CAST-IN-PLACE
CONCRETE PARKING STRUCTURES
This brochure contains case studies of 20 parking structures located throughout the United States. In most of these cases, a post-tensioned structural system was selected after careful economic studies and comparisons indicated initial or life cycle cost savings. In some cases, the initial costs were comparable to a competitive alternative, but life cycle cost comparisons or the other tangible advantages discussed below resulted in selection of post-tensioned concrete structural frames. The cast-in-place concrete structural system most commonly used for parking structures is a one way slab supported on beams. The slabs typically have spans in the range of 17 ft to 27 ft. The beams usually have spans in the range of 50 ft to 62 ft. Most of the examples in this publication illustrate the beam and slab structural system.

Two way flat plates and flat slabs are also used for parking structures as is illustrated on pages 10 and 31 to 33. An independent statistical analysis* of parking structure construction for 1986 to 1989 shows that cast-in-place post-tensioned concrete structural solutions were most often selected. These are the reasons:

**INITIAL AND LIFE CYCLE COSTS**

Analyses and competitive bids against alternative systems often show that post-tensioned structural systems provide initial cost savings. Alternative bids for the Indianapolis International Airport Parking Structure (see page 12) resulted in a savings of about $1.00 per square foot for the post-tensioned alternative. When initial costs are more nearly comparable, life cycle costs often show savings for post-tensioned alternatives. Quantities and cost information for the 20 case studies in this brochure are presented in the project summaries, pages 26-27. Additional quantities suitable for estimating purposes are presented on pages 31-33.

**LOW MAINTENANCE COST**

Properly constructed cast-in-place post-tensioned concrete floors are virtually crack-free and use widely spaced floor joints (joint spacing of 200 ft or more are common). The use of epoxy-coated reinforcement, encapsulation of post-tensioned reinforcement, low water/cement ratio air-entrained concrete, and concrete sealers in aggressive environments provide floor systems with minimal maintenance costs. See the detailed discussion of durability on pages 28-30. Precast floors, particularly “untopped” precast floors, require periodic maintenance repairs of the caulked joints.

*Numbers in raised () refer to references listed at the end of this section.
HIGHEST QUALITY AT COMPETITIVE COSTS

between the precast units. One consulting firm estimated that 30 percent of the caulked joints of precast floors will need to be replaced every three years after the five year warranty expires. Loss of parking spaces during maintenance work results in loss of parking revenue.

CRACK CONTROL AND WATERTIGHTNESS

In addition to elimination of caulked joints, post-tensioning helps achieve watertightness by introducing a state of bi-axial compression in the slab, thereby controlling cracks. That's an important advantage because water, dirt and de-icer chemicals leaking through cracks or joints may make parts of a parking structure unusable or require costly repairs.

SMOOTH RIDING SURFACE

The continuous riding surface with minimal joints provided by cast-in-place concrete construction creates a superior riding quality since most joints are eliminated and differential initial and long-term deflections across joints are not a concern. Cast-in-place floors are also readily warped to provide smooth geometry transition between ramps and floors.

ENHANCED LIGHTING AND PATRON SECURITY

The wide beam spacing and flat surfaces provided by cast-in-place parking structures enhance the installation and efficiency of the lighting system. This results in improved aesthetics and enhanced patron security.

FIRE RESISTANCE

The fire resistive characteristics of the flat surfaces and wide beams of post-tensioned structures provide fire resistive ratings to meet code requirements. Thin-stemmed structural elements provide less concrete insulation to delay strength loss of the main reinforcement. This results in shorter fire resistive periods.

(Riding surface of Xerox Centre Parking Structure (Phase 1), Santa Ana, CA)

(Lighting of Franklin/Van Buren Self Park, Chicago.)

(Photos courtesy Desman Associates.)
ADVANTAGES OF CAST-IN-PLACE

The ease with which architectural treatments of exposed concrete are achieved is a definite advantage of cast-in-place concrete structures. A notable example is the Williams Square West Garage, Irving, Texas shown at the left. In this structure, the concrete in exposed perimeter elements was made with a crushed granite aggregate. The concrete for the interior beams, slabs and columns used a more economical crushed limestone aggregate. To fully reveal the color of the granite, perimeter surfaces were sandblasted.

REDUCED STRUCTURAL DEPTH

Use of post-tensioning reduces the depth of the floor system by one-third or more in comparison to some alternative systems. Reduced structural depth enhances both the appearance and economy of post-tensioned concrete parking structures. In some cases, such as the Sands Hotel/Casino Parking Structure on page 11, depth reduction was an essential factor in meeting code height restrictions. For the Douglas Parking Structure (see page 10), reduction in height of the parking structure was a primary architectural consideration. For underground parking structures, reduced depth reduces excavation and shoring costs as well as improving parking efficiency due to shorter ramps.

DEFLECTION AND VIBRATION CONTROL

Because of their draped configuration, the tendons in a post-tensioned structure carry much of the load directly to the columns. This reduces flexural deflections in the framing system. Due to post-tensioning, the entire concrete section is effective in resisting load effects. In conjunction with the redundancy of monolithic concrete framing systems, this reduces vibrations of the completed structure.

FUNCTIONAL FLEXIBILITY

Cast-in-place, post-tensioned concrete construction provides long, column-free spans and is easily adaptable to the framing and functional requirements of parking structures. Post-tensioned construction easily accommodates the framing requirements of straight ramps, curved ramps, and irregular sites. There is no functional compromise, which can be the case with other framing systems.

ESTHETICS

The architectural appeal of cast-in-place concrete construction is widely recognized. In fact, structures with other framing systems often imitate cast-in-place concrete parapets and fascia. Curvilinear shapes and forms economically achievable in cast-in-place structures provide the necessary flexibility for creative architectural expressions. The aesthetic advantages of cast-in-place concrete parking structures are shown by the following project case studies.
CONCRETE CONSTRUCTION

FRAME RESISTANCE TO LATERAL LOADS

Monolithic connections between slabs, beams, and columns provide a rigid frame with built-in resistance to wind and other lateral loads. The use of this inherent frame action in the Texas - Medical Center Parking Structure No. 7 (see page 22) eliminated the need for shear walls or bracing, even under hurricane wind loads.

RESISTANCE TO SEISMIC LOADINGS

Hundreds of post-tensioned parking structures performed well in the 1971 San Fernando earthquake and in the 1989 Loma Prieta earthquake. Research has shown that unbonded post-tensioning improves the behavior of structural frames under seismic loadings. Code provisions developed by the Building Seismic Safety Council now recognize the helpful effects of unbonded post-tensioning in ductile moment resisting frames.

STRUCTURAL INTEGRITY

The 1989 ACI Building Code introduced reinforcement requirements for structural integrity. These requirements insure a minimal resistance to abnormal or catastrophic loading conditions not contemplated in the routine design loadings. Both research and experience have shown that post-tensioned structures inherently provide structural integrity under abnormal and even catastrophic loadings.

LOCAL LABOR AND MATERIALS

The predominant use of local labor and materials contributes to the low initial cost of cast-in-place concrete parking structures. Nearby ready-mix producers, rebar fabricators, formwork contractors, rebar and concrete placers, and other suppliers are convenient sources of abundant raw materials to be delivered when and as needed for cast-in-place construction. Federal projects to reduce unemployment recognize the advantages of using local labor. For maximum economic benefit to your community, and lowest total construction cost, the logical choice is a cast-in-place concrete parking structure.

CONSTRUCTION ADVANTAGES

Materials delivery: With cast-in-place construction, the contractor has direct control of the cost and delivery schedule of the concrete from local sources. Delivery of precast products is controlled by a separate organization, often located at a significant distance from the construction site, and is often disruptive to traffic flow.

