University Transportation Research Center - Region 2

Final Report

Modern Low Cost Maintenance of Concrete Bridges Using Effective NDT Test Data

Performing Organization: Syracuse University

September 2012

Sponsor:
Research and Innovative Technology Administration (USDOT/RITA)

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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Principal Investigators:

Dr. Riyad S. Aboutaha
Associate Professor
Civil and Environmental Engineering
Syracuse University
Email: rsabouta@syr.edu

Co-Authors:
Litao Li, Haotian Zhang, Jin Zhang,
Christopher J Ferguson, Fang Wang, Menglian Gu, and Chaoyi Fu

Performing Organization: Syrachuse University

Sponsor:
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To request a hard copy of our final reports, please send us an email at utrc@utrc2.org

Mailing Address:

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

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16. Abstract

According to the U.S. Department of Transportation, as of December 2008, of the 600,905 bridges 72,868 (12.1%) were categorized as structurally deficient (SD) and 89,024 (14.8%) were categorized as functionally obsolete (FO). Despite healthy economy during the period of 1995-2005, the numbers of SD and FO bridges were on the rise. It is very clear that the current bridge evaluation and maintenance policies are not working efficiently. The high numbers of SD and FO bridges should not be allowed to continue to rise. Given the current state of the US economy, smarter bridge management policies should be adopted, as we cannot afford the high cost of conventional maintenance of our huge transportation civil infrastructure. In addition, there is a need for more scientific approach for setting bridge inspection frequency based on safety, chemical and physical condition, design, age of the structure, and engineering judgment.

Practical experience coupled with non-destructive test (NDT) data produce good assessment of bridge condition. The question is how to utilize NDT data to develop a cost-effective preventive maintenance policy for highway bridges. NDT data should not only be used for assessing current condition of bridges, but also to predict its deterioration rate and its future maintenance needs. NDT data of the likelihood of corrosion in a bridge component is a very good indication of its future deterioration rate in the following few years. If implemented, low cost maintenance measures would stop or slow the deterioration rate resulting in lower maintenance cost over the service life of the bridge.

There is fundamental problem with the current NDT/inspection procedures, as they focus on identifying/measuring physical defects/damage through visual inspection complimented with NDTs. Such physical defects may include but not limited to cracking, rust stain, delamination, etc. Physical damage measurement approach has proved to be a very passive, and ineffective in preventing major deteriorations. An alternative approach would be an active NDT chemical measurement approach, which is less expensive and more effective in detecting potential problems before they even start.

This report presents smart use of NDT data to assess the near future service life of concrete bridge components, and its utilization for cost-effective maintenance policy, in a limited financial resources environment. The impact of this study enhances the followings: (1) development of better rational for setting maintenance frequency based on condition, (2) development of low-cost preventive maintenance measures for better control of deterioration rate, (3) understanding of financial consequences of delayed maintenance, and (4) reduction of the number of structurally deficient bridges.

In conclusion, the most economical way to maintain existing concrete bridges is by adopting an active preventive maintenance approach, which costs just fraction of the current passive approach. Such an active preventive maintenance approach requires chemical detection of potential deterioration problems before they even start.

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Syracuse University

L.C. Smith College of Engineering and Computer Science

Department of Civil and Environmental Engineering

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by

Riyad S. Aboutaha, Litao Li, Haotian Zhang, Jin Zhang,

Christopher J Ferguson, Fang Wang, Menglian Gu, and Chaoyi Fu

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Project Summary

According to the U.S. Department of Transportation, as of today, of the 607,380bridges 66,749 (11%) were categorized as structurally deficient (SD) and 84,748 (14%) were categorized as functionally obsolete (FO), (FHWA, 2013). Despite healthy economy during the period of 1995-2008, the numbers of SD and FO bridges were on the rise. It is very clear that the current bridge evaluation and maintenance policies are not working efficiently. The high numbers of SD and FO bridges should not be allowed to continue to rise. Given the current state of the US economy, smarter bridge management policies should be adopted, as we cannot afford the high cost of conventional maintenance of our huge transportation civil infrastructure. In addition, there is a need for more scientific approach for setting bridge inspection frequency based on safety, chemical and physical condition, design, age of the structure, and engineering judgment.

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There is a fundamental problem with the current NDT/inspection procedures, as they focus on identifying/measuring physical defects/damage through visual inspection complimented with NDTs. Such physical defects may include but be not limited to cracking, rust stain, delamination, etc. Physical damage measurement approach has proved to be a very passive, and ineffective in preventing major deteriorations. An alternative approach would be an active NDT chemical measurement approach, which is less expensive and more effective in detecting potential problems before they even start.

This report presents smart use of NDT data to assess the near future service life of concrete bridge components, and its utilization for cost-effective maintenance policy, in a limited financial resources environment. The impact of this study enhances the followings: (1) development of better rational for setting maintenance frequency based on condition, (2) development of low-cost preventive maintenance measures for better control of deterioration rate, (3) understanding of financial consequences of delayed maintenance, and (4) reduction of the number of structurally deficient bridges.

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Key Words: Bridge management, bridge inspection, deterioration, service life, NDT, cost effective maintenance, preventive maintenance

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Introduction

According to the U.S. Department of Transportation, as of December 2008, of the 600,905 bridges 72,868 (12.1%) were categorized as structurally deficient (SD) and 89,024 (14.8%) were categorized as functionally obsolete (FO). Despite healthy economy during the period 1995-2005, the numbers of SD and FO bridges were on the rise. It is very clear that our bridge evaluation and maintenance policies are not working efficiently. The high numbers of SD and FO bridges should not be allowed to continue to rise. Given the current state of the US economy, smarter bridge management policies should be adopted, as we cannot afford the high cost of proper maintenance of our huge transportation civil infrastructure.

Regardless of age and condition, current practice requires bi-annual inspection of highway bridges, which results in costly inspection caused by un-necessary frequent inspections of newer bridges and lack of frequent inspection of older bridges, (NYSDOT, 1997). There is a need for a more scientific approach for setting bridge inspection frequency based on safety, chemical and physical condition, design, age of the structure, and engineering judgment. In addition, there should be a clearer differentiation between maintenance and repair. The cost of major repairs is much higher than timely preventive maintenance measures. There is strong evidence of existence of many bridges where minor maintenance activity is delayed until it becomes a structural deficiency, which resulted in high repair cost for large number of bridges categorized as structurally deficient (Aboutaha, 2004).

Practical experience coupled with non-destructive test (NDT) data produce good assessment of bridge condition. The question is how to utilize NDT data to develop a cost-effective maintenance policy for our bridges. NDT data should not only be used for assessing current condition of bridges, but also to predict its deterioration rate and its future maintenance needs. For example, half-cell potential NDT data of the likelihood of corrosion in a bridge component is a very good indication of its future deterioration rate in the following few years, (ASTM, 2009). If implemented, low cost maintenance measures would stop or slow the deterioration rate resulting in lower maintenance cost over the service life of the bridge.

This report presents smart use of selective NDT data to predict the near future service life of concrete bridge components, and its utilization for cost-effective preventive bridge maintenance policy.

Deterioration, Assessment, and Rehabilitation of Deteriorated Existing Concrete Bridges (Best Available Current Practices)

The purpose of any concrete bridge evaluation is to assess its actual condition to ensure that there is adequate strength to carry external loads over its design service life. Bridges are affected by destructive external environmental factors that limit their service life. These factors include but not limited to chemical attacks, freezing and thawing cycles, corrosion of reinforcing steel bars, carbonation of concrete; and chemical reaction of aggregate. If bridges are not well maintained, these factors may lead to a structural deficiency, which reduces the margin of safety, and may result in structural failure. Such severely deteriorated bridges would be classified as structurally deficient.

Good understanding of deterioration mechanism of a concrete bridge subjected to chemical attacks by the surrounding environment is essential to predict its near future condition, conduct a meaningful evaluation; and developing appropriate maintenance program. For an existing deteriorated concrete bridge, if the cause of deterioration or structural deficiency is understood, it is possible to select a cost-effective durable repair system to extend its service life.

More important, good understanding of deterioration mechanism of concrete bridges is essential for developing a cost-effective preventive maintenance program for new undamaged/un-deteriorated bridges. Such program would allow the bridge to safely carry its traffic loads over its full design service life, if not extended service life.

The NDT methods can be classified in terms of mechanism, judgment method, and purpose, (Khalim et al, 2010).

In terms of mechanism, there are many methods that fall under this classification, including those that depend on sonic wave, e.g. Cross Sonic Logging, Sonic Echo/Impulse Response and Impact Echo. These methods are usually able to identify the details of a problem, including location and type of defect, properties of concrete. Some methods rely on visual sense, like Infrared Thermography. It quickly shows the presence of crack and delamination, which means it requires minimum traffic interruption, but fails to provide the details. Several methods such as Ground Penetration Radar and Half Cell Potential use electrical way to inspect the corrosion of rebar and delamination.

In terms of judgment, all NDT can be divided into subjective and objective method. Subjective methods, such as visual survey, rock hammer and chain drag, depend on worker's subjective judgment and experience. They are usually rapid and cheap, but the test result would be quite rough. The objective methods usually rely on high-cost technique and equipment. They can identify the detail of a problem; however, in order to operate the testing they frequently require the closure of a traffic lane or even the entire bridge.

In terms of purpose, each NDT method has its own specific testing aspect. Half Cell Potential is used to identify the potential corrosion of rebar. Infrared Thermography, Impact Echo, Crosshole Sonic Logging and Sonic Echo/Impulse Response can detect the damage of concrete, like cracks, delamination, voids and damage of concrete section.

Since each NDT has its own limits and advantages, engineers need to decide how to choose reasonable methods to form an effective plan. The following sections present evaluation, NDT, and rehabilitation of deteriorated existing concrete bridge elements. They are subdivided into three primary sections: Bridge Decks, Bridge Superstructure, and Bridge Sub-structure.

