Point Shilshole Condominium Building Concrete Deterioration



Causes and Repair Method



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Project: Evaluation and repair methods to restore structural integrity of the reinforced concrete beams at Point Shilshole Condominium Building

Mr. Norman Anderson, manager of Point Shilshole condominium building in Seattle, Washington, has asked me to evaluate the existing condition of the reinforced concrete beams that are deteriorating due to corrosion of the reinforcing bars and to proposed repair methods to restore the structural integrity of these members.

1.0 BACKGROUND:

In general, reinforced concrete has proved to be a highly successful material in terms of both structural performance and durability. Achieving good durability in reinforced concrete is a major factor in enabling a structure to perform its designed function for its expected lifetime. Most of today's concrete construction relies on the composite interaction of concrete and steel, which is aided by near equivalence their thermal expansion characteristics. Fortunately the alkaline environment within good quality concrete offers a high degree of protection to the embedded reinforcement against aggressive agents which promote the corrosion of the steel.

The reinforced concrete in Point Shilshole condominium building is suffering from durability problems arising from the corrosion of reinforcement, mostly due to poor quality concrete, inadequate cover to reinforcement, chloride in the concrete or combination of these. These have led to various forms of corrosion-induced damage such as cracking and spalling (Figure 1), and to reduction in structural capacity.



Figure 1: Corroded reinforcing bars separated and hanging from the structure

2.0 DETERIORATION MECHANISM

Reinforced concrete structures deteriorate under attack from external elements. In a composite material such as concrete, there are additional mechanisms caused by the greater complexity of its composition. Of particular concern is the corrosion of the reinforcing steel which is affected by the alkalinity of Portland cement concrete. Portland cement is made by burning constituents which include lime in a kiln and grinding the result to a fine powder. This produces a highly alkaline material which reacts with water and hardens. When it is added to coarse and fine aggregate and mixed with water, the cement combines with the aggregate and hardens to form concrete. The hardening process (hydration reaction) is complex and continues over many months if not years, depending on the amount of water in the mix. There must be excess water for workability and a pore network therefore develops as it dries out. Excess calcium hydroxide and other alkaline hydroxides are present in the pores and a solution of pH 12.0 to 14.0 develops (pH 7.0 is neutral; values below indicate acidity, and alkalinity above). It is this pore network and the solutions it contains that are critical to the durability of the concrete.

Although the alkalinity within the concrete pore structure can lead to alkali silica reaction (ASR), the high pH value also provides a protective coating of oxides and hydroxides on the surface of the steel reinforcement. Without this layer, which is known as a "passive" film, the steel would be exposed to the air and moisture in the pores, leading to rapid corrosion. Moreover, the surrounding concrete restricts ingress of carbon dioxide and chlorides which can promote corrosion. It is the main chemical reason why reinforced concrete is a durable construction material. The layer is durable and self repairing, and it can last for hundreds of years if the alkalinity is maintained. The duration of this protective oxide film, the thickness and physical integrity of the cover concrete, and how well this concrete acts as a barrier to the ingress of aggressive species. However, the passive layer itself can be attacked by chlorides in salt and the alkalinity of the concrete can be reduced by reaction with atmospheric carbon dioxide, a process known as "carbonation". The problem at Point Shilshole condominium building is most likely due to chloride-induced corrosion.

Oxidation of the steel in the presence of moisture causes rust. The presence of salt-rich moisture adds to the rate of deterioration. Corrosion is an active chemical process that exerts its own expansive stress.

Salt causes corrosion by a different mechanism. When dissolved in water sodium chloride forms a versatile, highly corrosive solution of sodium ions (Na+) and chloride ions (Cl-). Presence of salt in sea water is a major problem for reinforced concrete structures that are close to sea water, such as Point Shilshole condominium building. The very mobile chloride ions disperse through concrete pores in solution and where they come into contact with the reinforcing steel they attack the passive layer. Steel oxidizes in the presence of air and water to form rust which has a volume of up to 10 times that of the steel consumed. As concrete has a low tensile strength it will crack when as little as a tenth of a millimeter of steel has been consumed. Horizontal cracks form, causing corners to "spall" and surfaces to "delaminate" as the reinforcement's concrete cover becomes detached and falls away in sheets. The consequence can be seen on the underside of many buildings and structures beside the sea.