Cast-in-place construction eliminates the time and cost of hauling heavy prefabricated elements from the fabrication plant to the job site, as well as the need for heavy lifting equipment. There's also no need for a large storage area at the construction site (see write-ups of Sands Hotel/Casino and Texas Medical Center No. 7 parking structures, pages 11 and 22, respectively).

Large-panel flying forms, and modular forming systems, enhance the construction speed and economy of cast-in-place concrete parking structures. Review of the construction periods in the project summaries (see pages 2 and 27) reveals very competitive construction periods, even in locations with severe winters.

CASE STUDIES

The advantages of cast-in-place post-tensioned concrete parking structures discussed above are shown by the case histories that follow. These projects cover the spectrum of cast-in-place concrete garages, both in size and application. They illustrate there is no better value than cast-in-place concrete parking structures-now and for the future.

REFERENCES


(2) Performance of Precast or Prestressed Concrete in the San Fernando Earthquake. Kariotis & Kesler, Structural Engineers, South Pasadena, 1971.


(6) "Building Code Requirements for Reinforced Concrete" ACI 318-89, American Concrete Institute, Detroit, Michigan, 1989.

The structural system for this six level 7,350 car parking structure is a cast-in-place post-tensioned slab and girder system. The post-tensioning system includes complete strand encapsulation.

A 40-year durable structure with minimal maintenance was required by the Owner. Deterioration of existing surface parking, plus plans to construct a major addition to the Landside Terminal Building on the site of an overflow parking area, required that the structured parking be built quickly.

Cost comparisons with precast systems utilizing similar severe durability criteria proved that the cast-in-place system was the most economical, first cost and total cost. In addition to being cost-effective, fewer joints were needed and the cast-in-place frame provided site casting flexibility to accommodate ongoing airport activity.

The wide helix with 80-foot curved spans provides a pleasant driving experience while ascending the garage.

Low exterior walls on the ramps provide views of the airport grounds.

Wide beam spacing and high ceilings improved night lighting levels for increased patron security.
The South Parking Garage, located at Tampa International Airport, has an 11 acre footprint, and is located immediately south of the Landside Terminal Building. The two structures will be connected by a high frequency automated people mover.

Phase 1 construction includes five full parking levels with a capacity for 4,900 vehicles. The structural system, with 36' x 54' bays, has conventionally reinforced columns with post-tensioned beams and slabs. When Phase 1 is completed, level 6 and the remaining parking areas of levels 7 and 8 will be constructed, providing a total of 8,300 parking stalls.

The project team established design criteria for use in selecting the structural system. These criteria included the following:

- Large bay size (36' x 54' column spacing)
- Openness for patron comfort and security
- Minimal total height of the structure
- 50 year durability with minimum maintenance
- Ease of vertical expansion
- Acceptable initial construction cost

Using these criteria, four structural systems were studied. A cast-in-place, post-tensioned system was selected as best satisfying the project requirements.
This 4,368 space parking deck, located near the Pentagon, was constructed with a major shopping center development. The development includes a mall, a hotel, an office building, department stores, and a cinema. The cast-in-place post-tensioned deck includes one level below grade and five elevated levels. A four-lane external speed ramp provides access to the flat bays. This is supplemented by an internal ramp to enhance accessibility of all levels.

Cast-in-place, post-tensioned concrete was chosen after a comparison with a precast system. Contractors received pricing drawings from the designer, and priced both schemes. After analysis of the first cost and long term maintenance costs, cast-in-place post-tensioned concrete framing was selected.
This unusually inviting airport parking structure uses post-tensioned reinforced concrete slabs and beams.

The total of 1,247,573 square feet provides parking for 3,400 cars with easy access to the airport terminal through a direct tunnel connection. Designed to blend in with the other airport facilities, the garage was planned with two levels below grade to preserve views from the adjacent buildings.

Concrete was chosen for the long span (56') structural bays because, locally, it's more economical than steel. Post-tensioned reinforced concrete, while comparable in cost to precast concrete, offered advantages of fewer joints, cleaner joint treatment, and significantly fewer supporting elements. This enabled maximum visibility within the structure.

The improved interior visibility enhances the functionality of the atrium or “light well.” This brightens up all four parking levels, and helps direct travelers through the building.
The Douglas Parking Structure consists of three two-way traffic flat drive isles with double loaded 90 degree parking. One exterior bay is typically one-half level lower than the remainder of the structure. The split level is connected by two speed ramps, up and down. The structure measures 189' x 595' in plan. Attractive exterior cast-in-place stairs echo architectural expression of the adjacent office building.

Cast-in-place post-tensioned two-way flat slab floors provide parking on seven levels. The slabs are supported by site-cast rectangular concrete columns. The lateral support of the garage is provided by cast-in-place shear walls in each direction. Due to its excessive length, the structure is separated into two parts by one expansion joint.

To reduce the dominating effect of the large parking structure, an important architectural requirement was to lessen the total building height. This was achieved by use of cast-in-place post-tensioned flat slab floors. The flat slab provided a critical 13 feet reduction in height compared to the precast alternative, and proved to be the most economical solution.
In 1985, the Sands Hotel/Casino chose to expand its existing Atlantic City, N.J. casino complex with 650,000 square feet of structured parking. A large building on a limited site, the proposed parking structure presented multiple design challenges. Not least among these challenges was an accelerated, ten-month building schedule.

One of the first hurdles was the Atlantic City zoning code, which calls for low-rise buildings on the proposed site. The Sands Hotel/Casino, however, sought an eleven story structure, and thus the design team was required to propose a variance. The variance was required to show the Sand's commitment to reducing the structure’s height, without compromising the integrity of the building program. The properties of post-tensioned concrete (which allows for minimal beam depths and floor to floor heights) made such a proposal feasible.

The Sands Hotel/Casino Parking Structure occupies every available square foot of its site, and an adjacent site offered only limited staging, storage and erection space. For these reasons, the design team dismissed structural systems of multiple or prefabricated construction components (ie., precast concrete) as infeasible. The modular, repetitive formwork specified for the Sands Hotel/Casino Parking Structure was in continuous use throughout construction and did not require a storage area at the job site.

The Sands Hotel/Casino Parking Structure is an eleven story cast-in-place post-tensioned concrete beam and slab system. There are two separate buildings connected by pedestrian and traffic bridges. The self park structure has a 59' clear span typical bay. The valet structure has a 57' clear center bay and short spans in the side bays to accommodate the ramp system.
Two complete sets of structural plans were issued for bidding on the new parking structure at the Indianapolis International Airport. The new structure provides parking for 1,850 cars on 5 levels. Bids submitted for the cast-in-place post-tensioned, and the precast, prestressed alternates were as follows:

- Cast-in-Place Post-Tensioned: $7,580,000
  7,594,000 7,683,000 8,387,938
- Precast: $8,060,008 8,178,000 8,568,000

The $480,000.00 savings provided by the cast-in-place post-tensioned frame represented about $1.00 per square foot for the supported levels. In addition to the lower construction cost, the post-tensioned concrete system was also preferred for durability and lower maintenance costs.

**STRUCTURAL SYSTEM**

The cast-in-place framing is a post-tensioned, one-way slab and beam system with the beams spanning 62'. Since the structure is on a curve, the span of the 6" and 7" slabs varies from 14' to 27'.

The two helical ramps consist of post-tensioned slabs cantilevering 20' from a 20" thick core wall. The slab thickness varies from 6" to 20". An additional level was included in the design of the ramps. This level acts as a roof protecting the entire driving surface from direct exposure to rain and snow.

