35
Cracking Mitigation and Maintenance Considerations

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35.1 Overview of Crack Mitigation

When selecting the concrete configuration and reinforcement layout for a concrete building, the engineer typically considers strength requirements and then addresses serviceability concerns. During the serviceability check, attention is directed to deflection and durability, but many times detailing for serviceability to mitigate cracking is overlooked. Cracking in reinforced concrete buildings can be addressed early in the design process through judicious consideration of building layout, selection of appropriate connections, and use of appropriate reinforcement detailing. It is advisable to evaluate during the member design stage those members within a structure that may be subject to various types of cracks. Predicting possible crack behavior or crack development among members within a building typically allows application of appropriate mitigating detailing. Whether cracking is caused by restrained shortening of concrete or cross-sectional action, effective detailing of concrete members can significantly impact the long-term performance and durability of the concrete structure.

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The intent of this chapter is to provide a basic understanding of crack development as well as design detailing recommendations to mitigate cracking in concrete members. It specifically excludes the review of concrete member cracking due to unique or special materials used or the preparation (mix properties/proportions), placing, and conditioning of poured concrete. The design details presented herein are limited to building structures; special structures and non-building structures are not part of this review. This chapter is limited to cast-in-place concrete frames only; precast concrete and masonry elements are excluded. Post-tensioned concrete floor systems have become the predominate choice for concrete floor systems using cast-in-place construction. For this reason, examples within this chapter focus on post-tensioned concrete floor systems when evaluating crack mitigation, as such slabs have an added elastic shortening component and concrete creep to address due to the precompressed concrete cross-section.

Many publications offer a summary of standard details for the construction of concrete structures; however, it is a challenge to find documentation of appropriate or standard detailing to aid the designer in addressing concrete cracking. This chapter, however, aims to address the overall nature of a structure and how members may experience tensile stresses due to the restraint or other cross-sectional actions resulting in tension beyond the concrete modulus of rupture.

The first objective is to capture framing conditions where the crack development of a concrete member is directly or indirectly affected by the behavior of the neighboring elements or the overall framing system and to suggest detailing to avoid or minimize such cracking. Much of the information presented has been adapted from the work by Aalami and Barth (1988).

35.2 Member Selection

Member shape and frame compatibility are the basic foundations of a performing structure. An example of framing incompatibility would be found in a structure where concrete member sizes or strength requirements are simply out of scale. This can be the case when oversized architectural columns are used to support a thin slab. The restraining effects of oversized members on the surrounding members can be significant. For this reason, it is advisable to maintain compatible member sizes and connections to mitigate restraint cracking during concrete shortening. If geometry or architectural considerations dictate such incompatibility, special consideration should be given to incompatible member connections. Alternatively, incompatible framing geometry can also be addressed using built-up foam sections after the concrete frame is completed to achieve the architectural shapes desired. Frequently, new materials are introduced, whether as composite construction or simply performance-enhancing additives to the concrete mix. The resulting alteration in shortening effects must be understood. For composite construction, such as pan-filled metal decks, construction layout and long-term shortening effects should be evaluated. An important serviceability aspect of concrete material and mixture proportions selection is the resulting shortening behavior for the particular application and geometry.

35.3 Crack Causes and Types

Several factors, when combined, can lead to restraint cracks in two-way reinforced-concrete slabs. Concrete slabs tend to shorten, and structurally stiff elements such as walls, elevator and stairwell cores, and columns can restrain the slab. When the tensile stress exceeds the tensile strength of the concrete, a restraint crack occurs (ACI Committee 224, 1997). Depending on many factors, including the stiffness of the restraining elements and the length of the slab spans, multiple restraint shrinkage cracks may form. The specific factors that cause shortening of concrete slabs include:

- Shrinkage of concrete
- Creep of concrete due to sustained loads (including precompression)
- Elastic shortening (prestressed slabs only)
- Fall in temperature
For a typical parking structure in Southern California with 70% ambient humidity and a moderate temperature variation of 40°F, the contributions of the above factors to slab shortening are as given in Figure 35.1 and Table 35.1. It is noteworthy that two thirds of slab shortening is typically due to concrete shrinkage. Axial creep and elastic shortening, which are the only direct consequences of post-tensioning, contribute about one sixth of the total shortening.

To appreciate the magnitude of shortenings that are likely to occur in a post-tensioned slab, consider the example shown in Figure 35.2. For the 200 × 100-ft slab shown, the shortenings (if free to take place) are estimated to be 0.8 in. per 100 ft of slab length. Obviously, this shortening cannot materialize in most cases, because the slabs are commonly tied to supporting structural elements. The interaction of the slab with its restraining structural elements is the crucial factor in the formation of cracks. Referring to the breakdown of shortenings in Figure 35.2, only 18% of the calculated shortening is due to post-tensioning. The balance is common to nonprestressed as well as post-tensioned slabs. This shows that little difference exists between post-tensioned and nonprestressed slabs as far as crack initiation is concerned; however, crack propagation is fundamentally different between the two types of slabs.
Prominent characteristics of cracks in unbonded post-tensioned slabs as compared to regular reinforced concrete are the following:

