Guide for the Design of Durable Parking Structures

Reported by ACI Committee 362

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This guide is a summary of practical information regarding design of parking structures for durability. It also includes information about design issues related to parking structure construction and maintenance

The guide is intended for use in establishing criteria for the design and construction of concrete parking structures. It is written to specifically address aspects of parking structures that are different from those of other buildings or structures.

Keywords: Concrete durability; construction; corrosion; curing; finishes; freeze-thaw durability; maintenance; parking structures; post-tensioning; precast concrete; prestressed concrete.

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ACI 362.1R-97 became effective May 8,1997. This report supercedes ACI 362.1R94.

CHAPTER l-GENERAL

l.l-Introduction

ACI 318 requires a general consideration of the durability of concrete structures. Because some concrete parking structures have undergone significant deterioration, it is the purpose of this guide to provide specific practical information regarding the design, construction, and maintenance of parking structures with respect to durability.

The guide is primarily concerned with those aspects of parking structures that differentiate them from other structures or buildings. Thus, the guide does not treat all aspects of the structural design of parking structures.

1.2-Definition of terms

Reference is made to the following selected terms to help clarify the intent of the information provided throughout the document. Unless otherwise noted, the terms are as defined in ACI 116R and are repeated here for the convenience of the reader.

Admixture-A material other than water, aggregates, hydraulic cement, and fiber reinforcement, used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing.

Admixture, accelerating-An admixture that causes an increase in the rate of hydration of the hydraulic cement, and thus shortens the time of setting, or increases the rate of strength development, or both.

Admixture, air-entraining-An admixture that causes the development of a system of microscopic air bubbles in the concrete, mortar, or cement paste during mixing.

Admixture, retarding-An admixture that causes a decrease in the rate of hydration of the hydraulic cement, and lengthens the time of setting.

Admixture, water-reducing-An admixture that either increases slump of freshly mixed mortar or concrete without increasing water content or maintains slump with a reduced amount of water, the effect being due to factors other than air entrainment.

Admixture, high-range water-reducing-A water-reducing admixture capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

Air content-The volume of air voids in cement paste, mortar, or concrete, exclusive of pore space in aggregate particles, usually expressed as a percentage of total volume of the paste, mortar, or concrete.

Air entrainment-The incorporation of air in the form of minute bubbles (generally smaller than 1 mm) during the mixiig of either concrete or mortar.

Air void-A space in cement paste, mortar, or concrete filled with air; an *entrapped air void* is characteristically 1 mm or more in size and irregular in shape; an *entrained air void* is typically between 10 μm and 1 mm in diameter and spherical or nearly so.

Bleeding-The autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar; caused by the settlement of the solid materials within the mass; also called water gain.

Bond-Adhesion and grip of concrete or mortar to reinforcement or to other surfaces against which it is placed, including friction due to shrinkage and longitudinal shear in the concrete engaged by the bar deformations; the adhesion of cement paste to aggregate.

Bond breaker-A material used to prevent adhesion of newly placed concrete or sealants and the substrate.

Bonded member-A prestressed concrete member in which the tendons are bonded to the concrete either directly or through grouting.

Cast-in-place-Concrete which is deposited in the place where it is required to harden as part of the structure, as opposed to precast concrete.

Cementitious-Having cementing properties.

C.I.P.-Cast-in-place, referring to a method of concrete construction. See cast-in-place.

Chert-A very fine grained siliceous rock characterized by hardness and conchoidal fracture in dense varieties, the fracture becoming splintery and the hardness decreasing in porous varieties, and in a variety of colors; it is composed of silica in the form of chalcedony, cryptocrystalline or microcrystalline quartz, or opal, or combinations of any of these.

Cold joint-A joint or discontinuity resulting from a delay in placement of sufficient time to preclude a union of the material in two successive lifts.

Composite construction-A type of construction using members produced by combining different materials (e.g., concrete and structural steel), members produced by combining cast-in-place and precast concrete, or cast-in-place concrete elements constructed in separate placements but so interconnected that the combined components act together as a single member and respond to loads as a unit.

Concrete-A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate; in portland-cement concrete, the binder is a mixture of portland cement and water.

Concrete, precast-Concrete cast elsewhere than its final position.

Concrete, prestressed-Concrete in which internal stresses of such magnitude and distribution are introduced that the tensile stresses resulting from the service loads are counteracted to a desired degree; in reinforced concrete the prestress is commonly introduced by tensioning the tendons.

Construction joint-The surface where two successive placements of concrete meet, across which it may be desirable to achieve bond and through which reinforcement may be continuous.

Contraction joint-Formed, sawed, or tooled groove in a concrete structure to create a weakened plane and regulate the location of cracking resulting from the dimensional change of different parts of the structure.

Control joint-See **contraction joint**.

Corrosion-Destruction of metal by chemical, electrochemical, or electrolytic reaction with its environment.

Corrosion inhibitor-A chemical compound, either liquid or powder, that effectively decreases corrosion of steel reinforcement before being imbedded in concrete, or in hardened concrete if introduced, usually in very small concentrations, as an admixture.

Crack-A complete or incomplete separation, of either concrete or masonry, into two or more parts produced by breaking or fracturing.

Crack-control reinforcement-Reinforcement in concrete construction designed to prevent openings of cracks, often effective in limiting them to uniformly distributed small cracks.

Creep-Time-dependent deformation due to sustained load.

Deformed bar-A reinforcing bar with a manufactured pattern of surface ridges intended to prevent slip when the bar is embedded in concrete.

Deicer-A chemical such as sodium or calcium chloride, used to melt ice or snow on slabs and pavements, such melting being due to depression of the freezing point.

Delamination-A separation along a plane parallel to a surface as in the separation of a coating from a substrate or the layers of a coating from each other, or in the case of a concrete slab, a horizontal splitting, cracking, or separation of a slab in a plane roughly parallel to, and generally near, the upper surface; found most frequently in bridge decks and caused by the corrosion of reinforcing steel or freezing and thawing, similar to spalling, scaling, or peeling except that delamination affects large areas and can often only be detected by tapping.

Double-tee-A precast concrete member composed of two stems and a combined top flange.

Elastic design-A method of analysis in which the design of a member is based on a linear stress-strain relationship and corresponding limiting elastic properties of the material.

Elastic shortening-In prestressed concrete, the shortening of a member that occurs immediately on the application of forces induced by prestressing.

Expansion joint-A separation provided between adjoining parts of a structure to allow movement where expansion is likely to exceed contraction.

Flat plate-A flat slab without column capitals or drop panels (see also flat slab).

Flat slab-A concrete slab reinforced in two or more directions and having drop panels or column capitals or both (see also flat plate).

Fly ash-The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases.

Isolation joint-A separation between'adjoining parts of a concrete structure, usually a vertical plane, at a designed location such as to interfere least with performance of the structure, yet such as to allow relative movement in three directions and avoid formation of cracks elsewhere in the concrete and through which all or part of the bonded reinforcement is interrupted (see also **contraction joint** and **expansion joint**).

Joint sealant-Compressible material used to exclude water and solid foreign materials from joints.

Jointer (concrete)-A metal tool about 6 in. (150 mm) long and from 2 to $4^1/_2$ in. (50 to 100 mm) wide and having shallow, medium, or deep bits (cutting edges) ranging from $^3/_{16}$ to $^3/_4$ in. (5 to 20 mm) or deeper used to cut a joint partly through fresh concrete.

Nonprestressed reinforcement-Reinforcing steel, not subjected to either pretensioning or post-tensioning.

Plastic cracking-Cracking that occurs in the surface of fresh concrete soon after it is placed and while it is still plastic.

Plastic shrinkage cracks-see **plastic cracking.**

Post-tensioning-A method of prestressing reinforced concrete in which tendons are tensioned after the concrete has hardened.

Pour strip-A defined area of field-placed concrete used to provide access to embedments, improve tolerance control between adjacent elements, or enhance drainage lines. Pour strips are typically associated with pretopped, prestressed structures but may be utilized with other structural types as well (not defined in ACI 116R).

Precast-A concrete member that is cast and cured in other than its final position; the process of placing and finishing precast concrete (see also cast-in-place).

Prestress-To place a hardened concrete member or an assembly of units in a state of compression prior to application of service loads, the stress developed by prestressing, such as pretensioning or post-tensioning (see also **concrete, prestressed; prestressing steel; preten-**

sioning; and **post-tensioning).**

Prestressed concrete--See **concrete, prestressed.**

Prestressing steel-High-strength steel used to prestress concrete, commonly seven-wire strands, single wires, bars, rods, or groups of wires or strands (see also prestressed; concrete, prestressed; pretensioning, and post-tensioning).

Pretensioning-A method of prestressing reinforced concrete in which the tendons are tensioned before the concrete has hardened.

Pretopped-A term for describing the increased flange thickness of a manufactured precast concrete member (most commonly a double-tee beam) provided in the place of a field-placed concrete topping. (Definition by ACI 362.)

Rebar-Colloquial term for reinforcing bar (see reinforcement).

Reinforcement-Bars, wires, strands, or other slender members embedded in concrete in such a manner that they and the concrete act together in resisting forces.

Retarder-An admixture that delays the setting of cement paste, and hence of mixtures such as mortar or concrete containing cement.

Saturation-(l) in general: the condition of coexistence in stable equilibrium of either a vapor and a liquid or a vapor and solid phase of the same substance at the same temperature; (2) as applied to aggregate or concrete, the condition such that no more liquid can be held or placed within it.

Screeding-The operation of forming a surface by the use of screed guides and a strikeoff.

Shrinkage-Decrease in either length or volume.

Shrinkage, drying--Shrinkage resulting from loss of moisture.

Shrinkage, plastic-Shrinkage that takes place before cement paste, mortar, grout, or concrete sets.

SI (Systeme International)-The modern metric system; see ASTM E 380.

Silica fume-Very fine noncrystalline silica produced in electric arc furnaces as a byproduct of elemental silicon or alloys containing silicon; also is known as condensed silica **fume** and microsilica.

Slab-A flat, horizontal or nearly so, molded layer of plain or reinforced concrete, usually of uniform but sometimes of variable thickness, either on the ground or supported by beams, columns, walls, or other framework.

Spall-A fragment, usually in the shape of a flake, detached from a larger mass by a blow, by the action of weather, by pressure, or by expansion within the larger mass; a small spall involves a roughly circular depression not greater than 20 mm in depth nor 150 mm in any dimension; a large spall, that may be roughly circular or oval or in some cases elongated, is more than 20 mm in depth and 150 mm in greatest dimension.

Spalling-The development of spalls.

Span-Distance between the support reactions of members carrying transverse loads.

Span-depth ratio-The numerical ratio of total span to member depth.

Stirrup-A reinforcement used to resist shear and diagonal tension stresses in a structural member, typically a steel bar bent into a U or box shape and installed perpendicular to or at an angle to the longitudinal reinforcement formed of individual units, open or closed, or of continuously wound reinforcement. Note — the term "stirrups" is usually applied to lateral reinforcement in flexural members and the term "ties" to lateral reinforcement in vertical compression members (see also tie).

Strand-A prestressing tendon composed of a number of wires twisted about center wire or core.

Superplasticizer-See **admixture, high-range water-reducing**.

Tie-(l) loop of reinforcing bars encircling the longitudinal steel in columns; (2) a tensile unit adapted to holding concrete forms secure against the lateral pressure of unhardened concrete.

Tooled joint-A groove tooled into fresh concrete with a concrete jointer tool to control the location of shrinkage cracks. See contraction joint.

Unbended post-tensioning-Post-tensioning in which the post-tensioning tendons are not bonded to the surrounding concrete.

Unbended tendon-A tendon that is permanently prevented from bonding to the concrete after stressing.

Water-cement ratio-The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of cement in a concrete, mortar, grout, or cement paste mixture; preferably stated as a decimal by mass and abbreviated w/c.

Water-cementitious material ratio-The ratio of the amount of water, exclusive only of that absorbed by the aggregate, to the amount of cementitious material in a concrete or mortar mixture.

w/c-See water-cement ratio and water-cementitious ratio.

Yield strength-The stress, less than the maximum attainable stress, at which the ratio of stress to strain has dropped well below its value at low stresses, or at which a material exhibits a specified limiting deviation from the usual proportionality of stress to strain.

1.3-Background

Parking structures are built either as independent, free-standing structures or as integral parts of multi-use structures. Parking structures may be above grade, at grade, or partially or fully below grade.

Many different terms are used to describe parking structures. Some of the common terms include garage, parking garage, parking deck, parking ramp, parking structure, parking facility, multilevel parking deck, and open parking structure. This guide uses the general term "parking structure."

1.3.1 *Differences from other structures*-The open parking structure (defined in various building codes as having a large percentage of the facade open) is subjected, in varying degrees, to ambient weather conditions.

Similarly, a completely enclosed parking structure is often ventilated with untempered outside air. Frequently, parking structures are very large in plan compared to most enclosed structures. They are exposed to seasonal and daily ambient temperature variations. These temperature variations result in greater volume change effects than enclosed structures experience. Restraint of volume changes can create cracking of floor slabs, beams, and columns, which, if unprotected, may allow rapid ingress of water and chlorides, leading to deterioration.

The primary live loads are moving and parked vehicles. For roof levels, consideration is frequently given to some combination of vehicular and roof loads (water or snow). At barrier walls or parapets some building codes typically require consideration of a lateral bumper load.

Similar to a bridge deck, a parking structure is exposed to weather. The roof level is exposed to precipitation, solar heating, ultraviolet, infrared radiation, and chemicals carried by wind and precipitation.

The edges of an open parking structure may be subject to the same weather conditions as the roof, and other areas may experience runoff from the roof. All floors are subject to moisture in the form of water or snow carried in on the undersides of vehicles, as shown in Fig. 1.1. This moisture may contain deicing salts in some climates.

Unlike a bridge deck, the lower levels of a parking structure are not rinsed with rain. The structure's exposure to chlorides may be increased due to poor drainage of the slab surface. In marine areas, salt spray, salt-laden air, salty sand, and high-moisture conditions can produce serious corrosion.

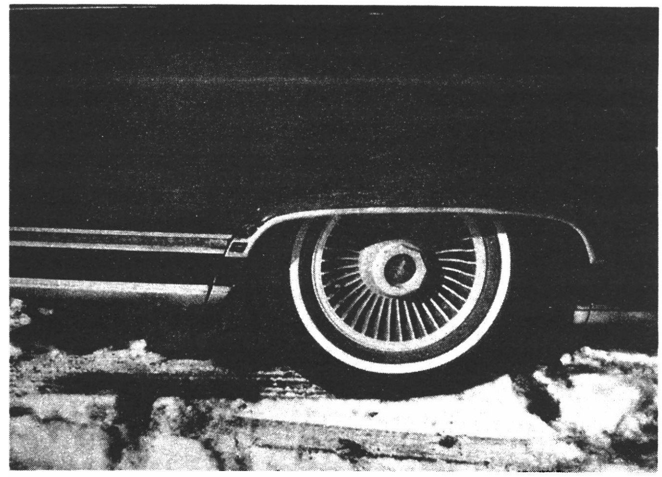


Fig. 1.1-Deicing salt-bearing slush brought into structure in car wheel well

1.4-Durability elements

The durability of parking structures is related to many factors, including weather, the use of deicer salts, concrete materials, concrete cover over reinforcement, drainage, design and construction practices, and the response of the structural system to loads and volume change. See Table 1.1 for common durability problems.

The most common types of deterioration and undesirable performance of parking structures are due to corrosion of reinforcement, freezing and thawing, cracking, ponding of water, and water penetration. In climates where deicer salts are used, symptoms of deterioration may include: spalls and delaminations in the driving surface, leakage of water through joints and cracks, rust staining, scaling of the top surface, and spalling of concrete on slab bottoms, beams, and other underlying concrete elements. Even walls and columns suffer distress from leakage, splash, and spray of salt-contaminated water. The lives of parking structures have been shortened by the same effects as described in NCHRP 57 *Durability of Concrete Bridge Decks.*

Even in climates where deicers are not used, water penetration through parking structure floors is often perceived as poor performance. In parking structure floors located over enclosed retail, office space, or other occupied space, water penetration through the slab or deck is objectionable.

1.4.1 *Corrosion of embedded metal*

1.4.1.1 *Reinforcement*-The electrochemical mechanism of chloride-induced corrosion of steel embedded in concrete is complex and continues to be studied. The high alkalinity of concrete inhibits corrosion of steel embedded in sound, dense concrete by forming a protective ferric oxide layer on the steel surface. Water-soluble chloride ions can penetrate and undermine this protective layer, decrease the electrical resistivity of the concrete, and establish electrical potential differences. These changes, in the presence of sufficient moisture and oxygen, promote corrosion of the steel.

When corrosion does occur, the resulting expansion frequently causes fracturing and spalling of the concrete. If the fracture extends to the concrete surface, it appears as a feather-edged fracture surface or spall, similar to that shown in Fig. 1.2.

When closely spaced reinforcement in a slab corrodes, horizontal fractures may occur that are not visible at the surface. These subsurface fractures may create one or more delaminations at the various reinforcement levels (Fig. 1.3 and 1.4).

Repeated traffic, freeze-thaw damage, or both, may dislodge the concrete above the delamination. With time, the loose material is lost, resulting in a spall or pothole (Fig. 1.3 and 1.5). Spalls can be hazardous to pedestrians and vehicular traffic as well as being detrimental to structural integrity. Spalls can be caused by corrosion of reinforcement, severe damage due to freezing and thawing, concentrated forces at bearing points and connections, or a combination of these factors.

Without effective protection, corrosion of reinforcement frequently occurs on bridges and parking structures. The source of chlorides is commonly deicer salts in northern sites and saltwater spray or salt laden air near oceans. Chlorides may also be placed in the concrete during construction in the form of admixtures or as constituents of the concrete mix.

Chloride ion content versus depth from the surface of

Table 1.1 — Potential durability problems

Potential problem area	Action to be taken to prevent or minimize the problem (guide section)
Cracking (1.3.3)-Cracking can be controlled but not prevented 100 percent	• Choice of structural system has significant influence (2.3-2.5, 3.5.2.5) • Design for volume change (2.51)
Leaking (1.3.3)	• Drainage (3.2.2) • See cracking (3.5.2.5) • Install and maintain joint sealant and isolation joint seals (3.5.2)
Freeze/thaw (scaling) (1.3.2)	• Air entrainment (3.3.3.4) • Drainage (3.2) • Protective coatings (3.5.1)
Corrosion (1.3.1)	• Drainage (3.2) • Quality concrete (3.3) • Concrete cover (3.4.1) • Protection of reinforcement (3.4.2) • Protective coatings (3.5.1) • Other embedded metals (3.4.3) • Silica fume (3.3.3.3) • Corrosion inhibitors (3.4.4) • Dampproofing admixture (3.4.5) • Cathodic protection (3.4.6)
Low quality concrete	• Water-cement ratio (3.3.3.1) • Air entrainment (3.3.3.4) • Admixtures (3.3.3.5) • Finishing (3.3.4) • Curing (3.3.4.2)

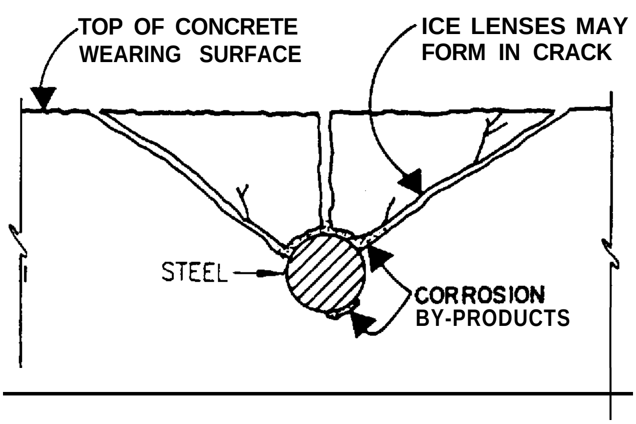


Fig. 1.2-Spa11 due to corrosion of exposed steel (excerpted from NCHRP Synthesis 4)

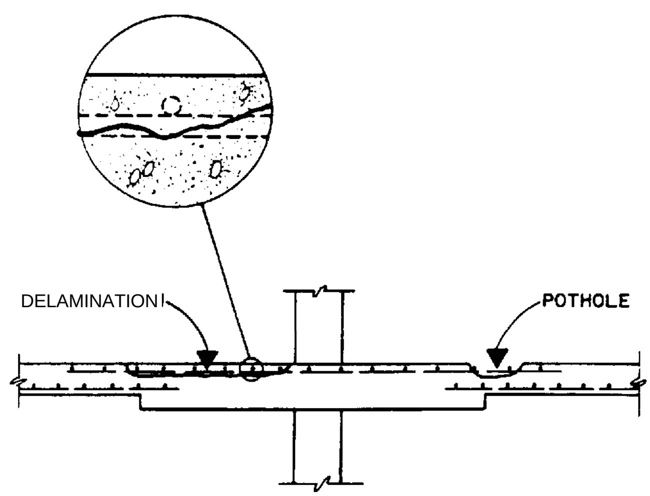


Fig. 1.3-Schematic of delamination and pothole in flat slab construction

a parking structure can be as high as the levels shown in Fig. 1.6, in regions where deicing salts are used. The core shown in the figure is from an unprotected 13-year-old concrete slab located in a corrosive environment. Chloride ion contents of concrete are reported in various ways: (1) percent by weight of cement, (2) percent by weight of concrete, (3) pounds per cubic yard of concrete, and (4) parts per million of concrete. Conversion among the four reporting methods requires knowledge of the cement content of the concrete and the concrete unit weight. The maximum water-soluble chloride ion content in the hardened concrete at ages from 28 to 42 days recommended by ACI 318 is 0.06 percent and 0.15 percent by weight of cement, respectively, for prestressed and nonprestressed reinforced concrete. It is generally believed that the corrosion threshold is a chloride ion content of 0.2 percent by weight of cement. In a normal weight concrete containing 564 lbs. of cement/yd^3, this equates to 1.1 lb/yd^3, 280 ppm, or 0.028 percent by weight of concrete. See NCHRP 57, *Durability of Concrete Bridge Decks*, for conversion factors expressing chloride content.