All reinforcing within the garage parking decks and ramps, as well as all post-tensioning anchors, are epoxy-coated.
The Ben Taub General Hospital Parking Garage is a 1,650 car, nine story cast-in-place concrete parking garage. The parking structure is located next to Ben Taub General Hospital in the Houston Medical Center. The structural system consists of a post-tensioned one way slab and beam system. The beams are 20 feet on center and span 58 feet 8 inches. The beams are 16 inches wide and 28 inches deep. A 5’2 inch thick post-tensioned slab spans between the beams. The columns in the building are 24 inches square. The building is supported on reinforced concrete spread footings.

The post-tensioned structural system was chosen over others because of its superior durability and lower maintenance costs. Life cycle cost studies were done comparing cast-in-place concrete to a precast concrete solution. The cast-in-place concrete structure had the lowest life cycle cost. Another important factor that influenced the decision to use a cast-in-place beam and slab system was the clean, relatively flat underside of the structure. This provided enhanced lighting. The improved lighting addressed the Owner's concern for safety in the 24-hour a day garage.
The design for the Circle Drive Parking Facility corresponds to the Hospital's ambitious master plan to locate staff parking in one centralized area. The structure design permits both horizontal and vertical expansion with minimal impact on the current parking operation. The facility also plays an important role in the hospital's health care operation by way of two helipads located on the structure's roof.

The parking facility's cast-in-place, post-tensioned concrete structural system provides long-span, column-free parking bays. The structural system also offers fire resistance and long-term durability at a reasonable cost. Use of epoxy-coated rebar, low water-cement ratio concrete and state-of-the-art sealers contribute to the structure's resistance to deterioration.
Montgomery County selected cast-in-place post-tensioned concrete for this garage for economic and functional reasons. A cast-in-place system also was the easiest to construct to meet a very irregular site dictated “footprint.” The structural system is a one-way post-tensioned slab spanning 17 feet, supported by 32 inch deep post-tensioned beams with 60 ft. spans.

Montgomery County’s Division of Parking has stipulated the use of cast-in-place post-tensioned concrete structural systems for all new garage construction. This decision was based on the County’s experience with their older precast and steel framed facilities. On the basis of this experience, cast-in-place post-tensioned concrete provides the least expensive alternative when the life cycle costs are considered.
The Pearl-Niagara Parking Facility consists of eight levels of parking off Pearl Street and nine levels of parking off Franklin Street. The two sections of the parking structure reach heights of 80 ft. and 90 ft., respectively. The structure accommodates 1,240 cars and includes space for commercial and retail development on the ground floor along Franklin and Pearl Streets.

The height of the parking structure is compatible with the scale of the surrounding buildings. A classical style of architecture was used to blend with the character of the older buildings in the district. In addition, materials and colors used for the facade blend esthetically with both the old and new buildings.

SIGNIFICANT DESIGN FEATURES:

- The post-tensioned concrete structure provides long-span, column-free parking bays. All reinforcing steel is epoxy-coated. A silane sealer protects the ramp against the highly corrosive environment in the Buffalo area.
- The double-helix system with a two-way traffic pattern provides two separate cycles up, and two. down. Two separate entry/exit points serve each ramp system. Since the facility provides parking primarily for employees in the area, the design is well suited for the peak-in/peak-out conditions.
- For maximum efficiency, 8’-6” wide stalls are provided, and an entire bay has been sized and designated for small cars.
- Glass enclosed stair/elevator towers and lobbies enhances the feeling of security.
- High pressure sodium lighting fixtures are provided with day time and night light circulating.
The Cambridge Center North Garage provides 1,176 parking spaces on 6½ levels. The structural system is a cast-in-place post-tensioned frame with an architectural precast concrete exterior facade. Exterior columns are 24" diameter round cast-in-place concrete. Interior columns of 24" x 28" square cast-in-place concrete. Floor to floor height is 9'-0" made possible by using shallow cast-in-place post-tensioned concrete beams 1'-8" deep and 4'-0" wide.

In comparing types of structural systems, the use of a cast-in-place post-tensioned system was chosen with the following advantages over precast:

- Construction cost was nominally less expensive.
- Due to the post-tensioned floor slabs, cast-in-place construction provides a virtually crack free deck. In place of temperature reinforcement, concrete was compressed with post-tensioning to compensate for tensile forces due to shrinkage and creep.
- The number of joints in a cast-in-place system was far fewer than a precast system.
- All exposed connections between columns and beams were eliminated.
- High strength concrete and epoxy-coated rebar were utilized to increase the life of the structure.
Driven by its surroundings, this 12 level parking structure’s design enhances the theatre motif of the Chicago North Loop. Billboard-like signage, brightly lit canopies and a musical floor reminder system make parking a fun part of an evening’s theatrical experience. During the day, the 3 bay, double helix parking layout maximizes the site’s space allowance while efficiently accommodating the large traffic turnover.

The design of the parking facility’s cast-in-place, post-tensioned concrete structural system provides long-span, column-free parking bays. The structural system also offers fire resistance and long-term durability at a reasonable cost. Use of epoxy-coated rebar, low water-cement ratio concrete and state-of-the-art sealers complement the structure’s resistance to deterioration.
Garden Plaza uses cast-in-place post-tensioned concrete for the structural frames of both the office building and the parking structure. Concrete was chosen for its unique combination of quality and economy. The quality inherent in a cast-in-place concrete frame is multi-dimensional. From a structural standpoint, the frame is highly redundant which enables loads to be carried multiple directions. This provides an extra margin of safety against temporary overload. From the standpoint of the user, a cast-in-place concrete system creates excellent sound dampening characteristics, and also results in floors with minimal vibrations.

Both the office building and the parking structure used post-tensioning to achieve longer spans and minimize deflections. The concrete mixes were custom designed to meet the needs of the various elements of the buildings. As an example, the water/cement ratio and other key characteristics of the parking structure slab concrete were specified to reduce permeability and minimize cracking. These characteristics were monitored closely during construction and did, in fact, result in durable, virtually crack-free slabs. Finally, the use of cast-in-place concrete permitted an accelerated construction schedule. Since all materials were locally available, the need for the long lead time sometimes associated with other competitive systems was eliminated. The project was completed and occupied on schedule.

The structural system is comprised of a long-span beam/slab system with lateral resistance provided by a combination of shear walls and ductile frames. Floor beams are 14 inches by 36 inches, with five-inch slabs spanning twenty feet. Both beams and slabs are post-tensioned using half-inch diameter unbonded tendons. The seismic system consists of cast-in-place shear walls in the longitudinal direction, with up-turned concrete ductile frames in the transverse direction.
Birmingham is a historic, southeastern Michigan community that blends commercial and upscale retail activity with many “village” characteristics (green space; picket fences; white, wood-framed houses with pitched roofs). Building a new parking structure in such a multi-faceted setting mandated a sensitive architectural statement with maximum user comfort and convenience.

The structure's architectural form and detail presented the greatest structural design challenges. Extensive computerized analytical methods were used to design the two curved, glass-enclosed stair/elevator towers. Other engineering solutions softened the mass, impact, and height of this 900 car facility. For example, the top tier is set back using buttress beams at a 45 degree angle. Terracing the western elevation also softens the height and eases the transition from a park-like setting to the bustling urban core. Finally, upturned/ downturned beams and round profile columns on the exterior facades reduces the visual mass of these elements.

The six-level Chester Street Parking Structure is constructed of cast-in-place concrete with post-tensioned supported slabs and beams. The interlocking helix ramping system reduces travel distance, lessens cross traffic situations, and allows recirculation at all levels.

