# Introduction to Maintenance & Repair of Concrete Structures in Industrial Facilities

By Tom Kline, Senior Director, Concrete Repair Solutions at STRUCTURAL TECHNOLOGIES

**Introduction**

Many of the industrial plants in the United States are more than 80 years old. As these facilities continue to age, there will be an increasing potential need for sound, proven condition evaluation and repair of their conventionally reinforced and prestressed concrete structures. After years of service and exposure, usually in severe environments, our aging industrial infrastructure that stores, manufactures, processes, treats and disposes of various substances and products is, in many cases, in need of substantial repair, restoration and strengthening.

Over the course of the next few years, industrial facilities will need to spend hundreds of millions of dollars on plant infrastructure that generates no apparent revenue. A plant's concrete infrastructure is a prime example: It carries piping, holds equipment, and provides foundations and flooring. Yet, since it is not in and of itself a generator of revenue, spending money on its repair can easily be dismissed as having little or no return. However, the failure of the infrastructure to perform it's intended purpose can definitely cost a facility in production losses, or even worse, plant personnel injury and harm to the surrounding environment.

STRUCTURAL TECHNOLOGIES provides tools and programs to evaluate, budget, repair and maintain various types of industrial structures as they age.

**Causes and Effects of Structural Deterioration**

In order to recognize concrete deterioration, it is necessary to understand a few basic concepts. The two most common areas of deterioration in an industrial facility are related to corrosion of reinforcement steel and/or deterioration of the concrete itself.