Corrosion can occur in uncracked concrete due to

Fig. 1.4-Core showing top delaminations

chloride ions, moisture, and oxygen permeating into the concrete (see Section 3.3.3.1). However, corrosion of reinforcement is generally more severe and begins earlier at cracks and places where water can easily penetrate. Information on corrosion of metals in concrete is available in ACI 222R, *Corrosion of Metals in Concrete.*

1.4.1.2 *Bonded prestressing steel*-The corrosion of prestressing strand in pretensioned double-tees and inverted tee-beams used in parking structures has normally occurred where there is a breach in the sealed joints and where brackish water reaches the bottoms of members.

Corrosion of grouted, prestressing steel has occurred where the grout did not encase the wires, bar, or strand within a grout duct, and moisture or chlorides gained access to the open void.

1.4.1.3 *Unbonded prestressing steel*-Most cases of corrosion of unbonded prestressing steel in parking structures have involved either natural saltwater or deicer salt exposure to loosely sheathed systems with inadequate amounts of grease. Other areas most susceptible to corrosion include poorly grouted stressing end anchorages, intermediate stressing points at construction joints, and regions of insufficient concrete cover.

1.4.1.4 *Other embedded metals*-Corroded electrical conduits have been observed in structures exposed to deicer salts. Likewise, uncoated aluminum has been observed to corrode in concrete containing chloride and particularly where the aluminum has been in contact with the steel reinforcement. Embedded metals of all kinds should be specifically reviewed for their durability and function.

1.4.2 *Freezing and thawing damage*-Scaling of concrete is a deterioration observed in parking structures

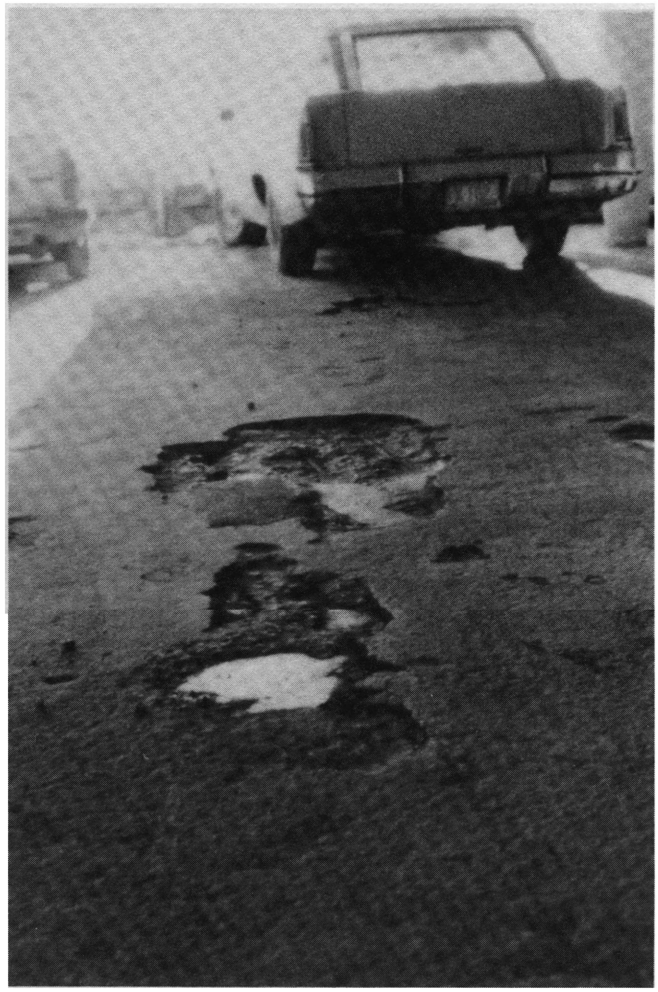


Fig. 1.5-Potholes in floor surface

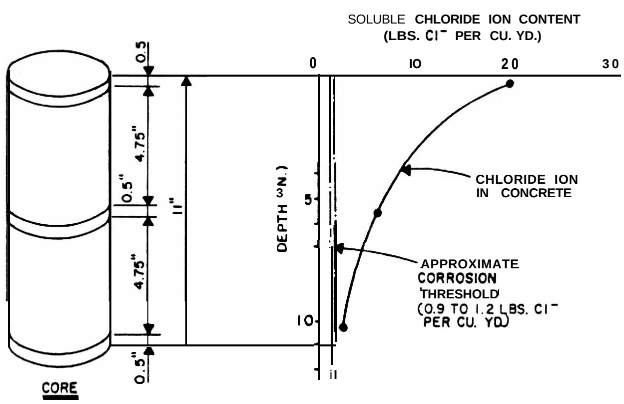


Fig. 1.6-Chloride ion content of concrete versus depth

exposed to a freezing and thawing environment. Cyclic freezing and deicer scaling is discussed extensively in ACI 201.2R Guide to *Durable Concrete.* The phenomenon usually begins with the loss of thin flakes at the surface. As deterioration progresses, coarse aggregates may be exposed. In advanced stages, the surface may progress from

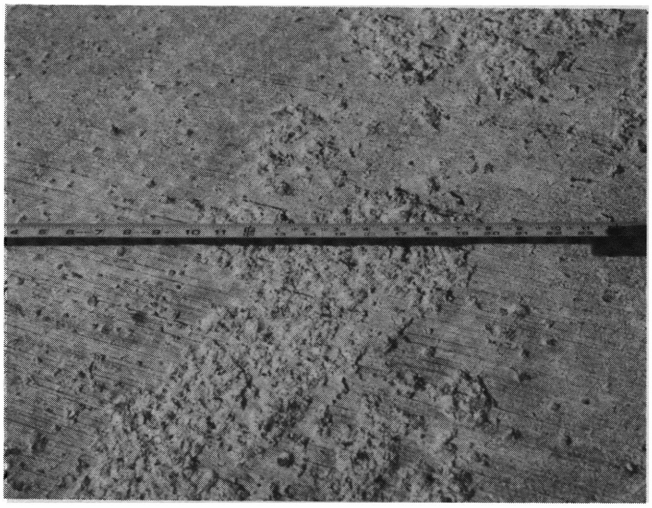


Fig. 1.7-Scaling of floor surface

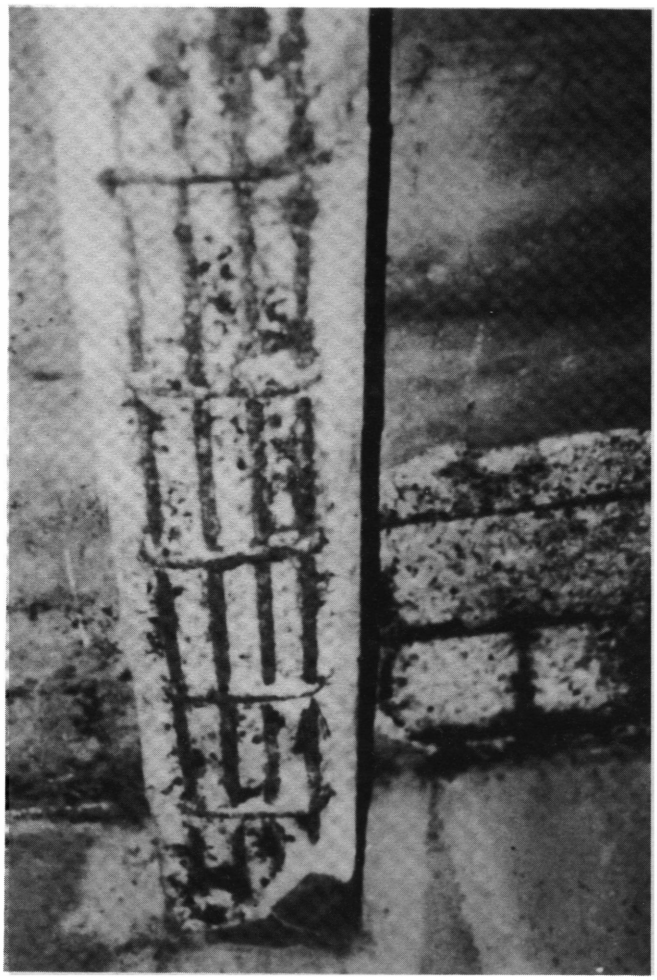


Fig. 1.8-Spalling of beam soffit beside leaking isolation joint

an exposed aggregate appearance to that of rubble. Frequently, with prolonged water saturation and repeated freeze-thaw cycles, the concrete will develop fine cracks paralleling the exposed surface. The presence of deicers will accelerate this deterioration (Fig. 1.7).

The addition of air entrainment is the most effective method of increasing the resistance of concrete to damage due to freezing and thawing. The entrained air-void size and spacing in. the concrete is also important (see ACI 345R). Severe abrasion accelerates the deterioration of concrete undergoing scaling. Good drainage (pitch of surface to drains) diminishes the severity of freezing and thawing exposure by reducing the moisture content of the concrete.

1.4.3 *Cracking and water penetration*-Cracking of concrete exists in many forms. Some common types are: microcracking, partial depth cracks in the top of members, and through-slab cracks. Observations of parking structures suggest that corrosion will occur earlier and is much more likely at wide cracks than at untracked or finely cracked areas. For information on resistance to cracking, see Section 3.5.2.5.

In addition to abetting corrosion, water penetration through the slab is undesirable. When substantial amounts of water penetrate completely through the slab at cracks and joints, corrosion and freeze-thaw damage of the sides or bottoms of underlying members may occur. Damage to ribs, joists, webs, beams, columns, heavily loaded joints, and bearings is more critical to structural integrity than damage to the slab because these elements support larger tributary areas. Severe damage to a beam at an isolation joint is shown in Fig. 1.8.

The potential problems and actions that may be taken to reduce or eliminate the problem are listed in Table 1.1. The action portion of the list references the section(s) of the text that discuss the action or problem.

CHAPTER 2-STRUCTURAL SYSTEMS

2.1—Introduction

The selection and design of a structural system for a parking structure involve making choices from many construction methods and materials. Other considerations affecting the design include the site, functional requirements, economics, appearance, performance for the purpose intended, durability, and building code requirements relating to strength and safety. This chapter examines the preceding factors and how they may affect the performance and durability of the structural system of a parking structure.

2.2-Factors in the choice of the structural system

2.2.1 *Site*-Geographic location and site selection will influence architectural and structural planning. Anticipated temperature and humidity ranges, and the probability of a corrosive environment, should be evaluated during the design process to determine what protective measures should be incorporated into the design.

2.2.2 *Functional requirements*-Complete functional design of a parking facility is not within the scope of this guide, but a limited review is necessary to discuss the selection of a structural system. In general, the structure should easily accommodate both vehicles and people. The functional design of the facility should consider various elements such as parking stall and aisle dimensions, ramp slopes, turning radii, traffic flow patterns, means of egress, security features,. and parking control equipment. Some or all of these factors may affect the layout of columns, depth of structural members, and the design of the structural system.

2.2.3 *Economics*-Construction cost is an important factor in selecting the structural system. The structural system must provide the needed level of durability, function, and aesthetics to be perceived as economical. Inclusion of one or more of the various available protection systems, in and of itself, however, will not adequately address the importance of structural system economics.

2.2.4 *Aesthetic treatment*-Aesthetics are not within the scope of this guide. However, parking structures are often designed so that a structural element serves a significant architectural function as well. For example, an exterior beam may be designed to carry gravity loads, barrier loads, and lateral loads. But, if exposed to view, it may also affect the aesthetics of the building. Further, the functional design may require sloping floors, but horizontal elements may be preferred at the building exterior for aesthetic reasons. These considerations may affect the choice of structural systems and the exterior framing.

2.2.5 *Building code requirements*-Requirements of model and local building codes vary. They affect:

- Structural design and loading criteria
- Fire resistance
- Barrier requirements
- Ventilation requirements
- Height and area limits related to type of construction
- Ramp slope limits
- Perimeter openness requirements
- Headroom clearance requirements
- Means of egress

2.2.5.1 *Gravity loads*-Building codes commonly require a uniformly distributedload of 50 psf or a 2000 lb concentrated wheel load (whichever is more critical) anywhere on a floor (whichever is more critical), with additional load for snow (see 2.2.5.2) on the top level. Some codes require that the size of the concentrated wheel load tread print be 20 square in. (Fig. 2.1). Most codes require designing members for the worst case among several patterned load cases. Typically, slabs are designed for bending and punching shear due to wheel loads.

The use of reduced live loads is usually appropriate, where allowed by code or permitted by appeal, since actual automobile loads in fully loaded parking structures seldom exceed 30 psf. However, added reserve capacity in design may be desirable to account for future increased loadings due to added material such as overlays used in repair. Unusual loads due to fire trucks, other special equipment, soil, and planter boxes require design consideration.

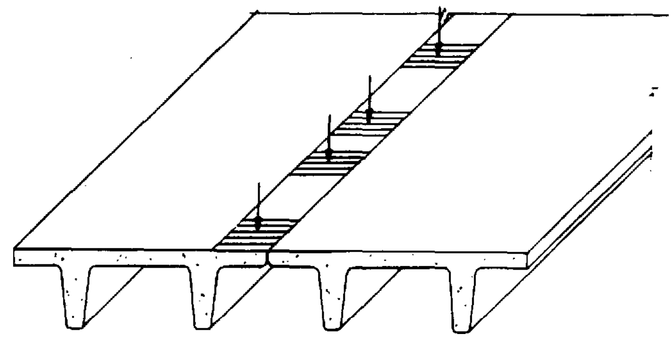


Fig. 2.1-Imprint of wheel loads

2.3.5.3 *Snow/live bad combination*-Many model or local building codes require consideration of roof loads (usually snow) in addition to the normal vehicular loads. Simple addition of vehicular and snow loads may be too conservative for the elastic design of principal members. For example, the required load may be 50 psf for parking plus 30 psf for snow, resulting in a design load of 80 psf. The estimated actual load, if cars and snow are on the deck at the same time and no supplemental uniform load such as an overlay is added, probably would not exceed 30 psf (maximum) for cars plus 30 psf for snow for a total of 60 psf. Thus the probability of maximum snow loads exceeding code requirements is unlikely, even when vehicular loading is at its maximum.

The committee recommends designing the structure to support the following load combinations:

a) Strength design for unreduced vehicular load and snow (that is, 50 psf + snow) at roof level. For example: 1.4D + 1.7L + 1.2S
b) Serviceability check on load combination of reduced vehicular load and snow at roof level. For example: D + 0.6L + S

2.2.5.3 *Wind loads*-Parking structures and their components should be designed to resist the design wind pressures indicated in the applicable building codes. Model building codes have methods with which to calculate wind pressures using basic wind speed, importance factor, exposure factor, and projected areas.

The building facade should be considered solid unless a rigorous analysis is made for the effective wind pressure on the members exposed to wind or if the applicable code requires a different approach.

2.2.5.4 *Seismic loads*-Continuously ramped floors commonly found in parking structures complicate the lateral force analysis (see Section 2.5.3). The ramp slabs, cast-in-place or precast, must be able to support the seismic bending and shear forces.

If seismic loading is required by the local building code, the seismic loading case should be checked to see

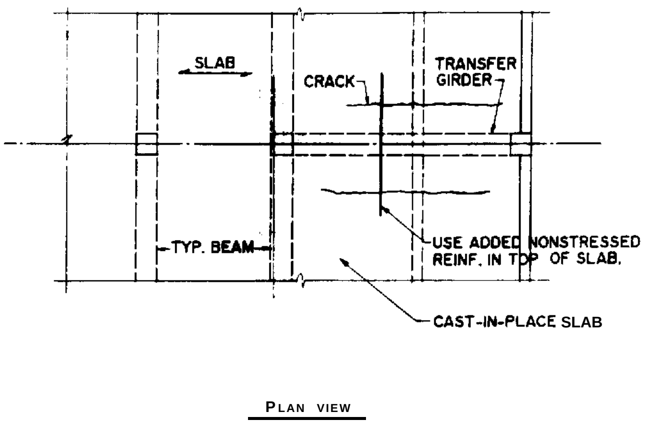


Fig. 2.2-Plan at transfer girder

whether it or wind load governs. In seismic regions, proportions and details required for earthquake resistance must be provided even if wind forces govern. ACI 318 (Chapter 21) and the Building Seismic Safety Council *Recommended Provision for Seismic Design Requirements for Buildings* are excellent sources of information for use with the local building code.

2.2.5.5 *Barrier loads*-Few model and local building codes prescribe lateral load requirements for vehicle barriers at the perimeter of floors. The design objective is to resist the load of a slow-moving vehicle. In its *Suggested Building Code Provisions for Open Parking Structures,* The Parking Consultants Council of the National Parking Association recommends a single horizontal ultimate load of 10,000 lb. One of the highest concentrated, lateral forces required on a barrier is 12,000 lb (City of Houston, Texas, Building Code). The South Florida Building Code requires that the barrier load be applied 27 in. above the floor. Other building codes require barrier type curbs and energy-absorbing capability at the perimeter of the floor. Curbs or wheel stops alone are usually not considered effective barriers against moving vehicles.

In the absence of a local building code that prescribes lateral vehicular load requirements, the committee recommends the National Parking Association single horizontal ultimate load of 10,000 lb, distributed over a l-ft-square area applied at a height of 18 in. above the adjacent surface at any point along the structure.

2.3-Performance characteristics of common construction types

Selection of a structural system should include consideration of those performance characteristics that are applicable to parking structures. Structural systems for parking structures require more attention to durability than do weather-protected structural systems. Vibration under moving loads should be checked during system selection; see *PCI Design Handbook,* Chapter 9 for guidance. Since many free-standing parking structures are constructed of precast prestressed concrete or cast-in-place post-tensioned concrete, detailed design information for these structural types may be obtained from the Pecast/Prestressed Concrete Institute and the Post-Tensioning Institute. See Chapter 6-References.

2.3.1 ***Cast-in-place (CIP) concrete construction***

2.3.1.1 *Post-tensioned CIP Construction*-Post-tensioning introduces forces and stresses into a structure in addition to those induced by gravity and applied loads. The post-tensioning forces are used to counteract gravity loads, reduce tensile stresses, and reduce cracking.

Post-tensioned spans may be longer for a given member size, or the members may be smaller for a given span, compared to concrete with nonprestressed reinforcement. It is not necessary, or even desirable, to design the post-tensioned reinforcement to carry all the gravity loads.

The quantity of post-tensioning included in the structure is based on the required structural capacity and the serviceability requirements. Generally, the post-tensioning will balance a portion of the dead loads (less than 100 percent) and will provide the minimum precompression indicated in Table 3.2. Precompression in excess of 300 psi for slabs or 500 psi for beams, and balancing more than 100 percent of the dead load should generally be avoided as this may result in undesirable cambers, additional cracking, and increased volume changes.

In addition to the drying shrinkage and temperature movements that affect all concrete structures, post-tensioning introduces volume changes due to elastic shortening and creep which must be accounted for in the design.

Post-tensioning a structure reduces cracking; however, if cracks do occur, they tend to be larger than those found in concrete structures reinforced with nonprestressed reinforcement. Providing additional nonprestressed reinforcement in areas where cracks are likely to occur has proven effective in controlling the size of cracks.

The cracks shown in Fig. 2.2, which run parallel to the transfer girder, are common. These cracks are most likely the result of tensile stresses caused by flexure in the top of the slab at the girder. Additional nonprestressed reinforcement in the slab will help control this type of cracking.

Adequately detailed, manufactured, and installed unbonded tendons include protection of the prestressing steel against corrosion. The latter is usually accomplished by placing the prestressing steel in a sheathing filled with grease. The Post-Tensioning Institute has developed and publishes specifications entitled *Specifications for Unbonded Single Strand Tendons.* The stressing pockets should be fully grouted to protect the anchorage devices and ends of tendons from moisture. Special care is needed to avoid the creation of a path at the interface between steel and grout permitting water to penetrate to the anchorage. In corrosive environments, the referenced PTI specification has stringent requirements for encapsulation of the tendon. Effective sealants, coatings, or bonding agents should be considered for added protection against water penetration at pockets (see Fig. 2.3).

Sealant installed at each construction joint will minimize water penetration through slabs, if properly installed and maintained (see Section 3.5.2.). At closure strips, tendons should be cut off and the anchorage protected before closure concrete is placed.

2.3.1.2 *Nonprestressed CIP construction*-Performance under conditions of vehicle-induced vibrations is generally good in reinforced CIP concrete structures with nonprestressed reinforcement.

Although no direct relationship between crack width and corrosion has been established, the committee's experience indicates that corrosion is frequently found in negative moment areas where flexural cracking has occurred. One method of reducing crack width is to increase the amount of reinforcement in the negative moment area. This reduces the steel stress and reduces the Z factor (ACI 318). The application of this concept requires engineering judgment in setting maximum values for steel stress or minimum values for Z factor. Some designers choose a maximum dead load steel stress of 15,000 psi or keep the Z factor as low as 55. The *PCI Design Handbook* illustrates a method that uses recommended maximum values for the Z factor.

The corrosion resistance of nonprestressed CIP systems can be increased by taking one or more of the following measures: increase concrete cover, add a concrete overlay, coat nonprestressed reinforcement with epoxy, apply traffic bearing membranes, reduce concrete permeability, or use a corrosion inhibitor.

2.3.2 *Precast/prestressed concrete construction*-Precast concrete members are typically manufactured with close dimensional tolerances. However, the design of a precast parking structure should provide for adequate casting and assembly tolerances. Units should not be forced into position during erection. Stresses developed by forced fitting can cause localized failure. Coordination of drains, expansion joints, blockouts, and embedded items is necessary to properly detail such structures. Member deflections and cambers are important and should be considered.

Correct detailing of connections between precast members is critical to achieving good performance. Because parking structures are typically exposed to the full range of temperature extremes, connections should not be too rigid. Because connections may be exposed to water through leaking joints or blowing rain, the exposed components should be protected. In corrosive environments, epoxy-coated, hot-dipped galvanized, or stainless steel may be used to reduce metal corrosion. Field-applied coatings may also be used to protect exposed welds and plates. The effectiveness of field-applied coatings is directly related to the thoroughness of surface preparation.

