Structural Strengthening

[Excerpts from the article "Keys to Success: Structural Repair and Strengthening Techniques for Concrete Facilities" May 2004 by Tarek Alkhrdaji]

1.0 Introduction

Concrete experts commonly use the terms structural repair and strengthening to describe building renovation activities. Although the two terms sound similar, they refer to slightly different concepts. Structural repair describes the process of reconstruction and renewal of a facility or its structural elements. This involves determining the origin of distress, removing damaged materials and causes of distress, as well as selecting and applying appropriate repair materials that extend a structure's life.

Structural strengthening, on the other hand, describes the process of upgrading the structural system of an existing building to improve performance under existing loads or to increase the strength of structural components to carry additional loads. For upgrade projects, design engineers must deal with structures in which every element carries a share of the existing load. The effects of strengthening or removing part or all of a structural element – such as penetrations or deteriorated materials – must be analyzed carefully to determine their influence on the global behavior of the structure. Failure to do so may overstress the structural elements surrounding the affected area, which can lead to a bigger problem and even localized failure.

2.0 Strengthening Methods

Many buildings that originally were constructed for a specific use now are being renovated or upgraded for a different application that may require higher load-carrying capacity. As a result of these higher load demands, existing structures need to be reassessed and may require strengthening to meet heavier load requirements.

In general, structural strengthening may become necessary because of code changes, seismic upgrade, deficiencies that develop because of environmental effects (such as corrosion), changes in use that increase service loads, or deficiencies within the structure caused by errors in design or construction. The structural upgrade of concrete structures can be achieved using one of many different upgrading methods such as span shortening, external composites, externally bonded steel, external or internal post-tensioning systems, section enlargement, or a combination of these techniques. Similar to concrete repair, strengthening systems must perform in a composite manner with an existing structure to be effective and to share the applied loads. The following gives a brief description of these methods and their applications.

2.1 Span shortening

Span shortening (Fig. 1) is accomplished by installing additional supports underneath existing members. Appropriate materials for span shortening include structural steel members and cast-in-place reinforced concrete members, which are simple to install. Connections can be designed easily using bolts and adhesive anchors. The structural steel system shown in Fig.1 was installed on a parking deck to shorten the span and carry part of the load, transferring it to the existing supporting system. On the down side, such applications may result in loss of space and reduced headroom.

Fig. 1: View of span shortening by providing structural steel members in a parking deck

2.2 Composites

Fiber reinforced polymer (FRP) systemsare high-strength, lightweight reinforcement in the form of paperthin fabric sheets(Fig. 2), thin laminates (Fig. 3), or bars that are bonded to concrete members with epoxy adhesive to increase their loadcarrying capacity. Important characteristics of FRPs for structural repair and strengthening applications include their non-corrosive properties, speed and ease of installation, lower cost, and aesthetic appeal.

Fig. 2: A column being strengthened with FRP sheets

A wide range of uni-directional, bi-directional and quadri-directional carbon fiber, glass and aramid fiber fabrics, available in different weights, are in the form of dry, flexible fabrics that should then be impregnated (saturated) with epoxy resins immediately before placement (wet layup) or during placement (dry layup). As the epoxy cures, a rigid composite is formed andshapes itself to the original structure in a monolithic bond. These fabrics are used for confinement of structural elements, such as columns, beams and slabsfor improved ductility and for load-bearing capacity, especially in seismic areas.

As with any other externally bonded system, the bond between the FRP system and the existing concrete is critical, and surface preparation is very important. Typically, installation is achieved by applying an epoxy adhesive to the prepared surface, installing the FRP reinforcement into the epoxy and, when required, applying a second layer of the epoxy adhesive. After curing, the FRP composite will add capacity to the element because it has a tensile strength up to 10 times that of steel.

Fig. 3: A roof slab being strengthened with FRP strips

In addition to FRP, steel reinforced polymer composites (SRP) (Fig. 4) may be used as externally bonded reinforcement. This steel-based, innovative strengthening system (known as Hardwire)is a low-cost, reinforcement system consisting of ultra-high-strength steel wires that are twisted together to form reinforcing steel cords approximately 1 mm in diameter(Fig. 5). This strengthening system can be applied using epoxy or cementitious materials and can be used to increase the shear and flexural capacity of structural elements.

