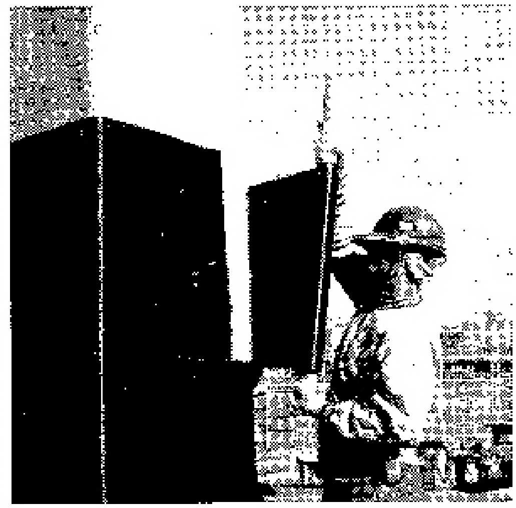
TECHNICAL
GUIDELINES

Prepared by the International Concrete Repair Institute February 2006


Guideline No. 03742

Guide for the Selection of Strengthening Systems for Concrete Structures

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About ICRI Guidelines

The International Concrete Repair Institute (ICRI) was founded to improve the durability of concrete repair and enhance its value for structure owners. The identification, development, and promotion of the most promising methods and materials are primary vehicles for accelerating advances in repair technology. Working through a variety of forums, ICRI members have the opportunity to address these issues and to directly contribute to improving the practice of concrete repair.

A principal component of this effort is to make carefully selected information on important repair subjects readily accessible to decision makers. During the past several decades, much has been reported in the literature on concrete repair methods and materials as they have been developed and refined. Nevertheless, it has been difficult to find critically reviewed information on the state of the art condensed into easy-to-use formats.

To that end, ICRI guidelines are prepared by sanctioned task groups and approved by the ICRI Technical Activities Committee. Each guideline is designed to address a specific area of practice recognized as essential to the achievement of durable repairs. All ICRI guideline documents are subject to continual review by the membership and may be revised as approved by the Technical Activities Committee.

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Synopsis

This guide is intended to provide guidance on the selection of strengthening systems for concrete structures. The guideline describes several methods of strengthening structures including externally bonded systems, post-tensioning, section enlargement and supplemental supports. It offers guidance on the selection of the appropriate strengthening technique which depends on many factors such as level of upgrade, primary or supplemental reinforcing requirements, constructability, aesthetics, and cost. Various issues regarding design considerations, advantages, and limitations are provided for the use of these systems. For each strengthening system, the engineering considerations, systems, methods and materials, durability, fire considerations, and field applications are discussed in detail.

Keywords

Active strengthening, axial strengthening, bending capacity, carbon fiber column capitals confinement, durability, external post-tensioning, external reinforcement, externally bonded systems, fiber-reinforced polymer, FRP, fire considerations, flexural strengthening, glass fiber, increased loading, load testing, moment strengthening, passive strengthening, primary strengthening, section enlargement, shear collar, shear strengthening, span shortening, stabilization, steel plate bonding, steel-reinforced polymer, SRP, strengthening, structural deficiency, structural analysis, structural design, structural evaluation, structural repair, structural upgrade, supplemental strengthening, supplemental supports, support extension, virtual strengthening.

Contents

Contents

1.0 Introduction

One of the challenges in strengthening of concrete structures is selection of a strengthening method that will enhance the strength and serviceability of the structure while addressing limitations such as constructability, building operations, and budget. Structural strengthening may be required due to many different situations.

- Additional strength may be needed to allow for higher loads to be placed on the structure. This is often required when the use of the structure changes and a higher load-carrying capacity is needed. This can also occur if additional mechanical equipment, filing systems, planters, or other items are being added to a structure.
- Strengthening may be needed to allow the structure to resist loads that were not anticipated in the original design. This may be encountered when structural strengthening is required for loads resulting from wind and seismic forces or to improve resistance to blast loading.
- Additional strength may be needed due to a deficiency in the structure's ability to carry the original design loads. Deficiencies may be the result of deterioration (e.g., corrosion of steel reinforcement and loss of concrete section), structural damage (e.g., vehicular impact, excessive wear, excessive loading, and fire), or errors in the original design or construction (e.g., misplaced or missing reinforcing steel and inadequate concrete strength).

When dealing with such circumstances, each project has its own set of restrictions and demands. Whether addressing space restrictions, constructability restrictions, durability demands, or any number of other issues, each project requires a great deal of creativity in arriving at a strengthening solution. This document seeks to illustrate typical strengthening techniques for concrete structures and provides guidance for the use of these techniques. Strengthening techniques such as section enlargement, externally bonded systems, external post-tensioning systems, and supplemental supports are presented. Engineering considerations, methods and materials, durability considerations, fire considerations, field applications, benefits, and limitations are discussed.

Strengthening of existing structures will always require detailed engineering analysis and design by a qualified engineer. This document does not present the detailed engineering methods of analysis but rather seeks to inform the reader of the various strengthening options and to assist the reader in determining which methods are more suitable for a given project.

2.0 General Engineering Considerations

The majority of structural strengthening involves improving the ability of the structural element to safely resist one or more of the following internal forces caused by loading: flexure, shear, axial, and torsion. Strengthening is accomplished by either reducing the magnitude of these forces or by enhancing the member's resistance to them. Typical strengthening techniques such as section enlargement, externally bonded reinforcement, post-tensioning, and supplemental supports may be used to achieve improved strength and serviceability.

Strengthening systems can improve the resistance of the existing structure to internal forces in either a passive or active manner. Passive strengthening systems are typically engaged only when additional loads, beyond those existing at the time of installation, are applied to the structure. Bonding steel plates or fiber-reinforced polymer (FRP) composites on the structural members are examples of passive strengthening systems. Active strengthening systems typically engage the structure instantaneously and may be accomplished by introducing external forces to the member that counteract the effects of internal forces. Examples of this include the use of external post-tensioning systems or by jacking the member to relieve or transfer existing load. Whether passive or active, the main challenge is to achieve composite behavior between the existing structure and the new strengthening elements.

As an alternative to strengthening an existing structure, the apparent strength of a structure can be virtually improved through a "virtual strengthening" approach such as: 1) reducing the loads on the structure by removing superimposed dead load or by reducing live loads; 2) demonstrating, by sampling and testing, that material properties are higher than those intended in the original design; or 3) demonstrating required capacity by full-scale load testing.

The load-carrying capacity of strengthened and unstrengthened members is computed using generally accepted engineering principles.

However, it can be helpful and is sometimes prudent to also conduct load tests to confirm load-carrying capacity. Load testing can provide valuable information regarding the strength and performance of an existing structure by simply applying loads to selected structural members and measuring their responses. Load testing can be used to evaluate the performance of deteriorated, overstressed, or strengthened structural members. It can also be used to proof-test new strengthening technologies and materials. A load test should be supervised by a qualified engineer, who is responsible for preliminary field and analytical investigations, selecting test areas, determining the magnitude of the load test, and evaluating the performance of the structural element during and after the completion of the test. For procedures for conducting in-place load tests and criteria for performance evaluation, the reader should refer to publications of the American Concrete Institute (ACI) [ACI 318 and ACI 437R].

The selection of the most suitable method for strengthening requires careful consideration of many factors including the following engineering issues:

- Magnitude of strength increase;
- Effect of changes in relative member stiffness;
- Size of project (methods involving special materials and methods may be less cost-effective on small projects);
- Environmental conditions (methods using adhesives might be unsuitable for applications in high-temperature environments, external steel methods may not be suitable in corrosive environments);
- In-place concrete strength and substrate integrity (the effectiveness of methods relying on bond to the existing concrete can be significantly limited by low concrete strength);
- Dimensional/clearance constraints (section enlargement might be limited by the degree to which the enlargement can encroach on surrounding clear space);
- Accessibility;
- Operational constraints (methods requiring longer construction time might be less desirable for applications in which building operations must be shut down during construction);
- Availability of materials, equipment, and qualified contractors;
- Construction cost, maintenance costs, and life-cycle costs; and
- Load testing to verify existing capacity or evaluate new techniques and materials.

The first step in the engineering of any strengthening activity is a condition assessment of the existing structure and its components. The purpose of the condition assessment is to identify the types and extent of any deterioration and damage, and to diagnose their causes. The condition assessment is followed by a structural analysis to compare the existing capacity to strength demand. Once the types and magnitude of structural deficiencies have been identified, a strengthening strategy can be developed. The following describes the various steps and decision points in a typical strengthening design process.

2.1 Strengthening Design Process

This section outlines typical steps that may be used for structural strengthening projects to ensure an effective, durable, and cost-efficient strengthening solution. The main objective is to highlight the main design and strengthening technique selection issues, as well as the constraints that may be encountered during a typical strengthening project.

Step 1: Structural Condition Assessment

The first step in any strengthening project is to establish a firm understanding of the existing structure and its condition. This could be achieved by studying existing drawings (or built drawings, if available), reports, and calculations, verified by an on-site inspection, as well as determining the loading history and material characteristics of the structure. Guidelines for the condition evaluation of concrete structures are given in ACI 364.1R, "Guide for Evaluation of Concrete Structures Prior to Rehabilitation," and SEI-ASCE 11-99, "Guideline for Structural Condition Assessment of Existing Buildings."

Step 2: Structural Analysis

Analysis of the existing structure can be used to determine the existing load capacity of various structural elements. These in turn are compared to the load demand on each structural member to establish the type and level of structural deficiency, if any. The analysis may be used to predict deformations of the structure during and after installation of the strengthening system. In some cases, an unknown structural condition, such as that caused by aging and deterioration, may complicate the analysis. In these cases, load testing may be used to obtain information regarding the existing capacity. Load tests may be performed according to Chapter 20 of ACI 318, "Building Code Requirements for Structural Concrete," ACI 437R, "Strength Evaluation of Existing Concrete Buildings," or a local building code.

Step 3: Strengthen or Stabilize the Existing Structure?

Strengthening is required when additional loads beyond those of the original capacity need to be carried by some of the elements of the structure.

Stabilization is required when the structure needs to be repaired to restore its original or intended loading condition after its capacity has been reduced due to deterioration or damage (deficiencies are typically related to defects, corrosion, and damage).

Step 4: Determine the Required Type of Strengthening

Primary or Supplemental

Primary Strengthening—When the design service loads (without load factors) exceed the nominal strength of an unstrengthened element, then the strengthening system is considered primary. This indicates that the strengthening system is needed to prevent collapse. This is critical to define, as some strengthening techniques may not be appropriate for primary strengthening applications. Primary strengthening systems include section enlargement, span shortening, and supplemental supports.

Supplemental Strengthening—When the design service loads (without load factors) are less than the existing capacity of an unstrengthened element, then the strengthening system is considered supplemental. Without strengthening, the structure may be overstressed and exhibit excessive deflection and cracking, but it will not collapse.

Passive or Active Strengthening

Passive Strengthening describes techniques in which the added systems will not be engaged until new loads are applied to the structure and deformations occur. Examples of this technique include externally bonded FRP or steel plates, concrete section enlargement, as well as other systems.

Active Strengthening describes techniques in which the added system is instantaneously engaged to carry the new loads. This could be accomplished by using some form of post-tensioning or jacking of the structure prior to strengthening.

Step 5: Determine the Appropriate Strengthening Technique

Several techniques may be evaluated for a strengthening application. Techniques such as section enlargement, externally bonded systems, external post-tensioning and supplemental supports may be used to stabilize or strengthen an existing structure or its components. The final selection of the strengthening system will depend on many factors including effectiveness, constructability, aesthetics, and cost.

Step 6: Evaluate the Structural Condition During Installation

During the installation and curing of the materials used in a strengthening system, the effects of excessive loading, vibrations, stress, ambient temperature, or deflections must be evaluated to determine design limitations and construction sequence. If not considered, these conditions may be detrimental to the effectiveness and durability of the strengthening system.

Step 7: Evaluate the Work Environment During and After the Installation?

Constructability issues

- Access to work area
- Work-site obstructions
- Dust and noise control
- Installation time frame
- Environmental conditions during repair

Building operations during repair

Building operations may influence the choice of a strengthening technique. Some techniques may be more expensive yet require shorter installation time.

Environmental exposure after installation

Chemical, temperature, abrasive, or impact exposures to the strengthening system after installation should be considered. Additional protection of the system may be required.

Aesthetics of the upgraded structure

The final appearance of the upgraded structure may be the controlling factor in selecting the strengthening system. Additional finishes may be required to ensure that the newly installed system "blends in" with the surroundings.

Step 8: Select the Best Strengthening Technique

Using the criteria evaluated in Steps 1 through 7, determine the options that best achieve the desired results. Sometimes, although the components of the strengthening option may be more expensive, they could be installed faster and with fewer interruptions to building operations, which could result in lower overall costs.

