Structural Strengthening Using External Post-Tensioning Systems

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The primary reasons for the strengthening of concrete structures are typically to increase existing elements' capacity to carry new loads or to resolve an existing deficiency. Several strengthening techniques such as section enlargement, externally bonded fiber reinforced polymer (FRP) reinforcement, supplemental steel elements, and post-tensioning can be employed to increase the load carrying capacity and improve serviceability of existing structures. However, there are many technical factors that should be considered when selecting a strengthening system. In addition to technical concerns such as serviceability, strength, durability, appearance, and fire rating, one should consider non-technical factors such as constructability, aesthetics and cost.

Strengthening systems can be classified into two categories: *passive systems* and *active systems*. Passive strengthening systems do not introduce forces to the structure or its components. Passive systems, such as steel reinforced concrete enlargement and the addition of structural steel elements, contribute to load sharing and the overall resistance of the member when it deforms under external loads. As such, the effectiveness and load sharing of passive systems significantly affects their axial and bending stiffness. Other examples of passive strengthening systems include the use of bonded steel plates and externally bonded FRP.

Active strengthening systems, such as external post-tensioning (PT), involve the introduction of external forces to the structural elements that would offset part or all of the effects of external loads. For example, new post-tensioned monostrands can be profiled along the span of an existing beam to produce uplift at mid-span that can be utilized to offset existing strength deficiency or allow the member to support additional load. Active systems are usually engaged in load sharing immediately after installation, and can provide strength increase and instantaneously improve the service performance such as by reducing tensile stresses (or cracking) and deflections. Strengthening with PT is particularly effective and economical for long-span beams and cantilevered members, and has been employed with great success to increase the bending and shear resistance and correct excessive deflections.

This article presents a general description and design considerations for the use of external post-tensioned system to restore or strengthen existing concrete structural members. The use of this technique is further demonstrated through a case study for two prestressed beams, supporting the top level of a parking structure, that were repaired using external PT.

Completing surface preparation, steel/dowel placement and PT placement.

How Does It Work?

Post-tensioning is the introduction of external forces to the structural member using high strength cables, strands or bars. The PT reinforcement is connected to the existing member at anchor points, typically located at the ends of the member, and profiled along the span at strategically located high and low points. When stressed, the tendons will produce upward forces (at low points) or downward forces (at high points) to create reverse loading on the member.

PT strengthening systems can be classified into two categories, *external* and *internal*. External PT involves exposed cables or steel bars that are anchored directly to the structure. Because the reinforcement is located outside the member, its use can be limited by fire rating and durability requirements. To improve durability, systems consisting of sheathed cables and coated anchors can be used. Alternately, the external cables can be placed inside plastic ducts and then filled with cementitious grout.

An internal PT system, on the other hand, consists of PT reinforcement that is placed inside the original member. It can be achieved by placing the new PT reinforcement in cores made along the axis of the member, trenches chipped along the span of the member, or by placing the reinforcement in a new concrete enlargement bonded to the existing member. The latter is typically more effective where a relatively large increase in strength and/or stiffness is required. An internal PT system can also address all fire rating and durability concerns. The following sections will discuss the design consideration of PT strengthening system placed in a new concrete jacket.

Failed PT beam due to snow overload.

What Do We Know About The Structure?

As with any repair or strengthening project, the first step in developing a PT solution is to establish a good understanding of the existing structure and its condition through a structural condition assessment. Once the assessment is completed, analysis can be performed and used to determine the existing (or residual) load capacity of various structural elements. The capacity results are then compared with new demands, and used to establish the type and magnitude of existing deficiencies for each member and the required level of upgrade to resolve them.

It's All About Anchorage

Tendons have an anchor at each end that consists of a bearing plate to transfer the tendon force to the concrete, as well as to stress the tendon. The end at which the PT reinforcement is stressed is referred to as the "live end," while the other end is known as the "dead end." Stressing of PT cables is usually achieved using hydraulic jacks.

The assembly of anchors from multiple cables, typically located at an end of the member, is referred to as the anchor zone. The force in stressed tendons is transferred from the anchors to the new concrete jacket through bearing, and from the new concrete to the existing structural member through shear friction. The designer should provide the proper amount of mild steel reinforcement to address all bearing and bursting forces created in the anchor zones. Concrete surface profiling and steel dowels should be designed and detailed to transfer horizontal shear forces at the interface of the existing concrete to the new concrete, therefore produce the desired composite behavior.

In general, most existing theories and guidelines for the detailing of anchor zones in new construction can be utilized for anchor zones in concrete enlargements. However, sound engineering principles should be used when modifying current standards to accommodate the case of PT enlargement.

Key Considerations for PT Strengthening Design

There are several design, detailing, durability, and construction issues that need to be considered when designing a PT strengthening system. Whether internal or external, the effects of the new forces being introduced to the structural element must be carefully evaluated. Anchor zones should be carefully designed and detailed to ensure effective transfer of forces from the post-tensioning system to the structure without failure. A combination of surface preparation, concrete placement, and mechanical or adhesive bonded anchors can be used to achieve the required horizontal shear transfer. The designer must evaluate the effects of any existing reinforcement (mild and prestressed) that may be interrupted or severed while installing the new strengthening system. Also, modification to existing member geometry and reinforcement must be accounted for in the design of the strengthening system. X-ray or ground penetration radar (GPR) are non-destructive techniques that can be used to map the existing reinforcement before finalizing the layout of the PT system.

Any existing damage, deterioration, or corrosion of the existing member should also be addressed prior to the installation of the PT system. Most available repair guidelines require that existing large cracks be epoxy-injected, steel corrosion treated, and concrete spalls properly repaired to ensure that the new post-tensioning force is uniformly distributed on the enlarged section of the member.