- Cracks are fewer in number; instead of a multitude of hairline cracks, fewer cracks form.
- Cracks are generally wider; they are spaced farther apart and generally extend deeper into the slab. In regular reinforced concrete, the spacing between cracks is of the order of slab depth, whereas in post-tensioned slabs it is more related to the span length and the overall dimensions of the slabs. In most cases, crack spacing is more than one quarter of the shorter slab span.
- Cracks are normally longer and continuous, and continuous cracks may extend over one span and beyond. In nonprestressed concrete, cracks are generally shorter in length.
- Cracks commonly do not coincide with locations of maximum moments. Restraining cracks do not necessarily develop at the bottom of midspan or the top of supports where the bending moments are maximum.
- Cracks occur at axially weak locations. Axially weak regions are typically found at construction joints, pour strips, cold joints, paths with reduced discontinuities in slab, and, finally, where precompression is reduced either due to termination of tendons or friction losses in tendons. Figure 35.2 compares typical crack patterns on the soffit of an interior panel of a two-way slab construction. For the regular reinforced-concrete structure, the shrinkage cracks are shown coinciding with the locations of maximum tension.

Unbonded post-tensioned slabs generally exhibit poorer cracking performance as a result of lesser bonded reinforcement, which mobilizes the concrete in the immediate vicinity of a crack. Hence, a series of large slab segments separated by wide cracks rather than well-distributed small cracks is produced unless either the unbonded post-tensioning is accompanied by a sufficient nonprestressed reinforcement or in-plane restraining actions are present that result in a similar improvement of the crack distribution. Examples of common cracks in slabs, columns, and walls due to restrained movement are illustrated below.

Due to the variety of member types and geometry and the array of crack initiation factors, it is imperative that each concrete member be reviewed individually and as part of the overall framing system during the design detailing process. Concentrated load application and vulnerable member joint conditions may require a very localized review of concrete detailing. On the other hand, the overall framing layout may cause indirect load transfer due to geometry or member incompatibility, resulting in concrete cracking based on overall behavior of the framing system. This chapter allows for a localized and overall performance review.

### 35.3.1 Slab Cracks

With regard to the overall crack behavior of a two-way slab, Figure 35.3 shows the crack formation in one of many similar slab conditions investigated by the authors. The example is representative of many slabs having similar crack patterns. The slab is post-tensioned in both directions and designed as a two-way system according to Chapter 18 of ACI 318 (ACI Committee 318, 2005). The precompression provided by the tendons in the longitudinal direction is dissipated into the supporting walls, as the primary transverse cracks extend across the entire width of the slab and through its thickness. The layout in Figure 35.3 demonstrates that the prime cause of cracks is the restraining effect of the perimeter walls. In a slab that is free to move, such as that illustrated in Figure 35.4a, the tendon force (F) is balanced by the precompression developed in the slab. If the slab movement (shortening) is restrained through stiff walls or columns, such as the walls in Figure 35.4b, a part of tendon force F is diverted to the supporting elements. One other major source of overall slab cracks is irregularities in slab geometry. Typical examples of irregularities occurring in slabs are shown in Figure 35.5. If not properly detailed, the discontinuities at the reentrant corners invariably lead to cracks that may extend as far as one quarter to one third of the shorter width at the location of crack. Figure 35.6 shows examples of localized cracks in post-tensioned slabs. The illustrated cracks normally initiate within the first few days after concrete is placed and before the application of post-tensioning.
35.3.2 Column Cracks

Short columns at split levels in parking structures, as illustrated in Figure 35.7, can develop severe cracks and spalling of concrete due to shortening of the parking decks immediately above and below. The same figure shows a release detail with a central dowel for prevention of such cracks. For simplicity, the stirrups in the short column are not shown. Columns tied to half-height walls, as shown in Figure 35.8a, develop cracks similar to those in the short columns described in Figure 35.7. The crack formation is especially severe in beam–slab floor constructions. Provisions of full-height or half-height joints between the walls

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and the columns, illustrated in Figure 35.8, are effective methods of mitigating such cracks. End columns of slabs 150 ft or more in length are particularly susceptible to cracks of the type illustrated in Figure 35.9. The moment generated in the column due to this displacement should be accounted for in the design of such columns.

### 35.3.3 Wall Cracks

Figure 35.10 illustrates the most common crack formation due to the overall behavior of walls tied to post-tensioned slabs. The diagonal tension cracks shown form at the ends of the walls due to the movement of the slab and extend over a region having a length of approximately one to two wall heights from the wall end. Such cracks can be reduced or eliminated by design.
35.4 Crack Mitigation Measures

The principle techniques of crack mitigation are described in the following sections.

35.4.1 Planning the Layout of Restraining Members

The most effective method of restraint-crack prevention is the good selection of wall and column locations during the architectural planning of the building. Equal numbers and lengths of walls may be positioned so as to reduce the tendency of crack formation by allowing the slab to move freely toward a planned point of zero movement (Figure 35.11a). Figure 35.11b shows examples of unfavorably arranged walls and layouts in which the walls impede the free movement, thus creating conditions conducive to crack formation.

