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DEVELOPMENT OF KNOWLEDGE BASE OF CONCRETE BRIDGE MAINTENANCE SYSTEM

by

Bahre Karam

A Thesis
Submitted to the
Faculty of the Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Civil and Construction Engineering

Western Michigan University
Kalamazoo, Michigan
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WE HEREBY APPROVE THE THESIS SUBMITTED BY

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ENTITLED Development of Knowledge Base of Concrete Bridge Maintenance System

AS PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science

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DEVELOPMENT OF KNOWLEDGE BASE OF CONCRETE BRIDGE MAINTENANCE SYSTEM

Bahre Karam, M.S.

Western Michigan University, 2007

Bridges are the key elements of any transportation system of a country. Bridges are expensive structures and therefore, it's essential to maintain and repair them on regular basis. Almost one third of the bridges in United States are reported to be in some what deteriorated conditions. This Research presents the development of knowledge base for decision support system for concrete bridges

During this research various concrete bridge problems are investigated including corrosion, delamination, cracks, spalling and scour etc. The inspection tools and techniques are addressed in order to identify these problems both for above and below water surface. The various repair materials and methods in order to overcome theses problems in concrete bridges are identified from literature. Numbers of repair activities involve are studied along with replacement options.

At the end flow charts were developed for the proposed decision support system for concrete bridge maintenance and rules are established by using EXSYS Professional Shell, to assist the bridge engineer in decision making about the repairs of concrete bridge beams.

ACKNOWLEDGEMENTS

This research study would not have been possible without the guidance and help of Allah the almighty and many worthy people.

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Bahre Karam

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Chapter 1

INTRODUCTION

1.1 Problem Statement

Transportation infrastructure is the backbone of this nation's prosperity during the present era of the globalized world. After analyzing the transportation system, it is revealed that bridges are key elements of the transportation system to ensure efficient movement of people and goods. It is very important to maintain and repair bridges on a continuous basis as they are not only expensive structures but also due to their strategic locations throughout the transportation infrastructure.

Most of the bridges in the United States were built in the nineteenth and twentieth centuries. Generally, experts' perception is that most of the bridges with deteriorated conditions are either functionally or structurally obsolete (ASCE 2005). This can be observed easily by the various disastrous incidents of bridge failures during the past half century. In order to prevent and minimize bridge failures and damage in the coming years, the federal government of the United States and the state governments have taken several bridge maintenance measures.

The common problems of concrete bridge beams and piers are corrosion, cracking, delamination, spalling, and scour. Inspection of concrete bridge beams and piers is vital for any repair and rehabilitation project. Generally, the repair and rehabilitation consists of an inspection of a deteriorated beam by an inspector and initiation of the repair strategy by the bridge engineer, using information collected from inspection data. However, the repair and rehabilitation strategy is influenced by human

bias and decision parameters. In order to reduce this influence and flaw, Pontis and various other bridge management systems are introduced.

Pontis is a network level Bridge Management System (BMS), which prioritizes bridges or groups of bridges for repair and rehabilitation funds. Although successfully used by various departments of transpiration it is not very valuable in project-specific Bridge Management Systems (BMS). One of the forms of a project-specific Bridge Management System (BMS) is a decision support system, which can be used to assist bridge engineers in the bridge repair decisions and rehabilitation.

This research focuses on the development of the knowledge base, which consists of identification of problems, repair methods, and tree diagrams for the proposed decision support system for concrete bridge beams that have deteriorated by cracking, delamination, corrosion, etc. The final product is expected to address some of the aforementioned problems.

1.2 Research Objectives

The objectives of the research are as follows:

- Search the currently available literature about the most common concrete bridge beam and pier problems, mainly focusing on corrosion, cracking, delamination, along with spalling, vehicle accident damage, and scour.
- Study the various repair and rehabilitation methods in practice.
- Develop a summary of the repair and rehabilitation strategies from the literature review.

- Develop a selection criterion and tree diagrams/flow charts for the proposed decision support system that can assist bridge engineers in making decisions about repairs to bridge beams and piers.

1.3 Research Methodology

This research focuses on the development of a knowledge base and tree diagrams for a decision support system. The research methodology can be broken down into the following stages in order to achieve these objectives:

- The problems associated with concrete bridge beams and piers were studied during the first stage.
- Inspection processes and tools to identify various concrete bridge beam and pier problems were studied during the second stage.
- Available literature was searched for repair materials, techniques, tools, and repair strategies for the concrete bridge beam problems discussed during the third stage.
- A decision support system was studied in general by using an expert shell called "EXSYS Professional," and selection criteria besides tree diagrams were developed during the final fourth stage.

1.4 Thesis Layout

Chapter Two discusses the problems that are most common to concrete bridge beams and piers. The problems of cracking, corrosion, delamination, spalling, vehicle accident damage, scour, and scaling are discussed. The phenomenon of corrosion is discussed in detail as it is one of the main causes of delamination and to some extent of

cracking. Various types of cracks are discussed in detail too. Underwater defects like scour are also addressed.

The third chapter is about the inspection of bridges. The various types of bridge inspections are discussed. Various inspection tools and techniques are explained in order to identify the concrete bridge beam and pier problems.

The fourth chapter explains the various repair methods and strategies for the problems of cracking, delamination, corrosion, scaling, and scour. Various types Repair materials and activities for repair are discussed. The important point in this chapter is that a specific criterion is developed for the choice of each and every repair method in order to develop rules in the decision support system.

The fifth chapter of this thesis is about the development of decision support systems. Particularly, rule-based decision support systems are discussed. This chapter also explains the development of knowledge base and flow charts for various concrete bridge beams and pier problems. Rules are derived from the flow charts for a proposed decision support system by using of software called EXSYS Professional.

Chapter 2

CONCRETE BRIDGE BEAMS PROBLEM

2.1 Introduction

Deterioration of superstructure and substructure of the bridge elements is a common problem with the transportation infrastructure in the United States. Some of the bridges were not designed to withstand the current environment and existing traffic requirements and consequently are experiencing significant distress. There are approximately six hundred thousand bridges on the public highway system in the United States (ASCE, 2005). The nation's existing concrete highway bridges are deteriorating at an alarming rate. It has been estimated that the cost of the structurally deficient and functionally obsolete bridges stands at $9.4 billion per year for next twenty years, (ASCE, 2005). Most common problems in concrete bridge beams and piers are:

- Corrosion
- Delamination
- Spalling
- Cracking
- Vehicular accident damage
- Scaling
- Scour

2.2 Deterioration of Superstructure of the Bridge

The deterioration of concrete bridges is defined as the existing defects in the components of the bridges that affect the structural safety and/or the function of the bridges. There are various causes of deterioration of beams and girders, which will be discussed briefly in the following subsections.

2.2.1 Corrosion

Corrosion is the deterioration of materials due to exposure to atmospheric conditions including water, oxygen, and acids. Corrosion or rust of reinforcement bars is a major and most recognized cause of deterioration of concrete bridges, which results in the loss of cross section of steel bars/stands. The consequences of corrosion can range from the progressive weakening of a bridge structure over a period of time to local or global sudden failures. Therefore, the effects of corrosion damage need to be carefully assessed with respect to all likely failure modes at the local, member, and structure levels by bridge inspectors.

Steel can be unstable in moist, oxygen rich environments unlike concrete, which is normally durable in these conditions. Concrete acts as a physical barrier for the reinforced steel against the outside environment. However if the physical integrity of the concrete is changed, the protective capability of the concrete barrier is reduced. A natural passive chemical environment for reinforcing steel is provided by the high pH (12 to 13) of the pure water in concrete (Habib et al. 2005). Corrosion occurs if the passive layer is destroyed and sufficient amounts of oxygen and moisture are present. Similarly, the presence of chloride ions or carbonation can damage the passive layer and accelerate the corrosion process significantly. Various factors that contribute to or effect the rate of

corrosion include high chloride content, poor quality concrete, carbonation, inadequate concrete cover, cracks in concrete, heterogeneities in the concrete and steel, pH of concrete pore water, and design features as well as cycles of freezing and thawing.

Corrosion process

The corrosion process is electrochemical in nature and is caused by the appearance of cathodic and anodic regions on the metal surface. The corrosion process can be the result of various factors which include

- Different chemical concentrations
- The varying availability of oxygen or moisture at different locations along reinforcing bars

Iron is dissociated to form ferrous ions and electrons at the anode site. The electrons travel towards the cathodic site where the ferrous ions dissolve in the concrete pore solution. At the cathodic site, hydroxyl ions are formed when oxygen in the pore solution combines with the electrons. The ferrous and hydroxyl ions move in opposite directions through the pore solution. Ferrous hydroxide is precipitated when they combine. The resulting precipitated corrosion products occupy a larger volume as compared to the non-corroded steel. Increasing pressure is exerted on the concentrate as the concentration of corrosion products increases, until concrete cracks and eventually spalls.

Corrosion stages

Corrosion of reinforced concrete is a two stage process as follows:

- Initiation process
- Propagation process

Corrosion begins after the period known as the corrosion initiation time, during which the steel reinforcement becomes depassivated due to carbonation or chloride ion ingress. For bridges, initiation of reinforcement corrosion is normally due to chloride ion ingress (Novokshchenov, 1989). Corrosion begins when the chloride content in the concrete at the depth of the steel reinforcement reaches a concentration that is sufficient to initiate the corrosion process. Once the corrosion has been initiated, the cross-sectional area of reinforcement decreases with time at a rate that is dependent on the number of reinforcement bars actively corroding, diameter of the individual bars, and the corrosion rate. Corrosion may also eventually lead to cracking, delamination, and spalling of the concrete bridge. In order to understand this well, corrosion of reinforced concrete can be divided into four stages as follows: (Christopher et. al, 2003)

Stage I is a corrosion initiation stage. In this stage, chloride accumulates on the structure surface and diffuses to the depth of the reinforcing steel to initiate corrosion.

Stage II is a period during which the corrosion propagates, leading eventually to cracking of the concrete and rust staining of the structure.

Stage III is a period brought on by structural deterioration (cracking and delamination), when the reinforcing steel becomes more accessible to the corrosive environment, particularly moisture and chloride ions. Corrosion continues at an accelerated rate with an attendant loss of steel cross-section.

Stage IV is characterized by spalling of the concrete to expose the reinforcing steel to the full impact of the corrosive environment.

Locations of Corrosion

In order to understand the behavior and location of corrosion damage to concrete bridges, (Michael P. and M. Frangopol, 2000) studied damage to twenty-one concrete bridges in Colorado that appear to be damaged from corrosion initiated by chloride ions. Two main sources of these chlorides are

- Deicing salts in colder regions
- Wind-borne salts in coastal areas

It has been revealed during the studies that most of the bridges show sign of damage near the transverse and longitudinal deck joints and that beams and pier caps are the most commonly damaged members. In fact it shows sixteen bridges had damaged beams, eight had damaged pier caps, three showed signs of column damage, and one had damage in abutment. The reason is once the chloride ions reach the elements below the deck they penetrate the core and corrosion of the steel begins.

Girders experience corrosion normally at the end region due to salt water leaking through failed expansion joints. The location of the damage on individual members is dependent on the following factors:

- Member type,
- Location of the element within the structure, and
- Source of damage

It has been found that high-risk areas are deck top surfaces and joints where de-icing salts are used along with the lower surface of bridge girders, particularly the lower "drip regions and the underside of the deck in coastal regions (Cramer, et. al 2000; Cramer, et. al 2002; Tinnea and Feuer, 1985).

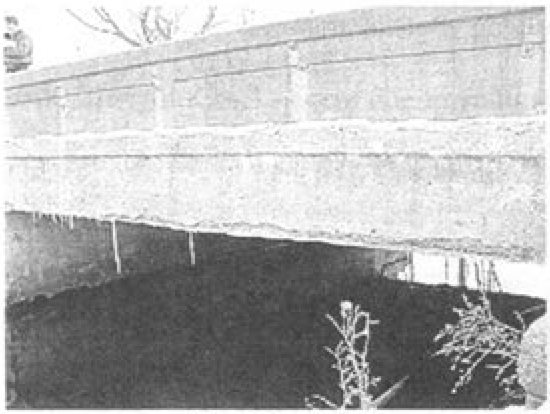
The conclusion is if deck joints leak, contaminated water reaches the ends of the beams where moisture tends to collect and remain in contact with the concrete longer than at the top of the decks. This leads to deterioration with steel corrosion followed by delamination, cracking, and finally spalling.

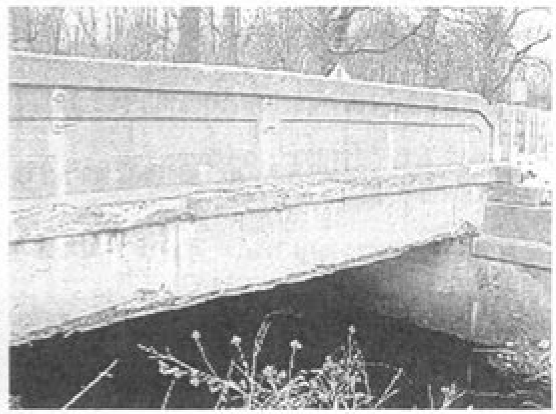
2.2.2 Delamination

The expansive reaction products from the corrosion of steel in concrete may cause sufficiently high stresses to result in the tensile failure of concrete. Depending on the ratio of cover-to-bar spacing, the resulting fracture planes will either form V-shaped trenches or cause a delamination parallel to the surface of the concrete member. With time, the size of the delamination will continue to grow. Other reasons for delamination growth are (1) Freeze-thaw cycles and (2) under traffic accident. If delamination is detected early, it can be repaired before severe damage occurs.

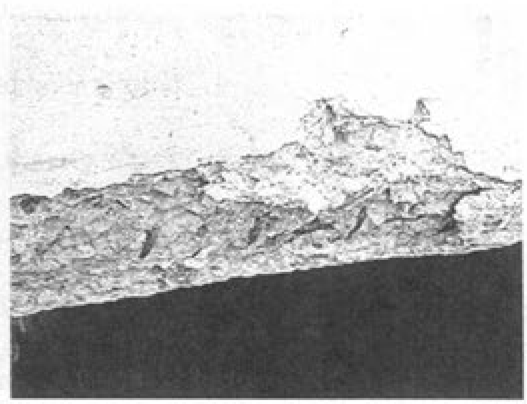
Delamination occurs when layers of concrete separate from bridge beams at or near the level of the top or outermost layer of reinforcing steel, generally parallel to the surface of the concrete member. Such areas give off a hollow sound when tapped with a rod or hammer. A chain drag or other mechanical device may be used to determine the extent of delamination. The delamination interface will eventually become dislodged and a spall will result.

Figure 1 below shows concrete spalled and severely delaminated along the bottom of the fascia beam on the west and east sides of a bridge on Old 27 over Tekoncha Creek in Calhoun County. The bars are exposed due to severe delamination and spalling.





West fascia East fascia



Close-up South East Close-up North East

Figure 1 Delamination in Concrete Bridge in Calhoun County (Courtesy of Calhoun County Road Commission, MI 2004)

The probable cause for this delamination and spalling of fascias is the water entrapped in the concrete and the tensile stress produced by the rust that developed at the steel level.

2.2.3 Cracking

Cracks are common in both new and old concrete because concrete has little tensile strength. Cracks occur due to volume changes as temperatures vary and a concrete member contracts or expands. Cracks may also be an indication of overloading, corrosion of the reinforcing steel, or settlement of the structure. Even when the cracks themselves are not structurally significant, they are often the early stages of more serious deterioration and they serve as a passage through which water and deleterious substances can enter the concrete.

Cracks can occur at any location on a substructure element. When *reporting cracks,* the length, width, location, and orientation (horizontal, vertical, diagonal, etc.) should be noted, and the presence of rust stains, efflorescence, or evidence of differential movement on either side of the crack should be indicated.