The *PCI Design Handbook, PCI Connection Manual,* and PCI's *Parking Structures: Recommended Practice for*

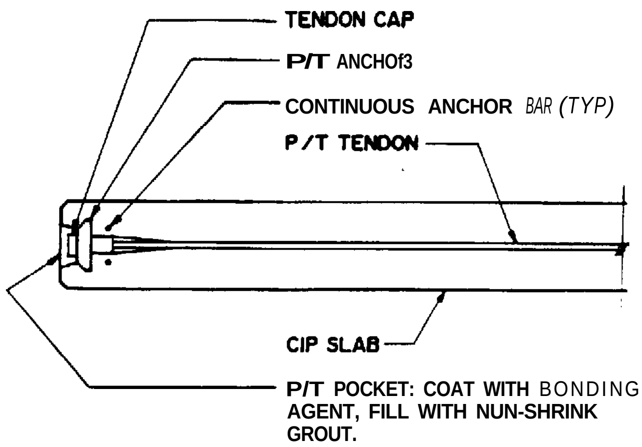


Fig. 2.3-P/T end anchorage detail

the Design and Construction cover many topics helpful in the design of precast prestressed parking structures.

Proper pretensioning reduces service load cracks, thus reducing the rate of water penetration into or through the member. Pretensioned concrete units have already undergone full elastic shortening prior to erection; however, the effects of temperature, long-term creep, and shrinkage of pretensioned members after erection should be considered, as indicated in Table 2.1.

2.3.3 *Structural steel construction*-Cast-in-place or precast concrete has been combined with structural steel framing for parking structures. Stay-in-place metal deck forms and other exposed steel will not perform well in areas where deicing salts are used or where there is airborne chloride unless the steel is protected with special coatings. Exposed steel framing should be treated with a weather-resistant, anti-corrosion coating. Joints between the steel and concrete should be adequately sealed to minimize moisture penetration.

2.3.4 *Other performance considerations*

2.3.4.1 *Drainage*-For a detailed discussion of drainage considerations, see Chapter 3. In general, CIP construction simplifies design for good drainage because variations in slope can be easily accommodated. Concrete topping placed over precast construction allows sloping of the CIP topping for drainage. Pretopped precast members can be sloped in two directions, but may crack if twisted excessively. The amount of torsion a member can tolerate without cracking depends on several factors that include length and cross section dimensions. For example, many pretopped double-tees with a 60-ft span will develop torsional cracking when the ends have a differential slope greater than approximately 1 percent. Differential slope is the difference in slope between transverse lines across the top of each end of the double-tee. Therefore, in some cases, proper drainage slopes may require the use of field-applied topping in limited areas of the structure.

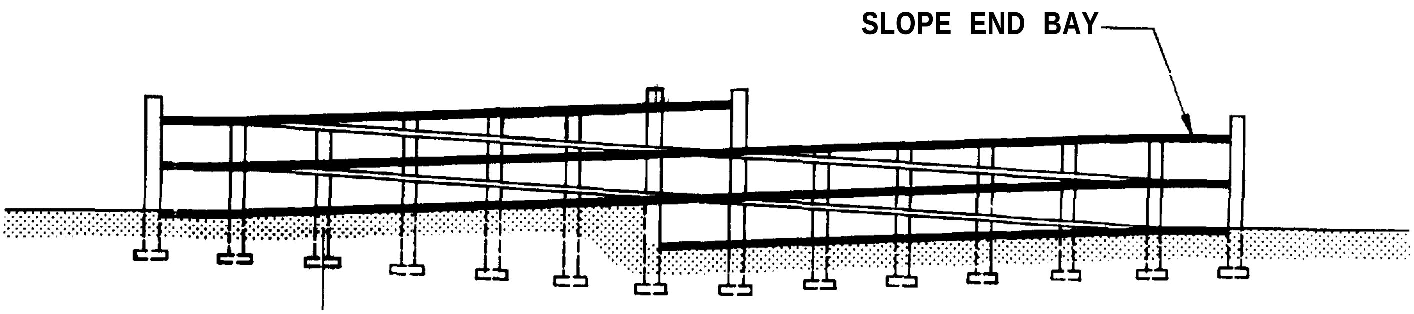


Fig. 2.4-Longitudinal section

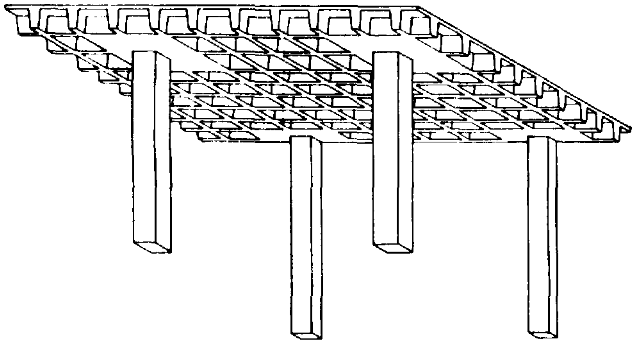


Fig. 2.5-Waffle slab

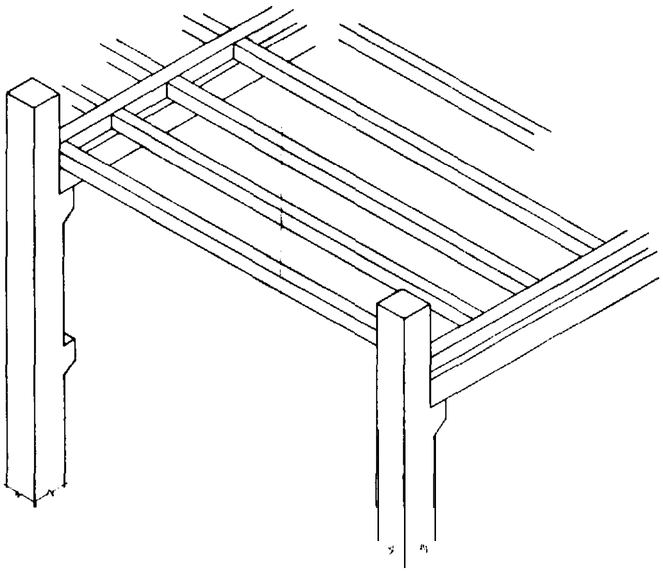


Fig. 2.6-Cast-in-place slab (not shown) on precast joists on inverted tee beams

2.3.4.2 *Lateral load resistance-Moment-resisting* frames are used in monolithic CIP structures to accommodate lateral loads. It is typical for every column line to provide such a frame, resulting in a distribution of lateral forces.

The segmental nature of precast concrete and its flexibility often require the use of connections that are simple and permit rotation. Precast structures normally have selected column lines with moment-resistant frames or shear-walls to resist lateral forces.

Lateral force resistance may be provided by frames, walls, and columns fixed to foundations. In certain cases, sloped floors may be used as truss elements (see Fig. 2.4).

2.4-Performance characteristics of structural elements

2.4.1 *CIP floor systems with thin slabs*

2.4.1.1 *CIP systems with nonprestressed thin slabs*-Thin slab systems, such as waffle slabs (Fig. 2.5) and pan joists may require less concrete than one-way slab designs. These systems involve slabs of 4 in. or less in thickness, stiffened by ribs or joists underneath.

Waffle slabs and pan joists typically develop through-slab cracking and may require special waterproofing and durability measures. Through-slab cracks can be expected to occur in these systems due to differential shrinkage between slab and joist. Flexural cracks in the negative moment region are also likely to fully penetrate thin slabs. The cracks permit water to reach the reinforcement, causing leaching on the underside and corrosion of unprotected reinforcement. Crack control using sealed joints is generally not practical for cast-in-place thin slabs.

An example of a composite system with thin slab characteristics is one that incorporates precast pretensioned joists spaced up to 8 ft-8 in. on centers and spanning 40 to 64 ft, and supporting a nominal 4-in. slab (see Fig. 2.6).

Waffle slabs, pan joists, cast-in void systems, and untopped hollow-core systems typically do not perform well in parking structures. Added protection such as vehicular trafficmembranes, epoxy-coatednonprestressed reinforcement bars and other protective measures should be considered (see Table 3.1).

Prestressed hollow-core units with topping (Fig. 2.7) behave like the thin-slab systems described previously and usually have higher deflections. The effects of elastic deflection and creep deflection on drainage should be considered. Weep holes in the downslope core ends will help drain condensation and water that may accumulate

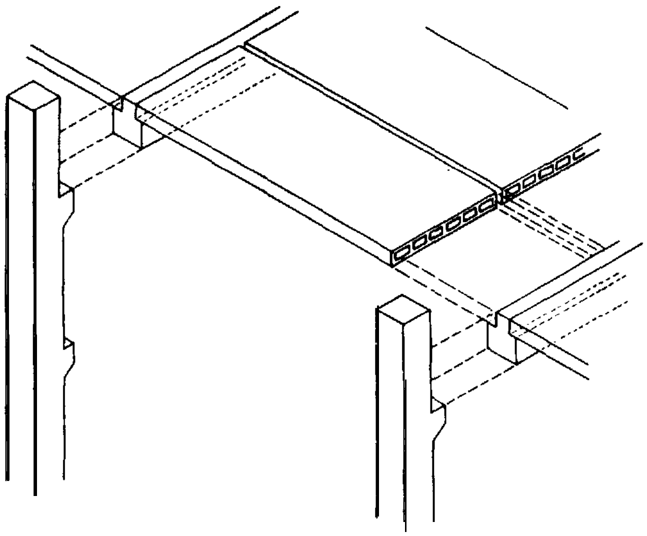


Fig. 2.7-Cast-in-place topping (not shown) on precast hollow core units

inside the cores.

One-way and two-way slab systems with nonprestressed reinforcement will generally produce visible cracks at supports due to flexure. When subjected to restraint of volume change forces, these cracks may penetrate the entire slab.

2.4.1.2 *CIP systems with post-tensioned thin slabs*-CIP post-tensioned joists or precast pretensioned joists with post-tensioned slabs have been used in parking structures. These systems often have large span-to-depth ratios as compared to other structural systems.

2.4.2 *CIP thick-slab floor Systems*-Two-way thick slab systems without drop panels are called flat plate slabs. Those with drop panels or column capitals are flat slabs. These slabs can be conventionally reinforced or post-tensioned.

In flat slab or flat plate construction (Fig. 2.8), the area at the intersection of the slab and column can become congested with nonprestressed reinforcement. This condition is especially true on roofs, where heavier loads may occur and where column bars are hooked into the slab. Proper consolidation may be impossible if reinforcement is too closely spaced. Entrapped air voids can fill with water and cause deterioration due to steel corrosion or freeze/thaw damage. If congestion cannot be avoided, access for concrete placement and special requirements for placement to eliminate voids should be provided in design.

Two-way slabswith nonprestressed steel reinforcement tend to develop cracks at the columns. These cracks may permit rapid corrosion of the reinforcement, and require special protection consideration.

2.4.3 *Post-tensioned slab and precast beam floor systems*-When grout is not used between the column and the precast beam end, rotation of the beam at the support can cause the slab to crack, as shown in Fig. 2.9.

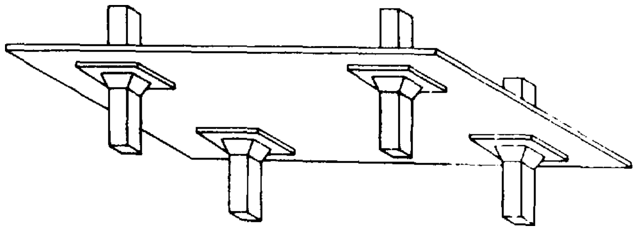


Fig. 2.8-Flat slab with column capitals and drop panels

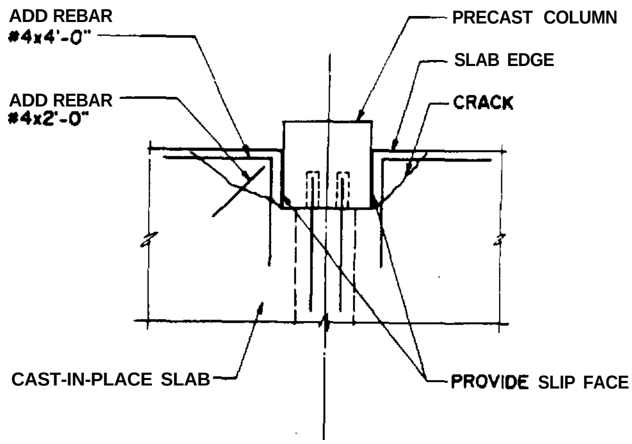


Fig. 2.9-Plan view of column-slab interface

The slab should be properly reinforced and preferably freed from the column along the column faces parallel to the beam span. When grout is used, yielding or pullout of the insert, as shown in Fig. 2.10, has been observed. This condition is caused by bending of the beam at the column. A large bending force ot rotation occurs upon removal of the temporary shores placed to support the beam during the slab placement. Installation of grout after removal of shores and with dead load in place will reduce the bending forces and limit subsequent problems due to rotation. Design and detail of the connection is critical to the durability of the structure. The slab should still be separated along the column side to prevent slab cracking due to beam rotation.

Post-tensioning applied to the slab section parallel to the beam will be partially transferred to the precast beam if there is a bond between them. The reduction of the post-tensioning force in the slab and the additional force introduced into the beam should be considered in the design.

2.4.4 *Nonprestressed slab and precast beam floor systems*-This hybrid system usually has a thin slab and nonprestressed reinforcement with precast prestressed joists (see Fig. 2.6). A variety of girder and column layouts are used to support the beams. With this system, slabs have an increased tendency to crack. Causes of cracking include: differential shrinkage between beam and slab, normal overall volume change shortening, reduction of

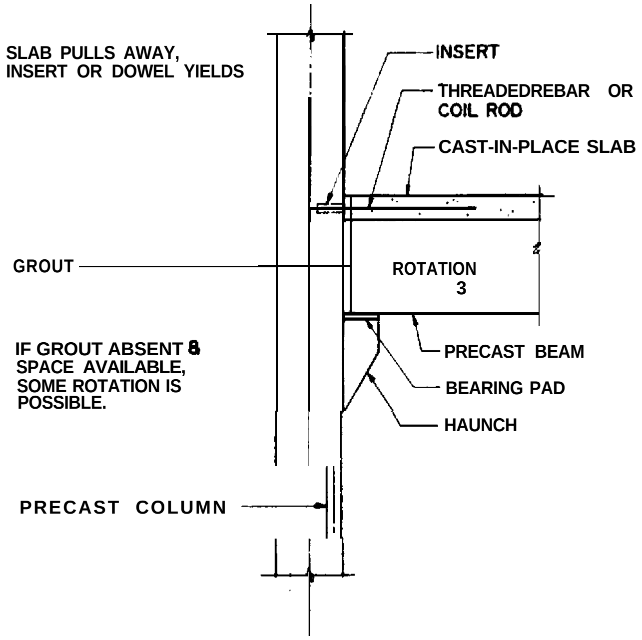


Fig. 2.10-Section of Fig. 2.9 at column

the slab cross section where the floor beams penetrate above the slab bottom, rotation of the beam at its support, and others as discussed in previous sections. Methods of crack control include: using thicker slabs, increasing reinforcement above code minimum requirements, and following recommendations for thin CIP slabs referenced in this report.

2.4.5 *Precastlprestressed concrete floor systems*-Parking structure floors are typically made of double-tee members; however, some limited use of single tees, hollow-core and other shapes are employed (see Fig. 2.11). Plank and tees may or may not use composite cast-in-place topping. The latter, referred to as "pretopped," "untopped," or "integrally topped," have become more common in recent years. "Pretopped" is the preferred term.

In both site-topped and pretopped precast concrete, welded connections between members are typically used to help equalize deflections between adjacent members and to transfer horizontal diaphragm forces across the joint.

If floor members have CIP toppings, shrinkage of the topping coupled with the change in section at the joint between adjacent members typically causes cracks in the topping over the joints. Contraction joints should be tooled, not sawn, into the fresh CIP concrete topping above all edges of the precast concrete elements. These joints should be sealed after the concrete has cured and shrunk. For specific recommendations, see Section 3.5.2 and refer to the PCI publication *Parking Structures: Recommended Practice for Design and Construction.*

2.5-Problem areas

2.5.1 *Volume change effects*-Volumetric changes affect frame action in structures of large plan area. Large shear and bending moments can occur in the first level and top level frames, especially at or near the building periphery. Aside from corrosion, distress from unanticipated volume changes or inadequate details to accommodate volume changes are the most common problems found in existing parking structures.

Volume changes of structural elements are due to drying shrinkage, elastic shortening, horizontal creep, and temperature change. The deformations and forces resulting from structural restraints to volume changes have important effects on connections, service load behavior, and strength. They must be considered in design to comply with ACI 318. The restraint of volume changes in moment-resisting frames causes axial forces, as well as moments, shears, and deflections. While these effects are not unique to parking structures, they are generally much more significant than in other common building types due to exposure to temperature and humidity changes. The basic types of concrete construction discussed in this chapter are each affected differently by volume change. The *PCI Design Handbook* provides recommendations for predicting the types of volume change described in this section.

2.5.1.1 *Drying shrinkage*-Drying shrinkage is a decrease in concrete volume with time. A significant portion of the shrinkage occurs in a short time. Drying shrinkage is due to the reduction in concrete moisture content, is unrelated to externally applied loads, and is a function of the ambient humidity.

When shrinkage is restrained, restraint forces may be reduced by cracking at weak points. For proper durability and serviceability, the design should consider drying shrinkage. See ACI 209R for typical methods of computing shrinkage, and ACI 224R and ACI 223 for methods of reducing the effects of shrinkage.

2.5.1.2 *Elastic shortening*-In prestressed concrete, axial compressive forces applied to the concrete by prestressing tendons cause the concrete to shorten elastically. Elastic shortening will cause loss of prestressing force that must be accounted for in determining final prestressing forces. Elastic shortening is additive to drying shrinkage. In precast pretensioned concrete members, elastic shortening occurs in the plant prior to erection, while in post-tensioned concrete, all elastic shortening occurs during construction and affects the structural elements in place at that time.

2.5.1.3 *Creep-Creep is the time*-dependent inelastic change of dimension in hardened concrete subjected to sustained forces. The total creep may be one to three times as much as short-term elastic deformation. Creep is primarily dependent upon the level of sustained concrete stresses. Creep is associated with shrinkage, since both occur simultaneously and provide a similar effect: increased deformation with time. In prestressed concrete structures, creep can result in additional axial movement

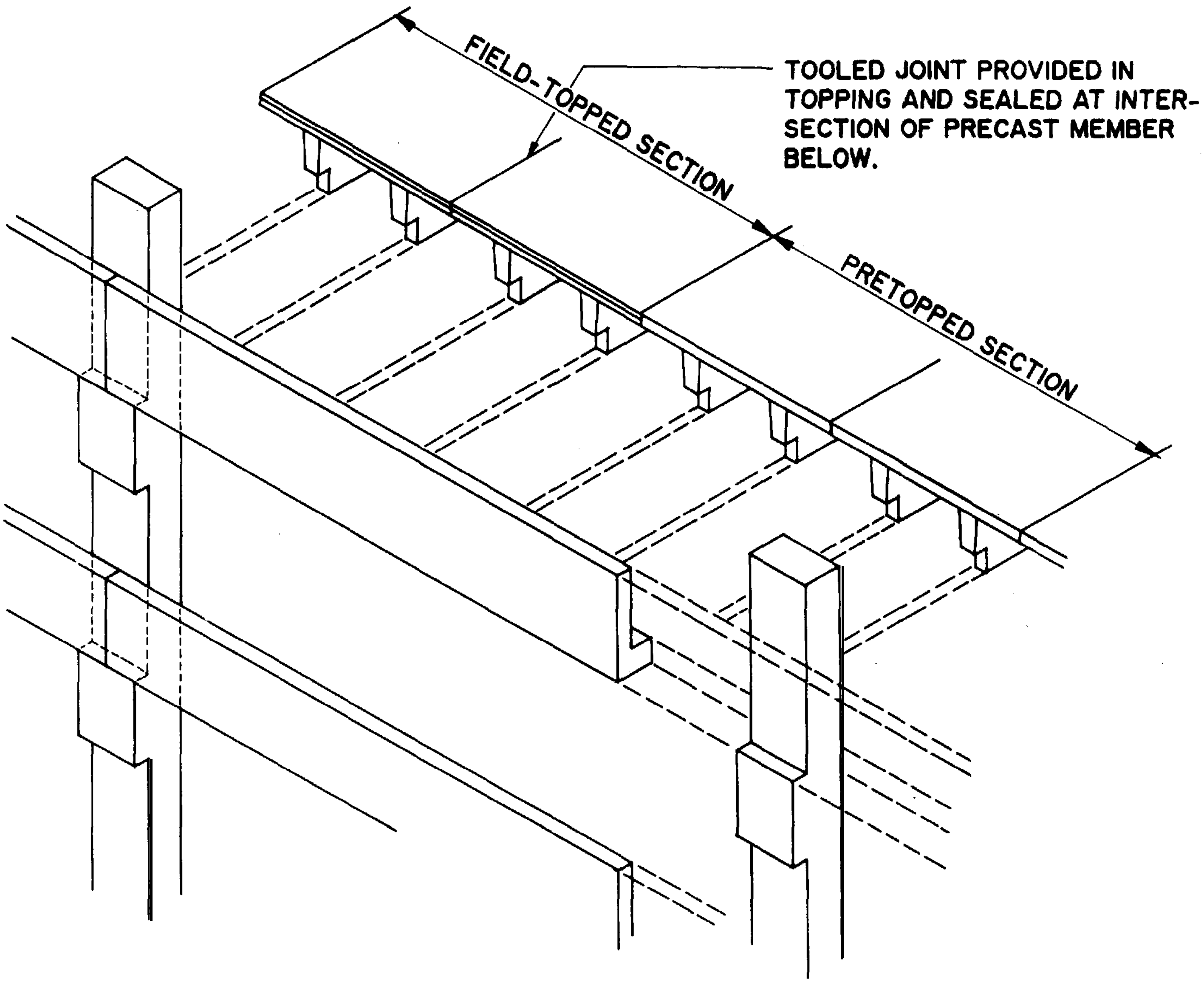


Fig. 2.11-Precast double-tee systems

of horizontal elements over time as well as increases in camber or deflection. In reinforced concrete structures, creep-induced deflections can change the slope of surfaces intended for drainage. The same may be true for creep-induced camber increases in prestressed structures, See ACI 209R for a detailed discussion of creep effects and the prediction of creep.

