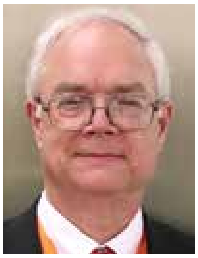
High-Performance Parking Structures Using Precast/Prestressed Concrete

— Ned Cleland, Ph.D., P.E.

More structures today are being challenged to be high performance, but what does this mean for a parking structure? High-performance structures are those that integrate and optimize all relevant attributes on a life-cycle basis. Therefore, designers and owners must consider what the relevant attributes are for a parking structure. Some of these include optimizing the layout and traffic flow for the site; meeting program requirements, such as efficiently providing the number of spaces needed; operational efficiency; providing a safe and secure environment for users; creating a durable structure to meet its intended service life, and reducing life-cycle costs, which includes energy use and maintenance.

However other relevant attributes might include meeting an aesthetic requirement; incorporating a mixed-use function, or being resilient enough to resist hurricane winds. Whatever the combination, it's important to integrate quality materials, design, and detailing to meet the demanding requirements of these facilities. Designers must also understand the advances in design methodology and practice to best achieve project goals.



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In the United States, the use of precast/prestressed concrete systems has been a favored method for parking structure construction for several decades. Throughout the years, there have been significant advances in techniques, technology, and details to make these structures more efficient, serviceable, and highly durable. Some of these advancements include new double tee widths up to 16-feet reducing the number of joints, increase in structural depth of stems to increase stiffness and reduce transient vibrations, and dry system connections and detailing so that use of cast-in-place concrete above the foundation can be limited to small transitions between sloped floors and pedestrian entrances. Overall, the strength, durability, resiliency, and sustainability of precast concrete have evolved to extraordinary levels. This article provides some guidance for system layouts and details to help designers achieve high-performance parking structures. More information can be found at http://www.pci.org/Project_Resources/Parking_Structures/.

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Framing Basics

Precast/prestressed concrete with long-span double tees is modular construction. Double tees are made in forms with standard widths with an allowance for joints. Typically precast concrete double-tee widths are 10 ft., 12 ft., 13 ft.-4 in., 15 ft., and 16 ft. Today, 12 ft. is the most common, but producers in various markets may offer a variety of double-tee widths. Framing layouts should be designed based on the double tee width, or module being used. For example when using a 12-ft double tee, a 48-ft. bay could be used. Narrow double tees can be made to fit spaces that are off-module because of functional features and constraints, such as stairwells, parking modules, and site limits.

Changes in framing must occur at the joints between the double tees. Ramps should start and stop at joints and at the end of beams. When needed for ramp slope and length limits, a small offset of the double tee joints can be made from the column centerline at the ends of ramps, but offsets greater than the width of the column will require a transition completed with cast-in-situ topping.

Ramps that provide the vertical circulation between levels are an essential feature of most parking garages. Unless exterior site grades provide direct access to upper levels, all parking structures must include ramps. The most efficient ramps are sloped full width bays that also accommodate parking. The slopes of the "park-on" ramps are limited to 1:15 (6.66%) by the International Building Code, but these ramps are commonly framed with 6% slope or less for higher levels of comfort and improved sight lines. Interior framing lines supporting ramps are framed more efficiently with walls than with back-to-back beams and columns. These walls can support the different framing levels on each side with less thickness and fewer components. It is common to provide module-spaced openings in these walls for ventilation, light, and security. The openings allow drivers and pedestrians better site lines, and reduced weight, reducing shipping costs.

Figure 1 shows part of the framing for a parking garage with modular bays and three long span bays with interior ramping. Other features of the high-performance details in this layout are drainage, joints and flange connections, and structural system design.

Drainage

Drainage of water from a structure is an essential part of designing a high-performance precast/prestressed concrete parking structure. Drainage requires attention to the global layout as well as to the local details. Water needs to be directed by slopes in two directions to the point where the drain is placed. On continuous ramp parking structures, the drains and drain lines typically are kept on the interior column lines to minimize the architectural impact of the vertical drain line on the exterior. This also minimizes the cost of the drainage system.