Bridge Decks

As they are subjected to direct contact with traffic and environmental loads, the usable life of a concrete bridge deck is ONE-HALF the life of the bridge (Bettigole, 1990). In severe environments, this could even be much shorter. Therefore, the deck slab needs special attention for damage assessment and to operate the rehab project during the early year. The common problems of bridge decks are cracking, leaching, scaling, spalling, rebar corrosion, poor quality of concrete and delamination. These problems usually occur slowly and have no significant effect on the workability and serviceability of the bridge at the first stage. However, without proper measures, it may become potential danger threatening public safety. All these problems associated with safety level and service life of bridge need to be inspected. Depending on the NDT testing results, effective maintenance and repair could be planned and executed, (Khalim et al, 2010).

NDT Combination Analysis for Bridge Deck

The commonly used NDT methods for deck evaluation are visual inspection, chain drag (CD), Impact echo (IE), Ground penetration radar (GPR), Infrared thermography (IR) and Half-cell potential (HCP). However, none of these methods can provide all the information in details. Combination of NDT is needed since response of single testing does not specify particular damage. Thus, according to the possible damage, how to choose and combine the NDT methods becomes very important in order to organize an effective solution, (Scott et al. 2003).

Figure 1 – GPR, (Global GPR Services, 2012)

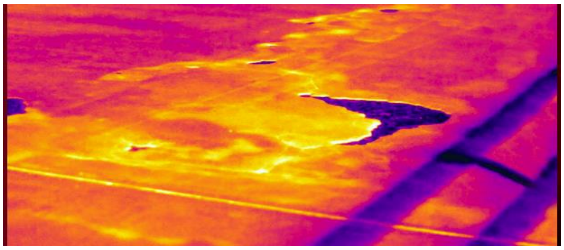


Figure 2 – IR, (S3 THERMAL IMAGING (2012)

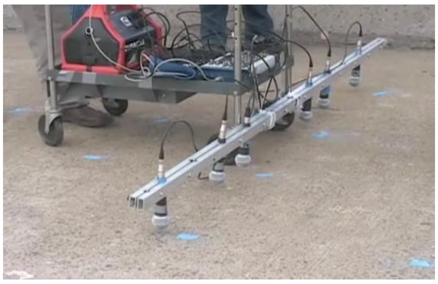


Figure 3 – IE, (SHRP 2, 2012A)

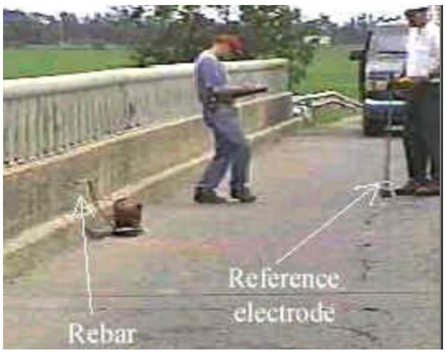


Figure 4 – HCP, (SHRP 2, 2012B)

Before making an NDT combination for specific situation, the limits and advantages of each method should be compared. Table 1 shows comparison among various NDT tests.

Table 1 – Bridge deck NDT comparison, (Khalim et al, 2010)

Methods	Time Consuming	Traffic Interruption	Delamination	Details of Delamination	Rebar Corrosion
Ground Penetration Radar	Rapid	No	Detect	No	Indication
Infrared Thermography	Rapid	No	Detect	No	No
Impact Echo	Long	Entire Traffic Closure	Assess	Type, depth, etc.	No
Chain Drag	Rapid	Lane closure for very short period of time	Detect	Surface Defects Only	No
Half Cell Potential	Long	Lane Closure	Potential Delamination		Active Corrosion

Methods	Concrete Properties	Depth of Slab	Cost	Limitation
Ground Penetration Radar	No	No	Low	No Details
Infrared Thermography	No	No	Low	Crack should be shallow and small
Impact Echo	Compressive Strength	Ok	Very High	Traffic Interruption
Chain Drag	No	No	Very Low	Subjective Method
Half Cell Potential	No	No	High	Traffic Interruption Indirect Method

From the Comparison, it is clear that the rapid methods are inexpensive, give rough test results, with no or little traffic interruption. In contrast, the slow method can identify detail of the deck and show more information of defects. But it is usually expensive and requires the closure of traffic.

Sometimes, a defect might show potential or be covert, only generating some indication of deterioration. In this case, the section of the deck needs to be checked with a different NDT combination. The significance of results from some different combination is presented in Table 2. (P: Positive. N: Negative.)

Table 2 – NDT Combination in terms of testing location, (Khalim et al, 2010)

Methods Combination	Purpose	Test Results	Confirmed Damage	Possible Damage
GPR & IR	Combination near the surface	GPR(P) IR(N)		Rebar corrosion, chloride contamination
		GPR(N) IR(P)	Delamination	
		GPR(P) IR(P)		Delamination, void, moisture
GPR & IE	Combination throughout entire depth of slab	GPR(P) IE(N)		Rebar corrosion, chloride, moisture damage
		GPR(N) IE(P)	Delamination	
		GPR(P) IE(P)		Void, delamination
IR & IE	Combination near the surface	IR(P) IE(N)	Moisture damage	
		IR(N) IE(P)		Void, delamination
		GPR(P) IE(P)		Void, delamination related to moisture
GPR, IR & IE	Combination throughout entire depth of slab	GPR(P), IR(N), IE(P)		Void, delamination around bottom rebar mat
		GPR(N), IR(P), IE(P)	Delamination around top rebar mat	
		GPR(P), IR(P), IE(N)	Moisture damage	

The reasonable and smart combination of NDT will reduce project cost by meeting only the needs of specific situation, potentially lowering the traffic interruption and covering long-term regular inspection to prevent issues from growing.

Deck Maintenance

Deck maintenance is an activity involving a series measures taken to restore or maintain such a condition so that the bridge can fulfill its design requirement and expectancy life span. It largely decreases the total life span cost, and guarantees safety level above the critical safety level of bridge. The maintenance methods are usually divided into two categories.

1. **Preventive maintenance (PM).** PM is placed when the bridge in under good to fair condition. Progressive deterioration can be retarded or sometimes avoided if proper systematical preventive maintenance is taken. It extends the life cycle of the bridge and preserves the investment. PM of deck includes a large variety of activity, ranging from sweeping the riding surface to joint replacement. It includes sealing, washing, caulking and crack repair[11].
2. **Responsive maintenance (RM).** RM is placed when the early deterioration begins. It includes small repairs, establishment of positive deck drainage systems, maintaining the functionality of deck joints and other similar activities that extend the serve life of other structural member[11].

Compared with the PM and RM, deck replacement required more time, tools, human resources and materials.

The main preventive maintenance objective for concrete bridge deck is to control salt and moisture penetration to prevent and/or retard corrosion of the reinforcement. A series of activities could be taken to meet the above objectives (Rossow, 2012A):

1. Keep the deck clean and provide good surface drainage by keep the drains open
2. Monitor the condition by testing for chloride penetration, delamination and active corrosion
3. Seal or overlay the surface to prevent and/or reduce salt and moisture penetration
4. Seal cracks to prevent and/or reduce corrosion of reinforcement

Before taking measures to repair cracks in a bridge deck, it is important to know the cause of the cracking. A specific maintenance technique should be implemented according to the type of cracking.

1. Cracking caused by **temperature and shrinkage**. With the improper water-cement ratio, for example, large quantity of water amount, it will produce void in the concrete paste, weakening strength of the deck.
2. Cracking caused by **improper curing process**. For example, when curing the fresh concrete, if the environment is too dry, the moisture in the concrete will evaporate easily, leaving transverse cracks in the deck.
3. Cracking caused by the **differential deflection**. This is common over the keyways of adjacent concrete box beams and void slabs.

Concrete Sealers

Concrete sealer can be divided into two classes, water repellent and pore blocker. It can improve the inner structure of concrete and prevent the steel from corrosion. Four types of concrete sealers are commonly used: penetrating sealer (includes silanes, siloxanes, and silicates), acrylics, polyurethane and epoxies. When applying the concrete sealer, it is better to place the sealer with brooms instead of spraying the concrete sealer, since the sealer evaporates and gets on the vehicles and other surfaces. Table 3 presents different types of sealer and their applications.

Table 3 - Sealers and their applications, (Rahim et al, 2006)

Sealer	Application
100% silane	Surface sealer
40% silane	Surface sealer
Reactive Methyl Methacrylate	Crack sealer
Modified polyurethane	Crack sealer
Two-component Epoxy	Crack/surface sealer
Dow 888 silicone	Crack sealer

Overlays

Placing overlays is a measure of preventive maintenance. Applying the overlays can easily obtain the low permeability; provide good skid resistance and excellent ride quality. Overlays have been used for decades. Earlier overlays were mainly based on Portland cement. More advanced materials have been applied in the modern overlays, such as air-entrained, water-reduced, polymeric admixture, silica fume and fly ash. Overlays can be used to prevent or repair the salt contamination and chloride penetration. When applying the overlays, the salt contaminated area should be removed totally or the deterioration will continue. A common problem of applying overlays is that it is hard to guarantee the high bond strength. A practice method is to remove about 13mm of the surface and make the surface rough in order to strengthen the cohesive force.

Concrete Replacement

Concrete replacement is taken according to the condition of the deck and the comparison with cost of rehabilitation (e.g. PM, RM). Usually, deck replacement demands more working hours, human resources and materials. The most difficult part of replacement of the deck is the removal of the original deck, since it may damage the beams. In order to shorten the working hours, some companies use casted deck plane, which eliminate the influence on traffic.

Conclusion

As can be seen above, most of the current practice in maintenance of bridge decks is based on physical measurements of extent of deterioration due to various deterioration mechanisms through basic and advanced NDTs, followed by extensive repair that may require extended closure of the bridge. Such passive maintenance approach is costly and inefficient.