Corrosion-induced deterioration of reinforced concrete can be modeled in terms of three component steps: (1) time for corrosion initiation, T_i ; (2) time, subsequent to corrosion initiation, for appearance of a crack on the external concrete surface (crack propagation), T_p ; and (3) time for surface cracks to progress into further damage and develop into spalls, T_d , to the point where the functional service life, T_f , is reached.¹ Figure 2 illustrates these schematically as a plot of cumulative damage versus time. Of the life component terms, T_i occupies the longest period in most cases, so corrosion control measures generally focus on this parameter.



Figure 2: Schematic illustration of the various steps in deterioration of reinforced concrete due to chloride-induced corrosion

Reinforced concrete is expected to exhibit some cracking. Design procedures and codes seek to limit width of cracks, depending upon exposure class the structure is designed for. Under normal service conditions crack widths up to about 0.3 mm might be anticipated. The effect of cracking on carbonation and on the corrosion of embedded steel appears to depend upon circumstance. There is a range of evidence and opinion as to what the effects are in different situations and their significance. Crack width seems to be less important to corrosion risk than crack frequency, cover depth and concrete quality. Cracks coincident with a reinforcement bar (Figure 3) will tend to expose a greater proportion of the bar to moisture and oxygen; cathodic and

¹ Tutti, K., Corrosion of Steel in Concrete, Report No. 4, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 1982.

anodic areas are likely to be reasonably equal in size and will typically lead to generalized corrosion, with the expansive forces potentially promoting further cracking depending on availability of moisture.



Figure 3: Cracking in reinforced concrete slab

When chloride penetrates the concrete from an external source, corrosion can be very severe where reinforcing bars intersect cracks because of the relatively small size of the anodic zones. In these situations intense localized corrosion of affected reinforcing bar can cause very large losses of cross-sectional areas. Point Shilshole condominium building case is considered to be an extreme case, where total local loss of a bar is over the length of a few feet and it seriously impairs the load carrying capacity of the structure, as depicted earlier in Figure 1.

3.0 INITIAL SITE RECONNAISSANCE AND DETAILED EXAMINATION

Aims of an initial inspection: As a part of a routine or diagnostic investigation, the purpose of an initial reconnaissance phase is to identify the presence and then determine the likely cause of any deterioration to a reinforced concrete structure. During this investigation, some determination of depth of carbonation and sampling for chloride content may be carried out to provide a preliminary indication of the extent of the problem, and to form the basis for a more detailed investigation. Deterioration generally manifests itself as cracking of the concrete, and the shape, pattern and location of cracks along a reinforced element are frequently a good indication of the likely cause.

A Visual inspection was performed on November 27, 2005 at Point Shilshole condominium building. While visual inspection alone will not usually be sufficient to determine whether steel reinforcement is corroding, it is, nonetheless, a powerful procedure, specially in this case since the deterioration is so advanced. Figure 1 depicts the fact that in some cases, the reinforcing bar has corroded and following the spalling of the concrete cover, it has been separated from the actual structure.

In other locations, the defects manifest themselves in variety of forms. Relevant indicators and defects which might be observed include cracking, scaling (local flaking of peeling of the surface portion of hardened concrete), spalling (concrete fragments, usually detached from the body of the concrete), rust staining (brown or rust color stains), weathering (changes in properties, such as color, texture or strength), and leakage through joints (generally water, but possibly contaminated with chloride and other substances), among many indicators.



Figure 4: Spalling



Figure 5: Cracking and rust staining



Figure 6: Leakage through joints and rust staining

Reinforced-concrete structures in the marine environment often deteriorate in the early stages of their service life. The main cause is corrosion of the reinforcing steel and the concrete, which may interact adversely with each other. The deterioration, which is influenced by various factors, such as the mix proportion of the concrete, the depth of cover and the environmental conditions, results from physiochemical processes, such as ion transportation and carbonation. Transport phenomena through the pores of concrete may occur by the penetration and diffusion of substances such as chloride ions, carbon dioxide and sulfate.