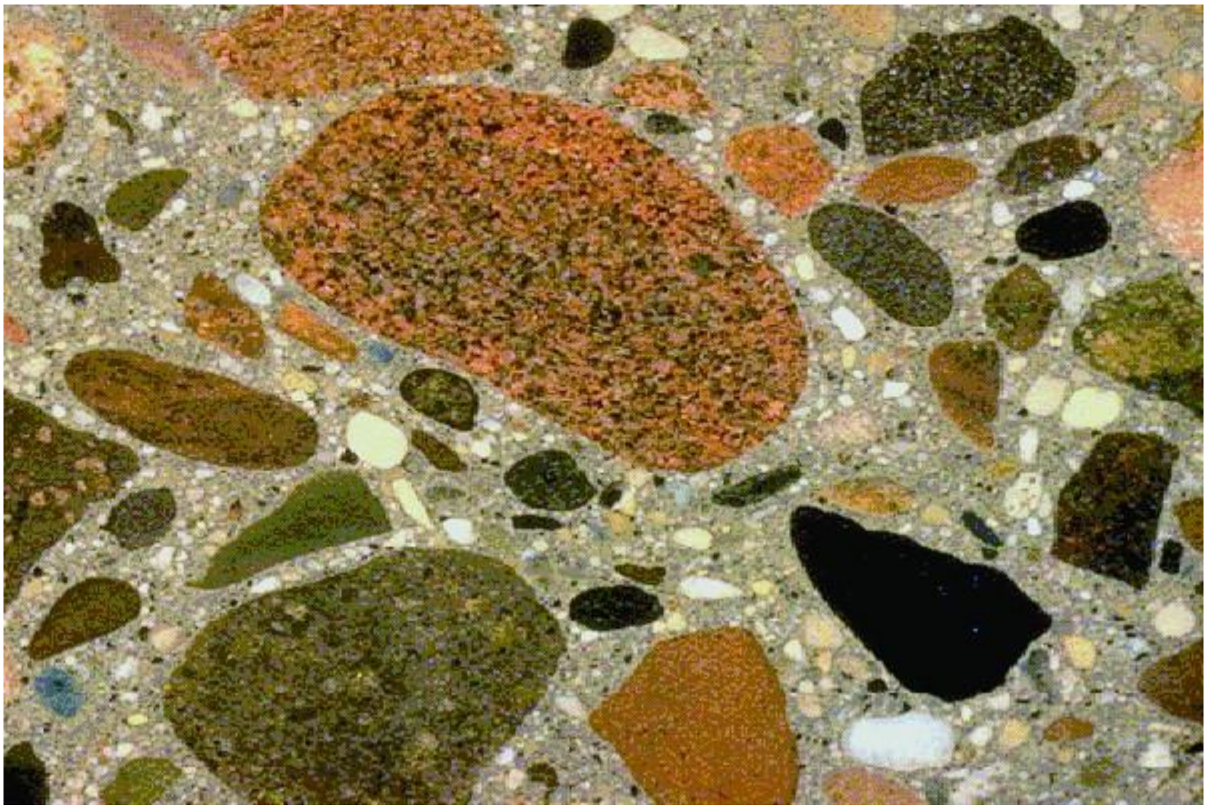

*Figure 1 - Aggregate (75%) + Cement (25%) + Water*

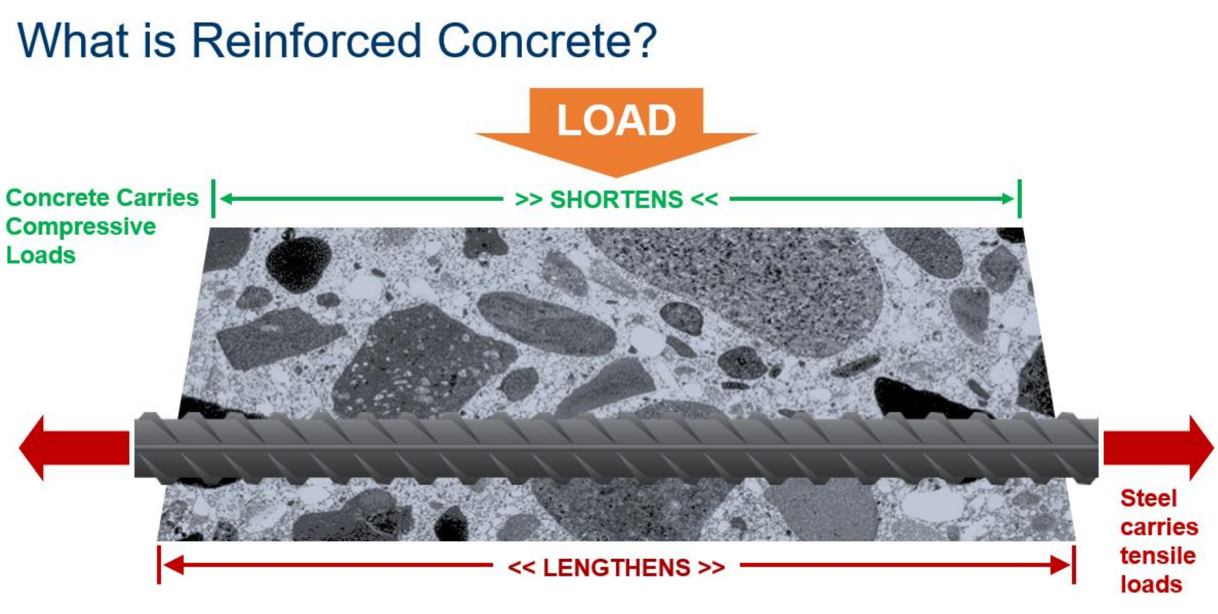

*Figure 2 - Composite action of reinforced concrete members subjected to loads*

Conventional concrete is made of Portland cement, aggregates of different sizes, water and associated admixtures. It is approximately 75% aggregate and 25% cement paste in its cured state (see fig. 1). It is basically aggregate (stone) of many sizes that are glued together with cement. As the aggregate is for the most part inert, the deterioration mechanisms of concrete are usually rooted in or related to the cement portion of the concrete mixture. This hardened mass, although it appears to be a dense material, is actually a "hard sponge," based on its permeability to gases and liquids.

Structures in industrial facilities are not constructed of just concrete; they also contain reinforcing steel as a tensile component. Concrete functions well in compression, but is inherently weak in tension, only approx. 10% of its compression strength. This composite is known as reinforced concrete (see fig. 2). There are two unique and beneficial synergies between the reinforcing steel and concrete: 1) Their thermal coefficients of expansion are similar, so they expand and contract at nearly the same rate. 2) Freshly placed concrete is an alkaline mixture and has an approximate pH of 13. Reinforcing steel, in this high pH environment, actually has a passivating layer or protective system surrounding it that prevents corrosion. Considering this condition, how then does the reinforcing steel corrode?