35.4.2 Structural Separation

Slabs of irregular geometry are particularly susceptible to cracking. Figure 35.12a shows a small slab area appended to a larger rectangular-shaped region. The structural separation shown in the figure between the two post-tensioned slabs consists of a physical gap between the slabs equal to 0.5 to 1 in. For the particular example shown, it is advisable to continue the slab separation through the supporting walls. The major difference between such structural separations and expansion joints is that the structural separation discussed herein loses its significance after a period of 2 to 3 months, during which time the bulk of the slab shortening takes place. The structural separation does not have to be designed to remain serviceable during the lifetime of the structure. An expansion joint that has been designed to accommodate temperature-induced movements must be detailed to remain operational during the in-service life of the structure. Smaller areas separated by openings or irregular slab geometries, such as the appendix shown in the top right corner of Figure 35.12b, cannot generally follow the overall pattern of shortening.
of the entire slab area. Their connection to the main slab is primarily over short lengths. Stairwells, elevator shafts, and other walls impart substantial restraint against free movement of small slab areas. Moreover, in most cases, it is neither economical nor practical to effectively post-tension small slab areas less than 20 ft in length. The author's practice has been to provide a separation between the two slab areas and construct the detached smaller region as a nonprestressed slab. The structural separation for such conditions need not extend through the supporting walls. Typically, the separation is achieved by placing Styrofoam™ sheets, 0.5 to 0.75 in. thick, vertically between the two slabs.

35.4.3 Closure Strips, Joints, and Favorable Pour Sequencing

A closure strip, also referred to as a pour strip, is a temporary separation of approximately 30 to 36 in. between two regions of slab that will be constructed and post-tensioned separately. Each region is allowed to independently undergo shortening. After a period of typically 30 to 60 days, the gap between the two post-tensioned slab regions (i.e., the closure strip) is closed by placing and consolidating nonshrink concrete. The reinforcement that extends from the concrete slab on each side into the closure strip provides the continuity of the slab over the strip.

The width of a closure strip is determined by the net distance required to position a stressing jack between the two sides of the strip and conclude the stressing operation. The reinforcement across the closure strip is designed on the basis of actions (moments and shears) occurring at the location of the strip when the entire slab is combined in a continuum. Between two adjacent supports, the preferred location of a closure strip is, for regular conditions, at a quarter span where the moments are typically small. Other considerations, however, may dictate the location of a closure strip. The position of the closure strip in relation to the entire slab is discussed at the end of this section. For corrosion protection, it is emphasized that, as a good practice, the stressing ends of the tendons terminating in the closure strip should be cut, sealed, and grouted in the same manner as at the free edges.

The time necessary to keep a closure strip open is determined by the extent of shortening deemed necessary before the two slab regions are tied together. Some engineers specializing in the design of post-tensioned slabs use an empirical value of 0.25 in. as the hypothetical displacement that can be accommodated in a post-tensioned member without apparent impairment of its serviceability. On this premise, a closure concrete should be placed when the calculated balance of shortening on each side of the closure strip is 0.25 in. or less. The shortenings are calculated using standard procedures in which concrete is assumed to be free to move. Obviously, when the closure strip has been poured and the two slab regions have been tied together, the balance of computed shortening referred to cannot take place. This empirical procedure is backed by the satisfactory performance of closure strips in place. It generally leads to closure-strip concreting between 14 to 120 days.

Construction joints are joints at predetermined locations in the slab between two concrete placements. The joints provide a planned temporary break between two slab regions for the purpose of crack control and construction operations. They are also used to subdivide a larger slab area into manageable sizes.
from a construction point of view. A construction joint as shown in Figure 35.13 differs from a cold joint in that (1) its location is determined by design as opposed to the location at which a concrete batch is finished, and (2) a gap of 3 to 7 days commonly occurs between the placement of first pour and the second pour; this time gap is applicable to joints that are designed for crack control. Construction joints may or may not have intermediate stressing. Intermediate stressing of tendons is carried out for long tendons where friction losses are appreciable.

From the performance experience of post-tensioned slabs, the following guidelines for the provision of closure strips or structural separations may be considered:

- If the slab length is less than 250 ft, no closure strip or structural separations are necessary, unless the supporting walls are unfavorably placed.
- If the slab length is longer than 250 ft but less than 375 ft, provide one centrally located closure strip.
- If the slab length is longer than 375 ft, provide a structural separation.

### 35.4.4 Released Connections

Released connections are effective means of crack mitigation when a favorable layout of supporting structural elements or provision of construction separations and closure strips cannot be fully implemented. Released connections are those in which a joint is detailed and constructed so as to permit a limited movement of the slab relative to its support. Released connections may be used in conjunction with closure strips and structural joints. Released connections with successful results are now common practice for post-tensioned slab construction in California. Released connections are grouped into wall/slab release, slab joints, and wall joints.