Following the initial phase, a more detailed examination is required. This may benefit from the earlier work by using the results to target the crucial areas of the structure.

Removal geometry

Before starting removals, the effect of removals on structural integrity should be reviewed. Shoring of members should be provided as necessary. Particular care shall be exercised at slab/beam connections to columns. Repair method is prescribed per Concrete Repair Manual².





² Concrete Repair Manual, Published jointly by: American Concrete Institute (ACI) International, Building Research Establishment (BRE), the Concrete Society, and International Concrete Repair Institute (ICRI), Second Edition, Volume 1, May 2003.

EXPOSING AND UNDERCUTTING OF REINFORCING STEEL

These detail are applicable to horizontal, vertical, or overhead locations. They are also applicable to removal by hydrodemolition, hydro-milling, and electric, pneumatic or hydraulic impact breakers.

- 1. Remove loose or delaminated concrete above corroded reinforcing steel.
- 2. Once initial removals are made, proceed with the undercutting of all exposed corroded bars. Undercutting will provide clearance for under bar cleaning and full bar circumference bonding to surrounding concrete, and will secure the repair structurally. Provide minimum ³/₄ inch clearance between exposed rebars and surrounding concrete or ¹/₄ inch larger than the largest aggregate in repair material, whichever one is greater.
- **3.** Concrete removal shall extend along the bars to locations along the bar free of bond inhibiting corrosion, and where the bar is well bonded to surrounding concrete.



- 4. If non-corroded reinforcing steel is exposed during the undercutting process, care shall be taken not to damage the bar's bond to surrounding concrete. If bond between bar and concrete is broken, undercutting of the bar shall be required.
- 5. Any reinforcement which is loose shall be secured in place by tying to other secured bars or by other approved methods.



CLEANING AND REPAIR OF REINFORCING STEEL

Cleaning of Reinforcing Steel

6. All heavy corrosion and scale shall be removed from the bar as necessary to promote maximum bond of replacement material. Oil free abrasive blast is the preferred method. A tightly bonded light rust build-up on the surface is usually not detrimental to bond unless a protective coating is being applied to the bar surface, in which case the coating manufacturer's recommendations for surface preparation should be followed.



Repair of Reinforcing Steel Due to Loss of Section

If reinforcing steel has lost significant cross section, a structural engineer should be consulted. If repairs are required to the reinforcing steel, which is obviously the case in Shilshole condominium building, one of the following repair methods should be used:

- Complete bar replacement, or
- Addition of supplemental bar over affected section.

New bars may be mechanically spliced to old bars or replaced parallel to and approximately $\frac{3}{4}$ inch from existing bar. Lap length shall be determined in accordance with ACI 318³; also refer to CRSI⁴ and AASHTO⁵ manual.



³ American Concrete Institute (ACI) 318: Building Code Requirements for Structural Concrete and Commentary.

⁴ Concrete Reinforcing Steel Institute (CRSI) Manual of Standard Practice.

⁵ American Association of State Highway and Transportation Officials (AASHTO) Manual.

Edge and Surface Conditioning of Concrete

These details are applicable to horizontal, vertical, and overhead locations. They are also applicable to removal by hydro-demolition, hydromilling, and electric, pneumatic or hydraulic impact breakers. For shotcrete repairs, refer to ACI 506 Edge Preparation Guidelines.

- 7. Remove delaminated concrete, undercut reinforcing steel (refer to "Exposing and Undercutting of Reinforcing Steel"), remove additional concrete as required to provide minimum required thickness of repair material.
- 8. At edge locations, provide right angle cuts to the concrete surface with either of the following methods:
 - Sawcut ¹/₂-inch or less as required to avoid cutting reinforcing steel.
 - Use power equipment such as hydrodemolition or impact breakers. Avoid feather edges.
- **9.** Repair configurations should be kept as simple as possible, preferably with squared corners.