It is important to consider that prestressed double tees have a natural camber due to the prestressing. This causes the middle of the span to be higher than the ends. The amount of camber depends on the double tee section, the span, the loads, and the strength of the concrete, but typical applications should plan for camber between one and two inches. Basic guidelines can be found in ACI 362.1R-12, *"Guide for the Design and Construction of Durable Concrete Parking Structures."*[1] For pretopped double tees, the design slope parallel to the double tee should be 1½% percent, and the transverse slope should be 1%. For a typical 48 ft. bay with 60 ft. long double tees, this would slope the double tees 11 inches from outside to inside beam, and then 6 in. for the beam to the low end at the drain. Some double tees having less camber may permit less longitudinal slope, but the total slope from high corner to low corner should not be less than 1½% percent overall, which would result in 14 inches for a 48-ft. bay. A corner bay with these variations form the high corner elevation at 0" is shown in Figure 2. This pattern is repeated along the length of the garage in the "level," or nonsloping bays so there is a drain in every other bay.

For this layout in Figure 2, the slope on the outside supports, which are walls in this example, is the same as the slope of the inverted tee beam at the low end of the bay. Hence, this configuration avoids warping or twisting the floor.

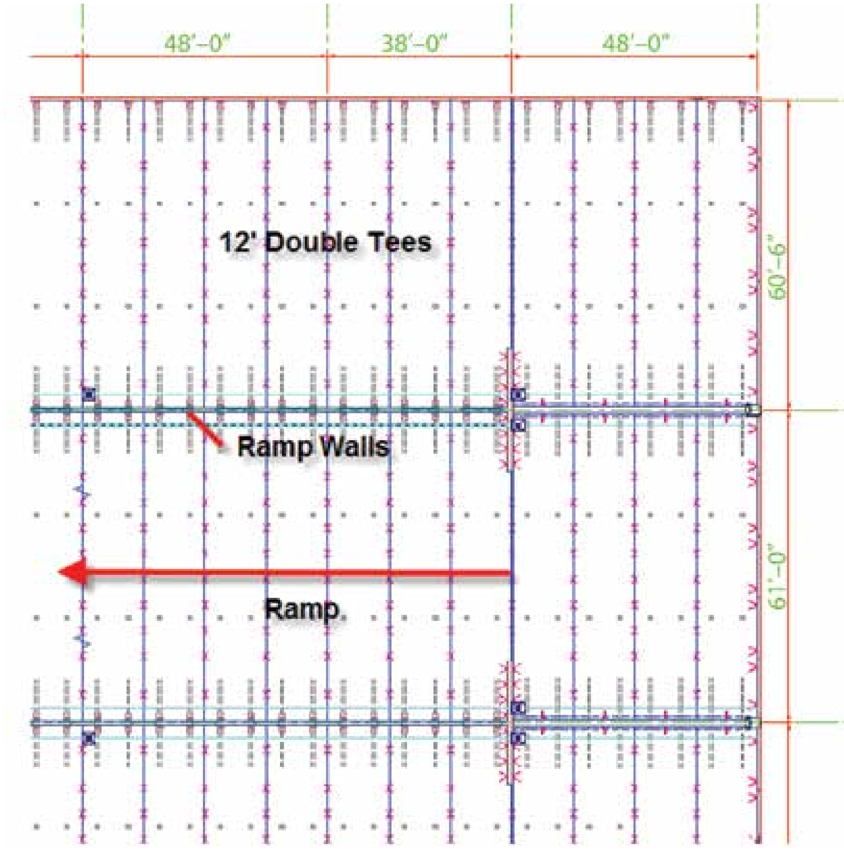

Figure 1 Common Framing Features.