Although an “architecturally driven” project, the Chester Street Parking Structure combines form and function. The creative design solution positively impacted the project without compromising its structural integrity, function, or durability. The structure fulfills its goals as an attractive and convenient addition to Birmingham’s parking system.
MINNEAPOLIS CONVENTION CENTER, MINNEAPOLIS, MINNESOTA

Located adjacent to the $200 million Minneapolis Convention Center, the parking structure provides Convention Center patrons a high level of comfort and security, including a climate-controlled pedestrian skyway connection.

The owner selected a cast-in-place concrete system to resist lateral earth pressure loads from foundation walls leaning against the frame. Post-tensioned cast-in-place concrete was also used to minimize cracking. Structural durability/low maintenance requirements were addressed by incorporating microsilica concrete.

CONVENTION CENTER PARKING FEATURES:

- Four-level below-grade structure; four-bay side-by-side single helix; one-way traffic.
- Three stair/elevator towers with glass walls adjacent to parking areas; pedestrian skyway connects southern stair/elevator tower to Convention Center.
- High-pressure sodium (HPS) lighting; painted walls and ceilings; closed circuit television (CCTV); intercom system.
- Cast-in-place post-tensioned long-span beams and slabs; caisson foundations.
- Landscaped pedestrian plaza above parking structure.
An estimated 107,000 people—including more than 50,000 employees—come to the Texas Medical Center daily. This creates a very large gathering of people and automobiles. Most of the activity is in an area of 134 acres at the center of the campus. To provide additional parking, Texas Medical Center wanted to build a garage on a 130' by 233' site for as many cars as practical. The site was occupied by a six-story dormitory and surrounded on three sides by existing facilities.

The design team worked together with Texas Medical Center and the neighboring institutions to create a structure for 878 cars on 14½ levels which meets their parking needs. At every step of the way, the team explored many design options to assure that the facility was functional, durable, flexible and economical. The result, now known as Texas Medical Center Parking Garage 7, is a balanced workable garage that was constructed 5% under budget, with a minimum of disruption to medical center operations. It has been very well-received by both user and the neighboring institutions.

The design team selected a post-tensioned, cast-in-place concrete structural system for the structure. The post-tensioned system was used to achieve economical long-span bays, and to assure a durable, virtually crack-free structure. In addition to providing durable, vibration resistant floors, the beam and slab framing system provided adequate lateral resistance to hurricane winds without shear walls or bracing. To provide an architecturally “clean” top for the garage, the stairs and elevator penthouses were concealed with a raised horizontal band of precast facing.
The typical level of the UCI Medical Center parking structure is 126’ x 277’ in plan. The parking layout is 90 degree stalls on each side of the bay with a central driveway. One bay is horizontal and the other functions as a ramp with a 5 degree slope.

The concrete frame is cast-in-place. The floor system consists of one-way post-tensioned slabs supported by post-tensioned beam at 20 feet on center. The beams were formed using a mechanized aluminum forming system developed by the Contractor. The structure is laterally supported by cast-in-place shear walls in each direction. 4000 psi concrete using hardrock aggregate was specified for the entire structure except for the foundations. The structure is supported on conventional spread footings.

Due to the involved exterior architectural finish stipulated by the University, pre-cast construction was considered. The University staged a design-build competition. A comparative cost analysis of several design build structural systems showed that cast-in-place, post-tensioned concrete was, by far, the most economical alternative. The University welcomed the cast-in-place solution as the successful system due to the redundancy against lateral forces, and the frames low maintenance requirements.
Located in downtown South Bend, this 138,700 square feet, 433-space parking facility was constructed to satisfy existing parking demand and to initiate economic development in the area. Cast-in-place, post-tensioned concrete was selected because it was more economical than any other system considered. The initial construction cost savings and the lower maintenance costs made the decision to choose cast-in-place, post-tensioned concrete the most prudent. Incorporated into this six-tier, post-tensioned concrete frame is 3,600 square feet of retail space at grade level. To help transfer patrons from an adjacent office and retail center, two pedestrian bridges were designed and added to the upper levels.

The architectural expression for this facility was a primary concern. To maintain the requirements noted in the City's Master Plan, a brick inlay was epoxied to the precast concrete facade panels. The concrete border was sandblasted and all interior walls, ceilings, beams and columns were painted white, creating a pleasing and bright environment.

Public opinion about the architecture and function has been extremely positive. The city of South Bend believes that their goals of stimulating local development and addressing parking demand were successfully met with this parking facility.

The St. Joseph/Wayne Street Parking Facility was awarded the 1990 IMPC (Institutional Municipal Parking Congress) Best Parking Facility Design Award for a structure under 800 spaces.
The use of cast-in-place concrete for the Carillon Point parking structure successfully solved a complex series of problems posed by the project. Parking structures typically must be constructed on tight budgets. The use of concrete for the structural frame resulted in a very economical construction price. Formwork, material specifications, and construction details were fine tuned to meet the unique demands of the project. This resulted in a parking structure of exceedingly high quality at a very attractive price.

Although construction economy was important, of equal if not greater importance was the necessity that the Carillon Point Parking Structure blend esthetically with the neighboring buildings. The overall character of the project is of extremely high quality. It was desired that the parking structure be designed and constructed to the same standards. The use of a cast-in-place concrete frame, which allows shallower spandrels than other competing systems, resulted in a very handsome finished product.

Finally, it was desired that the structure be nearly maintenance-free over its design life. Again, the use of high-quality, cast-in-place concrete floor slabs successfully filled this need. In addition to the use of a very low water/cement ratio, a variety of admixtures were also incorporated which resulted in dense, impermeable, and virtually crack-free floors. A fully encapsulated post-tensioning system was used along with a high level of air entrainment in the concrete and additional clear cover over the reinforcing steel. With these quality design and construction features, the Carillon Point parking structure should maintain its beauty and durability for many years to come.

The structural system is comprised of a long-span beam/slab system. Lateral resistance is provided by a combination of shear walls and ductile frames. Floor beams are 14 inches by 36 inches, with five-inch slabs spanning twenty feet. Both beams and slabs are post-tensioned using half-inch diameter unbonded cable. The seismic resistance is provided by concrete ductile frames in the transverse direction. Lateral loads in the longitudinal direction are carried by the interaction of the ramps and floors to form a vertical truss.
## PROJECT SUMMARIES