A preventive maintenance approach, which involves chemical and electrical measurements, allows pre-deterioration actions that would prevent deterioration from taking place. As a result, bridge would live longer, and cost less to maintain.

Superstructure

The superstructure of a bridge constitutes the structural elements that directly support the bridge deck, so it is very important part of the bridge. According to its functions, the common problems are cracking and corrosion. Most of superstructure cracks occur due to the shear and tension while corrosion is always due to the weather or environment. What's more, these two problems will threaten the safety of bridge seriously. Corrosion is critical, as it limit the service life of concrete bridges. For example, if corrosion-induced damage continues to occur after the first repair is performed, then future repairs will be required that will result in significant expense. The regular repair cycles can be avoided if the propensity for future corrosion-induced damage was known and appropriate measures were taken to control it. Therefore, the knowledge of future corrosion helps owners to identify cost-effective maintenance options, (Sohanghpurwala, 2006). The following section presents current practice used to maintain concrete bridge superstructure, which involves various NDTs and repair methods.

NDT Methods (Sohanghpurwala, 2006)

The following is a summary of most of the NDT tests that are used for evaluation of various properties in a bridge superstructure.

Visual Survey

A rapid, costless and direct way to inspect cracking, spalling, scaling, rust staining, efflorescence and patching or existing repairs, but depends on operator judgment and is prone to operator errors.

Delamination Survey

Sounding, Impact Echo (IE), Ultrasonic Pulse Velocity, Infrared Thermography (IR) and Ground-Penetrating Radar (GPR).

Cover Depth Measurements

The thickness of concrete cover over reinforcing steel will significantly affect the corrosion, because the cover is shallower, the speed of corrosion is faster. The location of a reinforcement bar and its depth of cover can be obtained nondestructively by using a pachometer or a covermeter. A pachometer (covermeter) is used to detect the presence of ferromagnetic materials (e.g. steel and iron) embedded in concrete.

Chloride Ion Content Analysis

Chloride ions are the primary cause of reinforcing steel corrosion. It is generally accepted that corrosion of reinforcing will only occur once a threshold value of chloride ion content adjacent to the bars is reached. It is generally given that this threshold value is approximately 0.025% to 0.033% by weight of concrete. Hence, it is important to determine the chloride ion distribution in a structure under investigation to be able to determine its susceptibility to corrosion

The chloride content in concrete can be determined through analysis of powdered concrete samples. Samples can be collected on-site at different depths up to and beyond the depth of the reinforcing steel using a hammer drill. Extreme care should be exercised to avoid inadvertent contamination of the samples.

Alternatively, cores can be collected and powdered samples can be obtained at different depths in the laboratory.

Electrical Continuity Testing

Continuity testing is performed to determine if various metallic objects (usually reinforcing bars) within the concrete are in direct contact, or electrically continuous, with each other.

This type of testing is needed for the following three reasons:

1. Results of this test are needed prior to conducting the corrosion potential survey and rate of corrosion tests.
2. Direct contact between reinforcing steel and other metals (e.g., aluminum or galvanized steel) can lead to corrosion due to dissimilar metals and the presence of electrical continuity supports the formation of macrocells.
3. The state of electrical continuity of all embedded metals must be known when considering cathodic protection as a long-term protection option.

Corrosion Potential Survey

The main idea of this survey is half-cell potential. It gives indication of the likelihood of corrosion.

Corrosion Rate Measurement

These techniques provide information on the rate at which steel is oxidized. The higher the rate, the sooner concrete cracking and spalling will appear at the surface. This information is very useful in estimating the time to additional damage and in selecting cost-effective repair and long-term protection systems.

Selection of NDT

When resources permit, many of the tests listed above should be performed during each evaluation. However, for cost-effectiveness, just few are used.

In general, two types of corrosion survey are conducted: "**Preliminary Corrosion Condition Evaluation**" (PCCE) and "**In-Depth Corrosion Condition Evaluation**" (In-Depth Inspection). The primary goal of the PCCE is to predict the future progression of damage and calculate SI (*Susceptibility Index*), whereas the primary goal of the In-Depth Inspection is to obtain sufficient data to prepare construction documents and calculate the SI, (Sohanghpurwala, 2006). Tables 4-6 present recommended tests, and the minimum sampling for both the PCCE and In-Depth Inspection types.

Susceptibility Index is a ratio of the average moment from threshold over the threshold. It is scaled to 10 for ease of use. The value of this index is 0 if all the chloride ion concentration everywhere at the steel depth is at the threshold and is 10 if there are no chloride ions anywhere at the steel depth, (Sohanghpurwala, 2006)

Table 4 – Recommendation for testing during PCCE and In-Depth Inspection, (Sohanghpurwala, 2006)

Type of Steel/Surface Treatment		Cover	Visual	Delamination	Chloride Profile	Epoxy-Coated Rebar Cores	Continuity	Carbonation	Petrographic	Half-Cell	Corrosion Rate
Black Steel	bare	√	√	√	√	N/A	√	↑	↑	↑	↑
	paints	√	√	√	√	N/A	√	↑	↑	↑	↑
Epoxy-Coated Rebar	bare	√	√	√	√	√	√	↑	↑	↑	↑
	paints	√	√	√	√	√	√	↑	↑	↑	↑

√ -mandatory ↑ -optional N/A –not applicable

Table 5 – Minimum Sampling Size for PCCE, (Sohanghpurwala, 2006)

Test Method	Minimum Sampling Size
Clear Concrete Cover (CCC)	30 measurements per span.
Visual Survey	Entire surface of the concrete element.
Delamination Survey	10% of the total surface area. If exposure is variable, use several test areas. The test areas should be selected to represent all variations.
Chloride Profile Analysis	1 location per 3,000 square feet or a minimum of 5, whichever is higher.
Epoxy-Coated Rebar Cores	Minimum of 5.

Table 6 – Minimum Sampling Size for In-Depth Inspection, (Sohanghpurwala, 2006)

Test Method	Minimum Sampling Size
Clear Concrete Cover (CCC)	30 measurements per span. If cover measurements from a previous PCCE are available, they can be used instead of collecting the data again in the in-depth evaluation
Visual Survey	Entire surface of the concrete element.
Delamination Survey	Entire surface of the concrete element.
Chloride Profile Analysis	1 location per 1,000 square feet
Epoxy-Coated Rebar Cores	Minimum of 5.
Electrical Continuity Testing	5 reinforcing steel bars in each span. Must include both transverse and longitudinal bars.
Petrographic Analysis	1 location per 3,000 square feet or a minimum of 5, whichever is higher.

Maintenance (Sohanghpurwala, 2006)

There are two steps in conducting a rehabilitation of a reinforced concrete element that has suffered corrosion-induced damage: (1) repair sections of the element that have suffered concrete failure in the form of cracking, delamination, and/or spalling and (2) provide a corrosion control system, if necessary, to prevent or minimize future deterioration.

In addition, there are various corrosion control strategies, such as:

Local Corrosion Control Systems

Patching, Reinforcing Bar Coating, Repair of Epoxy-Coated Reinforcing Steel and Corrosion Inhibitor.

Corrosion Inhibitor Patching

Type I uses a corrosion inhibitor-modified concrete patching material. Type II uses the same patching materials and also includes four applications of a spray-on inhibitor on the exposed reinforcing bars and patch cavity prior to patching.

Global Corrosion Control Systems

Overlays, Membranes, Sealers and Surface Coating.

Cathodic Protection Systems (CP) and Electrochemical Chloride Extraction (ECE)

These are similar methods using electrochemical. CP is the most cost-effective for long-term rehabilitation (greater than 15 to 20 years), but ECE is a short-term treatment.

Table 7 – Selection of Corrosion Control System (Sohanghpurwala, 2006)

<table>
<tr><th>REPAIR TYPES</th><th>SI < 2</th><th>SI ≥ 2</th><th>SI ≥ 4</th><th>SI ≥ 5</th><th>SI ≥ 7</th><th>SI ≥ 8</th></tr>
<tr><td>WHEN REPLACEMENT IS MORE COST-EFFECTIVE</td><td colspan="6">NEW CONCRETE ELEMENT (CORROSION CONTROL CAN BE INCORPORATED INTO IT)</td></tr>
<tr><td>TOP LAYER CONCRETE REPLACEMENT</td><td colspan="3">SEALERS, MEMBRANES, OVERLAYS</td><td colspan="3">SI TOO HIGH FOR TOP CONCRETE LAYER REPLACEMENT</td></tr>
<tr><td>PATCH REPAIR + OVERLAY</td><td colspan="2">CATHODIC PROTECTION EPOXY-COATED REBARS</td><td colspan="4">OVERLAY SERVES AS A CORROSION CONTROL SYSTEM</td></tr>
<tr><td rowspan="6">PATCH REPAIR</td><td colspan="5"></td><td>DO NOTHING</td></tr>
<tr><td colspan="4"></td><td colspan="2">SEALERS</td></tr>
<tr><td colspan="3"></td><td colspan="3">MEMBRANES</td></tr>
<tr><td colspan="2"></td><td colspan="4">OVERLAYS & OVERLAYS PLUS MEMBRANE</td></tr>
<tr><td></td><td colspan="5">CORROSION INHIBITORS</td></tr>
<tr><td colspan="6">CATHODIC PROTECTION & ELECTROCHEMICAL CHLORIDE EXTRACTION</td></tr>
</table>

Table 8 – Extensions in service life for various corrosion control systems (Sohanghpurwala, 2006)

Corrosion Control System	Service Life (years)	Comments
Patching	4 to 10, 4 to 7	Patching with Portland concrete cement and mortar.
Reinforcement bar coating		No information available in literature.
Repair of Epoxy-Coated Rebar	>3	Study did not monitor the repair procedure beyond 3 years; therefore, it is difficult to predict its service life.
Corrosion Inhibitor Surface Application	4 to 6	Service life is based on application of the inhibitor in the test patches in highly contaminated concrete.
Corrosion Inhibitor Plus Patching	4 to 6	Service life is based on application of the inhibitor in the test patches in highly contaminated concrete.
LMC Overlay	20	Based on study of several bridges in the state of Virginia.
LSDC Overlay	20	Numerous studies corroborate the findings of this study.
HMAM Overlay	<10, 25	Less than 10 years is based on the failure of the HMA overlay, which would also mean the end of service life of the waterproofing membrane.
Penetrating Sealers	5 to 7	The service of 7 years for penetrating sealers is generally accepted.
Surface Coatings		There are numerous kinds of coatings, and sufficient information is not available to define this category.
Corrosion Inhibitor Overlays		No information available in literature.
CP	5 to >25	There are numerous kinds of CP systems, and service life varies from one type to another.
ECE	10 to 20	Service life of ECE-treated concrete element is governed by ingress of chloride ions after the treatment. The service life quoted herein is based on no chlorides migrating into the concrete element.