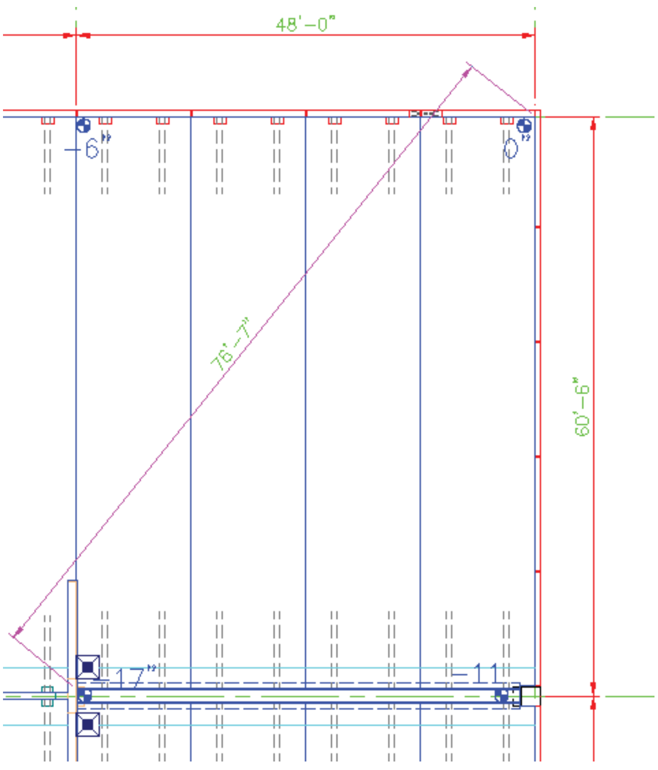

Figure 2 Slopes to Drain.

When spandrel beams are used for the exterior framing, they must be sufficiently deep to cover the depth of the double tees and the slope without the bottom of the double-tee stems showing below the beam. Slope can be developed in several ways such as:

1. The spandrel beam itself can slope,
2. The ledge within the spandrel

beam can be sloped, or

3. The dapped ends (blocked out sections) on the double tee stems can be variable to achieve the required slope.
4. For spandrel beams with corbel bearings, the corbels can be placed to provide the slope.

Twisting or warping the precast floor units is acceptable; provided they are sufficiently flexible and any transverse bending stress can be accommodated without cracking the flanges. Warping effects have been studied and reported in PCI papers.[2,3] Warping stress at the ends of the double tees is primarily an effect of transverse bending in the flange. The level of stress depends on the double-tee span, the amount of twisting, the stiffness and spacing of the stems, and the stiffness of the flange. These factors vary with the project layout and with the double-tee cross section, but in general 1 to 1½% of warping can be accommodated for pretopped members that span over 50 feet.

When the high ends of the double tees are held level, it is even more important to provide sufficient slope over the length. The floor parallel to the end spandrel beam should never be held level with the high ends of the tees. This configuration will result in ponding in the high corner because camber will prevent this configuration from draining

One particular type of parking structure design can cause difficulties in this regard. In a three-bay layout with a ramp in the center bay, it is difficult to achieve the recommended drainage slopes without unbalanced slopes across the garage. The outside bays slope to the inside beam lines at the ends of the ramp, so the elevations at each end of the interior double tees are the same. The slope along the beam will bring water toward the drains, but the camber of the double tees is often not sufficient for effective drainage. This can be addressed by providing a drainage "diamond" at the bottom of the ramp so that water follows the cross slope to the drain, shown in Figure 3. Note: drainage diamonds are typically only used with field-topped, double-tee applications.

After the drainage system is established, it is important to provide the local details to ensure that the system works. At the low end of the double tees, there needs to be a low line to collect water and direct it