There are two mechanisms that break down the passivating protective layer: the first being the introduction of chlorides and the second having atmospheric carbon dioxide combined with water and oxygen. Chlorides can be introduced into this "hard sponge" by coming into contact with environments containing chlorides, such as seawater, de-icing salts, or industrial processes. Penetration of chlorides begins at the surface, then migrates inward. The penetration time depends on: 1) the amount of chlorides coming into contact with the concrete; 2) the permeability of the concrete; and 3) the amount of moisture present.

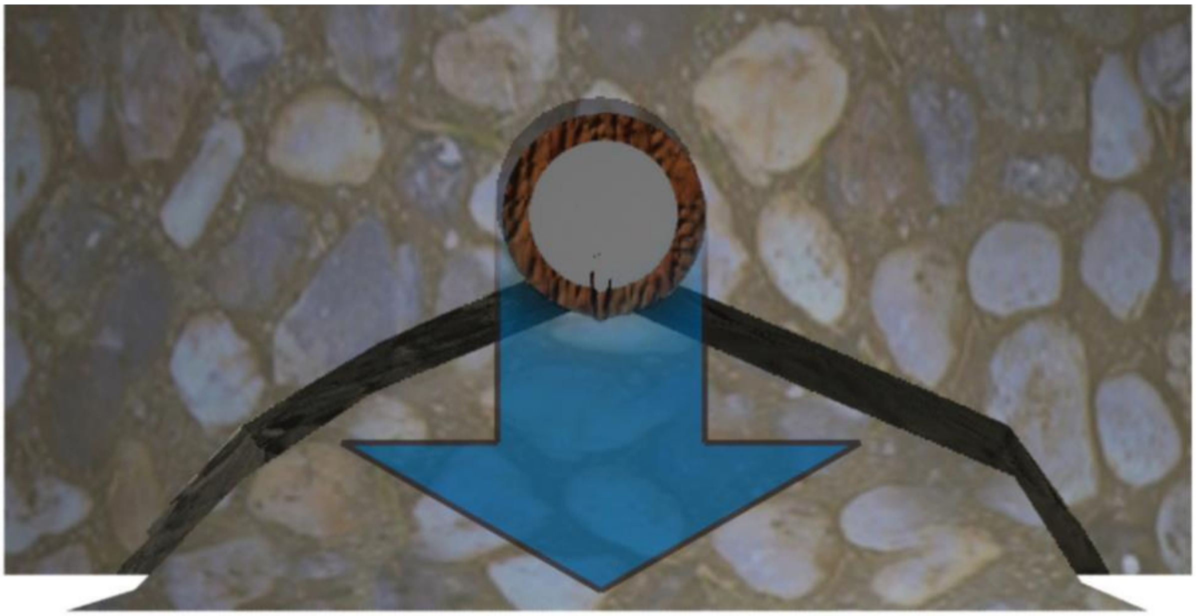

*Figure 3 – Concrete spalling mechanism involving corroding reinforcing steel bars*

Eventually a high enough concentration of chlorides comes in contact with the reinforcing steel and causes corrosion when moisture and oxygen are present. As the rust layer builds and expands (3-7 times its original size), tensile forces generated by expansion of the oxide cause the concrete to crack and delaminate. This is commonly known as a spall (see fig. 3).

Total delamination of the concrete occurs if the natural forces of gravity or traffic wheel loads act on the loose pieces. When cracking and delaminating progress, accelerated corrosion takes place because of easy access for corrosive salts, oxygen, and moisture through new conduits in the form of cracks and spalls. Corrosion then begins to affect reinforcing steel bars buried further within the concrete. Chlorides are essentially to concrete what harmful viruses/germs are to the human body.

The second mechanism, known as carbonation of concrete, is a reaction between gases in the atmosphere and the products of cement hydration. Normal air contains carbon dioxide (CO2) in relatively low concentrations (0.04%). The level of carbon dioxide in the industrial atmosphere is, as a rule, higher. Carbon dioxide penetrates into the pores of concrete by diffusion and reacts with the calcium hydroxide dissolved in the pore water. As a result of this reaction, the alkalinity of concrete is reduced to a pH value of about 10. As such, concrete protection, in the form of passivity, of the reinforcing steel is lost. The natural passivity resulting from high pH that protects the steel is destroyed by the carbonation process. When steel is depassivated and the environment is acidic or mildly alkaline, corrosion begins as moisture and oxygen gain access into the concrete. In good quality concrete, the carbonation process is very slow. It has been estimated that the process will proceed at a rate up to 0.04 in. (1 mm) per year. The process can accelerate with changes in moisture levels (i.e., from dry to damp to dry) and with elevated service temperatures. Carbonation will not occur when concrete is constantly under water. Basically, as concrete at the depth of the reinforcing steel is carbonated, it loses its "immune system".

