Concrete Problems and Repair Techniques

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INTRODUCTION

Concrete (mixture of cement, aggregates and water) is a mass of aggregates (75%) glued together by a cement matrix (25%) in between all different sizes of aggregates. The cement portion of the concrete although makes up 25% of the volume, really determines all the physical properties in durability and strength areas. It is also where a large portion of concrete problems originates. One of the most critical components of good concrete is water. As pointed out by Mehta et al (1992) that water is "at the heart of most of the physical and chemical causes underlying the deterioration of concrete structures". Among other effects, moisture levels determine the risk of corrosion attack occurring on steel reinforcement and the rate of deleterious mechanisms such as alkali-aggregate reaction (AAR). At the same time a long-term ageing effect caused by drying-out of the cement matrix in concrete will be evident and the result will be reduced strength. A combination of dry and wet concrete may cause differential shrinkage which in turn may well lead to cracking. A balanced and stable moisture level would seem to be desirable, but cannot be achieved since the structural members are subject to different environments.

“Durability of concrete is defined as its ability to resist weathering action, chemical attack, abrasion or any other process of deterioration. Durable concrete will retain its orinal form, quality and serviceability when exposed to environment.” (ACI 201.2 R92).

Repair and rehabilitation of deteriorated concrete is an art as well as a science. The repair engineer must have the imagination to select and adapt any of several repair techniques to fix the existing defect. Why Repair and Rehabilitation of Concrete?

1. Restore or improve structural integrity
2. Improve appearance
3. Improve durability
4. Improve functional performance
5. Provide water-tightness

Developing a proper repair strategy to address concrete problem requires an understanding of the CAUSE of the problem. Understanding the cause allows for a repair that addresses both cause and effect. One should keep in mind that the repair systems are not easily classified into a cookbook type code with design procedues. In fact the quality of a structure in the sense of integrity and potential durability is almost totally dependent on the quality of the construction. It could therefore be argued that condition assessment should be done at as early an age as possible preferably immediately following construction.

CONCRETE REPAIR PROCESS

The concrete repair process involves cause/effect relationship, concrete evaluation, analysis & repair strategy. The steps as illustrated in Figure 1 are as follows:

1. seeing an EFFECT
2. determining the CAUSE
3. deciding whether the problem needs to be repaired
4. conducting some form of condition survey to quantify problems
5. dealing with repair analysis and engineering issues in the repair
6. determine repair strategies that includes methods, techniques and repair materials
7. finally, accomplishing the repair

One challenge in determining cause/effect relations (step 1 & 2) in concrete problems is somewhat of a "chicken and an egg" correlation. After the cause/effect relationship has been determined the next question is: Is a repair actually required? (step 3) This is an issue that the owner deals with and he has various motivation to do so. The evaluation process (step 4) re-confirms the cause/effect relations as well as evaluates, quantifies, prioritize and documents the repair. The repair analysis (step 5)will have 2 perspectives: the owners (cost, urgency and life cycle, aesthetics) and the engineers (structural requirements, constructability, repair environment, safety. The issues reviewed in these perspectives will determine repair strategy specific means, methods and repair material. In the repair strategy (step 6) we develop means, methods and material to fix the problem:

i. *Surface repair* - removal and replacement of deteriorated concrete
ii. *Strengthening* - strengthen or enhance capacity of a structural member
iii. *Stabilization* - halting unwanted condition like cracking or settlement
iv. *Water-proofing* - stops fluid from entering or exiting concrete structure
v. *Protection*- protect concrete from aggressive environment

Accomplishing the repair (step 7) after selecting a repair method is by: (1) choice of the proper repair material or system for the inplace requirements that are needed and (2) selection of the best placement technique for that material. Placement techniques for horizontal, vertical or overhead repairs are:

i. Trowel applied (drypack)
ii. Form & Pump
iii. Form & Pour
iv. Full-depth repair
v. Shot-crete
vi. Overlays