#### 35.4.4.1 Wall/Slab Release

Figure 35.14 shows several types of commonly used wall/slab connections. To facilitate slippage, a slip material is normally provided at the interface of wall and slab. For simplicity in presentation, the connections shown are for the end walls and a terminating roof slab, but they are equally applicable, with appropriate modifications, to interior walls and intermediate slabs. The connection type with no ties between the slab and its supporting wall (Figure 35.14a) is the most effective release joint, but its application is restricted by the fact that, in many cases, walls must be designed to transfer shear forces, in addition to gravity loading, at their interface with the slabs. Moreover, the stability of the walls due to lateral loads may become a governing consideration. Such releases, where possible, are employed at the corners of the slab areas. It is recommended that the maximum length of a no-tie release be limited.
to the height of the respective wall. A permanent release with a dowel encased in a compressible material is shown in Figure 35.14b. The dowel is provided to impede catastrophic movements of the wall, as in the event of an earthquake. This permanent release detail is used more frequently than the no-tie connection; however, it is more costly and requires greater care during construction. A temporary release as shown in Figure 35.14d is one where the slab is initially constructed released from the wall. After the shortening of the slab has taken place, to the extent that the balance is considered acceptable, the joint is fixed by grouting the pockets.

35.4.4.2 Slab–Column Release
Columns may be designed to withstand the anticipated forces conducive to lateral displacements between their ends without signs of distress or may be released to accommodate relative displacements of slab to column at the joints. The latter option, where applicable, leads to superior slab performance. Several items must be reviewed in arriving at a satisfactory solution. Maximum displacements are typically at the end columns, as shown in Figure 35.15. A detail providing rotational release at the base of the column, as shown in the same figure, may prove adequate. Where columns are excessively bulky, as may be required for architectural reasons, it becomes necessary to provide a detail that accommodates displacements in addition to rotation.

35.4.4.3 Wall Joints
Wall joints are vertical separations between adjacent walls that enable the walls to accommodate displacements of slabs or beams supported by walls. Wall joints are very effective in mitigating cracks in slabs or beams, as well as cracks in the supporting walls themselves. Figure 35.16 shows the plan of a rectangular slab resting on perimeter walls and interior columns. For clarity, the columns are not shown. The wall joints (WJ) provided at the corners of the slab extend through the entire height of the walls. They allow the end wall to move toward the center of the slab without being impeded by the longitudinal
walls. Such wall joints perform best when accompanied by a slip joint between the slab and cross walls as shown in Figure 35.17. The detail shows joints with no ties at the corners which allows the wall shown at left to follow the movement of the slab to the right without interference from the cross wall shown in elevation. The size of the gap is estimated to be 0.75 in. per 100 ft of slab movement accommodated by the wall. Wall joints need not in all cases extend through the entire height of a wall down to the lower level.

35.4.5 Addition or Improved Layout of Mild Reinforcement

In addition to the well-planned layout of shear walls and supporting structures and provision of releases, it is necessary to place additional mild reinforcement at locations of potential distress to mitigate crack formation. Figure 35.18 and Figure 35.19 illustrate examples of typical cases. Figure 35.18 shows reinforcement added next to nonreleased exterior walls. Due to design shear-transfer requirements between a slab and its supporting wall, it might not always be feasible to provide sufficient release details to prevent all cracks. The reinforcement shown in Figure 35.18 has been found to be highly effective for such conditions. The steel is placed parallel to the wall over a width equal to approximately 10 ft normal to the wall. The steel area is determined as 0.0015 times the cross-sectional area of the slab over one third of the transverse span. The bars are spaced alternately at the top and bottom at approximately 1.5 times the slab thickness. Note that this is not a code requirement but rather a practice found to yield satisfactory results for the elimination of potential restraint cracks.
35.4.6 Addition or Improved Layout of Tendons

Figure 35.20 and Figure 35.21 show two conditions where wall restraints can lead to significant losses of precompression in the central region of the slab and consequently lead to formation of cracks. In addition to other measures, such as the releases described in the preceding sections, it is helpful to lay out the tendons so as to deposit additional compression in regions where losses are expected to be highest. Dead ending and overlapping of tendons as illustrated in Figure 35.20 and Figure 35.21 can serve this purpose. The detailing of strand layout around discontinuities and openings is also of importance. Figure 35.22 illustrates two arrangements for tendon layout at an interior opening. The detail on the right shows a common practice where the sides of the opening are pulled apart. Cracks at the corners of such openings are not uncommon. The detail on the left demonstrates an alternative tendon layout, where the opening is provided with an additional precompression ring to counteract crack-precipitating stresses at the corners.