More importantly, the concentration of chlorides necessary to promote corrosion is greatly affected by the concrete's pH. It has been demonstrated that a threshold level of 8,000 ppm of chloride ions was required to initiate corrosion when the pH was 13.2. As the pH was lowered to less than 10.5, corrosion was initiated with only 71 ppm of chloride ions. Like the human body, when the immune system is down, it takes fewer germs to cause distress. The same is true with concrete – when its pH is lowered, it takes one hundred times less the amount of chlorides to promote corrosion of the rebar.

Therefore, from an evaluation perspective of the "general health" of reinforced concrete, it is critical to know the level of chlorides and carbonation in order to develop repair strategies and prioritization of repairs. This is done by field testing for both mechanisms.

Another main source of deterioration in industrial facilities is the deterioration of the cement paste matrix (or the "glue") that holds the aggregate together. This usually occurs when the concrete is exposed to aggressive chemicals, sulfates, or freeze-thaw (wetting and freezing cycles).

Now, consider the aging process of a concrete structure. If you look at money spent on repair and maintenance versus time (see fig. 5), a typical curve will occur. There are three maintenance phases in the life of a structure (or equipment for that matter):

a) Preventive maintenance

b) Repair phase

c) Replacement/Repair phase

In the preventive maintenance phase, costs are usually fixed. They can be fixed at $0 (i.e., no maintenance) or at some fixed cost (i.e., coatings, washdowns, etc.). This phase, depending on the quality of the concrete and dollars invested in maintenance, can last 20 or more years. The desire of an owner would obviously be to make this phase last as long as possible by slowing down the effects of chlorides, carbonation and other exposures. Dollars spent here produce a good return on investment.