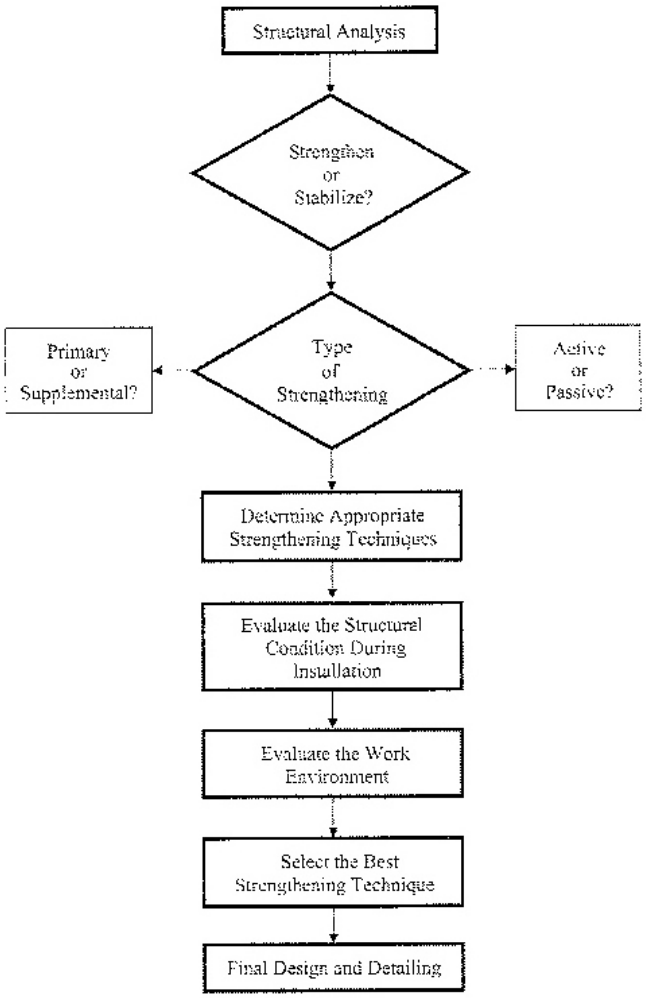
Step 9: Perform Final Design and Detailing

Once the structural strengthening system has been selected, final engineering may be conducted. This may include:

- Final design and detailing of the strengthening
- Serviceability checks

- Construction loads and sequence
- Quality control
- Project specifications: prescriptive, performance based, or design-build

Strengthening Process Flow Chart



3.0 Section Enlargement

Section enlargement is one of the oldest strengthening techniques known to the concrete construction industry. Enlargement is the placement of additional concrete on an existing structural concrete member. The additional concrete may be "structural" concrete reinforced with steel bar, wire mesh, or post-tensioning strands and designed to increase the load-carrying capacity of a structural member. It may also be considered "protective" concrete used to improve the fire resistance of the structural elements and protect them from mechanical and environmental damage. Using this method, columns, beams, slabs, and walls can be enlarged to add load-carrying capacity or increase stiffness. In all cases, the designer should include the weight of the additional reinforced concrete in the design loads. For example, a concrete overlay bonded on top of an existing slab can increase the structural capacity of the slab yet will add dead load to the slab.

3.1 Engineering Considerations

All of the general engineering considerations presented in Section 2.0 should be considered in the design of a section enlargement. The most applicable considerations with this method are:

- Achieving composite action between the existing member and the enlargement;
- Compensating for the dead load increase;
- Accounting for the increase in stiffness of the strengthened member as it may alter the load distribution in the entire structure. Detailed analysis of the affected structural system may be required to check the stress condition for other members; and
- For columns, design of the enlargement should account for effects of axial load eccentricity on the final stress condition and behavior of the column.

When using enlargement as a strengthening technique, the ability of the composite member to perform as an integrated system can only be achieved by providing adequate bond between the existing concrete member and the externally applied concrete and reinforcement. When bond between new and existing concrete is not sufficient to carry horizontal shear forces at the interface, the composite behavior can be achieved by using shear dowels, epoxy or mechanically anchored to the existing member. For design of horizontal shear reinforcement, the reader is referred to the requirements of ACI [ACI 318]. Stress concentrations resulting from adding material that induces a sudden local increase in stiffness may cause a localized failure, which should be addressed in the design of the repair. Concrete enlargement may also require steel reinforcement to control cracking due to volume changes

Concrete overlays bonded to the top of a slab, beam, or joist can increase the positive bending moment capacity by increasing the effective depth of the existing reinforcement. The overlay can be designed such that the increase in the depth of the existing reinforcement offsets effects of the weight of the overlay. In addition, lightweight concrete may be used to reduce the weight of the overlay. Embedding new reinforcement in the overlay can increase the negative moment capacity of slabs, beams, and joists.

Shoring of the enlarged member and isolation of its surrounding areas may be necessary to limit deflection and/or vibration that can interfere with the development of the bond during curing. Shoring and jacking may also be considered when the enlarged section is required to be an active strengthening system, as described in Section 2.0 of this document.

3.2 Systems, Methods, and Materials

Section enlargement techniques are used to add flexural, shear, torsional, or axial capacity or a combination thereof to a structural element. It may also be appropriate for improving ductility or limiting deflections. For beams, section enlargement may be achieved on one side or multiple sides of the member. For slabs, enlargement can be achieved on the top of the slab in the form of an overlay or on the bottom of the slab in the form of an underlay. Slab enlargement may also be achieved in the form of a drop panel at the columns. For columns, depending on the type and extension of deficiency, section enlargement may be achieved on one or more sides of the section and the enlargement may be achieved on the full height of the column or extended to a certain distance from the top or bottom supports.

The composite behavior of the enlarged section can only be taken into account if a monolithic structural condition is achieved. Composite behavior requires adequate bond at the interface between the existing and new concrete to ensure the ability of the final section to transfer horizontal shear forces along this interface. Poor bonding may cause premature deterioration under traffic loads or environmental and temperature stresses. Achieving a sound, rough, open-pore surface for bonding is critical to achieve the monolithic behavior. This can be achieved by aggressive abrasive blasting, high-pressure water blasting (typically 10,000 psi or greater) or mechanical profiling (scarification and bush hammering). It should be noted that after mechanical profiling, the resulting surface most likely has some level of micro-fracturing that will inhibit the bond of the new section. It is recommended that an abrasive or high-pressure water blast follow to remove the micro-fractured parts. Occasionally, the concrete at the surface of the member is weak and does not have adequate strength to ensure sufficient bond. In this case, the weak concrete should be removed to expose sound concrete. The composite behavior may also be achieved using doweled reinforcement to provide additional horizontal shear transfer capacity. This is typically achieved using epoxy or mechanically anchored steel dowels (refer to Fig. 3-1). For proper surface treatment, preparation, and bond testing, the reader is referred to the appropriate Guidelines provided by the International Concrete Repair Institute (ICRI) [ICRI Technical Guidelines No. 03732, 03733, and 03739].

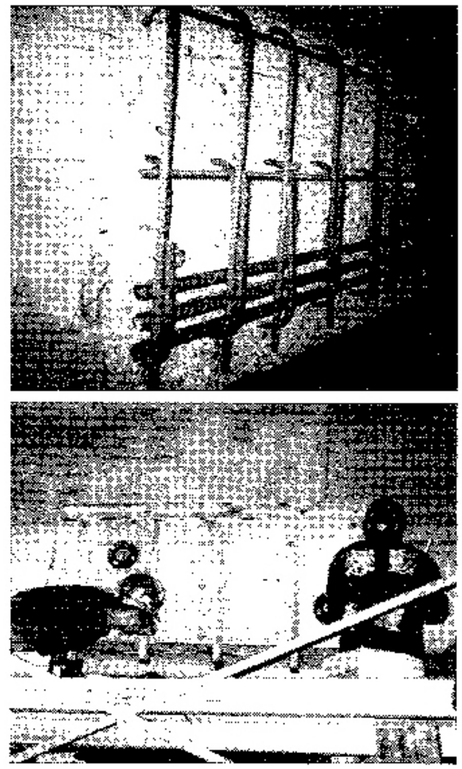


Fig. 3-1: Beam enlargement preparation and form and pump technique

The selection of materials should be based on constructability, enlargement size, placement method, compatibility with the existing concrete, dimensional behavior (shrinkage, thermal expansion, modulus of elasticity, and creep), mechanical properties (tensile, flexural, and compressive strengths) and durability concerns. In compression applications, the modulus of elasticity of the new repair material should be similar to that of the existing concrete to ensure that the added material will carry a proportional part of the compression load as it is added to the structure. For example, if the modulus of elasticity of the new concrete is significantly higher than that of the existing concrete, the enlargement will attract a larger portion of the load as it could cause the new material to become overstressed. For material selection guidance, refer to ICRI Technical Guideline No. 03733.

Typical concrete placement techniques include placing concrete on top of an existing member (as in the case of an overlay), form and cast in place, form and pump, and shotcreting. Selection of the placement technique will depend on a number of factors including constructability and repair environment, enlargement size, and material selection. In general, installing the repair materials under pressure will help achieve mechanical interlock with the existing prepared surface. Refer to ICRI Technical Guideline No. 03733 for guidance on selection of repair materials.Sufficient clearance should be provided between the surface of the existing concrete member and the additional reinforcement to ensure adequate flow of repair material around the steel bars. Clearance will depend on or dictate the maximum aggregate size of the repair material [ICRI Technical Guideline No. 03730].

3.3 Durability Considerations

Durability considerations for enlarged sections are similar to considerations with new concrete construction. Many of these considerations relate to the protection of the new reinforcing steel from corrosion. Durability considerations vary depending on the environmental exposure.Concrete is a durable material and, when proportioned appropriately, will perform well in harsh environments. However, there are a number of factors that may influence its durability including the physical properties of the hardened concrete [ACI 201.2R], the materials of which the concrete is composed, amount of concrete cover, manufacturing and construction methods, and the type of exposure. Concrete should have a low water-cement ratio, be dense to reduce permeability, and should be properly cured to minimize shrinkage. Shrinkage reinforcement may be required to control cracking that could cause premature deterioration.

3.4 Fire Considerations

Fire protection should be considered in the design of the concrete enlargements. The same requirements for new concrete construction apply to the design of concrete enlargements. For fire consideration and detailing, the reader is referred to ACI 318 and ACI 216. Additionally, when fire protection is critical, mechanical or cement grouted anchors may be used in place of epoxy anchors.

3.5 Field Applications

3.5.1 Slab Enlargement

An airport elevated ramp (cast-in-place slab on America Association of State Highway and Transporation Officials (AASHTO)-type girders) required strengthening for new loads due to a new canopy structure supported by steel tube columns that were being installed on the ramp. At each steel column, the slab was insufficient to carry the new loads. The slab was enlarged on the underside to create a reinforced concrete beam spanning between the AASHTO girders. The use of steel dowels and the form and pump technique ensured a composite behavior with the surrounding members.

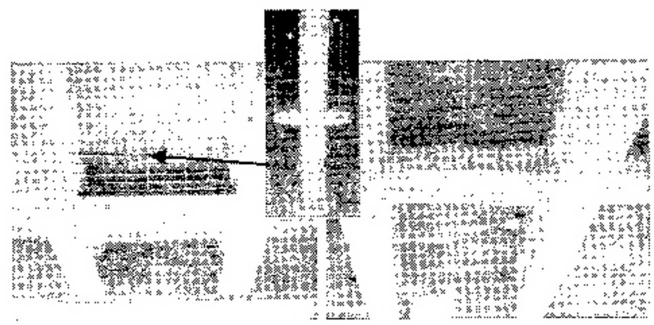


Fig. 3-2: Enlarged slab section to accommodate new loads from steel columns

3.5.2 Beam Enlargement

A series of beams in a parking structure were enlarged for additional flexural and shear capacity. The surfaces to be enlarged were properly cleaned and profiled using abrasive blasting. Stirrups were added for shear upgrade. In addition, post-tensioning strands were installed on both sides of each beam and deviated at two-quarter span locations using the transverse joists as deviators.

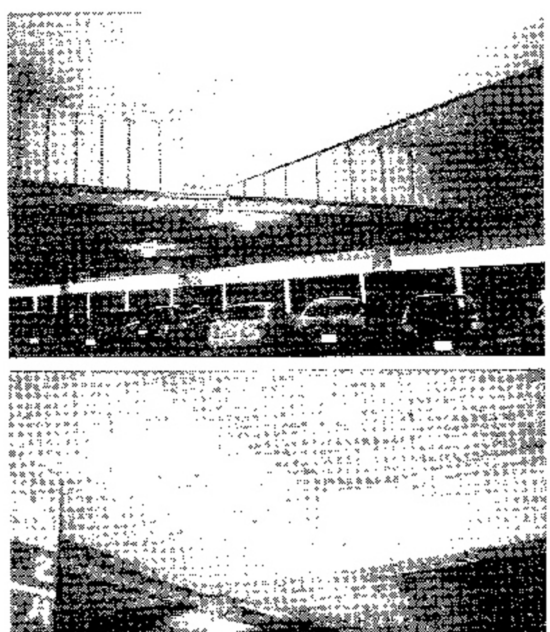


Fig. 3-3: Additional reinforcement is added to the beam then encased in concrete

Steel plates were fabricated for the end anchorages and installed on the ends of the beams. The section (sides and bottom) was then enlarged with concrete placed using a form and pump technique.