Fig. 4: Roof strengthened with combined FRP and steel plates

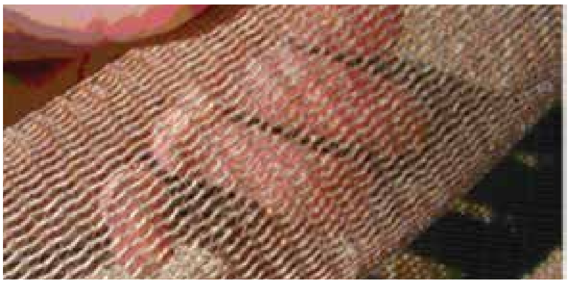

Fig. 5: 12WPI tape with cords held together by a polyester scrim for SRP composite bonding

2.3 Bonded steel elements

By using bonded steel plates method (Fig.6), steel elements are glued to the concrete surface by a two-component epoxy adhesive to create a composite system and improve shear or flexural strength. The steel elements can be steel plates, channels, angles, or built-up members.

In addition to epoxy adhesive, mechanical anchors typically are used to ensure that the steel element will share external loads in case of adhesive failure. The exposed steel elements must be protected with a suitable system immediately following installation. And regardless of the specified corrosion protection system, its long-term durability properties and maintenance requirements must be considered fully.

Fig. 6: A column being strengthened with steel plate bonding

2.4 External post-tensioning

The external post-tensioning (Fig. 7) technique has been used effectively to increase the flexural and shear capacity of both reinforced and prestressed concrete members since the 1950s. With this type of upgrading, active external forces are applied to the structural member using post-tensioned (stressed) cables to resist new loads. Because of the minimal, additional weight of the repair system, this technique is effective and economical, and has been employed with great success to correct excessive deflections and cracking in beams and slabs, parking structures, and cantilevered members.

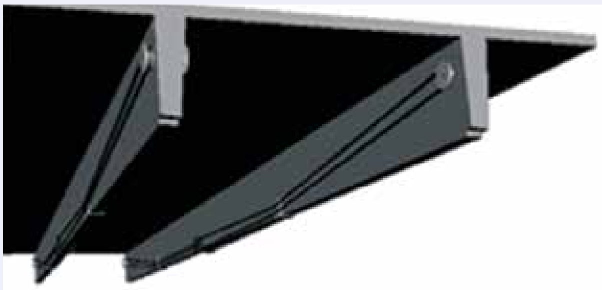

Fig. 7: View of external post-tensioning of beams

The post-tensioning forces are delivered by means of standard prestressing tendons or high-strength steel rods, usually located outside the original section. 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 into place. The desired uplift force is provided by deviation blocks, fastened at the high or low points of the structural element. Prior to external prestressing, all existing cracks are epoxy-injected and spalls are patched to ensure that prestressing forces are distributed uniformly across the section of the member.

2.5 Section Enlargement

This method of strengthening involves placing additional "bonded" reinforced concrete to an existing structural member in the form of an overlay or a jacket. With section enlargement (Fig. 8), columns, beams, slabs, and walls can be enlarged to increase their load-carrying capacity or stiffness. A typical enlargement is approximately 50 to 75 mm for slabs and 75 to 125 mm for beams and columns. This is popularly known as jacketing with micro concreting.

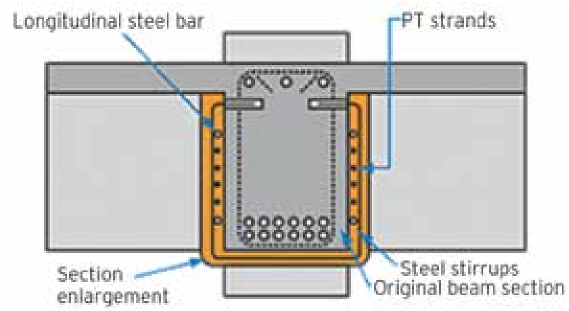

Fig. 8: Sketch showing strengthening of beam by section enlargement

2.6 Ferrocement Strengthening

Ferrocement, a thin structural composite material, exhibits better crack resistance, higher tensile strength-to-weight ratio, ductility and impact resistance than conventional reinforced concrete. These properties have been exploited through the use of ferrocement for structural upgrading and the rehabilitation of concrete structures. A number of successful commercial precast applications of ferrocement for use in the upgrading of building fixtures and services have resulted in repair industry.

Ferrocement repairs and rehabilitation can be done in RCC structures to increase the strength of columns, beams and slabs upto 30% as well as contribute towards prevention of crack formation. Ferrocement which can be made from non-formwork construction processes is an advantage over other types of repair and strengthening techniques; enhanced crack resistance combined with high toughness, its rapid constructions with no heavy machinery involved, small additional weight it imposes, and considering an economical aspect of rehabilitation, this material proves to be a cost effective solution for rehabilitation and general applications. It can totally replace deteriorated/damaged RCC chajjas with reduction in dead load.

