

Seismic Design of Precast Concrete Diaphragms According to ACI 318-19 & ASCE 7-22: A Comprehensive Course

An Online Continuing Education Course for Engineers

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Seismic Design of Precast Concrete Diaphragms According to ACI 318-19 & ASCE 7-22: A Comprehensive Course

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1. Introduction:

The seismic force-resisting system (SFRS) of a building consists of a three-dimensional ensemble of elements that transmit loads and forces from the point of origin down to the soil underneath the foundation. This system typically consists of horizontal and vertical structural elements. When the building is subject to seismic excitation, the horizontal elements—roof and floor slabs, bending in their own plane, act as diaphragms to transmit the forces horizontally from the point of origin to the vertical elements of the SFRS (**Figure 1-1**). The vertical elements (i.e., walls or frames) transmit the forces down to the foundation. Together, these elements function as a system to provide a complete load path for the seismic forces to flow through the building to the foundation and the soil underneath. Diaphragms not only act to distribute the forces horizontally to the vertical elements of the SFRS, but they also tie the vertical elements together to act as a system so that they respond to the seismic forces together rather than individually. The diaphragms are an integral part of the SFRS of a building and deserve significant attention during the design process.

Seismic design of diaphragms is required for buildings in Seismic Design Categories (SDC) B through F, as defined in the 2021 edition of the *International Building Code (IBC)* and *ASCE/SEI 7-22, Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Since SDC A is exempt from seismic design, it is not specifically addressed. However, many of the diaphragm analysis and design methods described herein are applicable to the design of diaphragms to resist wind forces and provide structural integrity in SDC A buildings as well.

Although horizontal structural elements acting as diaphragms can be truss elements or horizontal, diagonal bracing, in most cases, diaphragms utilize the floor system. They are constructed as essentially solid, planar elements made of wood, steel, concrete, or combinations of these. Concrete diaphragms can be conventionally reinforced or pre-stressed. They can be cast-in-place concrete slabs (often post-tensioned), topping slabs on metal deck or precast concrete, or interconnected precast concrete slabs without topping, though the last system has not been used much in structures assigned to SDC D, E, or F.

The design forces and analysis requirements for diaphragms are contained in ASCE/SEI 7-22, which is the latest published version of this standard. However, a local jurisdiction may reference an earlier (2016 or 2010) edition in its code regulations.