Cracks are defined as a separation of parts. Cracks may be vertical hairline cracks along the bottom of reinforced concrete beam or girder. These cracks are due to flexure stresses and usually will be many in number and spaced over some length. Surface cracks can permit moisture to enter; therefore, rusting may result along the bars. Cracking also occurs when the corrosion-induced tensile stress exceeds the tensile strength of the concrete.

Stresses resulting from changes in the atmospheric temperature or in the internal temperature of the concrete mass also causes cracking. Cracks are identified according to their width as follows: (Waheed et al, 2005)

Limitations:

Hairline – less than 0.1mm

Small – 0.1 to 0.3 mm

Medium – 0.3 to 1.0 mm

Wide > 1.0 mm

The hairline cracks along with spalling and small areas of concrete are present in the beams in the same bridge on Old 27 over Tekoncha Creek in Calhoun County, Michigan, as seen in Figure 2.

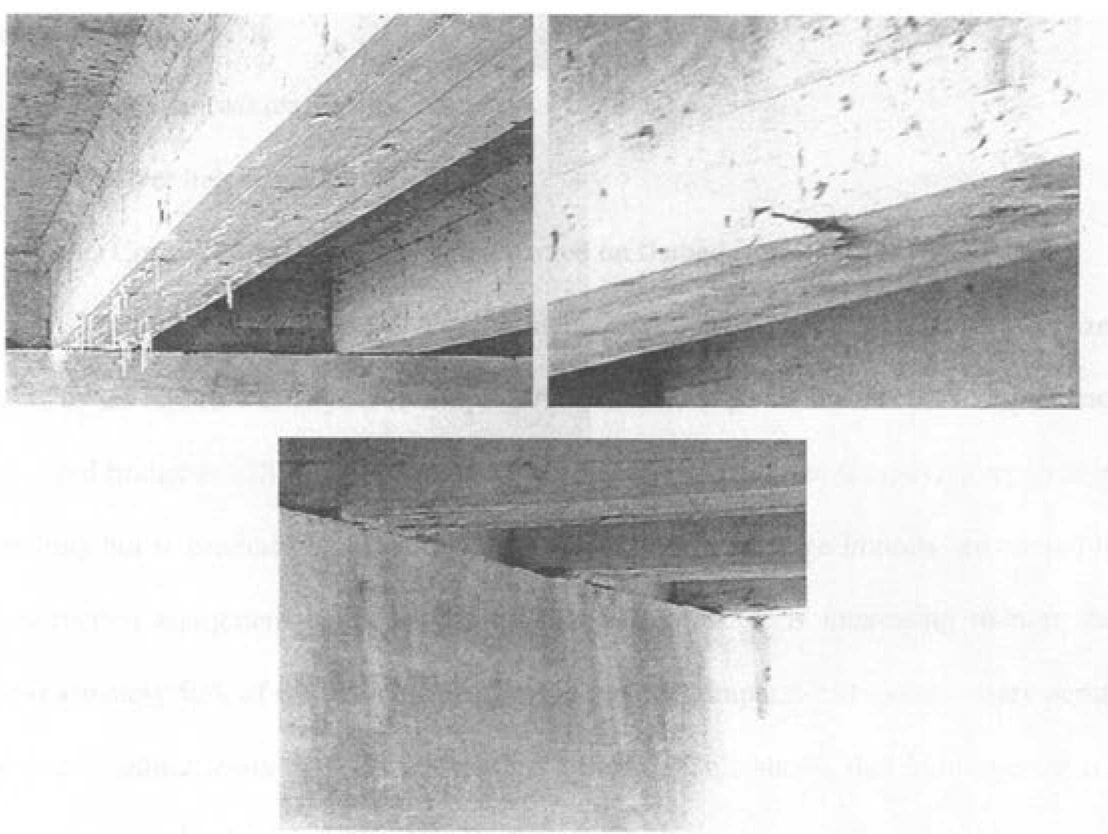


Figure 2 Cracked Concrete Beams (Courtesy of Calhoun County Road Commission, MI, 2004)

The probable cause of this hairline cracking spalls, and delamination is the expansion of the reinforcing steel caused by corrosion of the steel (which may be due to de-icers used or alkali contained in the concrete).

2.2.4 Vehicular Accident Damage

Each year, more than 150 pre-stressed concrete girders are damaged by oversized vehicles (TRNews). Concrete is crushed and the reinforcement is sometimes severely damaged. Shanafelt and Horn (1980) have shown that approximately 160 P/C bridge impacts are reported each year by transportation departments in the United States. This number is also likely to increase as the amount of traffic on the nation's highways continues to grow.

There are two reasons for this:

1) Over height vehicle

2) Construction equipment being hauled on flatbed trailers

In Iowa, approximately 5 to 6 significant bridge impacts due to oversized vehicles are reported each year (Phillips, 1995). The average estimated cost to repair each damaged bridge is $38,900. Minor impact damage (i.e., chips and scrapes) is repaired by patching but is generally not reported. The majority of the bridge impacts are caused by construction equipment being hauled on flatbed trailers. It is interesting to note that approximately 50% of the vehicles involved in recorded impacts had the necessary permit or were hauling loads that did not require a permit. This shows that human error is a major factor in bridge impacts.

Vehicle impacts are highly variable; each impact produces different types of section loss and cracking patterns. The assessment of the extent of damage to a girder is described as :(Waheed et al, 2005)

1) Minor damage:

This damage includes isolated concrete cracks, nicks, and spalls up to 30mm deep with no reinforcing or pre-stressing strands exposed. Aesthetics are adversely effected during minor damage but the structural capacity is not reduced at all. In order to prevent reinforcing steel from being exposed and corroded, the restoration of the concrete cover is essential.

2) Moderate damage:

This damage causes concrete cracks and wide spalls, and exposes reinforcing steel and pre-stressing strands. Although there is no immediate effect on the structural capacity, in the long run structure life can be reduced.

3) Severe damage:

This damage consists of exposed and damaged prestressing strands and reinforcing steel, in addition to the loss of significant cross-section. There is also the possibility of lateral misalignment due to girder distortion.

The investigation of Table 1 indicates that there are a number of similarities in the two definitions of damage levels. Both classification systems have essentially the same descriptions of minor and moderate damage.

Table 1 Damage Classifications of Beams Due to Vehicle Collision

Feldman, et al. (1996)	(NCHRP) Report 226
Minor damage • shallow concrete cracks and nicks, shallow spalls, and/or scrapes	**Minor damage** • damage only to concrete portions of girders • no exposed reinforcing bars or prestressing strands • cracks in spalled areas must be less than 3 mms in width
Moderate damage • large concrete cracks and spalls exposed undamaged prestressing strands	**Moderate damage** • damage only to concrete portions of girders • extensive spalled areas may expose reinforcing bars and/or prestressing strands • cracks in spalled areas are wider than 3 mms, but are closed below the surface damage • no severed prestressing strands
Severe damage • loss of significant portions of concrete cross section • exposed damage prestressing strands • girder distortion resulting in lateral misalignment	**Severe damage** • cracks extending across the width of the bottom flange but closed below the surface • major or total loss of concrete section in the bottom flange • major or total loss of concrete

2.2.5 Spalling

Spalling is the removal or loss of concrete from the girder and may range in extent from being minor to severe. With minor spalls, the aggregate within the concrete is exposed, whereas moderate spalls are deeper in the pre-stressing strands, and reinforcing steel is exposed. With severe damage, spalls will be deep and the inner structure of the girder is not only exposed but may also be damaged.

Spalling is more prevalent in lightweight concrete where the aggregate exposed is more porous, which can lead to freeze-thaw damage that would not occur in normal concrete.

There are various reasons for spalling of concrete some of which are mentioned below:

- Expansion (which causes tensile stresses) due to corrosion of reinforced steel; leads to regular patterns of cracks, and spall occurs over the entire surface.
- Batching of concrete with aggregate that is not chemically inert with cement; a pattern of map cracking and spalling can develop.
- Cycle of freezing and thawing causes spalls of the concrete as it is clear that the water freezes and expands below the surface of the concrete.

Figure 3 shows hairline cracks along with spalling in small areas of concrete are present in the beams in the same bridge on Old 27 over Tekoncha Creek in Calhoun County, Michigan.

The probable causes for this spalling and delamination in the above cases are water entrapment in the concrete due to surface porosity and tensile stress produced by the rust.

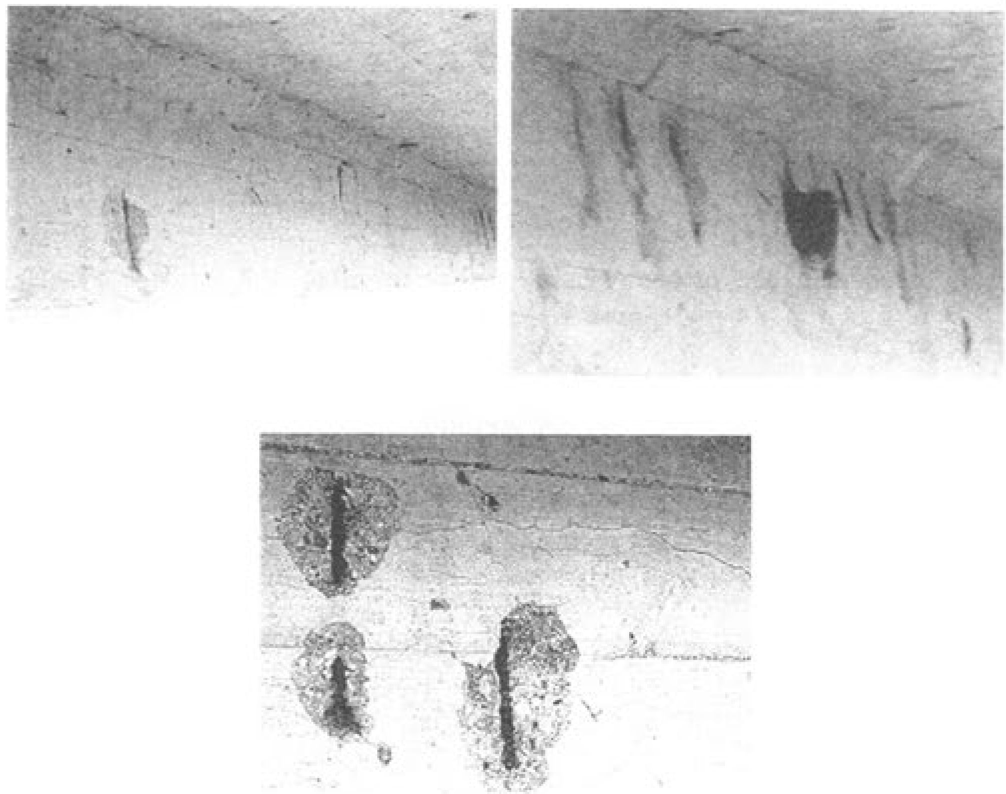


Figure 3 Miscellaneous Spalling and Delamintaion Areas on Concrete Beams
(Courtesy of Calhoun County Road Commission, MI, 2004)

2.2.6 Scaling

Scaling can be defined as the deterioration of the outermost layer of the concrete due to freeze-thaw cycles; it can be generally divided into the following categories:

a) Deep scaling: This type of scaling is caused by an improper water/cement ratio or lack of entrained air.

b) Surface scaling: This type of scaling is caused by improper construction techniques such as placement of concrete against soil with a high sulfate content or watering concrete during finishing.

Scaling can also be classified as follows (Al-Ostaz, 2004):

1) Light/minor scaling: loss of surface up to ¼-inch deep exposing coarse aggregate

2) Medium / moderate scaling: from ¼-inch to ½-inch deep with mortar loss between the concrete aggregate

3) Heavy scaling: loss of mortar from ½-inch deep to one inch deep, clearly exposing coarse aggregate

4) Severe scaling: Loss of surface mortar greater then 1 inch deep where coarse aggregate particles are lost and reinforcing steel is exposed.

Scaling is a gradual and continuous loss of surface mortar and aggregate from an area. At the waterline, conditions are ideal for scaling to occur on piers and piles. Pores and minor surface defects allow water to penetrate and saturate the concrete. When the temperature drops, the water freezes and expands, causing the surface of the concrete to "pop off" or appear to disintegrate.

When *reporting scaling*, the inspector should note the location of the defect, the size of the area, and the depth of penetration of the defect. To avoid confusion in reporting defects, a standard format and nomenclature should be used.

The location should be reported by horizontal distance from a known point such as a corner of an abutment and vertical distance by depth below water surface, in the case of substructures. The extent of the defect should be reported as height and width, with height referring to a vertical distance and width referring to a horizontal distance. The

extent of intrusion of the defect into the member should be referred to as "penetration" rather than "depth," since "depth" could also refer to the distance below water.

2.3 Substructure Problems

Bridge substructures in marine environments are more exposed to corrosion, since most parts are located in a splash zone. Concrete is used in piers, footings, abutment walls, etc. Concrete members in marine environments deteriorate because of chemical processes that occur in a marine environment. Magnesium ions in sea water salts attack the concrete by reacting with the calcium. Sulfate solutions react with tricalcium aluminate hydrate, a component of concrete, and substantial expansion follows this reaction, causing cracking and spalling. Deterioration takes place due to chemical reactions within the mass of concrete as well. Air and water penetrates through the concrete cover and corrodes the steel bars, which can cause the surrounding concrete to crack and spall.

2.3.1 Concrete Bridge Pier Problems

The use of bridge piers can easily be identified in structures crossing rivers and railways. Piers are the structures located at the end of a bridge span, which produce the basic function of supporting spans at intermediate points below the end support. Piers consist of three parts: a foot, a shaft, and a pier cap. Generally, reinforced concrete piers are used alongside pre-stressed concrete. Various types of piers include (i) Hammer head, (ii) Column bent, (iii) Pile bent, (iv) Solid wall, (v) Integrated piers, and (vi) Single column.There are various causes of pier deterioration, including (i) Scour, (ii) Scaling, (iii) Cracking, (iv) Collision, and (v) Corrosion.

2.3.2 Scour

In marine environments, scour can be defined as the removal of streambed, backfill, slopes, or other supporting materials by streams, tidal action, or propeller backwash. It can also be defined as the deterioration or removal of the soil under a submerged bridge substructure. All piers and abutments erected in water should be designed to be protected from scour and erosion. The degree of damage depends on various factors, including

- Character of the streambed
- Volume of water in a specific stream
- Shape and elevation of the structure

There are three forms of scour that may occur at bridge substructures (e.g., piers).

1) General scour

2) Contraction scour

3) Local scour

General scour is the degradation of the stream bed over a considerable length and width of the river. This type of scour occurs in the entire width of the river and results in lowering of the riverbed without obvious scour holes in most cases. The natural process of particle transport that a river experiences over the years results in general scour .It may be accelerated by various means, including

- Meandering river
- Dam construction upstream
- Dredging or the straightening or narrowing of the river channel

Contraction scour is a result of the contraction of the channel width in the vicinity of the bridge and produces an overall lowering of the streambed similar to the general scour. *Local scour* is the erosion of material adjacent to structural components, which usually results in discernable holes or depressions. It occurs in piers or piles as a result of the obstruction of flow. This obstruction accelerates the flow of water around the structural component, creating turbulence that removes sedimentary particles. The results may often be a hole or depression around the component. Bridges located in places where velocity is high are particularly susceptible to local scour. Scour depths from local scour are often much deeper than those occurring from general or contraction scour.

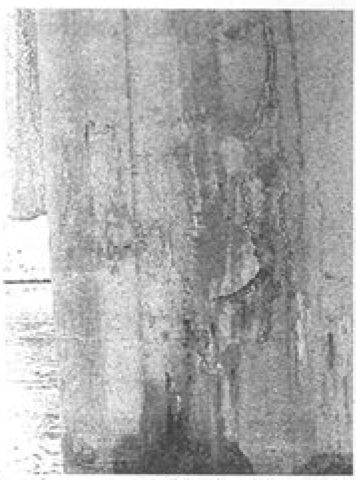
The environment at the waterline of bridges is especially susceptible to spalling and problems other than scour. The initial paths for moisture and oxygen to reach the steel can be provided by abrasion and constant wet-dry cycles. Salt water or water with acidic pollutants makes excellent electrolytes for the corrosion process, and the resulting film is regularly removed by waves and tidal action. In this way a new surface for rapid corrosion is provided. In colder regions, water freezing and thawing in small cracks also accelerates the spalling process.