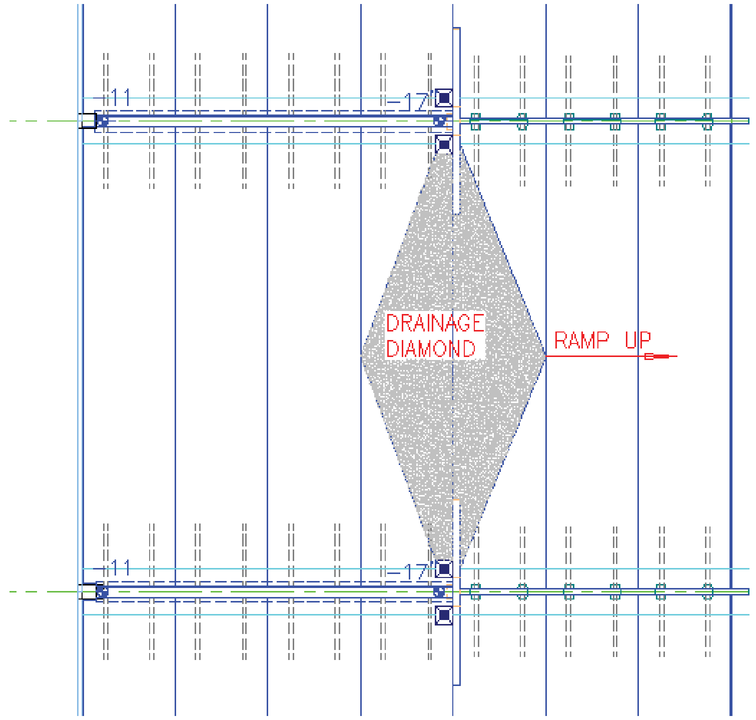

Figure 3 Drainage Diamond at Interior Base of Ramp.

to the drain. It is best that water not be directed across the sealed joints between the double tees and the inverted tee beam, so drains should be placed on either side of the beam. Figure 4 shows a layout with wash lines set to coincide with the centers of the drains. The ends of the double tees are made 2 inches higher than at the wash lines. When the system uses cast-in-place pour strips, the wash lines define the edge of the precast concrete pour strips. When the drains occur adjacent to a shear wall, as shown in this plan, it is necessary to provide openings for the water to pass though the wall to reach the drains.

When the precast double tees are cast with a wash and no pour strip is used, the drains can be cast into the flange. A section through a beam at an interior column illustrates this particular detail, in Figure 5. Specification-compliant drains for parking structures are commonly made in four parts. The iron casting for the rim is separate from the body of the drain that holds the strainer and has the pipe outlet. There are drains made with low rim profile (2 to 2½") that are suitable to be cast in the flange. After the rim is cast in, the drain body is mounted to the rim with a rubber gasket to seal the joint. The strainer and drain grate are then added to complete the drain. The double tee can be shipped to the site with the drain already set so that only the drain piping is needed. When the drains are set on the beam side of a shear wall at a cross-over bay, the walls also need openings below the drains for the piping to reach the drain leader piping that is usually placed on the inside corner for protection.

It is also important for headroom and piping efficiency to provide the drainage at the grade level in the same pattern used for the precast framing. The slab-on-ground needs to have similar variations in elevation to keep the same floor to floor heights.

Joints and Flange Connections

Parking structures are often subjected to severe and harsh environments. As with all precast concrete systems, the jointing and the connections define the behavior and performance, and therefore it is important to pay close attention to the details at joints, particularly in the flange-to-flange connections. Things such as weather, deicing salts, traffic loads, seismic strength, and ductility loads are more demanding on these types of joints than any other type of structure. The challenge can be met with attention to detail in design and construction, and the use of high-quality joint material.

Even when the parking garage is constructed with field-placed composite topping, the treatment of