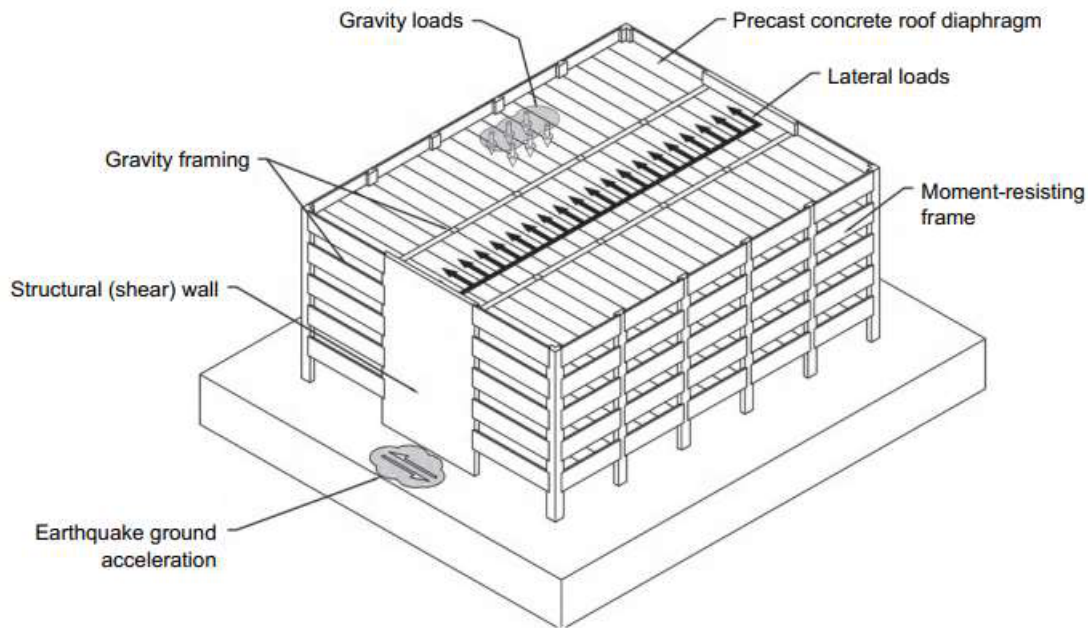


Figure 1-1. Building schematic showing SFRS elements, including diaphragms

This course is written primarily for practicing structural engineers and should also be useful to architects, building regulators (building officials and plan checkers), and contractors. Students, educators, and others interested in understanding the basis for the common design methods used for precast concrete diaphragms will find this document a useful beginning step in expanding that understanding.

Section 2 provides an overview of the construction and application of precast concrete diaphragms, and Section 3 summarizes research on their seismic behavior. Section 4 presents examples of diaphragm design force level calculations, and Section 5 discusses diaphragm analysis. Section 6 presents an overview of the diaphragm design procedure; Section 7 discusses the design and detailing considerations for flexure and shear, and Section 8 summarizes the qualification and classification of connectors.

2. Precast Concrete Diaphragm Applications

2.1 Precast Concrete Construction

Precast concrete is defined as concrete cast in a location different from its final position within a structure. It is produced by casting concrete in a reusable mold or form, which is then cured in a controlled environment, transported to the construction site, and lifted into place. It is important to note that all precast concrete is jointed, which in many ways dictates how it is designed and constructed.

A precast concrete diaphragm is a diaphragm consisting of precast components with optional cast-in-place pour strips along some or all boundaries and with or without cast-in-place topping slabs.

Precast/prestressed concrete components are used in many building types and for many functions. A review of common building types provides a context for the consideration of diaphragm analysis, design, and behavior.

2.2 Typical Applications in the United States

Parking garages are one of the most common building types constructed with precast/prestressed concrete. These structures can range from small, one-level decks to very large multi-story facilities. They are most commonly constructed with simple-span precast concrete double tees on gravity load framing consisting of simple-span beams and vertically continuous precast concrete columns. The typical bays range from 55 to 65 feet in span, with narrower bays sometimes used for ramps. To accommodate the vertical movement of vehicles, these structures include ramps, unless the building site has sufficient slope to permit separate access at each framed level. Ramp layouts may be single-helix or double-helix when the slope is sufficiently gradual to permit parking on the ramped bays (**Figure 2-1**). Steeper ramps can be used when they contain only traffic lanes. Parking structures often present formidable design challenges due to long floor spans, limited (often perimeter) seismic force-resistant system locations, and openings due to ramps.

Precast/prestressed concrete framing is also used for industrial facilities and food processing buildings. These buildings are usually constructed with single- or two-story framing, except for process towers. Roof framing typically consists of double tees with 2- or 3-inch thick flanges spanning 60 to 80 feet to provide more column-free interior space.

In recent years, the special requirements for hardened facilities with high resistance to extreme environmental loads have been met with precast/prestressed concrete framing. These buildings are typically single-story, except two-story framing may be used to support emergency generators. Roof framing uses precast concrete double tees with 2-inch thick flanges and 2- to 3-inch thick cast-in-place concrete topping slabs for additional diaphragm integrity.

When fire resistance and durability are important to the safe storage of materials, precast/prestressed concrete is used for warehouse framing. These are usually single-story buildings similar to industrial buildings.

Multi-family residential, high-rise condominiums, and hotels are common uses that are well adapted to precast/prestressed concrete. These buildings are framed with hollow core slabs on load-bearing precast concrete walls or load-bearing reinforced concrete masonry walls.