Chlorides that cause corrosion can be obtained from deicing agents, salt water, or admixtures. Sulfate attack is more common in old structures and those constructed with Type I cement. Polluted water can also cause various defects, and cracks, voids, and chipped corners can be caused by vessel impacts.

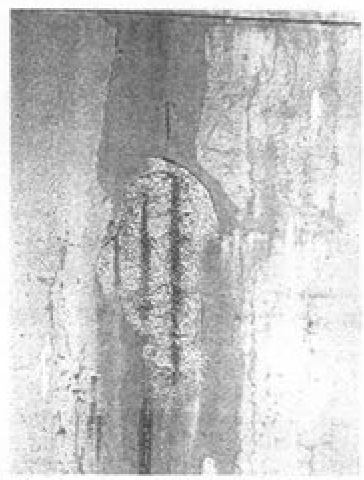
Several areas on the piers are significantly spalled, leaving rebar exposed in some areas along with cracks. This can be seen in Figure 4, which depicts the bridge on Old 27 over Tekoncha Creek in Calhoun County, Michigan.

Spalling in pier

Cracks in pier



Cracks in pier



Spalling in pier

Figure 4 Spalls and Cracks of Piers (Courtesy of Calhoun County Road Commission, MI, 2004)

It is important to note that structural damage to underwater portions of bridge substructures can be collision-related or a direct result of a collision. Collision impact can damage the immediate areas, adjacent areas or even distant structural components, depending on the structural frame and connection system used.

2.4 Summary

In this chapter several problems of concrete bridge superstructure and substructure such as delamination, cracking, corrosion, spalling, vehicular accidents, and scour were presented and discussed.

It is shown that some of these problems are interrelated and that one problem could cause or lead to another. For example, the consequence of reinforcement corrosion is cracking and spalling of concrete. Cracks of concrete may cause corrosion of reinforcement steel. Spalling of concrete can be a safety issue for vehicles passing by and could permit acceleration of further deterioration. Spalled concrete allows chloride water to reach the reinforcement, resulting in more corrosion. The effective cross section of steel is also reduced, resulting in a decrease of structure strength and/or functionality of the bridge.

For most corrosion protection measures, the basic principal is to prevent the chloride ions from reacting with the steel surface and also to increase the time needed for chloride ions to penetrate through the cover. While the measures generally do not stop the corrosion from eventually initiating, they do increase the life of reinforced concrete structures by slowing down the corrosion process.

Chapter 3

BRIDGE INSPECTION

3.1 Introduction

The main objectives of condition assessment of bridges in service are (1) better management of these structures, and (2) to provide useful information to make critical decisions regarding their replacement or rehabilitation. Currently, visual inspection is the way to obtain bridge condition information (Ghorbanpoor et al. 2003). A properly performed visual inspection can provide valuable information regarding bridge conditions. Visual inspection is very helpful to identify problem areas that may need further inspection.

In order to know a complete bridge condition assessment in detail, Non-Destructive Evaluation (NDE) is used along with visual inspection. These Non-Destructive Evaluations (NDE) can provide knowledge that may be impossible to deduce from visual inspection alone. Various guidelines that relate common flaws identified during visual inspection to possible non-destructive testing techniques can be very effective to those responsible for bridge inspections.

In most cases, visible defects in bridge structures are indications of underlying deterioration mechanisms. Non-Destructive testing techniques are often suited to a specific type of deterioration mechanism. These techniques are utilized in determining the extent of the damage caused by the deterioration mechanism.

The United States government requires inspections every two years on bridges over twenty feet in length on all public roads. This frequency can be decreased to every

four years based upon numerous factors, including satisfactory performance, favorable prior experience and analysis, structure age, or traffic in some special cases.

The inspection terms are the minimum required by law for *routine* inspections. The *interim* inspections are "hands-on," detailed inspections that may be required depending upon previous routine inspection results. Interim inspections may likely involve some non-destructive or exploratory techniques, and they occur at more frequent intervals.

3.2 Fundamental Aspects of Bridge Inspection

Knowledge of the fundamental aspects of bridge inspection is vital in order to ensure proper inspection. These various aspects of bridge inspection include the following (Ghorbanpoor et. al, 2003):

- Bridge inspection personnel qualifications
- Inspection preparation
- Inspection types (e.g., routine, in-depth)
- Appropriateness of various NDE techniques
- Quality control
- Safety

3.3 Types of Inspection

The use of a particular inspection type is determined by various factors, including structure age, structure condition, and use. There are five basic types of bridge inspections (AASHTO, 1994):

1) Initial inspection

2) Routine inspection

3) In-Depth (Interim) inspection

4) Damage inspection

5) Special inspection

3.3.1 Initial Inspection

Initial inspection is the first inspection after construction, which can be done for new construction or retrofitting. During this inspection, problem areas or potential problem areas, including fracture of critical members, are identified. All the subsequent inspections depend on the initial inspection.

3.3.2 Routine Inspection

Routine inspections are regularly scheduled inspections that keep an eye on any changes from previously observed conditions. The results from the routine inspection will determine areas for further in-depth, or interim, inspections. The state government sets the frequency of the routine inspection. The primary method used in routine evaluations is visual inspection. Some simple non-destructive techniques such as hammer sounding, rebound hammer, and dye penetrant could be used along with visual inspection.

The results from routine inspections and recommendations for further inspections and maintenance need to be documented along with appropriate photos and sketches.

3.3.3. In-depth Inspection

Close-up inspections of areas identified by routine inspections are called in-depth inspections. These inspections may likely use special lift equipment to gain close access

for details. These inspections can occur above or below the water line. The extent of a particular defect is determined during this in-depth inspection. Similar to routine inspections, the results from these inspections should be documented along with the various non-destructive techniques and procedures used.

3.3.4. Damage Inspection

To access physical damage resulting from human factors and the environment, unscheduled inspections are performed, which are called damage inspections. The results of these inspections may leads to closure of bridges or load restrictions. Documentation should include the extent of misalignment, section loss, or other damage. A timely in-depth inspection should reinforce this inspection.

3.3.5 Special Inspection

Special inspections may be needed to reinforce other inspections. These inspections may involve specialized techniques. One type of this inspection is underwater inspection for substructures. Advanced non-destructive techniques may be required during a special inspection.

3.4 Inspection Tools

A visual inspection of reinforced and non-reinforced concrete structures can disclose various flaws. The visual clues may disclose the problem directly or may give a possible symptom of a larger problem. Concrete problems may be due to one or more causes. These include cracking, delamination, corrosion of reinforcing elements, spalling, scaling, and vehicular impacts, all of which could affect adversely the performance of concrete structures. In addition, these can reduce the safe load carrying capability of the

affected structures and lead to failures. Various flaws in concrete structures as well as appropriate techniques and tools are tabulated and presented below.

Table 2 Summary of Types Concrete Bridge Beams Defects and Evaluation Methods

Concrete beam/girders problems	Inspection tools/tests
Corrosion	Visual inspection Ultrasonic testing Magnetic flux leakage Radiography Equipotential Cover meter Pachometer
Cracking	Ultrasonic testing Magnetic analysis Radiography Acoustic emissions Impact echo Petrographic analysis Visual inspection
Delamination	Visual inspection Hammer sounding Infrared thermography Ground Penetration radar Impact echo Core sampling Ultra sound pulse velocity Ultra sound pulse echo Acoustic impact
Vehicle damage	Visual inspection
Spalling / delamination	Visual inspection Hammer Sounding
Scaling	Petrographic analysis Infrared thermography Visual inspection/measurement

Some techniques listed above require subsequent repair after the completion of the test. The effective visual inspection by an experienced inspector is very important, as it will generally lead to the disclosure of defects. Visual inspection should always be

made a part of any bridge evolution and condition assessment program. Some of the techniques and tools for inspection are discussed below.

Ultra sonic testing

This can be used to determine crack sizes and locations. It is also used to determinate the quality of concrete. A pulse of ultrasonic vibrations is sent through the beams being tested; vibrations reflected from any discontinuity can be detected by the deficiency of the beams (Ghorbanpoor et al. 2003).

Petrographic analysis

This is a microscopic examination of the concrete sample that looks for voids, cracking in the coarse aggregate, or cracking/debonding between aggregates and substrate. This can very helpful in determining why a particular section of concrete is failing.

Infrared thermography

A video camera records the visual condition allowing any temperature irregularities to be matched the surface paths or to concealed substructure delamination. The theory used in this case is wherever there is a delamination below the surface of the concrete; the air in the void will be at a slightly different temperature. The infrared camera can pick up this change in temperature and the areas can be plotted and quantified (Ghorbanpoor et al. 2003).

Ground-penetrating radars

This is used to detect below-surface defects. It is suitable for detecting voids and other discontinuities in concrete. This is done by observing variations in the transmission of radio frequency pulses through the material.

Equipotential testing

This testing can be performed to determine the potential for steel reinforcements to rust, and ultimately predict future spalling of the concrete. An electric current is produced when steel molecules lose an electron as rust forms. The volume of the steel is expanding from 8 to 16 times due to this rust. The concrete surface is delaminated and eventually spalls away due to the resulting large internal pressure. The equipotential meters measure the amount of current in the concrete in terms of voltage. The more negative voltage measured, the greater the potential that the reinforcing steel is oxidizing unseen within the concrete.

If the areas of high potential readings are in tension, the cracks are active in the member and these cracks will allow further air and chloride infiltration. If the areas of high potential readings are in compression, the cracks are not active and the high potential readings may not be of as much concern.

Patchometer or R-meter

A patchometer is a magnetic device that can be used to locate reinforcements embedded in concrete, and is also called rebar locator. If the size of the reinforcement is known, the concrete cover can be found and if the approximate cover is known, the reinforcement size can be determined.

Stress propagation waves (pulse echo)

This is similar to ultrasonic methods and uses stress waves to locate deficiencies and flaws in concrete elements.

3.5 Underwater Inspections

The cause of damage for most of the bridges that are situated over waterways is underwater problems. The condition of underwater members should not compromise the structural safety of the bridge. This can only be achieved through inspection of these members by using one or more specialized underwater techniques. These techniques determine underwater structural and streambed conditions and may include visual and tactile inspections during the durations of low water. This can be achieved by various ways such as wading, diving inspections, and remotely operated vehicles; underwater cameras, radar and sonar, sounding equipment; and sampling equipment, as well as other specialized inspection equipment as needed.

For an underwater inspection of any bridge, the following information should be included (Thomas et. al, 1989).

- Type and location of the bridge
- Type and frequency of required inspection
- Location of members to be inspected
- Inspection procedures to be used
- Special equipment requirements
- Dates of previous inspections
- Findings of the last inspection
- Follow-up actions taken based on the results of the last inspection

3.5.1 Levels of Underwater Inspections

The levels of inspection by the Federal Highway Administration (FHWA) are

Level I: visual, tactile inspection

Level II: detailed inspection with partial cleaning

Level III: highly detailed inspection with Non-Destructive Testing (NDT)

Level I inspection: This level of inspection shows close visual examination and, if visibility is limited, a tactile examination using large sweeping motions of the hands. Level I inspection should include enough detail to detect major damage or deterioration due to corrosion, over-stress, etc.

A Level I inspection is normally carried out over the total exterior surface of pier, abutment, or any underwater structure element and may also include limited probing of the substructure and adjacent streambed.

A general overview of the substructure condition and verification of the as-built drawings is provided by the Level I inspection. The Level I inspection can also reveal the need for Level II or Level III inspections, and can also help in determining the extent and selecting the location of more detailed inspections.

Level II inspection: This level of inspection is a detailed inspection of substructures which requires cleaning of marine growth from some portions of the structure. This cleaning is a time-consuming activity and should be confined to critical areas of the structure. The selection of the locations for cleaning should be made in such a way that minimizes the potential for damage to the structure. Documentation of the extent and severity of the damage is also carried out in this level of inspection.

The Level II inspection is designed to detect and identify damaged and deteriorated areas hidden by surface biofouling. The cleaning should be controlled by what is necessary to distinguish the condition of the underlying material. Generally, removal of all biofouling staining is not required.

Level III inspection: This level of inspection is a highly detailed inspection related to a critical structure or structural element or to a member where extensive repair or possible replacement is considered. The aim of the Level III inspection is to disclose the hidden or interior damage or loss in a cross-sectional area, and to determine material homogeneity. This level of inspection includes various tasks such as extensive cleaning, detailed measurements, and selected non-destructive and partially destructive testing techniques, including ultrasonic, sample coring or boring, physical material sampling, and in-situ hardness testing. The use of testing techniques is generally limited to key structural areas.

3.5.2 Underwater Inspection Process

The diver is an important part of the underwater inspection team. There are various guidelines for divers ranging from qualification and training to equipment.

Using *visual and tactile* methods, divers should inspect piers in a circular pattern if possible. The inspection should be initiated by making a circular path around the base of the pier, followed by moving up a uniform increment, such as an arm's length, and circling the pier again. This pattern should be carried out in the same way until the inspection is complete. In case the driver cannot circle the pier for some reason, he should inspect one side of the pier in a back and forth motion starting at the bottom. The same procedure can be carried out on the other side of the pier. Exposed footing, or any defects within the martial and any evidence of scour, should be reported.

Along with pier inspection, the inspectors should examine the downstream reach for any signs of headcuts, and also look upstream to identify any potential debris sources, such as fallen or falling trees in or near the channel.

It is very helpful for the inspectors to examine previous inspection reports. If there is any visible scour problem already existing, the current inspection should look for improvement or worsening of that problem. Photographs of visible problems should be included in the inspection report. Several states have enforced "flag" systems. When bridge inspectors identify scour conditions or structural problems affecting the safety of the traveling public, these systems formalize communication channels, notification procedures, and immediate responses.

The various procedures during underwater inspections depend on the modes of the diving too. Two principal modes of diving for underwater inspections are used; namely scuba and surface-supplied diving. Selection depends on a number of factors, including:

- Depth of water
- Bottom time
- Inspection tasks
- Waterways
- Environment, experience, and capability of divers.

Scuba, which weighs 75 pounds, is limited to a depth of 130 feet as described by OSHA. Surface-supplied air is further divided in two categories: deep-sea (hard-hat) and light weight.

Table 3 Summary of Types of Concrete Bridge Piers defects and Evaluation Tools

Piers problems	Inspection / tests
Scour	Impact-echo, impulse response, SASW Fathometer Tuned transducers Ground penetration radar Impact echo Impulse response Remote viewing Portable sonars Physical probes Visual inspection/divers
Cracking	Ultrasonic testing Visual inspection V-meter Acoustic emission Impact echo Petrographic analysis Pulse echo
Spalling	Gamma radiography Infrared thermography Visual inspection
Corrosion	Using clippers Ultrasonic thickness gage(water proof D-meter) Transducers Half cell potential Magnetic Flux Leakage Pachometer Coating tolerance thermography Visual inspection
Scaling	Visual inspection /measurement

Scour can be determined by both underwater and above water inspection techniques. Various inspection techniques such as *impact-echo, impulse response, and SASW* are used for determining component geometry and scour extent from the exposed surface of the substructure. The main difficulty in evaluating scour is lack of access. In

order to address this issue, the above techniques are used, as these techniques need access to one face only. Table 3 includes most of the substructure problems and inspection tools.

3.5.3 Underwater Inspection Equipment

The diver must have the suitable tools and equipment to work more effectively; mostly cleaning of structural elements is involved during under water inspections. Sometimes sampling and testing is also required. Both power and hand tools are used underwater along with some specialized tools.

The various tools include the following.