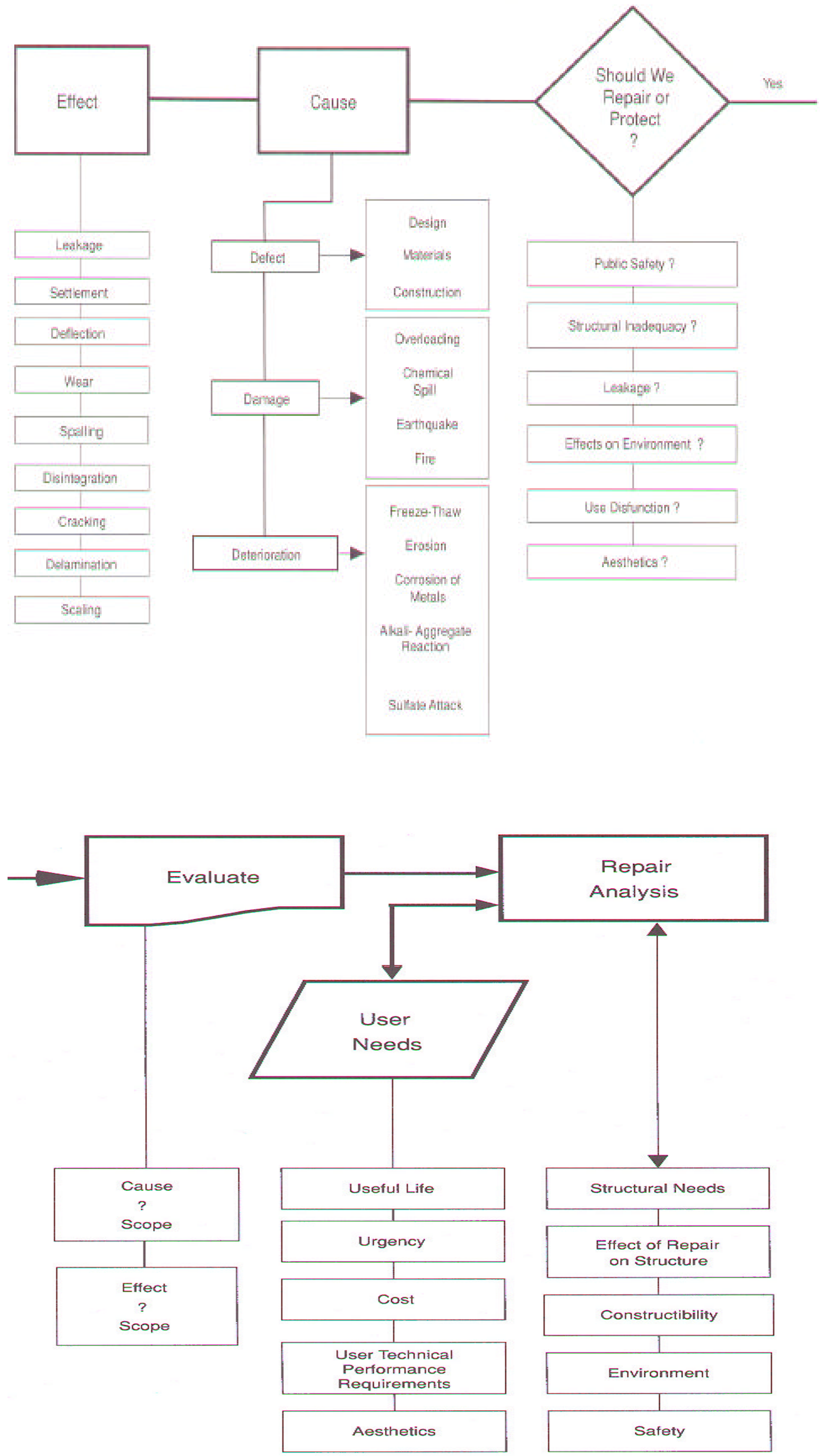


Figure 1. Concrete Repair Process (Emmons, 1994)

CONCRETE PROBLEMS

Concrete does not necessarily perform as we would like. Common causes of distress and deterioration of concrete are listed in Table 1. Causes of concrete problems can be classified as:

- Defects: design, materials, construction
- Damage: overload, fire, impact, chemical spill
- Deterioration: metal corrosion, erosion, freeze/thaw, sulfate attacks

When the concrete structure is newly taken into service there may occur damage which is attributable to unsatisfactory construction practice. The damage may have an immediate effect on the structural integrity, such as in the case of voids in walls of which there may be no visible evidence - concealed defects. Poor construction usually leads to reduced durability which will manifests itself in later years. The working life of the structure may be reduced or extensive maintenance may be required as a result of deterioration of materials, usually steel subject to corrosion attack or concrete subject to aggressive chemicals. Evidence of this type of damage may appear after 15 or 20 years and is strongly environment dependent. Corrosion may be detectable at an early stage and prior to serious damage occurring to the extent that the functionality of the structure is affected.

Table 1. Causes of Distress and Deterioration of Concrete
Accidental Loadings
Chemical Reactions
Acid Attach
Aggressive-water attach
Alkali-carbonate rock reaction
Alkali-silica reaction
Miscellaneous chemical attach
Sulfate attach
Construction Errors
Corrosion of Embedded Metals
Design Errors
Inadequate structural design
Poor design details
Erosion
Abrasion
Cavitation
Freezing and Thawing
Settlement and Movement
Shrinkage
Plastic
Drying
Temperature Changes
Internally generated
Externally generated
Fire
Weathering

Construction Errors

Poor construction practices and negligence can cause defects that lead to the cracking and concrete deterioration. These include:

i. Scaling, crazing and dusting of concrete
ii. Improper alignment of formwork
iii. Improper consolidation
iv. Movement of formwork
v. Improper location of reinforcing steel
vi. Premature removal of shores or reshores
vii. Improper curing

Errors made during construction such as adding improper amounts of water to the concrete mix, inadequate consolidation, and improper curing can cause distress and deterioration of the concrete. Proper mix design, placement, and curing of the concrete, as well as an experienced contractor are essential to prevent construction errors from occurring. Construction errors can lead to some of the problems discussed later in this fact sheet such as scaling and cracking. Honeycombing and bugholes can be observed after construction.

Honeycombing can be recognized by exposed coarse aggregate on the surface without any mortar covering or surrounding the aggregate particles. The honeycombing may extend deep into the concrete. Honeycombing can be caused by a poorly graded concrete mix, by too large of a coarse aggregate, or by insufficient vibration at the time of placement. Honeycombing will result in further deterioration of the concrete due to freeze-thaw because moisture can easily work its way into the honeycombed areas. Severe honeycombing should be repaired to prevent further deterioration of the concrete surface.

Bugholes is a term used to describe small holes (less than about 0.25 inch in diameter) that are noticeable on the surface of the concrete. Bugholes are generally caused by too much sand in the mix, a mix that is too lean, or excessive amplitude of vibration during placement. Bugholes may cause durability problems with the concrete and should be monitored.

Design Errors

The design errors can be broadly categorised into two types:

a) Inadequate structural design

The failure mechanism is due to over stressing the concrete beyond it's capacity. These defects will be manifested in the concrete either by cracking or spalling. If the concrete experiences high compressive stresses then spalling will occur. Similarly if the concrete is exposed to high torsional or shearing stresses then spalling or cracking may occur and high tensile stresses will cause the concrete to crack.. Such defects will be present in the areas where high stresses are expected. Through visual inspection, the engineer should decide whether to proceed for a detailed stress analysis. A thorough petrographic analysis and strength evaluation will be required if rehabilitation is considered to be necessary. These problems can be prevented with a careful review of the design calculations and detailing.

b) Poor design details

An adequate design does not guarantee a satisfactory function without including design detailing. Detailing is an important component of a structural design. Poor detailing may or may not directly lead to a structural failure but it may contribute to the deterioration of the concrete. In order to fix a detailing defect it is necessary to correct the detailing and not to respond to the symptoms only. Some of the general design and detailing defects include:

i. Abrupt changes in section
ii. Insufficient reinforcement at reentrant corners and openings
iii.Inadequate provision for deflection
iv. Inadequate provisions for drainage
v. .Inadequate expansion joints
vi. Material incompatibility

Disintegration and Scaling

Disintegration can be described as the deterioration of the concrete into small fragments and individual aggregates. Scaling is a milder form of disintegration where the surface mortar flakes off. Large areas of crumbling (rotten) concrete, areas of deterioration which are more than about 3 to 4 inches deep (depending on the wall/slab thickness), and exposed rebar indicate serious concrete deterioration. If not repaired, this type of concrete deterioration may lead to structural instability of the concrete structure.

Disintegration can be a result of many causes such as freezing and thawing, chemical attack, and poor construction practices. All exposed concrete is subject to freeze-thaw, but the concrete's resistance to weathering is determined by the concrete mix and the age of the concrete. Concrete with the proper amounts of air, water, and cement, and a properly sized aggregate, will be much more durable. In addition, proper drainage is essential in preventing freeze-thaw damage. When critically saturated concrete (when 90% of the pore space in the concrete is filled with water) is exposed to freezing temperatures, the water in the pore spaces within the concrete freezes and expands, damaging the concrete. Repeated cycles of freezing and thawing will result in surface scaling and can lead to disintegration of the concrete. Older structures are also more susceptible to freeze-thaw damage since the concrete was not air entrained. In addition, acidic substances in the surrounding soil and water can cause disintegration of the concrete surface due to a reaction between the acid and the hydrated cement.