3.5.3 Column Capital Enlargement

The slab around columns in a condominium parking garage required additional punching shear capacity. To accomplish this, the column heads were enlarged to create a larger bearing area. The concrete was first prepared by bush hammering followed by abrasive blasting. This was done to achieve the proper surface profile and to remove loose and fractured material resulting from the bush hammering process. Circumferential reinforcement was installed, the area formed and concrete was pumped into the formwork under pressure.

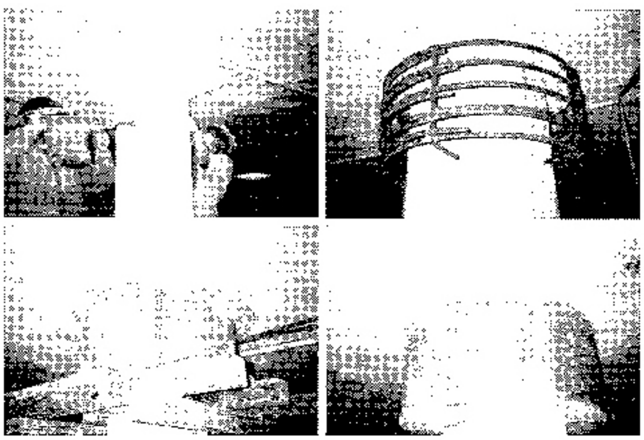


Fig. 3-4: Column enlargement for additional punching shear

3.6 Benefits and Limitations

3.6.1 Benefits

Concrete section enlargement is relatively easy and can be economical. It can be used to increase the flexural, shear, torsional, and axial load capacity of existing members. It may also be used to increase the stiffness or to improve ductility. This method provides considerable flexibility for applications that require a substantial increase in capacity, serviceability limitations (deflection and crack width), or fireproofing. Design principles and materials used in construction are well known to the contractor and the engineer. Because a structural fire rating is achievable, the enlarged element can achieve a substantial new load-carrying capacity and be considered a primary strengthening system.

3.6.2 Limitations

Limitations to this technique include loss of space or headroom, additional weight of the new concrete, and possible higher cost due to the extensive level of surface preparation, forming requirements, and concrete placement techniques. Therefore, section enlargement may require longer installation time than other strengthening methods. Corrosion of embedded reinforcing steel should be considered, especially in harsh environments. This problem can be minimized by providing adequate concrete cover, corrosion protection systems (coatings, cathodic protection, and admixtures), or reinforcement that is less prone to corrosion.

4.0 Externally Bonded Systems

The practice of externally bonding reinforcement consisting of mild steel, stainless steel, advanced composites, and other materials onto concrete has been successfully used for many years by the construction industry. Externally bonded systems can increase the strength of concrete, especially in flexural, shear, and confinement applications by providing additional tension reinforcement that shares load with existing (internal) reinforcement. Depending on the application and choice of material, externally bonded systems can change the strength, stiffness, and/or ductility of the structure.

Historically, steel plates were the materials of choice for external reinforcing due to their strength, stiffness, availability, and relative low cost. The composite behavior is typically achieved by bonding the plates with an epoxy resin and/or using mechanical anchors. The epoxy resin used in these applications is either in a paste consistency or as a liquid injected under pressure. Depending on structural and environmental requirements, anchor bolts may be used to supplement the bond provided by epoxy to improve horizontal shear-transfer capacity and hold the heavy plates in place until the epoxy resin cures.

More recently, FRPs are being used for externally bonded reinforcing systems for concrete. Their high strength-to-weight ratio makes them ideal for many civil engineering strengthening applications. In addition, their noncorrosive nature makes the maintenance and long-term cost of FRPs attractive to building owners, DOTs, engineers, and architects. Carbon FRP (CFRP), aramid FRP (AFRP), and glass FRP (GFRP) are most commonly used for external reinforcement of concrete structures. For additional information, refer to ACI 440.2R.

4.1 Engineering Considerations

All of the design issues presented in Section 2.0, General Engineering Considerations, should be considered when designing externally bonded strengthening systems. A qualified engineer having experience in this field should design the externally bonded strengthening systems. ACI has published a document [ACI 440.2R] that should be used when FRP is used as part of the upgrade. Design of external steel plates should conform to the appropriate ACI documents including ACI 318.

Externally bonded systems are designed to resist tensile forces while maintaining strain compatibility with the strengthened section. The FRP should not be designed to resist compressive forces. However, it is acceptable for the FRP to experience compression due to moment reversals or changes in loading patterns.

When considering FRPs for design, it is important to consider whether the structure will be subjected to sustained or event loading conditions. Some examples of sustained loads include increased dead- or live-load conditions, structural modifications, change in use, and upgrades from environmental degradation. Event loads include seismic upgrades, impact protection, and blast hardening. GFRP materials might be appropriate for event loads because the FRP is not subjected to active forces. CFRP, rather than GFRP, materials are typically used for sustained loads due to higher strength, stiffness, durability, and creep resistance. In all cases, special attention must be made to the proper anchorage including the development length of the materials.

Some engineering considerations for steel-plate bonding are epoxy bond line thickness, fire resistance of the system, and stress concentrations, especially at termination points. While projects may vary with regard to their appropriateness and complexity, it is possible to achieve load increases of up to approximately 60% with the use of externally bonded systems.

Epoxies are typically prone to degradation at elevated temperatures as they start to soften at a critical temperature known as the glass transition temperature. The designer should ensure that the operational or design temperature is below the glass transition temperature of the epoxy. When this is not feasible, mechanical anchors must be used in addition to the epoxy resin. The latter is more suited for steel plates and may not be appropriate for FRP composites.

4.1.1 Flexural Strengthening

Structural members can be upgraded for flexure by increasing the positive and/or negative bending resistance with externally bonded systems. One such application is the bonding of the external reinforcement onto the bottom of a beam or slab for positive moment upgrades of simply supported structures. For continuous structures, or in regions over the supports, the negative moment can also be increased with externally bonded systems. However,it is necessary to check to check new shear forces particularly at the supports. Walls can also be strengthened with externally bonded systems, typically for out-of-plane bending such as that resulting from wind loads.

4.1.2 Shear Strengthening

Externally bonded systems are very effective for increasing the shear capacity of elements, especially beams. Steel plates may be added to the sides of the member and FRP systems may be applied to the sides of the member or wrapped in a "U"-shaped configuration onto the beam. For columns, shear strengthening is achieved by installing the reinforcement system laterally, similar to standard steel stirrups. Steel or FRP straps may be used for column shear upgrade applications. The external systems may be applied to completely cover the affected area of the member or strips installed at a given spacing.

4.1.3 Column Strengthening and Confinement

Columns can be strengthened with externally bonded systems for increased ductility and increase their axial compressive strength. Both steel jackets and FRP systems have been used successfully in these applications. These systems confine the columns by confining the columns thus increasing the compressive strength and ductility of the concrete, bracing vertical reinforcement against buckling, and preventing cover spalling. This is especially important for seismic strengthening of columns and column-beam joints. The external reinforcement works similar to the hoop or spiral reinforcement typically found in columns.

4.2 Systems, Methods, and Materials

4.2.1 Steel Plates/Jackets

Steel plates have been successfully used for strengthening applications since the late 1960s.

For flexural and shear applications, the plates are typically bonded onto the concrete or masonry substrate with an epoxy resin and also bolted with either a mechanical or adhesive anchor. The plates can be bonded with an epoxy resin having either a paste or a low viscosity consistency. The typical preparation of the steel is to mechanically abrade until a white metal finish (SSPC SP-5/NACE No. 1) is obtained. The concrete should be sound and prepared to a minimum CSP 3 profile [ICRI Technical Guideline No. 03732].

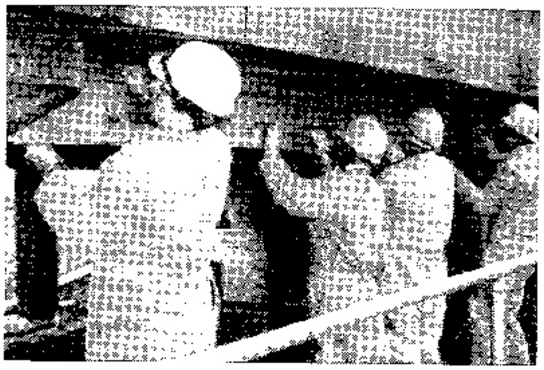


Fig. 4-1: Steel plate bonding

4.2.2 FRP Fabrics

Composite fabrics are an effective method for providing shear, confinement, or flexural strength to concrete and masonry. The most commonly used FRPs in the construction industry are carbon, E-glass, and aramid fibers. In all cases, they are used in conjunction with an adhesive, typically epoxy resins. FRP fabrics have high strength and high modulus, yet are very light and very flexible. As such, they can conform to most sizes and geometry found in the field. The fabrics can be applied in many different methods, including wet lay-up, dry lay-up, and vacuum bagging. The size and complexity of the project will usually dictate the installation method. Surface preparation is very critical for FRP applications. All surfaces to receive FRP must be clean and dry and free of contaminants. The surface concrete must be in good condition and all corrosion-related problems must be adequately addressed prior to FRP application. To check the strength of the substrate, a tensile pull-off test should be done as per ICRI Technical Guideline No. 03739. The substrate should meet the criteria of tensile adhesive strength of 200 psi (1.4 MPa) and exhibit failure in the concrete substrate. Lower strengths or failure between the FRP system and concrete or between plies should be reported to the engineer for evaluation and acceptance as set out in ACI 440.2R-02.

Fig. 4-2: Installing FRP fabric system on a slab soffit

4.2.3 FRP Plates

Composite strips or plates, most commonly carbon fiber, have been used for strengthening concrete and masonry since the early 1990s. The plates are manufactured using the pultrusion process and can be made to varying widths, thickness, shapes, and strengths depending upon the equipment and raw materials used. Because the pultruded plates are thicker and more rigid than FRP fabrics, they are generally limited to strengthening flat members such as beams or slabs for flexural applications as well as narrow elements such as joists. The members can be strengthened for positive moment (typically on the bottom) or negative moment (typically on the top).

The pultruded plates are manufactured under controlled conditions so the physical properties are generally more predictable. An epoxy paste adhesive is generally used for bonding the FRP plates onto the substrate; and because the FRP is so light, temporary supports are not necessary, even in overhead installations.

Fig. 4-3: Installing FRP plates on a concrete slab

4.2.4 Near-Surface-Mounted (NSM) Reinforcement

Another technique for flexural and shear strengthening of concrete is the use of near-surface-mounted

(NSM) reinforcement. This technique that has been successfully used for many years with conventional steel reinforcement and can also be used with FRP bars. Both CFRP and GFRP bars can be used for this application. Steel bars are typically bonded using cementitious grout or epoxy adhesive while FRP bars are typically bonded using epoxy adhesive. The size of the groove will depend on the size of the bar, type of the bonding agent (grout or epoxy), and durability requirements (cover thickness). FRP bars are noncorrosive; therefore, they can be installed in shallower grooves. This, in addition to their lightweight compared with steel, makes the installation of FRP bars faster than steel bars and may be more economical for this type of applications. The NSM reinforcement technique involves cutting a shallow groove in the surface of the member, cleaning the groove, installing steel or FRP reinforcing bar or plate, and leveling the surface. NSM reinforcement is well suited for cases in which the concrete surface is very rough, weak, or requires significant surface preparation. For these cases, creating surface groove could be more economical than preparing the surface. Because the reinforcement is embedded below the surface, NSM reinforcement is well protected from mechanical abrasion (such as traffic).

Fig. 4-4: Saw-cutting grooves for NSM reinforcement

4.2.5 Other Systems

Some of the other uses of FRP for externally bonded systems are precured shapes, such as jackets for confinement or L-shaped brackets for shear reinforcement (refer to Fig. 4-5).

FRP systems can also be post-tensioned (refer to Fig. 4-6), similar to steel tendons, provide more active strengthening to partially relieve forces carried by the existing reinforcement, close cracks in the concrete, and optimize the performance of the composite. Anchorages could be complex and should be designed to resist the tensile forces and prevent FRP damage.