LMC = latex-modified concrete LSDC = low-slump dense concrete HMAM = hot mix asphalt with a preformed membrane

Maintenance Methods

Repair- Batching Material and Sealant (Tadros et al., 2010)

Batching material and sealant are widely used to fill the cracks and create impermeable concrete surfaces that prevent moisture from getting into the girders and causing corrosion of the reinforcement.

Repair- Strengthening (Chhabra, 2012)

Enlarge Cross-Section Area

This is a simple construction process, adaptable and has a mature design and construction experience, but the work is heavy and needs a long time.

Steel Plates Bonding

A straightforward process that is reliable. Steel plates bonding does not increase the superstructure's self-weight and has no strengthening effect on other components of the structure. It has no significant influence on the structure shape and clearance height. However, the reinforcement effect largely depends on the glue selection and the operation proficiency. And due to the steel plates are exposed to the outer environment, this method is highly environment sensitive and may not be suitable for coast area or cold area that De-icing salt are widely used.

FRP Exterior Bonding

FRP exterior bonding is extremely useful when the beam is suffering from large deflection and shear force. It can be shaped easily according to the different shape of the girder. Also, it is lightweight and corrosion resistance that is perfect for extreme environment and fixed clearance height. However, the stress-strain curve of FRP does not have yield platform which leads to the possibility of brittle failure could be a problem that affects the ductility of the strengthened structure. Additionally, the initial cost of FRP exterior bonding is relatively high compared with other strengthen method, which is a great disadvantage given the current economic circumstance.

Post-Tension Strengthen

Post-tension strengthen method is placing additional post-tension tendons to change the internal force distribution of the original structure in order to enhance the bending stiffness or the bearing capacity of the structure. It can be easily installed and suitable for structures in high stress states. The disadvantage of this method is that reducing the clearance, affecting the beam appearance.

Comparison of Strengthening Methods for Superstructure

Table 13 – Comparison of strengthening methods

	Increase self-weight	Effect on Clearance height	Environment sensitivity	Difficulty of implement	Time of construction	Initial cost
enlarge cross-section area	High	High	Low	Low	Long	Low
steel plates bonding	None	Low	High	Medium	Short	Low
FRP exterior bonding	None	None	None	Medium	Short	High
Post-tension strengthen	Low	Medium	High	Low	Medium	Low

Replacement

Partially Replacement

When replacement is required, partial replacement is usually much cheaper than the entire replacement of the superstructure. The effects on traffic may also shorter than demolishing and rebuilding.

Rebuild

In some circumstance, rebuilding the whole superstructure may be the most cost-effective way to restore the structural and functional adequacy to the bridge.

Variable Affects The Decision Making Process (Long, 2010)

Structural Adequacy, Functional Adequacy, Essential for Public Use

These three factors are used to evaluate the sufficiency rating that assigns a numeric value for prioritizing bridges, which has great effect on funding for the repair or rehabilitation project and eventually influence the project scope.

Cost

Cost can be classified as initial cost and long-term cost. Even though the long-term cost, considering life-cycle cost including long term maintenance and rehabilitation, is more accurate and should be taken into consideration, some methods with low long-term cost could still be inappropriate due to the high initial cost.

Scheduling Constraints

Scheduling constraints is another variable that should be considered as the shut-down cost is extremely high on some particular bridges that need to be repaired or upgraded.

Durability

Considering the surrounding environment, durability has to be examined while choosing the rehabilitation strategy.

Constructability

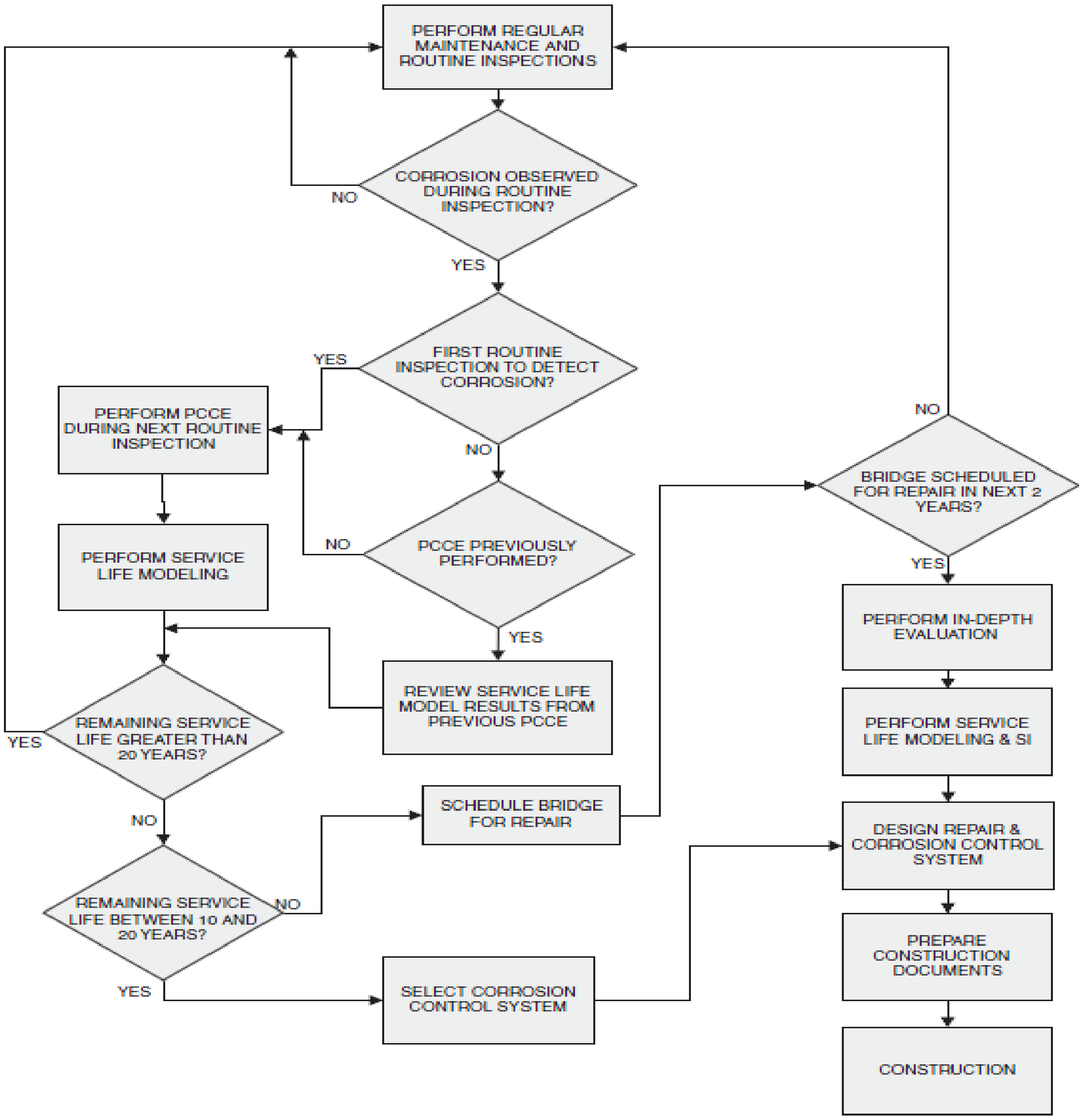
Some of the rehabilitation methods are cost-effective but are difficult to implement. For example, the quality of steel plates patching is mostly depends on the glue selection and the operation skill of the workers. In such situation, the construction procedure should be supervised restrictedly and the follow-up inspection should be delivered on time.

