EARTHQUAKE RESISTANCE

Precast concrete can be designed to resist seismic events, and recent advancements in connection approaches provide additional design options.

Earthquakes in Guam, the United States (Richter scale 8.1); Manila, the Philippines (Richter scale 7.2); and Kobe, Japan (Richter scale 6.9), have subjected precast concrete buildings, using both architectural cladding and structural components, to some of nature's deadliest forces. During the 1994 Northridge, Calif., earthquake (Richter scale 6.8), in which damage was estimated at $20 billion, most engineered structures within the affected region performed well, including structures with precast concrete components.

In particular, significant damage was not observed in precast concrete cladding due to either inadequacies of those components or inadequacies of their connections to the building's structural systems, nor was damage observed in the precast concrete components used for the first floor or first-floor support of residential housing. Parking structures with large plan areas, regardless of structural system, did not perform as well as other types of buildings.

The key reason designers have gravitated toward precast concrete components is because they can span long distances between attachments to the main structure. Design methods and details have been developed to accommodate these applications in seismic areas.

Earthquakes generate horizontal and vertical ground movement. When the seismic waves pass beneath a structure, the foundation tends to move with the ground, while the superstructure remains in position. The lag between foundation and superstructure movement causes distortions and develops forces in the structure. As the ground moves, distortions and forces are produced throughout the height of the structure, varying with the ground acceleration and the resonance of the building.

Ductility Needs

The current philosophy for the design of earthquake-resistant structures permits minor damage for moderate earthquakes and major damage for severe earthquakes, provided complete collapse is prevented. The design details often require large, inelastic deformations to occur to dissipate energy and shed inertial forces. This is achieved by providing member and connection ductility.

While this ductility helps resist total collapse, the resulting distortions may lead to significant damage to mechanical, electrical, and architectural elements. Seismic damage can be minimized by setting limitations on structural deflections, usually considered as interstory drift.

The response of a structure to the ground motion of an earthquake depends on the structural system's dampening characteristics and on the distribution of its mass. With mathematical idealization, a designer can determine the probable response of the structure to an imposed earthquake.

New Code Requirements

A number of changes have been made to existing codes in recent years based on new research and observations. These include:

- Recognition of jointed-panel construction as an alternative to emulation of monolithic construction.
- Achieving ductile structural behavior by using "strong" connections that remain elastic while nonlinear action (plastic hinging) occurs in the member away from the connection.
- Modification of drift computation and limiting drift.
- Deformation compatibility of structural elements and attached nonstructural elements.
- Additional soil-type classifications.
- Special considerations for building sites located near seismic faults.
- Special considerations for structures possessing redundancy.

PCI has worked in several of these areas to help create new design solutions that provide more effective responses to seismic events. A 10-year study by the Precast Seismic Structural Systems (PRESSS) Research Program produced three new approaches that have been or are in the process of being codified. These three systems are:

The Paramount's use of a precast hybrid, moment-resisting frame as part of its structural system is that it creates a restoring force provided by its elastic, post-tensioned strands that rights the building following a seismic event. Architect of Record: Kwan Henmi, Architecture/Planning; Photo: David Wakely Photography.

1. **A hybrid post-tensioned precast frame**, which was codified in 1999. Developed by the National Institute of Standards & Technology (NIST), this method has the precast concrete beams connected to multistory columns by unbonded, post-tensioned strands that run through a duct in the center of the beam and through the columns. Mild steel reinforcement is placed in ducts at the top and bottom of the beam, which is sleeved through the column and grouted.

   The reinforcement yields alternately in tension and compression and provides energy dissipation, while the post-tensioning strands essentially act as "rubber bands" that help right the structure after the seismic event ends. There are no column corbels, with the vertical shear resistance provided by the post-tensioning strand. The post-tensioning steel balances the mild steel reinforcement so the frame re-centers after flexing during a seismic event.

2. **A pretensioned precast frame**, which is applied at locations where the most economical connection method features one-story columns with multispan beams. The multispan beams are cast with partially debonded pretensioning strand set on the columns. The column's reinforcing steel extends through the sleeves inside the beams. Reinforcing-bar splices ensure continuity above the

A moment-frame beam form illustrates the center PVC duct that holds the prestressing tendons and the six corrugated tubes for the mild steel bars used in the hybrid system.

Rigorous tests performed on an experimental structure proved the success of the PRESSS program's connection technology.

beam. As the frame displaces laterally, the debonded strand remains elastic. While the system dissipates relatively less energy than other systems, it re-centers the structure after a major seismic event.

Although this frame has performed satisfactorily in tests, it would not be allowed to act as the sole seismic-force-resisting system in regions of high seismic risk or for structures assigned to high seismic-performance or design categories under Section 21.6.3 of ACI 318.

Such frames can be designed to satisfy all requirements for use as intermediate moment frames. These frames should also be acceptable for intermediate moment frames when designed using the same factors as those specified in the governing building code for cast-in-place concrete construction.

Analyses are still being done to verify the applicability of this system to various high seismic events. In the interim, the satisfactory performance of the frames in the PRESSS tests can be used to seek building-department approval for these designs in moderate seismic-risk zones and for structures assigned to intermediate seismic performance or design categories.

3. **A shear-wall system.** The PRESSS shear-wall design used an innovative approach for anchoring and connecting jointed walls to lengthen the structural period and reduce the design-based shear forces. Gravity loads were mobilized to partially resist overturning from the lateral ground motions. The system also considered the behavior of the jointed shear-wall system when the wall lifts off and rocks, along with its effect on design forces. An important level of hysteretic damping was added to the wall system through the connection devices located at the vertical joint between the wall panels.

   U-shaped flexure plates were used for vertical joint-connection devices where damping was achieved with flexural yielding of the plates. Unbonded post-tensioning forces re-centered the wall system when the load was removed, so there would be minimal residual drift after a design-level earthquake. Re-centering was ensured by relating the elastic capacity of the post-tensioning system to the yield strength of the panel-to-panel connection.

   The shear wall is expected to displace laterally to approximately 2% of story drift under a design-level earthquake. This is consistent with the drift limits specified by existing standards. Should the designer desire smaller design-story drift or less energy dissipation, the balance of post-tensioning and energy-dissipating connections could be altered.

   This shear-wall design and test has led to the adoption of an allowance for nonemulative design of special precast concrete shear walls to be accepted for the 2003 edition of the National Earthquake Hazard Reduction Program (NEHRP) Provisions.

Contract Document Requirements

Many precast concrete buildings are designed by a team including the engineer of record, the precast manufacturer's engineer, and possibly a specialty engineer retained by the manufacturer. It is the engineer of record's responsibility to provide pertinent information on the contract documents so that others providing the seismic design of the structure use the correct information for the location of the project. The 2006 International Building Code indicates what these requirements are in Section 1603.