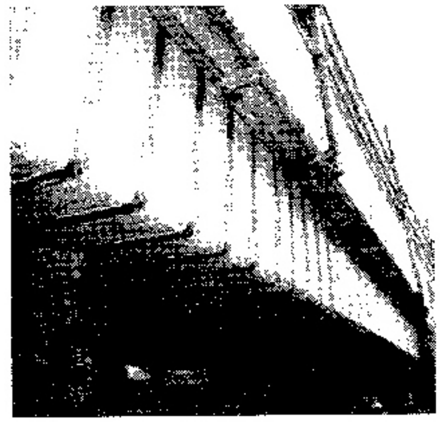


Fig. 4-5: L-shaped FRP brackets

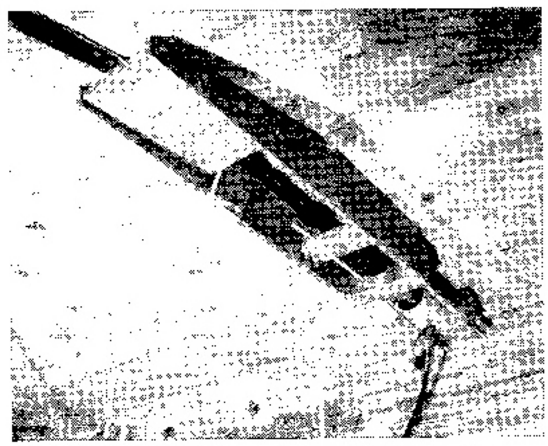


Fig. 4-6: FRP post-tensioning stressing device

Steel-reinforced polymers (SRP) is another material that can be used for structural strengthening concrete structures. SRP composites are thin

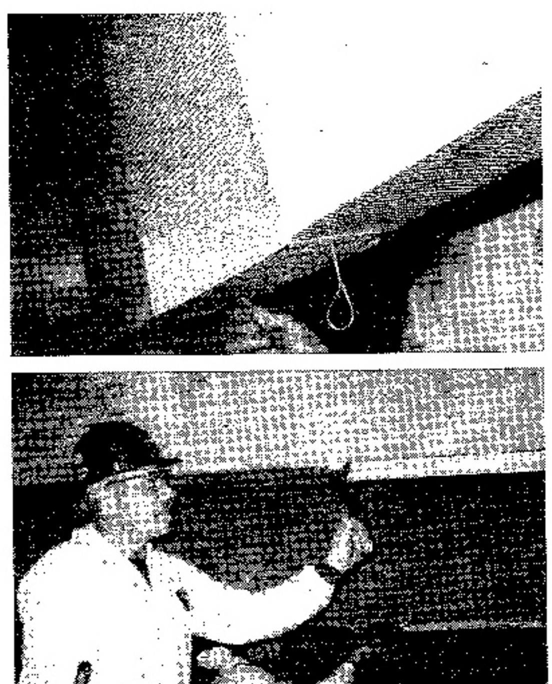


Fig. 4-7: SRP reinforcement applied with cementitious grout for precast joist upgrade

sheets manufactured with ultra-high-strength steel cords that are bonded onto the concrete substrate using epoxy resins or cementitious mortars. One of the key advantages of SRP materials is their ability to resist high temperatures when used with a cement-based bonding agent. Due to the high shear strength of the steel wires, SRP reinforcement can be mechanically anchored to the structural member.

4.3 Durability Considerations

The durability of any concrete repair or strengthening material is always an important criterion in the selection process. For externally bonded systems, durability of the substrate to which the system will be attached should be considered. The bond surface must be sound at the time of installation, as well as during the life of the system. Deterioration of this surface (freezing-and-thawing and abrasion) will adversely affect the strengthening system. If steel plates are used, they must be protected from the environment (moisture, chlorides, and chemicals) to guard against the damaging effects of corrosion. If epoxy resins or other adhesives are used in external reinforcement, special provisions must be made to protect against discoloration and degradation from UV exposure.

Special care must be taken when wrapping concrete in exterior applications. Most FRP materials are impermeable and will behave as a vapor barrier, not allowing the passage of water or vapor either into or out of the substrate. While it is certainly an advantage to protect the substrate from water, chlorides, carbon dioxide and other substances, it is also important to allow for moisture diffusion through concrete. If the moisture that is already contained within the concrete cannot escape, pressure can form behind the FRP that may lead to debonding of the FRP. In cold climates trapped moisture can lead to freezing-and-thawing deterioration. Thus, issues related to complete encapsulation should be considered whenever possible and openings may be left to allow moisture diffusion.

When using FRP strengthening systems, the engineer should consider the environment to which it will be exposed. This might include exposure to alkalinity, salt water, chemicals, ultraviolet light, high temperatures, high humidity, and freezing-and-thawing cycles. Several types of topcoats are available that could be used to increase the durability of FRP systems under various exposure conditions. For additional information regarding selection, design, detailing, and installation of FRP systems, refer to publications of ACI Committee 440.

4.4 Fire Considerations

Unless mechanical anchors are used, the use of FRP systems should be limited to supplemental reinforcement of existing structures. The primary reason for this limitation is that adhesive resins cannot resist the high temperatures generated from fire, so by restricting the FRP to supplemental reinforcement, the structure will still be capable of resisting the service level loads without collapse. The unstrengthened structure must exhibit enough reserve capacity, without the contribution from the strengthening element, to carry itself and the existing service loads without collapse. Intumescent coatings and fire barrier systems can be used to limit the flame spread and smoke development in the event of a fire, but they generally do not provide a fire rating per most building codes. Cement-based bonding agents are typically more resistant to higher temperatures than epoxies, but may have lower bond strengths.

4.5 Field Applications

Thousands of projects around the world have been successfully strengthened with externally bonded systems. The practice of steel plate bonding was first accomplished in France and South Africa in the late 1960s and early 1970s (Raithby 1980). Advanced composite materials have been commercially installed since the late 1980s, first in Japan and Switzerland, and later in the United States as part of the Caltrans seismic retrofit program for bridge piers. With the introduction of the state-of-the-art reports and design and construction guidelines from ACI [ACI 440R and ACI 440.2R], engineers now can base their designs on a resource that has been developed after years of laboratory and practical experience.

4.5.1 Beams

During construction of a garage, several post-tensioned strands in some beams were inadvertently overstressed, resulting in insufficient tensile strength in the beams. Carbon fiber plates were bonded to the bottom of the beams with an epoxy resin to restore the flexural capacity in the beams. This method was far more efficient and economical than the alternative of adding steel reinforcement encased in additional concrete. The carbon fiber plates were installed in 2 days, and the garage was opened to traffic soon after the installation is complete.

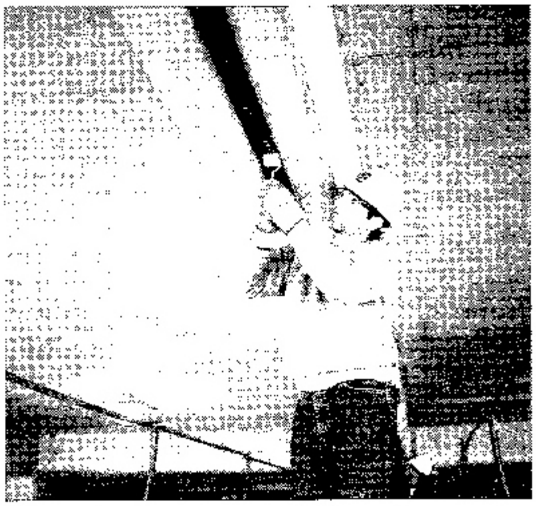


Fig. 4-8: Flexural strengthening of beam with CFRP plate

Fig. 4-9 illustrates the structural upgrade of an elevated reinforced concrete floor at a convention facility. The exhibition floor needed structural upgrading to accommodate new events and expositions that introduced higher floor loading. CFRP fabric, installed using the wet lay-up technique, was applied to bottom of the concrete girders for added flexural strength and wrapped around the stem of the concrete joist for added shear strength.

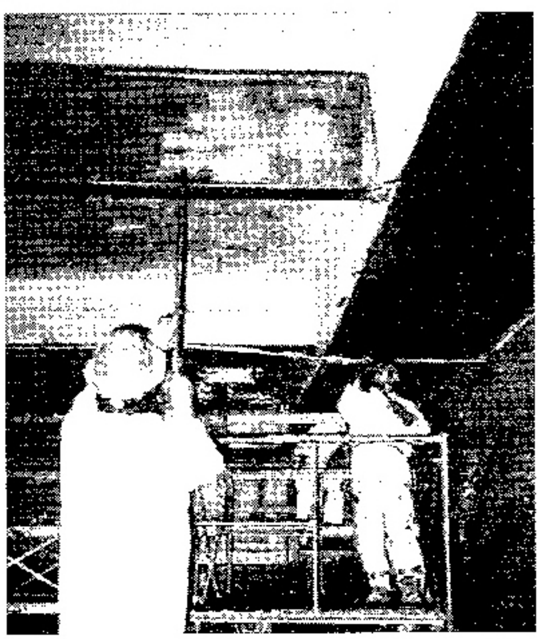


Fig. 4-9: Flexural strengthening of beam with CFRP fabric

Shear cracks were noticed in the spandrel beams of a newly constructed parking garage. To fix the problem, three layers of a CFRP fabric were installed in a 0/90 degree (horizontal and vertical) orientation. The CFRP material bridged the crack while reinforcing the beams in shear (refer to Fig. 4-10). The repairs were covered with an aluminum fascia masking the CFRP from occupants.

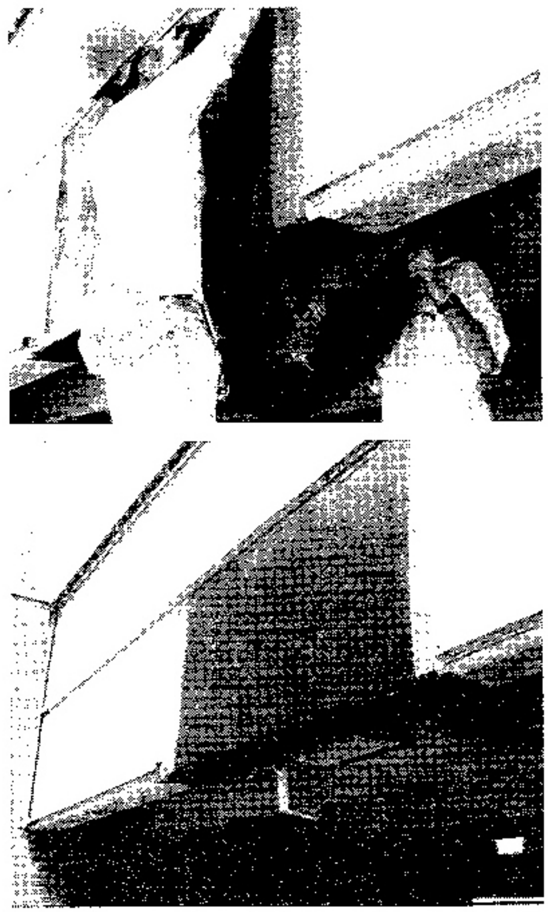


Fig. 4-10: Shear strengthening of spandral beam with CFRP fabric

4.5.2 Slabs

Large planters and landscaping elements were added to a plaza deck in a condominium project. The original deck, located over a parking garage, was not able to accommodate the heavy dead loads added to the structure. Consequently, externally bonded CFRP was added onto both the top and bottom sides of the deck for added strength (refer to Fig. 4-11). The picture below illustrates

Fig. 4-11: Slab strengthening with CFRP plates for negative moment reinforcement

CFRP plates bonded onto the topside of the plaza deck for negative moment reinforcement.

Fig. 4-12 shows the CFRP fabric installed on the topside of a structural reinforced concrete slab. This application was part of a project to convert a parking garage to office space. To meet the higher live load demand of the latter, additional moment capacities were required at the supports in the column strip in both directions (negative moment regions). The FRP was installed using the wet lay-up procedure. Because the floor was to be covered with carpeting, no additional measure was needed to protect it from damage.

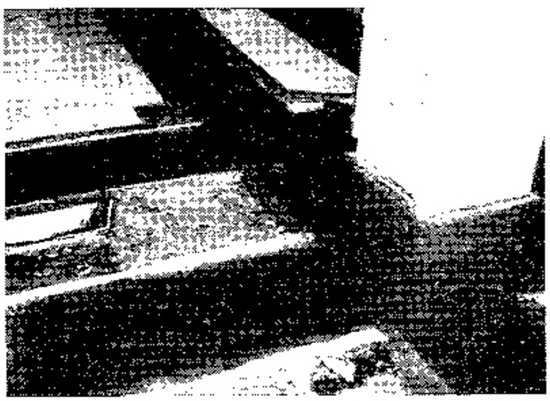


Fig. 4-12: Negative moment reinforcement for RC slab with CFRP fabric

Fig. 4-13 illustrates a structural slab in a parking garage that required flexural upgrade to increase the negative moment capacity. Strengthening was achieved using the near-surface-mounted CFRP bars technique, in which No. 3 CFRP bars were epoxy bonded in grooves made on the surface of the slab. This technique was well suited for this application as it provides protection to the FRP bars from mechanical abrasion that may result from vehicular and pedestrian traffic.