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>LEVELS</th>
<th>TOTAL AREA (sq. ft.)</th>
<th>BUILDING DIMENSIONS</th>
<th>CAPACITY (no. of cars)</th>
<th>RAMP SYSTEM</th>
<th>TYPICAL BAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orlando International Airport, Orlando, FL</td>
<td>6</td>
<td>2,400,000</td>
<td>2 Structures, 900' X 300'</td>
<td>7,350</td>
<td>External Spiral Ramps at Each End</td>
<td>60' X 20'</td>
</tr>
<tr>
<td>South Parking Garage</td>
<td>5</td>
<td>503,000 At Grade, 2,220,000 Elevated</td>
<td>685' X 796'</td>
<td>4,900</td>
<td>Two Double Threaded Helices</td>
<td>36' X 54'</td>
</tr>
<tr>
<td>Tampa International Airport, Tampa, FL</td>
<td>6</td>
<td>265,000 At Grade, 1,325,000 Elevated</td>
<td>780' X 180', 660' X 240'</td>
<td>4,368</td>
<td>External Speed Ramp</td>
<td>60' X 32'</td>
</tr>
<tr>
<td>Fashion Centre at Pentagon City, Arlington, VA</td>
<td>6</td>
<td>1,247,573</td>
<td>370' X 870'</td>
<td>3,400</td>
<td>Exterior</td>
<td>56' X 22.6'</td>
</tr>
<tr>
<td>Albuquerque International Airport, Albuquerque, NM</td>
<td>4</td>
<td>695,520</td>
<td>189' X 595'</td>
<td>2,180</td>
<td>Two Speed Ramps</td>
<td>28' X 34'</td>
</tr>
<tr>
<td>Douglas Parking Structure Long Beach, California</td>
<td>6</td>
<td>650,000</td>
<td>246' X 178', 100' X 149'</td>
<td>1,900</td>
<td>Double Threaded Helix Internal Speed</td>
<td>59' X 24', 57' X 20'</td>
</tr>
<tr>
<td>Sands Hotel/Casino Atlantic City, NJ</td>
<td>11</td>
<td>150,000 At Grade, 500,000 Elevated</td>
<td>1,850</td>
<td>Two Helical Ramps</td>
<td>14' - 27' Beam spans 62'</td>
<td></td>
</tr>
<tr>
<td>Indianapolis International Airport, Indianapolis, IN</td>
<td>5</td>
<td>476,000</td>
<td>440' X 118'</td>
<td>1,650</td>
<td>Two Bay Double Helix</td>
<td>58' X 20'</td>
</tr>
<tr>
<td>Ben Taub General Hospital Houston, Texas</td>
<td>8</td>
<td>488,000</td>
<td>488,000</td>
<td>1,628</td>
<td>Three Bay Double Helix</td>
<td>17' X 60'</td>
</tr>
<tr>
<td>Circle Drive University Hospitals of Cleveland</td>
<td>7</td>
<td>450,000</td>
<td>179' X 232'</td>
<td>1,240</td>
<td>Double Threaded Helix</td>
<td>60' X 17'</td>
</tr>
<tr>
<td>Montgomery County Parking Facility #7 Silver Spring, Maryland</td>
<td>9</td>
<td>350,000</td>
<td>106' X 529'</td>
<td>1,176</td>
<td>One Flat Bay, One Bay Double Ramp</td>
<td>53' X 27'</td>
</tr>
<tr>
<td>Pearl Niagara Municipal Parking Facility, Buffalo, NY</td>
<td>6½</td>
<td>385,000</td>
<td>260' X 305'</td>
<td>980</td>
<td>Interior Sloped Floors</td>
<td>60' X 20'</td>
</tr>
<tr>
<td>Cambridge Center North Cambridge, MA</td>
<td>12</td>
<td>348,000</td>
<td>169' X 332'</td>
<td>900</td>
<td>Three Bay Double Helix</td>
<td>55' - 0' X 19' - 6'</td>
</tr>
<tr>
<td>Theatre District Self Park Chicago, Illinois</td>
<td>4</td>
<td>300,700</td>
<td>277' X 361'</td>
<td>895</td>
<td>Four Bay Side-By-Side Single Helix</td>
<td>56' X 24'</td>
</tr>
<tr>
<td>Garden Plaza Renton, Washington</td>
<td>4</td>
<td>291,030</td>
<td>196' X 108'</td>
<td>934</td>
<td>Double Threaded Helix</td>
<td>52' - 3' X 21' - 8'</td>
</tr>
<tr>
<td>Chester Street Parking Structures, Birmingham, MI</td>
<td>6</td>
<td>213,825</td>
<td>126' X 277'</td>
<td>693</td>
<td>One Complete Bay at 5' Slope</td>
<td>61' X 20'</td>
</tr>
<tr>
<td>Minneapolis Convention Center, Minneapolis, MN</td>
<td>6</td>
<td>216,650 At Grade</td>
<td>185' X 123'</td>
<td>433</td>
<td>Single Threaded Helix</td>
<td>60' - 0' X 20' - 3'</td>
</tr>
<tr>
<td>Texas Medical Center Garage No. 7, Houston, TX</td>
<td>14½</td>
<td>117,050 Elevated</td>
<td>117,050 Elevated</td>
<td>400</td>
<td>Interior Sloped Floors</td>
<td>60' X 20'</td>
</tr>
</tbody>
</table>

