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Decision Support System for Bridge Maintenance

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DECISION SUPPORT SYSTEM FOR BRIDGE MAINTENANCE

by

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Three main problems that deteriorate bridge decks are cracking, delamination and corrosion. Once concrete bridge deck is infected with any of the three problems, it becomes susceptible to more serious structural and architectural problems. Corrosion, cracking and delamination sometimes occur in tandem in concrete bridge decks, which makes the situation even more worse.

Pontis, which has been successfully employed by various department of transportation is basically a network level BMS which prioritize bridges or groups of bridges for repair and rehabilitation funds. In this scenario researchers and scholars agree that along side Pontis certain other project specific BMS (Expert systems or decision support systems) are the need of the hour. This research is about the development of an expert system for bridge decks that are deteriorated by corrosion, cracking and delamination. The final product is expected to alleviate some of the above-mentioned problems

TABLE OF CONTENTS

Table Of Contents- Continued

Table Of Contents- Continued

Table Of Contents- Continued

Table Of Contents- Continued

Table Of Contents- Continued

Table Of Contents- Continued

LIST OF TABLES

LIST OF FIGURES

List of Figures - Continued

CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

Transportation infrastructure has emerged as one of the main indicator of a nation's prosperity at the advent of the 21st century. Bridges are the key elements of the transportation system of a country. Their importance is further enhanced by their strategic locations throughout the infrastructure lay out. Bridges are expensive structures and therefore, it is utmost important to maintain and repair them on continuous basis. In this scenario the importance of bridge inspection and maintenance can only be ignored at one's own peril.

There are approximately six hundred thousand bridges in the United States (ASCE 2005). Almost one third of these bridges are reported to be in dilapidated conditions. Most of these bridges were built in the nineteenth and twentieth centuries. Experts believe that most of these bridges can either be termed as functionally or structurally obsolete. This has been shown by disastrous incidents of bridge failure during the past half century, beginning with the most notorious Mount Pleasant bridge failure in the late sixties.

Following the fateful events of the late sixties, the government of United States in general and the state governments in particular have taken greater pains to minimize the chances of such mishaps in the future.

Three main problems that deteriorate bridge decks are cracking, delamination and corrosion. Once concrete bridge deck is infected with any of the three problems, it becomes susceptible to more serious structural problems. Corrosion, cracking and delamination sometimes occur in tandem in concrete bridge decks, which makes the situation even more worse.

Inspection of concrete bridge deck is one of the most important component of any repair and rehabilitation project. The traditional way of repair and rehabilitation is that an inspection of a deteriorated deck is done by the inspector and the repair strategy is initiated by the bridge engineer based on the information collected from the inspection data. The Engineer goes about the repair strategy by his knowledge and experience. This system of bridge deck repair and rehabilitation is intrinsically flawed because of the involvement of human bias and decision factor. The introduction of Pontis and various other Bridge Management Systems (BMS) is an attempt to reduce this flaw.

Pontis, which has been successfully employed by various departments of transportations, is basically a network level Bridge Management System (BMS) that prioritize bridges or groups of bridges for repair and rehabilitation funds. Pontis can be customized as a project specific BMS, as most states do rank the individual elements of bridge deck for their severity. But Pontis is not known for being very valuable in project specific Bridge Management Systems (BMS).

Researchers and scholars agree that along side Pontis, certain other project specific Bridge Management Systems (BMS) are the need of the hour. Decision support system, which is one form of a project specific Bridge Management System (BMS) would complement Pontis on one hand and act as a double check for the bridge engineer in the decisions that he or she would take for the bridge rehabilitation and repair.

This research is about the development of a decision support system for bridge decks that are deteriorated by corrosion, cracking and delamination. The final product is expected to alleviate some of the above-mentioned problems.

1.2 Research Objectives

The objectives of the research are as follows.

- Study the various maintenance strategies for bridge decks currently in practice.
- Search the currently available literature about the most common concrete bridge deck problem focusing primarily on corrosion, cracking and delamination.
- Study the various repair and rehabilitation methods in practice.
- A summary of the repair and rehabilitation strategies should be developed both from the literature review and the feed back from the experts currently working in bridge deck repair and rehabilitation through a questioner circulated among them.
- Development of a theoretical model for bridge deck maintenance.
- The development of a decision support system that can assist bridge engineers in making decisions about repairs in bridge deck.

1.3 Research Methodology

This research is about the development of a decision support system. The research methodology can be broken down into the following phases.