Fig. 4-13: Negative moment reinforcement of slab with surface mounted CFRP bars

4.5.3 Columns

Fig. 4-14 shows bridge columns that were seismically upgraded with GFRP fabrics to provide confinement in the event of an earthquake. The original columns were designed and built prior to code changes and were deemed inadequate to carry the horizontal and vertical loads of an earthquake. Multiple layers of the GFRP fabrics were wrapped around the columns to meet the current seismic codes.

Fig. 4-14: Seismic strengthening of bridge piers with GFRP fabrics

The concrete transmission tower shown in Fig. 4-15 exhibited signs of distress, with cracks appearing in the tension zones. All cracks were epoxy injected to structurally bond the concrete together and prevent moisture infiltration into the towers. CFRP fabric was then installed to strengthen the towers. To prevent premature CFRP failure due to stress concentration, all corners were rounded to 1/2 in. (12.7 mm) radius prior to wrapping with CFRP.

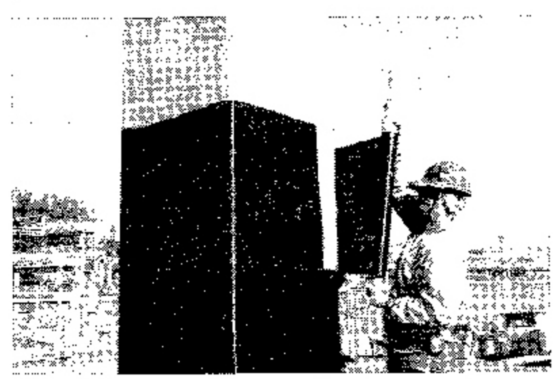


Fig. 4-15: Strengthening of columns with CFRP fabrics

4.5.4 Walls

Figure 4-16 shows the structural upgrade of a reinforced concrete wall that required strengthening due to out-of-plane bending caused by the backfill behind it. The wall was originally designed as a cantilever retaining wall and when the top of the wall was fixed by the building, it increased the flexural stress at mid-height of the wall and caused cracking in this area. The wall was strengthened using vertical strips of CFRP fabrics. The CFRP strengthening was then covered with a cementitious parge coat so there were no noticeable signs of strengthening.

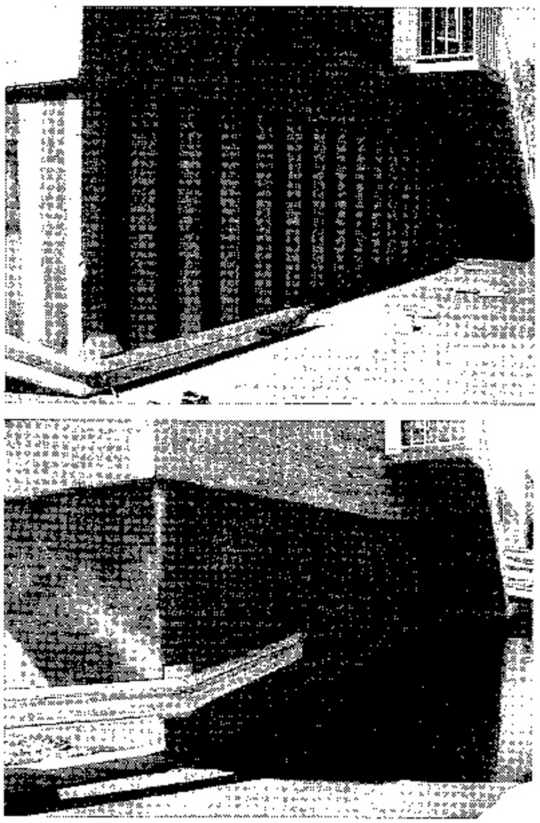


Fig. 4-16: Strengthening reinforced concrete wall with CFRP fabric

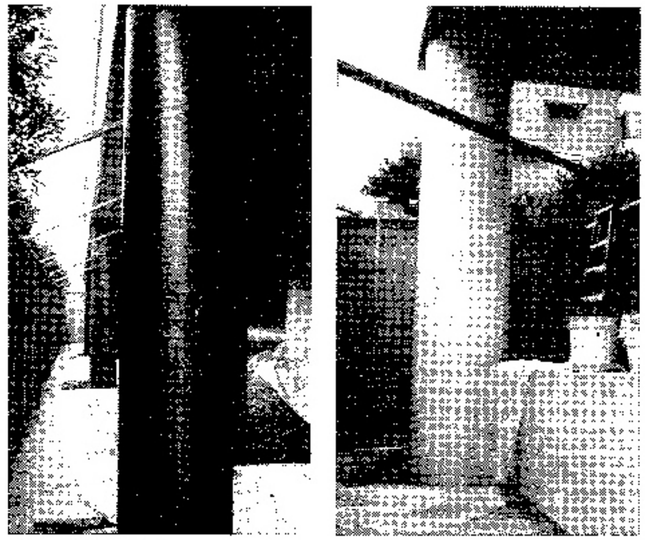


Fig. 4-17: Column confinement using CFRP fabric before and after the acrylic-based protective coating was applied

4.6 Benefits and Limitations

4.6.1 Benefits

The main benefit of externally bonded systems is the ability to retrofit existing structures to accommodate the new loading criteria, new codes, modifications, or damage with minimal alterations. This is especially true for the FRP systems due to the high strengths achieved with minimal thickness and weight added to the structure. The FRP materials also offer the advantage of being noncorrosive so that maintenance is minimal over its lifetime. FRP systems have proven to be cost-effective due to their ease and speed of installation, and they are very easy to conceal with coatings.

4.6.2 Limitations

The main limitation of epoxy-bonded systems is their inability to be used for primary reinforcement. Until an adequate fire protection or heat-resistant resin can be developed and tested, the systems should be restricted to be used as supplemental reinforcement. As with most resin systems, installation in cold weather (sub-freezing) should be avoided. However, special heating elements have been used for FRP plates, allowing installations in temperatures as low as 36 °F (2 °C). Another consideration for the epoxy resin used to bond steel and FRP plates to concrete is the thickness of the adhesive bond line. The bond line should be kept thin (typically 1/8 in. [3 mm] or less) in order to minimize creep and offer a coefficient of thermal expansion as close to concrete as possible.

Externally bonded systems should not be used as a restraint for punching shear applications. There are conventional alternatives, such as column capital enlargement or struts that will better handle the stresses from punching shear load. Also, FRP materials should not be exposed to direct vehicular traffic. They can be installed below the surface of the concrete (i.e. NSM reinforcement) or overcoated with a wearing course, such as a thin bonded polymer overlay system. If exposed directly to vehicular traffic, the fibers can be damaged prematurely and the system will be compromised.

Steel plate bonding has its own set of unique limitations as well. Steel is very heavy, making it difficult and expensive to install. Steel must also be protected and maintained against corrosion.

5.0 Post-Tensioning Systems

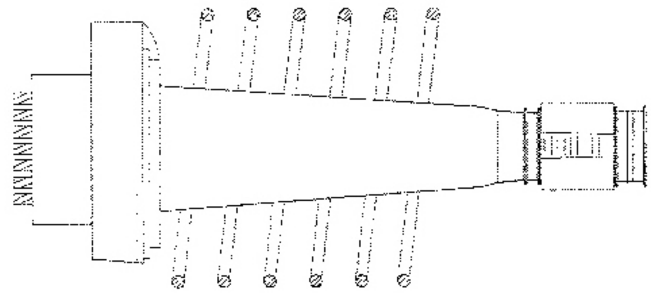
Post-tensioning is a strengthening technique that can be used to counteract tensile stresses and deflections from applied loads. Unlike mild steel reinforcement, post-tensioning provides "active" reinforcement. This is accomplished by introducing a prescribed magnitude and distribution of internal forces using external stressing bars or strand systems. Post-tensioned structures are known for their strength and durability.

Post-tensioned concrete has been used with success since the 1950s in the United States in a wide variety of new construction projects including bridges, dams, parking garages, commercial office buildings, water storage tanks, and industrial and residential slabs-on-grade. Post-tensioning has also been used extensively to strengthen existing structures for new or increased loading. Examples include upgrading existing floors for new computer or medical equipment, bridges for additional vehicular loading, and walls for increased lateral and impact loads.

5.1 Engineering Considerations

All of the general engineering considerations presented in Section 2.0 should be considered in the design of a post-tensioning system. Data related to loads, geometry, boundary conditions, mild reinforcement, and material properties of the existing structure should be gathered prior to starting analysis and design of the post-tensioning. The two primary engineering considerations are strength and serviceability. While sufficient post-tensioning should be provided to strengthen the member for factored load combinations, care should be taken not to overstress the member for the combination of post-tensioning and dead load only. Axially loaded members such as columns and walls should also be checked for buckling. This is especially important for unrestrained tendons or grouted internal tendons used to strengthen hollow core members such as masonry walls.

Special care should be taken during design to ensure an effective transfer of post-tensioning force between the structure and the post-tensioning system. Jacking forces can be quite large and can generate critical bearing, spalling and bursting stresses within the existing concrete member and/or new concrete anchor block. The two regions within the anchorage zone are the "local zone" and the "general zone." The region of very high compressive stresses immediately ahead of the anchor is the local zone. The region more remote from the anchor subject to spalling and bursting is the general zone. These areas must be carefully designed and detailed (refer to Fig. 5-1). More detailed information on reinforcement for these regions is available (refer to ACI 318; Wollman and Wollman [2000]). Anchorage at the ends of beams that are monolithic with supporting columns should be located at or beyond the beam/column joint (rather than inboard of the column face) to preclude development of significant axial tensile stress between the anchorage location and the column face.



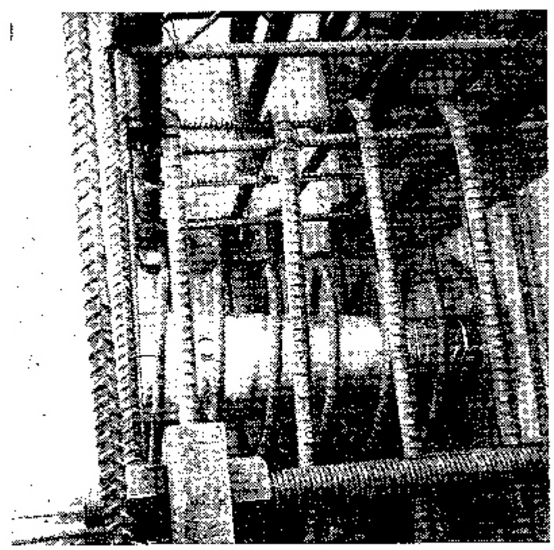


Fig. 5-1: Local zone reinforcement

When applying post-tensioning to relatively thin elements such as stems of precast T-beam flanges or hollow-core girder elements, localized compression and bursting and splitting stresses at the anchorage should be considered (refer to Fig. 5-2). For larger members where reinforced concrete anchor blocks are added to the ends or

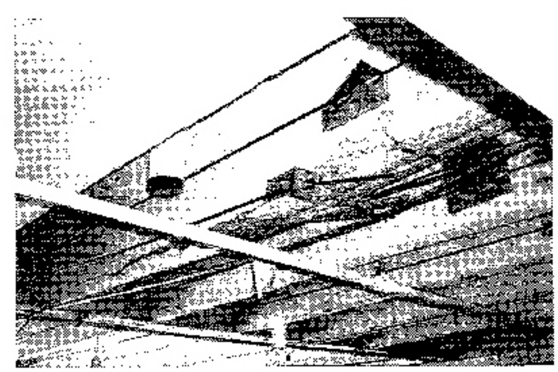


Fig. 5-2: Anchorage failure

sides of the existing member, local and general zone reinforcement are typically required in the anchor blocks.

From a serviceability standpoint, deflections, crack control, and reinforcing steel stresses at service loads should be checked for the strengthened member and for any other affected members. When an existing member is externally or internally post-tensioned, it will elastically shorten and creep to some extent. The effects on associated members should be considered. Relatively stiff elements such as shearwalls, elevator shafts, and stair tower walls create substantial restraint mechanisms. Supplemental reinforcing may be required at or near these areas of stiffness and discontinuity. Architectural considerations such as floor height limitations and aesthetics should be considered.

Prior to installation of new post-tensioning, the loss of structural capacity due to existing corrosion and spalling should be evaluated. Left unrepaired, deteriorated concrete and reinforcing may fail when new post-tensioning forces are introduced. Careful attention should also be given to protection (cover) of the new post-tensioning anchorages, tendons, and mild reinforcing.

Post-tensioning losses are another engineering consideration. These include seating, elastic shortening, concrete creep, concrete shrinkage, tendon relaxation, and friction losses. Information regarding estimation of these losses is available (refer to ACI 318 and Zia et al. [1979]).