35.5 Crack Evaluation Summary

From a study of crack formation in post-tensioned structures, a number of general conclusions have been formulated, as follows:
Shortening cracks (cracks due to constraint against free movement of the slab) are common in post-tensioned slabs supported on walls and stiff columns. Shortening cracks can be reduced significantly through crack-mitigation measures; the principal crack reduction procedures are:
- Planning for layout of constraints
- Structural separations
- Closure strips, joints, and favorable pour sequencing
- Released connections
- Addition or improved layout of mild reinforcement
- Addition or improved layout of tendons

With regard to implementation of crack-mitigation procedures, the following guidelines are suggested:
1. For small and simple slab geometries (10,000 ft² or less) supported on regular-size columns, design the slab to withstand the forces generated by shortening; it is not generally cost effective to implement crack-mitigation measures.
2. For slabs with substantial restraint, it is necessary to implement crack-mitigation measures.

Most shortening cracks are not structurally significant. The most common cause of shortening of shortening cracks is the exposure of reinforcement and post-tensioning to corrosive elements; aesthetics and leakage are the next most common considerations.

For slabs with significant support restraints, such as perimeter walls, it is often necessary to conduct a one-time maintenance routine to repair shortening cracks. In such cases, notes should be added to the structural drawings indicating the following:
- Shortening cracks are likely to occur.
- Shortening cracks do not normally impair the structural integrity of slabs.
- Slabs should have a one-time crack maintenance operation, which consists of (1) inspecting and evaluating slabs and supporting members 2 years after construction, (2) determining cracks to be repaired, and (3) repairing cracks.

### 35.6 Maintenance

#### 35.6.1 Structural and Preventative Maintenance

The most significant maintenance requirements in concrete structures are those associated with buildings having supported deck slabs and underlying structural frame members exposed to the environment such as open parking structures. Concrete is one of the most durable and low-maintenance construction materials available today; however, these attributes have led some building owners to believe that concrete structures are maintenance free. It is important for the engineer to point out to the contractor and owner that even concrete structures require continuous maintenance to retain the strength and serviceability of
the structure. One effective way to accomplish this is to add appropriate maintenance requirements in the form of general notes on the construction documents. An example of such a reference is provided below:

**Maintenance:**

The entire concrete frame, including elevated slabs, beams, walls, columns, slab-on-ground, and exterior concrete façade, requires continuous maintenance to remain serviceable and safe. Details of the maintenance program applicable to this project must be prepared by the owner (or designated consultant) and submitted to the facility maintenance department for execution. Failure to do so may render the structure nonserviceable or unsafe during the useful lifecycle of the structure. As a guide, the following references may be consulted as minimum requirements: Chapter 9 in *Parking Structures*, by Anthony P. Chrest and Sam Bhuyan (Routledge, 1989); *Guide for Structural Maintenance of Parking Structures* (ACI 362.2R); and *Design, Construction, and Maintenance of Cast-in-Place Post-Tensioned Concrete Parking Structures* (Post-Tensioning Institute, 2001).

When selecting a maintenance program it is necessary to address the strength and serviceability of the structural members. Structural maintenance requirements are those actions necessary to test the integrity of the material components of the structure and member configuration. Preventative maintenance requirements are those actions that improve or enhance serviceability (e.g., waterproofing, corrosion). See Table 35.2 for a summary of maintenance tasks.

**TABLE 35.2 Parking Facility Structural Maintenance: Tasks and Frequencies**

<table>
<thead>
<tr>
<th>Task</th>
<th>Recommended</th>
<th>Minimum</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep</td>
<td>W</td>
<td>M</td>
<td>Power sweep, vacuum, or hand sweep.</td>
</tr>
<tr>
<td>Wash down decks[^a]</td>
<td>S</td>
<td>A</td>
<td>Hose down decks, ramps, and curbs.</td>
</tr>
<tr>
<td>Touch-up deck sealer[^b]</td>
<td>AR</td>
<td>S</td>
<td>Reapply sealer as necessary.</td>
</tr>
<tr>
<td>Check for and evaluate cracks</td>
<td>AR</td>
<td>A</td>
<td>Check for leaks. Rout cracks and fill with sealant. Determine if cracks are structural or nonstructural.</td>
</tr>
<tr>
<td>Check joint sealants</td>
<td>AR</td>
<td>S</td>
<td>Look for leaks, adhesive or cohesive failure, tears, and adjacent concrete failures. Repair on spot basis as required.</td>
</tr>
<tr>
<td>Check isolation joint seals</td>
<td>AR</td>
<td>S</td>
<td>Review for leaks, nosing or gland damage, tears, and punctures. Repair as required.</td>
</tr>
<tr>
<td>Check traffic-bearing membrane[^b]</td>
<td>AR</td>
<td>S</td>
<td>Review wear, tear, blisters, delamination, cracks, and leaks. Repair on spot basis as required.</td>
</tr>
<tr>
<td>Repaint structural steel or exposed metal</td>
<td>AR</td>
<td>A</td>
<td>Inspect for chips, peeling, and rust. Repaint on spot basis. Use special coatings, if required.</td>
</tr>
<tr>
<td>Check for deck surface deterioration</td>
<td>AR</td>
<td>A</td>
<td>Review for cracks, joint edge spalls, scaling, and delaminations. Repair on spot basis, as required. Consult with an engineer if deterioration is extensive.</td>
</tr>
<tr>
<td>Check for water leaks</td>
<td>AR</td>
<td>S</td>
<td>Identify location and source.</td>
</tr>
<tr>
<td>Check for leakage</td>
<td>S</td>
<td>—</td>
<td>Take corrective action as required.</td>
</tr>
<tr>
<td>Inspect deck drain system</td>
<td>M</td>
<td>S</td>
<td>Drains: Remove debris and clean out drain. Drain lines: check for leaks and drainage.</td>
</tr>
<tr>
<td>Check for ponded areas</td>
<td>AR</td>
<td>A</td>
<td>If ponding is evident, consider installing an area drain or reestablishing drainage lines.</td>
</tr>
<tr>
<td>Evaluate condition of previous repairs</td>
<td>AR</td>
<td>A</td>
<td>Evaluate condition of previous repairs; note any additional maintenance required.</td>
</tr>
<tr>
<td>Have a condition survey performed</td>
<td>A</td>
<td>AR</td>
<td>Survey should be performed periodically by a qualified structural engineer as required by conditions.</td>
</tr>
</tbody>
</table>

