Methods of Upgrading Concrete Structures

By Tarek Alkhrdaji and Jay Thomas

Considering the worldwide population of concrete structures that are entering, or have entered, the "repair phase" of their life cycles, it is no wonder that the infrastructure upgrade market keeps growing annually. Another area within the repair market that is growing, that offers challenging but rewarding opportunities to specialty engineers, contractors, and material suppliers, is the upgrade and strengthening of existing structures.

In the past, functionally obsolete structures were routinely demolished, and new ones were constructed. Lately, with the higher cost of new construction, along with public conservation awareness, there is a trend to repair and upgrade deteriorated structures rather than replace them with new ones. This is especially true for buildings of historic value. With increased zoning and environmental regulations, it is more difficult to construct new buildings; thus, the volume of structural upgrades of concrete structures is increasing. In addition, structural upgrade and renovation may be the most economic, timely, and practical course of action.

Structures constructed using reinforced and prestressed concrete, although durable, do have a finite service life. When exposed to marine environments, deicing salts, and/or aggressive industrial environments, these structures may experience significant deterioration, which is demonstrated in the form of spalls, delamination, cracks, and/or other deficiencies. Deterioration problems may affect the integrity of a structure, and may require an upgrade of the structural elements to restore their load-carrying capacity. Structural upgrade or strengthening of an existing structure may also become necessary due to inadequacies arising from: 1) code changes such as seismic upgrade; 2) deficiencies that develop due to environmental effects such as corrosion; 3) changes in use that increase service loads; or 4) deficiencies within the structure caused by errors in design and construction.

The successful structural repair and upgrade involves four basic elements: concepts used in system design; compatibility and composite behavior of existing members with upgrade systems; field application methods; and most importantly, design details. One cannot overemphasize the importance of detailing and its direct effects on the durability of structural upgrades. In fact, inadequate detailing is one factor that can lead to the total failure of the structural repair system.

The structural upgrade of concrete structures can be achieved by span shortening, externally bonded steel elements, fiber reinforced polymer (FRP) composites, external or internal post-tensioning, section enlargement, or a combination of these techniques. No matter what strengthening technique is used, the ability to perform as an integrated upgrade system can be achieved only by providing an adequate bond between the existing concrete member and the newly applied reinforcement system.

Span Shortening

Span shortening has been used to reduce the force in overstressed beams and slabs, and can also be used to increase the load-carrying capacity of structural members. It is accomplished by techniques that involve installing additional supports at some distance away from existing ones to reduce the span length. The new supports (usually reinforced concrete or steel columns) may require footings, which may considerably drive up the strengthening cost. Another approach is to install diagonal members to carry load directly to the existing columns and their footings. The latter method requires that the existing column be adequate to resist the lateral force introduced by the new diagonal member to the base of the column. In addition, supported beams and slabs should be investigated to ensure that they have adequate strength (shear or punching shear strength) to resist forces exerted by the new supports at contact locations.

It should be noted that, unless designed to carry some of the existing structural loads, the newly installed members will only be engaged when additional loads are applied to the supported element. The span-shortening method may result in loss of space under existing beams or joists, and when additional beams are required between the braces to support intermediate beams or joists, headroom may be reduced. Materials used for span-shortening applications are structural steel members and cast-in-place reinforced concrete members. Connections can be easily designed using bolts and adhesive anchors, as these elements mostly carry compression and shear forces.

Figure 1 shows a project in which the span-shortening method was used to address deficiencies of a post-tensioned flat slab deck of a parking garage. Due to some deficiency in the original design, flexural forces induced by the self-weight

Figure 1(a)

Figure 1(b)

of the slab and parked vehicles exceeded the flexural strength of the slab in some locations. The upgrade solution consisted of installing a steel-framing system and diagonal bracing that were attached to the existing columns to reduce the clear span between the columns and eliminate the deficiencies in positive and negative moment regions of the slab (Figure 1(a)). This system was used to avoid losing parking spaces, which were crucial to the owner of the heavily occupied garage. At each of the new supports, a flat hydraulic jack was installed at contact points to "pick up" part of the self-weight of the slab, which resulted in an active load-carrying system. After the engineer-specified force was applied, each jack was locked in place and encased in a non-shrink grout as a permanent part of the structure. In addition, new columns were installed to support the end span of the second level deck (Figure 1(b)). New footings were constructed to support the loads of the new columns.