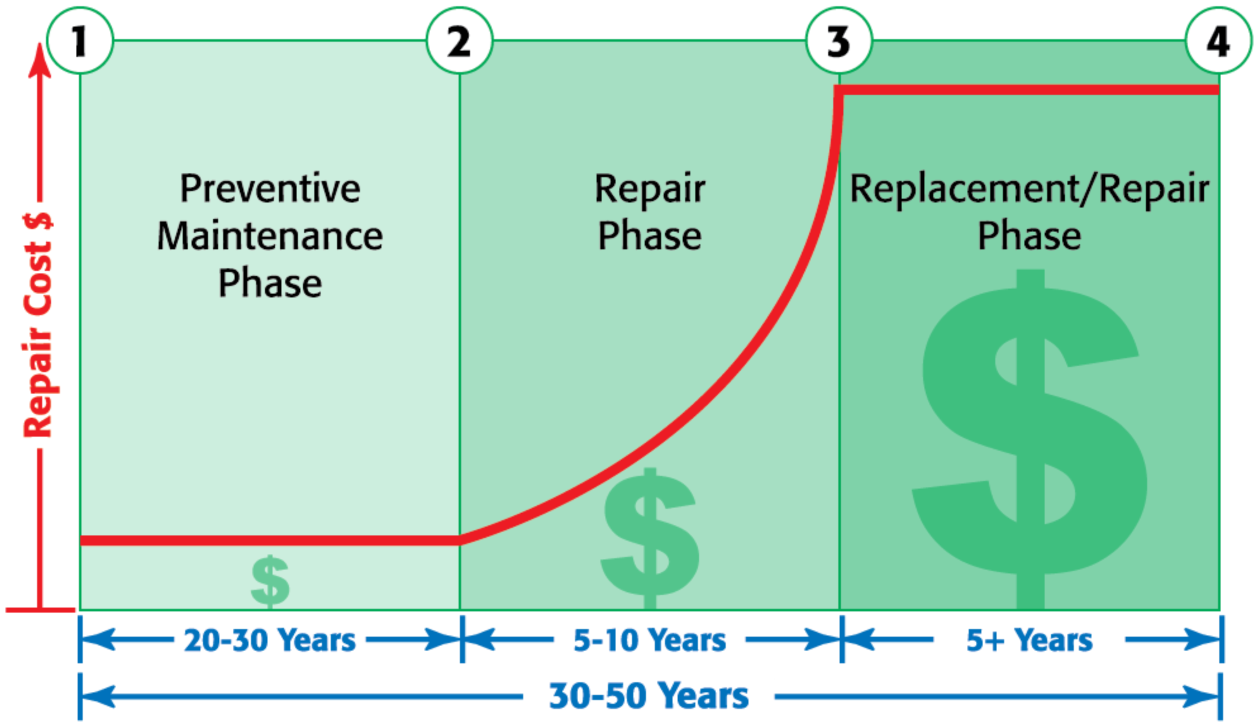


*Figure 4 – Repair Cost versus Service Life Diagram*

Once a structure has enough exposure to elements of deterioration, it enters the Repair phase (#2 - #3 on fig. 4). In this phase, repair costs vary and increase with time. The rate of the increase is a function of both how long repairs are left unaddressed and the quality of repairs or protection systems to slow down the inevitable deterioration. Also affected by these items is the length of the Repair phase. It can range from 5 to 20 years and involve multiple phases of proactive or preventive maintenance repairs, hence its variable costs and time frame. Extending this phase by evaluation and repair programs still has a good return on investment considering the next phase – Replacement/Repair.

At some point the structure enters the "Replacement/Repair" phase (#3 - #4 on fig. 4). In this phase, there is "wholesale" deterioration occurring such that the costs of repairs are equal to or greater than the costs of replacement. Unfortunately, repair scenarios in this phase are limited to high dollar options, considerable interruptions, or spending that utilizes expensive, "hold together" repairs to keep the process uninterrupted.

The problems that result in structural distress and deterioration, as well as the solutions for dealing with them, are often similar – whether they occur in bridges, parking structures, high-rise buildings, or industrial facilities. But industrial structures also have their own typical specifics and complexities. Within an industrial plant, there may be many different types of structures, each of which is exposed to different environmental conditions, and may suffer distress/deterioration from different mechanisms. Industrial structures are exposed to heavier loads, dynamic loading (vibration, impact), extreme temperatures and corrosive elements. Therefore, each may require a different repair procedure that is appropriate for its specific condition, service environment, and function in contrast to commercial concrete structures.

Industrial plants also contain structures that retain water, hazardous products, or other potentially deleterious liquids. In liquid-containing structures, inadequate joints and cracks in concrete are typically responsible for performance problems and concerns. To compound matters, it has been shown that the deterioration of concrete structures progresses more rapidly when heat and moisture are readily available. This phenomenon has been observed repeatedly with most degradation mechanisms including corrosion, alkali-silica reactivity, and sulfate attack.

While many industrial plants contain indoor structures and elements that are protected from their exterior environments, these same structures and members, in many cases, maintain high moisture contents and relative humidities for years … sometimes even decades. These high internal humidities alone can supply adequate moisture to sustain numerous deterioration mechanisms.

Another potentially harmful situation indigenous to some industrial facilities is the environmental condition whereby a concrete member is constantly exposed to relatively high temperatures. High temperatures, particularly when combined with high internal humidities and/or exposure to aggressive chemicals such as chlorides, sulfates, alkalis, and carbon dioxide, will accelerate deterioration.

**How Much Is Too Much Deterioration?**

Severe deterioration of either reinforced concrete or steel elements may eventually result in disastrous problems… even the collapse of a member or structural system. The acceptability limit of distress must be based upon the effect of a potential failure. For instance, it is more critical to protect a supporting member, such as a beam or column, from failing than it is to protect a non-load bearing element, such as a partition, curb, or floor overlay. One must also consider process interruption as a result of distress.

The safety of plant personnel may be jeopardized as a direct consequence of concrete deterioration. Employees may be injured by falling materials, leakage of hazardous materials, or by tripping and falling over degraded materials. The acceptability limit for potential injury to personnel is a major factor that must always be considered in any repair and/or maintenance program.