Degree of Certainty with Regard to Long-Term Performance

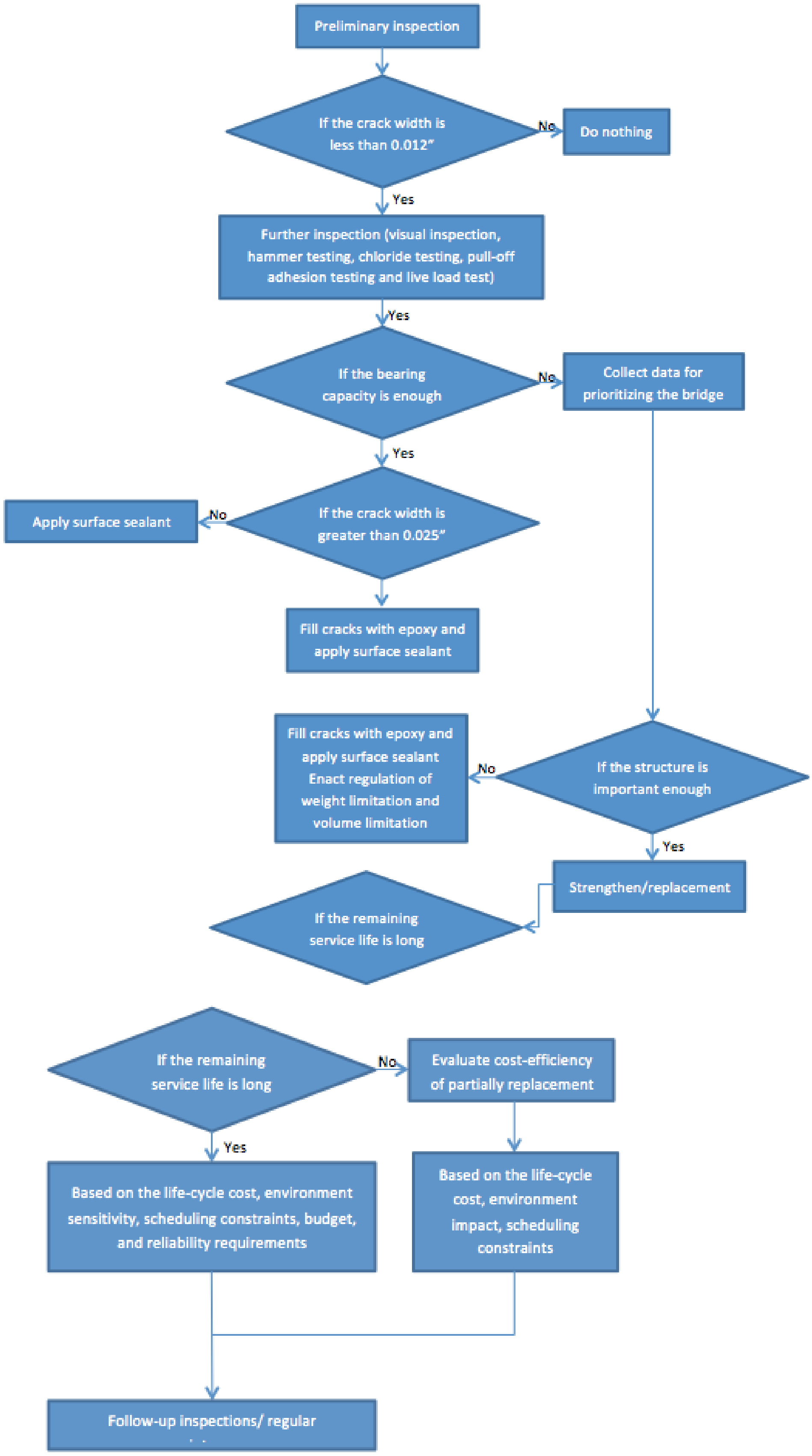
Certain methods of rehabilitation such as usage of FRP are not mature as the mechanism of the fatigue and the influence on structure ductility is still unclear. This kind of method should be used carefully with a lower impact of the possible structure failure.

Flowcharts FC1 and FC2 give examples of decision making process in maintenance of existing concrete bridges. These are very good charts for passive maintenance of bridges, where they guide users to detect damage and take appropriate action(s) to fix any problems. However, this process is costly and passive. A cost effective maintenance process involves chemical detection of potential durability problems and implementation of preventive maintenance before the problem starts, as presented in the following section.

FC1. Decision Flowchart (Sohanghpurwala, 2006)



FC2. Flowchart of the Decision Making Process (Tadros et al, 2010)



Substructure

Substructures of bridges consists of piers/columns, pier caps (beams), and pedestals that support the superstructure elements.

Substructure Problems

Substructure experience problems including: Cracking, caused by vehicle impact, chemical reaction, spalling due to freeze and thawing, carbonation; corrosion. Deterioration at water line, salt damage, foundation settlement (1.Compressible layer, 2. Downdrag, and 3.scour or bed degradation) Pile deformation, Abrasion of piles or cylinders, (Weyers et al, 1993, Collins Engineers, 2008), (Rossow, 2012B).

NDT Methods Application to Substructure

Most of the NDT methods can be used in detecting substructure problems. In this section, only foundation inspection will be mentioned. Foundation is a special part of the structure because it is hidden under ground. Crosshole sonic Logging, Tomographic imaging, Sonic Echo/Impulse Response, Parallel Seismic, Ultraseismic can be used to detect foundation problems, (IAEA, 2002).

Under Water Inspection (Cox, 2012)

Underwater Inspection investigates all bridge elements located below water lines.

Three Levels of Underwater Inspection

1. Inspection of 100% underwater elements: Check for obvious defects.
2. 10% of underwater elements: Check for damages which are hidden by biofouling.
3. 5% of underwater elements: NDT techniques, partially destructive techniques.

Underwater Inspection Methods

- Scuba Diving: Allows for a more detailed inspection of substructure condition
- Hard Hat diving: Under conditions like high water velocity, pollution unusual depth etc.
- Remotely Operated Vehicles (Rossow,2012B)
- Underwater camera

Maintenance, Repair, and Rehabilitation (Weyers et al, 1993, Winterbottom, G., and Goodwin, 2012)

Protection Methods

Sealers

Sealers are made of solvent or water-based liquid that can be applied to prepared concrete surface. Another kind of sealers are penetrating sealers. Penetrating sealers are silanes and siloxanes which can react with pore walls of the hardened cement paste to create a nonwettable surface. Surface sealers are used to block pores and holes using linseed oil or epoxy.

Estimated service life:

- Penetrating sealers: 5-7 years, reapplication every 6 years
- Surface sealers 3 years, reapplication every 2 years

Coatings

Coatings are made of one or two component organic liquid that is applied in one or more coats to a prepared concrete surface. Organic coating materials are normally epoxies, acrylics, or urethanes.

Many coatings have a limitation; it cannot be applied to concrete substructure with active corrosion sites or critically chloride-contaminated concrete.

Estimated service life:

- Bridge components subjected to sea spray have shorter service life.
- Epoxy 6-10 years (sea), 10-14 years (deicer salt runoff)
- Methacrylate 9-13 years, 13-17 years
- Urethane 10-14 years, 14-18 years

Cathodic Protection

Zinc Anodes: using clamping devices, small zinc anodes are attached to reinforced concrete piles below water to abate corrosion of piles located in salt or brackish water.

Jackets for Pile Protection (Cox, 2012)

Cementitious grout or epoxy resin pumped into the annular opening between existing concrete and the fiberglass liner. Deteriorated concrete piles can be encased with a concrete jacket after all unsound concrete has been removed and surface prepared.

Repair Methods

Substructure Patching

Patching is to restore the structural integrity and appearance of a deteriorated concrete bridge substructure element. Two kinds of patching are deep and shallow patching. Shallow patching reaches the level of reinforcing steel, and deep patching has a minimum of 0.75 in depth. Patching materials may be PCC, quick-set hydraulic mortar/concrete, or polymer mortar/concrete. If the problem is caused by corrosion of reinforcing steel, patching materials should be PCC.

Cast-in-Place Portland Cement Concrete (PCC)

PCC can be used to fill the prepared cavities of corrosion damaged concrete members. Remove damaged concrete to 0.75 in, below the first layer of reinforcing steel.

Estimated Service Life: The best estimate of service life of substructure PPC patches is 5 to 10 years

Shotcrete

Shotcrete (Gunite) is a pneumatically applied Portland cement mortar/concrete used to patch substructure and superstructure elements.

Estimated service life: 10-15 years

Substructure Encasement/Jacketing

Encasement is used on badly deteriorated columns or piers to recover its structural capacity. The damaged concrete is removed and concrete is used to fill the cavities and provide a cover over the as-built structural concrete element, completely encasing the element.

For badly deteriorated abutments and wing walls, a concrete jacket is utilized to restore the structural capacity of these elements. Prior to this, damaged concrete is removed and concrete is used to fill the removed concrete cavities and cover the as-built concrete face.

Estimated service life: 10-20 years

Patching with Corrosion Inhibitors

Two types are available:

1. A standard patching method using a corrosion inhibitor-modified concrete patching material
2. Uses a similar patching material but includes a four spray-on inhibitor to apply on the exposed reinforcing steel and patch cavity prior to patching.

   Estimated service life: Greater than 50 years

Epoxy Resin Injection

Two-component liquid epoxy conforming to ASTMC881 is injected through injection plugs that have been fitted into holes that were drilled along the crack.

Estimated service life: 5-10 years

Pressure Injection of Cracks Underwater (FLDOT,2012)

Underwater cracks (saturated with water) can be repaired using Epoxy resin. First clean the crack using high pressure water and then shape the concrete surface, drill injection holes, and finally inject epoxy resin from bottom to top. This is a very cost effective method.

Stitching and Doweling

Structural cracks can also be repaired with steel reinforcement to restore tensile strength across the crack (metal staples or stitching dogs attached across the crack) Steel reinforcement can also be used to repair structural cracks by embedding steel reinforcing bars across the crack.

Estimated Service life: More than 10 years (White and Hein, 2012)

Bandaging

When the crack will remain active and movement can be tolerated. A surface seal or bandage may be used. (flexible strip is placed over the crack with only the edges of the strip attached to the concrete.)

Estimated Service life: Based on the bandage material applied.

Post Tensioning

Applies a compression force against the crack, which can help close the crack.

Estimated service life: More than 10 years.

Concrete Repair Underwater (FLDOT, 2012)

Unless cathodic protection is used, the salt contaminated concrete must be removed to install fabric forms. A special technique should be used to protect underwater concrete.

Bagged Concrete

Bagged concrete can repair damaged portions of concrete structures. It is a quick and few skills and equipment-required method when water is shallow enough.

Prepacked Aggregate Concrete

After repair forms are in place, graded course aggregate is poured into the form. Later, a cement-sand grout is injected displacing water and filling the voids. Particularly effective, but expensive.

Tremie Concrete

Tremie concrete is placed underwater though a gravity-filled pipe, which is called tremie, best for large volume repairs. It is a simple method, most common method of placing concrete underwater.

Pumped Concrete

Pumped concrete is placed underwater using the same equipment as above water. Unlike Tremie, relocation is not required.

Free Dump Concrete

Use of anti washout concrete because it loses self-leveling properties and tends to stick to equipment, can only be used when the drop distance is around 1 meter.