5.2 Systems, Methods, and Materials

Two types of post-tensioning are commercially available: "bonded" and "unbonded" systems. Bonded systems are detailed to have the post-tensioning reinforcement continuously bonded to the surrounding concrete after stressing so that strain compatibility is achieved. An example of a bonded system would be strand(s) placed through a hole core-drilled longitudinally through the length of a concrete girder and grouted continuously. Unbonded systems include "monostrand" (single strand, greased, and sheathed) tendons or stressing bars that are detailed to remain unbonded after stressing.

External post-tensioning is a strengthening method in which new tendons are attached to existing members at discrete locations along the length of the members and stressed. Specially fabricated steel or concrete deviators are typically placed at midspan, third-points, or quarter-points along the span such that a harped profile is created. Depending on height clearance limitations, the tendons may be placed beneath the existing member or on adjacent sides of the member. Examples of external post-tensioning systems include those used to strengthen steel roof trusses, concrete bridge girders, and building framing systems. Examples of internal post-tensioning include grouted tendons placed through core-drilled holes along the length of a concrete member and grouted tendons placed inside the shells of masonry walls.

Positive end-anchorage and intermediate-anchorage connections are essential components of the post-tensioning design. The end-anchorages are typically referred to as "stressing end" and "dead end." Post-tension forces are introduced at the stressing end by means of a hydraulic jack with access through a stressing pocket that is later filled with non-shrink cementitious or epoxy grout. The dead end is embedded at the tendon's far end with sufficient anchorage to hold it in place. When the end anchors are more than approximately 120 ft apart, two-end stressing may be required. When the ends of the member are not accessible, center stressing may be required. This may involve construction of special steel brackets or reinforced concrete blocks (attached to the existing member) to couple or overlap the center anchors.

Harped or profiled tendons are commonly used for strengthening members including parking garage beams, steel roof trusses, and bridge girders. A variety of end-anchorage and deviators have been used for tendon profiling.

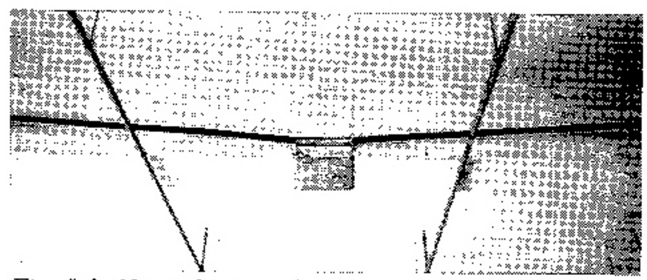


Fig. 5-3: Harped external post-tensioning system

These include welded steel assemblies bolted to the existing concrete, cast-in-place concrete anchorages, and cast-iron or fabricated steel assemblies that accommodate center stressing. Special care should be taken when profiling monostrand tendons that bear directly on the deviator. Smooth or cushioned edges should be provided to preclude damage to tendon sheathing.

In addition to post-tension strand, high-strength post-tension bars have been used to strengthen existing members. Applications include masonry walls (flexure and shear), commercial building beams and girders (flexure), and transverse reinforcing at anchorage blocks (shear). Post-tension bars are particularly advantageous for shorter length applications compared with post-tensioning strands due to the elimination of seating losses (reduction of the effective stress in the strand due to setting of the wedges in the anchorage wedge cavity).

5.3 Durability Considerations

Corrosion protection is required for post-tensioning systems (tendons and anchorages) exposed to harsh environmental conditions. Multistrand tendons are typically encapsulated in corrosion-resistant, high-density polyethylene or galvanized metal corrugated ducts. Low-bleed cementitious tendon grout is used to further encapsulate and protect the strands. Multistrand end-anchorages may be enclosed in a permanent grout cap or encased in concrete or epoxy grout.

Single post-tensioning strands not exposed to ultraviolet rays may be protected using the traditional "grease and sheath" system where a corrosion-resistant lubricant is placed on the strand. The strand and grease are encapsulated in a 50-mil thick continuous high-density polyethylene seamless sheathing that is extruded onto the strand during the manufacturing process. Other means of protection for strands and bars include galvanizing and application of corrosion-inhibiting coatings. Monostrand end anchorages can be protected using one of several coatings: epoxy, plastic, or galvanic. Plastic coatings are often favored due to their performance and economy. Anchorage assemblies are available that include a plastic trumpet to seal the last few inches of strand near the anchor and a plastic end cap to protect the tendon tail.

5.4 Fire Considerations

The post-tension strengthening system should be designed to provide a fire rating similar to that of the existing structure. Strength, modulus of elasticity, expansion, thermal conductivity, creep, and stress relaxation are all affected to some degree by elevated temperatures. Unprotected strands are particularly susceptible to fire damage. Approximately one-half of a tendon's strength is retained at 800 °F [ACI 216R]. This is considered the critical temperature for post-tensioning strand. Rational analytical procedures for the determination of the fire endurance of post-tensioning systems have been developed from analyses of results of fire tests [ASTM E 119] and are available (refer to *Post-Tensioning Manual* [1990]).

Grouted internal post-tensioning systems have the inherent benefit of full encapsulation. External systems (tendons and anchorages) may be encased in precast or cast-in-place concrete for fire protection. An external post-tensioning system encased in a precast fireproofing shell is shown in Fig. 5-4.

Fig. 5-4: External PT system encased in concrete

Heat-resistive tendons are also available that are specifically designed to mitigate the detrimental thermal effects of a fire on strength of post-tensioning strand (Fig. 5-5). While these tendons have the same grease coating and exterior extruded polyethylene sheathing as typical unprotected monostrand tendons, they also include a 25-mil thick fire retardant coating. These tendons are specifically designed to mitigate the detrimental thermal effects of fire on strength of post-tensioning strand.

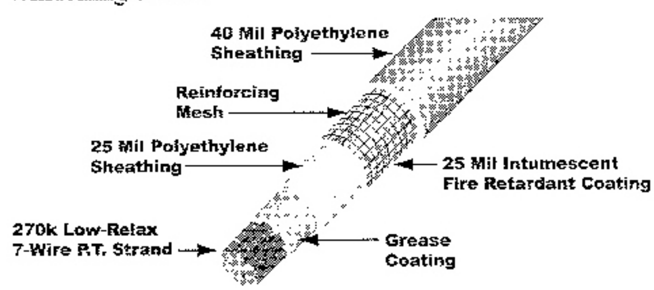


Fig. 5-5: Heat resistive post-tensioning tendon

5.5 Field Applications

5.5.1 Commercial Building

Post-tensioning was used on this two-way flat slab system shown in Fig. 5-6 when a retrofit was required to accommodate new tenants that required a greater floor load capacity. Multistrand tendons were placed directly beneath the slab and upward loads were introduced into the floor system at discrete points using specially fabricated steel deviators. Note the carbon-fiber composite material visible in this photo that was used to supplement the post-tensioning.

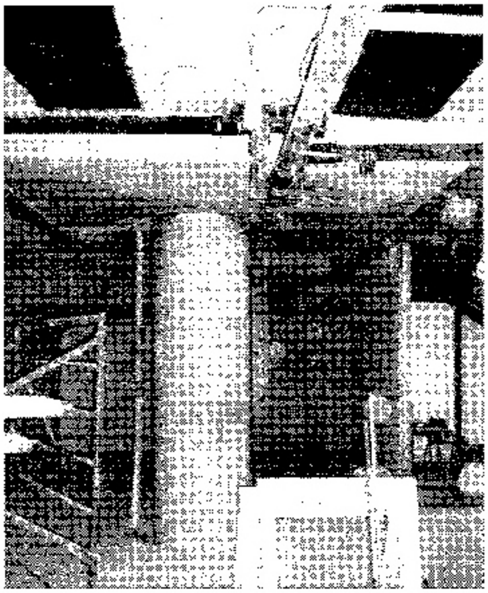


Fig. 5-6: Externally post-tensioned flat slab

5.5.2 Parking Garage

Post-tensioning tendons were placed on each side of the concrete beams in a parking garage with a low point deviator at midspan (Fig. 5-7). The external post-tensioning system was installed to supplement the original post-tensioning system, which had been compromised by deterioration due to corrosion of the prestressing steel and anchorages.

Fig. 5-7: Externally post-tensioned concrete beams

5.5.3 Historical Structure

Post-tension tendons were used to strengthen an architectural landmark built over a waterfall (Fig. 5-8).

Fig. 5-8: Historic structure strengthened with external PT

Multistrand tendons were placed on each side of several large concrete cantilevers that were deflected past tolerable limits. The tendon stressing process is shown in Fig. 5-9. After stressing operations were complete, the tendon tails were cut and the exterior access holes were repaired.

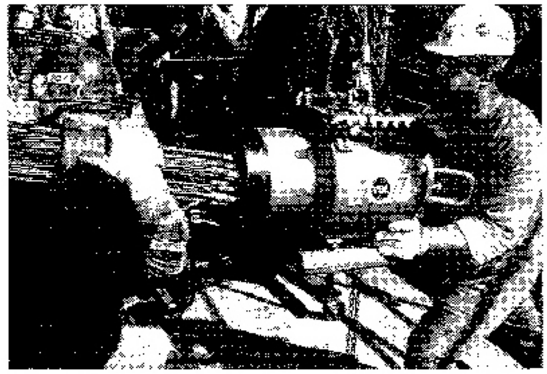


Fig. 5-9: Tensioning of external PT tendons

5.5.4 Industrial Plant Facility

Multistrand post-tensioning was used to strengthen girders of a concrete tower (Fig. 5-10). Holes were core-drilled along the length of each girder to provide access for the new tendons (Fig. 5-11). The core-drilled holes were scarified with high-pressure water to ensure a rough substrate to ensure bond to the existing structure. New reinforced

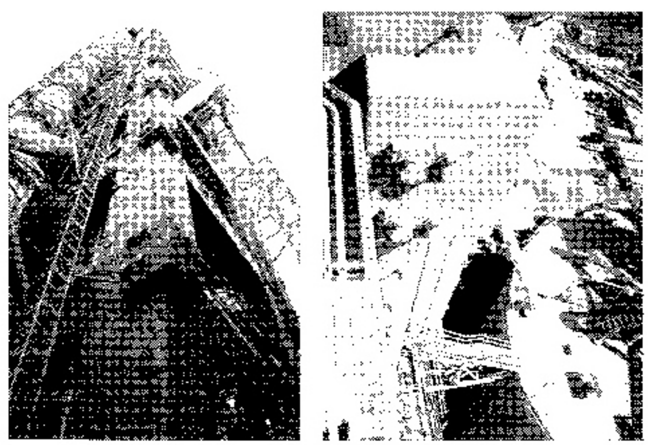


Fig. 5-10: Anchorage plates

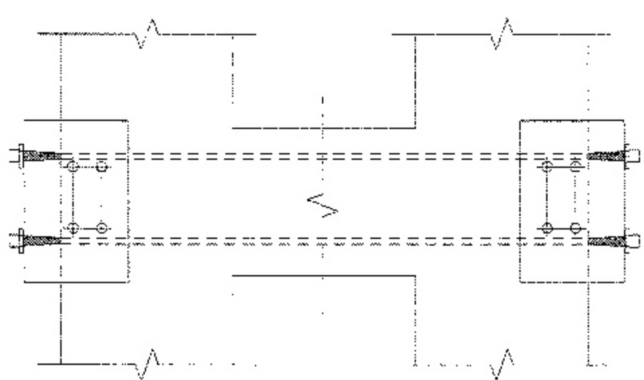


Fig. 5-11: Industrial frame

concrete anchorage blocks were doweled and cast to provide adequate anchorage zone capacity. The tendons were stressed and grouted after installation. Special end-anchorages including bearing assembly, anchor heads, and grout caps were fabricated for strength and long-term durability.

5.5.5 Sports Arena

An external post-tensioning system was installed on the ring beam of this folded dome (Fig. 5-12) to supplement corroded bare strands encased within the ring beam (Fig. 5-12). Forces were transferred to the ring beam by steel deviators that transferred the load directly to the structure (Fig. 5-13). Special shop-fabricated structural steel deviator brackets were placed at each existing column location. The prestressing steel was protected by high-density polyethelene duct and grouted after stressing.