Spalling and Popouts

Spalling is the loss of larger pieces or flakes of concrete. It is typically caused by sudden impact of something dropped on the concrete or stress in the concrete that exceeded the design. Spalling may occur on a smaller scale, creating popouts. Popouts are formed as the water in saturated coarse aggregate particles near the surface freezes, expands, and pushes off the top of the aggregate and surrounding mortar to create a shallow conical depression. Popouts are typically not a structural problem.

Steel Reinforcement Corrosion

Corrosion presents a problem for reinforced concrete structures for two reasons:

- As corrosion occurs, there is a corresponding drop in the cross-sectional area of the steel reinforcement; and,
- The corrosion products occupy a larger volume than steel, and therefore exert substantial tensile forces on the surrounding concrete.

The expansive forces caused by rebar corrosion can cause cracking and spalling of the concrete, and therefore loss of structural bond between the rebar and concrete. Thus, the structural safety of RC members will be reduced either by the loss of bond or by the loss of rebar cross-sectional area (ACI Committee 222, 1996).

Concrete typically is a very alkaline environment, with pH values between 12 and 13.5 (Broomfield, 1997). Therefore, since concrete is a naturally passivating environment, rebar is very well protected from corrosion in most reinforced concrete structures. Whether corrosion occurs or not depends on a large number of factors, including the electrode potentials, temperature, pH, concrete material properties, and the concentration and distribution of moisture, oxygen, aggressive species (chlorides, carbon dioxide), reactants and products. Corrosion occurs when the passivating environment of the concrete is destroyed. This is most commonly caused by the presence of aggressive species, such as carbon dioxide and/or chlorides.

(1) Chloride-induced corrosion

The presence of chloride ions (Cl^-) near steel rebar is generally believed to be the main cause of premature corrosion in concrete structures. Chloride ions are very common in nature, and are an extremely aggressive species. The diffusion of chlorides into concrete from an external source is the major cause of rebar corrosion in most parts of the world. It is believed that chloride ions destroy the protective passive film on the surface of the rebar, thereby increasing susceptibility to corrosion. There is a chloride threshold for corrosion, and it is typically approximated to a concentration of 0.4% chlorides by weight of cement if chlorides are cast into the concrete, and 0.2% if the chlorides diffuse into the concrete. The reason that a higher threshold exists with cast-in chlorides is that many of these chlorides are bound into the structure of the cement paste, and are unavailable to react. An often quoted threshold is one pound of chlorides per cubic yard of concrete (Broomfield, 1997).

(2) Carbonation-induced corrosion

Carbon dioxide in the air can cause corrosion of embedded steel through a process known as carbonation. In this process, carbon dioxide gas dissolves in the pore water to form carbonic acid, which in turn reacts with the hydroxides in the pore solution which are alkaline. Once these hydroxides are consumed, the pH of the pore solution will fall to a level (< 9) where corrosion of the steel can occur. Corrosion due to carbonation is most common when the cover to reinforcement is low. It can occur at greater depths if the pore structure is large and interconnected, allowing for easy diffusion of carbon dioxide gas to the steel. Carbonation is most common on older buildings constructed of concrete with a low cement content. Wet/dry cycling can accelerate carbonation by allowing carbon dioxide in during the dry phase, and providing the water to dissolve it during the wet phase. Rebar corrosion in reinforced concrete balconies is often caused by carbonation, due to their thin cross-sections, and high susceptibility for rain wetting.

EVALUATION OF CONCRETE

A thourough and logical evaluation of the current conditon of a concrete structure is the first step in any repair project. The evaluation of the condition of concrete structures (for the purpose of identifying and defining areas of distress) is possible by following guidelines set out in procedures and manuals, such as the "*Guide for making a condition survey of concrete in service*" (ACI 201.1 R92). The ACI guide provides the specialist with a checklist to facilitate a thourough survey as well as photographic illustrations (and definitions) of various types of distress manifestations. The system is designed to record the history of a project from inception through construction and subsequent life of the structure. However, "following the guide does not eliminate the need for intelligent observations and use of sound judgement." The individuals performing the survey should be experienced and competent in this field.

Regular inspection and monitoring is essential to detect problems with concrete structures. The structures should be inspected a minimum of once per year. It is important to keep written records of the dimensions and extent of deterioration as scaling, disintegration, efflorescence, honeycombing, erosion, spalling, popouts, and the length and width of cracks. Structural cracks should be monitored more frequently and repaired if they are a threat to the stability of the structure. Photographs provide invaluable records of changing conditions. All maintenance and inspection records should be kept.

Planning a Condition Survey

- Review existing records
- Visual durvey and recording observations
- Detailed crack mapping/measurement
- Surveying movements
- Core sampling (number, depth, location)
- Testing schedule for retrieved samples
- Non-destructive tests
- Evaluation and analysis of data
- Instrumentation/monitoring
  - -Crack movement
  - -Deformations
  - -Stresses
- Timing/costs

Testing

- Visual assessment (voids, cracking, deposits, damp patches, rebar, etc.)
- Half-cell potential survey
- Chloride analysis and/or depth of carbonation
- Strength of concrete (compressive, tensile, tension)
- Pulse velocity
- Absorption, density, voids
- Petrographic analysis (polished sections, thin sections)
  - -Air void system
  - -Permeability (H_2O, Cl, gas)
  - -Chemical/thermal analysis
  - -Expansion testing

Visual Survey

- **Cracking**
  - Type, pattern
  - Alignment
  - Exudation activity/staining
  - Measurement (width, depth)
- **Surface distress**
  - Spalling/scaling
  - Pop-outs
  - Leaching/dissolution
  - Abrasion/erosion
  - Staining/discoloration
  - Efflorescence
- **Water/moisture**
  - leakage thru joints /cracks
  - Surface dampness
  - Ponding/runoff
- **Movements**
  - Deflections/deformations
  - Misalignments
  - Heaving
  - Settlement
- **Metal corrosion**
  - Rust staining
  - Exposed rebar (delamination)
- **Joints**
  - Squeezing
  - Leaking
  - Concrete distress
  - Condition of joint compound
  - Movement
- **Delaminations**
  - Hammer sounding
- **Service**
  - Operation of components
  - Aesthetics