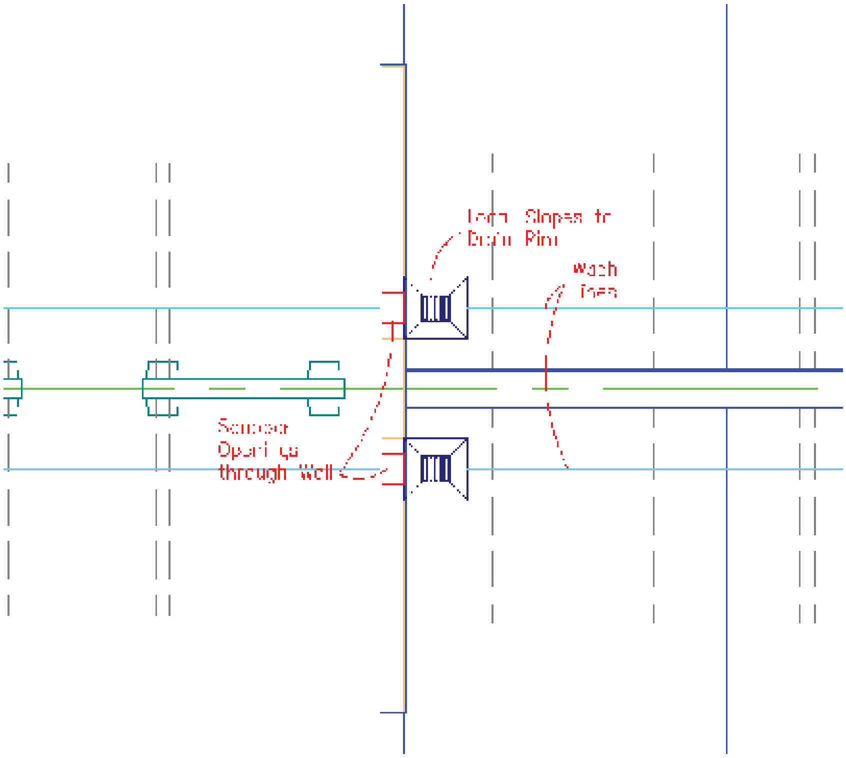

Figure 4 Local Plan at Interior Drains.

joints is critical. Wherever topping concrete crosses a joint in the underlying precast, there must be a tooled joint to provide control joints and a seam for waterproofing. Joints in the precast are natural locations for shrinkage and creep volume change movements to find relief. Tooled joints in a topping slab provide for movement to avoid irregular cracking in the topping, as well as provide a more resilient edge that can take the repetitive loading of traffic.

Experience has shown that movement in precast concrete systems is the sum of the small local movements that occur at joints. Lateral forces as well as volume changes (creep, shrinkage and temperature changes) put demands on flange connections and reinforcing. Temperature changes alone can create strain demands in the reinforcement that crosses these joints. For example, a welded wire reinforcement, with 10-inch-wide cross wire spacing, placed in the topping across joints might yield under movement caused from temperature change. Smaller diameter deformed bars may be a better solution for topping reinforcing as this type of reinforcement allows the joint opening strain to be distributed over the development length of the bars.

High-performance double tees in pretopped parking structures have the top edge of the flanges consolidated and shaped by tooling. Flange connections are spaced to provide for alignment of the flange surfaces, for continuity under moving traffic loads, and for shear transfer under lateral forces. These are typically spaced 4 to 5 ft. in the drive lanes, with wider spaces in the parking spaces and near the ends of the double tees. These connections are subject to transient loading and must be detailed for durability and fatigue. These connections must have the capability to flex without damaging the concrete that holds them. There are three essential points for connection performance.

1. The material for the connections should meet the recommendations of ACI 362.1R-12 for the exposure zone of the project. For the most aggressive environmental conditions, stainless steel is the recommended connection material.
2. These connections should not be over-welded. The strength of the connections is developed with welds that are about one half the length of the exposed weld surface. Limiting the weld to the center of this interface keeps the flexibility that is needed for the connection to tolerate traffic and volume change movements without damaging the underlying concrete.
3. The edges of the embedded part must be isolated from confining concrete so that the flexing of the parts does not cause a spall on the top, sides or bottom of the flange.