The “how much is too much” question also must consider the economics of concrete repair. Although rarely considered as a part of the facility (or equipment) that has a regular annual preventive maintenance budget to extend usable life, concrete has a distinct and sizable return on investment for early detection and repair. At the first sign of deterioration, the cost of repair and maintenance can be 100 times less than the cost of waiting. Recognizing distress, understanding the cause, and prioritizing repairs can save literally hundreds of thousands of dollars.

While several organizations – e.g., American Concrete Institute (ACI) and International Concrete Repair Institute (ICRI) – provide general guidelines on the durability and repair of reinforced concrete structures, only limited information and guidance is available on the specifics of condition evaluation, durability and repair of industrial facilities. Two useful resources are available for concrete evaluation include ACI 201.1R-08 & ASCE 11-99 - however they are more appropriate for Transportation & Commercial/Public Structures.

- **ACI 201.1R-08** *Guide for Conducting a Visual Inspection of Concrete in Service*
- **ASCE 11-99** - *Guideline for Structural Condition Assessment of Existing Buildings*

It should be noted that no document can replace the expertise of a skilled forensic engineer/concrete technologist experienced in the art & science of detecting and repairing defects in structures at industrial facilities.

When awarding condition evaluation and restoration/repair projects, clients are best served by involving all the key parties that will take part in the process – consulting engineer, condition evaluation agency, and repair contractor – to produce a reliable solution … a “value for money”.

**How STRUCTURAL TECHNOLOGIES Can Help**

The objective and mission of STRUCTURAL TECHNOLOGIES' approach (see fig. 5) is to identify structural problems and to develop and implement a cost-effective technology for repairing, maintaining and extending the service life of structures at industrial plants with little or no impact on service.

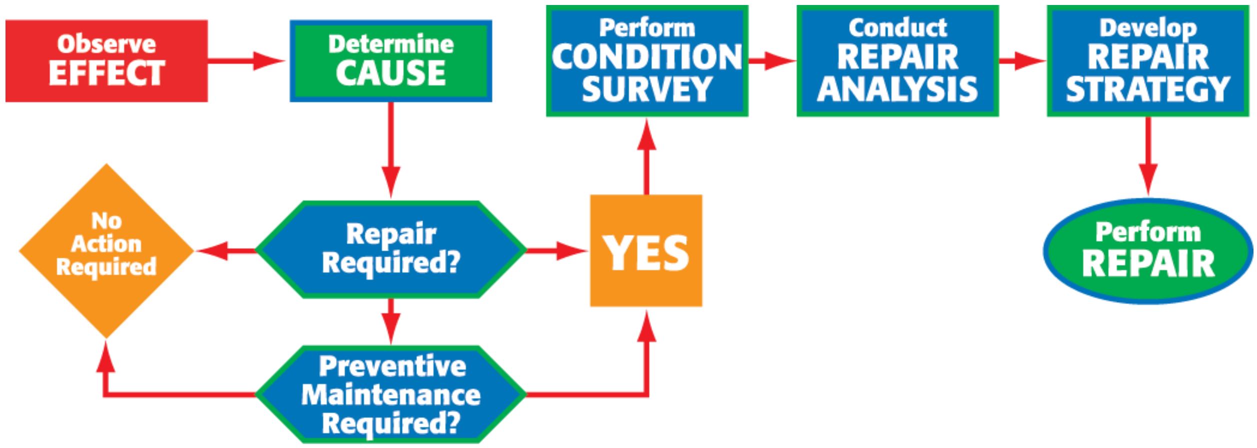


*Figure 5 – The Concrete Repair Process*

STRUCTURAL TECHNOLOGIES and its licensed contractors deliver experience unparalleled in the industry, providing clients with highest-quality engineering, condition assessment, and repair & protection services. And we provide these services while executing projects in a highly professional and safe manner, with minimal impact on day-to-day plant operations.

The information provided here sets forth a logical progression for the structural repair program offered and implemented by STRUCTURAL TECHNOLOGIES – moving from "broad brush" visual inspection toward effective, detailed testing. Our methodology includes structure-in-question studies, expert visual inspection, and representative nondestructive plus limited semi-destructive testing to determine the extent of damage as well as its causes, to establish a "quality pattern" for a structure.

