Describes several structural systems using both cast-in-place prestressed and precast prestressed concrete construction. The client's design criteria are presented in the form of key design parameters which are then discussed and a solution given. The precast and prestressed concrete system adopted for each set of design parameters is believed to be the best one for the particular project at the time it was used.

Prestressed concrete can be used in a vast number of structural systems to achieve safe, economical structures. Over the past few years our firm has used cast-in-place prestressed and precast prestressed concrete on a variety of projects. Some uses are perhaps new, or unusual, and others are systems in every engineer's repertoire.

Rather than describe one system in detail, we chose to place emphasis on ideas and present a number of problems (design parameters) with their solutions using brief descriptions and pictures.

We believe the solutions to the problems were the best ones for the particular project at the time they were used. Some of these systems have been used many times, others only once, and others are just being used for the second time and are again proving their economical and competitive worth.

Finding the best system to solve the problem is what all engineers strive for and, hopefully, this paper will give those who read it some new alternatives for future designs.

POST-TENSIONED FLAT PLATE PARKING GARAGE

Key design parameters
1. Minimum floor to floor height required to minimize difficult bedrock excavation
2. Minimum slab thickness required
3. Watertight garage slab without waterproofing
4. Large areas of repetition
5. Cost
Due to the high level of the underlying bedrock, a parking structure requiring minimum slab thickness in order to provide minimum floor-to-floor heights was required for this project. This minimized the amount of expensive excavation required into bedrock. An 11 in. thick post-tensioned 4000 psi sand-lightweight concrete slab, on 30 x 30 ft square bays, satisfied both the minimum slab thickness and punching shear stresses at the 24 in. diameter columns (no capitals).

This type of prestressed slab construction works out to be economical where stair-stepping the castings can be done (Fig. 1). This allows a small, efficient crew of workmen to place reinforcing steel and place two or three 60 x 60 ft segments of slab every week (Fig. 2). Construction of this subgrade parking structure went smoothly. We inspected all reinforcing steel before concreting the slabs and found minor problems involving items such as: tendon support chairs left out, too much curvature (kinks) in the tendons, interference of tendons and mild steel reinforcement at the columns, and tendon sheathing torn off. These problems were generally worked out in the field.

Maintaining a minimum average compressive stress (P/A) of 150 psi resulted in watertight slabs except where hairline cracks have occurred. The only cracks in the slab radiate off of concrete walls used as supports around various shafts at interior slab locations. Additional mild steel reinforcement placed in the slab around shaft wall supports would help to reduce this cracking considerably.

Lightweight aggregate concrete used in the Denver area has good deflection properties and combined with the pre-stressing in this flat plate, has resulted in very small slab deflections.

**SINGLE TEE AND VERTICAL CONSTRUCTION TECHNIQUE**

**Key design parameters**

1. Column free flexible interior floor space
2. Narrow site
3. Zone 2 earthquake
4. Tight construction schedule
5. Cost

The client required an economical column-free commercial 10-story office building designed for Zone 2 earthquake loading.

Due to the relatively narrow building, precast single tees, spanning 66 ft to exterior precast T-columns (Figs. 3 and 4), was the most economical structural system satisfying the design criteria. The cast-in-place concrete cores
were slip formed before any precast concrete was set, and provided Zone 2 earthquake and erection stability. The only major delay (2 weeks) during the construction of the structure, came while the precast erectors waited for the arrival of the 140-ton crane needed to erect the heaviest T-column sections.

The single tees were connected to the T-columns by straps welded to embedded plates in the top of the spandrel beam and tee. The floors act as diaphragms through the cast-in-place topping slabs, and tie each floor to the core walls and spandrel beams. Three round holes were provided through each tee stem for mechanical distribution (Fig. 3). This resulted in a smaller ceiling space and less floor-to-floor height.

Column bar splices were made using cad-welds. The precast T-columns were cast laying flat end-to-end with bars continuous through the splices; then the bars at the splices were cut, which assured a perfect fit in the field. The ends of the columns at the splices were held apart using a short steel W section as a spacer (Fig. 5). This W section was bolted to an embedded weldment in each column and provided erection stability while the bars were being cad-welded. The space between the ends of the columns was then filled with concrete to complete the splice.

This 10-story office building was completed enough in 10 months from the start of foundations to allow tenants to move in, and it was built for under $20 per sq ft.