Bonded Steel Elements

The process of strengthening reinforced concrete members using bonded steel plates was developed in the 1960s in Switzerland and Germany. In this method, steel elements are glued to the concrete surface by a two-component epoxy adhesive to create a composite system. The steel elements could be steel plates, channels, angles, or built-up members. Steel elements bonded to the tension face of a concrete beam can increase its flexural capacity and contribute to increases in flexural stiffness that, in turn, reduce further deflection and cracking of the member. Steel elements bonded to the sides of the member can improve its shear strength.

The preparation of all component surfaces, as well as the bonding operation itself, must be executed with great care to achieve the composite action of the system. The surfaces to be bonded must be clean (heavy abrasive blasting for the steel and concrete surfaces is preferred).

Mechanical anchors at appropriate spacings are strongly recommended, especially at the ends of the bonded element, to ensure that the steel element will still share some load in case of adhesive failure. Furthermore, considerable site work is required to accurately locate the existing reinforcement to avoid damaging it while placing the anchors. Steel plates can be long, heavy, and elaborate, and expensive falsework may be required to maintain the steelwork's position during bonding. The exposed steel elements must be protected with a suitable system immediately following installation. Regardless of the corrosion protection system specified, its long-term durability properties and maintenance requirements must be fully considered. Fire protection is also an important consideration when using bonded steel elements.

Figure 2 shows a single-span bridge in the Florida Keys consisting of longitudinal beams cast monolithically with a topping deck. Structural analysis for higher vehicle loading revealed that the longitudinal beams of the bridge were deficient in flexure and shear. Flexural deficiency was resolved using steel plates that were externally bonded to the soffit of each beam. External steel plates were also applied to the top of each beam to provide compression reinforcement and to anchor internal stirrups that were also installed. Heavy abrasive blasting was used to produce a rough surface on the steel, which

Figure 2

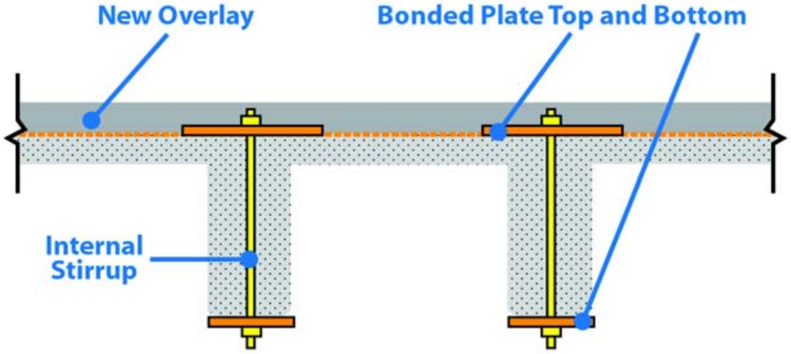

Figure 3

improved the adhesive bond and shear transfer. Heavy abrasive blasting was also used on the concrete surfaces to receive the plates. Bonding was achieved using an epoxy gel applied to the mating surfaces prior to final erection of the steel plates. Shear upgrade was achieved using internal shear stirrups installed along the entire length of each beam. The steel stirrups were epoxy-bonded in drilled holes, and were bolted at both ends to the bonded steel plates (Figure 3). In addition to improving the shear strength, the additional stirrups provided mechanical anchorage to the steel plates. The combined effect of epoxy gel and mechanical anchors furnished adequate shear transfer between the concrete and steel that ensured composite behavior of the upgraded members. The repair has been functional for over 15 years.

