Parking Structure Damage

Investigation and repair restores structure to service

BY SCOTT M. ADAN AND RENÉ W. LUFT

One morning, upon discovering severe slab cracking, visible deflection, and a partially collapsed slab, the owner of a Northern California parking garage contracted with us to investigate and determine a course of action. Originally constructed in the early 1970s, the L-shaped garage has two parking levels—one a slab-on-ground and the other a roof slab. The upper level is constructed of cast-in-place, sand-lightweight concrete and is post-tensioned with paper-wrapped unbonded tendons. The slab is 4 in. (100 mm) thick and spans between transverse post-tensioned concrete beams spaced at 18 ft (5.4 m) on center (Fig. 1). The cracking and deflection occurred in only one wing of the L. The partial collapse resulted in a 4 x 5 ft (1.2 x 1.5 m) hole in the slab (Fig. 2), but the failure did not rupture the tendon strands.

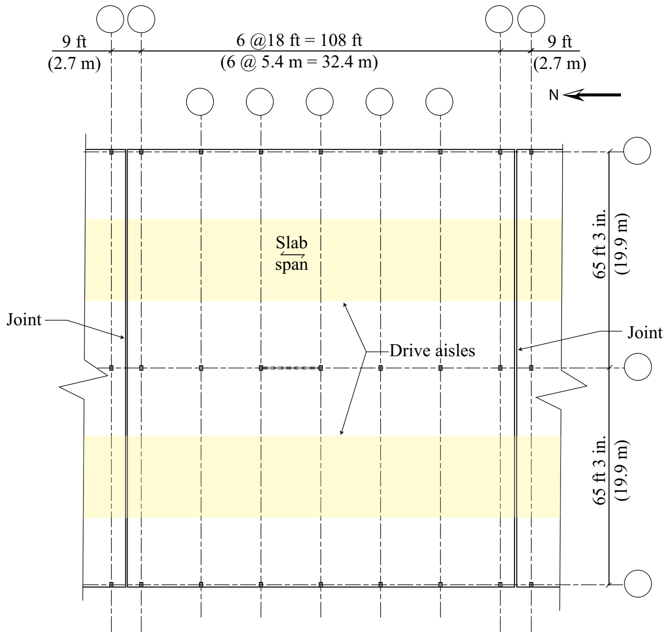

Fig. 1: Schematic plan of deck bays between expansion joints. Post-tensioning strand anchorage strips are located near the joints. Transverse post-tensioned beams are at the east-west grid lines

Surrounding the hole and at numerous other locations, we found severe slab cracking and deflection. Due to the extent of damage, the local building department "red-tagged" the structure and the entire garage was subsequently taken out of service. We also recommended that the owner have shoring installed around the hole.

Structural damage is normally associated with long-term degradation or a one-time extreme event. In this case, the evidence pointed toward a one-time overload. Cracking and deflection were concentrated in some of the drive aisles, but the garage appeared to be in good condition outside of those aisles. In particular, we found no damage in the second wing of the garage.

Each of the affected slabs had extensive cracking, both at midspan and near supporting beams (Fig. 3). In many of these spans, we measured maximum slab deflections of about 3 to 4 in. (75 to 100 mm) between beams. There was, however, no indication that post-tensioning tendons had ruptured.

Fig. 2: Cracked and partially collapsed concrete slab showing exposed post-tensioning strands

Fig. 3: Slab cracking at the edge of a supporting transverse beam below

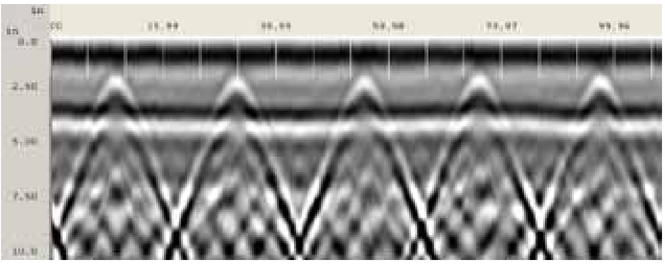

Fig. 4: Ground penetrating radar (GPR) was used to evaluate slab thickness and reinforcing bar locations

DETAILED ASSESSMENT

Following our initial investigation, we undertook a detailed assessment to establish the proximate cause of the damage and define repairs while considering long-term durability issues.[1] Tests of core samples established that the physical properties of the concrete, including density, compressive strength, and tensile strength, were within acceptable ranges. Powder samples indicated that the chloride ion content in the concrete was moderate but acceptable. Petrographic analyses provided no evidence of corrosion staining, long-term deterioration, alkali-silica reaction, sulfate attack, or other adverse expansive chemical reactions. Based on these findings, we determined the existing concrete to be in relatively good and reusable condition.