Ferrocement confinement (Fig. 9) is done around defective circular or square/rectangular RCC columns in order to enhance the strength, ductility and energy absorption capacity of existing concrete columns. A jacketing layer of 30 mm is created all around the RCC columns and ferrocement is done in order to increase its load carrying capacity. This confinement work also protects the existing reinforcement, provides water tightness and prevents ingress of the aggressive species to the surface of original concrete or steel surface. Ferrocement not only increases the performance/function of structures but also enhances the appearance of the existing RCC structure. The repair in the structural elements using ferrocement can withstand for long years without cracking provided the mortar used is of proper proportion using good quality materials, and the wire mesh is of anti-corrosive coating type.

Fig. 9: View of ferrocement repair of concrete with welded wire mesh reinforcement

2.7 Shotcrete

Shotcrete (Fig. 10) is a process in which compressed air forces mortar through a nozzle to be sprayed on a surface of a structural member at a high velocity and also called as spray concrete. The materials used in shotcrete are generally same as those used for conventional mortar. The reinforcement provided is generally welded wire fabric and deformed bars tacked onto the surface. Sprayed concrete repairs are particularly appropriate for larger repair volumes, such as large surface areas of repair or multiple repair sites situated close together. It can be noted that the spray-applied repair materials with a higher elastic modulus than the substrate attracts load from the parent concrete.

Shotcrete is applied using either wet or dry process. Shotcrete by dry process is known as guniting. The wet mix consists of cement and aggregate premixed with water and the pump pushes the mixture through the hose and nozzle. Compressed air is introduced at the nozzle to increase the velocity of application. In the dry mix process, compressed air propels premixed mortar and damp aggregate and at the nozzle end water is added through a separate hose. The dry mix and water through the second hose are projected on to a prepared surface. Generally shotcrete gun nozzle is held at 0.6 to 1.8 m from the surface. In most cases shotcrete can be applied in a single application for the required thickness. It is versatile as it can also be applied on curved or irregular surface. Its strength after application and its good physical characteristics make it ideal for strengthening weak members.

There are many strengthening methods that can be considered for RCC structures. Based on the requirement the structural consultant can select a suitable repair methodology considering the performance requirement, availability of the materials, cost, and ease of application and durability of the repair system. Table 1 gives guidelines for strengthening of different structural members for improvement of different properties.

Fig. 10: View of concrete repair by shortcrete method

Table 1. Strengthening of Structural members

RCC Members	Performance improvement	Recommended strengthening methods
Column	Enhancing load carrying capacity	Section enlargement, Fibre wrapping
	Improving ductility	Section enlargement, steel plate bonding, fibre wrapping
	Retrofitting joints	Section enlargement, providing steel collars, fibre wrapping
Beam	Flexural strengthening	Section enlargement, additional reinforcement in tension, MS plate bonding, high strength fibre wrapping, external post tensioning
	Shear strengthening	Section enlargement, shear ties anchored in compression zone, post tension strap around section, diagonally anchored bolts, MS plat bonding, fibre wrapping
	Retrofitting joints	Fibre wrapping
Slab	Control of deflection (negative moment deficiency)	Concrete overlays
	Control of deflection (positive moment deficiency)	Concrete underlays ,span shortening by structural steel members or cast-in-situ RCC members, fibre wrapping
Chajja & sunshade	Repair due to corrosion related damages	Ferrocement strengthening, jacketing with microconcreting
Foundation	Control of settlement	Shoring and underpinning
	Seismic retrofitting	Base isolation

3.0 Conclusion

It is crucial that structural engineers recognize that strengthening assessment and design is infinitely more complex than new construction. Typically, challenges arise because of unknown factors associated with the structural state – such as continuity, load path, and material properties – as well as the size and locations of existing reinforcement or prestressing. The degree to which the upgrade system and the existing structural elements share the loads also must be evaluated and addressed properly in the upgrade design, detailing, and implementation procedure. The importance of detailing and its direct effects on the effectiveness and durability of structural upgrades cannot be overemphasized. In fact, inadequate detailing is one factor that can lead to the total failure of a structural repair system.

In addition, engineers should consider the procurement process for specialty repair and strengthening projects to be different from new construction services. Engaging contracting firms that are familiar with all of the critical aspects highlighted here will ensure the most cost-effective and long-lasting results. Although it may appear that there is an up-front financial benefit to obtaining these specialty services from firms with experience in new construction, the real risk is that the repairs will cause an endless “repair of repairs” cycle, resulting in additional disruption and expenditure to owners. When it comes to structural repair and strengthening, the mantra “do it right the first time” pays dividends.