Figure 6 shows flange connection

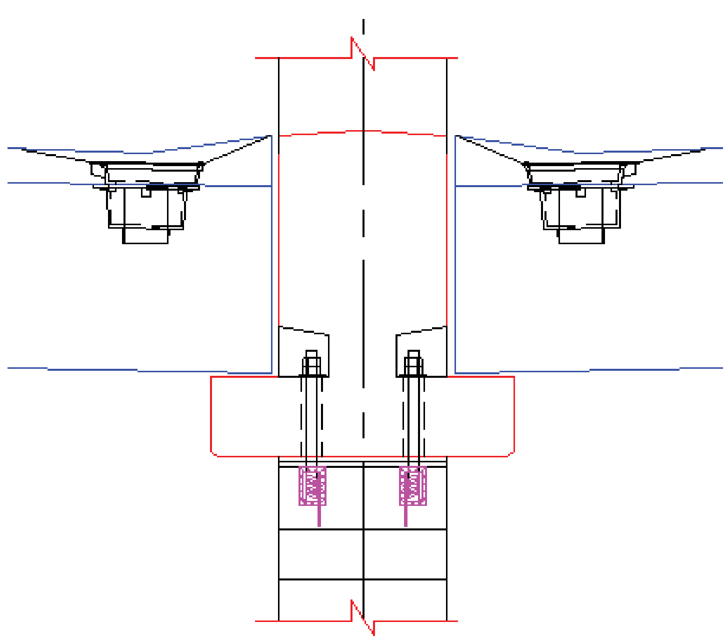

Figure 5 Drains Cast in Precast Wash.

details used with pretopped double tees with ¾" recess from the top surface. This detail also shows isolation to remove concrete immediately below the embedded part so that it is free to deflect without prying the edge of the flange that can cause a spall. There are variations on commercial and plant-fabricated parts that can meet the high demands of this application, but each needs to be installed to meet these three essential points.

The double tee also has chord connections at the ends to take the tension and compression of the floor acting as a diaphragm. In a system using pour strips, the chord reinforcing is mild steel placed in the cast-in-place concrete topping. Attention to durability in the pour strips is important. The cast-in-place concrete should be at least 5,000 psi concrete with air entrainment and a water/cementitious material ratio not greater than 0.40. Adding corrosion inhibitor or using epoxy-coated reinforcing as additional protection in higher exposure zones may also be needed. It is important that the field crews placing this concrete understand the final shape of the pour strip washes must positively direct water to the drains.

When the chord connectors are designed for the dry system, they should follow the same principles applied to flange connections. These connections usually link continuous bars that cross the ends of the double-tee flanges. A low-profile detail using vertical or slightly tilted plates with a slug weld link is shown in Figure 7. As these connections are placed at the ends of the double tees, they are subject to less movement, and are more rigid than typical flange connectors. These connections should also have some isolation around the face plates to accommodate movement, including expansion during welding. Concrete below the face plates is also subject to damage of this type.

The double tees are also connected across joints at the ends to beams, spandrel beams, or walls. When possible, it is best to locate these connections on the underside of the flange so that it is isolated from the exposure of the top surface and well below the sealed joint.

Completion of the joints requires proper placement of a high-quality joint sealant by a qualified installer.

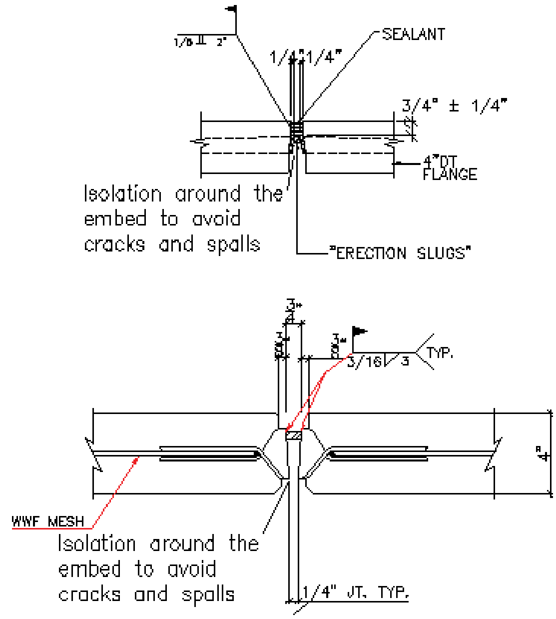

Figure 6 Flange Connection Details.