We had no information on post-tensioning reinforcement as the available partial set of construction drawings contained architectural but no structural drawings. To determine the extent and location of the reinforcement, we surveyed the slabs with ground-penetrating radar (GPR) (Fig. 4). Data from the GPR surveys were verified using limited destructive tests, allowing us to determine the size, depth, drape, and spacing of the tendons.

We removed the grout and concrete around one of the anchorage strips to investigate the physical condition of the tendon anchors and perform lift-off testing. In our limited sampling of tendons, we found no evidence of corrosion and no ruptured tendons. The lift-off readings indicated that the existing tendons were capable of being reseated at higher stress levels.

Using the in-place concrete strength values and gathered reinforcement information, we were able to analyze the structural capacity of the existing slab. Our analyses showed that the undamaged sections of the slab retained adequate capacity to carry code-prescribed loading at the time of design. However, to return the damaged drive aisles to their predeflected position and to provide a continued long-term service life, the slabs required repair and strengthening.

REPAIR SCHEMES

Upon completion of our investigative phase, we proposed several repair schemes, including:

- Complete removal and replacement of the upper level slab;
- Selective replacement of severely cracked or collapsed slabs, epoxy injection of other cracks, and application of fiber-reinforced polymer reinforcement to other damaged slabs; or
- Selective replacement of severely cracked or collapsed slabs, epoxy injection of other cracks, installation of external post-tensioning of the slabs, and reseating the existing tendons to a higher tension level.

Cost and implementation speed advantages led the owner and contractor to select the third scheme.

Our design called for the addition of six 1/2 in. (13 mm) diameter post-tensioning strands in an inverted king post truss configuration below each of the affected drive aisle slabs. The strand profile was selected to apply an upward reaction at the slab midspan and transfer the vertical force to the supporting beams at holes traversing their webs near the slab soffit. To avoid eccentricity at anchorage locations, the strand anchors were positioned at middepth of the slab in precut slots (Fig. 5). This also allowed the tendons to be anchored adjacent to the existing anchorages.

Although external post-tensioning of beams is a well-established technique, external post-tensioning of a thin slab presents challenges. The magnitude of the upward reaction was selected to lift the slab to its original elevation relative to the beams. To avoid a high concentrated load at each strand deflection point, a continuous hollow structural section (HSS) deviator was used (Fig. 6 and 7) to distribute reactions uniformly to the slab. The HSS also simplified construction by reducing the corresponding number of center post attachments. To prevent abrasion on the HSS surface, a prefabricated high-density polyethylene saddle was fitted at each strand intersection (Fig. 8). Each saddle could be field-

Fig. 5: Existing tendon anchors (lower right) were exposed to allow reseating. Here, a slot has also been provided to allow an external tendon to be anchored at middepth of the slab, near the existing tendon anchors

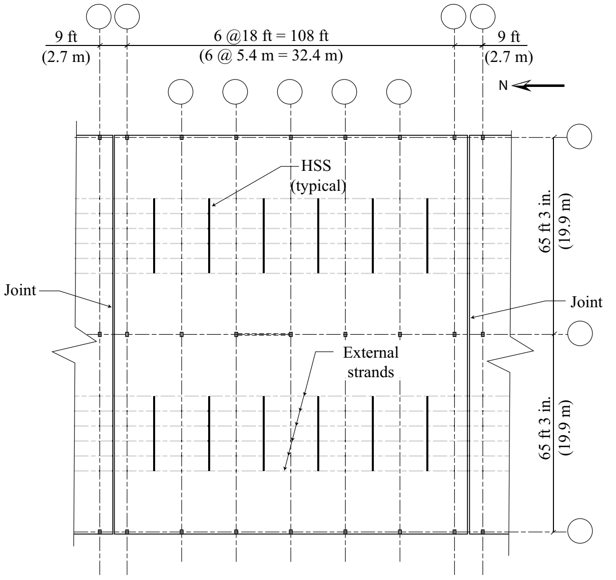

Fig. 6: Typical locations of HSS deviators and external post-tensioning strands

Fig. 7: HSS deviators were fastened to the slab soffit at the midspan of the slab. Post-tensioning strand traversed the beam webs near the slab soffit elevations and passed below high-density polyethylene saddles at the HSS

Fig. 8: Detailed view of HSS deviator, high-density polyethylene saddle, and galvanized strand

adjusted to match the location of the external tendon.