Table 2. Terms Associated with Visual Inspection of Concrete

Construction faults	Disintegration	Cracking
Bug holes	Blistering	Checking or crazing
Cold joints	Chalking	D-cracking
Exposed reinforcing steel	Delamination	Diagonal
Honeycombing	Dusting	Hairline
Irregular surface	Peeling	Longitudinal
Spalling	Scaling	Map or pattern
Popouts	weathering	Random
Spall	Distortion or movement	Transverse
Seepage	Buckling	Vertical
Corrosion	Curling or warping	Horizontal
Discoloration or staining	Faulting	Erosion
Exudation	Settling	Abrasion
Efflorescence	Tilting	Cavitation
Incrustation		Joint-sealant failure

CRACKS IN CONCRETE

All concrete structures crack. Cracks in concrete have many causes. They may affect the appearance only or indicate significant structural distress or lack of durability. Significance of cracks depends on the type of the structure. To properly repair cracks, the cause of the problem must be addressed, otherwise only temporary solution will be achieved. ACI 224.1R-93 guide on *"Causes, evaluation and repair of cracks in concrete structures"* provides the specialist with a summary of causes of cracks in concrete, the procedures to evaluate cracking in concrete and the principle techniques and application for crack repairs.

Concrete can crack in any or in each of the following three phases of its life, namely:

- plastic-phase while it has still not set
- hardening-phase while if is still green
- hardened-phase and in service

In its plastic-condition (before it has set), the concrete can crack due to

i. Plastic shrinkage
ii. Plastic settlement
iii. Differential settlement of staging 'supports'

In its hardening-phase (three to four weeks after setting), concrete can crack due to:

iv. Constraint to early thermal movement
v. Constraint to early drying shrinkage
vi. Differential settlement of 'supports'

In its hardened-state and in service (after 28 days), the concrete can crack due to:

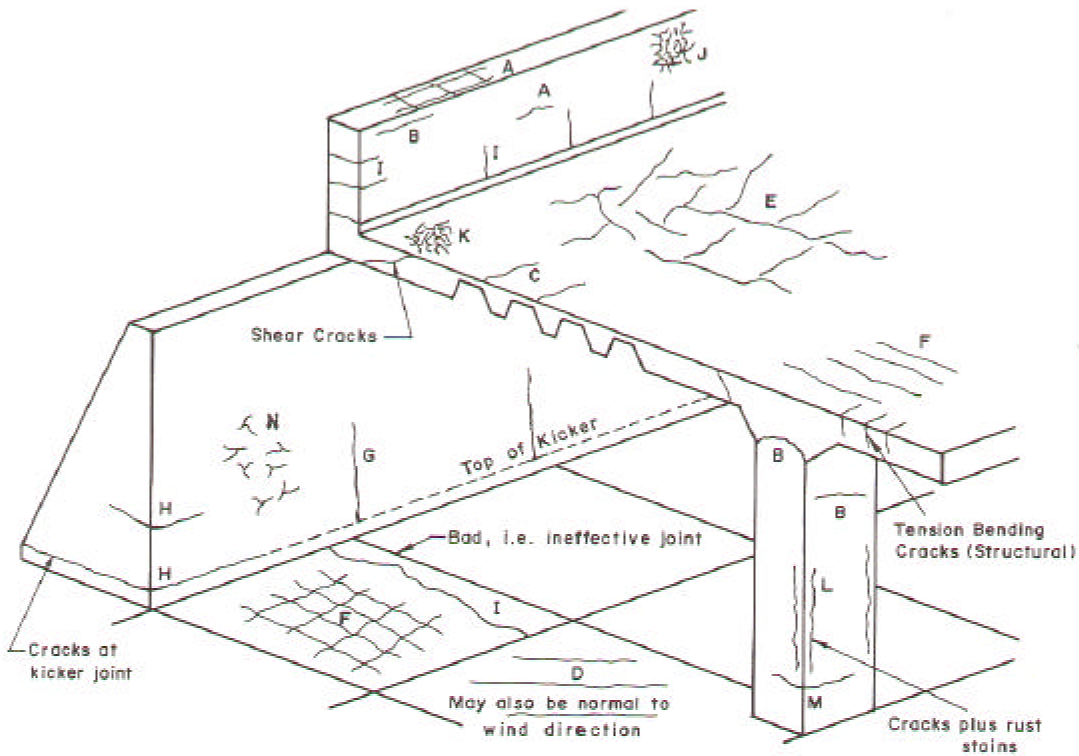
vii. Overload
viii. Under-design
ix. Inadequate construction
x. Inadequate detailing
xi. Differential settlement of 'foundations'
xii. Sulphate attack on cement in concrete
xiii. Corrosion of steel reinforcement
  a- Chloride attack on reinforcement
  b- Carbonation effect on concrete
  c- Simple oxidation of reinforcement due to exposure to moisture
xiv. 'Alkali-aggregate' reaction
xv. Fabrication, shipment and handling cracks in precast concrete members
xvi. Crazing
xvii Weathering cracks
xviii Long term drying-shrinkage cracks

Cracks in the concrete may classified as structural or surface cracks. (1) Surface cracks are generally less than a few millimeters wide and deep. These are often called hairline cracks and may consist of single, thin cracks, or cracks in a craze/map-like pattern. A small number of surface or shrinkage cracks is common and does not usually cause any problems. Surface cracks can be caused by freezing and thawing, poor construction practices, and alkali-aggregate reactivity. Alkali-aggregate reactivity occurs when the aggregate reacts with the cement causing crazing or map cracks. The placement of new concrete over old may cause surface cracks to develop. This occurs because the new concrete will shrink as it cures. (2) Structural cracks in the concrete are usually larger than 0.25 inch in width. They extend deeper into the concrete and may extend all the way through a wall, slab, or other structural member. Structural cracks are often caused by overloads. The structural cracks may worsen in severity due to the forces of weathering.

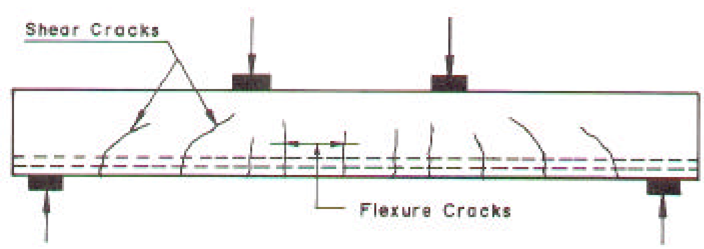
Cracks due to effects (i), (ii) (iv), (v) and (xii) – (xviii), are sometimes loosely referred to as 'Non-Structural' cracks and the remaining ones as 'Structural'cracks although the former too can lead to 'Structural distress' and therefore are not non-structural in effect. Examples of concrete cracks are shown in Figure 2.