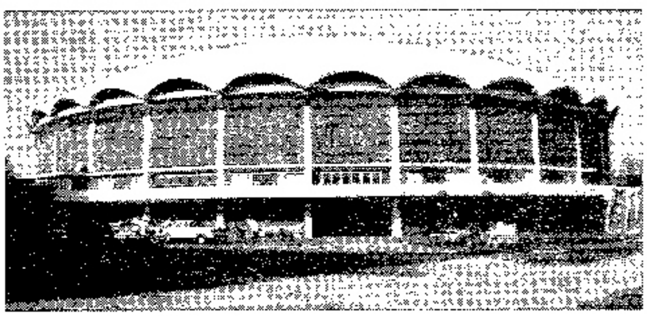


Fig. 5-12: Sports arena

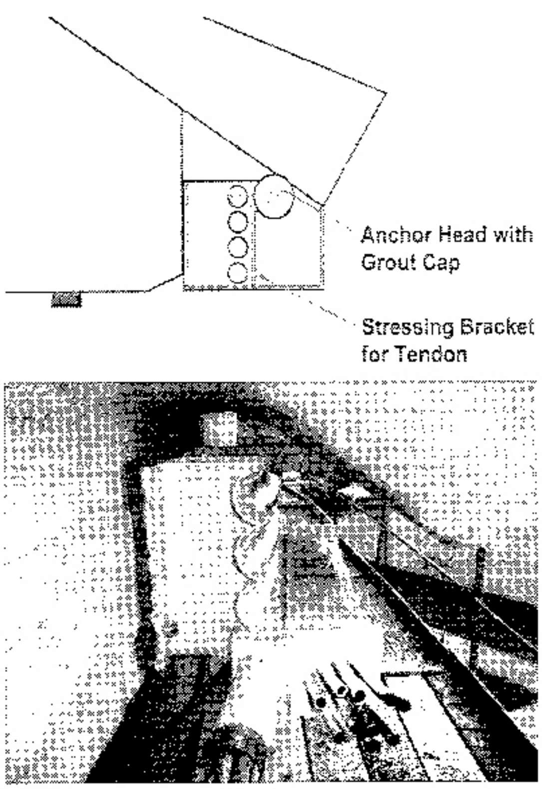


Fig. 5-13: Deviator brackets

5.5.6 Bridge

Post-tensioning was used to strengthen the pier cap of a major bridge (Fig. 5-14). Vertical cracks had opened in the cap due to an insufficient amount of reinforcing steel. The external post-tensioning system consisted of bar tendons that were encapsulated in a double corrosion protection system and anchored by a welded structural steel grillage. The tendons were stressed after the cracks were injected with epoxy.

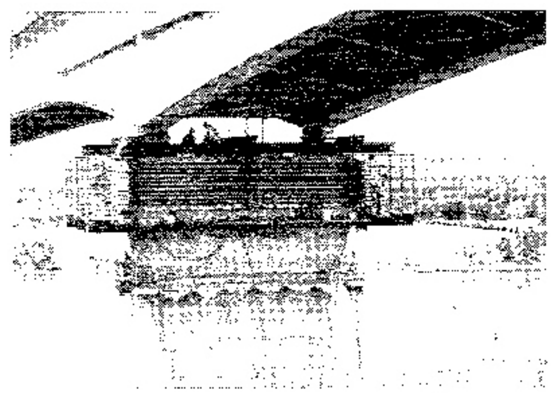


Fig. 5-14: External post-tensioning of pier cap

5.6 Benefits and Limitations

5.6.1 Benefits

The technical benefits of post-tension strengthening include upgraded strength and serviceability. Forces generated by post-tensioning are generally used to offset flexural tensile stresses and vertical deflections. With such active strengthening, existing structures can be upgraded to support more loads than those included in the original design. Post-tensioning can provide greater strength increases than can be provided by passive techniques. Another benefit is that the concrete will be more resistant to water penetration because post-tensioning causes existing cracks to tighten. From a construction viewpoint, savings may be realized due to decreased amounts of material and labor compared with mild reinforcement strengthening.

5.6.2 Limitations

Post-tension strengthening is limited primarily by constructability challenges. Interferences such as existing mechanical, electrical, and plumbing utilities must be considered. Only specially trained technicians should conduct installation and stressing. Careful drilling through existing concrete may be required to provide access for new tendons. Also, a positive means of anchoring (such as reinforced concrete or structural steel) the post-tensioning system to the existing structure is required. This may be difficult when access to the ends of the member is limited. Careful records of new post-tensioning locations should be kept in the event that future structural modifications are required.

Post-tension strengthening may also be limited by the magnitude of overstress in the existing structure. The amount of post-tensioning required to counteract relatively large live loads may overstress the structure in the unloaded condition. Staged stressing may be required when additional dead and live loads are added to certain structures during the installation of the strengthening system. Such situations may warrant the use of post-tensioning in conjunction with other strengthening methods including span shortening, section enlargement, and composite strengthening.

6.0 Supplemental Supports

Supplemental support strengthening involves the addition of new structural element(s) to an existing structure to reduce the effects of external forces on a deficient structural component. This technique can also be used to increase the load-carrying capacity of the existing structural components. The new supplemental support could be a single structural element or a system consisting of several elements such as beams, columns, and hangers. In addition, a supplemental support system can be used to completely bypass a damaged or deteriorated element. In this case, the supplemental system is designed to act as a stand-alone system that supports the service loads.

Supplemental supports can be used to reduce shear and flexural stresses, increase the load-carrying capacity of a structure, or increase the stiffness and reduce deflections. It may also be used to improve the lateral stability of the structure or its components. Similar to other strengthening techniques, the effectiveness of a supplemental support system may be greatly affected by design and detailing of its components, material selection, and installation procedure.

6.1 Engineering Considerations

All of the design issues presented in Section 2, General Engineering Considerations, should be considered when designing a supplemental support system. Key considerations for this method of structural strengthening include:

- Sizing of the new members—Initial sizing of the member should be determined based on strength requirements to carry the specified loads. In addition to strength, stiffness, which is a function of the new member size, plays a key role in determining the effectiveness of the supplemental system. The designer should consider the effects of the stiffness on load sharing between new and existing members. For example, a stiffer member typically attracts a higher portion of the applied load. In addition, the increase in stiffness created by the new members may alter the original state of load distribution for adjacent elements. The new state of stresses in these adjacent elements must also be checked to verify adequacy.
- Material selection—supplemental systems may be constructed of steel, concrete, or other suitable construction materials. The type of materials used to construct a supplemental support system carries design impacts similar to those of member sizing (e.g., impact of stiffness). In addition, compatibility of the new materials with those of the existing structure may affect the overall performance and durability of the upgraded structure.
- New load path considerations—Introducing a supplemental support system may produce new load paths that need to be thoroughly investigated. The new members will carry all resulting forces and transfer them to existing elements and eventually into the foundation system. Existing elements affected by the new load path should be checked for possible overstress conditions. If not properly addressed, the new load path may shift the deficiency problem to other parts of the structure. For example, a new column installed to support an existing beam may produce bending and shear forces in the beam at the new connection that may exceed the localized shear and flexural capacities of the beam.
- Detailing of connections—Connections must be designed to adequately transfer all loads from the new members to the existing members. In addition, connections should be designed and detailed for forces resulting from the relative movement of the structural components. These include movement caused by thermal effects or load deformations. Special care should be given to detailing connections, as the design approach may be different from that of new construction. Connections can be established using mechanical or adhesive anchors. Both require drilling holes into the existing

structure. Friction connections may also be used. Challenges include designing connections that can be properly installed while avoiding damage to existing reinforcement.

- Intimate contact requirements—To ensure that the new members are actively engaged in load sharing, the new supplemental members must have intimate contact with the existing structure. For example, if the new concrete column supporting an existing beam does not have full contact with the beam (e.g., due to shrinkage after placing the new concrete column), it will not be engaged until the beam has deformed enough to transfer load to the column. To resolve this, supplemental supports may be set to allow for a small gap between the existing members and the new supporting member. A non-shrink grout is then dry-packed in the gap between the two members to establish intimate contact. The use of hydraulic jacks to lift or relieve existing loads on the existing member prior to installation of the supplemental support can also be used to achieve intimate contact.
- Achieving composite action—When designing a supplemental support that requires composite action with the existing structure (e.g., steel beam to be composite with existing concrete slab), the ability of the system to perform as one unit can only be achieved by ensuring ability to transfer horizontal shear forces. This can be accomplished using shear dowels and mechanical or adhesive anchors. See ACI 318 for design of shear reinforcement.

6.2 Systems, Methods, and Materials

The intent of a supplemental strengthening system is to improve the load-carrying capacity of a structural system by sharing part or all of its current loads. This can be achieved using several methods such as installing new supports to shorten the span of a structural member or extending existing supports to increase the reaction or bearing area. This typically results in reductions in the magnitude of external forces acting on the member such as bending and shear stresses. This method can also reduce deflections. Examples of this technique include installing new members between, under, or alongside existing ones, the use of tiebacks, and new structural framing to support walls to improve strength or performance. Prefabricated steel or concrete elements and cast-in-place reinforced concrete members can also be used to construct a supplemental support system.

Bearing extension is another example of a supplemental support system. This method is intended to engage a larger part of a member at its supports to relieve stresses such as bearing and punching shear.

6.2.1 Span Shortening

The span shortening method consists of erecting new supports some distance away from the existing supports to shorten the span of an overstressed member. The new supports may consist of a vertical column, diagonal bracing, or lateral beam. All these new supports can be constructed using reinforced concrete, structural steel shapes, or a combination thereof. This technique is very effective for increasing the load-carrying capacity of existing horizontal members that are dominated by the flexural behavior. However, span shortening of vertical flexural members such as walls may be achieved using lateral support systems consisting of tiebacks or lateral beams.

Shortening the effective span of a member will reduce the effects of external loads acting on the member, such as bending moment, shear forces, and deflections. The effectiveness of this technique depends on the member geometry, boundary conditions, and the ratio of existing span to the shortened span. For example, reducing the span of a beam to one-half that of the original results in bending and shear forces that are one-fourth and one-half, respectively, of the original forces. Design and detailing of the new support system should account for support configuration and materials used in construction. The designer should verify that the supported member is able to resist the new forces exerted at the new supports. For example, a knee brace supporting an existing beam and reacting to an existing column may exert new bending and shear forces on the beam and the column. These new forces will change the stress condition at the new connections. If not addressed, new forces created by the supplemental support may overstress the existing structural members and produce localized failure. If a new concrete or steel column is used for span shortening, it should be properly founded. New spread footings, drilled piers, or helical anchors can be used to create a new foundation.

Span shortening may also be achieved using lateral elements that run transverse to the span of the member and parallel to the existing line of support. The new lateral member is typically connected to the existing structure or to new column supports. Mechanical or adhesive anchors are typically used to connect the new lateral member to the existing structure.

The use of span shortening techniques may require sacrificing floor space or headroom and may have a negative impact on the aesthetics of the structure. Intimate contact with the existing structure must be achieved in order to ensure an effective load-sharing system.

6.2.2 Supplemental Framing

Extensive damage or deterioration of existing structural members may dictate the use of supplemental framing to provide an alternate load path that relieves part or all of the loads acting on the damaged member. Supplemental framing could be made of a single element or several elements that would restore or increase the capacity and stiffness of the deficient structure. An example of this method is the installation of new concrete or steel beams under, alongside, or between existing beams or joists. These new members would carry part of the external load and transfer it to existing or new supports. Another example of this strengthening method is the use of steel frames and diagonal braces to increase the lateral load resistance of a structure and provide a strengthening system for wind, hurricane, and blast loading.

Most supplemental framing systems are constructed using structural steel shapes or concrete. Selection of the material type depends on many issues such as compatibility with the existing structure, loss of headroom, fire performance, cost, and aesthetics. Steel members can be installed quickly and have well-defined design and detailing standards. Typical challenges associated with using steel shapes include their heavy weight and length restrictions to account for transportation, access, and handling issues. The use of concrete can resolve these issues since it can be cast in place and formed into any shape to accommodate the existing geometry of the structure with minimal impact on aesthetics. In addition, concrete is known to be a durable material with very good fire-resistance properties.

Similar to other methods of strengthening, the use of a supplemental framing requires intimate contact with the existing structure. This could be achieved by using dry packing, post-tensioned elements, or the use of hydraulic jacks to apply lifting forces prior to installation.

6.2.3 Support Extensions

Deterioration or deficiency of a member at its supports may create the need for extending the existing supports to improve its capacity or bearing area. Systems used to extend the existing support may be detailed to share load with the existing support or to replace it completely. It can be achieved using steel shapes such as stiffened steel angles and steel hanger assemblies. It can also be achieved using reinforced concrete. Casting a new section to an existing concrete corbel is an example of using reinforced concrete to achieve a bearing extension.

Integrity of the structural member at the supports must be restored and the source of deterioration must be identified and corrected prior to strengthening. Attachment of the new extension to the existing structure is typically achieved using mechanical or epoxy adhesive anchors. Connection details must be designed to accommodate all forces acting on the supports including lateral movement that may result from thermal variations or load deformation. Bearing pads may be used to reduce friction that may restrain the lateral movement of the element. Bearing pads or slide bearings are typically installed at the simply supported ends of structural members such as concrete tees, inverted tee girders, and bridge girders.

6.3 Durability Considerations

Environmental exposure conditions will typically determine the durability of a strengthening system. Depending upon exposure and life expectancy, several factors that affect durability such as material selection and protection methods such as coatings, galvanizing, stainless steel, and others should be considered.

Some construction materials may exhibit reduced mechanical properties after exposure to certain environments, such as alkalinity, salt water, chemicals, ultraviolet light, high temperatures, high humidity, and freezing-and-thawing cycles. Materials properties used in design may need to be adjusted to account for the anticipated service environment to which the upgraded system may be exposed during it's service life. The designer should select the strengthening system based on the known behavior of that system in the anticipated service conditions, which can be obtained from the manufacturer.