Hand-Placed Concrete

Placed by hand by the diver and packed or rammed for consolidation. Suited for isolated repair sites, deep, and narrow cavities.

Table 6 – Comparison of different methods

Method	**Problem Solving**	**Service Life**	**Cost Effective (Y/N)**
Sealers	Protection	3-7 based on material	Y
Coatings	Protection	13-17 years	Y
Substructure Patching	Cracks, surface damage	5-10 years	Y
Shotcrete	Cracks, surface damage	10-15 years	N
Substructure Encasement/Jacketing	Badly deteriorated substructure elements	10-20 years	Y
Patching With Corrosion Inhibitors	Corrosion related problems	More than 50 years	Y
Epoxy Resin Injection	Cracks	5-10 years	Y
Stitching& Doweling	Cracks	10 years	Y
Bandaging	Cracks	Based on material selection	Y
Post Tensioning	Cracks	More than 10 years	Y
Pressure Injection Of Resin Underwater	Cracks	5-10 years	Y
Bagged Concrete	Concrete repair	Based on concrete quality and environmental conditions	Y
Prepacked Concrete Agregate	Concrete repair		N
Tremie Concrete	Large volume concrete repair		Y
Pumped Concrete			N
Free Dumped Concrete	Shallow underwater concrete repair		Y
Hand-Place Concrete	Small volume concrete repair		Y
Jackets For Pile Protection	Protection	5-10 years	Y

Proposed Low-Cost Preventive Maintenance

It can be seen from the extensive review of current bridge maintenance policies, presented above, that the current practice for evaluating and maintaining concrete bridges is fundamentally wrong. The NDTs are primarily focused on detecting physical damage in concrete bridge elements. If no physical damage is detected, then no maintenance action would be taken. This is the main reason why the number of US bridges that are classified structurally deficient is on the rise. Given the need for future expansion of the US transportation network and increase in number of new bridges, there is a need for much more efficient maintenance process that prevents deterioration mechanism from starting, or at least stops it at a very early stage.

Figure 5 shows simplified deterioration mechanism in severe environments. The combined effects of these mechanisms are more damaging. These mechanisms do not cause physical damage to concrete bridges over-night, but rather over a long period of time. During that period chemical reactions take place. A smart maintenance process is the one that stops that chemical reaction from taking place.

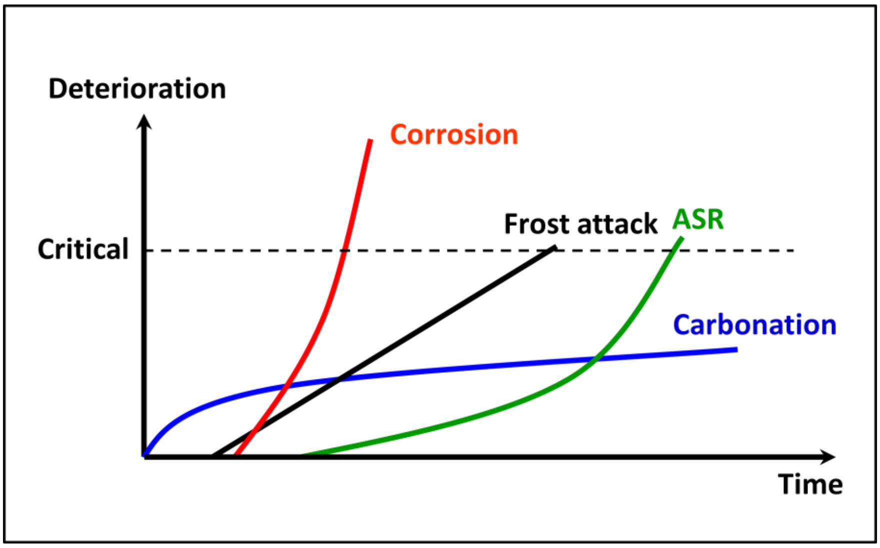


Figure 5- Simplifies deterioration mechanism

Avoiding the detection of the damaging chemical reactions and stopping them in concrete bridges will results in physical damages that are expensive to fix. Figure 6 shows the consequences of not adopting preventive maintenance policy. The longer the maintenance actions are delayed, the higher the cost of bridge maintenance. Figure 7 shows the effects of various types of maintenance policies. This figure shows that an active preventive maintenance process does not just maintain bridge strength and stability, it also costs just fraction of the cost of the current adopted delayed/ignored policies. Figure 8 shows the missing link in the current conventional bridge maintenance process. If a bridge is physically sound, that does not mean that chemical deterioration mechanism are not taking place. Such chemical reactions and their elements should be measured though smart NDT tests.

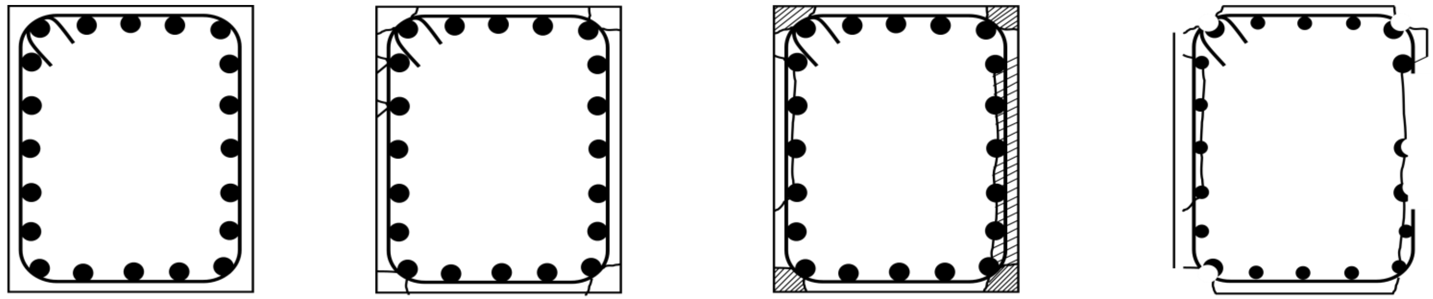
(a) Passive Delayed Maintenance
(1992)

(b) Ignored Maintenance
(2002)

(c) Ignored Maintenance
(2002)

(d) Ignored Maintenance
(2002)

Figure 6 - Deterioration of concrete bridge piers in the state of passive-delayed (1992) and ignored maintenance (2002), (Aboutaha, 2004).



Maintenance Type	Active Preventive	Passive	Passive Delayed	Ignored
Condition	Sound	Cracked	Cracking & Delamination	Loss of section
Strength	High	Medium	Medium	Low
Safety	High	Medium	Low	Critical
Retrofit Measures Involves	Protective coatings /Sealers	Replace damaged concrete Corrosion protection system	May require bridge closure May require Bridge Lifting Chip concrete behind bars Corrosion protection system Replace damaged concrete	Close Bridge Lifting Bridge Superstructure Chip concrete behind bars Corrosion protection system Add steel rebars Replace damaged concrete
Cost	$	$$	$$$	$$$$

Figure 7 – Cost of maintenance versus type of maintenance process, (Aboutaha, 2012)