Strengthening with FRP Composites

Used extensively in industries such as defense, aerospace, automotive, shipbuilding, and others, the typical FRP composite material is comprise reinforcing fibers embedded in a polymer matrix. Two important characteristics of FRPs for structural repair and strengthening applications are speed and ease of installation. The higher material cost is usually offset by reduced costs of labor, equipment, and downtime—all of which make FRP strengthening systems competitive with traditional strengthening techniques.

The most common fiber for concrete strengthening applications is carbon FRP (CFRP), due to its superior mechanical properties (strength and stiffness) and durability. The most common types of CFRP are fabrics, plates, and rods.

As with any other externally bonded system, bond between the strengthening system and the existing concrete is critical, and surface preparation is very important. CFRP plates are limited to certain geometrical shapes—flat surfaces, to be specific. An option for this strengthening technique involves using CFRP fabric sheets that come in continuous rolls. These sheets can be easily and quickly tailored and wrapped around almost any profile. CFRP fabrics may be adhered to the tension side of structural members (that is, slabs or beams) to provide additional flexural strength, adhered to web sides of joists and beams to provide additional shear strength, and wrapped around columns to increase shear strength and boost the axial strength and ductility of the columns.

Prior to applying the fabric, it is necessary to resolve any existing corrosion problems. Failure to perform this task locks in the cause of corrosion, which may worsen the condition rather than remedying it. The strengthening can only be applied after all corrosion problems have been determined and resolved by following the appropriate procedure(s) (refer to ICRI Guidelines). In addition, existing cracks should be injected with epoxy prior to FRP application.

Externally bonded FRP reinforcement is designed to supplement existing interior reinforcement. Should something cause the FRP reinforcement to be compromised, the structure must still be able to carry existing service loads without collapsing.

Figure 4 shows one of three bridges that were upgraded with externally bonded CFRP composites. The single- span, simply supported bridge was constructed in 1970 and has a deck made of precast reinforced concrete (RC) channel sections tied together with 1-inch-diameter steel bolts and fasteners to ensure composite deck behavior. Analysis based on HS20 truck loading indicated that the code-specified flexure and shear forces exceeded the strength of the structural element. Approximately 3600 vehicles per day cross the bridge, with an estimated 10% truck usage. Due to weight restrictions, loaded trucks from a rock quarry and asphalt plant located in the same area have had to avoid this bridge. Upgrading the bridge allowed these businesses to access the bridge and cut their transportation costs considerably.

To upgrade the bridge, CFRP strips were bonded to the soffit of the joists to increase their moment capacities at midspan. FRP strips were also applied

Figure 4

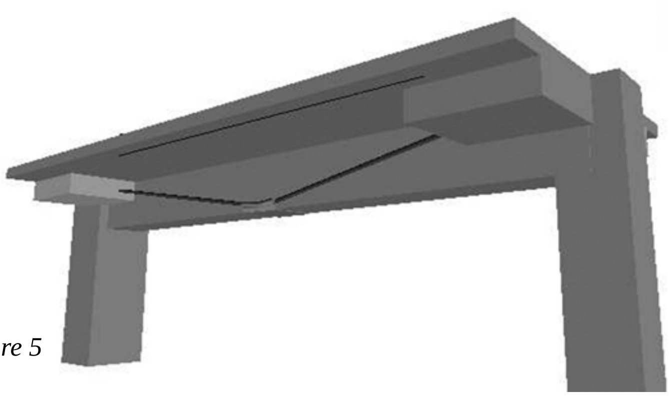

Figure 5

Figure 6

to the sides of the girders to increase their shear strengths. A CFRP strengthening system was applied by wet layup procedure (Figure 4). In this procedure, the CFRP fabric was epoxy-saturated, applied to the members, and cured in place. The surface of the concrete was prepared prior to CFRP application using sandblasting, which removed loose concrete and other contaminants that may have hindered the development of adequate bond. Since bond is the main shear transfer mechanism between the concrete and the CFRP system, achieving a composite behavior is very sensitive to the method of surface preparation and FRP application procedures. It is, therefore, recommended that FRP strengthening systems be installed by a contractor with a good understanding of these systems and their limitations as well as a record of successful application for similar projects.