(1) Concrete price variation reflects inclusion of different factors in cost calculations. Higher prices reflect forming and finishing costs, and, in some cases, use of special durability additives.
<table>
<thead>
<tr>
<th>CONCRETE (cy)</th>
<th>REBAR 1,000 lb.</th>
<th>POST-TENSIONING 1,000 lb.</th>
<th>CONCRETE $/cy</th>
<th>REBAR $/lb.</th>
<th>POST-TENSIONING $/lb.</th>
<th>TOTAL COST</th>
<th>COST (per car)</th>
<th>COST (per sq. ft)</th>
<th>DATE Begun</th>
<th>DATE Finished</th>
</tr>
</thead>
<tbody>
<tr>
<td>110,000</td>
<td>12,800</td>
<td>2,800</td>
<td>$54.09 Material only</td>
<td>$0.38</td>
<td>$1.08</td>
<td>$51,000,000</td>
<td>$6,939</td>
<td>$21.25</td>
<td>A: 5/87</td>
<td>B: 5/89</td>
</tr>
<tr>
<td>90,000</td>
<td>9,000 Uncoated 1,600 Epoxy</td>
<td>2,860</td>
<td>$230.00</td>
<td>$0.40</td>
<td>$1.25</td>
<td>$45,000,000</td>
<td>$9,103</td>
<td>$20.27</td>
<td>10/89</td>
<td>11/91</td>
</tr>
<tr>
<td>100,000</td>
<td>4,200 Uncoated 2,200 Epoxy</td>
<td>1,600</td>
<td>$86.00 Material only</td>
<td>$0.31</td>
<td>$1.07</td>
<td>$24,000,000</td>
<td>$5,495</td>
<td>$15.09</td>
<td>11/87</td>
<td>9/89</td>
</tr>
<tr>
<td>46,180</td>
<td>8,000</td>
<td>980</td>
<td>$155.00</td>
<td>$0.32</td>
<td>$1.13</td>
<td>$22,746,000</td>
<td>$6,690</td>
<td>$18.23</td>
<td>2/88</td>
<td>5/89</td>
</tr>
<tr>
<td>23,000</td>
<td>3,600</td>
<td>475</td>
<td>$47.00 Material only</td>
<td>$0.43</td>
<td>$1.15</td>
<td>$9,000,000</td>
<td>$4,128</td>
<td>$12.95</td>
<td>7/88</td>
<td>8/89</td>
</tr>
<tr>
<td>20,000</td>
<td>610 Uncoated 1,826 Epoxy</td>
<td>488</td>
<td>$60.00 Material only</td>
<td>$0.50</td>
<td>$0.70</td>
<td>$14,300,000</td>
<td>$7,526</td>
<td>$22.00</td>
<td>9/86</td>
<td>7/87</td>
</tr>
<tr>
<td>25,000</td>
<td>800 Uncoated 1,320 Epoxy</td>
<td>520</td>
<td>$7,580,000</td>
<td>$15.16</td>
<td>5/87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11,000</td>
<td>1,340</td>
<td>360</td>
<td>$5,650,000</td>
<td>$3,424</td>
<td>3/85</td>
<td></td>
<td></td>
<td></td>
<td>1/86</td>
<td></td>
</tr>
<tr>
<td>12,100</td>
<td>1,220 Uncoated 488 Epoxy</td>
<td>439</td>
<td>$190.00</td>
<td>$0.55</td>
<td>$1.30</td>
<td>$10,300,000</td>
<td>$6,326</td>
<td>$20.39</td>
<td>1989</td>
<td>1990</td>
</tr>
<tr>
<td>15,400</td>
<td>1,380 Epoxy</td>
<td>450</td>
<td>$202.60</td>
<td>$0.55</td>
<td>$1.60</td>
<td>$10,800,000</td>
<td>$7,879</td>
<td>$24.00</td>
<td>12/86</td>
<td>9/88</td>
</tr>
<tr>
<td>9,550</td>
<td>1,350</td>
<td>330</td>
<td>$110.00</td>
<td>$0.55</td>
<td>$1.50</td>
<td>$9,800,000</td>
<td>$7,900</td>
<td>$25.45</td>
<td>4/88</td>
<td>3/89</td>
</tr>
<tr>
<td>9,722</td>
<td>1,450</td>
<td>380</td>
<td>$53.00 Material only</td>
<td>$0.48</td>
<td>$0.85</td>
<td>$10,200,000</td>
<td>$7,800</td>
<td>$26.00</td>
<td>5/88</td>
<td>9/89</td>
</tr>
<tr>
<td>8,635</td>
<td>870 Uncoated 348 Epoxy</td>
<td>313</td>
<td>$180.00</td>
<td>$0.53</td>
<td>$1.20</td>
<td>$8,600,000</td>
<td>$8,557</td>
<td>$26.46</td>
<td>1987</td>
<td>1988</td>
</tr>
<tr>
<td>8,000</td>
<td>1,166</td>
<td>120</td>
<td>$39.00 Material only</td>
<td>$0.20</td>
<td>$0.60</td>
<td>$3,896,436</td>
<td>$5,166</td>
<td>$15.00</td>
<td>12/87</td>
<td>8/88</td>
</tr>
<tr>
<td>12,000</td>
<td>1,400 Total</td>
<td>170</td>
<td>$275.00</td>
<td>$0.49</td>
<td>$1.78</td>
<td>$9,879,000</td>
<td>$10,967</td>
<td>$35.76</td>
<td>6/88</td>
<td>11/89</td>
</tr>
<tr>
<td>16,200</td>
<td>1,590</td>
<td>193</td>
<td>$147.00</td>
<td>$0.50</td>
<td>$1.38</td>
<td>$13,327,000</td>
<td>$14,891</td>
<td>$44.32</td>
<td>5/88</td>
<td>10/89</td>
</tr>
<tr>
<td>6,300</td>
<td>560</td>
<td>240</td>
<td>$60.00 Material only</td>
<td>$0.40</td>
<td>$1.20</td>
<td>$5,405,000</td>
<td>$5,787</td>
<td>$18.57</td>
<td>9/87</td>
<td>8/88</td>
</tr>
<tr>
<td>8,200</td>
<td>1,100</td>
<td>150</td>
<td>$47.00 Material only</td>
<td>$0.43</td>
<td>$1.15</td>
<td>$4,000,000</td>
<td>$5,772</td>
<td>$18.70</td>
<td>12/88</td>
<td>6/89</td>
</tr>
<tr>
<td>3,500</td>
<td>400 Uncoated 100 Epoxy</td>
<td>150</td>
<td>$175.00</td>
<td>$0.50</td>
<td>$1.07</td>
<td>$3,197,087</td>
<td>$7,384</td>
<td>$23.05</td>
<td>7/88</td>
<td>9/89</td>
</tr>
<tr>
<td>3,830</td>
<td>481</td>
<td>46</td>
<td>$40.00 Material only</td>
<td>$0.40</td>
<td>$1.25</td>
<td>$1,949,012</td>
<td>$4,875</td>
<td>$15.94 Elevated</td>
<td>1/89</td>
<td>7/89</td>
</tr>
</tbody>
</table>

(c) Price variations reflect regional differences in costs of labor and materials, the additional cost of underground construction, difference in architectural treatment, landscaping costs, and use of special mechanical equipment such as a high frequency automated people mover.
DURABILITY RECOMMENDATIONS

Post-tensioned concrete parking structures inherently provide enhanced durability due to the minimization of cracks that provide access for corrosive agents to reinforcement. The use of post-tensioning also eliminates most slab joints that provide access for corrosive agents to beams and columns. The durability potential of post-tensioned parking structures has been illustrated by the excellent durability performance of many post-tensioned parking garages exposed to aggressive environments. Most of these structures were built without any specific design consideration of durability. Inspection of a 15 year old parking structure in Baltimore following demolition to make room for expansion of the adjacent office tower concluded, “Visual examination of the unbonded tendons following demolition confirmed that no significant corrosion had occurred over the 15 year service life.”* (1)

Nevertheless, many older parking structures of all types of construction have suffered durability problems. A survey of 215 parking structures in Toronto, Ottawa, and Montreal stated, “The evidence indicates that durable garages can be built, and that poor performance must be attributed to design and construction practices whose effectiveness falls short of that required by the environment.” (2) In recognition of the validity of this statement, the purpose of this section of the brochure is to provide design and construction recommendations for durability that will ensure realization of the excellent durability characteristics of post-tensioned concrete parking structures.

EPOXY-COATED REINFORCEMENT

One of the first and most effective responses to parking structure durability problems was the use of epoxy-coated reinforcement. The LaCrosse Center Parking Structure in LaCrosse, Wisconsin, shown in the photo, may have been the first parking structure constructed with epoxy-coated reinforcement. Construction of the LaCrosse Center Parking Structure was completed in 1981. A 1989 inspection of this structure by an independent inspection agency indicated that the deck was in very good condition with no apparent durability problems.

Since epoxy-coated reinforcement has exhibited excellent durability in parking structure applications, its use in accordance with ASTM Specifications (3) and CRSI recommendations (4) is suggested in all parking structures in aggressive environments (other than Durability Zone I, as defined in Figure 2 on page 30).

POST-TENSIONING TENDONS

The Post-Tensioning Institute (PTI) published specifications for unbonded post-tensioning tendons in 1985 (5) that included special durability requirements for tendons used in structures exposed to aggressive environments. These specifications provide for watertight encapsulation of the strand used in the tendon over its entire length (including watertight closure of tendon ends). The specifications also require the use of a specially formulated corrosion inhibiting grease, and include many other provisions to insure enhanced durability. Some designers require use of epoxy coated anchors in addition to the requirements of the PTI specifications. When tendons, including anchorages, are fully encapsulated to the point that they are electrically isolated from the structure, they are covered by a patent.”

LaCrosse Center Parking Structure, LaCrosse, Wisconsin

(Numbers in raised () refer to references listed at the end of this section.)
MINIMUM PRESTRESS LEVELS
For crack control and durability considerations, minimum average prestress levels for primary slab and beam post-tensioning are recommended as follows:

- Zone I: Min. P/A = 150 p.s.i.
- Zones II, III, CC-I, CC-II: Min. P/A = 200 p.s.i.

Minimum P/A for unbonded tendons used as slab shrinkage and temperature reinforcement to be 100 p.s.i. in accordance with ACI 318 building code requirements.

SURFACE TREATMENTS, CONCRETE ADDITIVES, SEALERS AND MEMBRANES
Studies have shown that the use of Calcium Nitrite and/or Microsilica as concrete additives are cost effective methods to enhance the durability of cast-in-place post-tensioned parking structures. Initial application and periodic reaplication of a concrete sealer have also been shown to be cost effective. Accordingly, use of an additive and/or a concrete sealer is recommended for parking structures in aggressive environments. The referenced studies also show that traffic toppings (membrane plus asphaltic concrete riding surface) are significantly more expensive than use of additives or sealers to obtain the same service life.