Hand tools

Almost all standard hand tools can be used underwater, although they require better care and maintenance. Screwdrivers, scrapers, ice picks, hammers, axes, hand drills, wire brushes, pry bars, and hand saws are typical tools used during inspections. In order to avoid losing tools, they are attached to the divers with a lanyard. Hands tools are useful for small underwater jobs.

Power tools

There are two types of power tools, namely pneumatic and hydraulic, that are used underwater. Underwater hydraulic tools are modified versions of hydraulic tools used on land. The disadvantages of hydraulic tool are that a hydraulic power source can be costly and extra measurements are needed by the divers in order to counteract the torque or vibration produced by these tools.

Pneumatic tools can usually be readily transformed to perform the underwater required tasks as they are not usually designed for underwater use. Pneumatic drills, chippers, hammers, scalers, and saws are available.

Photos

Underwater documentation can be done in the form of photography or video in an economical way under almost all water conditions. This includes photography, lighting, film, Clearwater box, videos, dive platform and Remote Operated Vehicles (ROV).

Standard equipment for an inspection should include a hammer or scraper. These tools can be used for Level II inspections, and for probing and sounding defective areas to determine the extent of distress. If the water is not clear, underwater light can also be used. In such circumstances it is most effective if the driver examines the underwater elements by moving his hands and arms in large sweeping motions to cover all area of each underwater element.

3.6 Inspection Forms

Inspection reports reflect information that is necessary to ensure the safety of public bridges. These inspection reports contain information that allows evaluation of the current condition of the bridge, and the basis for determining future maintenance costs, scheduling, and manpower requirements. Reports may also be used in legal proceedings if any damage is caused. In order to identify areas of damage and distress, the reports should include written descriptions, with sketches as necessary.

Agencies also assign numerical values for various conditions or degrees of deterioration. The data are entered into a computer, which can store and summarize the conditions of all the structures throughout the state. Standard sketches should be attached to the forms with coding of all members indicated if available. All the items on the forms may not always be filled out. Prior to inspection it should be determined which items are not applicable for the particular bridge to be inspected.

3.7 Summary

This chapter concludes the fundamental aspects of bridge inspections. Various types of inspections for concrete bridges were discussed. A definition of each type was discussed as well as the requirements of each one. Many of the techniques were addressed in order to identify the various problems of the concrete bridges as discussed in Chapter Two. Underwater inspections and the levels for this inspection along with tools and techniques were also presented.

Chapter 4

REPAIR AND REHABILITATION STRATEGIES

4.1 Introduction

Deterioration of bridge superstructure and substructure elements is a common problem in the United States. Deterioration in concrete bridges can take several forms and stem from various causes. It is very important that careful examination of the problem and then the study of the best methods and materials available for repair should be carried out before bridge maintenance.

The goal of permanent repair is to correct the cause of the defect. Temporary maintenance can slow down the deterioration but not eliminating the cause.

4.2 Repair Materials

Depending on various factors such as the size, location, and the general function of bridge components, different materials are available for repair of concrete bridges. There are a number of considerations in choosing an appropriate repair material, including the following (Silano L, 1993):

- Compatibility of the material to the original concrete
- Environmental consideration, including aesthetics
- Expected service life
- Availability
- Familiarity of contractors with products
- Strength and durability of the repair material should be at least as strong and durable as the existing concrete
- Constructability

- Cost effectiveness

Generally cost increases when the following activities take place:

- Admixtures are included in the mix
- Special cement or aggregates are utilized
- Quantity of the cement is increased
- Repair method is labor intensive
- Repair areas is hard to reach
- Traffic constraints limit application and curing time

4.2.1 Conventional Concrete

One of the many repair materials is conventional concrete, which is a mixture of Portland cement, aggregates, and water. Admixtures are added for different reasons which include 1) to entrain air, 2) accelerate or retard hydration, 3) improve workability, 4) reduce mixing water requirements, and 5) increase strength or alter other properties of the concrete (ACI 546R-04).To minimize shrinkage cracking, the repair concrete should have a minimum w/c ratio as low as possible and a coarse aggregate as high as possible.

Advantages

The various advantages of conventional concrete include it being economical, readily available, well understood and easy to produce, place, finish, and cure. It can be easily placed underwater using specific techniques and precautions too.

Limitations

This repair material is used when the cause of deterioration is removed only.

Application

Typically this repair material is used for partial and full depth repairs. This is suitable for marine environments because the typically high humidity in such environments minimizes the potential for shrinkage (Troxell et. al, 1958).

4.2.2 Grouts

Grouts are used for repairs and can be grouped as chemical grouts and hydraulic grouts.

Chemical grouts

The main difference between chemical grouts and cement grouts is that chemical grouts are composed of chemical solutions that react to form either a gel, foam, or a solid precipitate opposite to that of cement grout, which consists of solid particles in a fluid. When the chemical grout has injected, the chemical reaction causes a tendency to solidify and fill voids in the material.

Advantages (ACI 546R, 2004)

- Applicability in moist environments
- Cracks as narrow as 0.05 mm (0.002 in) have been filled with chemical grouts.
- For control of water flow through cracks and joints, the gel type of foamed chemical grout is best suitable

Limitations

- High-skilled labor needed
- More expensive
- Not used to restore strength

Applications

- Mostly used for repair of fine cracks
- Restore structural integrity of a structural member

Cement grouts

These are mixtures of hydraulic cement, fine aggregate, and admixtures, which yield a plastic, flowable, or fluid consistency without segregation of the constituents after mixing with water. To accelerate or retard setting time, minimize shrinkage, improve workability and durability, admixtures are included in the grouts.

Advantages

- Cost-effective
- Readily available
- Admixtures can modify cement grouts to meet job specifications

Limitations

- It can be used only for repairs by injection when the width of the opening is sufficient to receive the solid particles suspended in the grout.

Applications

- Filling of large dormant cracks
- Filling of voids under or around concrete structure
- Non shrinkage cement grouts can be used to repair spalled concrete

4.2.3 Polymer Cement Concrete

The two types of concrete materials that use polymers to form composites are polymer cement concrete (PCC) and polymer concrete (PC). It is recognized as Portland cement and aggregate combined at the time of mixing, with organic polymers that are

dispersed or re-dispersed in water. This dispersion is called latex. The organic polymer is a substance that consists of thousands of simple molecules combined in large molecules. The simple molecules are known as monomers and the reaction that combines them is called polymerization. The most effective and predictable for concrete restoration are styrene butadiene and acrylic latexes. The first one has extraordinarily good durability for exterior exposures or environments where moisture is present. In order to avoid discoloration, the second one should be used. Mixing proportions depends on factors such as the specific application and the type of polymers used in the PCC.

Advantages

- Good workability
- Ease of applications
- Bonding characteristics are excellent

Limitations (ACI 546R, 2004)

- Temperature range is 45 to 85 F
- For small batches mixing time is limited to 3 min
- Epoxy emulsions are more expensive than latexes

Applications

- Commonly used for repair of bridges and patching
- Effective patching material for shallow repair

4.2.4 Shotcrete

Shotcrete is a mixture consisting of Portland cement, sand, and water that is projected into place by compressed air. In order to provide other properties of the concrete, coarse aggregate, fibers and admixtures can also be added to the mixture. Shotcrete can be used

as wet or dry. Besides placing conventional Portland cement concrete, the shotcrete process is also used for placing polymer–cement concrete, fiber and concrete containing silica fume and other pozzolans (ACI 546R, 2004).

Advantages

- It can be used for repair of large or small surface areas with irregular contours or shapes.
- More economical than conventional concrete because of saving in forming costs.
- Can be applied to overhead and vertical places.
- Excellent bond and good performance

Limitations

- Needs training, experience and skill labor.
- Depends on the preparation of the old surface.

Applications

- Use to repair deteriorated concrete bridges
- Proper surface treatment of old surfaces to which shotcrete is being applied
- Skill of the nozzle operator

4.3 Repair Procedure

Several activities are involved in the repair of superstructures and substructures of concrete bridges. They are discussed in the following subsections.

4.3.1 Removal of Deteriorated Concrete

The amount or extent of concrete removal on a given bridge component can vary from large regular areas covering most of the component to small irregular patches in random locations. There are various techniques that can be used to remove the

deteriorated concrete, and selection of these techniques depends upon three factors: 1) depth, 2) area, and 3) location, as well as the method used to identify the concrete to be removed. Visual inspection, sounding (chain drag or hammer), core sampling, and half cell potential measurement are some of the methods that can be used to identify the concrete to be removed. The last two methods are able to detect the contaminated concrete and determine the risk of corrosion in the area of measurement.

The depth to which the concrete is removed has a significant effect on the method to be used and the cost of work. The various methods that are available for concrete removal are grouped based upon the four removal depth categories.

Surface removal

Surface removal is the first task to be considered in repair operation. Surface removal is the minimum amount of work required to remove surface contamination and thus provide a clear, long-lasting bond between the existing material and the material used to repair or rehabilitate the bridge.

Concrete cover removal

It is the concrete that lies outside or above the first layer of reinforcing of steel.

Matrix concrete removal

It is the concrete that lies around and just below the first layer of steel reinforcements. Contaminated concrete in this area is extremely difficult to remove. The depth of the zone should be extended as small a distance below the steel to allow for replacement material in the voids created.

Core concrete removal

Core concrete forms the core of the structural elements and lies between the reinforcing zones. Conventional cutting, grinding, and sawing techniques cannot be used. Removal in excess of the required minimum should be avoided as this is expensive in terms of both removal and replacement costs. Excess removal also contributes nothing to the quality of the completed product. Removal tasks must be performed in a manner that ensures that the remaining concrete and reinforcing steel maintains its structural integrity.

It is important to note that only deteriorated concrete and rusted reinforcing steel marked for removal must be removed. Any impact forces should be applied in such a way that minimize cracking in the rest of the concrete section and minimizes the damage to the bond between the remaining concrete and steel.

4.3.2 Surface Preparation of Concrete

It is known that removal tasks are only a part of the repair and rehabilitation process. Any new repair material that is needed to replace damaged and contaminated concrete should form an effective bond with the remaining concrete and steel. Thus, the remaining surface must be clean and sufficiently textured to provide the required bond. The following four methods are used in order to obtain clean surfaces for long-lasting bonds.

Scrabbling

They vary in size from large, self–propelled machines that can work on horizontal surfaces to small hand held tools used in vertical, restricted, or irregular surfaces.

Planning

A plane or diamond grinder removes concrete by abrasion. Various diamond-tipped concrete saw blades are mounted close to one another on a horizontal spindle that is rotated to cut and remove up to 1/2-inch of concrete in a single pass. Water is required during the process to cool the blades along as vacuuming for collection of debris.

Sandblasting

Compressed air is used by sandblasters to drive sand particles at high velocities in order to clean and roughen the exposed concrete or steel. Small, hand held tools are used on vertical or irregular surfaces, followed by vacuuming.

Shot-blasting

A rotating paddlewheel is used by shotblasters to propel steel shot against the concrete surface at high velocities. The impact is capable of removing concrete up to ½-inch. The roughness is governed by selecting different shot sizes. Shotblasters vary in sizes but are limited to horizontal surfaces only and are followed by vacuuming.

4.3.3 Application of Repair Materials

There are various methods of applying repair materials. They can be divided into the following three groups.

Hand application

Hand application is common for small or overhead areas where forming and casting are not feasible. Generally after removing the deteriorated concrete, the surface is prepared and the bonding coat is applied before application of the material. The troweling can be used to apply the Portland cement mortar, polymer cement grout, and polymer grouts. This method is not recommended when reinforcing steel is exposed and undercut.

The reason for this is the difficulty of consolidation of repair materials around and behind the reinforcing steel.

Cast in place concrete

This type of application is used for large quantities of repair. It is feasible and economical. Forming is necessary if concrete is to be cast over vertical and overhead surfaces. This type of application is used for spalls covering a large area of three inches or more in depth. First, forms are attached to the sound concrete surrounding the spall, which can be done either by expansion bolts or other anchoring devices. This is followed by depositing repair materials in the space between the form and concrete, which can be done either from the top by gravity or by pressure grouting. In the case of pressure grouting, the material is injected from a porthole (in a vertical repair) until it appears through the top bleeding hole. A similar method can be used for overhead repair.

Limitations (Silano L., 1993)

One of the major problems in this method is a premature hardening of bonding compound before the application of the repair material. Selecting a repair material without a bonding compound is a remedy for this problem. It is difficult to seal the form edges, especially in bridge substructures exposed to tidewater where large spalls are surrounded by numerous smaller spalls. This is another problem related to this method.

Pneumatically applied (Silano G., 1993)

Shotcrete is best known for overhead repairs and is actually a sprayed concrete. Shotcrete is desirable for a number of reasons including the following:

- Needs no bonding compound
- Uses almost half as much as water as compared with conventional concrete.

- High strength and high density
- Better resistance to weathering, frost action, salt intrusion and chemical attacks.
- Needs no forms
- Lowest in costs
- Can be used as coat to exiting concrete

Wet and dry methods are used for the application of sprayed concrete or spray shotcrete. In the wet process all ingredients are mixed before they enter the gun. In the dry process only sand and cement are mixed before handling, coming into contact with water at the nozzle head. The wet process is usually not preferred because of the downtime required to clean up the mixers, hoses, and nozzles.

The various repair methods for various problems of concrete beams and piers along with their selection criteria were found in the literature review and are summarized in Tables 4 and 5 below.

Table 4 Summary of Concrete Bridge Problems and Repair Methods for Beams
(ACI 546R-04, Concrete Repair Manual 2nd edition, Vol.1, Silano, 1993)

Concrete beam problems	Repair method	Criteria for Selection
Delaminations / spalling and Void	Epoxy injection	Cracks & Steel bars not exposed
	Convention Portland cement + aggregate + admixture	Small Area, shallow depth & Steel not exposed
	Cement grout with non-shrinkage material	Small Area, shallow depth & Steel exposed with no corrosion - overhead surface or aggressive weather
	Polymer cement concrete	Medium area, medium depth & Steel exposed and coated
	Patching concrete - Shot Crete or cast in place concrete	Large area, thick depth & Steel exposed coated or replaced
Scaling	Convention Portland cement + sand + admixture	Surface coating less than ¼ in.(6mm) thick is used for early stages of scaling
	Cement grout with non shrinkage material	Medium, shallow depth & Steel exposed no corrosion - overhead surface-aggressive weather
	Patching concrete - Shot Crete	Large area, on overhead or vertical surface.
Hair Cracks for all types of cracks	Epoxy resins injection (bonding matrix)	Hair cracks width > 0.1 mm in tension or shear cracks and expect to be active
	Cement grout	Small Cracks width < 0.3 mm in compression and inactive crack
Diagonal Cracks at end of beam	Crack stamping or shear dowels	Small cracks and shear is safe
	Glue sided plates (steel strapping)	Unsafe of shear + good quality of concrete
	Adding new steel stirrups and concrete jacket	Unsafe of shear load and, low strength concrete and steel corroded
Vertical cracks at mid span	Steel or FRP straps at bottom of beam or 2 exterior plates	Good quality of concrete
	Exterior post tensioning by adding external tendons, rod, or bolts - prestress	Strengthen both shear and flexure
	Concrete jacket	Low strength concrete and steel corroded
Cracks parallel to steel bars	Corrosion	See corrosion Repair
Corrosion	Epoxy injection	Hair cracks < 0.1 mm
	Polymer cement concrete + coating of steel bars	Steel exposed, losses of bars < 20%
	Replacement of bars + Concrete patching + coating of steel bars	Steel exposed, losses of bars > 20%
	Concrete jacket	25 % of steel bars corroded
	Replacement of beam partial or global	More than 25 % of steel bars corroded and the chloride ions reached to depths behind the steel bars

Table 5 Summary of Substructure of Concrete Bridges and Repair Materials
(ACI 546R,2004, Arockiasamy et al, 2000, Thomas j et al, 1989)

Concrete piers problems	**Repair method in literature**	**Criterion for Selection**
Spalling / delamination	SEE TABLE 4.1	
Scaling	SEE TABLE 4.1	
Cracks	Epoxy resin injection	Hair cracks < 0.1 mm
	gel epoxy or foam epoxy	Hair cracks in moist condition
	Polymer cement concrete	Small area of corrosion
	Patching concrete + additional main steel and stirrups	Large area of corrosion + concrete section safe.
	Concrete jacket	Large area of corrosion + concrete section unsafe
	FRP(fiber reinforced polymer) jacket	No corrosion and concrete section unsafe
Corrosion	Epoxy injection	Hair cracks < 0.1 mm
	Polymer cement concrete	Steel exposed, losses of bars < 20%
	Encasements, concrete jacket	Steel exposed, losses of bars > 20%
	Replacement of pier	Extreme deterioration, Inherent material of design problem, bridge reconfiguration or if over than 25% of steel bars lose
Scour	Jet grouting	Hair Cracks < 0.1 mm
	Grout bags	small cracks
	Pre place aggregate concrete	Fill voids that are difficult to access
	Riprap Armoring	Availability and limited resource
	Encasement, concrete jacket	Corrosion of steel > 20 % or strengthening
	bagged concrete	No need of forms work, small crew, limited equipments
	Concrete filled tubes	For larger voids

4.4 Repair Methods

The following is a discussion about various available repair methods for different problems with concrete bridge beams and piers.