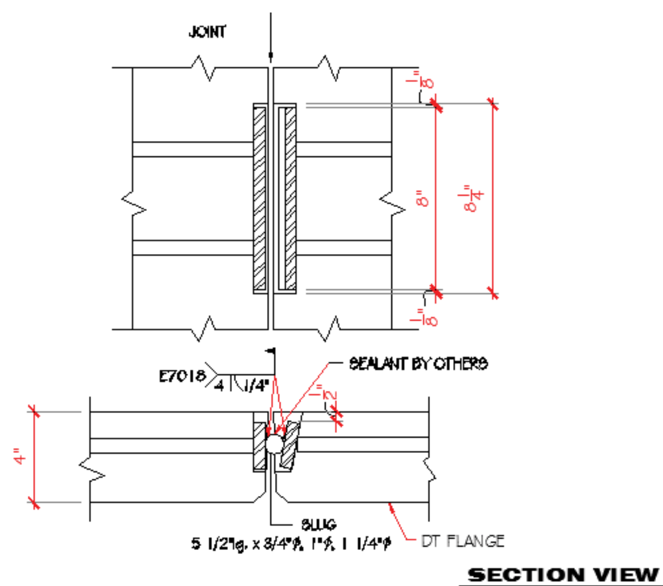

Figure 7 Dry System Chord Connector.

One-part or multipart urethane sealant is most commonly used in high-performance precast parking structures. These materials must be installed with proper joint preparation, which includes the use of a compatible primer for most installations. Tooled joints make this installation easier, but any irregularities or tight joints should be ground to provide a uniform substrate without soft edges or laitance. The sealant shape should be maintained using a backer rod placed at the proper depth below the floor line. Where the sealant crosses connections, it is important to use a bond-breaker over the link so the seal can move with the remaining parts of the joint. In areas of high exposure, such as open roofs, silicone sealers are sometimes used for longer effective life.

Structural System Design

After considering the basic framing guidelines as well as the drainage and joint details, the designer must assure that the overall structural system layout meets the needs due to gravity, lateral, and volume change forces. The strength and stiffness of the structure is required to resist wind and earthquake loads. The structural system performs best with simple and symmetric lateral force-resisting elements such as shear walls which are favored due to their strength and economy. In many high-performance structures, ramp walls provide the dual function of resisting gravity and lateral loads.

Sight lines when using shear walls can be improved by limiting the wall lengths to only what is necessary, and by casting in wall openings as long as the remaining portion of the wall can transfer the required loads. The typical framing layout shown in Figure 1 uses shear walls instead of columns at the ends of the ramp. If the wall obstruction at a cross-over bay is too great, these transverse shear walls can be located further into the structure away from the end of the ramp. These transverse shear walls can also be connected to the ramp walls forming a cruciform shape and benefitting from the resistance to overturn due to the dead load from the ramp walls.

The structural system must be configured to accommodate volume changes. Location, orientation, and connections to the lateral force-resisting system should be considered to reduce restraint and allow the structure to respond to temperature movements. The *PCI Design Handbook*[4] provides guidance on the acceptable lengths of buildings without expansion joints. Well-configured framing with ductile connections can allow these limits to be stretched to eliminate the need for expansion joints, but the designer must take care not to create excessive movement in the joints that are provided. Because expansion joints create additional demands for seismic detailing, for gravity load transfer, and for attention to maintenance, when a layout is near the limits, it is usually best to leave expansion joints out.

Conclusion

Precast concrete is an outstanding material and system to build high-performance parking structures. Precast concrete is an inherently durable material that provides design and aesthetic versatility, accelerated construction, with a high degree of quality. However, careful attention to planning, detailing, and fabrication of the structure, along with the proper routine maintenance will lead to increased service life and reduced life cycle costs. Ultimately, all of these considerations help designers and owners build and operate high-performance parking structures.

References

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For more information on these or other projects, visit www.pci.org/ascent.