STRUCTURAL SYSTEM SELECTION – WHICH IS RIGHT FOR YOU?

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Introduction

What structural system is right for a new parking structure? The answer is...IT DEPENDS! This chapter will compare the primary structural systems used in parking structures so owners, parking professionals, structural engineers, and architects can be better informed to make this important decision. This investment decision is crucial because the structural elements make up about two thirds of the cost of a new parking structure and a significant portion of the maintenance budget. Several alternative structural systems are described below and their advantages and disadvantages are presented. Key factors that should be considered when selecting the structural system are also presented.

Modern parking structures are often architecturally enhanced.
The primary structural systems used in parking structures today include:

- Cast-in-Place Post-Tensioned Concrete Systems
- Precast Concrete Systems
  - Field Topped Double Tees
  - Pretopped Double Tees
- Steel Framed Systems
  - Cast-in-Place Post-Tensioned Concrete Floor Slabs
  - Precast Concrete Floor System

**The Ideal Structural System**

The structural system is one of the most important components of a parking structure. The structural engineer typically recommends what structural system should be selected to the owner, who then must decide which system best meets his objectives. The ideal structural system should have good quality, be highly durable with low maintenance cost and would have the following characteristics:

- Meets owner preferences
- Product and labor availability
- Suitable to achieve project objectives
- Economical first cost and low life cycle maintenance cost
- Minimal construction schedule
- Addresses user acceptance issues
- Achieves structural engineering requirements

**Meets Owner Preferences**

Many owners have existing parking structures or have some knowledge of parking structure construction, so they have developed a preference for a specific structural system. They may have had a good or a bad experience with a particular system that influenced their opinion. Further, previous experience with one structural system may lead an owner to prefer to build a new structure using the same system for consistency. Owner preferences should be determined at the beginning of the project.

**Product and Labor Availability**

Product and labor availability are two of the most critical issues in selecting the structural system. Product availability usually is a critical issue with precast concrete. Precast concrete may not be economical for the geographic region of the project if there are no precast plants in the area. Further, other large precast projects in the area may have local plants booked solid. In this case, the owner may receive no bids at all, or if bids are received, they may be
too costly for the budget. Labor availability usually is a critical issue with cast-in-place concrete, since large concrete projects in the area may have all qualified concrete workers employed. In this case, the owner would most likely receive bids for the work, but the quality of the finished product may not be acceptable. Also, there may not be qualified contractors in the area to install post-tensioning tendons or to place and finish quality cast-in-place concrete.

**Suitable to Achieve Project Objectives**

Whether the structural system is suitable to achieve project objectives can take many forms. Questions to consider include:

- Is the system capable of long spans for both efficiency and functionality?
- Is there access room for a crane suitable to erect precast concrete?
- Is the site accessible by trucks carrying the large precast concrete members?
- Is the structure’s shape too irregular for precast concrete?
- Does the material meet the architectural treatment goals?
- Is the garage part of a multi-use facility with occupied space above?

The list could be longer, but each of these questions may expose a “fatal flaw” that should be given strong consideration in the structural system selection.

**Economical First Cost and Low Life-Cycle Maintenance Cost**

The cost of the project takes two forms: first cost and long-term costs for maintenance. First cost is the cost of construction. Depending on the geographic location, the first cost may be lower for one system over another. In many areas of the country where the cost of labor is high and trade unions are strong, precast concrete is more economical. There are other regions where strong cast-in-place concrete contractors have invested in formwork and efficient production processes so that cast-in-place post-tensioned concrete is more economical.

Some owners are more driven to select the lowest first cost structure and are less concerned about the long-term maintenance costs. This is often true if the owner does not intend to own the property for an extended period. It is also sometimes true for owners who intend to hold the parking structure for its entire life, but desire to keep costs to the absolute minimum. Unfortunately, a lower first cost structure may result in maintenance costs that far exceed the initial savings compared to building a higher quality, more durable structure.
Life-cycle maintenance cost is the total cost over the life of the parking structure for maintenance. When comparing alternative structural systems, a life-cycle maintenance cost analysis may be used in combination with the estimate of construction cost to determine the most economical system over the long term. Often the lowest first cost structure does not have the lowest life-cycle maintenance cost. This analysis can also be used to evaluate which durability features to include in a new parking structure based strictly on a cost benefit assessment.