Steel elements must be protected with a suitable corrosion protection system and its long-term durability properties and maintenance requirements must be fully considered. Structural steel elements may not be suited as a long-term solution for a structure subjected to aggressive environment.

6.4 Fire Considerations

Fire protection should be considered in design of supplemental support systems, especially if the new element is being required to carry primary loads. The same requirements for new concrete construction apply to the design of concrete and steel supplemental support systems. For fire consideration and detailing, the reader is referred referred to ACI 318, ACI 216, and the American Institute of Steel Construction (AISC) Design Guide 19. Local and national building codes should be followed regarding fireproofing these new or supplemental members. Additionally, when fire protection is critical, mechanical or grouted anchors may be used in place of epoxy anchors.

6.5 Field Applications

6.5.1 Span Shortening

A parking garage that supplies approximately 1000 parking spaces for a commercial office rental property consists of four parking levels with the lowest level built on-grade. The garage deck is two-way, cast-in-place concrete, post-tensioned, flat slab supported by cast-in-place concrete columns with drop panels. Analysis of the slab indicated that large overstress existed in the column strip at the second level end bays. The structural deficiencies were resolved using diagonal steel supports installed under the second floor slab. The new supports reduced the clear span between the columns and eliminated deficiencies in both positive and negative moment regions of the slab. Fig. 6-1 shows typical new steel framing in the end bay of the second level. In addition, due to excessive deflections of the cantilevered end bays that developed over the years, additional steel supports were installed to arrest further displacement. Fig. 6-2 shows typical support of the cantilevered bay. At each additional support point, a hydraulic jack was used to "pick up" part of the dead load of the slab prior to installing the new supports.

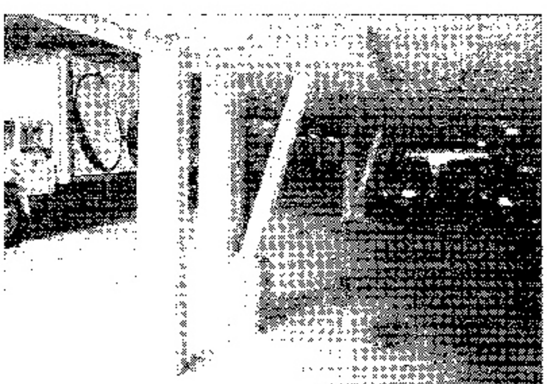


Fig. 6-1: Diagonal steel support and new foundation installed to support the slab

Fig. 6-2: New steel support to support the cantilevered slab end

6.5.2 Supplemental Framing

During a forensic investigation of the strands and anchors of a post-tensioned beam, it was discovered that extensive corrosion of the post-tensioning system had occurred which degraded the structural capacity of the beam. The corrosion appeared to be progressive, and the engineer was concerned about the long-term effectiveness of the beam. A new supplemental steel frame consisting of beams and columns was installed directly under the deficient beam. The steel beam was set slightly lower than the concrete beam, and the gap was dry-packed with a non-shrink cementitious material. Intimate contact and proper connection details of the steel frame to the existing structure ensured an adequate new load path (refer to Fig. 6-3).

Fig. 6-3: Supplemental steel frame under deteriorated beam

Supplemental strengthening was used to reinforce a cracked concrete wall in the basement of a parking garage structure. The wall was found to be under-reinforced, and the reinforcement that existed had been improperly placed. The resulting load from the soil pressure caused flexural cracking of the wall allowing groundwater to seep through the cracks and corrode the existing reinforcing steel. The cracks were sealed and a supplemental steel framing system was installed to stabilize the wall, as shown in Fig. 6-4.

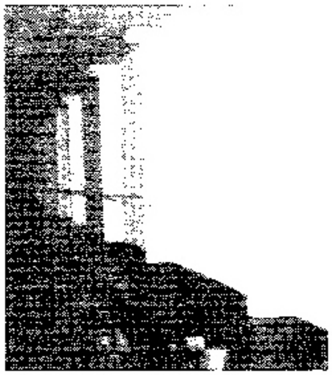


Fig. 6-4: Supplemental steel framing for wall stabilization

A change in use of a concrete structure required an upgrade of an existing slab and joist system. Additional live loads from new storage and filing systems exceeded the capacity of the existing elements. A combination of two methods was used to achieve the new live-load requirements. For the joist system, supplemental steel C-sections were installed alongside deficient joists. The slab section was upgraded using steel I-sections to cut the span in half. Steel angle X-bracing was then used to connect and stabilize these new elements (refer to Fig. 6-5).

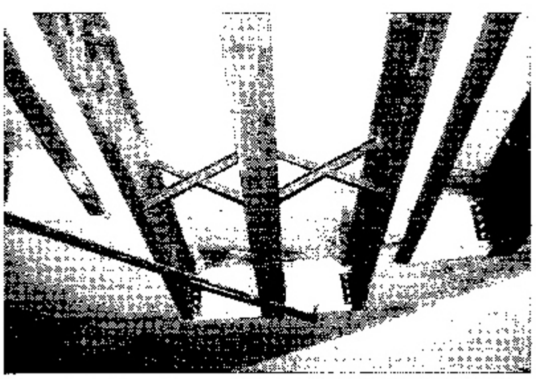


Fig. 6-5: Supplemental steel beams installed to share load with concrete joists

6.5.3 Support Extensions

The ledges of precast-prestressed inverted tees on an elevated parking deck were inadequate to carry loads from double tee stems. Deficiency was limited to the free ends of the ledges and was caused by increased truck loading on the elevated garage deck. Strengthening of the ledge was achieved by installing a steel tube assembly that provided supports to the free ends of the ledges of the inverted tee beams (refer to Fig. 6-6). Neoprene pads were installed between the new steel assemblies and the concrete ledge to allow for lateral movement of the inverted beams.

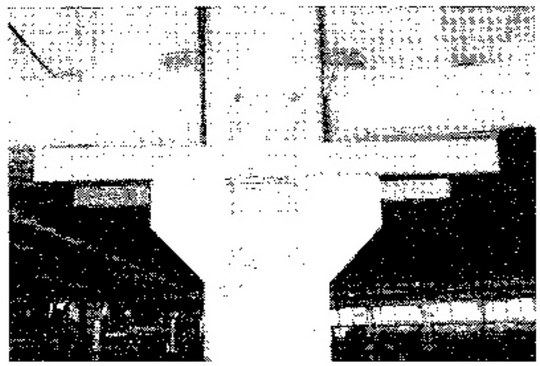


Fig. 6-6: Steel tube assembly used to support the free edge of inverted tee beam

Due to aging and deterioration, restraint of the lateral movement caused cracking and spalling at the supports of the double tees that degraded the capacity at the bearing areas. This was resolved by installing a new steel hanger that provided support extension and increased the bearing areas (refer to Fig. 6-7).

Typical punching shear cracking indicated a deficiency in the slab/column connections in

Fig. 6-7: Joist bearing extension with steel assembly bolted to inverted tee beam

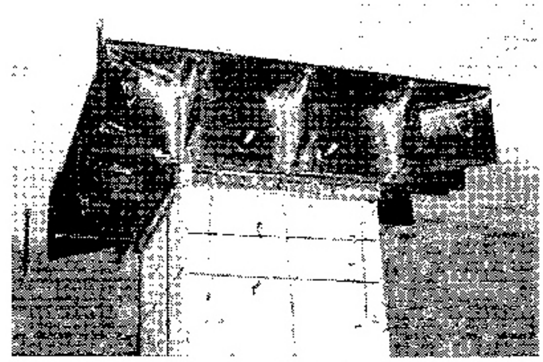


Fig. 6-8: Support extension at top of column to increase punching shear capacity

an office building. To strengthen the connections, steel angle brackets were epoxy bonded and bolted to the four sides of each column face to extend the bearing area. A gap was intentionally left between the steel angle and the slab so it could be dry-packed with cementitious grout to ensure intimate contact (refer to Fig. 6-8).

6.6 Benefits and Limitations

6.6.1 Benefits

Performed properly, strengthening using the supplemental support method can be used to increase the flexural, shear, and torsional capacity of existing members. This method is effective for highly deficient members that require significant reduction in external load effects. It is also effective for members that require a substantial increase in stiffness and improved serviceability limitations (deflection and crack width). Design principles and materials used in construction are well known to the contractor and the engineer. With the use of a standard fireproofing system, fire rating is achievable. The supplemental system can be designed to carry a substantial portion or all of the existing or new loads and could be treated as a primary load-carrying member.

6.6.2 Limitations

Limitations to this technique include loss of space or headroom, significant additional weight of the new concrete and possible higher cost due to the extensive work to provide access to prefabricated steel and concrete elements, connection to existing structure, and the possible need for new foundations. Depending on the complexity and size of the new support system, it may require longer installation time than other strengthening methods or may create challenges related to delivering the new support elements to the work site due to access. Supplemental systems typically require the use of connections consisting of mechanical or adhesive anchors, both require drilling holes into the existing structure. Challenges include designing connections that can be properly installed while avoiding damage to existing reinforcement. Corrosion of exposed steel shapes is possible, especially in harsh environments. This can be avoided by using adequate corrosion protection systems (coatings and encasing in concrete).

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ACI 216R, "Guide for Determining Fire Endurance of Concrete Elements"

ACI 318, "Building Code Requirements for Structural Concrete and Commentary"

ACI 437R, "Strength Evaluation of Existing Concrete Buildings"

ACI 440R, "State-of-the-Art Report on Fiber-Reinforced Plastic (FRP) Reinforcement for Concrete Structures"

ACI 440.2R, "Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures"

ACI 364.1R, "Guide for Evaluation of Concrete Structures Prior to Rehabilitation"

ACI 201.2R, "Guide to Durable Concrete"

American Society for Testing and Materials (ASTM)

ASTM E 119, "Standard Test Method for Fire Tests of Building Construction and Materials"

SEI-ASCE 11-99, "Guideline for Structural Condition Assessment of Existing Buildings"

International Concrete Repair Institute (ICRI)

ICRI Technical Guideline No. 03730, "Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion"

ICRI Technical Guideline No. 03732, "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays"

ICRI Technical Guideline No. 03733, "Guide for Selecting and Specifying Materials for Repairs of Concrete Surfaces"

ICRI Technical Guideline No. 03739, "Guide to Using In-Place Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials"

"Strengthening and Stabilization of Concrete and Masonry Structures," Various authors.

Society for Protective Coatings

SSPC-SP 5/NACE No. 1, "White Metal Blast Cleaning"

American Institute of Steel Construction

AISC Design Guide 19

These publications may be obtained from these organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428

International Concrete Repair Institute
3166 S. River Road, Suite 132
Des Plaines, IL 60018

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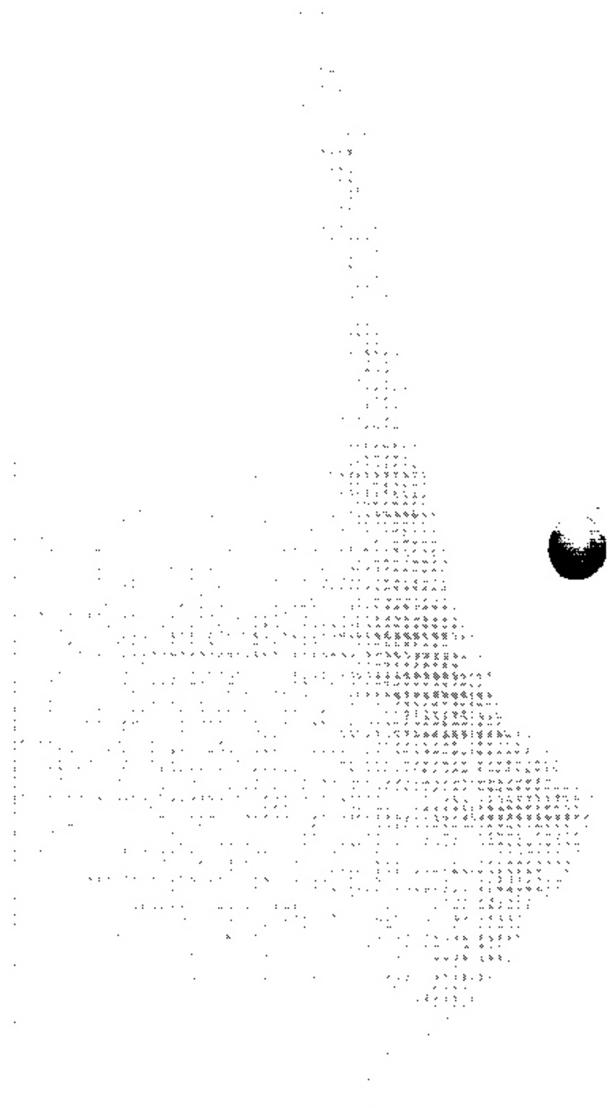

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