2.5.1.4 *Temperature change*-A temperature change may cause a volume change that will affect the entire structure. Parts with different cross sections, and different sun exposures, are affected by temperature change at different rates. This difference can cause restraint between attached members and bending in members with varying temperature across their depth or thickness.

Solar heat can affect specific areas, such as the roof and sides of buildings, more than the rest of the structure. A temperature-induced volume change can be expansion or contraction, so it may increase or decrease the overall dimensions of the structure. Temperature changes occur in both daily and seasonal cycles. The structural movements and forces resulting from temperature changes are a major design consideration in most concrete parking structures. Rotations or forces at the ends of members caused by this effect can cause distress in both simple span and rigid frame construction.

2.5.1.5 *System comparison for volume change effects*-Table 2.1 compares the relative effect of various causes of volume change on the horizontal elements of three structural systems. See Section 2.5.1.7.

2.5.1.6 *Considerations for volume change*-The degree of fixity of the column base has a significant effect on the magnitude of the forces and moments caused by volume changes. Assuming that the base is fully fixed in the analysis of the structure may result in a significant overestimation of the restraint forces. Assuming a pinned base may have the opposite effect. The degree of base

Table 2.1 — Relative effect of volume changes on structural frames

Volume change type	Structural system		
	Cast-in-place nonprestressed concrete	**Precast pretensioned concrete**	**Cast-in-place post-tensioned concrete**
Elastic shortening	**None**	**None**	**Full**
Shrinkage	**Partial**[1]	**Partial**[2]	**Full**
Creep	**None**[3]	**Partial**	**Full**
Temperature change	**Partial**[1]	**Full**[4]	**Full**

Notes: 1) Cracks in the concrete slabs and beams absorb a significant amount of movement, resulting in a reduction of the volume change effects on the structural frame.
2) Shrinkage of topping placed over precast elements primarily results in cracking of the topping over joints in the precast elements.
3) Primary effect of weep is increased deflection of beams or slabs which may affect dminage. Creep can also affect precast and post-tensioned member deflection.
4) May be "partial" under some conditions, with connection details absorbing part of the volume change movement (see Sections 2.3.2 and 2.4.5).

fixity used in the volume change analysis should be consistent with that used in the analysis of the column forces and slenderness. A change in center of rigidity or column stiffnesses will change the restraint forces, moments, and deflections.

Areas of a structure that require careful analysis for control of volume change are:

a) Any level with direct exposure to the sun and the columns and flexural members directly beneath.
b) The first supported level and the attached columns.
c) In the northern hemisphere, the south face.
d) The west face.

Creep and drying shrinkage effects take place gradually. The effect of shortening on shears and moments at a support is lessened somewhat by creep and microcracking of the member and its support. The adjustment of effects due to creep and drying shrinkage can be estimated using the concept of equivalent shortening as described in the *PCI Design Handbook.*

2.5.1.7 *Design measures for volume change effects-* Volume change forces must be considered in design according to ACI 318. Isolation joints can permit separate segments of the structural frame to expand and contract without adversely affecting structural integrity or serviceability. Dividing the structure into smaller areas with isolation joints may be complicated by the presence of interfloor connecting ramps. Expansion joints may be required to transmit certain forces across the joints.

It is often desirable to isolate the structural frame from stiff elements, such as walls, elevator cores, and stair cores (Fig. 2.12). This isolation is particularly important in post-tensioned structures. Of course, the resulting frame should be designed for necessary lateral stability and all required loads and deformations.

Measures such as pour strips reduce the effects of elastic shortening and shrinkage. To be effective, pour strips must continue vertically and horizontally through the entire structure.

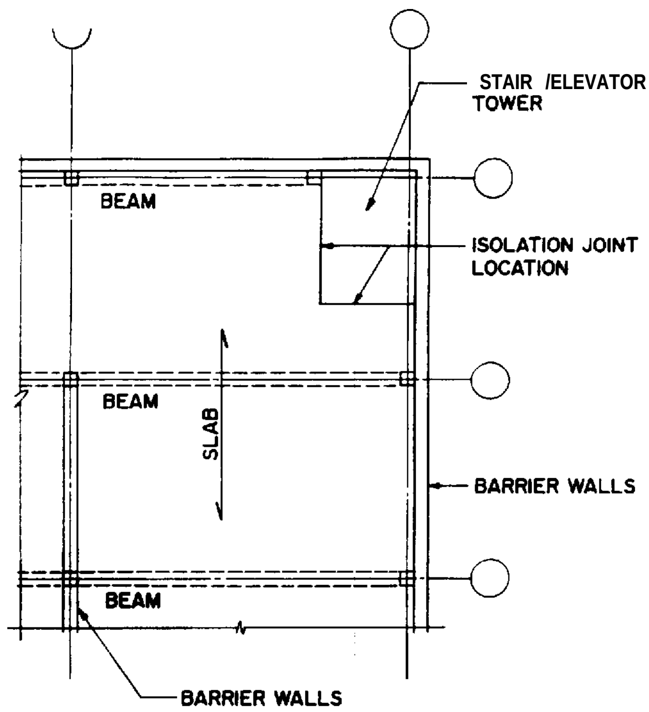


Fig. 2.12-Partial plan of cast-in-place post-tensioned floor structure

Experience and practice have shown that the distance between expansion joints can vary with construction method. Cast-in-place structures with nonprestressed-steel reinforcement typically contain shrinkage cracks that can relieve a buildup of temperature related strains. Expansion joints in such structures are typically spaced at 250 to 300 ft. Precast structures contain numerous joints

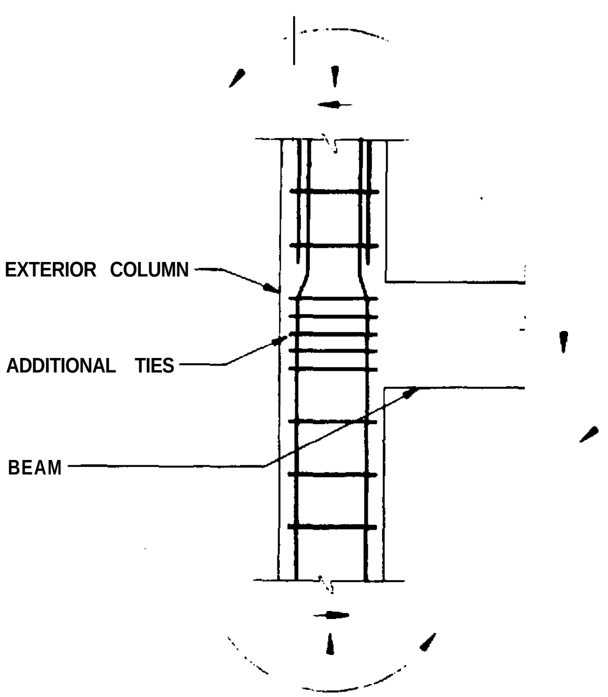


Fig. 2.13-Free-body diagram of beam-column joint in rigid frame

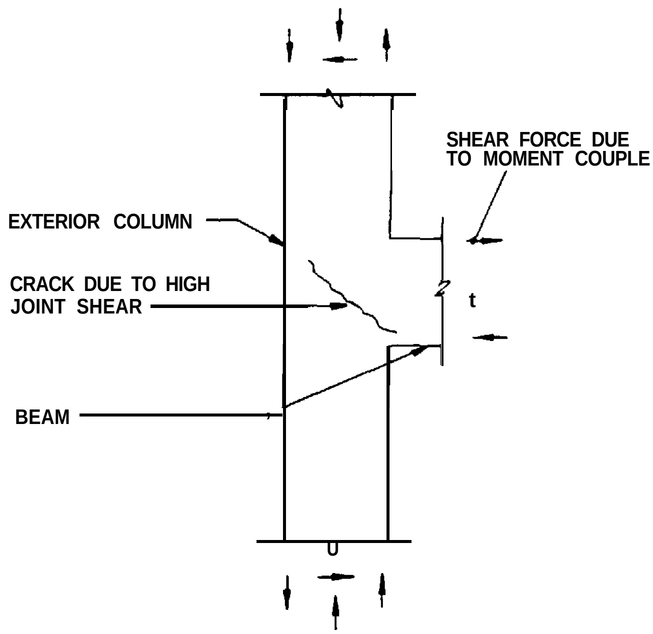


Fig. 2.14-Shear in joint caused by moment at beam end and restraint at column ends

that also can relieve a buildup of temperature-related strains; and expansion joints can be spaced at approximately 300 ft. Cast-in-place post-tensioned structures, however, typically exhibit few shrinkage cracks and have no joints or connections. Therefore, expansion joint spacing of approximately 250 ft is recommended for post-tensioned structures. Volume change effects may have a significant effect on the design when the distance between isolation joints or total building length exceeds the previously recommended values, or when stiff elements are located away from the center of the structure, and columns are relatively stiff.

Plan shapes, such as *"L"* or *"U"* shapes, with re-entrant corners, should be divided into simple rectangles with isolation joints between adjacent rectangles.

Connecting CIP post-tensioned horizontal members to columns or walls after post-tensioning has been applied can eliminate forces on the structure caused by the elastic shortening of those horizontal members.

2.5.2 *Beam-column joints*-Columns in parking structures are often subjected to unusual forces compared to those in other buildings. The local effects of the elastic shortening, relatively high joint moments and shears associated with long spans, and the effects of volume change all contribute to highly stressed beam-column joints.

Exterior columns and beams typically will have high joint moments, which require special attention to the anchorage of the beam top bars and post-tensioning where applicable. In columns, the shear within the joint caused by beam negative moments can exceed the shear capacity of the column concrete alone. Ties may be required within the joint (Fig. 2.13 and 2.14). See reports from ACI committee 352R for additional information. Shear in the columns between the joint regions may require increased tie reinforcement to resist shear within the column height. Where column vertical bars lap, both development of those bars and the corresponding column tie requirements need evaluation.

In cast-in-place post-tensioned structures, shortening of the first supported level beams due to elastic shortening, creep, and shrinkage, may induce tension in the beam bottoms at columns near the building end. Similar, but lesser, effects will occur at intermediate levels. Appropriate reinforcement should be provided. In special situations, it may be desirable to temporarily or permanently separate beams from supporting walls or columns or both. Hinges or slide bearings may be employed to reduce restraint.

In nonprestressed flat slab and flat plate construction, column-slab joints merit similar design considerations. These types of slabs often crack adjacent to the column or joint, reducing durability.

Precast concrete beam-column joints also require special attention. Joints in precast concrete structures are often subjected to repeated movement or forces due to cyclic volume change and vehicular traffic, which may result in member cracking, and water ingress, resulting in deterioration and structural distress. Such joints should be detailed to allow for temperature movements.

2.5.3 *Variable height columns*-Successive levels of a multilevel structure are typically serviced by sloping ramps (Fig. 2.4). These ramps may comprise entire floors

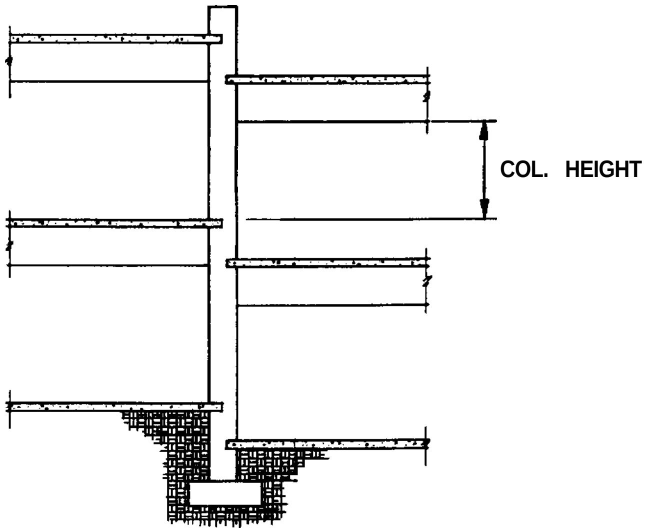


Fig. 2.15-Section at interior column

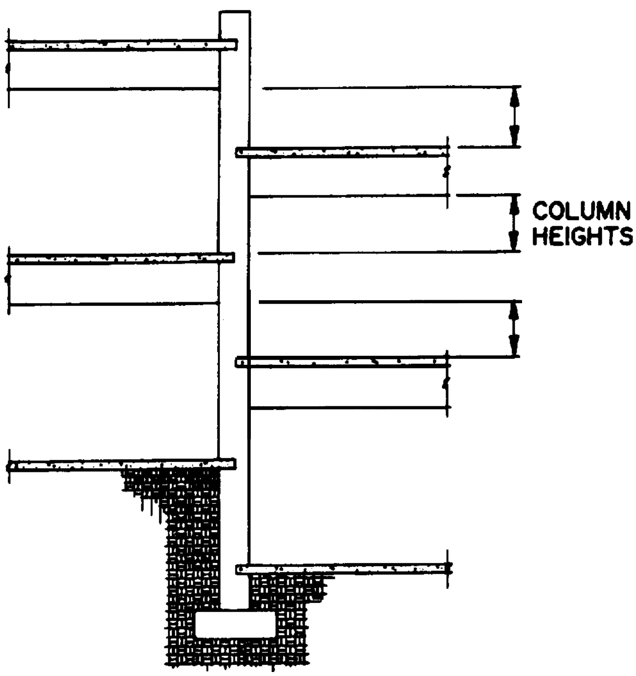


Fig. 2.16-Section at interior column

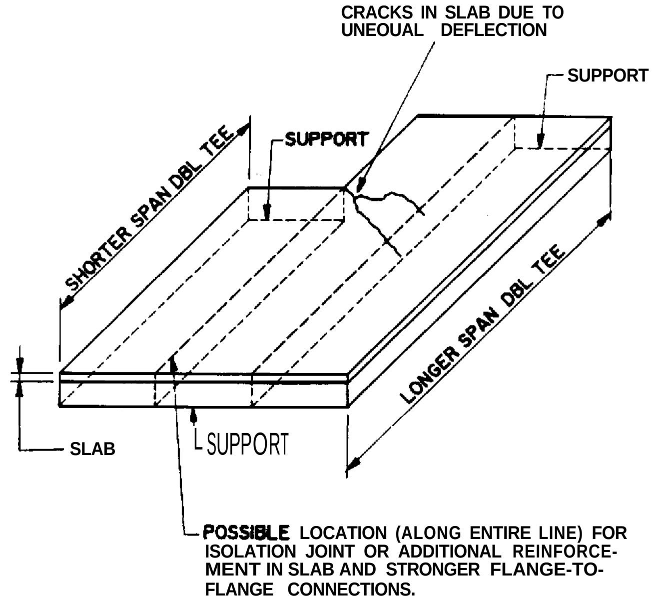


Fig. 2.17-Floor cracking due to incompatible deformation

and be used for both parking and through traffic. Ramps may also be for traffic only, with no on-ramp parking permitted.

The presence of integrated ramps has a significant effect on the behavior of the structure. Internal ramps interrupt floor diaphragms and complicate their analysis. High moments and shears due to gravity loads and restraint of volume change are induced in columns adjacent to ramps where monolithic beams enter opposite sides of the columns at varying elevations (Fig. 2.15 and 2.16). Restraint of volume change in the direction perpendicular to the beam span can induce high moments and shears in that direction as well.

2.5.4 *Torsion*-Exterior spandrel beams built integrally with the floor slab are not only subjected to normal gravity loads and axial forces, but may also be subjected to torsional forces equal to the restraining moment at the beam-slab joint. AC I 318, Chapter 11, addresses design requirements with respect to torsion in combination with shear and bending for nonprestressed members. Design must also control cracking to provide adequate durability.

Precast spandrel beams are among the most complex members to analyze in precast parking structures. ACI 318 addresses combined shear and torsion in nonprestressed members. See the PCI Specially Funded Research and Development Project No. 5 for recommendations for such precast prestressed members.

2.5.5 *Stair and elevator shafts*-Shafts sometimes interrupt the regular pattern of structural framing. Differential deflections in the adjacent structure may result, causing localized cracking (see Fig. 2.17). For instance, one beam or tee may end at the wall of a shaft while the adjacent one continues. The effect of dead load deflection may be minimized by prestressing; however, differential deflections due to live load will surely occur between the beams and cause stress concentrations in the adjacent slab or connections. Differential movement between the shaft walls and the structural slab should be anticipated and proper detailing applied. In precast structures, local differential cambers may also create a problem. Refer to Grid B in Fig. 2.18. Design solutions may include adding nonprestressed reinforcement across Grid B, cast-in-place topping across the Grid B joint, or installing an isolation joint between the two members on either side of Grid B.

2.5.6 *Isolation joint*--An isolation joint should be achieved by making the structure on one side of the joint independent from the opposite side. This independence is usually obtained through the use of separate columns on either side of the joint.

2.5.7 *Sliding joint*-A sliding joint will provide one side of the joint with vertical support only, and little or no lateral force buildup for the other side. The joint is usually a bearing assembly that will slide and rotate while supporting the vertical load. Only slide-bearing materials that will not corrode should be used. These materials might include stainless steel and a low friction polymer. All slide-bearing materials develop some friction, thus the bearing assembly should he designed to transmit limited horizontal force, often combined with variable rotations, and should be adequately attached to tbe respective structural elements. It is desirable to prevent differential vertical movement of each side and horizontal movement parallel to the joint because expansion joint seals generally have little ability to deform in this manner.

Slide bearings may deteriorate with time, especially if they are not maintained in a clean and dry condition. It is recommended that bearing stresses on the sliding joint material be designed for half of the manufacturer's allowable stress. Experience has shown poor performance may result when full allowable bearing stresses are developed on some assemblies. Retainers may be required to keep bearings from moving out of the joint. Well-designed slide bearings that are protected from weather have been observed to perform reasonably well. Sliding joints should only be used for supporting slabs and precast floor units.

The performance of slide bearings in supporting beams and girders has been found to be unsatisfactory in many cases. The heavy reactions of most beam bearings may cause undesirable cracks due to volume changes. Details should clearly show concrete being excluded from the required open joint space.

2.6-Below-grade structures

Below-grade structures of any kind present special problems. In parking structures, these problems may be magnified by the large plan area, the presence of an upper structure, or both.

Peripheral foundation walls are generally of monolithic construction. Walls may be in place well before the supported floor systems so that much of their shrinkage has already occurred by the time the slabs are constructed, but they may not be backfilled. Connecting floor structures to these walls, without allowing for temporary or permanent differential horizontal movement, frequently results in distress within the floor system and walls.

One approach is to make isolation joints continuous across an elevated structure and its underlying below-grade structure; however, it may be impractical to place joints in retaining walls and their foundations in the same locations. Wall joints may have volume change characteristics different from the interior floor structure. Other

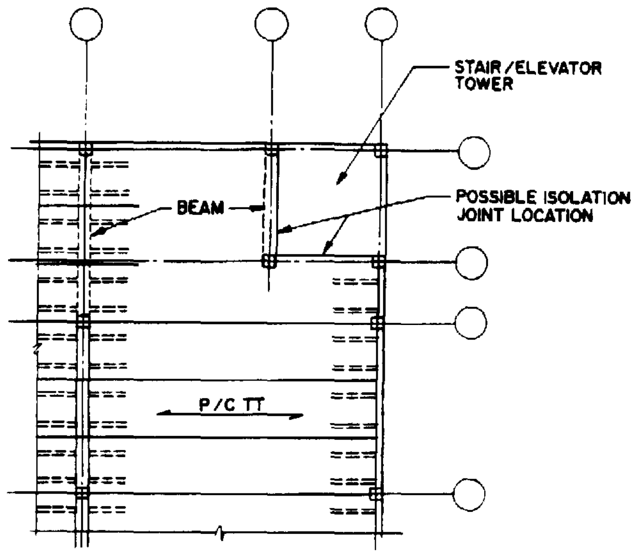


Fig. 2.18-Partial plan of double tee floor structure

possibilities include using expansive or shrinkage-compensating concrete (ACI 223) to reduce shrinkage effects.

Entrance ramps approaching the underground garage usually should be separated from the main structure, even if this separation requires construction of below-grade expansion joints in retaining walls.

There may be substantial temperature differences between portions of the structure above and below grade, particularly in an unheated structure. The structure should be designed to accommodate the resulting volume change differential, possibly by introducing a vertical expansion joint in the upper structure beginning at ground level.

2.6.1 *Structural features of below-grade structures*-In the design of below-grade structures, three factors should receive due consideration: possible moderated temperatures and movements; greater chance of problems due to higher relative humidity and ground water; and vertical and lateral loads from the structure above and from the surrounding soil.

2.6.2 *Volume change in below-grade structures*-Volume changes in open parking structures are greater than in enclosed parking structures, due to their exposure to wider temperatures and relative humidity changes. However, the range of temperature changes to which below-grade parking structures are subjected is not as great. In those parking structures that extend partially above grade, appreciable bending and shear forces may be generated in columns by differential movement of floor framing between levels (most notably between the foundation and first supported level). Also see Section 1.3.1.

2.7-Multiuse structures

In buildings with garages underground or built into the lower levels, special problems occur. The most economical column spacing for offices or apartments is not necessarily the best for garage facilities, where columns are spaced 56 to 60+ ft on center measured perpendicular to the drive aisles. Because upper level column spacings differ from those of the garage, deep girders may be needed to transfer upper story loads to the garage columns. Deep transfer girders often require more floor-to-floor height at the transfer girder level. Resulting discontinuities in story stiffness may complicate lateral analysis of the building.