The analysis must be specific to the project and address local conditions that affect availability, suitability, cost, quality, schedule, etc. We are often asked how long a parking structure should last? Today, a new parking structure designed with quality and durability in mind and effectively maintained should have a life span of about 50 years before major structural repairs are necessary. Thus, life-cycle maintenance costs should be determined over the 50-year life and brought back to present value costs for comparison with alternative structural system costs.

**Minimal Construction Schedule**

The axiom that “time is money” is typically true for construction projects. Thus, the structural system selection is often heavily influenced by its construction schedule. This is often the case when a parking structure is being constructed on an existing surface parking lot and the goal is to minimize the time span where the parking is lost at that location. The project schedule may also be driven by tenant occupancy dates, the start of school, the beginning of the holiday season, or the need to be complete before winter. The time of the year when construction starts may also influence the structural system selection. Winter concrete construction is more difficult and costly in cold regions, and summer concrete construction is more difficult and costly in hot regions.

**Addresses User Acceptance Issues**

Parking facility users are more accepting of parking structures that are easy to drive through without obstructions from walls or other concrete elements. Interior walls that block visibility and openness are also a negative. Users prefer facilities with a higher perceived vertical clearance from the floor to the bottom of the concrete beams so that it doesn’t seem like they need to duck every time they drive or walk beneath a beam. The vertical clearance and spacing of the beams also affects the visibility of signage and distribution of lighting. The structural system also affects user acceptance if there is perceptible vibration of the floors and puddles of water due to poor drainage. Another structural impact on user acceptance is the spacing of columns. They should be located so that they are not between parking spaces encumbering vehicle access in and out of the stall, interfering with door opening clearance, or blocking the walking path between parked cars.
Achieves Structural Engineering Requirements

The structural system must achieve the engineering requirements in an efficient and cost effective manner. This might include the following:

- Ability to provide longer spans for column-free parking modules.
- Ability to support the floor loads. This is more of an issue if there are heavily loaded areas integrated into the parking structure such as loading docks, fire truck access, bus access, etc.
- Meet the depth requirements for beams to achieve the required vertical clearance.
- The lateral load resisting system must withstand wind and seismic forces, and for underground parking structures it may need to carry lateral forces from the earth retaining walls. New code requirements have made the design for seismic loads much more complex than in the past. Moment frames typically carry lateral loads in cast-in-place post-tensioned concrete structures. These frames use the same beams and columns used to carry gravity loads. However, shear walls typically carry lateral loads in precast concrete structures. The shear walls can be problematic because if they are located at the exterior of the structure, they affect the architecture. If they are located at the interior they can affect openness and visibility, reduce the parking space count, and interfere with vehicular turn clearances.
- The structural system must meet the durability criteria for the project. Parking structures are like bridges in that they are exposed to freezing conditions, extreme heat from sun exposure, rain and snow, and deicing salts. Durability elements include:
  - Positive drainage
  - Either prestressed or post-tensioned concrete to minimize concrete cracks
  - Corrosion protection of reinforcing bars and connections
  - Minimal water penetration through slab cracks and joints
  - Quality concrete to resist freezing conditions
- Maintain floor vibration within acceptable limits for user comfort.
- Attain code required fire resistance ratings of structural elements.

By now, you are probably wondering to what extent each of the primary parking facility structural systems achieve the ideal structural system characteristics described above. In the following section each of the systems is described in no particular order and their advantages and disadvantages are presented.
**Cast-in-Place Post-Tensioned Concrete**