Table 3. Intrinsic cracks in concrete

Type of Intrinsic Cracking (not caused by structural loading	Letter Legend (see Fig. 4.1)	Subdivision	Most Common Location of Occurrence	Primary Cause (excluding restraint)	Secondary Causes/ Factors	Remedy, Assuming Basic Redesign Is impossible (In all cases reduce restraint)	Time of Appearance
Plastic Settlement Cracks	A B C	Over the reinforcement Arching Change of depth	Deep sections Top of columns Trough and waffle slabs	Excess bleeding	Rapid early drying conditions	Reduce bleeding do air entrainment or revibrate mildly	Ten minutes to three hours
Plastic shrinkage cracks	D E F	Diagonal (may be normal to wind direction) Random Over reinforcement (even mesh type)	Road and slabs Reinforced concrete slabs Reinforced concrete slabs	Rapid early drying Ditto plus steel near surface	Low rate of bleeding and fast surface evaporation	Improve early curing and towel	Thirty minutes to six hours
Early thermal construction cracks	G H	External restraint Internal restraint	Thick walls Thick slabs	Excess heat generation Excess temperature gradients	Rapid cooling, curing by relatively cold water	Reduce heat and/or insulate	One day to two or three weeks
Long-term drying shrinkage cracks	I		Thin slabs (and walls)	Absence of movements joints, or, inefficient joints	Excess shrinkage and Inefficient curing	Reduce water content and Improve curing	Several weeks or months
Crazing cracks (occur only on surface)	J K	Against formwork Floated concrete	Fair faced concrete slabs	Impermeable formwork Over trowelling	Rich mixes Poor curing	Improve curing and finishing	One to seven days sometimes much later
Cracks due to Corrosion of reinforcement (expansive reaction can lead to spalling of concrete)	L (and rust stains) M (and rust stains)	Natural and slow, or fast if excessive Calcium chloride present	Columns and beams Precast concrete	Lack of cover, and dampness Excess calcium chloride and dampness	Poor quality concrete	See details ahead	More than about two years
Cracks due to Alkali-aggregate reaction (expansive reaction)	N (and may show gel type or dried resin type deposit in crack)		(Damp locations)	Reactive silicates and Carbonates in aggregates acting on alkali in Cement		See details ahead	More than five years



Examples of intrinsic cracks in a hypothetical concrete structure, essentially showing how each type may show up. See details of A, B, C etc. (*Courtesy*: Concrete Society)



Typical flexure and shear cracks in a simple beam (load induced)

Figure 2. Cracks in Concrete (ACI-ICRI Manual, 1999)

REPAIR

Concrete repair refers to bringing the structure to its original capacity. It can be classified either as cosmetic-repairs or rehabilitational type repairs (Table 4). Figure 3 shows the anatomy of surface repair while Figure 4 illustrates few compatibility requirements between repair material and parent concrete. Repair of cracks is illustrated in Figure 5.

The following are commonly used methods for repairs.

i. *Dry-Pack Method* for deep and narrow cavities

ii. *Preplaced Aggregate Method* for restoration of large areas such as walls, foundations and spillways,

iii. *Partial or Full Depth Concrete Replacement* by casting or patching, using various types of concrete, e.g. ordinary concrete, mortar, low-slump highly-dense concrete, latex-modified concrete, epoxy resin, polymer concrete

iv. *Shotcrete and Gunite*

v. *Epoxy Mortar Injection*

vi. *Cement Mortar Injection*

vii. *Crack Sealing and Filling* by epoxy injection or cement grout-injection

viii *Surface Protection by Overlays* or by various Sealing coats

ix *Prestressing* for water tanks, slabs, deflection control

Table 4. Concrete Repair: 'Methods' and 'Materials'

Defects	Repair Methods	Materials
• Live Cracks	- Caulking - Pressure injection with 'flexible' filler - Jacketing: * Strapping * Overlaying - Strengthening	Elastromeric sealer 'Flexible' epoxy (resin and hardener mix) filler Steel wire or rod Membrane or special mortar Steel plate, post tensioning, stitching, etc
• Dormant Cracks	- Caulking - Pressure injection with 'rigid' filler - Coating - Overlying - Grinding and Overlay - Dry-pack - Shotcrete/Gunite - Patching - Jacketing - Strengthening - Reconstruction	Cement grout or mortar, Fast-setting mortar. 'Rigid' epoxy (resin and hardener mix) filler Bituminous coating, tar Asphalt overlay with membrane Latex modified concrete, highly dense concrete Dry-pack Mortar (cement), Fast-setting mortar Cement mortar, Epoxy or Polymer concrete Steel rod Post tensioning, etc. as needed
• Voids • Hollows and • Honeycombs	- Dry pack - Patching - Resurfacing - Shotcrete/Gunite - Preplaced aggregate - Replacement	Dry-pack Portland cement grout, mortar, cement Epoxy or Polymer concrete Fast-setting mortar Coarse aggregate and grout as needed
• Scaling Damage	- Overlaying - Grinding - Shotcrete/Gunite - Coating - Replacement	Portland cement concrete, Latex modified concrete, Asphalt cement, Epoxy or polymer concrete Fast-setting mortar, Cement mortar Bituminous, Linseed oil coat, Silane treatment as needed
• Spalling Damage	- Patching - Shotcrete/Gunite - Overlay - Coating - Replacement	Concrete, Epoxy, Polymer, Latex, Asphalt Cement mortar, Fast-setting mortar Latex modified concrete, Asphalt concrete, Concrete Bituminous, linseed oil, Silane, etc. as needed

