U.S. Experience with Seismic Design and Construction of Precast Concrete Structures

S. K. Ghosh Associates Inc.
Palatine, IL and Aliso Viejo, CA

This paper discusses the seismic force-resisting structural systems that are recognized by U.S. codes and standards and that are in common use. Innovative structural systems that are newly recognized by U.S. codes and standards and their application are also discussed. The precast building market in the United States is dominated by parking structures and office buildings. This is very different from the situation in Europe. And this provides context to much of the discussion in this paper. The structural systems discussed are mainly geared towards the parking structure and the office building.

The other piece of information needed for context is that some degree of seismic design of structures is required in most of the United States. Thus seismic force-resisting systems are the focus of much of the discussion that follows.

U.S. Codes and Standards

State and Local Codes, Model Codes

The building code development and adoption process in the United States is quite complex. State and local building codes, which are the legal codes that must be followed for design and construction, are typically based on a model code. There have been three model codes in the recent past, the best known of which was the Uniform Building Code (UBC). These have now largely been replaced by the International Building Code (IBC). While much of the country has adopted the IBC, isolated big cities such as Chicago continue to use the older regional codes, now called the “legacy” codes.

Standards

The model code organizations do not have resources to develop code provisions on every aspect of design and construction covered by the building code. Thus, it is common for the model codes to adopt standards. The ASCE 7 Minimum Design Loads for Buildings and Other Structures and the ACI 318 Building Code Requirements for Structural Concrete are two important standards that are adopted by all model codes for design loads on structures and for concrete design and construction provisions, respectively. The latter document is a standard and not a code, even though the word Code appears in its title. The various standards published by the ASTM International are also widely adopted by all the model codes as well as by many other standards such as ACI 318.

Seismic Design Criteria

Seismic Zones

Until relatively recently, seismic design criteria in building codes depended solely upon the seismic zone in which a structure was located. Zones were regions in which seismic ground motion on rock, corresponding to a certain probability of occurrence, was within certain ranges. Under the UBC, which had significant worldwide influence, the U.S. was divided into Seismic Zones 0 through 4, with 0 indicating the weakest earthquake ground motion. The level of seismic detailing (including the amount of reinforcement) for concrete structures was then indexed to the Seismic Zone. Also indexed to the seismic zone were height limits on structural systems, minimum requirements concerning the analytical procedure that must form the basis of seismic design, and other restrictions/limitations/requirements.
Seismic Design Categories

The most recent development in the mechanism for triggering seismic design requirements and restrictions is the establishment of Seismic Design Categories (SDCs). It was recognized that building performance during a seismic event depends not only on the severity of sub-surface rock motion, but also on the type of soil upon which a structure is founded, and that building design requirements should depend not only on the building configuration, but also on its intended occupancy. As a result, the SDC is a function of location, building occupancy, and soil type.

Table 1 shows correspondence (not equivalency) between Seismic Zones and SDCs. Seismic design criteria that were applicable in the UBC to structures located in Seismic Zone 3 or 4 are now typically applicable in the IBC to structures assigned to SDC D, E, or F.

<table>
<thead>
<tr>
<th>1997 UBC Seismic Zone</th>
<th>A, B</th>
<th>C, D, E, F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 UBC Seismic Zone</td>
<td>A, B</td>
<td>C, D, E, F</td>
</tr>
</tbody>
</table>

Table 1: Correspondence between UBC Seismic Zones and IBC Seismic Design Categories

Table 2 shows the sections and subsections of Chapter 21 of ACI 318-11 that are applicable to a structure, depending on its SDC. The detailing required as a minimum for SDC A and B (Columns 2 and 3 of Table 2) is termed ordinary detailing. The detailing required as a minimum for SDC C (Column 4 of Table 2) is termed intermediate detailing. The detailing required as a minimum for SDC D, E, or F is (Column 5 of Table 2) is called special detailing. It should be noted that while intermediate or special detailing is fully allowed for a structure assigned to SDC B, neither ordinary nor intermediate detailing is allowed for a structure assigned to SDC D, E, or F; special detailing is the minimum requirement.

Seismic force-resisting systems of concrete consist of frames or shear walls or combinations thereof. The different categories of frames and shear walls of cast-in-place and precast concrete that are recognized by ACI 318-11, ASCE 7-10, and the 2012 IBC are shown in Table 3.