Cast-in-place post-tensioned concrete refers to a structural system where the concrete is delivered to the job site in concrete trucks, placed into wood and steel forms in which the rebar and prestressing tendons are installed, and then the concrete floor slab is finished to create a uniform broom finish, and lastly the concrete is cured until it reaches the required strength. Two or three days after placement, the concrete strength is sufficient to post-tension the prestressing tendons. “Post-tensioned” means that the tendons are stressed after the concrete is placed, resulting in the concrete is being precompressed to mitigate tensile stresses and cracking. Post-tensioning tendons are typically isolated from the concrete by a plastic encapsulation assembly filled with corrosion resisting grease. This assembly must provide a waterproof environment for the tendon in areas where freezing weather occurs. The columns, beams, and floor slabs are monolithic so there is only a small quantity of sealant joints. Typically, the columns and beams are spaced between 20 and 27 feet and slabs are six to seven inches thick. Cast-in-place post-tensioned concrete has the following advantages and disadvantages when compared to the other primary parking facility structural systems.
Cast-in-Place Post-Tensioned Concrete

Advantages

- Monolithic construction so fewer sealant joints
- Positive drainage is easier to achieve
- Floor vibration generally imperceptible
- Post-tensioning forces reduces cracking in slabs
- Flexible column spacing of 20’-27’
- Generally no shear walls except in high seismic zones or very tall structures
- Lower maintenance costs due to less joint sealant upkeep
- Wider beam spacing creates a more open feeling with higher perceived head room, better signage visibility, and more uniform lighting distribution
- More accommodating for unique structures with irregular shapes, circular helix ramps, underground parking structures, or parking structures beneath other buildings
- Can be performed by local subcontractors in many cities.

Disadvantages

- Potentially higher construction cost in some regions of the country, particularly in areas where field labor costs are high
- Quality control is more difficult to attain due to exposed weather conditions
- May require architectural cladding to improve exterior aesthetics
- Slightly longer on-site construction schedule
- Less adaptable to winter construction in freezing climates
- Closer expansion joint spacing
- Congestion of tendons and rebar at beam column joints
- Slightly larger on-site staging requirement.

Open, well lit, painted cast-in-place parking structure
Precast Concrete

Precast concrete refers to concrete members that are fabricated in a plant and shipped by truck to the project site where the individual members are erected to provide a complete structure. The precast members commonly consist of columns, beams, spandrels, shear walls, lite walls, and double tees. The double tees are the floor deck members, which in appearance look like two T's side by side when viewed from the end. The top, horizontal surface of the double tee is called the flange and the vertical legs are called the stems (please refer to diagram below). The double tees are “pretensioned”, meaning that the prestressing tendons are stressed before the concrete is placed in the forms. The double tee floor deck can be either field topped or pretopped. Most precast concrete producers offer either a 10 or 12 foot wide tee, although there are a few producers who produce a 15 foot wide tee. Column spacing is most economical when a multiple of the tee width is used such as 30 feet for 10 foot tees or 36 feet for 12 foot tees. Precast concrete has the following advantages and disadvantages when compared to the other primary parking facility structural systems.
Precast Concrete Advantages

- Quality control because members are fabricated at a plant that should be certified by the Precast/Prestressed Concrete Institute
- Potentially lower construction cost in some regions
- Shorter on-site construction schedule
- Greater expansion joint spacing (i.e. up to 300 feet)
- More adaptable to winter construction
- Architectural façade spandrels also serve as structural load bearing elements

Precast Concrete Disadvantages

- More propensity for leaking at the joints between tee flanges (i.e. every 10 to 12 feet)
- Higher maintenance cost for sealants
- The tee stems (vertical elements) are spaced five to six feet on center and are generally just over seven foot clear above the floor. The close spacing of the tee stems creates the perception that the ceiling height is lower and the stems can block visibility of signage and interfere with lighting distribution
- Wind and seismic lateral loads are resisted by shear walls or shear frames. At the exterior of the structure they affect the architecture. At the interior they can reduce the number of parking spaces achieved, reduce visibility and openness, and interfere with vehicular turning maneuvers.
- Reduced drainage slopes
- More bird roosting ledges
- Might not be performed by local subcontractors in many cities

Field topped double tees typically have a two-inch thick flange and then a three-inch thick cast-in-place concrete topping is placed over the tee at the project site after the precast is erected. The topping becomes the top surface of the floor. Many owners, engineers, and precast concrete manufacturers prefer field topped systems over pretopped tees because of the advantages offered as shown below, even though it may have some cost and schedule implications.
Field Topped Double Tee Advantages