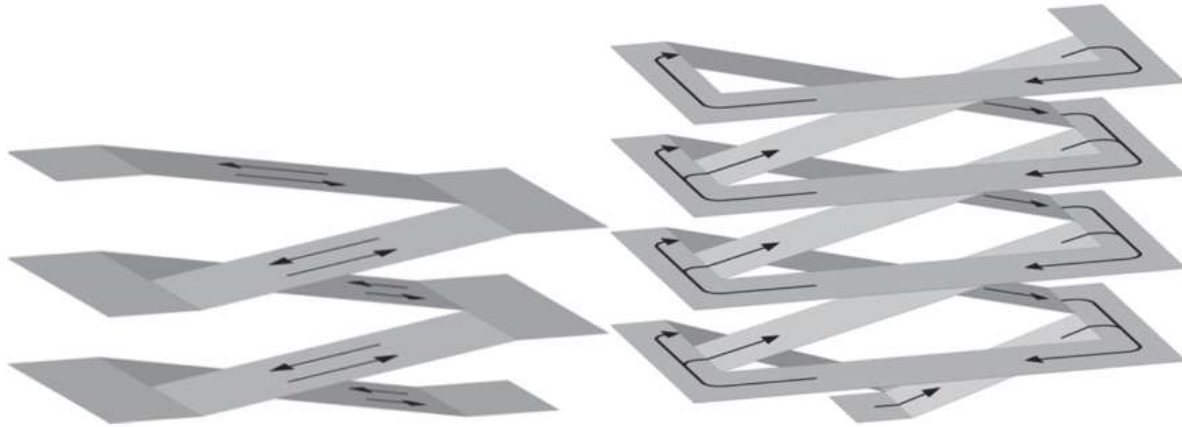


Figure 2-1. Single-helix and double-helix ramp configurations

Hollow core slabs typically have no structural topping slabs in low and moderate seismic design categories. However, topping slabs are used in high seismic design categories to develop diaphragm behavior when the in-plane lateral forces are larger. The seismic force-resisting system is most commonly load-bearing and non-load-bearing shear walls, with additional specific detailing requirements for structural integrity and resistance to disproportionate collapse. Details of structural integrity include interior and perimeter ties in the floors that may contribute to diaphragm behavior.

Although not as common as for parking garages, there are several regions in the United States where Precast/prestressed concrete is used for office buildings. Office building framing is similar to parking garage framing but does not require ramping. Interior bay spans may be shorter, and cast-in-place concrete topping slabs over double tees are used to provide level floors due to the natural camber in these prestressed floor members. Spandrel beams on columns or load-bearing and non-load-bearing walls may provide the perimeter gravity support. Interior framing may include simple-span beam and column framing and walls at stair and elevator cores.

2.3 Precast Floor Units

Floor units form diaphragms in precast concrete structures. Precast concrete floor units are primarily double tees, hollow core planks, and flat slabs. Other types of components are less often used, such as quad tees (shallow 4-stemmed members), but the first three types are used for most floors and roofs. Double tees are the most common, with the highest square footage placed. Double tees get their name from the cross-sectional shape shown in **Figure 2-2**.