**What Sets Us Apart?**

A unique philosophical, yet basic approach in condition assessment differentiates STRUCTURAL TECHNOLOGIES from other structural repair specialists. We feel the purpose underlying every condition assessment we undertake is to determine the existing "health" of a structure. From an engineering, constructability, economic and common-sense basis, we ask, "Is it good enough to be improved?" If the answer is "yes," we develop a cost-effective, prioritized repair program for the troubled structure, and then, once the client has approved the proposed remedial project, we can proceed to implement it. It is our 45 years of experience in the engineering and contracting side of the repair market that allows us to do this.

**The Condition Assessment**

The development of rational, cost-effective strategies for the repair and rehabilitation of industrial building components necessitates the acquisition of reliable information on both the level & rate of deterioration. This process begins with a professional evaluation of the existing condition of the structures in question. Each condition assessment must address some if not all these issues:

· Causes of deterioration/distress

· Load-bearing capacity and structural safety

· Need for and extent of repairs

The condition assessment is divided into three major phases:

· Recording of data and visual symptoms

· Measuring and testing

· Analysis of investigation results and prioritizing activities required

The philosophy behind performing the condition survey using the methodology described above is to obtain just enough pertinent information about existing conditions to proceed with the appropriate activities for the lowest cost. Essentially, we want to be in a position to limit repair program expenditures yet assure we don't "under-repair".

Obviously, good management of building structures requires knowledge of their structural and service conditions via a visual survey. Our forensic engineering specialist undertakes a visual survey of each structure with a detailed appreciation of the structural design, as-built drawings, history of repairs and modifications, its functional use, and the internal and external environments it must withstand. This kind of survey establishes not just where deterioration/distress is apparent, but more importantly, where it also may be hidden in the structure. It provides a sound basis for planning a program of detailed Non-Destructive (NDT) and Semi-Destructive (SDT) testing in selected representative areas.

The condition assessment process usually begins with a review of the available as-built drawings. The next step is a detailed visual examination of the structure. The purpose of this initial visual examination is to document easily obtained information on defects such as honeycombing (i.e., visible surface voids) and cold joints in the concrete, as well as instances of problems that can either result from or lead to structural distress – such as cracking, spalling, leakage, delamination, efflorescence, chemical attack, or any other visually observable indicators. Photographs are taken to record & capture the information pictorially, and detailed notes are written to indicate and describe the photographed areas.

**The Testing Program**

In addition to the visual survey, the testing program usually includes a delamination survey for the detection of any internal delaminations – near-surface planes of weakness – which are not visible. For horizontal surfaces, chains are dragged over the concrete surface to quickly locate hollow-sounding areas. Hammers or steel bars are used on vertical and overhead surfaces; their impact against the surface usually results in a more distinctive difference in tone (i.e., metallic sounds signify a "sound" concrete condition versus a hollow-sounding tone indicating an "unsound" condition).

The results of the visual and delamination surveys are used to identify portions of the structure that will be studied in greater depth. Detailed examination of representative suspect areas can include measuring half-cell potential/rate of corrosion testing, removing and testing of concrete and steel samples for physical property tests. Additionally, removing concrete samples for petrographic, depth of carbonation, and chloride content analysis can provide microscopic characteristics as well as chemical anomalies in the collected specimens. Locating embedded steel, additional nondestructive testing evaluations, and, in extreme cases, load testing can also be added to the testing protocols should it be necessary, based on existing service conditions and service life expectations.

By studying the results of all three categories of condition evaluation – visual survey, field testing & sampling, and laboratory analysis – our engineers and skilled concrete technologists are able to reach very reliable conclusions on any deterioration mechanisms taking place, as well as their causes. We continue to develop objective inspection and condition assessment techniques and criteria. This objectivity helps prevent vague, ambiguous condition assessments and eliminates most inspector bias, which results in more reliable, concrete data for determining where to allocate repair program resources.

**The Comprehensive Report**

After all of the field and laboratory results have been collected and studied, our engineers prepare an in-depth report, which includes the following information:

1. Visual identification of areas showing signs of apparent deterioration.

2. Assessment of the risk of deterioration in other parts of the structure based on the identification of:

· Areas where aggressive agents ingress, and where deterioration is likely to be aggravated by wetting and drying, high humidity, ponding, etc.