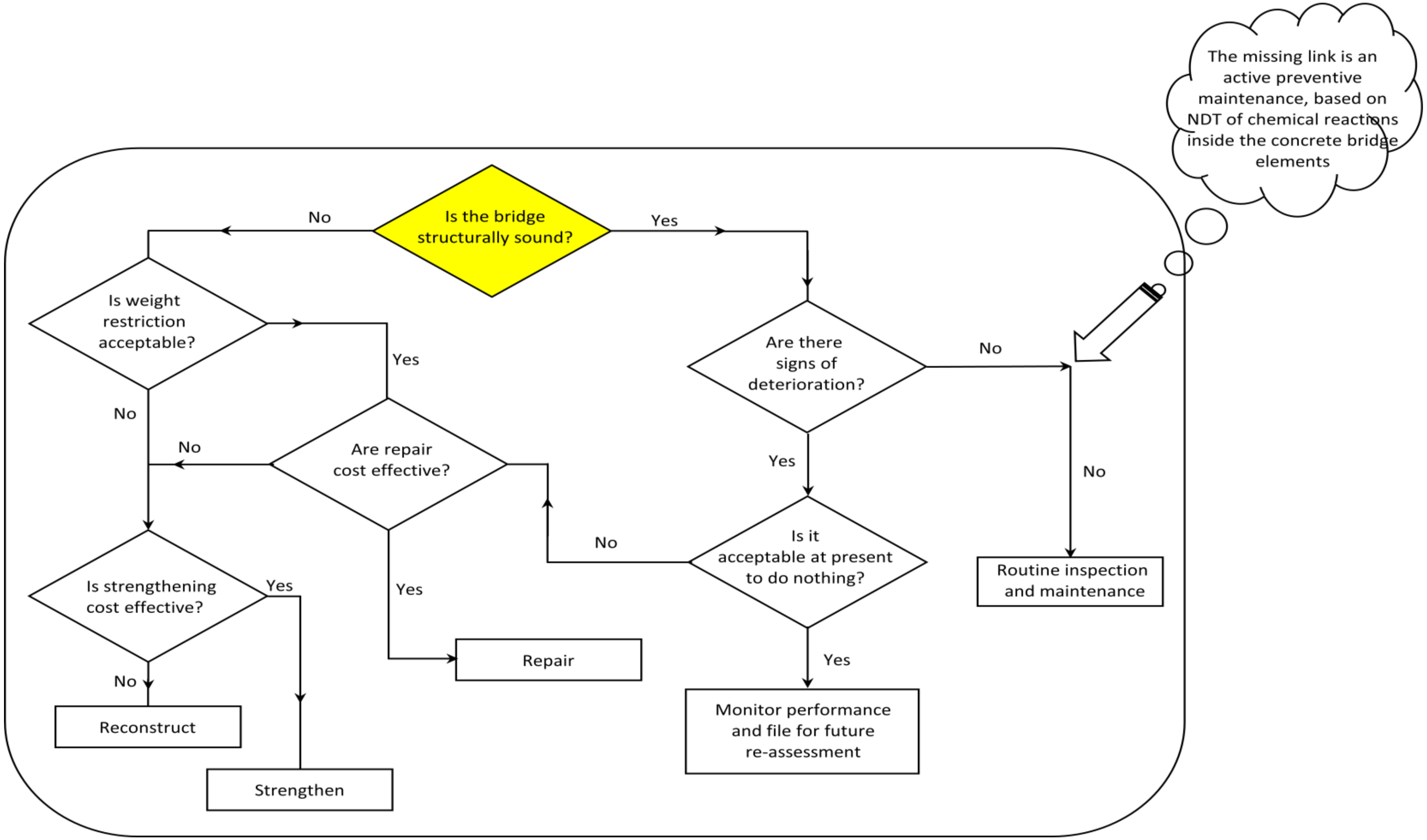
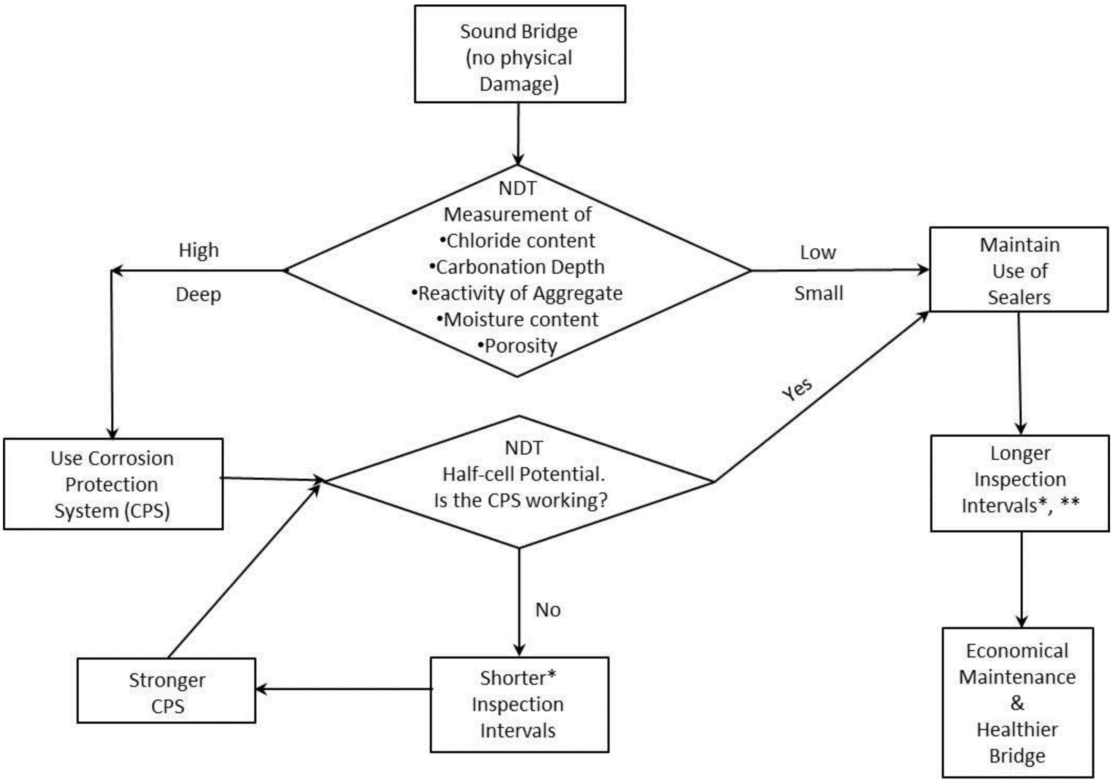


Figure 8 – shows the missing link in current conventional bridge maintenance process

How Does An Active Preventive Maintenance Approach Work?

Smart maintenance starts before any signs of physical distress have developed. **Smart NDTs** are those which measure the contents of the harmful chemicals in concrete bridge elements, not those that just measure the amount of physical damage. **Smart maintenance** is the one that prevents physical deterioration, not the one that repairs the physical damage to concrete elements due to deterioration. The Flowchart FC3 shows active preventive maintenance process in severe environments. Please note that application of sealers/coatings does not mean corrosion activities are arrested. When a harmful element exceeds a certain threshold, then the corrosion activities must be measured.

A smart maintenance system could be complimented with a remote monitoring system of corrosion activities.



True Active Preventive Maintenance of Concrete Bridges in Corrosive Environment

* Reference is made to two year interval (biennial inspection interval)
** Longer Inspection Intervals must involve NDT of corrosion activities.

FC3 - Preventive Maintenance Process in Severe Environments

For existing bridges that are experiencing localized corrosion damage, the deteriorated zone should be repaired, and the rest of the bridge element should be inspected and maintained as shown in the Flowchart FC3.

What do smart NDTs consist of?

There are several factors/elements that should be measured. They include, but not limited to, chloride contents, carbonation depth, moisture content, porosity of concrete, and reactivity of aggregate. There are several AASHTO and ASTM standard test that could be used to conduct these tests.

When the carbonation depth exceeds a certain limit, and almost reaches the steel reinforcing bars, then something should be done about it before corrosion of steel bars starts. Figure 9 shows the effect of drop in the pH value on the rate of corrosion at various chloride concentration levels. The higher the carbonation damage, the lower the pH value, consequently, the higher the corrosion rate.

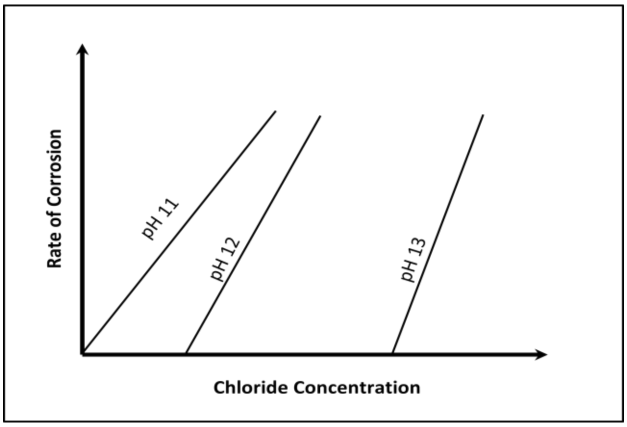


Figure 9 - Relationship between rate of corrosion and chloride concentration, (Verbeck, 1975)

When any harmful element exceeds a certain threshold, then the corrosion activities must be measured. What makes the problem more complex is the combined effects of these chemicals on concrete bridges due to their accelerated deterioration effects. Figure 10 shows a simplified degradation mechanism due to the combined effects of corrosion, frost attack, and carbonation.

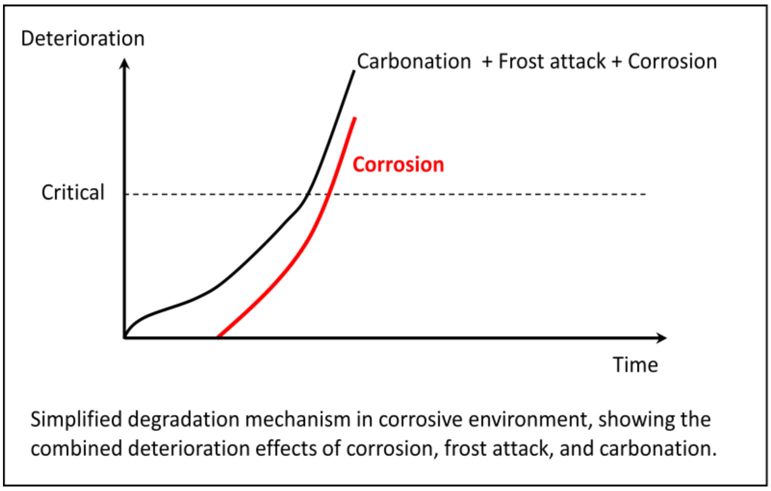


Figure 10 – Simplified degradation mechanism due to the combined effects of corrosion, frost attack, and carbonation

Summary and Conclusions

The current practice for evaluating and maintaining concrete bridges is fundamentally wrong. Most NDTs are primarily focused on detecting physical damage in concrete bridge elements. If no physical damage is detected, then no maintenance action would be taken. This is the main reason why the number of US bridges that are classified structurally deficient is on the rise. Given the need for future expansion of the US transportation network and increase in number of new bridges, there is a need for much more efficient maintenance process that prevents deterioration mechanism from starting, or at least stops it at a very early stage.

The most economical way to maintain existing concrete bridges is by adopting an active preventive maintenance approach. Such approach requires chemical detection of potential problems before they happen. Chemical NDTs are less expensive and more effective in detecting potential problem before they even start.

In lieu of measuring crack width or detecting delamination using chain dragging technique in a deteriorated bridge deck, at much earlier stage, the chloride contents and depth of carbonation should be measured during biennial inspection of sound bridge decks. The cost of chemical NDTs along with preventive maintenance are by far lower than the cost of the current physical NDTs and repair measures that might also involve bridge closure. Flow chart FC3 presents an example of a preventive maintenance process. The chart could be expanded to include detection and maintenance against other deterioration mechanisms/loads. Preventive maintenance would allow for longer inspection intervals. However, frequent simples chemical NDTs might be needed to ensure detection of potential deterioration mechanisms before they start.

In order to adopt an active preventive maintenance approach, an in-depth experimental and analytical investigation of the combined deterioration effects of various deterioration mechanisms is needed to establish a sound threshold for harmful chemicals in concrete bridge elements. Such established threshold is critical for decision making in a timely fashion before any deterioration starts.

In conclusion, a well-maintained bridge that’s makes frequent uses of chemical NDTs will cost considerably less to maintain, and safely serves its full service life.

References

Aboutaha, R.S., (2004) "Guide for Maintenance and Rehabilitation of Concrete Bridge Components with FRP Composites – Research into Practice," NYSDOT sponsored research report, Syracuse University, Syracuse, NY, USA.