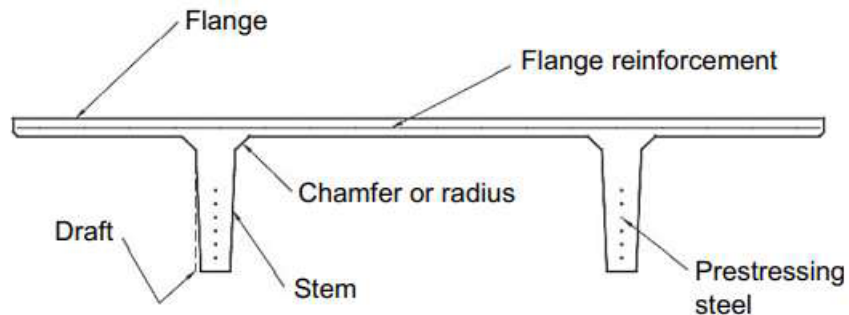


Figure 2-2. Double tee cross-section with common terms for parts and features

A hollow core plank unit (see **Figure 2-3** for cross-section) is a precast/prestressed concrete component with continuous voids that reduce the concrete volume and weight compared to a solid slab. These members are manufactured using various methods, including dry-casting (extrusion), fixed forming, and slip-forming. Hollow core casting methods generally preclude the installation of embedded steel plates with anchorage and, therefore, make assembly with mechanical or welded connections impractical.

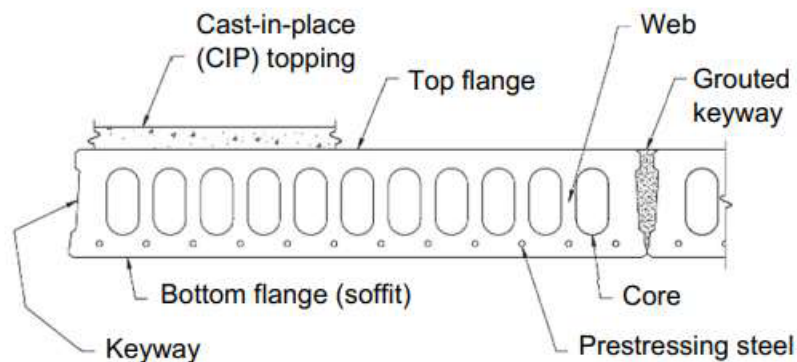


Figure 2-3. Hollow core plank cross-section with common terms for parts and features.

Pretensioned precast components are usually cast in long-line beds, normally 300 to 600 feet in length, Sharing the set-up of a prestressing strand with several members reduces the effect of strand seating and anchorage losses in each because it experiences only a small part of the overall elongation of the strands.

2.4 Topped and Untopped Precast Diaphragms

Precast concrete diaphragms can be designed as topped or untopped (also known as pretopped). Topped diaphragms use cast-in-place concrete placed over precast units as the primary load-transfer medium to collect and transmit the in-plane loads. Diaphragms with cast-in-place topping slabs are further distinguished as composite (the topping is cast together as the diaphragm) or non-composite (the topping is cast separately following the provisions of ACI 318-19).

A composite diaphragm is one in which the topping is cast against the surface of the previously cast precast units and is intended to act as a single unit. The thickness may be determined by the design requirements for parking garages that are subject to heavy loads and adverse weather, the minimum required thickness of the topping is 2 1/2 in. For these conditions, the bottom orthogonal reinforcement is required to be placed in the topping.

ACI 318-19 also permits the design of non-composite topped diaphragms. The minimum thickness in this case is 2 1/2 in. Non-composite topped diaphragms not relying on the composite action of the topping slab are not considered as precast concrete diaphragms. The topping slab over the precast units may cause reflection of cracks from the precast concrete joints to prevent these cracks from being irregular. This can result in joint opening at the precast joints similar to that in composite topping slabs, which would then require topping slab thickness considerably greater than the minimum thickness or the thickness needed for the cover. It should be noted that noncomposite topping slab diaphragms must be designed by ACI 318-19 Section 18.12.5.1 and all other applicable provisions of Section 18.12, four of which are particularly important: (1) Section 18.12.6.1 for minimum thickness of 2 1/2 in.; (2) Section 18.12.7.1 for minimum wire reinforcement spacing of 10 in.; (3) Section 18.12.9.1 for shear strength of topping slab diaphragms; and (4) Section 18.12.9.3 for shear strength of topping slab diaphragms. Thus, non-composite topping slabs do have prescriptive requirements that differentiate their design from that of cast-in-place slabs.

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