[^a]: As weather permits.

[^b]: This element should be maintained under warranty or service contract. Check with the manufacturer or authorized representative for terms of coverage.

*Frequency:* W, weekly; A = annually; AR = as required, M = monthly; S, semiannually. For items marked “As Required,” select a maintenance frequency appropriate for the particular element. Perform local repairs or replacement as needed. Special attention should be paid to areas exposed to direct sunlight or high wear, such as entries and exits, ramps, and turning aisles. Review with an engineer if uncertain about structural effects.
35.6.1.1 Concrete Slabs
The most common cause of deterioration of deck slabs and surfaces is the penetration of water and deicing chemicals into and through the slab. Preventive-maintenance measures, such as applying a protective sealer, elastrometric coating, or sealants, are most effective when applied to a new slab. On existing structures with chloride-ion contamination, the ability of a coating or sealer to suppress corrosion will depend on its ability to reduce the moisture content of the concrete. Coatings are normally more effective than sealers in reducing moisture absorption. They will not stop the corrosion completely, however, unless the chloride-ion contamination of the underlying substrate is below the corrosion threshold.

To reduce the impact of progressive deterioration and maintain serviceability, spall delaminations in the deck slab should be evaluated and patched in an appropriate manner. Temporary repairs may sometimes be required because of the time or weather constraints. Temporary repairs can be done with appropriate repair materials until long-term repairs are possible. Tar and asphaltic materials should not be used for temporary patches, however, as these will allow the migration of water and chloride ions into the concrete. Refer to ACI 546 for additional information for guidance on repair options.

Long-term repairs will require removal of all of the deteriorated concrete. Corroded reinforcement should be completely exposed, cleaned, and covered with a corrosion-inhibiting coating. Reinforcing that has lost more than 20 or 25% of its cross-sectional area may require replacement. The repair area should then be patched with an appropriate patching material. If a Portland cement-based material is used for the patches, proper curing is essential to ensure durability.

Cracking is a key cause of more serious deterioration problems in deck slabs. Fine hairline cracks can often be sealed with a low-viscosity silane sealer. Larger cracks should be routed out and sealed with a flexible, traffic-grade sealant (the rout-and-seal method). For numerous, closely spaced cracks, a traffic-bearing membrane should be installed over the area. Before the membrane is installed, the cracks should be routed and sealed or otherwise detailed in accordance with recommendations from the membrane manufacturer. If there are concerns that the cracks compromise the integrity of the structure, they should be evaluated by the engineer of record or a professional engineer with experience in structural restoration.

Ponding can also lead to significant deterioration and leakage problems. Poor finishing of the concrete can result in small areas of local ponding. Large areas of standing water are usually an indication that wither slopes to drains are not adequate or the drains do not have enough capacity. Ponding can usually be corrected by installing supplemental drains. Resurfacing to reestablish proper drainage lines may be required if the problem is widespread. Adding supplemental drains is typically the most economical approach to correct poor drainage situations, however. Refer to ACI 515.1R (ACI Committee 515, 1985) for additional information.

35.6.1.2 Beams, Columns, and Facades
Beam and column deterioration can adversely affect the structural integrity and load-carrying capacity of the structure. Deterioration of these underlying members is primarily caused by water leakage through failed joints and deck slab cracks. The vertical surfaces of columns and exterior concrete facades (spandrel railing) are also susceptible to damage from ponding water and salt splashing from moving vehicles. Beams and columns adjacent to and below expansion joints are especially susceptible to deterioration. Water leakage can contribute to freeze–thaw deterioration, corrosion of reinforcement and connections, rust staining, and leaching. Degradation can be minimized by proper maintenance of the joint sealant systems and application of a sealer or elastomeric membrane to the column bases and spandrel railing. These members are also vulnerable to user damage such as vehicle impact. They should be examined periodically for cracking and spalling. Runoff water that collects along or adjacent to interior face of exterior spandrel walls and columns can contribute to corrosion of exposed steel embedments and exposed reinforcement of these elements. This can lead to unsightly rust staining and, in extreme cases, safety concerns about the load-carrying capacity of the embedded steel. If significant ponding is present, it may be necessary to install a curb or supplemental drain to slope the concrete and move water away from the affected areas.