Aboutaha, R.S. (2012) "Rehabilitation of Civil Infrastructure," Lecture notes, Syracuse University, Syracuse, NY, USA.

ACI 345, (2006), "Guide for Maintenance of Concrete Bridge Members" Reported by ACI Committee 345, *American Concrete Institute*, Farmington Hills, MI.

ASTM C876 - 09 (2009), "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete".

Bettigole, N.H. (1990), "Designing Bridge Decks to Match Bridge Life Expectancy in Extending the Life of Bridges", *ASTM Special Technical Publication 1100, ASTM Committee D-4 on Road and Paving Materials,* Philadelphia, Pennsylvania, pp. 70-80.

Chhabra, Y., (2012) "Bridge Rehabilitation Techniques," *The Ds Brown Company*, http://www.dsbrown.com/resources/articles/masterbuilder.pdf

Collins Engineers, Inc., (2008) "NAVY BRIDGE INSPECTION PROGRAM", User Guide UG-60020-OCN, Chapter 2 Underwater Inspection, Bridge Inspection and reporting guidelines, NFESC EAST COAST DET.

Cox., W.R., (2012), "In-Depth Inspection, Bridge Inspection Manual," Director, Bridge Division Manual Notice 2002-1.

FLDOT, (2012), "Bridge Maintenance and Repair Handbook," *Florida Department of Transportation*, Office of Maintenance.

FHWA, (2013), http://www.fhwa.dot.gov/bridge/deficient.cfm

Global GPR Services, (2012), "How GPR works", http://www.global-gpr.com/gpr-technology/how-gpr-works.html.

IAEA (2002), "Guidebook on non-destructive testing of concrete structures," International atomic energy agency, BIENNA.

Khalim, A.R., Sagar, D., Kamruzzaman, M., and Hasan, A.S.M.Z., "Problem with Deck and Evaluation, Combination of nondestructive evaluations for reliable assessment of bridge deck", *IABSE-JSCE Joint Conference on Advances in Bridge Engineering-II*, August 8-10, 2010, Dhaka, Bangladesh.

Long, H.P., (2010), "The Rehabilitation Alternatives," Seminar Presentation, http://mceer.buffalo.edu/education/bridge_speaker_series/2009-2010/presentations/Bruce%20Peterson%20color%20slides%201%20per%20page%20w%20QAslide.pdf.

NYSDOT, (1997), "Manual of Bridge Inspection," New York State Department of Transportation, Albany, NY.

Rahim, A., Jansen, D., and Abo-Shadi, N.,(2006), “Concrete bridge deck crack sealing: an overview of research”, California Polytechnic State University, Final report.

Rossow, M., (2012A), “Decks”, General, FHWA Bridge Maintenance Substructure, Course No: S05-005.

Rossow, M., (2012B), “Repair of Substructure”, General, FHWA Bridge Maintenance Substructure, Course No: S04-012.

S3 THERMAL IMAGING (2012), AFFILIATE APPLICATION, http://s3imaging.com/affiliate-application.

Scott, M., Rezaizadeh, A., Delahaza, A., Santos, C.G., Moore, M., Graybeal, B & Washer, G. (2003), “A comparison of nondestructive valuation methods for bridge deck assessment”. *NDT & E International.* 36: 245-255.

SHRP 2 (2012A), field validation testing of NDT technologies on a concrete bridge deck 02 – coupled impact echo – University of Illinois, The National Academics, 2011, http://vimeo.com/26123878

SHRP 2 (2012B), field validation testing of NDT technologies on a concrete bridge deck 15 – coupled half cell potential – University of Illinois, The National Academics, 2011, http://vimeo.com/26164616

Sohanghpurwala, A.A., (2006), “Manual on Service Life of Corrosion-Damaged Reinforced Concrete Bridge Superstructure Elements”, *NCHRP Report 558*, CONCORR, INC., Sterling, VA.

Tadros, M., Badie, S.S., and Tuan, C.Y., (2010) “Evaluation and Repair Procedures for Precast/Prestressed Concrete Girders with Longitudinal Cracking in the Web” Section “1.2.3. Batching material and sealant, *NCHRP Report 654*.

Verbeck, G., (1975) “Mechanics of Corrosion of Steel in Concrete,” Corrosion of Metals in Concrete, ACI Special Publication SP-49, American Concrete Institute, Farmington Hills, MI, USA, pp. 21-38.

Weyers, R.E., Prowell, B.D., Sprinkel, M.M., and Vorster, M., (1993) “Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual,” *SHRP-S-360*, The Carles E. Via department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

White, C, and Hein, D.K., (2012) “Optimization of Concrete Maintenance to Extend Pavement Service Life,” http://www.csuchico.edu/cp2c/documents/Library/2d-white-hein.pdf

Winterbottom, G., and Goodwin, F., (2012) “CONCRETE CRACKS; CAUSES, CORRECTING, and COATING”, Degussa Construction Systems Americas. Shakopee, MN 55379.

Appendix "A"
Field Chemical Tests

Several NDT equipment manufacturers have developed chemical agents and lightweight apparatus to investigate, in the field, the following concrete properties:

1. Alkali-silica reaction (ASR)
   This test involves application of chemical agents on a newly removed concrete core from the concrete bridge member under investigation. Depending on the chemical agents used, when the sprayed core shows yellow spots it indicates beginning stages of ASR degradation. While if the sprayed core turns pink, it indicates an advanced stage of ASR.

2. Carbonation of concrete
   This is a simple test; it involves immediate application of phenolphthalein on a newly removed concrete core from the concrete bridge member under investigation. Un-carbonated sound concrete turns pink, while the color of carbonated concrete remains unchanged. By spraying the phenolphthalein on the sides of the removed core, the depth of carbonation can be determined.

   The depth of carbonation can also be determined by collecting powder of a freshly drilled concrete in a special chemically treated container. When the color of the concrete powder starts changing to pink, then the sound concrete has been reached. Drilling is stopped and the depth of drilling is measured.

3. Chloride content (AASHTO-T260)
   This test involves mixing powder of freshly drilled concrete with an extraction of liquid which consists of a precise measured concentration of acid. The chloride ions react with the acid of the extraction liquid in an electrochemical reaction. An electrode, with integral temperature sensor, is inserted into the liquid and the electrochemical reaction measured. An instrument converts the voltage generated by the chloride concentration. The chloride concentration is shown on an LCD display.

4. Concrete penetrability
   There are several test method used to measure concrete penetrability, non of which is standardized. Many of the deterioration mechanisms in concrete involve the penetration of aggressive materials, e.g. chloride ions, carbon dioxide, and sulfates. In most cases water is required to maintain the deterioration mechanism. Therefore, concrete that has surface highly resistant to penetration of water is generally durable, otherwise, surface treatment may be required. There are several non-standardized tests to investigate concrete resistance to ingress of water. The tests are summarized in the ACI 228 committee report (1998). Table A1 summarizes the advantages and limitations of these tests.

Table A1. Advantages and limitations of penetrability methods (ACI 228.2R-98)

Method	Advantages	Limitations
ISAT	Simple and inexpensive to perform. Portable lightweight equipment. Sensitive to changes in concrete quality. Totally non-destructive.	Measures absorption of outer surface concrete only and is affected by surface coatings. Difficult to seal circular cap at the concrete

	Considerable experience has been gained in its use.	surface. Sensitive to concrete moisture condition.
Figg Water-Absorption Test	Not affected by coatings and surface concrete layer. Inexpensive and simple to use.	Intrusive because drilling is necessary. Drilling may affect concrete under test. Sensitive to aggregate characteristics. Sensitive to concrete moisture condition.
Covercrete Absorption Test	Gives an integrated measure of the entire cover zone.	Intrusive because drilling is necessary. Drilling may affect concrete under test. Sensitive to concrete moisture condition.
CLAM (Water Permeability)	Measures flow under constant pressure conditions.	Provides a permeability index, not sufficient of permeability. Sensitive to concrete moisture condition. Concrete surface is damaged. Long test time required.
Steinert Method (Water Permeability)	Measures unidirectional flow. Easier to interpret than CLAM.	Provides a permeability index, not coefficient of permeability. Sensitive to concrete moisture condition. Concrete surface is damaged. Long test time required.
Figg Air-permeability Test	Inexpensive and simple to use. Not influenced by surface layer or coatings. Less sensitive to moisture condition than water tests.	Sensitive to aggregate characteristics. Intrusive because drilling is required. Drilling may affect concrete under test. Provides a permeability index, not coefficient of permeability.
Schőnlin Test (Air Permeability)	Nondestructive. Less sensitive to moisture condition than water tests. Includes concrete moisture conditioning procedure.	Provides a permeability index, not coefficient of permeability. Measures outer surface concrete only and is affected by surface coatings.
Surface Airflow Test	Nondestructive. Less sensitive to moisture condition than water tests. Includes concrete moisture conditioning procedure.	Provides permeability index, not coefficient of permeability. Measures outer surface concrete only and is affected by surface coatings.

5. Permeability of concrete to chloride ions, laboratory test (AASHTO T 277-83)
   Accelerated tests can be performed to assess the permeability of concrete to chloride ions. The test involves the application of an external electric field across the specimen and the measurement of certain parameters, which are considered to be related to the diffusion coefficient. The major drawback of this accelerated test is that the acceleration coefficient is not constant. When the test is performed according to AASHTO T 227, the quality of concrete can be assessed by the amount of the electrical current passing across the sample as shown in Table A2 (AASHTO T 277-83):

Table A2. Chloride Permeability (AASHTO T 227-83)

Concrete Quality	Chloride Permeability	
	Evaluation	Criteria
Good	Low	< 2000 Coulombs
Average	Average	2000 – 4000 Coulombs
Poor	High	> 4000 Coulombs

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Region 2 - University Transportation Research Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: (212) 650-8050
Fax: (212) 650-8374
Website: www.utrc2.org