CONSTRUCTION PRACTICES
It is recommended that post-tensioning tendons be fabricated in a plant certified under the Post-Tensioning Institute Program for Certification of Plants Producing Unbonded Single Strand Tendons. Installation of tendons should be according to the Post-Tensioning Institute, “Field Procedures Manual for Unbonded Single Strand Tendons.” Concrete construction practices should follow the requirements of the ACI 301-89 “Specifications for Structural Concrete for Buildings.”

CONCRETE QUALITY
Many durability studies have conclusively shown that reduction of the water/cement ratio of the concrete reduces the permeability of the concrete to corrosive agents. Reduced permeability enhances the corrosion protection afforded by concrete cover. The relationship between water/cement ratio and permeability of concrete to chlorides is illustrated in Figure 1. Use of a low water/cement ratio is obviously desirable in reducing potential corrosion.

Durability and resistance to freeze/thaw effects are greatly enhanced by use of air-entrained concrete.

CONCRETE COVER
The durability recommendations in Table 1 provide for increased cover over top slab reinforcement in aggressive environments. The increases consider the normal tolerances for placing reinforcement. The CRSI Manual of Standard Practice gives tolerances of ± inch for placement of reinforcement in members less than 8 inches thick, and ± A inch in members more than 8 inches thick.
The map shown in Figure 2 divides the United States into five zones determined by the use of deicing salts, or airborne salts from oceans. Structures in Zones CC-II (coastal chlorides) and III should be built to meet stricter durability requirements than those needed for structures in Zones I, II, and CC-I. Durability provisions recommended for the various zones are presented in Table 1. Some local building codes include severity of deterioration maps. The requirements of these maps should be applied when they are more restrictive than the recommendations presented here. Variations from these recommendations may also be appropriate to reflect local experiences of parking structure consultants.

**FIGURE 2.**

Zone I — All areas south of Zone II and west of the Continental Divide except as designated in another zone and except those areas geographically in Zone I but above elevation 3,000 feet.

Zone II — In all areas south of Zone III and within 100 miles south of Interstate Highway I-40 from the Atlantic Ocean west to the Continental Divide plus all areas in Zone I above 3,000 feet elevation, plus areas in Oregon and Washington State west of the Cascade Mountains.

Zone III — All areas north of and within 100 miles of Interstate Highway I-70 from the Atlantic Ocean west to Salt Lake City, Utah, then northwest on I-84 to Portland, Oregon, then west to the Pacific Ocean.

Zone CC-I — All areas within 10 miles of a major salt water body such as the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean.

Zone CC-II — Spray zone—all areas within ½ mile of a major salt water body.

**TABLE 1.**

<table>
<thead>
<tr>
<th>DURABILITY DESIGN ELEMENT</th>
<th>ZONE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td>( f'c ) (PSI)</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>4000</td>
</tr>
<tr>
<td>Air % (1) (10% aggregate)</td>
<td>NR</td>
</tr>
<tr>
<td>W/C Ratio (maximum)</td>
<td>0.45</td>
</tr>
<tr>
<td>Reinforcing Cover &amp; Protection:</td>
<td>1&quot;</td>
</tr>
<tr>
<td>Slab Top</td>
<td>( \frac{3}{16}&quot; )</td>
</tr>
<tr>
<td>Slab Bottom</td>
<td>1-1/8&quot;</td>
</tr>
<tr>
<td>Beam</td>
<td>1-1/8&quot;</td>
</tr>
<tr>
<td>Column</td>
<td>1-1/8&quot;</td>
</tr>
<tr>
<td>Walls</td>
<td>1/2&quot;</td>
</tr>
<tr>
<td>P:T Tendons (4)</td>
<td>PTI Spec</td>
</tr>
<tr>
<td>Silane Sealer (5)</td>
<td>Root Only</td>
</tr>
</tbody>
</table>

**NOTES:**

1. Air content may be reduced 1% for \( f'c > 5000 \) psi.

2. Use of epoxy coated (EC) reinforcement in beams, columns, and for bottom reinforcement in slabs, to be in accordance with the practices of the Engineer of Record.


4. PTI Spec = Minimum requirements per PTI Specification.

Encap = Encapsulated tendon per PTI Specification requirements.

5. 40% solids Silane Sealer; may be deleted if 5% minimum silica fume is used in slab concrete.

6. Exceeds cover requirements of ACI 318-89.

* Some members of the advisory committee specify electrically isolated tendons. **
REFERENCES


* Litvan, G., and Bickett, J., "Durability of Parking Structures, Analysis of Field Survey," ACI SP 100-76, American Concrete Institute, Detroit, 1987.


* Guidelines for Inspection and Acceptance of Epoxy-Coated Reinforcing Bars at the Job Site, Concrete Reinforcing Steel Institute, Schaumburg, Illinois.


* ACI Committee 301, "ACI 301-89 Specifications for Structural Concrete for Buildings," American Concrete Institute, 1989.


APPROXIMATE QUANTITIES FOR ESTIMATING COST OF POST-TENSIONED FLOOR SYSTEMS*

The approximate quantities presented in Tables 2 and 3 for flat, plate, and beam and slab floor systems, respectively, were calculated for an interior span representing a typical mid-story of a multi-level parking structure. Adjustment of these quantities may be appropriate based on local practices. The quantities are intended only as approximate guidelines for cost estimates.

Calculations were based on a single level-frame with columns extending one level below and above the floor investigated. Quantities do not include columns, shear walls, foundations, or perimeter parapet walls. Details used for the one-way beam and slab studies are shown in Fig. 3. Details of the flat plate studies are shown in Fig. 4. Other details or parameters used in the studies were as follows:

DL = gravity plus 2 psf miscellaneous
LL = 50 psf uniformly distributed, reducible according to UBC, or a concentrated load of 2000 lb per UBC.
Concrete: 4000 psi, hardrock, 150 pcf
Rebar: 60 ksi
Tendons: ½ inch diameter, 7 wire strands; 270 ksi, low relaxation steel
Effective prestressing force 175 ksi
Cover dimensions over top slab reinforcement are 1 in., and ½ in. (see cover recommendations in durability section).

For one-way systems, the Uniform Building Code (UBC) requirement to provide rebar for DL + 0.25 LL is considered.

For computations based on the ACI Code, beam depths of 30 inches were used. For the computations based on the Uniform Building Code, the beam depths of 36 inches were used to reduce the impact of the additional UBC rebar requirements.

The rebar quantities in Tables 2 and 3 include the miscellaneous reinforcement tabulated below in addition to rebar reinforcement required by design and obtained from ADAPT Computer output.

Quantities are in psf of elevated post-tensioned floor.

<table>
<thead>
<tr>
<th>Description</th>
<th>One-Way</th>
<th>Two-Way</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PT anchorage steel (back-up bars, hair pins)</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>2 Shrinkage and crack control (rebar for restraining elements)</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>3 Trim steel (openings, penetrations, corners, discontinuities)</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>4 Support steel (#4 @ 42°; #6 or #7 for banded tendons)</td>
<td>0.20</td>
<td>0.35</td>
</tr>
<tr>
<td>5 Caps at columns</td>
<td>---</td>
<td>0.14</td>
</tr>
<tr>
<td>6 Up-sizing beam bars for construction (2#8 top and bottom of cage plus 2#5 at midheight of stem all continuous)</td>
<td>0.30</td>
<td>---</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.94</strong></td>
<td><strong>0.91</strong></td>
</tr>
</tbody>
</table>

Not included are reinforcement which may be necessary to resist wind/seismic loading (drag and chord bars), closure strips, and construction joints.