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35.6.1.3  Stair and Elevator Towers
Leaks often occur at the joints between deck slabs and stair and elevator towers. These leaks are typically due to poor drainage around the towers. If not addressed, these leaks can cause severe deterioration of underlying elements such as metal doors, light fixtures and electrical conduits, metal stairs, exposed structural steel members, and precast connections. Drainage can be improved by providing curbs to divert the water. Frequent inspection and immediate repair of damaged isolation joints between the tower and the deck surface will also reduce the potential for deterioration. Masonry walls should typically be sealed. If a masonry wall is exposed to the weather, however, nonbreathing paints should not be used on both sides as this will tend to trap water and cause the paint to peel. Stair and elevator wall cracking should be repaired, as appropriate, to minimize moisture penetration.

35.6.1.4  Exposed Metals
An exposed concrete frame such as a parking structure may have exposed metals in the form of stairs, pedestrian railings, vehicular guardrails, precast connections, columns, or beams. Exposed metals should be visually monitored on a regular basis. Premature deterioration of metal components can be the result of atmospheric exposure, neglect, or chemical reactions between metals. Galvanic processes between two dissimilar materials such as aluminum and mild steel at a connection may cause especially severe corrosion. Treatment of metals with a proper surface preparation and appropriate paint or anticorrosion coatings will help minimize corrosion and resultant problems. Metal pan stairs with concrete infill are particularly susceptible to corrosion-related deterioration. They are not recommended in areas that use deicing salts.

35.6.2  Operational and Aesthetics Maintenance
Operational maintenance involves the regular inspection, repair, and maintenance required to keep the structure functional for its intended users. It includes housekeeping tasks such as routine cleaning, sweeping and wash-downs, snowplowing, and ice control.

35.6.2.1  Housekeeping Requirements
Routine cleaning is one of the most important aspects of good housekeeping. A clean environment makes the concrete structure more pleasant, reduces required maintenance, and extends service life. Sweeping, for example, should be done at least monthly and can be done with hand brooms, mechanized sweepers, or vacuums designed for use in parking structures. All dirt and debris should be removed from the facility. Special attention should be paid to keeping dirt and debris out of drain basins, pipes, expansion joints, and other openings. Grease buildups should be removed regularly using appropriate degreasers. In freezing climates, road salts will accumulate over the winter months. They should be removed each spring by flushing the surface with large volumes of water at low to moderate pressure. A second wash-down is recommended in the fall to remove surface debris and contaminants. Parking structures should be equipped so a 1.5-in.-diameter hose can be used to wash the deck. Areas that tend to get a higher buildup of salt such as entrances and exits and flat or ponded areas should be washed more frequently. Care should be taken not to damage joint sealants, expansion joints, or deck coating materials. Drains should be flushed carefully to avoid plugging the drainage system with sand, dirt, and debris.

35.6.2.2  Snow Removal and Ice Control
Snowplows can damage joint sealants, isolation joint seals, and concrete traffic-deck coatings. Columns, curbs, walls, and even the decks themselves can be damaged by snow removal activities. Care should be taken to use equipment that had been properly adapted to avoid direct contact with the structure. Rubber-tipped snowplow blades are one solution to this problem. All isolation joints should be marked and pointed out to the snowplow operator. Hand removal may be necessary in certain areas to avoid damage to the seals. Piling snow on the deck slab is not permissible. Packed snow can be heavy and may exceed the load capacity of the deck and contribute to cracking. Piles of snow may also create a reservoir of salt-
contaminated water that contributes to leakage and chloride buildup. Deicing chemicals are used to control ice buildup and reduce slipping and skidding hazards; however, most common chemical deicers can damage the concrete or reinforcing steel, and they should be used with caution. Calcium magnesium acetate (CMA) is considered to be less corrosive than common road salt or calcium chloride. Care should also be taken to ensure that any deicers used comply with local health and environmental codes.

### 35.6.2.3 Other Operational Maintenance

A parking structure has a number of operational systems. These include mechanical and electrical systems, lighting, elevators, signage, parking control equipment, security systems, graphics, and striping. Although they typically do not affect structural performance, it is sometimes cost effective to coordinate the maintenance or updating of these systems with structural maintenance. Refer to the *Parking Garage Maintenance Manual* (Parking Consultants Council, 2004) for additional information.

### 35.6.2.4 Aesthetics-Related Maintenance

Maintenance must address the aesthetic as well as structural and operational aspects features of a concrete structure. Aesthetics includes items such as landscaping, painting, and general appearance. Patrons appreciate a clean facility and are more inclined to treat it properly, which can ultimately reduce repair costs.