• Better drainage achieved
• Less floor vibration
• More forgiving during erection to correct problems with misaligned connections, repair of cracked tee flanges, or differential member camber
• More consistent and durable tee to tee joint sealants as they are tooled into the topping
• Lower maintenance costs

Field Topped Double Tee Disadvantages

• Potential in some regions of the country to have a higher construction cost
• Slightly longer construction schedule

Pretopped double tees typically have a four-inch thick flange. The top of the pretopped flange is the top surface of the floor. Commonly there is a cast-in-place concrete pour strip around the perimeter of the floor to cover connection hardware or to create sloped drainage washes. Many owners, engineers, and precast concrete manufacturers prefer pretopped systems because of the potential cost and schedule advantages compared to field topped precast despite the disadvantages shown below.

Pretopped Double Tee Advantages

• Potential in some regions of the country to have a lower construction cost, particularly in areas where field labor costs are high
• Slightly shorter construction schedule
• Higher quality control as there is little on-site concrete work

Pretopped Double Tee Disadvantages

• Positive drainage is more difficult to achieve
• More noticeable floor vibration
• Less forgiving during erection to correct problems with misaligned connections, repair of cracked tee flanges, or differential member camber
• Less consistent and less durable tee to tee joint sealants with a higher propensity for leaking
• Higher maintenance costs due to joint sealant upkeep

Interior view of painted precast concrete parking structure.

Precast shear frame at interior of parking structure.
Steel Framed Systems

A steel framed system refers to a structural scheme where the columns and beams are constructed of steel sections and the floor slab is of cast-in-place or precast concrete. Typically, the columns and beams are spaced between 18 and 22 feet. The most common slab systems are:

- Composite cast-in-place post-tensioned concrete where headed steel studs attached to the top of the beam are cast into the concrete slab to provide a stiff beam system with less vibration and less deflection.
- Precast concrete double tees (either field topped or pretopped)
- Solid precast plank with a field topping. The author does not typically recommend this system due to the difficulty in keeping the floor system from leaking.

Steel framed parking structures with a cast-in-place post-tensioned concrete slab have similar advantages and disadvantages as listed above for the cast-in-place post-tensioned concrete system. Also, the precast double tee floors would have similar advantages and disadvantages as listed above for the precast concrete option. The cast-in-place post-tensioned concrete slab system with the steel frame may sometimes be preferred over a precast double tee floor. The slab is monolithic with less potential for leakage than with precast floors and because it creates a more open feeling structure with higher perceived head room, better signage visibility, and more uniform lighting distribution. However, the potential cost and schedule advantages of the precast floor may be preferred in other cases. A steel framed system has the following advantages and disadvantages when compared to the other primary parking facility structural systems.
Steel Framed System Advantages
- Flexible column spacing of 18’-22’
- Generally no shear walls except in high seismic zones or very tall structures
- Can be performed by local subcontractors in many cities
- Speed of construction is faster than for a completely cast-in-place system
- Potentially lower construction cost
- Easily accommodates vertical expansion

Steel Framed System Disadvantages
- Erection concerns due to mixing foundation, steel, and precast subcontractors
- Steel painting for corrosion protection
- Maintenance of steel paint system
- Steel delivery times can fluctuate
- Not recommended where the steel is required to be fire rated by the building code
- Extensive bird roosting ledges on the beam flanges
- Depending on code requirements, steel structure may need to be fireproofed

There are many other potential structural systems for parking structures than the most common ones described above. Typically, the other potential structural systems are more prone to durability problems and more rapid deterioration, thus they are not generally recommended.

- **Cast-in-Place Concrete – Mild Reinforced (not post-tensioned):** Typically, a cast-in-place concrete system with only mild reinforcement is used with short-span construction, meaning there are columns between the parked vehicles. Generally, the floors are two-way flat slabs or pan joist systems. Because the concrete is not prestressed, the floors are prone to cracking. A short-span, mild reinforced, cast-in-place concrete floor is sometimes used when parking is located beneath an office, hotel or other building use. Thus,
because the parking is the foundation for the other building, it is very important that a waterproof traffic bearing membrane be used on the floor to keep the cracks from leaking and to prevent deterioration.