4.4.1 Cracks Repair

Cracks in concrete can reflect that severe damage has occurred, or may lead to severe deteriorations if not repaired. Spalling and scaling damage can be accelerated when water enters the cracks. The repair method of concrete cracks depends on various factors which include size, orientation, and the location and activity of the crack. There are various methods of repairing cracks; some of them are discussed below.

Epoxy injection

Cracks can be repaired with epoxy injections both above and below water. First, the area around and within the crack should be thoroughly cleaned. A high-pressure water blaster is very effective for this purpose. The outside of the crack should then be sealed with a hand or trowel-applied epoxy grout and injection ports placed at regular intervals in the epoxy along the crack. Epoxy is injected through the ports, working from one port to the next, after the epoxy seal is allowed to harden. Generally, cracks up to ¼-inch are filled with epoxy resin. For larger cracks, a fine aggregate is added to the epoxy as filler.

Epoxy grout

Epoxy grouts are generally used, because of its excellent bonding qualities to repair cracks. Cracks varying in width from 0.003 to 0.25 inches (0.08 to 6.0mm) can be filled with epoxy grouts of different viscosities. Epoxy grout, which includes a filler material, is used for the repair of cracks with an area wider than 0.25 inches. A common practice is to grout cracks that are 1/16-inch or wider (Silano G., 1993).

4.4.2 Repair of Scaling

Scaling is a gradual and continuous loss of surface mortar and aggregate from an area and is commonly found at the waterline on piers and piles. The main reason is freeze-thaw action, which is found in colder climates. Pores and minor surface defects allow water to penetrate and saturate the concrete. When the temperature drops, the water freezes and expands, causing the surface of the concrete to appear to disintegrate. Sealers are used for the repair of scaling both above and below water. Sealer is a solvent or water based liquid applied to a prepared concrete surface. It may be of two types:

- Penetrating sealers
- Surface sealers

Penetrating sealers: They are Silanes and Siloxanes, which react with the pore walls of the hardened cement paste to create a non-wettable surface. Penetrating sealers should be capable of reaching depths in excess of ¼-inch under ideal conditions.

Surface sealers: They are pore-blocking materials such as linseed oils or epoxy. It is important to note that individual site exposure conditions must be considered while selecting sealers to be used.

Limitation

- Not applied to active corrosion sites and critically chloride contaminated areas
- Depth of the penetration varies by the product and with the properties of concrete on which the sealer is applied.

Estimated service life

Estimated service life of penetrating sealers applied to a substructure or a superstructure component is about 5 to 7 years with a recommendation of reapplication every 6 years after that. The estimated service life of surface sealers is about 1 to 3 years.

Application

There are various ways to apply sealers. They are applied by low pressure pump (with either nozzle or spray bar combinations) and by flood and brush techniques. The sealers should be applied to the rate determined during approval testing. Before application the surface should be cleaned of various compounds, if present. Various cleaning methods that can be used for this purpose include sandblasting or grit-blasting, followed by vacuuming. Epoxy injection of visible dormant cracks should be considered before the application of sealers. It is important to note that sealers should not be used if the temperature of the concrete is below 40° F or 4° C. Sealers should be protected from rain and traffic spray for six hours after application.

Surface coating of less then ¼-inch thick is used for early stages of scaling. Shotcrete can also be used for repair of scaling. For the surface preparation of these coatings and applications, refer to the Repair of Corrosion section of this chapter.

4.4.3 Repair of Spalling / Delamination

The various causes for delamination include corrosion, freeze and thaw cycles, and the penetration of water through cracks. Patching can be used for repair of spalling and delamination. Patching is used to restore the structural integrity and appearance of deteriorating concrete bridge substructure and superstructure elements such as piers, beams and abutments. Depth of the patching should be shallow (to the level of the

reinforcement steel) or deep (a minimum of 0.75 inch) below the first layer of the steel reinforcement steel.

Various patching materials are available which include, PCC, quick–set hydraulic mortar/concrete, or polymer mortar concrete. Patching material is normally limited to PCC in case of corrosion damages in reinforcing concrete. A pneumatically applied Portland cement mortar/concrete, also called Gunite, is used to patch substructure and superstructure elements. The damaged concrete is normally removed to a depth of 0.75 inches below the first layer of reinforcing steel.

Shotcrete is another option for repair of delamination and spalling. The best service life for shortcrete repairs, for elements exposed is about 10 to 15 years. It can be applied as wet or dry mix. Superstructure and substructure repairs are mostly carried out using dry mix mortar. Unsound concrete should be removed to a depth of 0.75 inch below the level of the first layer of reinforcing steel.

Preparation of repair cavity

Once all the unsound concrete has been removed, the cavity should be blasted clean to remove all the loose material and provide a dust-free surface. All scale and rust should be removed. Reinforcing bars with greater than 25% sectional loss as determined by engineer should be enwrapped with reinforcings bar of equal diameters on each side of the deteriorated area. Bonding agents are usually not recommended for shotcrete.

Successful application of shotcrete

It can be obtained by considering the following factors:

- Placement by experienced crew
- Equipment should meet specification

(When encasing reinforcement the nozzle should be held closer and at slight angle to minimize the accumulation of rebound)

- Vertical cavities should be filled from the bottom up.
- Over head surfaces may require the application of multiple layers to prevent sagging.

Limitation

Shotcrete should not place under the following conditions:

- High winds
- Temperature below 40 F
- Rain or threat of rain

4.4.4 Repair of Corrosion

The penetration of chlorides into concrete can cause corrosion of the reinforcing steel. Chlorides may enter the concrete from deicing agents, saltwater, or admixtures. Also spalling and cracking of the concrete is likely to take place when chlorides are present. Sulfates are present in seawater and are common in ground water, especially when high proportions of certain clays are present. Therefore, structures in seawater can suffer sulfate attacks in the tidal zone. A sulfate attack is usually identified as a softening of the surface of the concrete. With further deterioration, the surface can be seen as material is easily chipped away. Moreover, the newly exposed surface is often white in color. Coating is one of the options for corrosion control. Coating consists of one or two component organic liquids, which are applied in one or more coats to prepared concrete surface. The coating material has a high solid content. Organic coating materials are normally epoxies, acrylics, or urethanes. Epoxies are abrasive-resistant and have a high

adhesive strength, but are liable to degradation by UV light. Acrylics are brittle and normally have low impact strength. Urethanes have high impact strength but have a low resistance to abrasive forces. Coating usually does not permit water vapor transmission, and thus permeability to both water vapor and liquid water is very low. Individual site conditions must be considered in the selection of coating materials. It is important to note that most coating failures occur because of debonding of a weak surface layer of the substrate concrete. Such debonding is caused by the high internal stress in the coating (ACI 515, 1991).

Surface preparation for coating and sealers

The surface should be free from any wastes such as grease, oil, wax, or residual curing compounds. Most coating failures occur because of debonding of the weak surface layer of the substrate concrete.

Cleaning methods

Various methods of cleaning the surface are discussed earlier in this chapter, including sand blasting to prevent surface contamination. Oil should be removed and oil water traps installed on the compressed air source before blasting. Blasting should be followed by vacuuming to remove the dirt and dust. Acid etching is strongly discouraged because it requires water flushing, which may leads to corrosion.

Application of coating

Coating may be applied by brush, roller, or spray as necessary for even coverage. For spray applications a low-pressure externally atomized spray gun should be used. The temperature limitation for this application is between 50° and 90° F (10° to 32°C). Two applications of coating should be applied to ensure even coverage and minimize the

likelihood of pinholes. Each application should produce a dry film thickness of 2 to 3 mils. The second coat is applied normally 24 hours after the application of the first layer.

Corrosion control methods

Several inhibitor methods that could be used to control corrosion of the reinforcing bars are discussed below.

Chemical inhibitors

Corrosion inhibitors are an admixture to the concrete whose aim is to prevent the corrosion of embedded metal. These admixtures may be organic or inorganic in nature. Inorganic inhibitors are potassium dichromate, stannous chloride, zinc and lead chromates, sodium nitrate, and calcium nitrate, while organic inhibitors include sodium benzoate, ethyl aniline and mercoptobenzothiazle. Sodium nitrate and calcium nitrate has been used in Europe and United States, respectively.

These chemical inhibitors should be added as an admixture during the concrete batching and mixing phase; however, these chemical inhibitors are not applicable to the existing reinforced concrete structure.

Cathodic protection

Cathodic protection is a proven procedure to control the corrosion of steel in contaminated concrete. Corrosion is an electrochemical process so the basic principal involved in this method is to make the embedded reinforcing steel cathodic, thereby preventing further corrosion of the steel. This can be achieved by electrically connecting the reinforcing steel to another metal that becomes the anode with or without the application of an external power supply. A cathodic protection system in which an external supply is not used is referred to as sacrificial passive system.

Protective Methods from Chloride ions

One way to prevent the corrosion of reinforcement steel in corrosive environment is that, the reinforcements must be made of non-corrosive material. The other way is that conventional reinforcing steel must be coated to isolate the steel from contact with oxygen, moisture and chlorides.

Non corrosive stainless steel

Stainless steel is very expensive and cannot be used to replace mild-steel reinforcements in most applications. However, when used it usually reduces the frequency of corrosion-induced cracking compared to mild steel but cannot prevent it.

Coating

Nickel, cadmium and zinc have all been shown to be capable of delaying and in some cases preventing the corrosion of reinforcing steel in concrete, but only zinc-coated (galvanized) bars are commonly available. Numerous nonmetallic coatings for steel reinforcements have been evaluated but only fusion–bonded epoxy powder coatings are produced commercially and widely used. The epoxy coating isolates the steel from contact with oxygen, moisture, and chloride. The process of coating the reinforcing steel with epoxy consists of electrostatically applying finely-divided epoxy powder to thoroughly cleaned and heated bars.

The main difficultly in using epoxy-coated bars is preventing damage to the coating, which might happen during transportation and handling. However, damaged coating can be repaired by using a two-component liquid epoxy.

4.4.5 Repair of Scour

Several repair techniques found in the literature showed that repair of large void areas in concrete members, especially piers and columns, using cement and epoxy grouts is generally not economical. These large voids must be formed to restore the member to its original cross section with concrete placed underwater. Forming methods may be conventional wood and steel forms. Several methods can be used to place concrete underwater; however, the main concern with placing concrete underwater is to prevent washout of the cement and concrete. Various methods are used for the repair of a scour and placement of concrete for underwater repair; tremie concrete, pre-placed aggregate, the bottom opening bucket, pumped concrete, and bagged concrete are described below.

Tremie Concrete

In this method, a funnel-shaped hopper is attached at the top of a vertical pipe (6 or 8 inches in diameter) through which the concrete is fed (Thomas et. al, 1989). A high-slump concrete is recommended for this method for easy flows. The bottom of the tremie is maintained below the top surface of the fresh concrete. The reason for this is that the concrete exiting the bottom of the tremie forces the previously placed concrete upward and displaces the water in the form. As the level of the concrete rises, the tremie pipe is moved upward, but is always kept in the fresh concrete. At the start of the pour process, the end of the tremie is plugged to prevent water from entering the pipe. Placement must continue once started until the entire form is filled because even short delays can cause blockage in the pipe. It is necessary that a sufficient head be maintained on the concrete in the tremie to raise the surface of the fresh concrete.

Pre-placed aggregate

The pre-placed aggregate method is composed of packing forms with coarse aggregates and injecting the element mortar or grout into the mass. The aggregate is packed around tubes through which mortar is injected. This method is advantageous for underwater placement as compared to conventional methods, which would result in segregation. The pre-placed aggregate method allows the larger aggregate to be placed by hand if necessary, and permits pumping of the mortar to fill the voids.

The aggregate must be well graded, high quality, and clean to achieve quality concrete. In order to ensure proper coverage and to be able to develop good strength, the grout must be fluid. The grout should be pumped from the lowest point upwards using a smooth and continuous operation.

Bottom Opening Bucket

Special buckets are covered at the top to protect the concrete and are also used to place concrete underwater. The procedure involves the lowering of bucket into place by crane and the opening of bottom to place the concrete. These buckets are usually provided with a skirt around the outside of the bucket which is lowered to protect the concrete during placement.

Pumped Concrete

Pumped concrete is greatly used in above water construction but can be used underwater as well, especially when highly skilled workers are not available for concrete placement. Concrete can be pumped through pipes or hoses, but pipes are more suitable, as resistance to the concrete is lower and they will not kink. Aluminum pipes are generally not used in order to avoid reaction with concrete. Concrete pumped underwater

should start at the bottom of a form and continue upwards. The concrete should not be allowed to free-fall through the water.

Bagged Concrete

Concrete can also be placed in bags. The bags should be small enough to be handled by a diver. These bags may be jute bags or synthetic bags that are filled with dry cement and aggregate, and are placed in contact with each other to allow bonding. These bags harden in place due to the hydration process of the surrounding water. Another method is to fit nylon bags with injection ports for mortar or grout. The bags are placed below water and the mortar is pumped into these bags from the surface. These bags can be sewn to any size to fit the cavities. This method is preferred over the hand placed small bags, as these bags can be pumped to completely fill a void under an existing structure.

In order to prevent scour at piers, these bagged concrete methods can be used to construct a riprap blanket. It is also used on badly deteriorated columns and piers to restore the structural capacity. The damaged concrete is removed and concrete is placed to fill the cavities and provide a layer of concrete over the as-built structural concrete element, completely encasing the element. Procedures used to encase badly deteriorated columns, piers, or piles in a manner that restores the load carrying capacity are termed as encasement. Bagged concrete is used by the Oregon, Pennsylvania and New Hampshire Departments of Transportation for the treatment of scour problems.

Areas to be removed: Unsound concrete should be traced by sounding with a hammer. Outline the areas to be removed with a saw cut, since the entire external surface of the component will be encased.

Removal of unsound concrete: Unsound concrete should be removed using various pneumatic breakers of less than 35 nominal pounds (15.9 kg). Pneumatic breakers should be fitted with bull-point chisels (pointed). Small hand chisels should be used to provide clearance around reinforcing bars. Pneumatic breakers should be operated at an angle no greater than 45 degrees to the substrate.

4.5 Strengthening Techniques

Several strengthening techniques are available, which can be selected based on the previous evaluations and analytical results. There are several ways to achieve strengthening of an element. It may be the placement of reinforcements within existing concrete or the placement of new reinforcements exterior to the existing concrete member. The ultimate goal is to resist tension caused by flexure, shear, torsion, and axial forces so that the strengthened structure meets the requirements for strength and serviceability.