The FRP solution cost less than all other options and resulted in approximately $50,000 in savings over conventional strengthening techniques. The bridge was shut down for only one week, which includes the curing time of the CFRP system.

Post-Tensioning

External post-tensioning of concrete members was already a mode of construction by the 1950s, and has been effectively used to increase the flexural and shear capacity of both reinforced and prestressed concrete members. With this type of upgrading, active external forces are applied to the structural member using post-tensioned (stressed) cables to resist some of the internal forces caused by certain loading conditions. Due to the minimal additional weight of the repair system, this technique is particularly effective and economical for long-span beams and has been employed with great success to correct excessive and deflections and cracking in parking structures and cantilevered members.

The post-tensioning forces are delivered by means of standard prestressing tendons or high-strength steel rods, usually located outside the original section. To achieve external post-tensioning, the tendons are connected to the structure at anchor points typically located at the ends of the member. End anchors can be made of steel fixtures bolted to the structural member or reinforced concrete blocks that are cast in-situ (Figure 5). The desired uplift force is provided by deviation blocks fastened at the high or low points of the structural element.

A variety of deviators have been used in the field, but they typically consist of structural steel brackets or saddles seated on the soffit of the member or bolted to the stem of the member. In all cases,

Figure 7

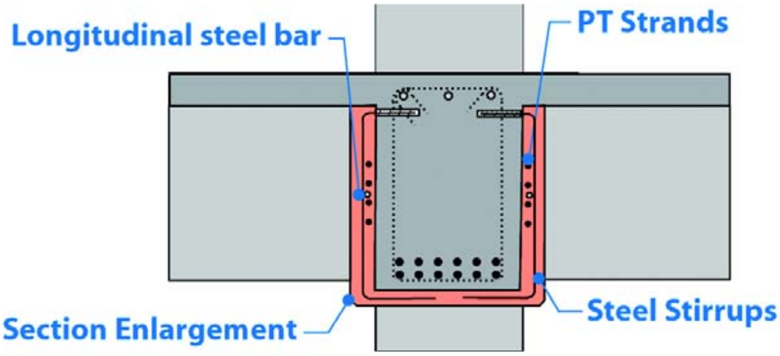

Figure 8

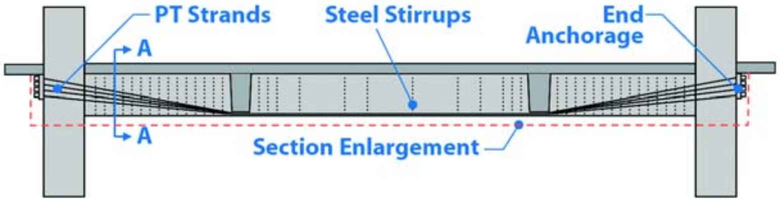

Figure 9

extreme caution should be taken to avoid damaging or cutting the existing reinforcement of the member. Prior to external prestressing, all existing cracks need to be epoxy-injected and the spalls patched to ensure that prestressing forces are distributed uniformly across the section of the member.

Because post-tensioned reinforcement is located outside the structure, one should consider issues such as corrosion, fire, and aesthetics. Encasement in concrete, grouted ducts, or other protection/ encasement methods can resolve these issues.

Figure 6 illustrates the upgrade of a parking garage ramp for a shopping mall. Inadequate detailing of the existing post-tensioning system resulted in a structurally deficient ramp—a deficiency further magnified by the corrosion of the steel tendons. Both time and cost constraints were important considerations in this project, as the ramp provided the only access to the back portion of the mall. Proposed solutions included demolition of the existing ramp and construction of a new ramp, or the installation of a steel frame underneath for support. Both options would render the ramp out of service. The option to install a new post-tensioning system was more economical, required less time to complete, and allowed half of the ramp to be open at all times. The system was installed in grooves made in the existing slab whose depths varied to accommodate the profile of the steel tendons. Tendon anchors were then embedded within the concrete slab (Figure 7). After the tendons were installed, the concrete was cast, and after the appropriate concrete strength was achieved, the tendons were stressed to the desired level. This option saved the owner approximately $500,000 in construction and operation costs.