BUILDING BLOCK COMPONENTS

Key design parameters
1. Minimum floor depth
2. Repetition of standard components
3. Architectural expression of structure
4. Cost
The design of this research office building was based on providing a flexible and inexpensive structure for the client. It was decided that it would be a tower of precast concrete and that the infill between the precast concrete would be painted concrete block.

The structural system was a precast composite concrete system which provided repetitiveness and minimum floor depth. The system consists of precast interior columns and precast exterior “ladder columns.” The floor beams bear on an interior composite girder and on the “steps” of the exterior “ladder columns” (Fig. 6).

Precast slabs were placed over the precast beams to act as lost forms (Fig. 7). Composite concrete topping was then placed over the entire precast component slab, completing the floor structure.

This system had some problems in placing additional top steel over the columns due to its shallow depth, and the reinforcement congestion that usually occurs at column-beam connections. The large number of pieces that have to be handled during precasting and erection is a cost disadvantage in this system. This is somewhat offset by the repetition and number of pieces, but it is an area which bears careful consideration before a decision is made to use this type of system.

“DIADECK” SYSTEM

Key design parameters
1. Convention floor loading of 250 psf
2. Shallow floor depth at midspan to accommodate utility lines for exhibit spaces above
3. Exposed structure that was architecturally pleasing

The patented “Diadeck” was developed to carry a heavy exhibition floor load of 250 psf, and a concentrated load of 10,000 lb at any point on the floor.

The system consists of precast triangular pans which act as a composite “lost-form” for a cast-in-place slab and two-way post-tensioned beams on 30 ft square bays. Three hundred (300) precast triangular pans were cast using a daily cycle with four forms. Erection crews averaged 1 hr per 30 x 30 ft bay in setting the precast pans with the steel.
Fig. 8. Erecting precast triangular "lost form." Two corners of the form bear on the column capitals while the third corner is shored. Only one shore per 900 sq ft is required.

Fig. 9. "Diadeck" slab ready for placing concrete. Beams are haunched and post-tensioned.

Fig. 10. Four-way haunch allows for two-way mechanical distribution at midspan.

The system cost was 20¢ per sq ft less than an equivalent twin tee-girder system. Part of the reason for the lower cost is that the very heavy design loads favor the four-way haunched "Diadeck" system, and part is due to the simplicity and ease of erecting four pieces per bay, compared to six pieces per bay for the double tee-girder system.

The "Diadeck" has performed extremely well and has carried loads above its design load with negligible deflections, which has been verified using levels. The four-way haunch allows two-way mechanical distribution at midspan, and results in an architecturally pleasing bottom surface (Fig. 10).

**PRECAST CONSTRUCTION IN REMOTE AREAS**

**Key design parameters**
1. Rapid erection (short building season)
2. Durability and low maintenance
3. Small skilled labor force
4. Architecturally exposed concrete

The architect and owner wanted this mountain ski area gondola terminal to be constructed out of concrete for appearance, fire resistance, and durability. Being in the mountain ski area of Vail,
Colorado, where the building season is short and the availability of the skilled labor required for cast in place concrete work is many times nonexistent, precast concrete was picked as the best building material.

To maintain the short design-construction schedule, the components were cast during the winter months at a Denver precast concrete plant, then hauled to the site and erected as soon as the foundations were installed in the spring. The precast manufacturer erected the structure using his own experienced erection crews, which eliminated the need for several different crews of skilled trades, as would have been required for a cast-in-place concrete structure.

This structure was not ideal for precast concrete because of the many different shapes, special corner details, varying roof elevations, many small pieces, and little repetition (Figs. 11 and 12). However, to build the same concrete building, which the architect and owner wanted, out of cast-in-place concrete would not have saved money and/or time.

With the great variety of different pieces required for this building, considerably more coordination time was spent during all phases of the project. Also, more field time was spent solving problems involving missing connection plates and fitting tolerances, than is normally required on a precast job having more repetition. However, precast concrete is still a good material to use in remote areas where skilled labor is in short supply and quality workmanship is difficult to maintain.

**SPECIAL WAFFLE SLAB**

**Key design parameters**

1. Client wanted exposed waffle slab using special large pans for lighting and acoustics
2. 5-ft module both ways
3. As much interior open space as possible
4. Cost

A special waffle slab with ribs spaced at 5 ft on center was designed to satisfy structural and architectural requirements. The architectural requirements consisted of using the large pan spaces for recessed lighting and acoustical control.