- 10. After removals and edge conditioning are complete, remove bond inhibiting materials (dirt, concrete slurry, loosely bonded aggregates) by abrasive blasting or high pressure waterbalsting with or without abrasive. Check the concrete surfaces after cleaning to ensure that surface is free from additional loose aggregate, so that additional delaminations are not present.
- **11.** If hydrodemolition is used, cement and particulate slurry must be removed from the prepared surfaces before slurry hardens.

5.0 APPLICATION METHODS:

Consistent success in concrete repair begins with the recognition that each repair situation is defined by a unique combination of circumstances shaped by engineering, exposure, constructability, cost, and time considerations.

The installation method must deliver the selected repair material to the prepared substrate with predictable results. The properties of repair materials generally specified are compressive strength, bond strength, shear strength, and those properties that influence volume changes, such as drying shrinkage, modulus of elasticity, and coefficient of thermal expansion. Other properties such as resistance to freeze and thawing, low permeability, or sulfate resistance may be specified. The repair material must fully encapsulate exposed reinforcing steel, achieve satisfactory bond with the substrate, and fill the prepared cavity without segregating. If these requirements are not achieved, the repair will not perform its intended purpose.

Bonding of the repair material with the existing substrate depends upon the repair material reacting with, and interlocking to, the profile of the prepared concrete surface. Some materials may require a bonding agent to insure intimate contact with prepared surfaces. If the repair material is self-bonding, it must have sufficient binder (e.g. cement paste, epoxy resin) to thoroughly wet out the substrate.

Force must be applied to drive the repair material into intimate contact with the prepared surface. The type of force will vary with the application method. In trowel applied systems, the repair material is forced into the prepared surface by the pressure applied to the trowel by the finisher or cement mason. In cast-in-place systems, the pressure is provided by initial vibration, or hydraulic pressure developed by concrete or grout pump. High velocity pneumatic placement techniques develop exceptional forces through impact. The dry packing process generates pressure when the rodding tool pounds the material against the substrate.

The requirement that the repair materials be mixed and applied without segregating is equally important. Any segregation of material components will alter physical properties and reduce or negate the ability of the repair to fulfill its primary function – to restore the structure to its original condition to the fullest extent possible.

Application Methods

Trowel applied

General description: Repair material is mixed into a trowlable, non-sag consistency. Trowel or other suitable placing tools are used to transport the repair material to the prepared substrate. The repair material is pressed into the substrate to develop intimate contact without voids.

Best application: Surface restoration when reinforcing steel is not encountered.

Material requirements: Fine-grained material easily finished, with non-sag properties to stay in place in vertical or overhead applications.



Dry packing

General description: Repair material is mixed into a uniform, cohesive plastic state, then transported to a confined space and compacted with rodding tools to produce a dense repair material.

Best application: Post-tensioning grout pockets; tie holes; Pan joist bottoms; waffle pan joists; vertical, overhead and horizontal locations.

Material requirements: Mortar with consistency capable of being molded into a ball without sagging.

Reference: Headquarters, United States Army Corps of Engineers (1995), "Evaluation and Repair of Concrete Structures," EM 1110-2-2002, Washington, D.C.



Form and Cast-in-Place

(Partial-depth replacement)

General description: The placement of repair material into a confined space with formwork defining all exposed boundaries. Repair materials are deposited into the formwork and consolidated by rodding or conventional vibration.

Best application: Columns, walls, and exterior slab edges.

Material requirements: Castable concrete or mortar with proper bond properties, low shrinkage, low water/cement ratio, and highly flowable mixture.

Reference: ACI 304R, Guide for Measuring, Mixing, Transporting, and Placing Concreting"



Form and Cast-in-Place

(Full-depth replacement)

General description: In lieu of partialdepth repairs, the member in question can be removed and replaced in total. Placement methods should follow good concrete practice.

Best application: When deterioration is extensive throughout the member.

Material requirements: Conventional castin-place concrete with low shrinkage, low water-cement ratio, and highly workable mixture.

Reference: ACI 304R"Guide for Measuring, Mixing, Transporting, and Placing Concreting"



Form and pump

General description: Repair material is mixed and pumped via concrete line connected to the formwork, until the cavity is filled and pressurized. Consolidation and bonding is provided by the internal form pressure.