**TABLE 2. TWO-WAY FLOOR SYSTEM QUANTITIES**

<table>
<thead>
<tr>
<th>SLAB THICKNESS in.</th>
<th>TOP COVER in.</th>
<th>TENSILE STRESS $V_{Te}$</th>
<th>CONCRETE cy/sq. ft.</th>
<th>REBAR lb/sq. ft.</th>
<th>PT lb/sq. ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0.0248</td>
<td>1.09</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0</td>
<td>0.0248</td>
<td>1.12</td>
<td>0.59</td>
</tr>
</tbody>
</table>

FIGURE 3.

ONE-WAY SYSTEM MODEL

(a) ELEVATION

Beam Depth, ACI 30 in/UBC 36 in

(b) PLAN

(c) SECTION THROUGH SLAB

Slab Thickness: 5" & 5 1/2" (18' Span)
6 1/2" & 7" (24' Span)

Study Spans: 18 ft & 24 ft

16" Typical

FIGURE 4.

TWO-WAY SYSTEM MODEL

(a) ELEVATION Transverse Direction

(b) PLAN

(c) ELEVATION Longitudinal Direction

Study Span

Study Frame
<table>
<thead>
<tr>
<th>SLAB SPAN FT.</th>
<th>SLAB THICKNESS IN.</th>
<th>TOP COVER IN.</th>
<th>TENSION $\sqrt{f'_c}$ PSI</th>
<th>CODE</th>
<th>CONCRETE cu yd/sq. ft.</th>
<th>REBAR lb/sq. ft.</th>
<th>POST-TENSIONING lb/sq. ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>ACI</td>
<td>0.0216</td>
<td>1.57</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0226</td>
<td>1.61</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>ACI</td>
<td>0.0216</td>
<td>1.60</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0226</td>
<td>1.61</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>ACI</td>
<td>0.0216</td>
<td>1.60</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0226</td>
<td>1.61</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>ACI</td>
<td>0.0238</td>
<td>1.64</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0252</td>
<td>1.67</td>
<td>0.77</td>
</tr>
<tr>
<td>5.5</td>
<td>1.5</td>
<td></td>
<td>6</td>
<td>ACI</td>
<td>0.0238</td>
<td>1.64</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0252</td>
<td>1.67</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>ACI</td>
<td>0.0238</td>
<td>1.67</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0252</td>
<td>1.67</td>
<td>0.60</td>
</tr>
<tr>
<td>6.5</td>
<td>1</td>
<td></td>
<td>0</td>
<td>ACI</td>
<td>0.0255</td>
<td>1.70</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0264</td>
<td>1.78</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>ACI</td>
<td>0.0255</td>
<td>1.70</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0264</td>
<td>1.78</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>ACI</td>
<td>0.0255</td>
<td>1.70</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0264</td>
<td>1.78</td>
<td>0.63</td>
</tr>
<tr>
<td>24</td>
<td>7.0</td>
<td>1.5</td>
<td>0</td>
<td>ACI</td>
<td>0.0268</td>
<td>1.76</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0279</td>
<td>1.84</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>ACI</td>
<td>0.0268</td>
<td>1.76</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0279</td>
<td>1.84</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>ACI</td>
<td>0.0268</td>
<td>1.76</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UBC</td>
<td>0.0279</td>
<td>1.84</td>
<td>0.71</td>
</tr>
</tbody>
</table>

*(a) Includes 5% for details. *(b) Includes 0.09 lb/sq. ft. for slab temperature tendons.
ACKNOWLEDGEMENTS

This brochure was developed by Clifford L. Freyermuth, Inc., Phoenix, AZ., for the cosponsors PTI, CRSI, and NRMCA. An advisory committee consisting of representatives of firms active in the design of parking structures assisted in the development of the brochure. Cosponsor representatives involved in the development of the brochure were Gerard J. McGuire, Post-Tensioning Institute; Anthony L. Felder and Peter J. Steiner, Concrete Reinforcing Steel Institute; and, James A. Rossberg, National Ready Mixed Concrete Association.

ADVISORY COMMITTEE:

FLORIAN BARTH
Bijan, Florian & Assoc., Inc.
Redwood City, CA

JAMES R. CAGLEY
Cagley and Associates
Rockville, MD

GIRI CHHABRA
Desman Associates
New York, NY

ANTHONY P. CHREST
Walker Parking Consultants/Engineers Inc.
Kalamazoo, MI

WILLIAM HANUSCHAK
Wm. Hanuschak and Assoc.
Ltd. Winnipeg, Manitoba, Can.

CARY KOPCZYNSKI
Cary Kopczynski & Co., Inc.
Bellevue, WA

HOWARD R. MAY
Desman Associates
Chicago, IL

RAYMOND F. MESSER
Walter P. Moore & Assoc.
Tampa, FL

KOLBJORN SAETHER
K. Saether & Associates
Chicago, IL

H. CARL WALKER
Carl Walker Engineers
Kalamazoo, MI

DESIGN AIDS

CONCRETE REINFORCING STEEL INSTITUTE PUBLICATIONS:


• Reinforcing Bar Detailing, 3rd Edition, 256 pp., Price $63.00.

• Guidelines for Inspection and Acceptance of Epoxy-Coated Reinforcing Bars at the Job Site, 12 pp., Price $10.00. Prices subject to change without notice. Please call CRSI at (708) 517-1200 for ordering information.

POST-TENSIONING INSTITUTE PUBLICATIONS:


• Restraint Cracks and Their Mitigation in Unbonded Post-Tensioned Building Structures, 1988, 49 pages, Public price $15.00, Member price $10.00.

• Strength and Behavior of Closely Spaced Post-Tensioned Monostrand Anchorages, 1987, 49 pages, Public price $15.00, Member price $10.00.

POST-TENSIONING INSTITUTE
PTI provides research, technical development, marketing, and promotion activities for companies engaged in post-tensioned prestressed concrete construction. Members of the Institute include major post-tensioning materials fabricators in the U.S. and Canada, manufacturers of prestressing materials in the U.S., Canada, Mexico, Japan, and Europe, companies supplying miscellaneous materials, services and equipment used in post-tensioned construction, and approximately 900 professional engineers, architects, and contractors. Established in 1976, PTI has concentrated on structural research projects directed towards development of specifications and design recommendations, publication of technical literature on applications of post-tensioning, and an annual program of technical seminars to disseminate information on post-tensioned design and construction technology. PTI publishes a quarterly newsletter dealing with developments in the post-tensioning industry.

CONCRETE REINFORCING STEEL INSTITUTE
One of America’s oldest trade associations, CRSI has helped the growth of reinforced concrete construction to its present multi-billion dollar status. Founded in 1924, CRSI’s primary objective has always been “to foster and increase the use of reinforced concrete construction.” An investment of millions of dollars in promotion over the years has helped reinforced concrete construction achieve its record of growth. A second CRSI objective is, “To carry on research work and disseminate information as to the safe and proper materials to be used in reinforced concrete construction.” To this end, CRSI has a technical staff of experienced engineers who have developed many publications for use by designers, contractors and others. CRSI’s professional staff of engineers is nationally recognized for its skills and experience in the field of reinforced concrete design and construction. CRSI also continuously works for standardization of materials, specifications, building codes and engineering practices.

NATIONAL READY MIXED CONCRETE ASSOCIATION
The National Ready Mixed Concrete Association is an international association representing the producers of ready mixed concrete. Its members produce the majority of ready mixed concrete delivered annually in the U.S. The industry consumes approximately 75% of all portland cement sold in the U.S., and provides the most basic materials for much of the construction of the nation’s “infrastructure,” as well as residential and commercial buildings.