Forming for the garage slabs may differ from the upper level slabs, and additional nonprestressed steel reinforcement may be required at the transfer girder level. For this reason, designers should try to eliminate transfer girders. Closer column spacings may require compromises in parking layout and ramp locations, but will generally be satisfactory for parking if the columns form a regular grid.

Some garages support earth fill above. Others support plazas, pools, fountains, sculptures, full-sized trees, small buildings, mounded gardens, clock towers, recreational areas, streets, bridges and other loads. Most of these "roof-top" facilities require the structural frame to have substantially more load-carrying capacity with larger members than a typical parking level.

CHAPTER 3-DURABILITY AND MATERIALS

3.1-Introduction

There are many measures that may be taken in a parking structure to improve durability and reduce the probability of premature deterioration. Selecting the right combination of protection systems is not a prescriptive process. It requires careful analysis of the facility's physical and structural characteristics as well as the environment to which it will be subjected. These considerations should be balanced against the economic requirements of the project. For example, higher initial costs may be offset by increased longevity and lower life cycle costs.

For durability of concrete structures, ACI 318 defies several exposure conditions and sets durability measures for each. These exposure conditions are:

- Concrete intended to have low permeability when exposed to water. (This criterion is interpreted to apply to all parking structures not covered by subsequent criteria.)
- Concrete occasionally exposed to moisture prior to freezing and where no deicing salts are used.
- Concrete exposed to deicing salts, brackish water, seawater or spray from these sources and that may or may not be subject to freezing.

To assist in the specification of the appropriate level of protection to be provided in a parking structure, it is suggested that five geographic zones be defined:

- Zone I represents the mildest conditions where freezing temperatures never occur and deicing salts are not used.
- Zone II represents areas where freezing occurs and deicing salts are never or rarely used.
- Zone III represents areas where freezing and the use of deicing salts are common.
- Coastal Chloride Zone I (Zone CC-I) represents areas which are in Zone I and within 5 miles of the Atlantic or Pacific Oceans, Gulf of Mexico, or Great Salt Lake.
- Coastal Chloride Zone II (Zone CC-II) is area in Zones I and II within one-half mile of the salt water bodies described in Zone CC-l.

A map of the United States depicting the approximate boundaries of these zones is shown in Fig. 3.1. However, it is intended that the criteria for durability measures used in ACI 318 apply and that the map be used only to remind designers to incorporate the appropriate measures.

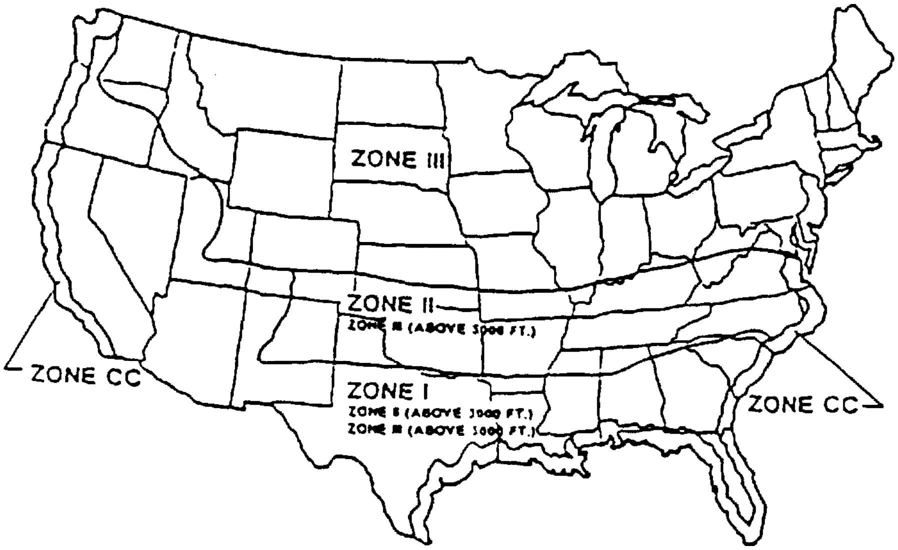
It is neither economically feasible nor necessary to incorporate all the available measures in a single facility. To guide the specifier in selecting an effective combination of protective measures, the following categories will be discussed:

- Good design practice
- Internal measures
- External measures requiring periodic maintenance

3.1.1 *Good design practice*-Good design practice includes: provision of adequate drainage, design and detailing for crack control, proper cover, concrete mix design considerations, concrete finishing, and curing. These measures are basic to all facilities, regardless of physical, structural, or environmental characteristics. When freezing-and-thawing-induced deterioration is a concern (generally in Zones II and III), air entrainment, concrete consolidation, finishing practices, and aggregate quality are items that should be given special consideration. In parking structures, all floors should be considered exposed to weather, and thus should meet the recommendations of this guide as well as the minimum requirements of ACI 318.

3.1.2 *Internal measures*-Internal measures are those that are incorporated into the initial concrete construction, including concrete mix design choices (see Section 3.3.3). Adequate concrete cover over reinforcement, coatings for reinforcement, protection of post-tensioned and pretensioned tendon systems, and other embedded metals is also included. Considerations for this type of protection are included in Sections 3.3 and 3.4.

3.1.3 *External measures requiring periodic maintenance*--This category includes products generally applied to the concrete once it has cured. Sealant systems used for isolation (expansion), contraction, and construction joints are a part of this category. Also included are protective coatings used to bridge cracks (traffic bearing



For durability of concrete structures, ACI 318 defines several exposure conditions and sets durability measured for each. These exposure conditions are:

- Concrete intended to have low permeability when exposed to water. (This is interpreted to apply to all parking structures not covered by the subsequent criteria.)
- Concrete occasionally exposed to moisture prior to freezing and where no deicing salts are used.
- Concrete exposed to deicing salts, brackish water, sea water, sea water or spray from these sources and may or may not be subject to freezing.

To assist in identifying these exposure conditions, five exposure zones are defined and approximately illustrated on the map.

- Zone I represents the mildest conditions where freezing is rare and salt is not used. This area is generally defined as all areas south of Zone II and south and west of Zone III except those areas above an elevation of 3000 feet where freezing occurs.
- Zone II represents areas where freezing occurs and deicing salts are not or rarely used. This area is generally defined as the area south of Zone III and within 100 miles south of interstate highway 40 from the Atlantic Ocean west of the Continental Divide, plus all areas in Zone I above an elevation of 3000 feet and below an elevation of 5000 feet, plus areas in the State of Oregon and Washington west of the Cascade Range except for those areas above an elevation of 5000 feet.
- Zone III represents the areas where freezing and deicing salts are common. This area is generally considered to be areas north of and within 100 miles south of Interstate Highway 70 from the Atlantic Ocean west to Interstate Highway 15, then north to Interstate Highway 84, then northwest to Portland Oregon then west to the Pacific Ocean plus areas with Zones I and II above an elevation of 5000 feet when deicing salts are used.
- Coastal Chloride Zone I (Zone CC-I) represents areas with Zone I and within 5 miles of the Atlantic Ocean, Gulf of Mexico, Pacific Ocean, and the Great Salt Lake.
- Coastal Chloride Zone II (Zone CC-II) is areas within zones I and II and within one half mile of the salt water bodies described in Zone C-l.

* Where deicer salts are used.

It is intended that the local exposure conditions and actual use of deicing salts be used to determine the appropriate exposure zone. The map is only a guide to assist in the application of the zone definitions outlined above (Ref. 6.3).

Fig. 3.1 -Corrosion zones

membrane and membranes with protective wearing course) and treatments to reduce moisture penetration (concrete sealers) (see Section 3.5).

3.2-Drainage

The slope of the slabs should be designed in such a manner that water flows in the desired direction without ponding. A minimum slope in any direction of $1^1/_2$ percent is recommended with 2 percent being preferred. This slope does not usually require special slab tolerances, and will generally overcome inaccuracies in construction and deflection estimates. Camber and deflections, however, should be taken into consideration when establishing a drainage pattern.

Water flow should be directed so that its path is not obstructed by islands, curbs, columns, or any other element that would impede or trap it. Flow should be directed away from stairs and elevators, which should be raised above the parking surface. Integral curbs or thickened slab edges should be used where necessary to direct water away from the slab edge. Where curbs are placed as an addition to the slab, the construction joint should be sealed.

To reduce leakage, isolation, contraction, and construction joints should be located at high points. If this is not possible, care should be taken that joints do not dam water. Joints should not be located adjacent to drains.

If localized ponding occurs after construction is complete, adding additional drains is the preferred corrective measure. Grinding the concrete surface to correct drainage is an alternative. The application of overlay materials to the slab to correct drainage has often not performed well.

Drains should not be located in the main path of pedestrian or vehicular traffic. Roof water should be collected by large drains with traps to catch sand and debris. Continuous trench drains should be avoided if possible. Trench drains require frequent cleaning because they trap silt and other sediment. Ledges supporting grates are frequently damaged by traffic or corrosion, resulting in unsupported or missing grates. Concrete trench drains often crack and leak at their inverts. If a trench drain is used, a premolded system with cast-in-slopes and outlets at both ends should be considered. For structural floors, sloping the floor to several separate drains is preferable in order to minimize structural discontinuity.

When protective wearing courses are used over membranes, drainage at both the level of the membrane and the top of the wearing course should be provided.

3.3-Concrete

Selecting and specifying concrete for a parking structure involves many components, that affect the durability. These include: strength, permeability, aggregates, cement, air entrainment.

3.3.1 *Strength*-The specified design compressive strength should be the result of structural and environmental considerations. Additional strength generally increases durability and abrasion resistance. Tables 3.1 to 3.4 specify the minimum design compressive strength recommended, for each structural type and exposure zone.

The required water-cementitious ratio in Tables 3.1 to 3.4 may result in concrete strengths greater than noted in the table.

3.3.2 *Permeability-Low*-permeability concrete is of paramount importance in reducing corrosion of embedded steel. Such concrete is more resistant to penetration of water, chloride, and oxygen than that with higher permeability. Low-permeability concrete also has lower electrical conductivity, further reducing the opportunity for corrosion. Special attention should be given to practices that help produce less permeable concrete such as: proper finishing and curing, low water-cement ratio, admixtures, silica fume, and polymer-modified concretes. Fig. 3.2 illustrates the relationship between permeability and water-cement ratio.

The use of ASTM C 1202, Rapid Chloride Permeability Test, is frequently referred to as a standard of performance for resistance to chloride absorption. Concrete mix designs with resistance levels of 1000 coulombs or less are often represented as being resistant to chloride-induced corrosion. Some have questioned the reliability of this test as a standard because of a lack of supporting data showing correlation to salt ponding tests which may be considered more representative of field conditions. See NCHRP 244.

3.3.3 *Mix proportioning*-As noted previously, many of the choices made in selecting the mix proportions affect the performance and durability of concrete. It is important to understand how the various components of the mix contribute to durability or lack of durability.

3.3.3.1 *Water-cementitious ratio*-AC1 318 requires a water-cementitious ratio no greater than 0.40 for corrosion protection of concrete exposed to deicing salts, but allows the ratio to increase to 0.45 for normal weight concrete if concrete cover is increased by 0.5 in. This Guide recommends maintaining the water-cementitious ratio at 0.40 with the increased cover. This recommendation is applicable to Zone III and Coastal Zone II. Fig. 3.3 shows the effect of water-cementitious ratios on chloride penetration. Low water-cementitious ratios in conformity with the requirements of (Table 3.1 to 3.4) produce significantly less permeable, more durable concrete. Because concrete with a low water-cementitious ratio may require special placing techniques, a high-range water-reducing admixture (superplasticizer) should be considered. Silica fume and some types of fly ash are considered cementitious materials. When these are added to the concrete, their presence should be considered in calculating the water-cementitious ratio. See ACI 211.1.

3.3.3.2 *Aggregates*-ACI 201.2R discusses aggregate quality with regard to concrete durability. Absorptive aggregate particles such as chert or lignite can create

Table 3.1 -Cast-in-place reinforced concrete (Recommended minimum Considerations for durability. The recommendations in these tables assume drainage as noted in Section 3.2.2, cover tolerance as specified in ACI 318, and maintenance as noted in Chapter 5[h])

Design element[b] Note cracks and construction joints to be sealed to prevent leakage		Durability zone (see Fig. 3.1)		
		I	II/CC-I	III/CC-II
Concrete	Strength. psi	3500	4000	5000
	Air, percent[g]	Not required	6½ ± 2	6½ ± 2
	W/C ratio (maximum)	0.45	0.40	0.40
Reinforcement covering in in. and protection[c] 2-in. cover recommended for #6 through #18 bars	Slab top slab bottom Beam Column Walls (exterior face)	1½ ¾ 1½ 1½ 1%	1½ ¾ 1½ 1½ 1½	2[e] 1[e] 1½ 1½ 1½
Sealer/membrane[d,f]	—	Sealer-roof only	Sealer-all floors membrane roof	Membrane-all floors and roof

a) Nomenclature: W/C = water/cementitious.

b) These recommendations are for thick slab structural systems as described in Chapter 2 and are not intended for slabs on grade. (If thin slab systems are used, a membrane is recommended for all exposure conditions.)

c) Fire-resistive considerations may require greater bottom cover than noted herein.

d) Sealer should meet the criteria developed in NCHRP Report 244. Abrasion resistance and skid resistance should be considered in addition to NCHRP 244 criteria.

e) If a corrosion inhibitor or epoxy-coated non-prestressed reinforcement is used, the top cover may be reduced to 1½ in.

f) Silica fume may be used in lieu of sealer application if the permeability of that concrete is determined to be low by acceptable standards.

g) Only required where freezing occurs. Measure at the point of placement. Target air content for ¾ in. aggregate. See Section 3.3.3.4

h) Additional protection is recommended for mixed use structure and when maintenance is unlikely.

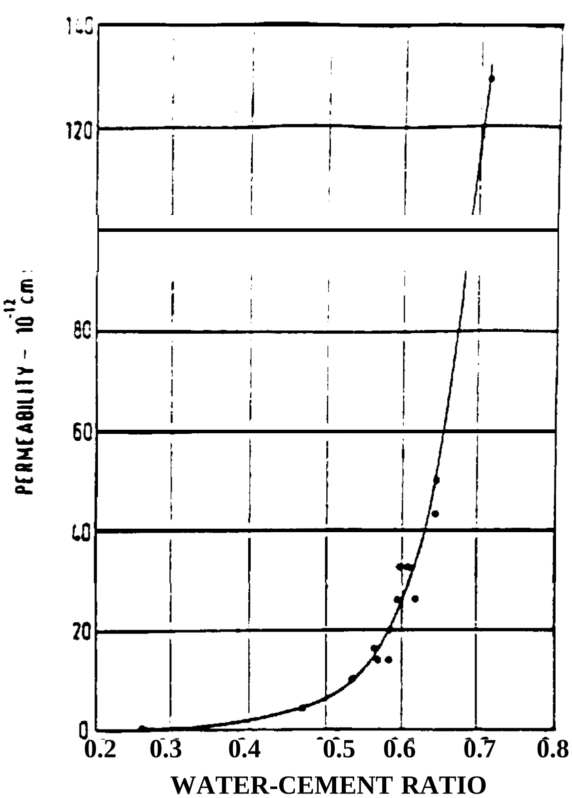


Fig. 3.2-Relationship between coefficient of permeability and water-cement ratio for mature portland cement pastes (Note, this is FROM ACI 225R, Fig. 6.6)

surface pop-outs due to freezing and thawing. ASTM C 33 sets maximum limits on the amount of chert in the coarse aggregate for various climatic regions. When specifying architectural concrete or where local experience shows excessive pop-outs, it may be desirable to set lower limits for chert content than those required by ASTM c 33.

In addition to freeze-thaw aspects of aggregates discussed earlier, other qualities, covered in ACI 201.2R, also have an effect on durability. A well-graded aggregate tends to produce more durable concrete than concrete that has a predominance of one aggregate size, because it is more dense and has less paste for a given volume. Combinations of cement and aggregate subject to deleterious alkali-aggregate reactions should not be used in parking structures. It may also be necessary to evaluate aggregates for their abrasion characteristics in areas where experience indicates that abrasion resistance may be less than desired.

3.3.3.3 *Silica fume*-Silica fume (microsilica) concrete has become widely accepted as providing a high degree of resistance to chloride intrusion by reducing the mortar matrix permeability.

When permeability and corrosion resistance are part of the design criteria, it is suggested that trial mixes be made and examined under ASTM C 1202 or AASHTO T 277 prior to construction start-up. Test specimens should be made in accordance with ASTM C 31, cast in 4 x 8-in. cylinder molds, and tested at 56 days of

Table 3.2 -Cast-in-place post-tensioned concrete (Recommended minimum considerations for durability. The recommendations in these tables assume drainage as noted in Section 3.2.2, cover tolerance as specified in ACI 318, and maintenance as noted in Chapter 5[h])

Design element[b] Note cracks and construction joints to be sealed to prevent leakage		Durability zone (see Fig. 3.1)		
		I	II/CC-I	III/CC-II
Concrete	Strength, psi	3500	4000	5000
	Air, percent[g]	Not required	$6^1/_2 \pm 2$	$6^1/_2 \pm 2$
	W/C ratio (maximum)	0.45	0.40	0.40
Reinforcement cover, in in. and protection[c] 2-in. cover recommended for #6 through #18 bars	Slab top Slab bottom Beam Column Walls (exterior face)	$1^1/_2$ ¾ 1½ 1½ $1^1/_2$	1½ ¾ 1½ 1½ $1^1/_2$	2[e] 1[e] 1½ $1^1/_2$ $1^1/_2$
P/T tendons	—	PTI Spec	ENCAP	ENCAP
Sealer[d,f]		Roof only	All floors and roof	All floors and roof

a) Nomenclature.: PTI Spec = minimum requirements of PTI specifications for unbonded single strand tendons; ENCAP = encapsulated tendons per PTI specifications; = water/cementitious.

b) These recommendations are for thick slab structural systems as described in Chapter 2 and are not intended for slabs on grade. (if thin slab systems are used, a membrane is recommended for all exposure conditions.)

c) Fire-resistive considerations may require greater bottom cover than noted herein.

d) Sealer should meet the criteria developed in NCHRP Report 244. Abrasion resistance and skid resistance should be considered in addition to NCHRP 244 criteria.

e) If a corrosion inhibitor or epoxy-coated non-prestressed reinforcement is used, the top cover may be reduced to $1^1/_2$ in.

f) Silica fume may be used in lieu of sealer application if the permeability of that concrete is determined to be low by acceptable standards.

g) Only required where freezing occurs. Measure at the point of placement. Target air content for $^3/_4$ in. aggregate. See Section 3.3.3.4.

h) Additional protection is recommended for mixed use structure and when maintenance is unlikely.

maturity. In addition, chloride penetration should be checked by AASHTO T 259. The accepted mix design should then be used throughout the duration of the project, with only minor modifications allowed for construction and weather variables.

The use of silica fume may require modification of the timing of finishing processes because bleed water is reduced or eliminated. Trial slabs and consultations with a manufacturer's representative are recommended. Early curing of silica fume concrete is critical due to fast drying and the potential for plastic shrinkage cracking. Fogging and other special procedures may be required with silica fume concrete (see ACI 234, awaiting publication).

3.3.3.4 *Air entrainment*-Deterioration of saturated concrete may occur when concrete freezes. Water expands by approximately 9 percent when it freezes. This change in volume causes stresses to develop, sometimes resulting in a rupture of the concrete at the surface (see ACI 201.2R).

Freezing and thawing deterioration can be avoided by the use of properly entrained air in the concrete. Air entrainment is achieved by adding an air-entraining admixture to the concrete mix. The type and quantity of air entraining admixture should be selected and batched to be compatible with other admixtures and additives. Air contents should follow recommendations in Tables 3.1 to 3.4 and ACI 318. In Tables 3.1 to 3.4 the committee recommends target air contents slightly higher than the minimums shown in ACI 318, but with increased tolerances, which keep the lower bound consistent with ACI 318. As noted in ACI 318, the air content required to provide freeze-thaw resistance varies with aggregate size. These recommendations are based on the collective experience of the committee.

The air content of each load of concrete should be determined at the point of placement (not at the truck) to verify that the concrete meets specifications. Air content can be diminished due to pumping or other placement techniques. Estimates of air loss can be made by measuring air content at both the point of discharge and the point of placement until consistent air loss data has been established. An adjustment can then be made to the air content measured at the point of discharge for the sake of convenience. The actual air loss should be established, however, at the beginning of each concrete placement as well as each time the placement conditions change. Experience has shown the incidence of truckloads of concrete not meeting the specifications, and the prevalence of problems related to inadequate levels of air entrainment, justifies this level of testing for parking structures in Zone III.

3.3.3.5 *Admixtures*-The use of admixtures in appropriate quantities and combinations is often required to achieve a workable wncrete with the desired durability.

Table 3.3 — Precast pretensioned concrete with CTP topping (Recommended minimum considerations for durability. The recommendations in these tables assume drainage as noted in Section 3.2.2, cover tolerance as specified in ACI 318, and maintenance as noted in Chapter 5[h])

Design element Note cracks and construction joints to be sealed to prevent leakage		Durability zone (see Fig. 3.1) I	II/CC-I	III/CC-II
Topping concrete	Strength, psi Air, percent[d] W/C (maximum)	3500 Not required 0.45	4000 6½ ± 2 0.40	5000 6½ ± 2 0.40
Precast concrete	Strength, psi Air, percent W/C (maximum)	5000 Not required 0.45	5000 6½ ± 2 0.40	5000 6½ ± 2 0.40
Reinforcement cover in in. and protection[b,g] 2 in. cover recommended for #6 through #18 bars	CIP - topping P/C - TT P/C - beam P/C - column Walls (exterior face)	1½ 1½ 1½ 1½ ¾	1½ 1½[g] 1½[g] 1½[g] ¾[g]	2[e] 1½[g] 1½[g] 1½[g] 1½[g]
P/C flange edge connectors	—	Liq. galv	Liq. galv	SS
P/C exposed plates	—	Rust preventive paint	EC[h] or HD galv	EC[h] of HD galv
Sealer[c,f]	—	Roof only	All floors and roof	All floors and roof

a) Nomenclature:E/C = epoxy-coated; HD = hot dipped: SS = stainless STEEL; W/C = water/cementitious ratio; P/C = precase concrete; Liq. galv = liquid galvanizing.

b) Fire-resistive considerations may require greater bottom cover than noted herein.

c) Sealer should meet the criteria developed in NCHRP Report 244. Abrasion resistance and skid resistance should be considered in addition to NCHRP 244 criteria.

d) Measured at point of placement-only required in freezing temperature regions. Target air content is for 3/4-in. aggregate. See Section 3.3.3.4

e) If a corrosion Inhibitor or epoxy-coated non-prestressed reinforcement is used, t e top cover may be reduced to 1½ in.

f) Silica fume may be used in lieu of sealer application if the permeability of that concrete is determined to be low by acceptable standards.

g) Ends of strands to be protected in Zones II, III, CC-I, and CC-II.

h) Note the exposed plate only need be epoxied; the anchors are not required to be epoxy-coated.

i) Additional protection is recommended for mixed use structure and when maintenance is unlikely.

