Garage No. 49 Post-Tensioned Slab Repairs

Constructed in 1988, Garage No. 49 extends five levels below grade. Each level consists of approximately four main parking regions, made up of flat sections around the perimeter, with two central ramps. The total square footage of the elevated levels is approximately 275,000 ft^2 (25,550 m^2).

The structural system of the parking garage is a long-span, post-tensioned concrete slab and beams, supported by reinforced concrete columns with spread footing foundations. The concrete floor slabs are approximately 5 in. (13 cm) thick; they were designed as one-way slabs, reinforced with post-tensioned tendons as well as a nominal number of conventional reinforcing bars. Most of the concrete post-tensioned beams supporting the slabs are 24 x 30 in. (61 x 76 cm), spaced 17 ft (5 m) apart, framing directly into the columns. Along with the main profiled tendons running perpendicular to the beams, each slab section between beams also contains four individual post-tensioned tendons in the longitudinal direction at middepth to control thermal stresses.

The post-tensioned system specified in the original structural plans for the slabs and beams was an unbonded monostrand tendon system using seven-wire low relaxation strand steel of 270 ksi (1862 MPa) strength, conforming to ASTM A416.

The slabs had continuous pour strips that were cast after tendons on both sides of the strip were stressed. These pour strips did not have any post-tensioned force and were reinforced with only mild reinforcing steel. Dowels extending from each side of the strip provided the anchorage for the 3 ft (0.9 m) wide slab section. In addition, the pour strip was supported on a 1.5 in. (3.8 cm) ledge cast into the two adjacent edges of the slab.

Construction joints were used in the slabs at each intermediate stressing line. To stress post-tensioned tendons at the construction joint, stressing anchors were cast into the slab edge at the joint. Although the uniform post-tensioned tendons pass through the joint, the original design details did not specify any mild steel reinforcing dowels across the joint. Intermittent concrete keys were specified to transfer slab shear forces from one side of the construction joint to the other.

Excessive Cracking

In 2004, the owner authorized an engineer to perform an investigative study of excessive concrete slab cracking observed on the uppermost parking tier. Early in the survey, a section of the slab along a construction joint, normally used as an intermediate stressing point, was observed to have severely deflected with respect to the abutting slab at the joint. Post-tensioned tendons across the joint at the deflected slab were all determined to be broken, leading to immediate partial closure of the parking level due to safety concerns. An exploratory investigation of the remaining three elevated levels of the garage revealed similar results.

Further investigation showed that the leading factors related to the slab displacement were noted on each of the six elevated ramps throughout the garage.

Cause of Failure at Intermediate Stressing Joints

At the construction joints, the intermittent shear keys were found to be structurally deficient and prone to shear fatigue failure. Design details showed the concrete shear keys to be rectangular keys, approximately 24 in. (61 cm) long, installed intermittently between tendon anchorages at the construction joint. In actuality, the shear keys were 12 in. (30 cm) long, with a triangular profile, and appeared to have been installed too low within the slab, not at middepth as intended.

Example of existing conditions of spalled and/or loose concrete present behind existing intermediate anchors

Fracture surfaces from tendon and anchor samples sent for tensile and forensic testing

Typical full depth demolition of 6 ft (1.8 m) slab section at the existing intermediate anchors

The hypothesis behind the demise of the construction shear keys is that the keyway was positioned too low in the slab section at the joint to be effective. The section of slab concrete below the keyway acting in shear was structurally weaker than the shear key itself, and quite inadequate to transfer shear forces. If the slab had been detailed where its top and bottom reinforcing extended through the construction joint, or alternatively, if there had been dowels through the joint, the reinforcing could have been able to sustain the shear forces in shear-friction, without overloading the post-tensioned tendons. For example, the existing pour strips, which are also stressing points, do have additional reinforcing bars passing through them, together with a more effective type of shear key, and have not experienced structural problems. At the construction joints, however, upon failure of either the concrete below the shear key or the shear key itself, the gravity forces at the construction joint interface are automatically transferred to the tendons, overstressing them, and causing tendon rupture. Most, if not all, broken tendons occurred in the vicinity of cracked or failed shear keys.