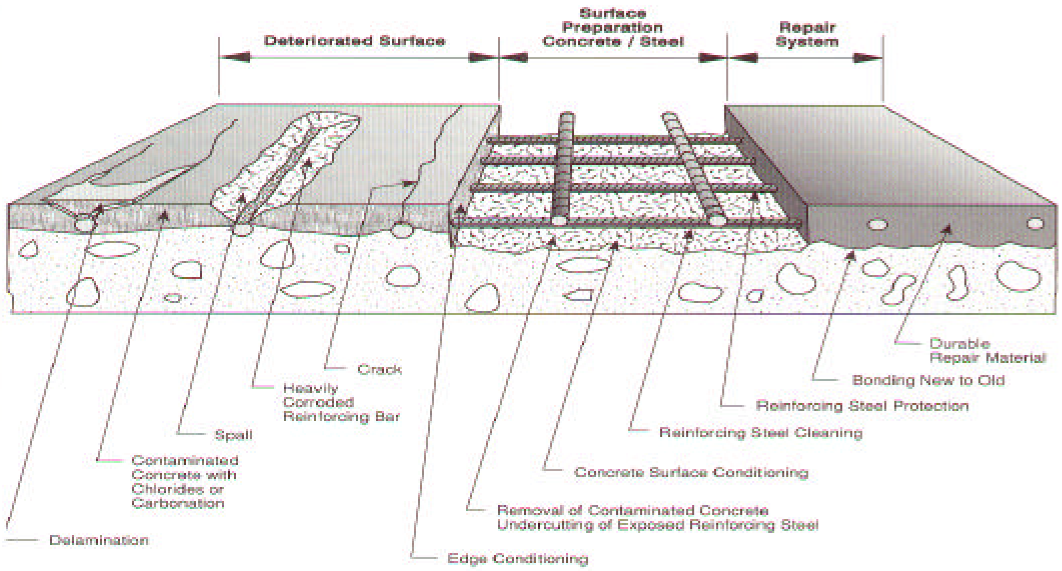


Figure 3. Anatomy of Surface Repair (Emmons and Vaysburd, 1995)

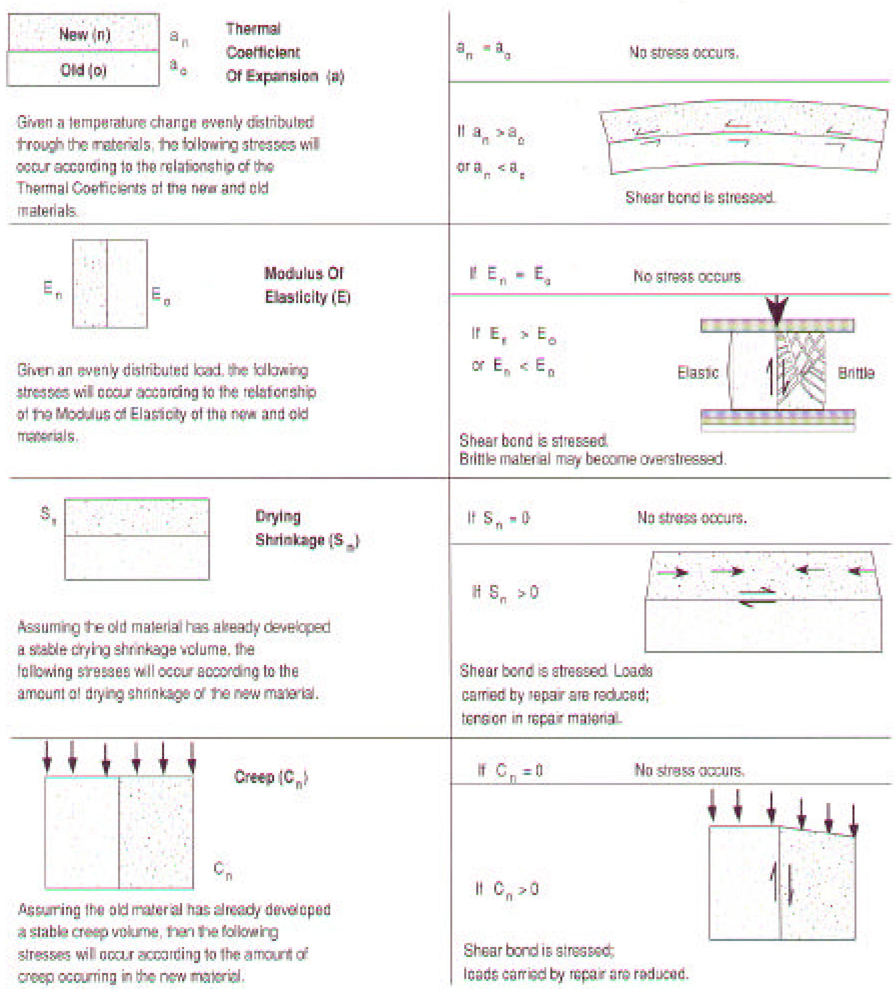


Figure 4. Compatibility Requirements for Repair Material (Emmons, 1994)