· Areas where the quality of concrete or cover to steel is poor due to shortcomings in design, detailing or construction practice.

· Areas where severe localized corroding conditions are likely to develop, driven by large cathodic/anodic areas.

· Areas where structural detailing is particularly sensitive to corrosion and deterioration.

3. Results of the detailed testing for carbonation, chloride levels, and half-cell potential/rate of corrosion testing are carried out, for a representative selection of the identified trouble spots.

4. Observations based on the opening up of the concrete via inspection “windows” to expose the reinforcement at a few representative locations of varying surface chloride and half-cell/rate of corrosion conditions selected from #3 above.

5. Assessment of the structural significance of the present severity of deterioration at each location.

6. Estimation of present deterioration of the structure as a whole based on the range of conditions found in the selected test areas.

7. Prediction of future problems, such as corrosion trends and concrete deterioration.

8. Evaluation of the technical, operational and long-term economic implications of the options for repairing and maintaining the structure.

9. Repair recommendations, which might include some or all of the following typical options:

· Proactive repair of damage.

· Slowing down of the deterioration by providing protection.

· Local strengthening of the structure to make damaged elements structurally redundant.

· Modifications to prevent safety hazards or interruption of service resulting from concrete spalling.

· Cosmetic measures.

· Toleration of deterioration, by carrying out the certain structurally essential repairs as required, until reconstruction of part or all of the structure becomes necessary or available.

A primary objective in the analysis of the findings is to identify those areas and parts of the structure which have a high level of importance because of the potential consequences of their failure. The comprehensive report presents an analysis of the relation between the quantity of distress and its effect on the condition of the overall structure.

In developing a repair program, the experts consider the possible causes of distress; evaluate the effect on structural integrity, serviceability, and function; and predict the severity of likely direct consequences of the distress such as failure, shutdown, slowed operations, chronic maintenance, major repairs, etc. They explain the causes of the deterioration and prepare a detailed description of the extent of the damage. They determine the condition of the remaining portions of the structure, identify any unsafe conditions, and recommend temporary corrective actions.

The final section of the report discusses the recommended repair techniques, details and materials which appear to be appropriate in view of the results of the investigation, as well as the environment of the structure. The location of repairs is a critical consideration in the development of repair recommendations.

For example, limited access may restrict the type of equipment that can be used. Good ventilation is required when using polymer-based repair materials. If ventilation cannot be provided, cementitious or polymer-modified cementitious materials should be used in such environments. Special consideration is given to repairs within containment areas having limited short-term access. The potential need for shoring and additional support for load-carrying members is also weighed carefully prior to demolition or removal of deteriorated concrete. On an individual case basis, all significant factors that might impact the successful execution of the repair require and involve careful judgement by experienced engineers and the entire team implementing the repair program.

A professional report prepared in this manner provides reliable, objective information on which a sound economical repair project can be based.

**The Repair Process**

The overarching goal for any repair strategy is to choose the very best material or system, and then proceed to implement the program with effective “means & methods”.

STRUCTURAL TECHNOLOGIES' licensed contractors have a demonstrated proficiency to carry out the optimum solutions to structural repairs … with minimal impact or intrusion on day-to-day plant operations. Since repair work typically takes place in functioning facilities, we recognize the need to take a team approach. Every project is carefully planned in close conjunction with plant operations personnel, and the work is carried out in ways that won’t interfere with critical manufacturing or processing activities.

**An Important Economic Message to Owners of Industrial Facilities**

Structural repair and protection problems almost always boil down to economic considerations. The service life of most structures can be divided into four phases, as follows:

Phase A: Design, construction and commissioning of the structure

Phase B: Initiation of the deterioration process is underway, but distress manifestations have not been revealed visually

Phase C: Propagating deterioration has just begun

Phase D: Advanced state of deterioration with extensive damage evident

Based on these four structural condition phases, DeSitter introduced his Law of Fives, which states:

"One dollar spent in Phase A equals five dollars in Phase B, equals twenty-five dollars in Phase C, equals one hundred twenty-five dollars in Phase D."

Inspection, repair and maintenance procedures are necessary to ensure that existing structures do not progress to Phase D. Money can be saved and used for better purposes. Moreover, owners should also realize that if a structure is in Phase D, even the very best repair project will not restore it to Phase A.