4.5.1 Exterior Reinforcement of the Beams

Exterior reinforcement may consist of steel brackets, steel plates, reinforced concrete shrouding, and composite material such as CFRP, etc. The new reinforcement may be encased with concrete, shotcrete, mortar, plaster, or waterproofing.

The reinforcements may be steel plates, steel-rolled sections and steel strapping, FRP, etc. In order to repair damaged concrete, remove and place a new reinforcement installed around and adjacent to the remaining concrete. This new reinforcement can be encased in concrete or shotcrete. If the existing concrete is in good condition, bond the

new reinforcement directly using epoxy and Portland cement concrete. Various mechanically fastening techniques can also be used.

Advantages (ACI 546R, 2004)

There are various advantages of this method. It is best suitable when obstruction limits or confines access of equipment needed for placement of the interior reinforcement. In case concrete rehabilitation is required, this may be accomplished in same construction process. Steel plates can be attached to existing girders using bolts. Beams and piers have recently been strengthened by carbon fiber, CFRP, glass fiber, or equivalent composite materials installed with bonding resin. Strengthening with strips is cost-effective.

Limitations

- Load distribution should be analyzed
- Occupy space
- Surfaces preparation is critical
- Lost of strength at elevated temperatures caused by epoxy, if used as structural adhesive

4.5.2 Jackets

In order to restore an existing structural member to its original dimensions or increase in size by encasement, a process known as jacketing can be used. A steel reinforcement cage or composite material wrap can be constructed around the damaged section onto which shotcrete or cast-in-place concrete is placed.

The jacket form is placed around the section to be repaired; this form is provided with spacers to ensure equal clearance between the jacket and the existing member.

Various techniques are used to fill these jackets, including pumping, tremie, or pre-placed aggregate concrete with different materials such as conventional concrete, epoxy, grout, and latex-modified mortar and concrete (ACI 546R, 2004).

Advantage

- Particularly applicable in repair of deteriorated column and piers etc
- Permanent forms are suitable for marine environment

Limitations

- Jackets are more often expensive when used under water
- Occupy available space

4.5.3 Girder Replacement

The various repair methods for minor, moderate, severe, and critical damage due to the collision of oversized vehicles with girders and beams are discussed below.

For minor damage, spalled areas on girders are repaired by patching with PCC mortar, as discussed earlier. In the case of spall, repair with few other type of materials as well. Cracks in this case are repaired by epoxy injection and the injection sequence is from the bottom areas of the girder to the top areas. Restoring the original section of the girder with an approved epoxy mortar is another option. Removal of unsound concrete is done more safely through hand tools. Precautions should be taken to avoid damage to the reinforcement.

For moderate damage, use of epoxy cement binder is necessary before any repair work. Exposed reinforced steel should be cleaned by sandblasting. Injection of cracks with epoxies is the same as in the case of minor damage. It is also important to note that placed formwork may be required and all the shattered concrete must be removed.

For severe damage, straighten reinforcing bars and tie back as necessary. Extreme care should be taken not to damage the exposed reinforcement and no impact tools should be used. Approved epoxy mortar should be used to obtain the original size and shape of the girder. Epoxy grout, and epoxy mortar, high strength mortar should be used for the bonding compound. Repair of severe damage should always be preceded by a structural analysis of damaged reinforcements related to service load, ultimate load, and overload.

Critical damage may require the installation of false work to safely guard the public and the facility during the replacement operation.

The most common method to replace a damaged girder is to remove portions of the roadway slab and diaphragms, allowing the girder to be lifted up and out of the structure. Sufficient length of reinforcing steel is required to be left in place, extending from the slab and diaphragms, to provide lap length requirements. Prior to concrete removal, saw-cuts are made in the slab to obtain good break lines in sound concrete. The choice of whether to replace from above, to replace from below, or to replace with a precast section that might include roadway deck and curb must be determined according to the site conditions.

4.6 Summary

This chapter included discussions of the repair and rehabilitation methods for concrete bridge beams. It also contained various repair materials and repair procedures. The application of the repair methods to the identified problems in concrete bridges such as cracks, corrosion, and delamination were discussed in detail. The limitations, the advantages, and disadvantages of each repair material were presented.

Chapter 5

DEVELOPMENT OF KNOWLEDGE BASE FOR DECSION SUPPORT SYSTEM

5.1 Introduction

It's important to observe that although decision support systems have been in existence since the early seventies, the construction industry has been slow in using them to eliminate the problems (Kaetzel et al. 1991) At present decision support systems or knowledge–based systems are having greater attention from construction industry to help in decision making processes in key areas including diagnostics, design repair, and rehabilitation.

Decision support systems are not an alternative to the bridge inspector, in fact it is support to the bridge inspectors and its purpose is to validate, confirm and authenticate the decision taken by inspectors. Knowledge based systems or expert systems can be used to model human reasoning and decision-making process. Fully developed systems are able to accept facts from the users process these facts and deliver solutions that are close to the solutions that would have been offered by human experts (Foo et al., 1995).

There are various definitions of decision support systems available in the literature. It can be defined as "An intelligent computer program that uses knowledge and inference procedure to solve problems that are difficult enough to require significant human expertise for their solutions (Kaetzel et al., 1995). Also, "an expert system consists of a knowledge base which represents acquired knowledge in a certain format, an inference engine which makes inferences based on knowledge base, and a user interface which interacts with user and presents inference results (Miyamotto, 1997).

Therefore, it's clear that decision support system is a computer program equipped with an interface engine in order to enhance the problem solving behavior of a human. Knowledge base, interface engine, and the end user interface are the basic components of any decision support system. The decision support systems can be utilized in diagnostic, repair and rehabilitation in construction industry. It will provide the engineers and inspectors with another tool to identify the problem or distress, determine the cause and recommend the solutions. Budgets constrain, increase attention to maintenance, lack of experienced inspectors, and advances in data gathering methods are the various factors that lead to the increase importance of decision support systems.

5.2 Ruled Based Decision Support System

Decision support systems can be divided into many types. The type of decision support system that is based on rules is called rule based expert system. Rule based decision support system is easy to use and modify. Rules represents the IF condition and THEN statements for example, If the age of concrete is before hardening, the crack pattern is random, then the crack may be plastic shrinkage crack ((Kaetzel et al., 1991). As we see this type of decision support system is basically in a question answer format. The users enter the answers to the questions asked by computer. The software uses interface engine to give meaning to the information and select the answer. EXSYS Professional is an example to the software, which can be used to develop rule, based decision support system.

Identification of a problem that has many alternatives or solutions is the first step. A decision tree is developed and then that decision tree is converted to rules that are the driving forces to the already built in interface engine. The rules are then feed into the software. Once the software starts acquiring data from the user through a question answer

session, these rules deicide the direction in which the user will go in the decision tree diagram.

5.3 Parameters Affecting Development of Decision Support Systems

The first step in the development of a decision support system is to identify a problem. One of the main requirements is that the problem selected should be well understood and the solutions should be universal so that the decision support system can be verified by almost any one. This means that if problems that cannot be solved by human brain; cannot be solved by decision support systems. The development of the knowledge base of this study can be divided in the following stages:

- Investigate the main problems normally in the bridge beams and piers.
- Investigate the repair methods for the identified problems
- Develop the flowcharts and relations which will lead to the development of the decision support system

The knowledge base for this decision support system was made mainly from input from literature. The following discussion consists of the developing of the knowledge base, decision tree and then subsequently the rules, which are building blocks of the decision support system.

5.3.1 Knowledge From the Literature

The first step in the development of this decision support system is to gather information from the literature. Various problems such as delamination, cracking, corrosion, spalling, vehicle damaged, and scour were well searched in literature along with their repair methods and strategies. Criterion for selection of particular repair

methods was developed and summarized in the Table 4.1 and Table 4.2 of this thesis. This criteria was then used for the development of the tree diagram and the rules.

5.3.2 Tree Diagram/ Flow Chart for Decision Support System

A decision tree for the problem on hand is one of the favorable methods for building decision support system. The tree diagram help developing rules, which will control the decision process. Knowledge gathered from literature review was utilized to develop tree diagram for each specific problem. Each branch in the tree leads to a group of choices. Nodes within the tree are very important as these nodes direct the rules. At each node the program makes a choice among the various paths available. Figures 5 to 8 show flow chart diagrams for the decision support system for delamination /spalling, cracking, vehicle damage and scour.

Delamination and spalling are the identified causes/problems for concrete bridge beams deterioration. Figure 5 starts with a question if the reinforcing steel is exposed or not. If the answer is "yes" then flow chart leads to repair and additional questions are asked in order to understand the extent of the problem so that suitable repair methods are recommended.

Similarly, in Figure 6 for cracking, the first question asked is about pattern of the cracks. If irregular then regular routine maintenance is the option recommended. The next question added is the activity of the crack, whether it is inactive shallow or active hair, cement grout and epoxy injection are the repair material; respectively. In case of regular cracks, then crack size and orientation is asked which can be parallel to bars, vertical and diagonal. If the cracks are diagonal, in that case it has been asked whether the shear capacity of the beam is safe or not. If answer is "yes" then go for stamping or dowels

other wise check the quality of concrete. If the concrete is good then go for plate steel strapping etc as a repair method. If the concrete is not good then concrete jacketing should be use as a repair method. In the same manner, other cracks such as vertical and parallel to bars can be traced to the end repair methods in the flow diagram.

Figure 7 shows the minor beam damage, which consists of isolated concrete cracks, nicks and no reinforcement steel exposed, the choice of repair is epoxy injection under routine maintenance. In case of medium damage, which consists of concrete cracks and wide spalls exposing reinforcing steel, the choice of repair is coating of steel and then cement grouting. for exposed and damage steel as in case of severe damage due to vehicle collision of the concrete beam, the options are replacement of steel bars and fallowed by patching if percentage of damaged steel is greater than 20 % other wise go for coating of steel and accompanied by concrete patching.

From Figure 8, it is shown that in case of scour, soil movement beneath the pier, concrete and steel deterioration need to be evaluated. Repair selection can be based on the problem identified. Repair selection can be determined from Figure 5 and Figure 6. For loss of section of concrete jacketing will be the proposed repair methods. It can also be seen that if steel is corroded and not damage then best suitable repair is coating of steel and fallowed by cement grouting and the other case is discussed earlier.

In case of soil movement, check for the stability of the pier, if not stable then sheet piling and stones are the options for repair. Other wise use bagged concrete, prepalced aggregate concrete and termie concrete etc. The use of these depends upon various factors which include availability, cost, ease to use, size of the defect, repair conditions, and accessibility.

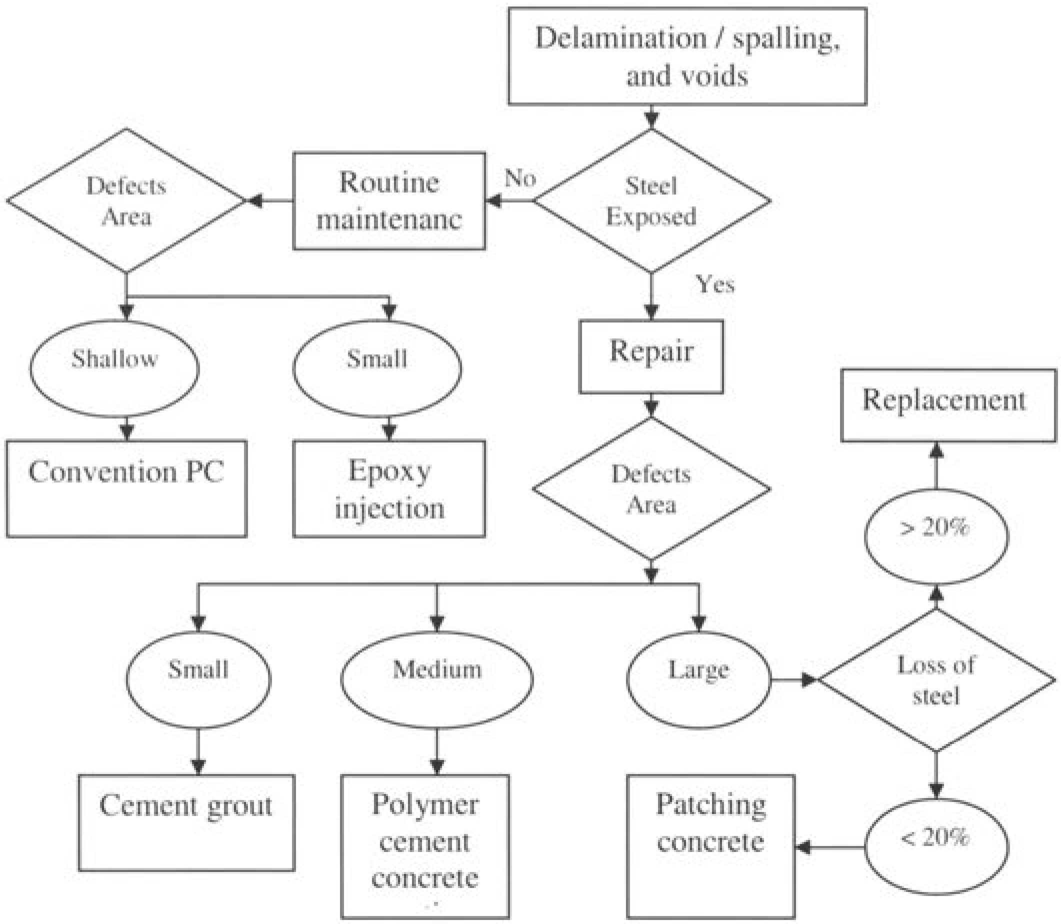
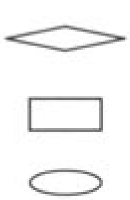


Figure 5 Flow Chart for Delamination / Spalling Identification and Repair Method of Bridge Element

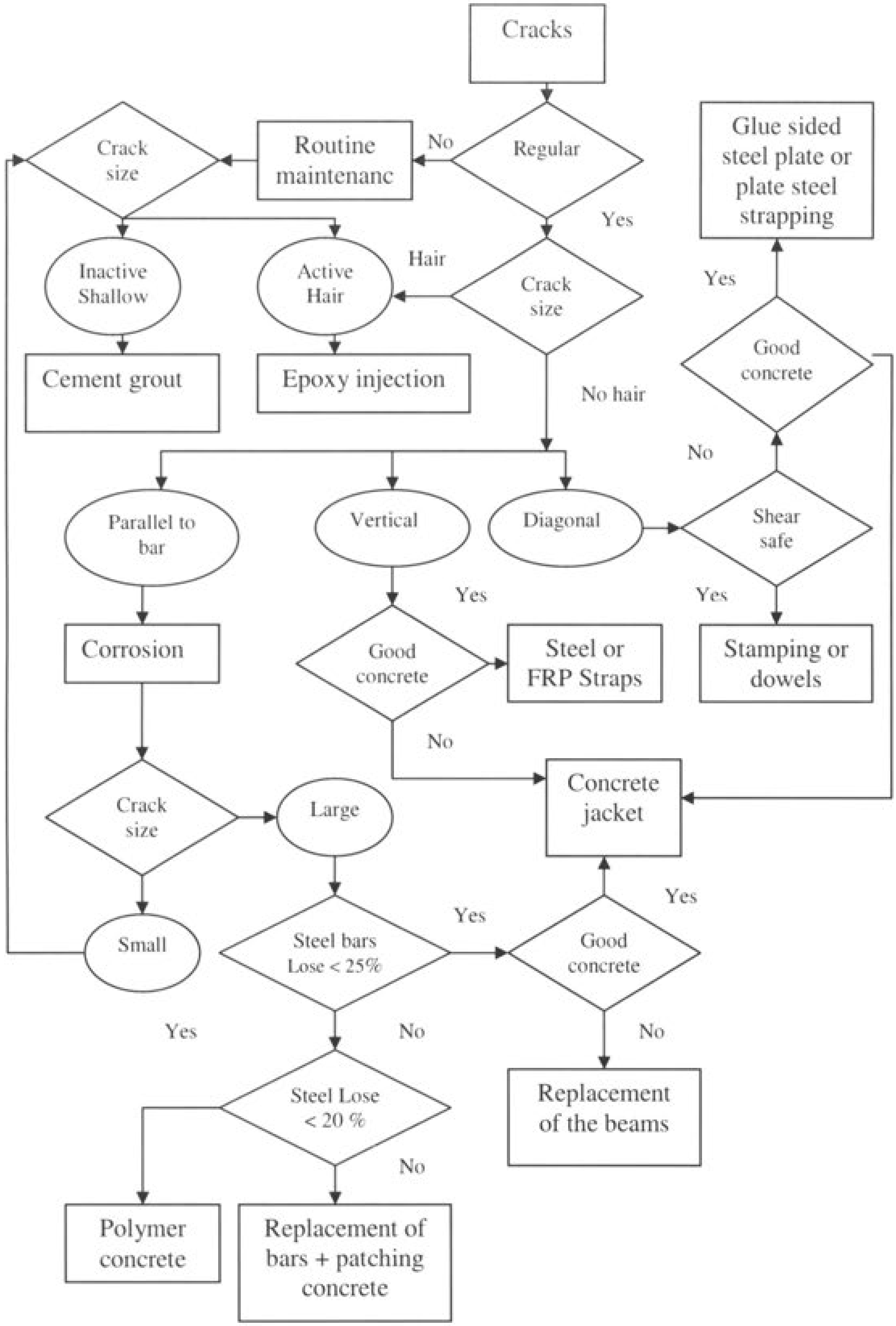
Note:



Decision yes or now

Process activity

Start or stop of flow



*FRP =Fiber Reinforcement Polymers

Figure 6 Flow Chart for Crack Identification and Repair Method of Bridge Element

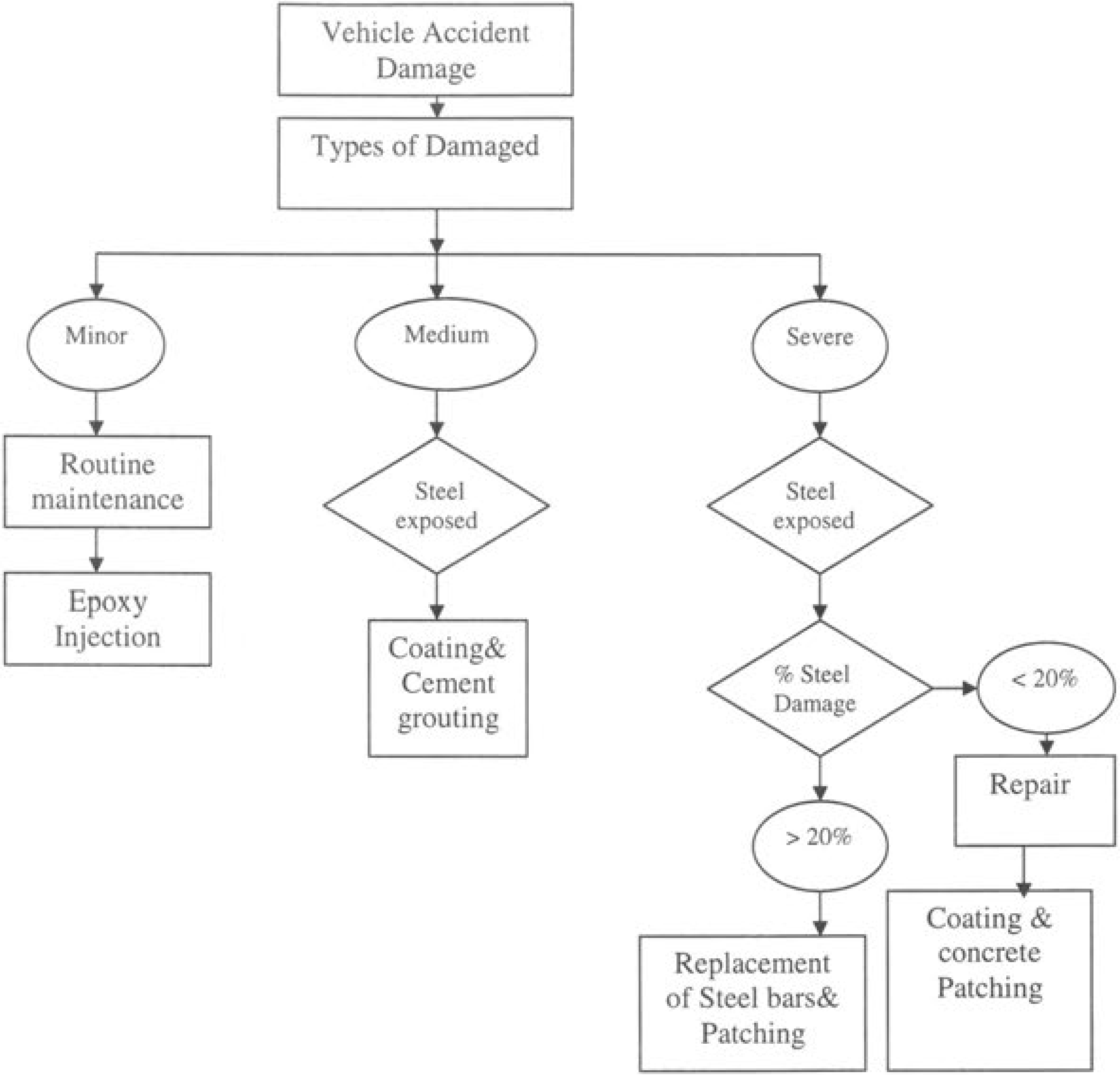


Figure 7 Flow Chart for Vehicle Accident Damage Identification and Repair Method of Bridge Element

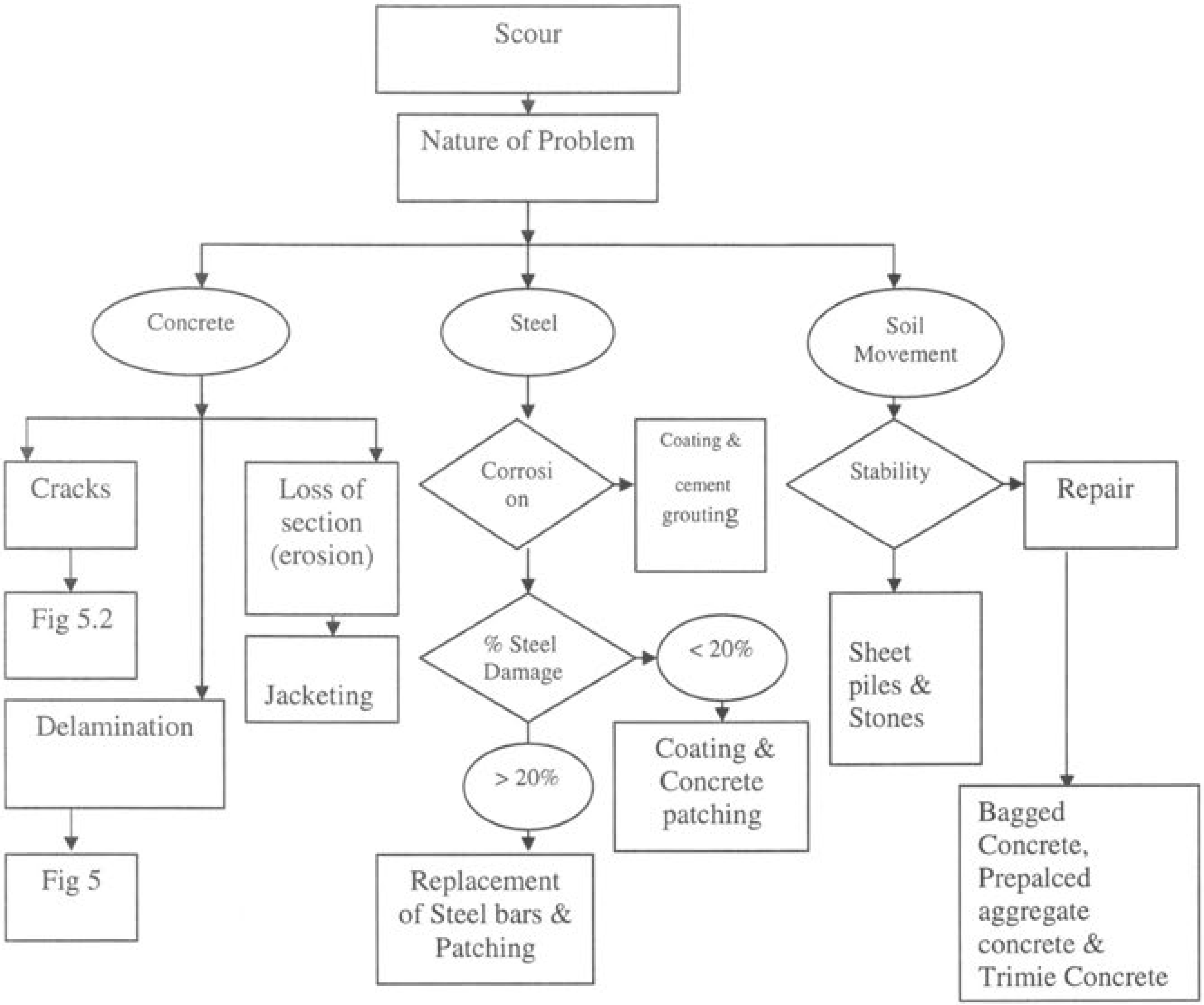


Figure 8 Flow Chart for Scour Identification and Repair Method of Bridge Element

5.3.3 EXSYS Professional

Expert system can be developed using different system shells. EXSYS Professional is the software, which provides the same capabilities. It has built-in interface engine and is suitable for small sized decision support program. Rule editor is the main component of EXSYS Professional, which can be edited and modified easily. The following is a brief description of EXSYS Professional software to be used in developing the proposed system:

5.3.4 Components of EXSYS Professional

EXSYS Professional consists of four main features:

- Knowledge base
- rule
- parameters
- printing the knowledge base

Qualifiers, choices and variables are the integral parts of the knowledge base. In fact, knowledge base is the data, which will be input into the system by an expert. Qualifiers are multiple choices questions, which can be added into the knowledge base through a command. Choices are the basis of all EXSYS expert system since they are the results, which are displayed to the end user. The system asks the operator to provide the choices when a new knowledge base is started. Choices are the possible solutions to the problems that the expert system will select from for a specific problem. Repair methods, which were discussed in previous chapters will be used to build the choices for the proposed expert system in this study. Rules are the components of the decision support system, which direct or control the interface mechanism. Rules can be created by creating

condition in the IF, THEN, and ELSE part of the rule. Rules can be added, edited through rule editor. It is important to note that the IF, THEN, and ELSE part of the rule is linked to the existing lists of variables choices and Qualifiers.

In order to build the "IF" part of the rule using a qualifier, select the Qualifier option; the complete list of the Qualifiers will be displayed. Once appropriate variable is selected, the value will also be highlighted, "IF" part can be completed by choosing the appropriate value of a specific qualifier. When a new knowledge base is started the system asks to set the parameters for the decision support system. Most of the parameters can be changed except of the confidence mode. The decision system will not move forward until and unless, these parameters are set in advance.

Rules

As discussed earlier, the flow charts or tree diagrams are the second stage of the development of rule based decision support system. From all the flow charts, one can create rules for a decision support system for concrete bridge maintenance. For example, fourteen rules are developed for a rule based decision support system to deal with the cracking problem as fallows.

<u>RULE NUMBER: 1</u>

IF:

The pattern of the cracks in beam is regular

and The size of the crack in the beam is hair line

THEN:

Epoxy Injection– Confidence = 1

RULE NUMBER: 2

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is small

and The activity of the crack is in active

THEN:

Cement Grout - Confidence=1

RULE NUMBER: 3

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is small

and The activity of the crack is active

THEN:

Epoxy injection. - Confidence=1

RULE NUMBER: 4

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is large

and The steel bars damaged are < 25 %

and Loss of steel cross-section is < 20 %

THEN:

Polymer Concrete. - Confidence=1

RULE NUMBER: 5

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is large

and The steel bars damaged are < 25 %

and Loss of steel cross-section is > 20 %

THEN:

Replacement of Bars. - Confidence=1

RULE NUMBER: 6

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is large

and The steel bars damaged are < 25 %

and Condition of concrete is poor

THEN:

Replacement of Beams. - Confidence=1

<u>RULE NUMBER: 7</u>

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is parallel to bars

and The size of the crack is large

and The steel bars damaged are < 25 %

and Condition of concrete is good

THEN:

Concrete jackets. - Confidence=1

<u>RULE NUMBER: 8</u>

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is vertical

and Condition of concrete is poor

THEN:

Concrete jackets. - Confidence=1

RULE NUMBER: 9

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is vertical

and Condition of concrete is good

THEN:

Steel Straps. - Confidence=1

RULE NUMBER: 10

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and Th

e orientation of cracks is vertical

and Condition of concrete is good

THEN:

FRP Straps. - Confidence=1

<u>RULE NUMBER: 11</u>

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is diagonal

and Condition of shear is not safe

and Condition of concrete is good

THEN:

Steel Plate Strapping. - Confidence=1

<u>RULE NUMBER: 12</u>

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is diagonal

and Condition of shear is not safe

and Condition of concrete is poor

THEN:

Concrete Jackets. - Confidence=1

RULE NUMBER: 13

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is diagonal

and Condition of shear is safe

THEN:

Stamping - Confidence=1

RULE NUMBER: 14

IF:

The pattern of the cracks in the beam is regular

and The size of the crack in the beam is others

and The orientation of cracks is diagonal

and Condition of shear is safe

THEN:

Dowels - Confidence=1

Each rule consists of qualifier(s), variable(s) and choice(s). For Qualifiers, Variables and Choices in the case of cracking can be seen below. These rules can be then entered into any expert shell accordingly and then run in order to have a complete decision support system for concrete bridges. In case of EXSYS Professional, Rules, Qualifiers, Variables and Choices are discussed in detail in the above paragraph of this chapter.

Table 6 Summary of Qualifiers, Choices, and Variables for Cracking

Qualifiers	**Choices**	**Variables**
1.The pattern of the cracks in the beam is • Regular • Irregular 2. The size of the crack in the beam is • Hair line • Others 3.The orientation of the crack is • Horizontal to steel bars • Vertical • Diagonal 4. Crack size due to corrosion is • Small • Large 5. Steel bars damaged due corrosion • < 25 % • Others 6. Loss of steel cross-section due to corrosion • < 20% • others 7. Condition of concrete in case of corrosion • Good • Poor 8. Condition of concrete in case of vertical cracks • Good • Poor 9. Condition of shear is • safe • Not safe 10. Condition of concrete at diagonal cracks • Good • Poor 11. The activity of the crack is • Active • Not active	1. Replacement 2. Epoxy Injection 3. Polymer Cement Concrete 4. Patching 5. Concrete jackets 6. Steel Strips 7. FRP Strips 8. Stampling 9. Dowels 10. Steel Plate Strapping 11. Cement Grout	1.CRACK WIDTH The Width of the Crack Numeric variable 2.MIN CRACK The Minimum Crack Width Numeric variable Upper limit = 0.250000 Lower limit = 0.003000

Table 7 includes the various bridges with different problems and repair methods used in Calhoun County, Michigan.