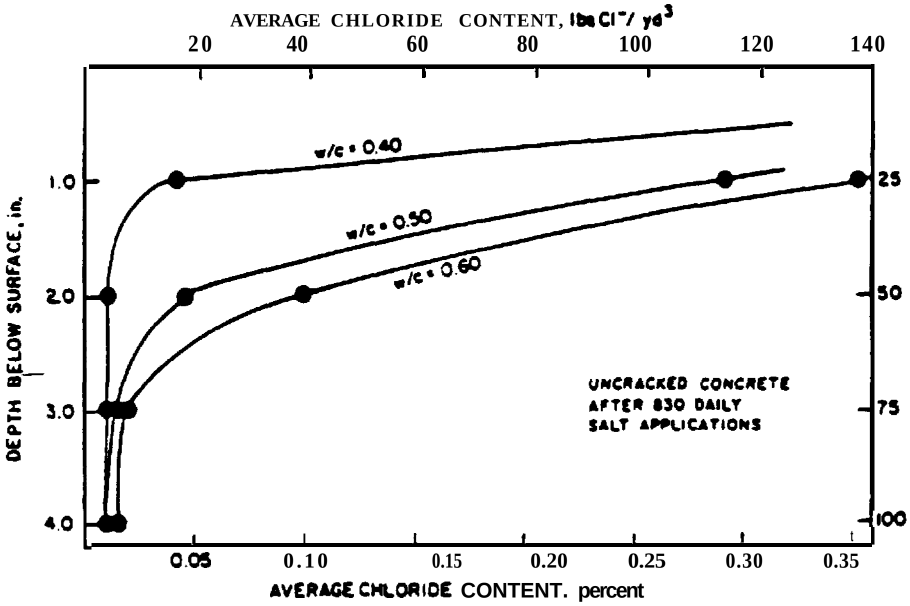


Fig. 3.3-Effect of water-cement ratio on salt penetration (Note, this is from ACZ 222R, Fig. 3.1)

Table 3.4-Precast concrete — pretopped (Recommended minimum considerations for durability. The recommendations in these tables assume drainage as noted in Section 3.2.2, cover tolerance as specified in ACI 318, and maintenance as noted in Chapter 5[h])

Design element Note cracks and construction joints to be sealed to prevent leakage		Durability zone (see Fig. 3.1) I	II/CC-I	III/CC-II
Concrete	Strength, psi	5000	5000	5500
	W/C ratio maximum	0.45	0.40	0.38
	Air, percent[e]	Not required	6½ ± 2	6½ ± 2
Reinforcement cover in in. and protection[b,g,i] 2-in. cover recommended for #6 through #18 bars	P/C top of flange P/C - TT - other sides P/C - beams P/C - column Walls (exterior face)	1½ 1½ 1½ 1½ ¾	1½ 1½[g] 1½[g] 1½[g] 1½[g]	2[d] 1½[g] 1½[g] 1½[g] 1½[g]
P/C flange edge connectors[d]	1 in. minimum top cover	Liq. galv	HD galv or SS	SS
P/C exposed plates	—	Rust preventive paint	EC[j] or HD galv	EC[j] or HD galv
Sealer[c,f]	—	Roof only	All floors and roof	All floors and roof

a) Nomenclature:E/C = epoxy-coated; HD = hot dipped; SS = stainless steel: W/C = water/cementitious ratio; P/C = precase concrete; Liq. galv = liquid galvanizing.
b) Fire-resistive considerations may require greater bottom cover than noted herein.
c) Sealer should meet the criteria developed in NCHRP Report 244. Abrasion resistance and skid resistance should be considered in addition to NCHRP 244 criteria.
d) If a corrosion inhibitor or epoxy-coated non-prestressed reinforcement is used, the top cover may be reduced to $1^1/_2$ in.
e) Only required where freezing occurs. Measure at the point of placement. Target air content for $^3/_4$ in. aggregate. See Section 3.3.3.4.
fl Silica fume may be used in lieu of sealer application if the permeability of that concrete is determined to be low by acceptable standards.
g) Ends of strands to be protected in Zones II, III, CC-I, and CC-II.
h) Additional protection is recommended for mixed use structure and when maintenance is unlikely.
i) Any field cast elements should meet the requirements for CIP topping Table 3.3 or applicable portions of Table 3.1.
j) Note: the exposed plate only need be epoxied; the anchors are not required to be epoxy-coated.

However, admixtures should be used with care and compatibility verified by a testing laboratory or experience. Water-reducing and set-controlling admixtures are classified by ASTM C 494 into seven types:

A. Water reducing
B. Retarding
C. Accelerating
D. Water reducing and retarding
E. Water reducing and accelerating
F. Water-reducing high range
G. Water-reducing high range and retarding

Type B, C, D, and E admixtures may be used to normalize setting characteristics of concrete during abnormally hot or cold temperatures. High-range water-reducing admixtures (superplasticizers) may be needed in concrete with a water-cement ratio of 0.40 or less to provide a workable concrete. The reduction of water in the mix will tend to reduce shrinkage. Bleeding will be greatly reduced, however, increasing the tential for plastic shrinkage cracking. The water- educing or set-controlling admixture must be compatible with the air-entraining admixture discussed in Section 3.3.3.4.

ACI 318 sets overall chloride limits for parking structure concrete. Calcium chloride and admixtures containing chlorides should not be used in concrete for parking structures.

3.3.3.6 *Fibers*--When fibers are considered for use in concrete, they are usually compared to welded wire fabric. Although each of these products helps to control cracking, they differ as to how and when they function.

Alkali-resistant synthetic fibers added to concrete help control the incidence of plastic shrinkage cracking. Synthetic fibers can reduce plastic shrinkage cracking as much as 80 percent when compared to a control specimen. Synthetic fibers only control plastic shrinkage, however, and thus cannot replace structural welded wire fabric. Steel fibers, on the other hand, are added to concrete to increase flexural strengths and impact resistance, and restrict crack widths after the cracks form. Synthetic fibers provide most of their benefit early after concrete placement by controlling shrinkage cracks, while steel fibers are also effective after the concrete sets. See ACI 544.3R for information relating to steel fibers.

3.3.4 *Finishing and Curing*-Finishing the concrete surface at the proper time and the subsequent curing of the concrete are the final steps in the basic construction process. All too often these activities do not receive the proper attention, although they significantly contribute to the durability of the structure.

3.3.4.1 *Finishing*-Recommendations for finishing as

Permeability to water rapidly reduces with cement hydration

Days of Curing	Coefficient of Permeability
1	36,300,OOO
2	2,050,000
3	191,000
4	23,000
5	5.900
7	1,380
12	195
24	46

Fig. 3.4-Curing versus permeability

outlined in ACI 302.1R should be followed. Although consolidation is necessary to eliminate entrapped air, it is important not to finish with free water on the surface because this practice can cause loss of air entrainment, and increase the water-cement ratio at the surface. Trueness of the surface affects drainage and merits special attention. The surface texture should be appropriate for vehicular and pedestrian traffic as well as to provide adequate skid resistance. A light-to-medium broom finish or a swirl finish with texture similar to a broom finish are most commonly used.

3.3.4.2 *Curing*-Proper curing of concrete is essential because it decreases permeability and reduces the potential for shrinkage cracking. Fig. 3.4 shows the effect of curing time on coefficient of permeability.

Early and proper curing is especially important for concrete that doesn't bleed or that bleeds very little. Examples are concretes containing entrained air, silica fume, a corrosion inhibitor, or other modifiers. Curing practices should follow ACI 308. Curing of each area should begin immediately following the start of the finishing operation for that area. Field experience has shown that curing with wet burlap covered with plastic sheets for a minimum of 7 days (ACI 345R) produces good results for cast-in-place concrete. Sodium silicate solutions are not recommended for use as a curing agent. The heat curing methods typically used in the production of precast concrete elements have generally reduced chloride penetrability.

3.4-Protection of embedded metals

Corrosion is a severe problem that may render the parking structure deficient before it has reached its full service life. Various protection measures for conventional reinforcement and prestressing steel are discussed in this section. See ACI 201.2R and ACI 222R.

3.4.1 *Concrete cover over reinforcement*

Concrete cover is important in protecting reinforcement from corrosion. ACI 318 Section 7.7 provides minimum cover requirements. The cover recommendations provided in Tables 3.1 to 3.4 may exceed the minimum requirements of ACI 318 (Zone III) in order to provide some extra protection in corrosive environments as suggested in ACI 318. A reduction in cover to the minimum ACI 318 requirements is allowed in these tables when extra corrosion protection for the reinforcing steel is provided through the use of epoxy coating or a corrosion inhibitor.

The following are recommendations when specifying concrete cover:

a) Increased cover over reinforcement does not provide absolute corrosion protection but significantly postpones the onset of chloride-induced corrosion. Adequate (or generous) cover over reinforcement is important in reducing corrosion.

b) Cover tolerances should be specified and ACI 117 gives guidance for specifying these tolerances. It may be difficult to place reinforcement so that concrete cover is within the specified tolerances. Other tolerances for placement of reinforcement, formwork construction, concrete thickness, and finish are sometimes not compatible with the cover tolerance.

c) Cover over column and wall reinforcement should be similar to top cover in adjacent slabs, particularly if these are at or near gutter lines or in areas exposed to salt-laden slush.

d) Precast members exposed to salts should have cover requirements at their ends, as well as along their sides, bottoms, and tops.

All parking floors within a parking structure should be considered "exposed to weather" in interpreting ACI 318, Section 7.7. Detailing of connections is an especially important part of obtaining adequate concrete cover.

Areas that deserve special attention are:

a) Slab-to-beam junctions where slabs are sloped transverse to beam. (Watch for minimum cover on low side of beam.)

b) At changes in slope, bars should be properly bent in slabs and in beams to maintain proper cover at high and low ends.

c) At beam-column connections, avoid interference between slab top steel and beam reinforcing by adjusting depths accordingly, both in design and detailing. Maintain minimum spacing requirements. Check for interference among post-tensioning, beam reinforcement, and column vertical reinforcement.

Project specifications and details should define supports for reinforcement. Slab bars and post-tensioning tendons should be chaired separately from beam reinforcing to assure that slab tendons and bars are in their correct position.

3.4.2 *Protection of reinforcement*-In addition to the concrete cover discussed earlier, additional protection of the reinforcement can be provided by coatings and other techniques. These are discussed in the following.

3.4.2.1 *Coated steel reinforcement*-Epoxy-coated reinforcement requires longer tension development lengths than does uncoated reinforcement (See ACI 318). Tests of beams with epoxy-coated bars have shown increased flexural crack widths and larger spacing between cracks. Limited observations of structures constructed with epoxy-coated reinforcement have shown similar results.

Epoxy-coated reinforcement should conform to ASTM A 775. Zinc-coated (galvanized) reinforcement should conform to ASTM A 767. The project specifications should include job site requirements for coated reinforcement. Requirements should include handling, placing, supports, and repair of damage to the coating (see ACI 301). Epoxy-coated wire and welded wire fabric should conform to ASTM A 884.

Epoxy-coated prestressing strands meeting ASTM A 882 may present a fire resistance problem. The epoxy may melt at relatively low temperatures resulting in a reduction or loss of bond along the pre-tensioning strand. End anchorages should be provided for epoxy-coated strand in fire-resistive precast concrete construction.

The Fourth Edition of the *PCI Design Handbook* recommends against the use of epoxy-coated prestressing strand in precast members because of the potential deterioration of the epoxy coating during normal heated curing practices. It has been observed that the bonding capabilities of epoxy coatings can start to deteriorate at temperatures ranging from 160 to 180 F.

3.4.2.2 *Post-tensioned tendons*-Unbonded systems should be specified in accordance with the Post-Tensioned Institute's *Specifications for Unbonded Single Strand Tendons.* Tendon protection by encapsulation should be used in Zones II and III.

For bonded systems, procedures that provide adequate grouting of ducts should be used.

3.4.2.3 *Pretensioning/connections for precast systems*-Although many precast concrete systems for parking structures have good corrosion-resistance characteristics, corrosion damage to prestressed and non-prestressed reinforcement in precast members has occurred. Flange-to-flange connections and bearing areas, such as ends of double-tees, beams, ledges, haunches, etc., are particularly vulnerable. Most corrosion of embedded reinforcement in precast members is associated with unrepaired failure of joint seals.

Connections in precast systems require special attention. Since they are located near the driving surface, tee-to-tee connections may suffer premature corrosion damage if exposed to water. Minimum protection for all connections should be provided as suggested in Tables 3.3 and 3.4. Unprotected connections should not be used in any area exposed to water, whether chloride-contaminated or not.

3.4.3 *Other embedded metals*-To reduce the formation of galvanic cells in the structural system, electrical contacts between dissimilar metals, particularly between uncoated reinforcement and stainless steel, lead (sometimes used to flash floor drains), brass, copper (also used as flashing materials), and bronze should be avoided. These metals are less susceptible to corrosion than uncoated reinforcement and will tend to promote corrosion of the reinforcement if in contact or close proximity. It is also desirable to isolate any galvanized or aluminum elements from the reinforcement to avoid a small anode-(galvanizing or aluminum) large cathode (reinforcing system) effect, which can promote premature loss of the galvanized coating or the aluminum element. Electrical components can affect structural performance. For example, embedded metal conduit with insufficient cover may lead to rusting, spalling, leaks, and even failure of circuitry. Unprotected aluminum conduit can be susceptible to severe corrosion in moist concrete. If used, embedded conduit should be located below the top reinforcement and meet or exceed the minimum cover requirements. For these reasons, it is better practice to place metal conduit on the concrete surface. Embedded plastic conduit is an alternative.

Double-tee stainless steel edge connectors should be of ferritic, not austenitic, stainless steel, to lessen the chance of stress corrosion in a chloride environment.

3.4.4 *Corrosion inhibitor*-Corrosion inhibitors offer protection to embedded reinforcement. With a corrosion inhibitor the initiation of corrosion is delayed, the corrosion rate is reduced, and the service life of the structure is extended.

One type of corrosion inhbitor is calcium nitrite. Calcium-nitrite-based corrosion inhibitor assists in chemically passivating the outer surface of the reinforcement.

3.4.5 *Dampproofing admixture*-An organic admixture consisting of amines and esters in a water medium has also been used to delay the initiation and rate of corrosion through its hydrophobic properties. See ACI 212.3R and ACI 222R. Other known dampproofing agents may have similar effects.

3.4.6 *Cathodic protection*-Cathodic protection of reinforcing steel is primarily used for the rehabilitation of existing structures rather than for new parking structures. However, cathodic protection is a method of protecting steel reinforcement from corrosion.

Use of cathodic protection may be considered in lieu of epoxy coatings, concrete sealers, or corrosion inhibitors. Concrete additives and concrete mixes specifically formulated to resist chloride intrusion are not required with cathodic protection. Concrete cover in excess of ACI 318 Section 7.7 is also not required.

Cathodic protection requires that all of the steel reinforcement have electrical continuity. Electrical continuity of uncoated reinforcement is typical in many structural systems, but must be assured for cathodic protection to function effectively. Special connections are required to assure electrical continuity of epoxy-coated reinforcement.

Although cathodic protection of high-strength steel (pretensioned and post-tensioned) is theoretically possible, the possibility of hydrogen embrittlement has discouraged its use.

Detailed information, design, and maintenance considerations for cathodic protection of steel-reinforced concrete structures can be found in the National Association of Corrosion Engineers Standard Recommended Practices RP 0187 and RP 0390.

3.5 Protection of concrete

3.5.1 *Protective treatments*-Specifying protection of concrete provided by applied sealers or membranes requires a basic understanding of the benefits and limitations of the products. Leaking joints can be a constant source of frustration and may lead to extensive structural damage.

3.5.1.1 *Concrete sealers*-Concrete sealers slow the rate of moisture absorption and chloride penetration. They should be used to assist rather than be a substitute for durable concrete. Sealers cannot bridge cracks and should not be expected to provide protection from moisture absorption or chloride penetration at cracks. Silanes and siloxanes may prevent entry of water into cracks by rendering the crack sides water-repellent. The water-repellency is limited by the width of the crack, shape of crack, and the movement present. There are numerous concrete sealers available that vary greatly with respect to their makeup, characteristics, and performance. Sealers should be evaluated based on the criteria established in NCHRP 244 *(Concrete Sealers for Protection of Bridge Structures)* and ASTM C 672 *(Scaling Resistance to De-icing Chemicals)* for the following:

1. Moisture absorption
2. Chloride penetration protection
3. Ability to withstand harsh climatic conditions

Abrasion resistance and skid resistance should be considered in addition to NCHRP 244 criteria.

High-quality sealers meeting the criteria established in NCHRP Report 244 typically screen out over 90 percent of chlorides.

All sealers require adequate surface preparation. Light sandblasting, water blasting, or steel shotblasting are often recommended by the sealer manufacturer. However, such preparation may not be needed for new concrete if it is free of contaminants and properly finished. Most sealers must be applied to dry concrete with a specific amount of concrete curing completed.

Sealers can be categorized as surface (film forming) or penetrants. Compatibility of all concrete sealers with subsequent striping or other specified finishes should be verified.

Surface sealers, including various acrylics, epoxies, urethanes and methyl methacrylates, provide a film over the surface to which they are applied and may penetrate slightly into the pores of the concrete surface. They are subject to wear and deterioration when exposed to traffic, and may need replacing more frequently than penetrants. Their presence can be visually monitored and the need to replace may be easily determined and accomplished on a spot basis. Their effect on skid resistance should be considered. Some materials are subject to deterioration when exposed to light. In general, surface sealers are not recommended for parking structures.

Penetrants, including silanes and siloxanes, penetrate the concrete, reacting with cementitious materials. They typically last longer than surface sealers, and are less subject to wear under traffic or deterioration from sun exposure.

Recommendations vary with differing environments and structural systems. See Tables 3.1 to 3.4.

3.5.1.2 *Traffic-bearing membrances*-A traffic-beating membrane typically consists of a fluid-applied, multilayer elastomeric polyurethane or neoprene material with an integral nonskid traffic topping of similar material or modified epoxy. These materials are designed to allow direct exposure to pedestrian and vehicular traffic. Graded sand or traprock is embedded in the traffic topping layers to provide a non-skid surface. The number and thickness of the traffic topping layers and amount of aggregate can be varied to provide different levels of resistance to wear. For example, entry/exit lanes, driving aisles, and turning areas receive more wear than do parking areas. Proper surface preparation is important for all traffic-bearing membranes.

Traffic-beating membranes provide waterproofing protection that is superior to concrete sealers, and their elastomeric properties allow them to bridge small cracks successfully. Many manufacturers offer systems that are resistant to deterioration from sunlight exposure. Most can be economically maintained by replenishing with additional traffic topping and aggregate, provided that the lower layers that provide the waterproofing protection have not deteriorated.

Recommendations vary with differing environments and structural systems. See Tables 3.1 to 3.4.

3.5.1.3 *Membranes with protective wearing courses*-These systems typically consist of a bonded, hot-applied rubberized membrane that is approximately $^1/_8$-in. thick. An asphaltic material or a concrete topping is placed over the membrane to provide a durable driving surface.

The thickness of the membrane and its initial flexibility provide crack bridging capabilities, particularly with systems that incorporate fabric sheet reinforcing at pre-existing cracks and joints. The need for preventive maintenance of the protective wearing course is generally minimal. However, since the membrane is concealed by the protective wearing course, repair of the membrane is generally expensive, and leaks are often difficult to locate if the membrane is not bonded to the concrete deck. The weight and thickness of the protective wearing course should be considered when analyzing a parking structure for allowable design load and determining floor-to-ceiling clearance.

3.5.2 *Joint sealant systems*-The placing of joints in parking structures introduces discontinuities in the surface, allowing penetration of water and deleterious waterborne chemicals into the slab if not properly sealed. Joint sealing systems must be watertight to avoid leakage and premature deterioration of underlying structural elements.

Joint design is important to prevent early joint system failure. Refer to ACI 504R for information regarding design of joints and installation of sealants.

Proper maintenance of the joint sealant system is critical to the long-term performance of parking structures (see Chapter 5).

3.5.2.1 *Isolation and expansion joints*-Isolation and expansion joints are provided in parking structures to relieve stresses associated with volume change forces. Their function is to reduce the length of structure subject to volume change; to facilitate change of direction of the predominant shape of the structure; and, where desired, to separate stair towers or other stiff building elements from the parking structure. In special situations, it may be desirable to provide for load transfer across an expansion joint to minimize vertical displacement across the joint or to transfer lateral loads parallel to the joint. Transfer of lateral loads parallel to the joint should be done with caution and with consideration of all aspects of structural behavior. Isolation joints may also separate grade beams from the structure, and isolate columns from a slab-on-grade. Isolation joints are characterized by a complete break through the full cross section of the structure, allowing predicted movement to occur without harmful repercussions. Joint movements may occur vertically as well as horizontally. Related isolation joints for earth-quake design are referred to as seismic joints.