In-place test results indicated that tensile overloading was the most likely cause of the broken tendons in the slab. Although the outer wires failed along the primary shear plane at an angle to the wire axis, shear failure was not the direct cause of the breakage. The additional vertical force component imposed on the tendons due to the slab weight and service loads increased the tension force in the tendons beyond their capacity, resulting in tendon breakage. It is likely that the shear key failures and tendon breakages had developed in a progressively deteriorating manner over a period of time.

Analysis showed that the shear forces involved would easily increase the tensile force in each tendon to beyond its ultimate tensile capacity, causing rupture of the tendon, especially because the tendons were already experiencing outer diameter damage from the wedges biting into the individual wires. As failure of the individual outer wires took place, the inner wires had to carry the full effective post-tensioned force in addition to the overload from the deflected slab and traffic wheel loading. These wires broke gradually as evidenced by the necking and ductile failure of the inner group of wire within each strand.

Post-Tensioned Cable Repairs

Project specifications for full scale post-tensioned repairs throughout the garage were issued in June 2005 with the contract being awarded and mobilization taking place in late October of the same year.

Twelve construction joint locations were identified on the six elevated ramps as requiring post-tensioned repairs, one joint location on each of the east ramps and three joint locations on each of the west ramps. The locations of existing construction joints and pour strips would allow for all of the necessary repairs to take place within the boundaries of the ramps—the flow of traffic throughout the garage would not be impacted.

The repair approach was to create a new pour strip location at each of the intermediate construction joint locations where the structural integrity of the slab had been compromised. The existing post-tensioned cables were exposed at the intermediate stressing location and a 6 ft (1.8 m) width of concrete adjacent to the construction joint was demolished through the full thickness of the slab. The exposed post-tensioned cables were slowly detensioned behind the anchor to create two individual tendon sections. The first section maintained its post-tensioned force, being bound between the existing intermediate and end anchors, whereas the second section was completely destressed yet still anchored at one end by a second

Typical prepour layout of reprofiled tendons, new pour strip and, where necessary, the 1 ft (0.3 m) anchor strip at the location of the previous intermediate anchors

intermediate anchor. The original post-tensioned cable was then reprofiled within the first 3 ft (0.9 m) section and a new live-end anchor was installed. A new conventionally reinforced pour strip was then created within the remaining 3 ft (0.9 m) section. New keyways with dowels were included in the design of the new pour strips.

Once the existing intermediate anchors were exposed, more extensive concrete damage and anchor deterioration was observed along the construction joint where the anchors were scheduled to remain intact and undisturbed. In some locations, concrete deterioration had extended beyond the keyway at the joint and sections of concrete located in front of the anchors were either loose or had spalled. Some anchors also showed signs of excessive corrosion. As this section of cable extended beyond the ramp and across an active drive lane, additional repairs needed to be performed to adequately support the drive lane and return sufficient post-tensioned force to this region.

Due to the layout of the garage, closing a section of the drive lane located immediately at the base or head of any ramp would create blind turn around areas within the garage and possibly lead to accidents and/or traffic back-up within the garage. Therefore, to address these areas, lock-off devices were used to provide a temporary stress to approximately 25 uniform tendons at a time spanning across the drive lane while new cable sections were being spliced to the existing tendons with dogbone couplers and new anchors.

Exterior view of the main garage entrance after the urethane-based waterproofing membrane was applied

Intermediate parking deck where the urethane-based waterproofing membrane was applied after the post-tensioning repairs were completed

Even with all the unforeseen conditions leading to additional repairs, the contractor was able to complete all structural repairs by November 2006 and the associated waterproofing membrane application by April 2007, completing the project only 3 months past the initial completion date and only approximately 10% over the original contract cost.

Garage No. 49

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