Strength or Service Improvement?

There are three main factors that can influence the final design of the PT system: increase in strength, service stress limits, and the ability to transfer the PT force to the member. While in most cases the system is designed to achieve a target strength increase, care should be taken not to overstress the member in use. For example, excessive uplift can produce high tensile stresses and can cause cracking, especially when no live load is acting on the member. Increasing the amount of the PT force can also make it difficult to transfer the force to the member without using a complex anchorage system. In these cases, the combination of PT and mild steel reinforcement can be used to achieve a balance between the desired strength increase and service stresses, while reducing the PT force to an acceptable limit. The designer generally will have to try different combinations of PT force, profile, size of section enlargement, and amount of mild steel to achieve the final solution.

New post-tensioned enlargement on a bridge pier.

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Fire Considerations

Performance of the strengthened element under fire must be evaluated and the system must be detailed to provide the code-specified fire rating. Structures strengthened with PT to carry significantly higher loads may require more stringent fire rating. Compared with external PT systems, internal systems have the inherent benefit of full encapsulation in concrete. A proper fire rating can therefore be easily achieved by selecting the appropriate concrete cover thickness.

Form-and-Pump! Do Not Cast!

Form-and-pump is a concrete placement technique that consists of a multi-step process of surface preparation, formwork installation, and pumping of repair material into the cavity confined by formwork and existing concrete surfaces. The forms are typically pressurized to 10-12 psi which would force the new concrete into the pores of the existing concrete surfaces, therefore enhancing the chemical and mechanical bonds. Form pressurization will also consolidate the repair material and provide full encapsulation of exposed and new reinforcement. Without full bond of the new concrete jacket to the existing concrete, no composite action will be achieved and the new section will not perform as designed. To achieve the right bond, the surface must be profiled to produce ¼-inch amplitude and the concrete pores should be opened using sandblasting or pressure washing. The use of self-consolidating concrete (SCC) is preferred for this technique since the high flowability of SCC allows for better concrete consolidation and flow into the steel congested areas, especially the anchor zones. While constructability of the repair materials requires good pumpability and flowability, other characteristics such as low drying shrinkage (which can cause cracking, delamination, and reduced durability and load transfer) should be considered.

Case Study

During the spring of 2007, external PT was used to strengthen two damaged PT beams at a government facility parking structure in the Washington D.C. area. The garage is a six-story, freestanding, post-tensioned structure with approximately 500,000 square feet of parking area. The typical deck consists of one-way PT slabs supported on long span PT beams. Failure of two beams was caused by the snow removal contractor who piled a significant amount of snow on a small area of the roof deck above the two beams. An approximate eight-foot pile of snow was accumulated on top of the beams, which corresponds to approximately 200 pounds per square foot. The existing PT beams are 12 inches (305 mm) wide and 36.5 inches (927 mm) deep, and support a 5.5-inch (138 mm) thick PT slab.

Form-and-pump formwork set for SCC pumping.

The excessive damage of the beams made it impossible to estimate their residual capacity. As such, initially, the design team was only considering replacement of the damaged beams. Full replacement created numerous challenges, as it would require de-tensioning of the slab above and installation of shoring on multiple levels. This would severely disrupt the parking system in the garage. Structural Preservation Systems, a repair contractor who completed similar repair projects, recommended a strengthening option that consisted of external PT placed in new concrete jacket that was six inches (150 mm) wide on each side and four inches (100 mm) thick on the bottom. The proposed PT solution provided adequate repair at half the cost of the removal option, with minimal disruption to garage operations.

The external PT design assumed that the original reinforcement would no longer contribute to the strength of the beams. The external PT system consisted of ten grade 270 ksi, ½-inch, seven-wire low relaxation strands coated with corrosion preventive grease and encased in a continuously extruded polyethylene plastic sheathing. Longitudinal mild steel reinforcement consisted of additional #7 top bars, #9 bottom bars, and #5 skin reinforcement that extended the full span of the member and installed with 90-degree hooks at the ends of bars.

The existing concrete surface was roughened to create a profile with ¼-inch amplitude, and then cleaned using high-pressure water blasting to produce porous, open substrate.

Two rows of six #5 dowels were installed immediately behind the anchors to withstand bursting forces. Four #5 dowels were installed along the entire span at 18 inches on center to improve the composite behavior of the jacket with the existing member. #4 stirrups were placed in the concrete jacket at 18-inches on-center and doweled to the underside of the slab using epoxy adhesive. Additional dowels and stirrups were installed at the cable's deviation points to allow for proper confinement and force transfer.

The formwork was designed for a minimum of 14 psi (100 kPa) and detailed to fit tightly against existing concrete surfaces. After all steel dowels, mild steel and PT reinforcement were installed, the beams were formed and self consolidating concrete (SCC) pumped into the forms. When the concrete strength reached 3,500 psi, the tendons were stressed by means of hydraulic jack to approximately 80% of their ultimate strength. All gauge pressures and cable elongations were recorded and reviewed for final approval.

The newly repaired beams appeared very similar to the original beams, with concrete enlargements that have the look of an original cast-in-place concrete element.

Conclusion

Strengthening of existing structures involves one of the more complex design and construction processes. Strengthening work is typically more challenging than new construction work due to complex logistics and the extensive coordination required to deal with occupied, and sometimes fully functional, structures. External post-tensioning systems provide many benefits including improved strength, improved service performance, and improved durability due to precompression of the concrete encasement.

The importance of addressing all design issues, and proper detailing of PT strengthening systems, cannot be overemphasized. Inadequate detailing has led to past failure of PT strengthening systems. As such, it is generally recommended that the design and detailing of post-tensioning strengthening systems be designed by experienced engineers with a focus on structural strengthening and use of post-tensioning for structures.▪

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