Effectively sealing isolation and expansion joints is difficult and some periodic maintenance will be required. Problems can be minimized by selecting the proper seal for the expected service conditions and by locating joints at high points and away from areas where water must pass to reach drains. In no case should water be allowed to pond on these joints. At areas of pedestrian use, select systems that reduce potential tripping hazards. On design drawings, a section should be shown along the length of every isolation or expansion joint to ensure proper detailing of conditions at ends, curbs, columns, walls, etc.

Proper sealing of isolation and expansion joints is a function of several factors. Total movement of a joint should account for the volume changes discussed in Chapter 2. Failure to adequately account for volume changes during design can be a contributing cause to joint failure in post-tensioned parking structures. Volume and speed of traffic over the joint and exposure to snowplows may be important design factors. Ease of splicing, transitions, terminations, and repair are also important.

Various types of joint sealing systems for structural isolation and expansion joints are available. Appropriate selection involves an understanding of design features and limitations of each type of joint system, including ADA requirements associated with tripping hazards.

3.5.2.2 *Types of isolation and expansion joint sealing systems*-Types of isolation and expansion joint sealing systems commonly used include factory-molded elastomeric seals, extruded elastomeric seals, and strip (or gland) seals.

Factory-molded expansion joint seals involve the use of an elastomeric material, usually urethane. The urethane joint seal is adhered to the sides of the joint, but is not bonded across the bottom to allow free movement of the elastomeric material.

Urethane joint sealing systems are factory premolded to minimize the problems associated with field application (see Fig. 3.5). These seals are susceptible to damage from snowplows and should not be used in such areas. They also may become slippery in some weather conditions.

Extruded elastomeric seals differ in material as well as manufacturing process. One common type is the compression seal, characterized by a compartmentalized (honeycombed) cross section, predominantly manufactured by extruding polycholoroprene (neoprene), a material offering resistance to compression set. Another type of compression seal is a flexible cellular foam or expanded vinyl acetate, impregnated with polybutylene or similar compound. This type of joint has been observed to perform poorly in parking structure applications because of a tendency to take on a compression set in colder weather.

For compression seals to be effective, some degree of compression must be maintained at the joint interface and the joint material must remain elastic. This need requires a uniform joint width and clean, straight, smooth, spall-free joint faces. This requirement can be accomplished by armoring the joint with metal angles.

Some of the problems associated with displacement of

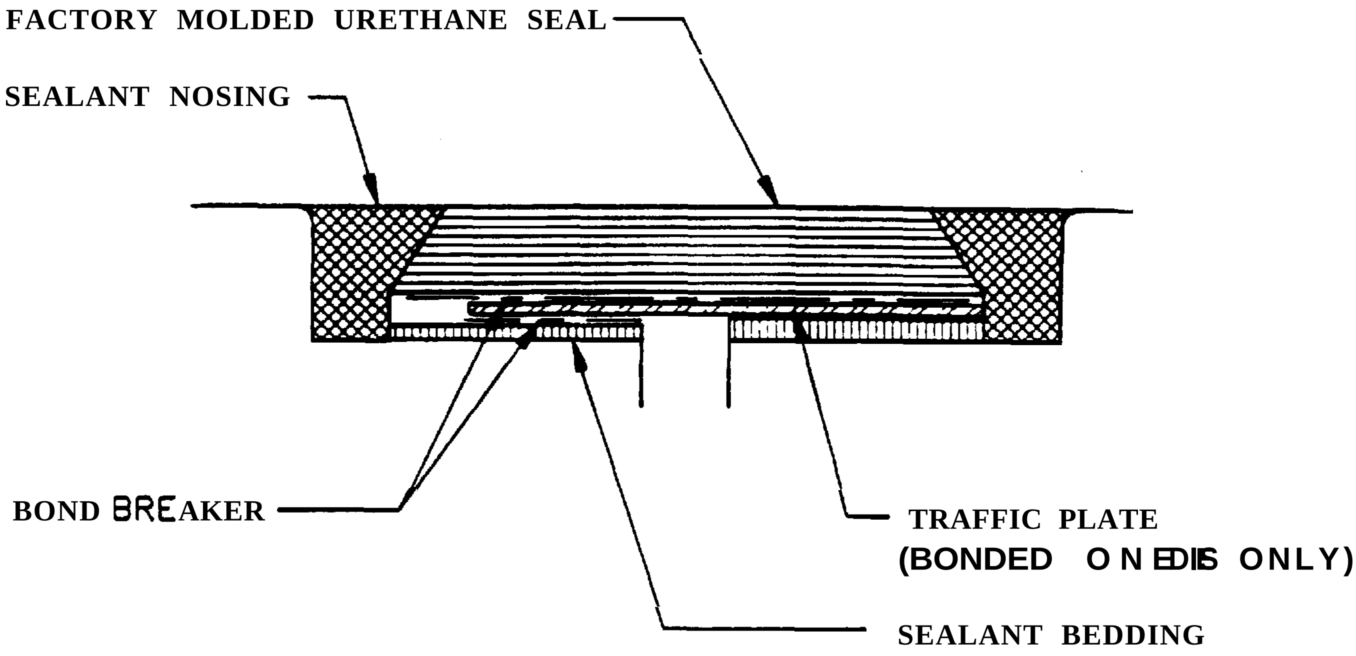


Fig. 3.5-Factory molded urethane expansion joint seal

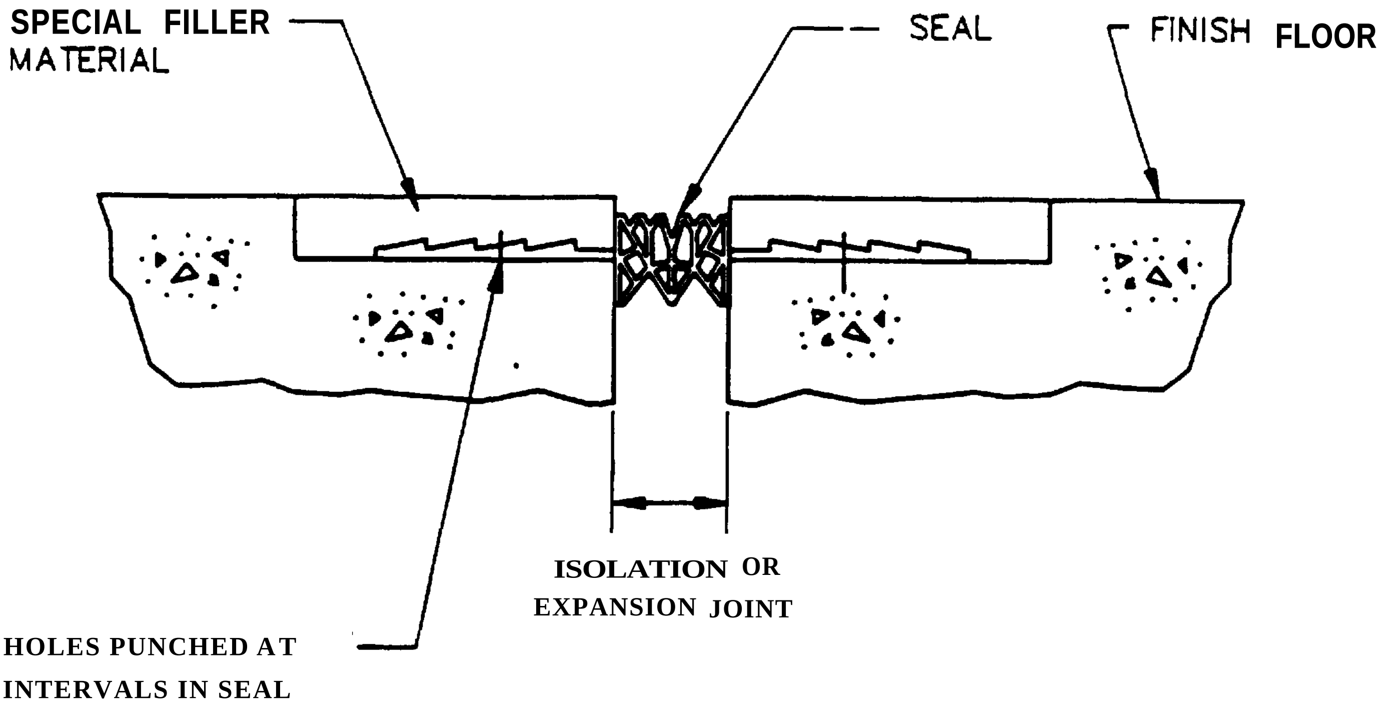


Fig. 3.6-Example of a chemically adhered, extruded rubber expansion joint seal

compression seals may be reduced or eliminated by the use of mechanically locked seals with metal retainers or membrane flanges, allowing the seal to remain functional beyond its nominal width (see Fig. 3.6).

Strip (or gland) sealing systems have become popular in recent years in response to field problems associated with other types. These seals consist of a preformed elastomeric sealing element mechanically locked, fixed, or otherwise bonded at each side of the joint face. Movement is accommodated by a fold or bulb within the ele-

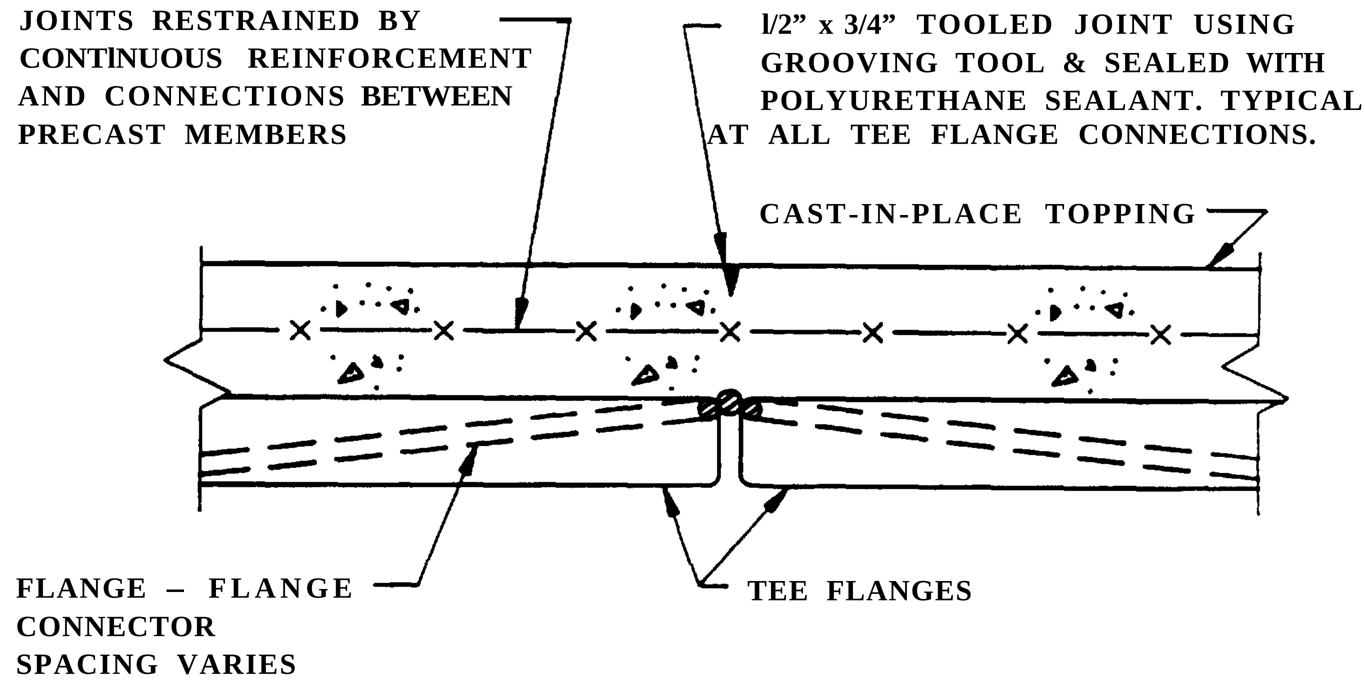


Fig. 3.7.1-Typical control detail in field-placed topping at precast tee flange-to-flange joint

ment. A small face is presented at the top to wheel and foot traffic, reducing traffic exposure problems. An armored edge or a special nosing is commonly employed to minimize snowplow damage. These systems come in a wide variety of configurations and are not easily categorized.

Joint fiiers that do not retain moisture are suggested for use on parking structures. Joint fillers that absorb or retain moisture can contribute to accelerated failure of the sealant, corrosion of adjacent steel, or increased scaling due to freeze-thaw cycling. Care should be taken when installing these materials during times of temperature extremes. Sealing these joints should be deferred until normal temperatures exist.

3.5.2.3 *Contraction joints*-Contraction joints (sometimes called control joints) are used to make various structural systems more watertight. To be successful, the following criteria should be met:

1. Controlled cracking should be induced at predetermined locations where cracking is likely to occur.
2. A sufficient number of joints to reduce stresses in the concrete must be included so that formation of additional cracks will be minimized.
3. The joints should be installed and maintained in such a way as to provide long-term watertightness.

Type and location of joints and detailing of their seals are unique to each type of structure and require special consideration. Sealant effectiveness depends on the quality and durability of the surrounding concrete, the amount of traffic, direct exposure to sun and weather, the amount of cyclical movement in the joint, the use of proper preparation and installation techniques, the presence of standing water over the joints, and proper maintenance.

Precast, prestressed structures with cast-in-place concrete topping with a joint system have shown a high degree of success in controlling anticipated cracks because of the highly predictable cracking pattern that occurs. Contraction joints should be placed at all edges of every precast member (see Fig. 3.7.1 and 3.7.2). Joints should be extended through any cast-in-place elements, such as curbs or islands, and placed over joints between precast members. Cracking may occasionally occur in the topping at random locations due to restraint from the underlying precast section. These cracks should be sealed.

Contraction joints iu concrete topping over precast concrete are created during the concrete finishing process. Joints should be accomplished by tooling a "V" configuration into the plastic concrete with a common concrete groover similar to the tool used to provide sidewalk joints. The "V" should be at least ¾-in. deep and ½ in. wide at the top with a ⅛-in. radius edge at the driving surface. After curing, the grooved joint should be prepared by grinding with a V-shaped abrasive wheel, cleaned, primed, and sealed with a quality sealant recessed slightly below the driving surface to minimize contact with wheel traffic. Movement in these joints is typically restrained by the presence of reinforcement steel, welded wire fabric, or welded connections through

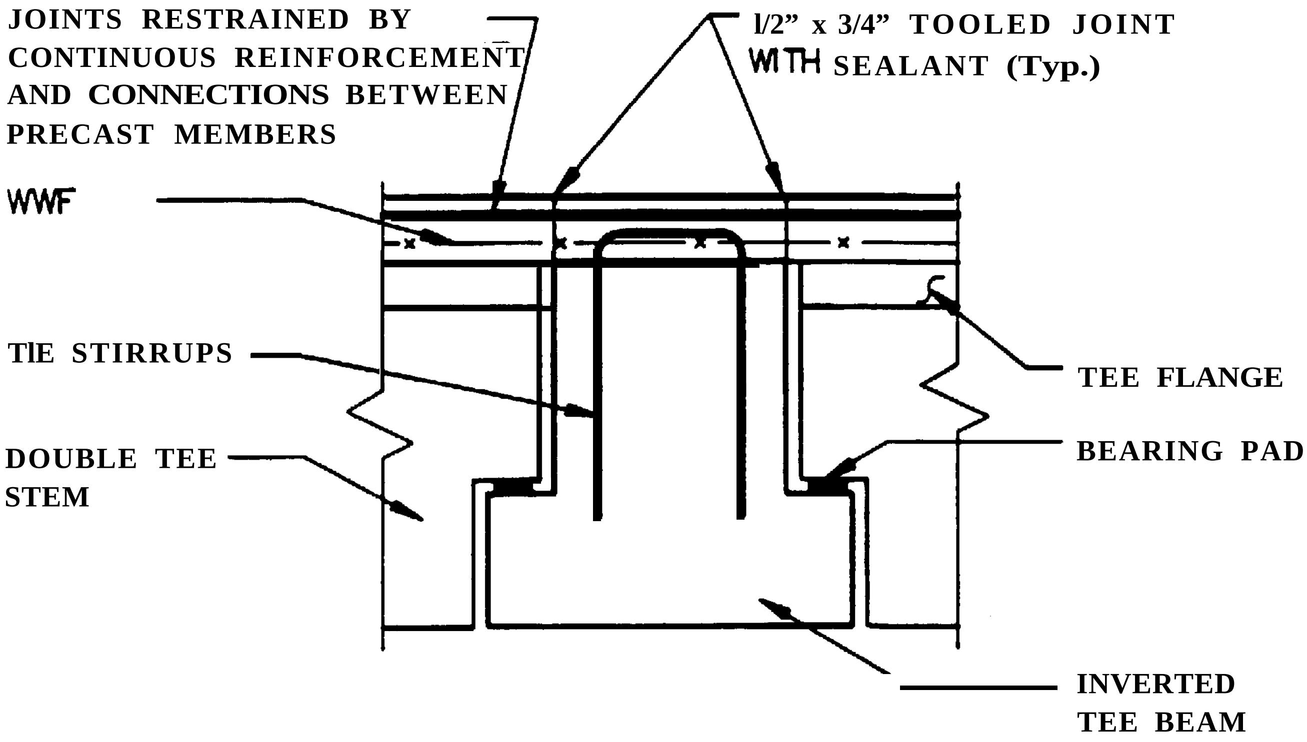


Fig. 3.7.2-Typical control detail in field-placed topping over tee and inverted tee beams

tions through the crack or joint. No bond breaker or filler rod is normally required to successfully seal joints of this type because movement is restrained across the joint or crack.

A "V" shape sealant cross section has very little movement capability, and if the crack or joint is not restrained, the shape factor of the sealant or seal element becomes critical to success. Refer to ACI 504R for sealing of a moving joint.

Sawing joints is not a recommended alternative to tooling. The main advantage of a tooled joint over a sawed joint is that it creates a reduced cross section before the concrete has reached initial set. The reduced section minimizes the probability of cracking adjacent to the joint or prior to the time the joint is provided. Tooling rounds and compacts the edges, providing a shape more resistant to spalling than the square edge of a sawed joint.

3.5.2.4 *Construction joints*-Construction joints are created at predetermined locations where one concrete placement is terminated and another is begun later. Depending on structural design, joints may be monolithic (that is, the interfaces of the joint are soundly bonded to insure complete structural integrity of the slab), or function as isolation or contraction joints.

Construction joints are often sources of leakage in parking structures. Deicers allowed to penetrate through the joint may result in corrosion of reinforcement or other embedded metals.

Leakage at monolithic construction joints may be reduced if, before the second casting, laitance is removed to promote a positive bond.

Following placement, monolithic construction joints should be tooled and sealed. Sealing should be accomplished by filliug the construction joint with an elastomeric sealant (see Fig. 3.8). Monolithic construction joints are usually restrained from movement because of the amount of reinforcement crossing the joint.

Optimum configuration of the joint sealant is dependent on the amount of movement anticipated during the service life of the structure (see ACI 504R).

3.5.2.5 *Cracks*--Cracks in concrete occur for a variety of reasons. Since cracks are a source of moisture and chloride intrusion into the concrete, sealing them is an important issue.

There are several common methods of sealing cracks. The effectiveness of a given method is dependent upon the underlying cause and behavior of the crack. See ACI 224R and ACI 224.1R for a more complete discussion of the causes of cracking. Many cracks in parking structures are subject to dynamic movement due to temperature change. Effective repairs for these cracks must be able to withstand ongoing movement in the crack. The most effective method to accomplish this repair is to provide a groove of approximately ½ in. wide by ½ in. deep sealed with an elastomeric sealant.

For small cracks (approximately 0.015 in. or less) that show little or no movement, treatment with a penetrating

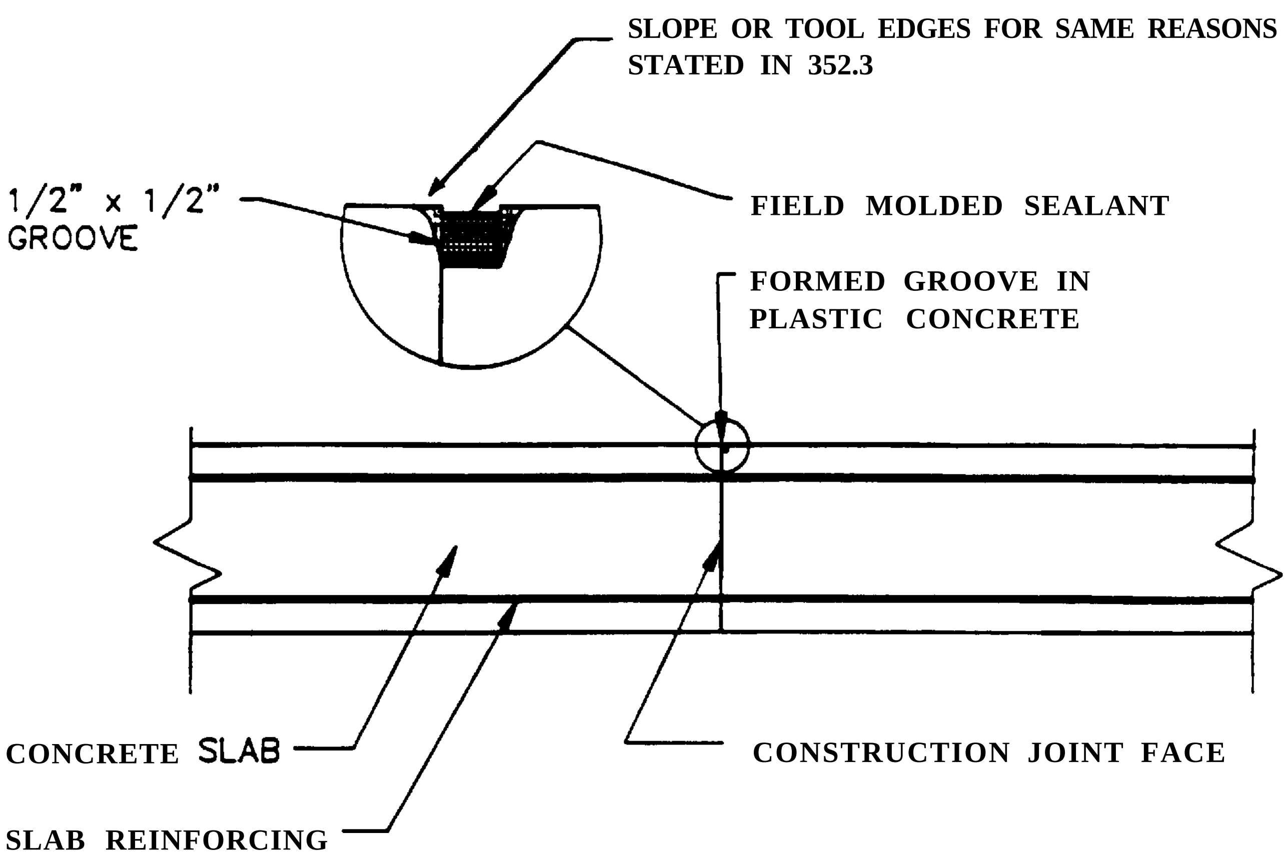


Fig. 3.8-Typical sealant detail over construction joint in cast-in-place structural slab

silane or siloxane sealer may render the crack hydrophobic. One course of action to repair multiple small cracks is to treat the surface area with a silane or siloxane sealer, then retreat specific cracks that continue to leak at a later date with the rout and seal method.