Table 7 Summary of Bridges with Potential Problems and Repair Methods in Calhoun County Michigan

Bridge No	Elements	Problems	Repair
# 7	Beams/Piers	Spalling, Crack, Corrosion, Delamination	High strength repair material, Coating with a rust inhibitor, Epoxy injection,
# 34	Beams	Hairline Cracks, Spalling, Delamination	Epoxy injection, Installation of rebar in case of section loss > 20%,Coating to exposed rebars, Epoxy injection for Cracking,
# 44	Beams	Cracking/Spalling	Coating of all exposed rebars, Overhead hydraulic concrete, Epoxy injection,
# 48	Beams	Cracking/Spalling	High strength concrete, Penetrating epoxy, Zinc-rich urethane,
# 45	Piers	Cracking, Spalling, Delamination	Installation of rebar where necessary, Coating of all exposed rebar, High strength hydraulic concrete, Water proofing membrane,

Note:

* # 7= Bridge on Raymond Road over the Kalamazoo River south of Columbia Ave.E

* # 34= Bridge on Old 27 over Nottawassepee Creek north of L Dr. S

* # 44= Bridge on S Dr. S over Pine Creek east of 2 Mile Road

* # 48= Bridge on Old 27 south of V Drive N over Indian Creek

* # 45= Bridge on V Dr. S over Pine Creek east of 1 Mile Road

From Table 7, it's clear that high strength hydraulic concrete is used for spalled repair and epoxy injection for cracking as well as coating with migratory rust- inhibited bonding agent or zinc rich urethane for corrosion in the field. *The reasons for using identical repair methods for different methods may be that the inspection forms used are too general and doesn't contain a detail and specific information about the problems and also it's convenient for the contractor to go for it for many reasons.*

The application of flow charts for various problems in the field is discussed below. For example in case of Bridge # 34, installation of rebar is used if loss of steel due to delamination/spalling is greater then 20 % as repair method. However, if we fallow the flow chart for delamination/spalling, we can observe that this flow chart also leads to replacement or installation of bars along with many repair methods for the delamination and spalling by asking more questions about the exact condition of the problem as highlighted below in Figure 10. The first question asked if the steel is exposed or not then regular maintenances is suggested. But if the steel is exposed then the next question asked is the defected area is small, medium or large. If small then cement grout is suggested other wise go for polymer cement concrete. However, if it is large then next question is asked about the loss of steel and if it is < 20 % then go for patching other wise go for replacement option which is highlighted in Figure 10. But if we consider case of bridge # 44, then it is clear that the contractor go for high strength concrete as a repair material in case of delaminating or spalled areas. However, if we use flow chart for delamination/ spalling we have to gather more information during inspection and then proceed by using that information in the flow chart and suggest repair method for

delamination/spalling. For this reason an auxiliary inspection form is proposed at the end of the chapter because the inspection forms which are in practice are too general.

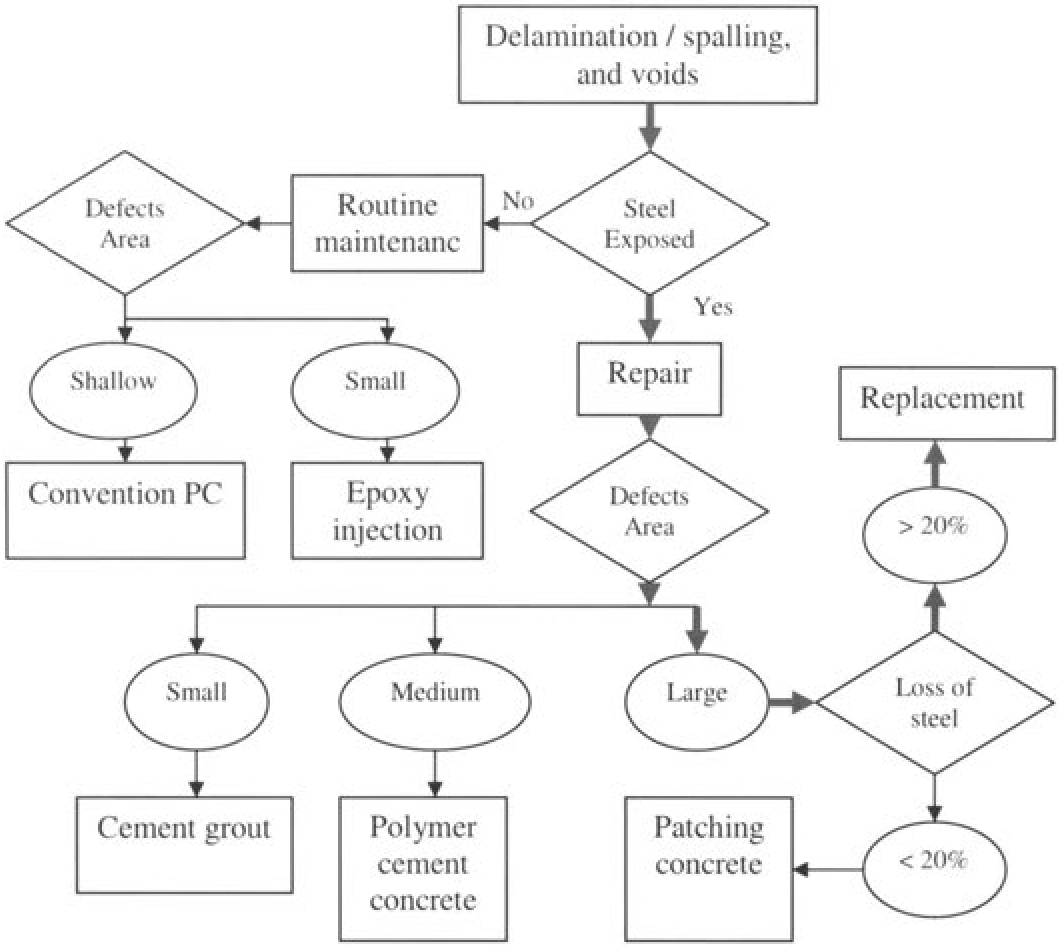
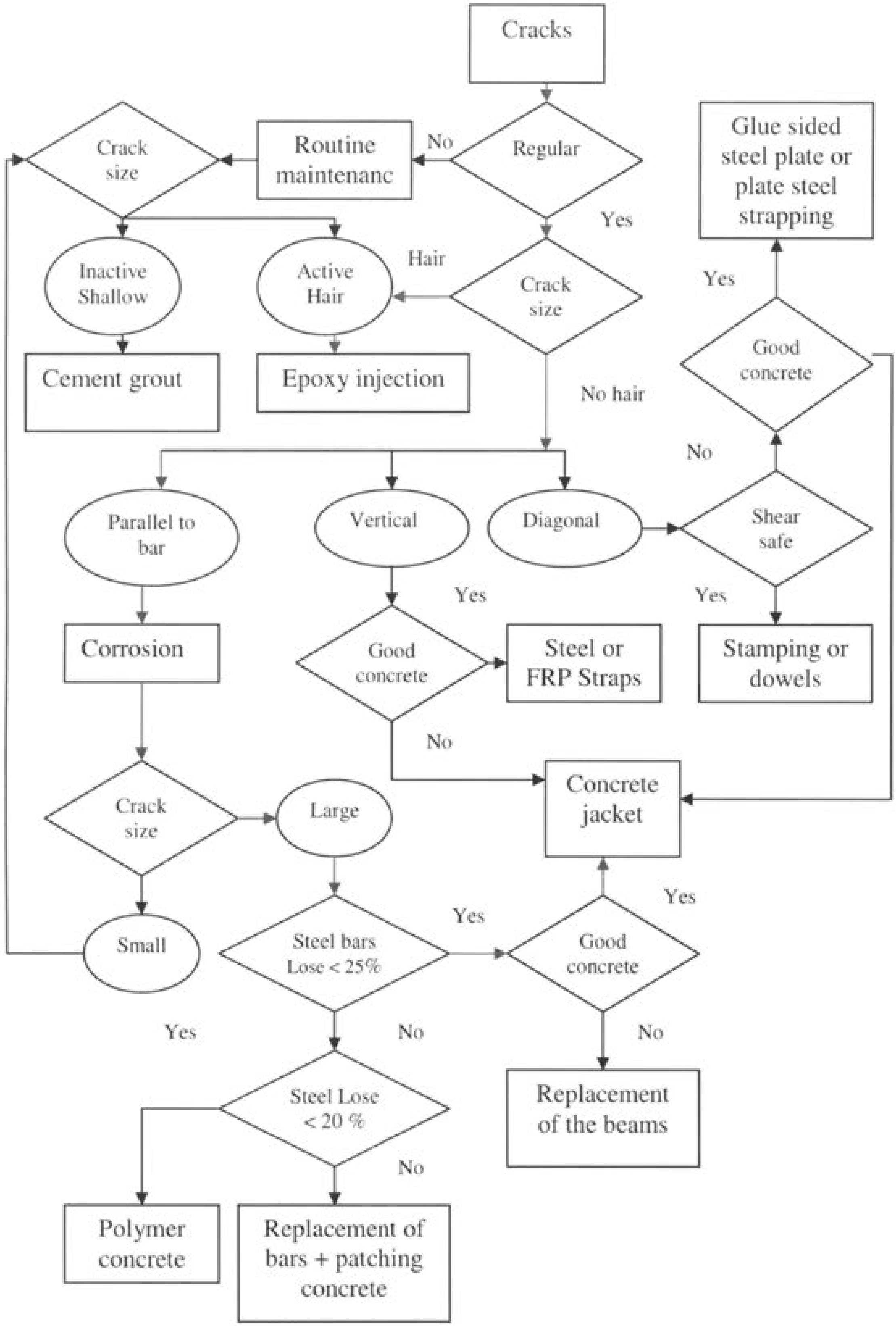


Figure 9 Flow Chart for Delamination/Spalling Identification and Repair Method of Bridge Element

Most of the bridges which were listed in Table 7, the epoxy injection is used for crack repair in case of beams. The reasons for this were discussed earlier. In this case, we see that flow chart for cracking leads us to same epoxy injection only if the cracking is *regular and hairline*. This is highlighted in the Figure 10 below and for other repair methods additional questions are asked and then repair methods are suggested accordingly. Since the contractor is using general inspection form so the detail



*FRP =Fiber Reinforcement Polymers

Figure 10 Flow Chart for Crack Identification and Repair Method of Bridge Element

information is missing for this reason it is difficult to validate the rest of the flow chart in case of cracking.

Similarly for corrosion, coating with zinc urethane is recommended by the contractor. However, if additional information is available about the size of cracking, exposure of steel, condition of steel, and condition of concrete then various kinds of repair methods are suggested by the flow chart for cracking. For example, if the steel is exposed, loss of steel is less then 20 % and the condition of concrete is good then concrete jacketing is recommended. This selection is highlighted in the above Figure 10.

General inspection form is used in the Calhoun County for inspection purposes, which leads to general repair methods but in our case each flow charts leads to a particular repair method after a detail inspection of various problems by using a proposed inspection form as shown below.

Auxiliary Inspections Form

The current inspection forms are too general and cannot be used for the proposed decision support system. In order to extract more data for the decision flow charts, the auxiliary form shown in Figure 11 has been proposed to help collecting the necessary information to run the decision support system based.

5.4 Summary

This chapter includes the various stages of development of decision support system for bridge maintenance. The knowledge base and flow charts were discussed. Rules, Qualifiers, Choices, and Variables that were used in EXSYS Professional were explained. A modified inspections form is proposed to support the proposed decision support system for concrete bridge maintenance.

Figure 11 Auxiliary Inspection Form for Proposed Decision Support System

DOT Bridge ID		NBI Bridge ID
Location	Latitude	Longitude
Year Built	Year Rehabilitation	Bridge Area
Bridge Type	Beam Type	
CORROSION		
Tools of Inspection		Are the bars Exposed
Causes of Corrosion		% Loss of steel section
% of the number of corroded bars		Locations of corrosion
CRACKING		
Tools of Inspection	Pattern of Cracking	Orientation of Cracking
Size of Cracking	Width of Cracking	Locations of Cracking
Condition of Steel		Condition of Concrete
DELAMINATION		
Tools of Inspection	% Area of Delamination	Causes of Delamination
Condition of Concrete		Condition of Steel
Additional Information (if any)		
Inspected by		Date

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Summary

Transpiration system of any country has vital role in the economy of toady's fast pace world. This system has to provide fast and safe movement of goods and people. Bridges are the key elements of transpiration system in the United States; therefore, great care should be taken to maintain these elements. Deterioration of concrete bridges has reached a level which can result in loss to both human and business. It is estimated that it will cost $9.4 billion a year over the next twenty years to eliminate all bridges' deficiencies (ASCE, 2005). Concrete bridge beams and piers are deteriorated to many reasons which can result in loss to both human and business. Several new bridge management systems are introduced recently; to manage the repair and rehabilitation of nations deteriorated bridges. Among them is Pontis, which a network level bridge management System (BMS), which prioritize bridges or group of bridges for repair and rehabilitation funds. However, there is also a need of project based bridge management system to focus on repair of each element of the bridge. This system is called decision support system. This decision support system will assists the bridge engineers in their rehabilitation /repair of bridges.

In order to develop this decision support for concrete beams and piers, the study of causes, responsible for the deterioration of concrete bridge beams and piers is carried out. The inspection tools and techniques are discussed in order to identify the problems but it is observed that the traditional means of beams and piers inspection and also the repairs are not providing the actual assessment of the elements and thus occasionally

accelerate deterioration instead of decelerate. The bridge engineers take the decision about the repair and rehabilitation after having feed back from inspectors and inspection reports. This decision knowledge of bridge engineer is mostly based on his experience etc. The ultimate goal of this thesis is to establish a procedure and knowledge which will lead to the decision making process by the bridge engineer. The product of this research will be a decision support system for concrete bridge maintenance.

Delamination, cracking, corrosion, vehicle damage and scour are the common problems of concrete bridges, which were identified and thoroughly investigated in the literature. The research goals were achieved and summarized as follows:

- State of the art knowledge about the causes of various problems of corrosion, cracking, delamination, spalling, vehicle accident damage, and scour was prepared utilizing various books, departments of transportation manuals and journals.
- Repair and rehabilitation strategy were studied for the problems in consideration. A criterion for selection was set up after extensive study of various available repair material and methods.
- Decision trees or flow charts were built based on the knowledge obtained from the literature review for these problems and their repair methods.
- Rules were made from the flow charts for the proposed decision support system for bridge maintenance.

6.2 Conclusion

Pontis does not provide any information about the individual bridge because it is not a project level Bridge Management system (BMS). The proposed knowledge based

system, which is a project based project management system, can be used for individual elements of the bridge and will assist the bridge engineer in decision of repair and rehabilitation. There are several stages to develop a decision support system. In this thesis, a knowledge base is developed by comprehensive literature review for common problems of concrete bridge beams and piers. These common problems include delamination, cracking; spalling, corrosion, accident damage, and scour were studied in detail. Then the identification of these common problems was examined in the literature through various inspection methods and inspection tools. Various inspection forms and reports were studied in order to fully understand the nature of identified problem. It is noticed that these forms are very general which are really ineffective for the identification of the problem and needs to be restructure. Various repair methods were studied in order to fix the common problems in concrete beams and piers. Various repair methods along with their selection criteria were developed for the problems discussed earlier after literature review. Data from these tables was used to develop flow charts or tree diagrams for the proposed decision support system. Rules are then derived from these flow charts or tree diagrams for any Rule based decision support system such as EXSYS Professional. Therefore, database will be available for a proposed decision support system for concrete bridge maintenance.

The various contributions in this thesis are:

- Development of trees diagrams or flow charts for proposed decision support system for delamination, cracking, vehicle damage, and scour.
- Development of layout plane for decision support system for bridge maintenance.

- Development of the auxiliary inspection form, in order to extract more data for running of the propose decision support system.

6.3 Limitations

The limitations of the proposed decision support system will be as follows:

- Can suggest repair only for problems of concrete beam corrosion, cracking and delamination etc
- Should be used with specially made inspection forms as this needs specific data as input.

6.4 Recommendations

The recommendations for future research are as fallows;

- This study should be extended to cover all the bridge problems.
- The inspection process and procedures should be changed through out the DOT's utilizing advanced inspection techniques.
- The available inspection forms are too general and require being more specific. Some auxiliary forms need to be use along with the already used forms to run the proposed decision support system one such sample can be seen in chapter five.
- Cost should be included as a factor in the decision making process.
- From the flow charts, rules can be developed for all cases and a decision support system can be developed using different available shells, such as EXSYS professional.

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