, "Simplified Alternative Structural Design Criteria for Simple Bearing Wall or Building Frame Systems." A building must satisfy a number of conditions to be eligible to be designed by this section. Some of these conditions are rather onerous, detracting from the simplicity that is intended to result from this section. In all the work leading up to the inclusion of section 12.10.3 in ASCE 7-16, scant attention was paid to section 12.14. This section also provides a diaphragm design force level in section 12.14.7.4. It applies to diaphragms in buildings designed by section 12.14.

There is an apparent conflict here with ACI 550.5[25] section 4.1.2, which states, "Earthquake loading forces for precast concrete diaphragms designed in accordance with this standard shall be determined using Section 12.10.3 of ASCE/SEI 7-16." The following question arises: If the diaphragms in a building designed by ASCE 7-16[1] section 12.14 are untopped or have a noncomposite topping, requiring their design by ACI 550.5, can the design force level still come from section 12.14.7.4, or must it be the design force level given by section 12.10.3?

It is important here to understand the hierarchy of codes and standards. In the case of any conflict between IBC[10] and any of its referenced standards, the IBC governs. The IBC does not directly contain any diaphragm-related provisions; therefore, this point does not affect diaphragms. The 2021 IBC adopts ASCE 7-16[1] for minimum design loads and ACI 318-19[9] for concrete design and construction. ACI 318-19 in turn adopts ACI 550.5.[25] In the case of any conflict between ACI 318 and ACI 550.5, ACI 318 governs. ASCE 7 deals with design loads or required strength or demand. ACI 318 deals with design strength or supply. In the case of a conflict between ASCE 7 and ACI 318, if it is a design-load-related matter, ASCE 7 governs; if it is a strength-related issue, ACI 318 governs. Diaphragm design loads are the purview of ASCE 7, not ACI 318 nor ACI 550.5. Thus, the design force level of ASCE 7-16 section 12.14 cannot be overridden by the requirement in ACI 550.5 section 4.1.2.

Conclusion and recommendations

Diaphragm seismic design force level

The modified exception (b) to ASCE 7-22[8] section 12.10 clarifies that cast-in-place concrete equivalent precast diaphragms, as defined in ASCE 7-22 section 14.2.2.1, which include cast-in-place noncomposite topping slab diaphragms conforming to ACI 318-19[9] section 18.12.5, are permitted to be designed using the force level in ASCE 7-16[1]/7-22 section 12.10.1 or 12.10.3. All other precast concrete diaphragms, as defined in ASCE 7-22 section 14.2.2.1, must be designed using the force level in ASCE 7-16/7-22 section 12.10.3. Where the conditions of ASCE 7-16/7-22 section 12.14 are met, the force level in ASCE 7-16/7-22 section 12.14.7.4 is also permitted.

Topping thickness

Design choices for topped precast concrete diaphragms, as provided in ACI 318-19[9] section 18.12, are summarized in Table 4.

According to the commentary for ACI 550.5,[25] post-earthquake reconnaissance following the 1994 Northridge Earthquake[28] revealed that when precast concrete diaphragms with topping thickness of 3 in. (75 mm) or less were subjected to significant earthquake motions, the topping was likely to crack along the edges of the precast concrete members. Consequently, reinforcement crossing the edges was susceptible to damage, and the susceptibility increased as the aspect ratio for the diaphragm increased and as the larger dimension of the diaphragm between seismic-force-resisting vertical elements increased.

According to ACI 318-19[9] section 18.12.6.1, “Topping slabs placed over precast floor or roof elements, acting as diaphragms and not relying on composite action with the precast elements to resist the design earthquake forces, shall be at least 2½ in. thick.” Thus, a cast-in-place concrete topping on a precast concrete floor system that is 2½ in. (64 mm) thick or thicker may serve as the diaphragm, provided the cast-in-place topping acting alone is proportioned and detailed to resist the design forces. It is strongly recommended that the minimum topping thickness for cast-in-place noncomposite topping slab diaphragms be 3 in. (75 mm).