Normally, the deformation of highly deflected slabs is associated with creep, and releveling is not considered feasible. In this case, however, we believed the deflection was associated with cracking caused by a brief overload. We anticipated that the external post-tensioning would reverse the slab deflection as well as close the cracks. This was confirmed during construction.

Our analysis considered the external tendons as secondary reinforcement to strengthen and relevel the deflected slab. We determined that the existing slab was capable of carrying the code-prescribed loading, so fireproofing the tendons was not required. To protect against corrosion, however, we did require galvanized strand.

Our proposed repair scheme was not a commonly implemented one. To manage the risk of unforeseen problems, we required that a mock-up of the repair be constructed on a smaller subsection of the garage. Following our inspection and assessment of the completed mock-up, the scope of the repair could be evaluated and modified prior to proceeding with its full implementation.

REPAIR IMPLEMENTATION

Prior to implementing the repairs, the contractor shored the drive aisle of every affected slab. Existing tendon anchors were then exposed by removing strips of grout and concrete.

As planned, external tendon installation and repairs were first implemented on the designated mock-up. The contractor measured slab deflections in each of the shored spans prior to stressing the tendons. All the tendons were then stressed and, upon remeasuring, it was verified that the applied forces had closed the cracks and returned the slabs to their predeflected position. Following our evaluation of the mock-up, we directed the contractor to implement repairs on the remaining affected slab sections.

Areas of slabs showing severe damage were removed. Prior to the placement of new concrete, holes were drilled

Fig. 9: In areas with severe damage, unsound slab concrete was removed and replaced. Here, reinforcing dowels have been anchored into the existing slab and exposed strands have been wrapped to prevent bonding with the new concrete

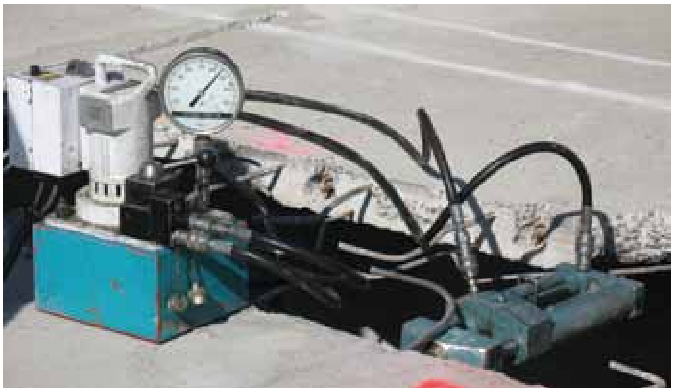

Fig. 10: Reseating an existing tendon anchorage. A slot for an external tendon is visible behind the pump

in the vertical faces of the repair area and reinforcing dowels were anchored with epoxy adhesive (Fig. 9) to tie the new concrete to the existing slab. Also, exposed strands were wrapped with tape to prevent bonding with the new concrete. In less severely damaged areas, cracks were repaired using epoxy injection. To verify tendon integrity and tension, the contractor reseated the existing strands at a higher tension level (Fig. 10). Remarkably, during the reseating process, only one strand was found to be ruptured. The contractor removed and replaced the ruptured strand by welding a new strand to the existing strand and pulling the existing strand at the opposite end.

Following the reseating of the existing strand and stressing of the external tendons, the contractor replaced the concrete in the anchorage strips and epoxy-injected all remaining cracks. Finally, the contractor installed vehicle access control devices or "headache bars" at each parking garage entry point to warn oversized vehicles against access.

RESTORED TO SERVICE

Our investigation of the damaged garage indicated that the concrete structure was in good condition but certainly in need of repair. By using external post-tensioning, we were able to provide a cost effective repair solution with relatively minor structural modifications. In the process, we were able to restore the garage to its original level of structural capacity while eliminating excessive deflection in the slabs.

A BAD MIX

Several months after the damage occurred and while repairs were underway, a witness came forward and reported that a loaded concrete truck had accessed the upper level of the structure (prior to the repair, the garage had no vehicle height barriers to prevent such an occurrence). Reportedly, the truck circumnavigated a large portion of the deck, explaining why the damage was primarily concentrated in the drive aisles. The axle load imposed by such trucks typically would be much higher than the code-prescribed loads and can (as in this case) cause serious damage.

References

1. ACI Committee 362, "Guide for the Design of Durable Parking Structures (ACI 362.1R-97)," American Concrete Institute, Farmington Hills, MI, 2002, pp. 4-29.

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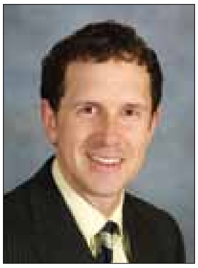

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