Best application: Overhead and vertical applications where congested reinforcing is present. Beam bottoms, ribs, slab soffits, or sectionalized areas.

Material requirements: Pumpable, good flow characteristics, self-bonding, aggregate size compatible with size of cavity and space between bars.

Reference: ACI 304.2R, "Placing Concrete by Pumping Methods"



Preplaced aggregate

General description: gap-graded aggregate is placed into formed cavity. Grout is then pumped into form via grout pump until all voids are filled and pressurized. Shrinkage is minimal because of aggregate contact and volume.

Best application: Vertical and overhead applications where extremely low shrinkage of repair material is required; column enlargements.

Material requirements: Gap-graded aggregate (40-50% void ratio), pumpable grout, self-bonding portland cement or resin-based binder. One inch (25 mm) or larger aggregate typically used in cementitious applications.

Reference: ACI 304.1R, "Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications."



Dry-mix Shotcrete

General description: Repair material is placed dry or slightly damp into shotcrete machine and mixed with compressed air. The mixture is transported via hose to the exit nozzle where water and admixtures, if any, are introduced. The ingredients are propelled onto the prepared substrate by the force of the compressed air.

Best application: large vertical and overhead areas with small bars, No. 6 (19 mm) or less, and minimal congestion of embedded reinforcement.

Material requirements: well-graded aggregate with necessary binders (usually portland cement). Mixture must be proportioned to compensate for rebound losses. Admixtures are frequently used to shorten set time, and/or to allow thicker layers to be built-up in a single pass.

Reference: ACI 506.2, "Guide to Shotcrete"



Wet-mix Shotcrete

General description: Pre-batched and thoroughly mixed repair material is placed into a concrete pump and transported via pump line to an exit nozzle where compressed air and admixtures, if any, are introduced. The repair materials are propelled onto the surface by the compressed air.

Best application: Large vertical areas with small bars, No. 6 (19 mm) or less, and minimal congestion of embedded reinforcement.

Material requirements: Pumpable, lowslump mixture which does not sag when impacted on the prepared substrate.

Reference: ACI 506.2, "Guide to Shotcrete"



6.0 RECOMMENDATIONS:

It is often necessary to consider the strength of a structure before devising a repair or maintenance strategy. The implications for safety and serviceability in concrete structures with reinforcement corrosion are best assessed by considering the effects of the attack at three levels: (a) direct effect of corrosion on the performance of reinforcement, (b) effect of corrosion on the performance of the overall structure.

The reinforced concrete at the base of Point Shilshole condominium building is in a serious state of decay as the result of severe corrosion of the reinforcing steel. This problem should be addressed and repaired as soon as possible to restore the structural integrity and provide corrosion protection.

A survey and detailed investigation of the entire base is highly recommended to determine the extent of corrosion and damage to the structure.

Besides the conventional repair method recommended in this report, there are other methods that should be considered and studied further. Among such methods is application of fiber reinforced shotcrete covered by fiber reinforced polymer (or plasic) sheets.

The inclusion of fibers in concrete and shotcrete generally improves material properties including ductility, toughness, flexural strength, impact resistance, fatigue resistance, and, to a small degree, compressive strength. Given the corrosive environment where the structure is located, Polypropylene fiber shotcrete is more durable than steel fiber reinforced shotcrete. With shotcrete, hard to reach areas can be concreted and in most cases there is no need to erect formwork prior to concrete placement.

As a measure to prevent future corrosion, the use of fiber reinforced plastic (FRP) materials are also recommended. FRP sheets are being considered for use in the construction industry due to their lightweight, high strength, high stiffness, and excellent corrosion resistance.

Externally bonded FRP reinforcement is the basis of a new repair technology that combines advanced composite material forms with an installation method originally introduced for steel plates approximately 30 years ago. Repair with externally bonded FRP reinforcement is attractive to owners, engineers, and contractors because of ease and speed of installation, corrosion resistance, low profile, and versatility.

If there are any questions, please feel free to contact me. I would be willing to meet with the Board of Dirctors or your contractor if need be.

Sincerely yours,

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