### 35.6.3 Checklist for Structural Inspection

A regular visual inspection of the structural and waterproofing components of the parking structure is an essential element of a preventive maintenance program. The inspection should be conducted in conjunction with a wash-down of the structure so any active leakage can be noted. The structure should be inspected systematically and the nature, location, and severity of any observed problems recorded. It is helpful to have a notebook-sized plan of each floor to use as a base sheet for taking notes during the inspection. In addition, it is helpful to develop a system of marks for use in representing various conditions while taking field notes. A digital camera or videocamera can be of great assistance in documenting developing problems. While most problems can be observed by a layperson familiar with the structure, an inspection should be performed by a qualified engineer every few years or when new or significant changes in deterioration are observed. Visual inspection of the parking structure should include the following items. (Any “Yes” answers should be followed up with action to remedy the situation.)

#### Deck

| Yes □ No □ | Are there any cracks? |
| □ □        | If so, do they leak? |
| □ □        | Is the surface sound (or are there areas where surface scaling is present)? |
| □ □        | Is there any evidence of corrosion of reinforcing steel or surface spalling? |
| □ □        | Is there any evidence of corrosion of exposed metals? |
| □ □        | Is there any evidence of concrete delamination? |
| □ □        | Is any steel reinforcing exposed? |
| □ □        | Are there any signs of leakage? (Describe conditions and note location.) |
| □ □        | If there is a traffic-bearing membrane, are there any tears, cracks, or loss of adhesion? |
| □ □        | Are there low spots where ponding occurs? |
| □ □        | Has the concrete been tested for chloride ion content? (When was it last monitored? Are there records available?) |

___________ When was the deck last sealed?

#### Beams and Columns

| Yes □ No □ | Are there any cracks? (If so, are they vertical or horizontal; how long and wide?) |
| □ □        | Are there any signs of leakage? (Describe conditions and note location.) |
| □ □        | Is there any concrete spalling? |
| □ □        | Is any steel reinforcement exposed? |
Stair and Elevator Towers
Yes ☐ No ☐ Are there any signs of a leaking roof?
Yes ☐ No ☐ Are there any cracks in the exterior finish?
Yes ☐ No ☐ Is any other corrective action required?

Isolation Joints
Yes ☐ No ☐ Are there any leaks through isolation joint seals?
Yes ☐ No ☐ If so, are they related to seal failure or failure of the adjacent concrete?
Yes ☐ No ☐ Could the cause of these leaks be snowplows?
What type of isolation joint seal is it? Who is the manufacturer?
Yes ☐ No ☐ Is there any isolation joint warranty in force? (Consult with the manufacturer for repair recommendations.)

Joint Sealants
Yes ☐ No ☐ Are there any signs of leakage, loss of elastic properties, separation from adjacent substrates, or cohesive failure of the sealant?
Yes ☐ No ☐ Are there any failures of the concrete behind the sealant (edge spalls)?

Exposed Steel
Yes ☐ No ☐ Is there any exposed steel (structural beams, handrails, door frames, barrier cable, exposed structural connections)?
Yes ☐ No ☐ Is rust visible on any exposed steel?
Yes ☐ No ☐ If so, is it surface rust?
Yes ☐ No ☐ Is there significant loss of section due to the rust?
Yes ☐ No ☐ Is repainting required?

Drains
Yes ☐ No ☐ Are the drains functioning properly? (When were they last cleaned out?)
Yes ☐ No ☐ Are the drains properly located so they receive the runoff as intended?

Previous Repairs
Yes ☐ No ☐ Are previous repairs performing satisfactorily?

References
ACI. 2007. Manual of Concrete Practice. American Concrete Institute, Farmington Hills, MI.
ACI Committee 224. 1997. Cracking of Concrete Members in Direct Tension, ACI 224.2R. American Concrete Institute, Farmington Hills, MI, 12 pp.
ACI Committee 224. 2001. Control of Cracking in Concrete Structure, ACI 224R. American Concrete Institute, Farmington Hills, MI, 46 pp.
ACI Committee 318. 2005. Building Code Requirements for Structural Concrete and Commentary, ACI 318. American Concrete Institute, Farmington Hills, MI.
ACI Committee 515. 1985. Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete, ACI 515.1R. American Concrete Institute, Farmington Hills, MI.
Cracking Mitigation and Maintenance Considerations


Litvan, G. and Bickley, J. 1987. Durability of Parking Structures, Analysis of Field Survey, ACI SP 100-76. American Concrete Institute, Farmington Hills, MI.


Suarez, M.G. and Posten, R.W. 1990. Evaluation of the Condition of a Post-Tensioned Concrete Parking Structure after 15 Years of Service. Post-Tensioning Institute, Phoenix, AZ.

(a) Sunshine Skyway Bridge across Tampa Bay, Florida, a 4.2-mile-long, segmented, prestressed, cable-stayed bridge that is one of the longest in the world. (b) Trump Towers in New York City, built using 12,000-psi silica fume concrete. (Photographs courtesy of the Portland Cement Association, Skokie, IL.)