- **Composite Metal Deck on Steel Frame:** Composite metal deck (or any other type of metal deck) is generally a poor choice of material for the exposure conditions of a parking facility, because the decking tends to trap water between the slab and the metal deck. Corrosion of the decking will occur with no outward indication of problems until such time that serious problems exist.

- **Bar Joist With Metal Deck on Steel Frame:** Steel bar joists are not recommended in parking structures. This system generally consists of a relatively thin slab on light-gage metal form deck with closely spaced bar joists supported by steel girders. Although this system is well suited for general office and retail occupancies, it has proven to be a poor choice of material for the loading and exposure conditions of a parking facility.

Bar joists floor systems tend to exhibit unacceptable differential deflections when subjected to large concentrated loads (i.e. automobile wheel loads) that cause the thin slabs to deteriorate. This condition was recently documented as part of a due diligence evaluation of a parking facility that was only three years old. The cracking and deterioration was so extensive that the owner/developer who was selling the property, was forced to take a considerable loss due to “diminished value” of the parking facility portion of this complex.

- **Filigree Slab Soffits on Steel Frame:** Filigree slabs are ideal for load-bearing masonry construction and this product is used quite extensively in multi-family housing projects. The system is a hybrid composite design, which utilizes prestressed concrete for positive bending and mild reinforced concrete for negative bending, and has good depth/span characteristics. However, the product has two disadvantages that may make this material an undesirable choice for parking facilities.

First, to achieve economical span ratings, the slab panels must be shored during construction. A typical design might be a 5-1/4” Filigree slab (2-1/4” panel + 3” topping) spanning 22’ to 24’, supported on W27 or W30 steel girders. After the topping is placed, the shores are removed, which causes the floor panels to deflect, and it is not unusual to see a significant amount of flexural cracking in the mild-reinforced topping in the negative bending zone.

Second, because of the tendency for cracking of the topping, Filigree slabs are prone to leaking and require more maintenance to maintain joint sealants.

Alternatively, Filigree slabs can be used in a hybrid system with a cast-in-place concrete frame for garages beneath office buildings.
- **Hollow Core Slabs on Steel (or Concrete) Frame**: With water intrusion being such a problem with durability, voided (hollow) systems are generally not recommended for exposed floors of parking facilities.

- **Keystone Joist with Beam Soffits**: Keystone joist with beam soffits are somewhat common in certain parts of the country such as Florida where there are several producers of the system. The precast joists come in nominal depths of 8, 12, 16, and 24 inches and may be used with either mild-reinforced or post-tensioned slabs. The system is a hybrid composite design, which utilizes prestressed concrete for positive bending and mild reinforced concrete for negative bending and has good depth/span ratios. However, there are some peculiarities of the system that make it less desirable than the more common systems.

With so many options, each with a relatively long list of advantages and disadvantages, you may be wondering how the decision is ever made on which structural system is best for a particular project. Each project is unique and the structural system selection should be given careful consideration by the owner, parking professional, structural engineer, and architect. As described in more detail above, the decision is often made considering the following:

- Owner preferences
- Design team preferences
- Schedule
- Construction cost budget
- Owner’s tolerance and budget for maintenance
- User acceptance criteria such as openness, perceived headroom, light distribution, sign visibility, floor vibration, and leakage potential
- Ability to achieve structural engineering requirements specific to the project
- Local availability of product and labor

Because of the complexity involved in the proper selection and design of the structural system, it is highly recommended that owners retain a specialty-parking consultant as the structural engineer on parking structure projects. This will help ensure that the most economical and durable structure is provided consistent with the owners’ goals. Achieving the balance between an economical first cost and a durable low maintenance cost parking structure requires special expertise often not commonly understood by engineers who do not specialize in parking structure design. It is also recommended that parking structures be designed in accordance with the American Concrete Institutes (ACI) Guide for the Design of Durable Parking Structures, as published in ACI 362.1R-1997.