Section Enlargement

This method involves the placement of additional concrete on an existing structural member in the form of an overlay or a jacket. The additional concrete can be reinforced or used without reinforcement. With section enlargement, columns, beams, slabs, and walls can be enlarged to add load-carrying capacity or to increase stiffness. In all cases, the designer should incorporate the effect of the weight of additional concrete in the design of the enlargement. Sufficient clearance should be allowed between the surface of the concrete member and the newly added reinforcement to ensure adequate flow of concrete around the bars. This is achieved by ensuring that the clearance is larger than the maximum aggregate size. Typical enlargement is approximately 2 to 3 inches for slabs and 3 to 5 inches for beams and columns. Lightweight concrete may be used to minimize the weight of the overlay, thus making better use of the increased member strength due to enlargement.

The composite behavior of the existing member-added concrete can only be taken into account if monolithic structural bond is assured. This requires good bond, horizontal shear transfer mechanism, or both, at the interface that does not prematurely deteriorate under cyclic traffic and environmental and temperature loads (for adequate surface treatment and preparation, refer to guidelines provided in ICRI publications). Code requirements for reinforcement anchorage, development length, spacing, and concrete cover for new construction should be met when performing section enlargement.

Figures 8 and 9 depicts details of a combination of section enlargement and external post-tensioning (PT) upgrade that was used to increase the capacity of a main girder in a parking garage. The girder was supporting the topping slab in addition to four transverse beams adjoining to the beam from both sides at approximately one-third of the span from each end. The girder, which was evaluated due to a change in the loading condition, was found to be deficient in flexure at midspan and in shear from the locations of the adjoining beam to the end of the member. To address flexural deficiencies, the design of the PT system called for eight 7-wire strands (four on each side of the beam). The strands were bundled together between the adjoining beams and splayed toward the ends of the beam. The adjoining beams were used as deviators, thus maximizing the contribution of the PT system by having them placed as low as possible. Specially designed steel plates, mounted to the back sides of the columns, were used to anchor the strands (Figure 10). The shear deficiency was corrected by doweling additional steel stirrups to the sides of the beam. Longitudinal mild steel reinforcement was also installed at midheight of the new concrete jacket. After the strands were stressed to the specified level, a 4-inch-thick concrete jacket was cast to protect the system from corrosion, provide fireproofing, and maintain a uniform look with surrounding members.

In addition to external PT, other upgrade solutions were also investigated. Most of these options were ruled out due to head room and space restrictions. External post-tensioning, on the other hand, provided the most economical solution, did not require the use of any additional space, and reduced the head room by only 4 inches.

In conclusion, we should recognize that, regardless of the experience and experimental knowledge gained in more than 100 years of reinforced concrete construction, structures will nevertheless require upgrade or strengthening due to natural causes, human error, and change in loading conditions. The structural repair and upgrade of concrete structures is an art form that involves the use of conventional cement-based materials as well as new techniques and materials. A blend of skills including technical (structural behavior and strength), construction (constructability), architectural (aesthetics), and financial (economics) are usually needed. Many opportunities exist for engineers, contractors, and material suppliers who can work together to supply these perspectives to an upgrade project. This explains the trend of design-build-type teams for delivering a competitive end product to owners. As practitioners, we must also recognize that strengthening assessment and design is infinitely more complex than new construction, and should not be treated lightly. Challenges usually arise due to unknown actual structural states such as continuity, load path, material properties, size, and locations of existing reinforcement or prestressing. The degree to which the upgrade system and the existing structural elements share the loads must be evaluated and properly addressed in the upgrade design, detailing, and implementation procedure.


Figure 10

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