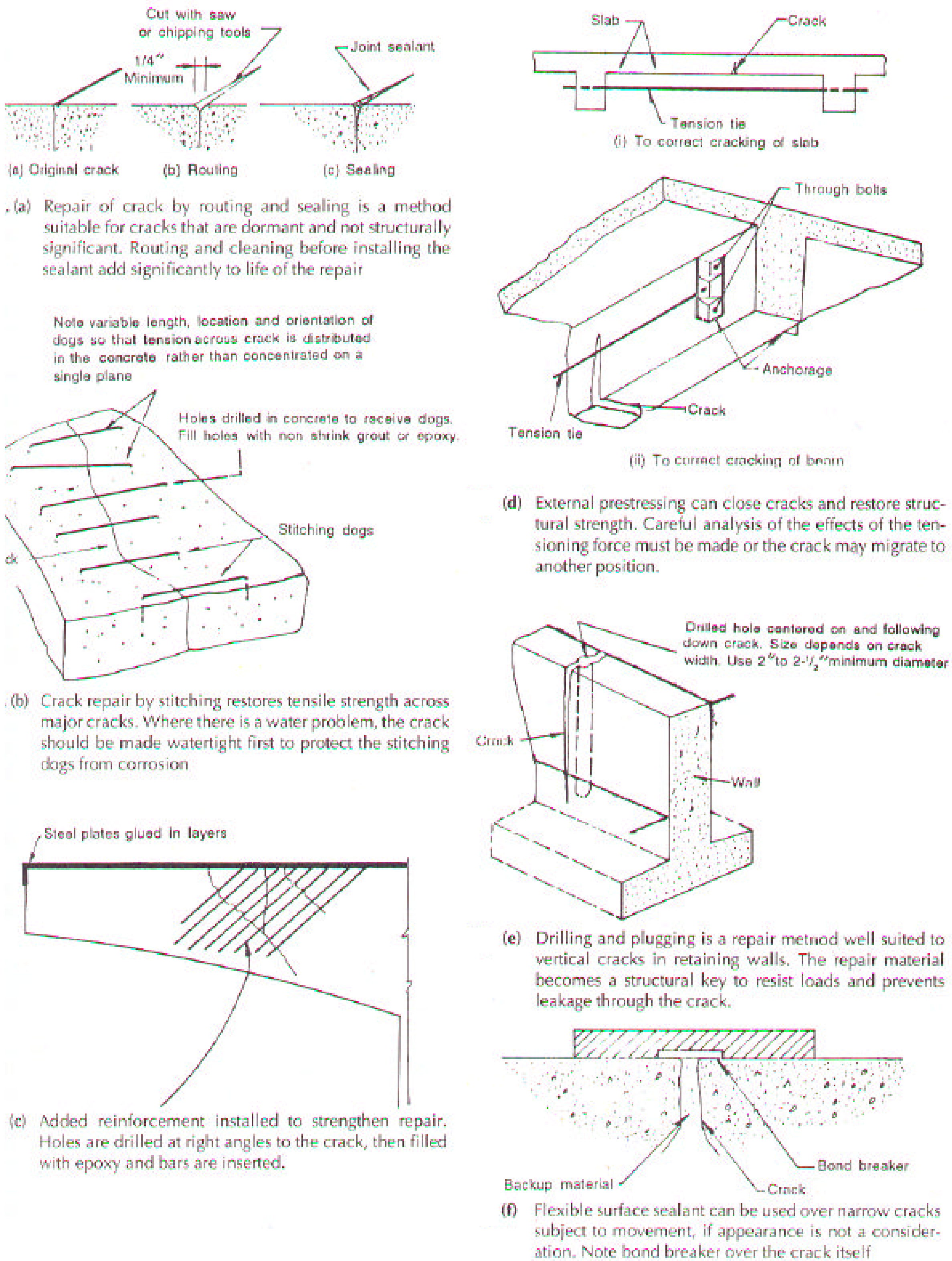


Figure 5. Crack Repair (ACI-ICRI, 1999)

STRENGTHENING

Strengthening refers to upgrading the capacity of a structure over its original design. The distinction in strengthening is made between "active" or "passive" strengthening as illustrated in Figure 6. In active strengthening, the repair engages immediately in sharing the loads as with prestressed elements. Passive strengthening will carry the additional load once the structure is overstressed, as for example with external steel plate bonding.

Strengthening of a concrete structure can be achieved in a number of ways (Figure 6).

1. *Enlargement*
   - New concrete and reinforcing steel
   - Bonded to existing concrete

2. *Composite Construction*
   - Placement of steel plates or structural shapes to add stiffness or load capacity
   - Load transfer by adhesive, grouts, anchors

3. *Post-tensioning*
   - Prestress reinforced concrete (active)
   - Internal or external systems applied by jacking
   - Relieves over stress, displacements,..

4. *Stress-Reduction*
   - Reduce stress in a structure by:
     cutting new expansion joints, jacking structure,
     isolation bearings, removal of portions of structure

5. *Internal Grouting*
   - Pressure inject flowable material into cracks, voids,
   - Polymers, cement-based materials

6. *External Grouting*
   - Pump cement based materials to fill voids between structure and soil

Strengthening of structural concrete can be attempted by the following means:

- 'replacing' poor quality or defective material by better quality material
- 'attaching' additional load-bearing material
- 're-distribution of the loading actions' through 'imposed deformation' on the structural system.

The new load-bearing material will usually be:

- highly quality concrete
- reinforcing steel bars (longitudinals, laterals, stirrups, etc.)
- thin steel plates and straps (externally bonded by epoxy)
- various combinations of these

The main problem in strengthening is to achieve 'compatibility' and a 'continuity' in the structural behavior between the original material structure and the new material/ repaired structure (Figure 4). It has to be clearly understood that the strengthening effect (e.g. increased section properties) can participate only for live load and subsequently imposed load actions (e.g. removal of temporarily applied load, reversed prop reactions, etc.) and possibly the dead loads applied subsequently.