Note that there is no intermediate precast concrete moment frame and that there is no intermediate cast-in-place concrete shear wall. Note also that ASCE 7-10 makes a distinction between ordinary reinforced concrete and ordinary precast concrete shear walls.

The elements shown in Table 3 make up the various seismic force-resisting systems of cast-in-place and precast concrete, as described below.

Seismic Force-Resisting Systems

The basic structural systems that may be used to resist earthquake forces are listed in ASCE 7-05 Table 12.2-1. A general description of each of the seismic force-resisting systems is given below.

For concrete structural members within a building assigned to SDC D, E, or F that are not proportioned to resist forces induced by earthquake motions, the deformation compatibility requirements of ACI 318-11 Section 21.13 must be satisfied (ASCE 7-10 Section 12.12.4). In short, every structural component not included in the seismic force-resisting system in the direction under consideration must be designed to be adequate for vertical load-carrying capacity and the induced bending moments and shear forces resulting from the design story drift.

Moment-Resisting Frame Systems

This is a structural system with an essentially complete space frame providing support for gravity loads. Lateral forces are resisted primarily by flexural action of the frame members. The
Bearing Wall Systems

This is a structural system without an essentially complete space frame that provides support for the gravity loads. Bearing walls provide support for all or most of the gravity loads. Resistance to lateral forces is provided by the same bearing walls acting as shear walls.

Dual Systems

A dual system is a structural system with the following essential features:

1. Resistance to lateral forces is provided by moment-resisting frames capable of resisting at least 25 percent of the design base shear and by shear walls.
2. The two subsystems (moment-resisting frames and shear walls) are designed to resist the design base shear in proportion to their relative rigidities.

The 2012 IBC and ASCE 7-10 recognize dual systems in which the moment-resisting frame consists of special moment frames and dual systems in which the moment-resisting frame consists of intermediate moment frames.

The concept of the dual system loses its validity in buildings assigned to SDC B, since it is questionable whether the moment frames, which are required to have only ordinary detailing, can act as a back-up to the ordinary shear walls (the inelastic deformability of both systems are comparable). In areas of low seismicity, utilizing a shear wall-frame interactive system is more logical. In this system, the shear walls and frames resist the lateral forces in proportion to their rigidities, considering interaction between the two subsystems at all levels. There are additional requirements imposed by ASCE 7-05 Section 12.2.5.10. It is important to note that a shear wall-frame interactive system is not allowed in structures assigned to an SDC higher than B.

Building Frame Systems

This a structural system with an essentially complete space frame that supports the gravity loads. Resistance to lateral forces is provided by shear walls. No interaction between the shear walls and the frames is considered in the lateral force analysis; all of the lateral forces are allocated to the walls.

As in the case of dual systems, the concept of the building frame system loses its appeal for structures assigned to SDC B, since there is little to be gained from assigning the entire lateral resistance to the shear walls in the absence of any special detailing requirements for the frames. As noted above, a shear wall-frame interactive system, where there is no 100% shear wall requirement, is more practical and economical in such cases.

Undefined Structural Systems

Undefined structural systems are any systems not listed in ASCE 7-10 Table 12.2-1. The seismic design coefficients are to be substantiated based on approved cyclic test data and analysis.

Special Moment Frames, Intermediate and Special Shear Walls of Precast Concrete

Explicit provisions for precast concrete structural elements with intermediate or special detailing were first introduced in ACI 318-02. Until then, precast concrete structures could be built in areas of moderate or high seismicity only under an enabling provision of ACI 318, which became part of all the model codes adopting ACI 318. The provision allows precast concrete construction in a highly seismic area “if it is demonstrated by experimental evidence and analysis that the proposed system will have a strength and toughness equal to or exceeding those provided by a comparable monolithic reinforced concrete structure…. “ The enforcement of this vague, qualitative requirement was, for obvious reasons, non-uniform. The need for specific enforceable design requirements for precast structures in regions of moderate and high seismicity existed for a long time. The provisions introduced in ACI 318-02 have evolved some through the 2005, the 2008, and the 2011 editions of ACI 318.

ACI 318 presents two alternatives for the design of precast lateral-force-resisting systems. One choice is emulation of monolithic reinforced concrete construction. The other alternative is the use of the unique properties of precast concrete elements interconnected predominantly by dry connections (jointed precast). A “wet” connection uses any of the splicing methods of ACI 318 to connect precast or precast and cast-in-place members, and uses cast-in-place concrete or grout to fill the splicing closure. A “dry” connection is a connection between precast or precast and cast-in-place members that does not qualify as a wet connection.