Another method of sealing cracks is the use of epoxy injection. This process involves injecting epoxy into a crack under pressure to fill the void and adhere the surfaces back together. This approach should be considered if the crack is static and it is desirable to restore the structural integrity of the cracked section. A variation on this method is to gravity feed a low-viscosity epoxy, methacrylate, or other polymer into the crack to fill the void and make it watertight. In either case, it is important that the underlying cause of the crack be determined and corrected prior to the repair, or a new crack may develop to replace the one being fixed. Epoxy injection is not a recommended procedure for repairing moving cracks.

3.6-Guidelines for selection of durability systems for floors and roofs

3.6.1 *Introduction*-The performance of parking struo tures requires special attention to durability systems in all environments. Selecting the right combination of protection systems is not a prescriptive process. This section is provided to assist the designer in selecting an appropriate combination of protective measures.

Recommendations in the text differentiate between parking levels exposed directly to the elements (roof) and parking levels not exposed directly to the weather (floor). The recommendations refer to general parking areas and adjacent drive lanes. Isolated ramps, helices, or access lanes with concentrated traffic may require protection greater than the minimum recommendations. Other physical or functional characteristics that may justify exceeding these minimum recommendations are:

1. Multiple use structure
2. Perimeter of parking level exposed to the weather
3. Occupied space directly below parking level
4. Heated space above or below parking level
5. Isolated single-lane entrance or exit without alternate access
6. High traffic volumes

Section 3.6.4 provides descriptions of these characteristics and their effects on the durability system.

Not all available protection measures are appropriate or compatible. Tables 3.1 through 3.4 provide minimum recommended durability measures for different types of structural systems and service environments.

3.6.2 *Structural considerations*-Recommended durability measures are dependent upon the structural system chosen and their service environment. For example, slabs that tend to crack (thin slabs and nonprestressed slabs) should be provided with traffic grade membranes on the roof in certain conditions and on all floors in others. Measures to isolate and protect internal metal elements in the slab will also vary from system to system.

3.6.3 *Environmental considerations*-Chapter 1 discusses various exposure conditions and types of deterioration that may occur. Fig. 3.1 defines various exposure zones to provide the designer with initial guidance to address each of these concerns. Where appropriate, different approaches have been recommended in this chapter for different zones.

3.6.4 *Physical and functional considerations*-In addition, there are other physical and functional characteristics that should be considered. Recommendations provide a minimum level of protection. Anticipated difficulties in repairing or rehabilitating the structure in the future should be considered in selecting the protection system. Concern for the future must be balanced with the economics of providing more protection initially, as well as the annual maintenance costs.

3.6.4.1 *Multiple-use structures*-Parking structures are often an integral part of a building providing space for commercial, office, hotel, residential, or other uses. In multiple-use structures such as these, the building will likely be occupied as long as it stands. If the parking portion is allowed to deteriorate, rehabilitation may adversely affect building occupants. Consideration should be given to providing more than minimum protection in such cases.

3.6.4.2 *Occupied space directly beneath parking* level-Leaking from a parking level into occupied space beneath is generally more damaging and annoying than leaking from one parking level to another. The minimum protection system over occupied space should be a traffic-bearing membrane. Dependent upon the use of the space below and the anticipated life of the facility, a membrane with protective wearing course may also be considered.

3.6.4.3 *Heated space above and beneath parking* level-when an underground garage in Zone II or III is heated, caution should be exercised iu deleting the recommendations in Tables 3.2 through 3.4. Freezing and thawing could stilI occur at exits and entrances should air curtains not function, or throughout if heating systems do not function properly. Due to melting of snow, ice, and deicing salts carried in on the undersides of vehicles, the potential for corrosion-induced deterioration and leaking may be greater.

3.6.4.4 *Isolated single-lane entrance or exit without alternate access*-When an isolated single-lane entrance or exit is provided to a parking level without alternate access, consideration should be given to the difficulties that would be encountered in repairing corrosion-induced deterioration once the facility is operating. A greater degree of protection than is otherwise recommended should be considered for these areas.

3.6.4.5 *High traffic volumes or valet parking*-In a parking structure with high traffic volumes or valet parking, abnormal abrasion of the surfaces in the drive lanes may be a problem. Elements of the floor or roof protection system that are in contact with the vehicle tires may undergo extensive wear. Design and detail the joints to prevent tire contact with joint sealants. A membrane with a protective wearing course should be considered for these conditions.

CHAPTER 4-DESIGN ISSUES RELATED TO CONSTRUCTION PRACTICE

4.1-Introduction

There are many aspects of the construction process that directly affect long-term durability of parking structures. Many of the items in this chapter have been covered in previous chapters because they should be considered in the design/specification process. They are repeated here for emphasis.

4.2--Concrete cover

4.2.1 *Placement of reinforcement*-In addition to normal concern for placement of reinforcement to satisfy structural requirements, placement of reinforcement to obtain the required concrete cover is important. Top concrete cover and, in some cases, side concrete cover are significant durability factors. Because of the importance of cover, periodic inspections during construction are desirable to verify reinforcement placement. There are certain chronic deficiencies in concrete cover that occur on many jobs and to which the parking structure inspector should be particularly alert. Tltese include bumper wall inside face cover, cover at changes in floor slope, cover over ends of bars at outside edges of pour strips and expansion joints, column ties, cross-overs, and heavily warped slab areas. Slab bars and slab post-tensioning tendons should be chaired separately from beam reinforcing to assure that slab tendons and bars are in their correct positions.

4.2.2 *Thickness of slabs and other concrete elements*-It is important to verify that slab thickness is maintained to assure proper cover. Screed rails fixed in place to maintain the required slab thickness are recommended. Slabs that are screeded and finished to less than their design thickness can reduce concrete cover, resulting in loss of durability and perhaps reduced structural capacity. Sloped floors present a challenge to the contractor in maintaining proper concrete thicknesses.

4.3-Vertical clearances for vehicles

Variations in vertical dimensions during construction have created less than desirable vertical clearances for vehicles or pedestrians. Extra care in this area is warranted.

4.4-Floor elevations for drainage

Drainage is an important aspect of durability. Drainage is affected during construction by several variables, depending on the structural system:

- Setting edge forms to proper height
- Setting slab forms to proper slopes
- Setting screed rails
- Casting tolerances
- Setting drains
- Special drainage areas
- Finishing tolerances
- Casting tolerances of precast members
- Camber
- Warping of precast members to achieve desired slope

Parking structures often have sloping or warped floors, which make construction more difficult than level floors. Drainage slopes warrant extra attention to assure that specified drainage is achieved.

4.5-Materials

Inspection and review of construction procedures should be undertaken to verify that conformity with the specifications has been achieved. Some aspects of quality control that should have special attention during construction are noted in the following paragraphs.

4.5.1 *Mixproportions*-The mix proportions should insure the various constituents combine into a workable mix that can be placed without compromising durability and strength.

4.5.2 *Water-cementitious material ratio*--Water content affects concrete permeability, shrinkage, and cracking. Limitations for adding water to concrete at the jobsite should be specified. Concrete with slump values greater than the specified tolerance limit should be rejected. High-water-cementitious-ratio concrete shrinks and cracks more than low-water-cementitious-ratio concrete. Although ASTM C 94 allows on-site addition of water to the mix, there is no guarantee of uniform mixing. Tables 3.1 through 3.4 recommend low water-cementitious ratios. The addition of on-site water may compromise the quality of the concrete and is not recommended.

4.5.3 *Admixtures*--The use of admixtures or additives to the concrete in the appropriate quantities and combinations may be necessary to achieve durable concrete. Admixtures, however, must be used with a clear understanding of their intended effect and limitations.

4.5.3.1 *Air entrainment*-Field verification of the total air content should be made for each batch at the point of placement. Concrete with out-of-tolerance air content should be rejected.

4.5.3.2 *High-range water-reducing admixtures (super-*plasticizers)-High-range water-reducing admixtures may be added at the plant or at the jobsite after verification of the initial slump. If added at the jobsite, adequate mixing time is important to assure dispersion throughout the batch. Varying travel time to the jobsite and varying time periods before usage at the jobsite may require redosage at the jobsite to maintain the desired slump level. Air content must be monitored carefully after redosage.

4.5.3.3 *Silica fume*-The use of silica fume may require modifications of the timing and procedures of finishing and curing. Trial slabs and consultation with a manufacturer's representative are recommended. Fogging may be necessary to prevent shrinkage cracking during some weather conditions.

4.5.3.4 *Other admixures*-Other admixtures also may require special attention during the construction process to assure that they are being used as recommended.

4.6-Placement and consolidation

The placement and consolidation on the sloped floors of parking structures requires special consideration. Placement should normally proceed in the uphill direction to achieve best results. Some have reported better results proceeding in the downhill direction when working with HRWR mixes and vibrating screeds. If the timing of vibration and screeding is not correct for the mix, the concrete tends to slide downhill and create small humps at transverse reinforcement. The amplitude of these variations is generally slightly greater than the finishing tolerance but is not likely to significantly affect the use or durability of the deck. Consolidation to eliminate entrapped air should be performed. Forms that are too flexible may cause concrete to flow away from the point of consolidation or placement.

4.7-Finishing

Recommendations for finishing as outlined in ACI 302.1R should be followed. It is important to consolidate and close the surface. Finishing should not proceed with free water on the surface because it can cause loss of air entrainment and increase the water-cementitious ratio at the surface. A light-to-medium broom finish or a swirl finish with texture similar to a broom finish is most commonly used. Quality finishes can be achieved by brooming the surface immediately after bullfloating, spraying an evaporation retarder, and fogging until the concrete has hardened sufficiently to apply curing covers. No further floating or finishing is done after brooming.

4.8-Curing

Moist curing is recommended to provide the best quality. If a curing compound is used, its compatibility with a future sealer or membrane must be reviewed. A seven-day wet cure followed by a membrane-curing compound is recommended to enhance impermeability and minimize shrinkage of cast-in-place concrete. In hot, dry, windy weather, spraying a membrane curing compound on formed areas after form removal should be considered to minimize long-term shrinkage problems. Heat curing utilized in most precast concrete plants provides a satisfactory cure. Silica fume concretes require more attention to curing than do most other concretes.

4.9-*Reinforcement*-Repair of corrosion protection

Damage to the corrosion protection provided for reinforcement during construction is not an uncommon occurrence. Inspections should be conducted prior to concreting to identify and repair damaged conditions.

Cut ends and damaged areas of epoxy-coated reinforcement should be repaired in accordance with established procedures and recommendations.

Post-tensioning sheathing and encapsulation systems should also be inspected and repaired as necessary prior to concreting to maintain the necessary corrosion protection.

4.10-Application of sealers

Critical factors for the application of sealers that should have special attention during the construction phase include:

- Surface preparation
- Coverage rate
- Uniformity of coverage
- Moisture condition of concrete

In new construction, concrete cured with water should not require any special preparation, provided the concrete has been kept free of grease, oil, dirt, or other contam-inants.

4.11-Application of membranes

Critical factors for application of membranes include:

- Surface preparation
- Coverage rate
- Pretreatment of cracks
- Curing temperature

4.12-Specialty concretes

Specialty concretes containing high-range water reducers or silica fume require special procedures and guidelines for transport, placement, finishing, and curing.

4.13-Environmental considerations

Special attention must be given to specifications for hot-and-cold weather concrete placement. Minor changes in the concrete mix design may be required to compensate for changing weather conditions (see ACI 305R and 306R).

4.14-Field quality control

ACI has certification programs for concrete finishers and concrete technicians to verify field workers' qualifications. The PCI (Prestressed Concrete Institute) and the PTI (Post-Tensioning Institute) have plant certification programs that establish standards for commonly used structural components. In addition, there are many other programs sponsored by trade organizations and individual companies to increase the level of employee craftsmanship and improve overall quality of the project. The committee recommends designers and specifiers make use of these programs by specifying compliance in construction documents.

CHAPTER 5-DESIGN ISSUES RELATED TO MAINTENANCE PRACTICE

5.1-Introduction

The building designer should advise the owner of maintenance tasks that should be performed during the life of the structure. Just as owners receive instructions for operation of a piece of mechanical equipment, they should understand maintenance appropriate for the parking structure. The term maintenance, as used in this context, includes many routine tasks and observations, repairing anything that is not working as it should, and those tasks that are in the realm of preventive maintenance. These tasks might be separated into housekeeping, preventive maintenance, and repairs.

The purpose of maintenance is to prevent the need for significant repairs by taking preventive measures and repairing or replacing malfunctioning elements on a timely basis.

5.2-Suggested minimum maintenance program

The heart of a maintenance program is regular cleaning and inspection of the various elements of the structure. The second requirement is preventive maintenance and repair of specific elements.

5.3.1 *Cleaning*-There are two aspects of cleaning that have impact on durability. Fist, it is desirable to assure that drains are kept free of debris so that they function as intended. Second, it is desirable to wash the floors of a parking facility at least once a year. In areas where deicer salts are used, two floor washings are recommended; one in the spring and one in the fall.

5.2.2 *Inspections*-The purpose of regular inspections or observations is to insure that all of the parking structure elements are performing properly. In the next sections, various elements of the structure, or indication of problems, that can be visually observed are discussed. An inspection log should be maintained by the owner or operator at the facility.

5.2.2.1 *Water leakage*-Leaks may occur at isolation joints, construction joints, cracks, walls, windows, and other locations. Any leak is a potential problem, and should be investigated and corrected. Failure to correct leaks is likely to result in corrosion damage. Isolation joints and sealing systems can be expected to need replacement at regular intervals. Variables affecting service life include materials, workmanship, traffic, joint details and exposure to sunlight.

5.2.2.2 *Membrane*-Membrane systems are subject to abrasion wear due to traffic. When surface wear is first observed, the membrane may be intact, but appropriate measures should be taken to restore the wearing course. Reapplication of the wearing course may be required in 3 to 5 years, with spot repairs required more frequently. Should the membrane fail to bridge a crack, repair procedures should be implemented as soon as practical.

5.2.2.3 *Sealers*--Many sealers that perform as a moisture and chloride screen are not visible, making it difficult to visually determine whether the sealer is present and capable of performing its intended function. Sealers usually require periodic tests to assess their performance. One of these tests is commonly called a "water uptake test." At present, there is not a standard test method for this procedure and it should be considered as a general guide. The water uptake test consists of: using a sealant to seal a graduated tube against the concrete; filling the tube with water; reading the level of the water initially and after 20 min or an hour to determine the amount of water absorbed by the concrete during the test period. A test of this type is best performed shortly after the sealer has been applied and cured, then at 1- to 3-year intervals thereafter. If any water uptake test shows a significant change, then it may be time for a reapplication of a sealer as a preventive maintenance measure.

Another method of checking the performance of a sealer is to take initial samples of the concrete for determination of chloride content. These samples can be small, with partial depth cores or powder recovered from drill bit holes. Samples taken at intervals of 1- to 3-years can be compared to the initial sample. When tests indicate the sealer is not performing its desired function to minimize chloride ingress, a new sealer should be applied. Sealers may require reapplication as early as 3 years, yet some may perform well for more than 10 years.

5.2.2.4 *Ponding*-Observations should note areas of the structure that allow ponding of water. If ponding occurs, it is recommended that steps be taken to eliminate the ponding. See Chapter 3.

5.2.2.5 *Sealants*-Inspection and prompt repair of sealant is important for overall durability of the structure. Sealant failure may permit water to reach steel elements, such as at the connections of flanges of precast elements, or at construction joints such as those where prestressing tendons or anchors are located.

5.2.2.6 *Other elements*-other elements in a parking structure that should be included in regular inspections include:

- Connections in precast concrete construction
- Bearing pads and sliding joints
- Concrete that shows any evidence of deterioration or corrosion

5.3-Fix it now!!

When any element or area of a parking structure is not performing as intended, that element should be repaired or replaced as soon as is practical.

Suggested references for additional information include the *Parking Garage Maintenance Manual* prepared by the Parking Consultants Council of the National Parking Association and the book *Parking Structures* (see references).

CHAPTER 6-REFERENCES

6.1-Cited references

The documents of the various standards-producing organizations referred to in this document are listed with their serial designation. Since some of these documents are revised frequently, the user of this report should check for the most recent revision.

American Association of State Highway and Transportation Officials

T 259 Standard Method of Testing for Resistance of Concrete to Chloride Ion Penetration
T 277 Rapid Determination of the Chloride Permeability of Concrete

American Concrete Institute

116R Cement and Concrete Terminology
117 Standard Specifications for Tolerances for Concrete Construction and Materials
201.2R Guide to Durable Concrete
209R Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.3R Chemical Admixtures for Concrete
222R Corrosion of Metals in Concrete
223 Standard Practice for the Use of Shrinkage-Compensating Concrete
224R Control of Cracking in Concrete Structures
224.1R Causes, Evaluation, and Repair of Cracks in Concrete Structures
225R Guide to the Selection and Use of Hydraulic Cements
234 Guide for the Use of Silica Fume in Concrete*
301 Specifications for Structural Concrete for Buildings
302.1R Guide for Concrete Floor and Slab Construction
305R Hot Weather Concreting
306R Cold Weather Concreting
308 Standard Practice for Curing Concrete
318 Building Code Requirements for Reinforced Concrete
345R Guide for Concrete Highway Bridge Deck Construction
352R Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures
504R Guide to Sealing Joints in Concrete Structures

*Awaiting publication.

544.3R Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete

American Society for Testing and Materials

A 767 Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement
A 775 Specification for Epoxy-Coated Reinforcing Steel Bars
A 882 Specification for Epoxy-Coated Seven-Wire Prestressing Steel Strand
A884 Specification for Epoxy-Coated Steel Wire, and Welded Wire Fabric Reinforcement
c 31 Standard Method of Making and Curing Concrete Test Specimens in the Field
c 33 Standard Specification for Concrete Aggregates
c 94 Standard Specification for Ready Mixed Concrete
c 494 Standard Specification for Chemical Admixtures for Concrete
C 672 Test for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
c 1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
E380 Metric Practice Guide

Building Seismic Safety Council

NEHRP (National Earthquake Hazards Reduction Program) for the Development of Seismic Regulations for New Buildings, 1991.

National Association of Corrosion Engineers

RP 0187 Design Considerations for Corrosion Control of Reinforcing Steel in Concrete Structures
RP 0390 Maintenance and Rehabilitation Considerations for Corrosion Control of Existing Steel Reinforced Concrete Structures

National Cooperative Highway Research Program

4 Concrete Bridge Deck Durability
57 Durability of Concrete Bridge Decks
244 Concrete Sealers for Protection of Bridge Structures

National Parking Association

Parking Garage Maintenance Manual, National Parking Association, Washington D.C., 1987.

Precast/Prestressed Concrete Institute

Parking Structures: Recommended Practice for Design and Construction, Precast/Prestressed Concrete Institute, Chicago, IL, 1988.

PCI Connection Manual, 2nd Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1988.

PCI Design Handbook, 4th Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1992.

"Design of Spandrel Beams," Specially Funded Research Project #5, Precast/Prestressed Concrete Institute, Chicago, IL, 1986.

Post-Tensioning Institute

"Specifications for Unbonded Single Strand Tendons," *PCI Journal,* V. 30, No. 2, Mar.-Apr. 1985.

Other Publications

Chrest, Smith & Bhuyan, *Parking Structures: Planning Design, Construction, Maintenance, and Repair,* Van Nostrand Reinhold, New York, New York, 1989.

Referenced publications are available from the following organizations:

American Association of State Highway and Transportation Officials
444 North Capitol St., NW
Suite 225
Washington, D.C. 20001

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American Society for Testing and Materials
1916 Race Street
Philadelphia, PA 19103

Building Seismic Safety Council
1201 L Street, N.W., Suite 400
Washington, D.C. 20005

National Association of Corrosion Engineers
P.O. Box 218340
Houston, TX 77218

National Parking Association
1112 16th Street NW
Suite #300
Washington, D.C.

Precast/Prestressed Concrete Institute
175 West Jackson Blvd.
Chicago, IL 60604

Post-Tensioning Institute
1717 W. Northern Ave.
Suite No. 218
Phoenix, AZ 85021

The National Cooperative Highway Research Program documents can be obtained from:

Transportation Research Board
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, D.C.

6.2-Acknowledgement

Fig. 3.1 and Tables 3.1 through 3.4 were first presented by H. Carl Walker in an unpublished paper presented to the American Concrete Institute Annual FalI Meeting in Philadelphia, Pennsylvania, on Nov. 15, 1990, and titled *"Durability Criteria Recommendations for Reinforced Concrete Parking Structures."* They are used herein, including changes by the committee, with permission.

Table 2.1 first appeared in *Handbook of Concrete Engineering*, edited by Mark Fintel, Van Nostrand Reinhold, 2nd edition, p. 738.

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