With the square footage of floor involved, it was economically feasible to make special steel pan forms $4\frac{1}{2} \times 4\frac{1}{2}$
Fig. 13. Special 4½ x 4½ x 1½ ft pan and prestressing tendons

Fig. 14. Detail of column and slab prestressing tendons intersection

x 1½ ft for building this 14-story government office building (Fig. 13). These large pans considerably reduced the waffle slab dead load on bay spacings of 30 x 40 ft and 30 x 30 ft. Prestressing was used as the most economical reinforcement due to the 5 ft joist spacing and relatively shallow joist depth. Prestressing was helpful in controlling slab deflections and increasing the slab punching shear capacity at the columns.

This special waffle slab was more economical than a conventional waffle slab reinforced with mild steel. The savings were mainly due to a lighter slab and reduced reinforcement placing costs.

When using this type of system, consideration must be given to the possible interference of tendons at the joist intersections and over columns (Fig. 14). This system resulted in a pleasing exposed modular structure.

HYPAR SLAB

Key design parameters

1. Contractor worked with engineer to devise the most economical structural system
2. Minimize expensive end prestressing hardware by making tendon pulls longer
3. Easy forming system
4. Watertight parking garage slab without waterproofing
5. Cost

This 30 x 30 ft bay parking garage slab system was designed while working with the contractor on cost and feasibility. The basic idea used in the design is to balance moments by draping the center of gravity of the concrete section and running the prestressing tendons straight the same distance from the top of the slab. This is achieved by forming the bottom of the slab as a hyperbolic paraboloidal surface which is 24 in. deep at the columns and 7 in. deep at the midspans.

The forming system is no more difficult to set than a conventional flat plate which is the easiest of all systems to form (Fig. 15). Tendon pulls of up to 240 ft long were made since there was little friction loss in the straight tendons. This resulted in a substantial cost savings in end hardware, and no threading of tendons is required as in a conventional flat plate. This saved considerable placing time and problems with tendon interference. Also, mechanical and electrical lines can be located near midspan where the slab depth (7 in.) is a minimum, saving headroom.
The finished slab has a pleasing bottom surface appearance (Fig. 16), and the prestressing resulted in a watertight slab. Cost savings, as well as 4 weeks of construction time resulted in the building of this prestressed "hypar" slab.

We have recently used this "hypar" slab on another project to carry heavy (250 psf) superimposed landscaping and live loads on a plaza. This system works well for heavy loading because of its plate action and its ability to carry high punching shears at the columns where its depth is greatest.

**MONOLITHICALLY TIED DOUBLE TEES**

**Key design parameters**

1. Contractor preference of structural system
2. Climbing crane capacity
3. Architecturally exposed cast-in-place concrete building frame
4. Structural floor system which could provide ramped slabs for lower story parking garage and upper story office floors
5. Cost and construction time

The contractor preferred to use 16 plus 2 double tees having a maximum span of 42 ft for the floor slabs in this 30-story office building. Structurally, cast-in-place concrete core walls and spandrel beams were required to carry the lateral wind and Seismic Zone 1 loads.

The core walls were cast one level ahead of the precast floor erection. Double tees were then set into pockets in core walls, and on shores at exterior wall lines (Fig. 17). Following the tee erection, spandrel beams forms were placed around the double tee legs. Prior to casting the spandrel beams, the ends of the legs were wrapped with polyethylene to break the bond be-
tween the tee and spandrel beam and allow the double tees to shorten. The final tee-to-spandrel beam connection is shown in Fig. 18. Later, a topping slab (2 in. minimum) was cast on the tees which acts as a diaphragm tie between the exterior frame and central core, making them work together to carry lateral loads.

The bottom 8 floors of the tower are ramped in a continuous spiral for a parking garage (Fig. 19), and the remaining 22 floors are level and used for office space. The precast, prestressed double tee floor slabs combined with the cast-in-place exterior frame and core worked well on both the spiral parking garage and office floors to save forming and construction time.

The double tees were made using lightweight concrete to reduce the climbing crane capacity required to lift the heaviest (42 ft long) tee. Using lightweight concrete increased the tee camber and resulted in more concrete required in the topping slabs to make a level finished floor.

During the early stages of construction, problems existed in scheduling crane time between the precast and cast-in-place concrete trades. However, once the crane scheduling was solved, the combined precast and cast-in-place construction worked fine.

Discussion of this paper is invited. Please forward your discussion to PCI Headquarters by August 1, 1973, to permit publication in the September-October 1973 issue of the PCI JOURNAL.