Figure 1 illustrates the scope of the design provisions for precast concrete structures assigned to intermediate or high seismic design categories (C, D, E, or F).
Special Moment Frames (ACI 318-11 Section 21.8)

Emulative Design (Sections 21.8.2, 21.8.3) - Precast frame systems composed of concrete elements with ductile connections (Section 21.8.2) are expected to experience flexural yielding in connection regions. Precast concrete frame systems composed of elements joined using strong connections (Section 21.8.3) are intended to experience flexural yielding outside the connections. Strong connections include the length of the coupler hardware. Capacity design techniques are used to ensure that the strong connection remains elastic following the formation of plastic hinges in the connected members. Additional requirements are provided to avoid hinging and strength deterioration of column-to-column connections.

Non-Emulative Design (Section 21.10.3) – Special structural walls constructed using precast concrete and unbonded post-tensioning tendons and satisfying the requirements of Section 21.10.2 are permitted provided they satisfy the requirements of ACI ITG-5.1.

The non-emulative or jointed systems are of particular interest in U.S. practice. The Precast Seismic Structural Systems (PRESSS) research program played an important role in the development of non-emulative systems. The program had two primary objectives: to develop comprehensive and rational design recommendations needed for a broader acceptance of precast concrete construction; and to develop new materials, concepts, and technologies for precast concrete construction in regions of different seismic hazards. As the key element to the final phase of the PRESSS research program, a 6/10-scale five-story precast concrete building was constructed and tested under simulated seismic loading at the University of California, San Diego (UCSD). The structure combined five different seismic force-resisting systems in regions of varying seismic hazard. Of these, the hybrid frame (utilizing post-tensioning strands as well as mild reinforcement in the beams and through the beam-column joints) and the precast post-tensioned shear wall system are highly suitable as components of the seismic force-resisting systems in structures assigned to SDC D, E, or F. Much effort has gone into their codification in recent times. The hybrid system in particular has seen important applications.

Applications of PRESSS Systems

Several commercial structures completed in the field have demonstrated the viability of the jointed precast concrete special moment frame system. The most prominent building using this system is the 39-story Paramount apartment building in San Francisco.

A recent application of the hybrid moment frame in a parking structure is shown in Figure 3.

An application of both the hybrid frame and the unbonded post-tensioned shear wall was found in Santiago, Chile by a PCI team sent to investigate damage from the February 2010 earthquake. The precast manufacturer Preansa constructed a five-story structure at their convention/exhibition site that used unbonded post-tensioned walls and frames following the research of the PCI PRESSS program. The structure is braced in the short direction by post-tensioned shear walls placed at the ends of the building. The post-tensioning strands are...
located near the center of the walls. In the other direction, there are three bays framed with unbonded post-tensioned moment-resisting frames. A view of the structure is shown in Figure 4. Although the erection of the structure was complete, the building was unfinished at the time of the earthquake. The first floor was in operation as a kitchen for the convention center. The upper floors remained to be completed. The structure experienced no damage from the earthquake.

Concluding

The application of precast structural systems in parking structures, office buildings, and other construction is increasingly successful throughout the United States including its regions of moderate and high seismicity and is being increasingly recognized in U.S. codes and standards.

This includes innovative structural systems that do not emulate cast-in-place reinforced concrete construction.

This Paper was Presented at FIB - Days 2012 International Conference held at Chennai.

Architects MacKay-Lyons Sweetapple have designed a cantilevered two hull house for a family of four suitable to extreme coastal climate in Nova Scotia. The hull house consists of a steel-framed structure with a wooden skin, and it boasts a geothermal-heated in-floor hydronic system and extensive glazing that provides substantial daylighting and mind-boggling views of the dramatic landscape. The house designed as a pair of binoculars with two pavilions resembling ship hulls that are elevated to allow rushing sea water to pass below. The 32 foot cantilevers are supported on concrete foundations that permit seawater to flow freely underneath without causing any damage to the house. Eight foot vertical rain screens made of wood provide further protection to the interior. Deep overhangs create shelter and shade while floor to ceiling windows on the sides of the home bring natural light into every corner. A weathered wooden block protected clad in 4” horizontal shiplap linking the two “hulls” contains an entry foyer, core, and the kitchen. A full time home that respects its natural environment, the two hull house also retains some sense of energy independence heated as it is by the earth.