Irrespective of whether a topping slab is composite or noncomposite, it is often impractical to achieve proper concrete cover over reinforcement at critical locations with a topping thickness of less than 3 in. (75 mm).

Topping reinforcement

It is recommended that reinforcement in the cast-in-place concrete topping be deformed reinforcing bars. Note that ACI 318-19[9] Table 20.2.2.4(a) limits the yield strength of reinforcement f_y to 60 ksi (414 MPa) for shear friction over the joints. Therefore, higher-strength reinforcement can be used only in the chords and the collectors. Thin welded-wire reinforcement (WWR) has been observed to neck and break quickly when there is localized strain opening at the joints. ACI attempts to address this by requiring the following in ACI 318-19 section 18.12.7.1:

> Where welded wire reinforcement is used as the distributed reinforcement to resist shear in topping slabs placed over precast floor and roof elements, the wires parallel to the joints between the precast elements shall be spaced not less than 10 in. [250 mm] on center.

Many knowledgeable engineers think that this requirement is insufficient and advocate against the use of WWR in topping slabs. An argument can be made that large-diameter wire (D11 [MD 71] or greater) could also perform well, though the higher yield strength of WWR makes it less desirable.

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Notation

A_{vf} = area of shear friction reinforcement

C_{pi} = diaphragm design acceleration force coefficient at 80% of structure roof height

C_{pn} = diaphragm design acceleration force coefficient at structure roof height

C_{px} = diaphragm design acceleration force coefficient at level x

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

C_s = seismic response coefficient

f_y = yield strength of reinforcement

F_{px} = diaphragm seismic design force at level x

R = seismic response modification factor

R_s = diaphragm seismic design force reduction factor

Γ_{m1} = first mode contribution factor

μ = coefficient of friction

Ω_o = overstrength factor

Ω_v = shear overstrength factor

Appendix: Publication histories for selected standards and codes cited in this paper

Organization	Standard or code title	Editions (publication years)
American Concrete Institute	*Building Code Requirements for Structural Concrete* (ACI 318)	ACI 318-71 (1971) ACI 318-77 (1977) ACI 318-83 (1983) ACI 318-89 (1989) ACI 318-95 (1995) ACI 318-99 (1999) ACI 318-02 (2002) ACI 318-05 (2005) ACI 318-08 (2008) ACI 318-11 (2011) ACI 318-14 (2014) ACI 318-19 (2019)
American Society of Civil Engineers	*Standard Minimum Design Loads for Buildings and Other Structures* (ASCE 7)	ASCE 7-05 (2006) ASCE 7-10 (2010)
	Standard Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE 7)	ASCE 7-16 (2017) ASCE 7-22 (2021)

Organization	Standard or code title	Editions (publication years)
Building Officials and Code Administrators International	*The BOCA National Building Code* (BOCA NBC)	1993 BOCA NBC (1993) 1996 BOCA NBC (1996) 1999 BOCA NBC (1999)
International Code Council	*International Building Code* (IBC)	2000 IBC (2000) 2003 IBC (2003) 2006 IBC (2006) 2009 IBC (2009) 2012 IBC (2011) 2015 IBC (2014) 2018 IBC (2017) 2021 IBC (2020) 2024 IBC (scheduled to be published in 2023)
International Conference of Building Officials	*Uniform Building Code* (UBC)	1979 UBC (1979) 1982 UBC (1982) 1985 UBC (1985) 1988 UBC (1988) 1991 UBC (1991) 1994 UBC (1994) 1997 UBC (1997)
Southern Building Code Congress International	*Standard Building Code* (SBC)	1994 SBC (1994) 1997 SBC (1997) 1999 SBC (1999)

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Abstract

This paper provides guidance for determining seismic design force level for topped precast concrete diaphragms. This has been a controversial topic ever since ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*,[1] introduced a section titled "Alternative Design Provisions for Diaphragms" and mandated its use for precast concrete diaphragms in buildings assigned to seismic design category C, D, E, or F.

Keywords

ACI 318, ASCE 7, IBC, *International Building Code*, seismic design force level, topped precast concrete diaphragm, UBC, *Uniform Building Code*.

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