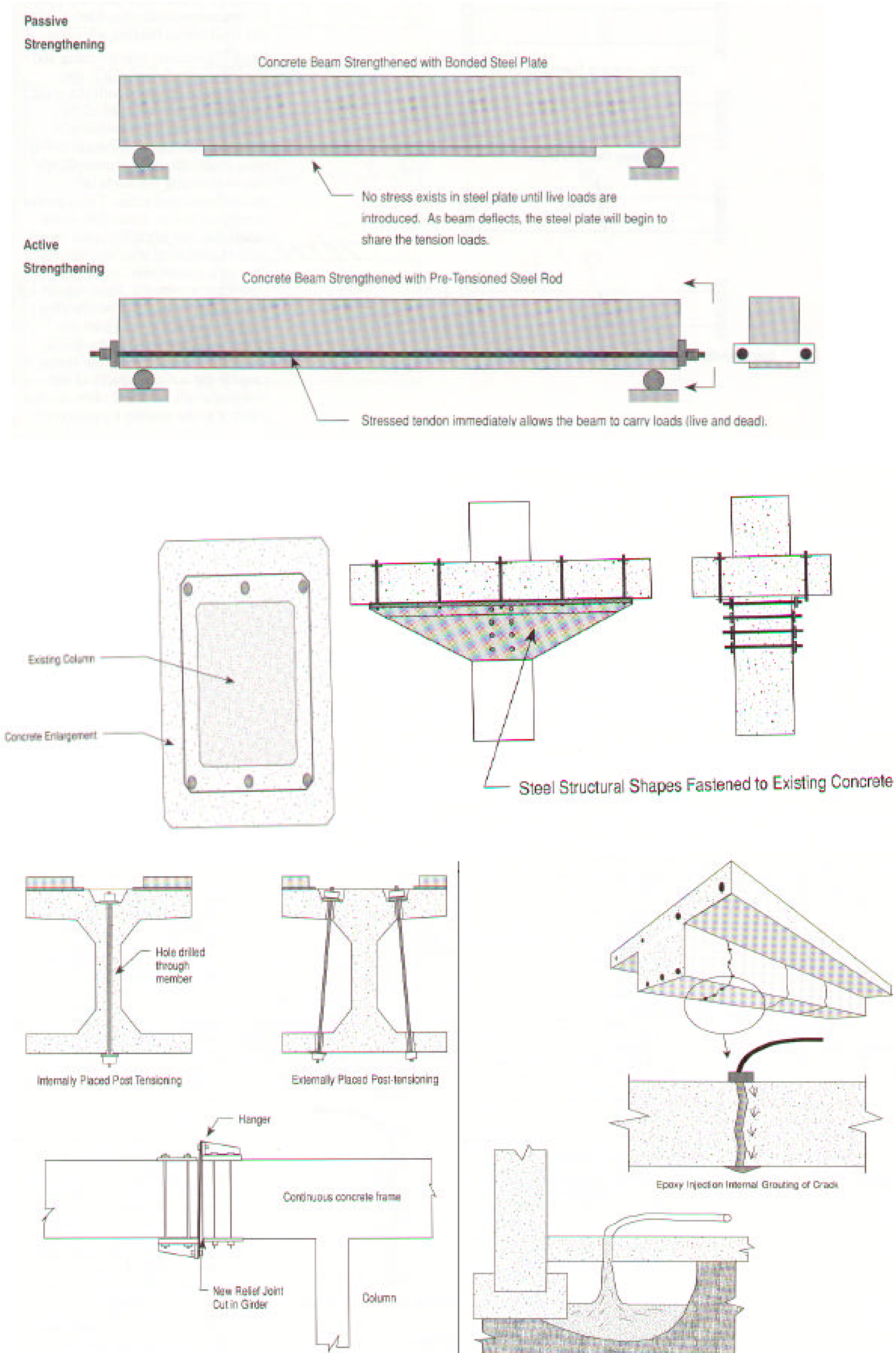


Figure 6. Strengthening Techniques (Emmons, 1999)

FRP Repair and Strengthening

For about 25 years, existing reinforced concrete structures have been strengthened using externally bonded steel plates in order to improve their performance under service and ultimate conditions. This method of repair does, however, present some difficulties. It is difficult to shape steel plates to fit complex profiles. The plates are heavy and inflexible, and are difficult to manipulate and bond under site conditions. Also, their weight imposes a restriction on their length, resulting in a large number of plates, and consequently a great number of lap joints. This creates a quality control challenge since the proper formation and sealing of the joints between adjacent plates is difficult to ensure. Expensive falsework is required to maintain the steel plates in position as the adhesive gains strength. Finally, possible corrosion of the steel plates at the steel-adhesive interface requires continuous maintenance of such a repair system. These difficulties led researchers to investigate whether steel plates could be replaced by lightweight, non-corrosive; fibre reinforced polymer (FRP) composite laminates.

FRP composite laminates are very thin (1-3mm) laminates of high strength fibres embedded in polymer matrix material. Laminates are produced by embedding continuous high strength fibres (i.e. carbon, glass, or aramid) in thermosetting matrices (i.e. polyester, epoxy). The fibres can be arranged in a unidirectional, bi-directional or off-axis fashion, depending on the load distribution and strength requirements. Laminates can be classified into three groups: glass-reinforced polymers (GFRP), carbon-reinforced polymers (CFRP), and aramid-reinforced polymers (AFRP). Table 5 gives properties of common composite materials.

Table 5. Typical Properties of Various FRP Composites (ACI 440R-96)

Type	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (mm/mm)	Coefficient of thermal expansion	Specific gravity
Glass FRP	517-1207	41-62	0.035-0.05	9.9	2.4
Carbon FRP	1650-2410	150-165	0.01-0.015	0	1.5
Aramid FRP	1200-2000	50-74	0.02-0.026	-1	1.25
Steel	483-1862	186-200	>0.04-0.1	11.7	7.9

FRP laminated products is the state-of-the-art for the rehabilitating and upgrading concrete structures (Soudki, 1999). This application seems to have a promising prospect for the following reasons:

a) quantity of composite material involved is small, thus the material high cost plays a smaller role
b) analysis and application is relatively simple
c) light weight of the laminates eliminates the need for heavy equipment or extensive labour and thus rehabilitation techniques employing FRPs are similar or lower in costs than conventional ones
d) well established manufacturing facilities exist since similar products have been used for years by the defence, aerospace and other industries
e) high durability of FRPs, is valuable in environments that promote corrosion; and,
f) FRP laminates give negligible clearance loss compared to other forms of rehabilitation, this is particularly important in bridges.

In view of these advantages, government agencies and municipalities are increasingly adopting repair and strengthening applications involving FRP laminates across North America, Japan and Europe. The key issues facing FRP laminates can be addressed by diversification of the composite industry, new manufacturing techniques, and intensive research efforts. Wider acceptance of FRP repair applications is possible through low-cost manufacturing of composite products and the development of guidelines and codes for their use. Field applications of various repair systems using FRP laminates have only been employed within the last ten years.

FRP STRENGTHENING FOR FLEXURE

One reason for strengthening a structure is to enhance its flexural resistance. By bonding reinforcing laminates to the surface of the tensile zones, the flexural capacity of the member is enhanced by up to 50%. In addition, the internal reinforcement is relieved of some of its load, which leads to smaller deflections, reduced fatigue effects, and finer crack distribution.

FRP STRENGTHENING FOR SHEAR

Structures in need of rehabilitation may not only be deficient in flexural resistance but often there is a need to strengthen the shear resistance as well. This may possibly be achieved by bonding FRP laminates to the sides of the beam in the high shear zones (Fig. 7).

FRP STRENGTHENING COLUMNS

Recent earthquakes in California and Japan demonstrated that inadequate lateral reinforcement of columns might result in catastrophic failures. Inadequate lateral reinforcement can be improved by retrofitting the column with external confinement that is wrapped around the column. Until recently retrofitting of columns was done using steel jackets filled with concrete or grout. An alternative method is to retrofit the columns with FRP fabrics. These fabrics are easy to handle and install, and are resistant to corrosion.

FRP STRENGTHENING FOR CORROSION DAMAGE

Another application of retrofitting using FRP laminates is the protection of concrete members against corrosion in harsh environments such as coastal areas or where de-icing salts are used. Structural performance of FRP strengthened concrete suffering from corrosion may be improved by a combination of two mechanisms: 1) confinement of the concrete section, thereby lessening corrosion cracking and bond splitting cracks, and 2) increase in both the flexural and shear resistance of the concrete member.

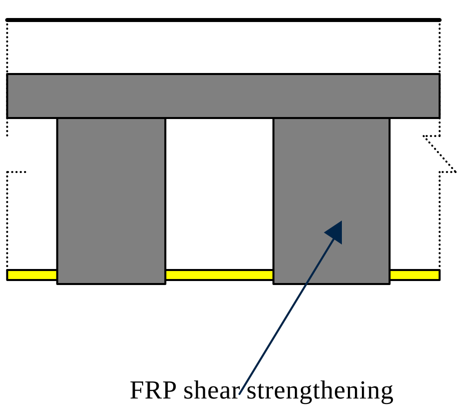


Fig. 7. Rehabilitation of Bridge No 3284 at Saint-Emillie de l'Energie (Neale, 1999)

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