- During the first phase of the research the problems associated with concrete bridge decks were studied.
- During the second phase available literature was searched for repair material, techniques and strategies for the concrete bridge deck problems discussed in the first phase.

- During the third phase literature about decision support system in general, inspection processes and current practices were studied and analyzed.
- During the fourth phase a questioner was developed from the available literature. The questions were concerned with the three problems and their methods.
- The data received from the experts was compared with the data that was taken from the literature. Effort was made to explain and reconcile the differences (if any) between the expert's solutions to the problem and the textbook solution.
- A theoretical model was made based on the combined knowledge taken from experts and literature.
- A decision support system was developed using an expert shell called "EXSYS Professional".

1.4 Research Layout

Chapter two discusses the maintenance process in general. Various categories and types of maintenance are discussed in general with particular emphasis on bridge decks. Various common problems with concrete bridge decks are also discussed in brief. The importance of preventive maintenance is outlined since it proves to be very beneficial in the long run.

The problems that are most common to concrete bridge decks are discussed in the third chapter. The problems of cracking, corrosion and delamination are discussed. Various types of cracks are discussed in detail. The phenomenon of corrosion is discussed in detail since this in itself is one of the main causes of delamination and to some extent of cracking.

The fourth chapter explains the various repair methods and strategies for the problems of cracking, delamination and corrosion. Various types of shallow, deep, protective and non-protective repair methods are discussed. The most important point in this chapter is that a specific criterion is outlined for the choice of each and every repair methods, which is necessary for the development of rules in the decision support System.

The fifth chapter of the thesis introduces the reader to decision support Systems. Decision support systems are defined and discussed. The characteristics of decision support Systems are explained with examples. Rule-based, case-based and hybrid decision support systems are discussed. The difference between backward chaining and forward chaining with in a decision support System is explained.

The sixth chapter is not much different than the previous one. This chapter explains the various tools that are available for the development of a decision support system.

The seventh chapter is about the Inspection of bridges. The current practice of inspection is discussed. The differences between project level and network level Bridge Management Systems (BMS) is discussed.

The eighth chapter discusses the development of the software by using EXSYS Professional.

CHAPTER TWO

CONCRETE BRIDGE DECK MAINTENANCE

2.1 Introduction

Infrastructure development has emerged as one of the most important need of the new millennium. Bridges are the key elements of road infrastructure to ensure efficient movement of people and goods. Bridges are one of the most important elements of our transportation system.

Road bridges are designed to provide services over long period, at least over a hundred years. However, the deterioration of road bridges due to ageing and increasingly bigger traffic and deteriorating environmental conditions leads to some serious problems such as:

1. Loss of comfort for the riders and eventually safety problems arises
2. In some cases, reduction of structural safety.
3. Risk of collapse and necessity for bridge closure.
4. Expenditure of large sums for repairs, which could be avoided if reasonable funds were devoted to maintenance.

Bridges are vital links in roadway networks as their failure may cause major public and private catastrophes. There are approximately six hundred thousand bridges on public highway system in the United States. (ASCE 2005). Most of these bridges are in deplorable conditions. It is generally stated that almost one third of these bridges are in a dire need of repair and rehabilitation. Bridges in Northern United States and Canada are more susceptible to deterioration because of their location. Continuous freeze and thaw actions coupled with chloride ingress from de-icing salts used during winter deteriorates the bridge decks. Many concrete structures that were expected to last for more than forty years are in dire need of major repair services after 5 to 10 years and some of them may be replaced after 15 years. The rapid deterioration of the decks has necessitated the introduction of a continuous maintenance plan that can minimize bridge deck problems. Some of the most common problems associated with bridge decks are as follows.

- Cracking
- Delamination
- Spalling
- Popouts
- Scaling

2.2 Maintenance

Maintenance is a process that retards deterioration by restoring or improving pavement performance to acceptable level of service. (Foo et al. 1995).

Maintenance is the work performed on an asset such as a road, building, utility or piece of equipment trying to preserve it in a useable condition and to realize its normal life expectancy. In general maintenance can be classified into the following categories: (MMS 2002)

a. Routine: ongoing maintenance activities, which are required because of continuing, use of the facilities.
b. Preventive: periodic adjustment and inspection to ensure continuing working condition.
c. Emergency: unexpected breakdowns of assets or equipment.

Routine and emergency maintenance are of fairly big importance but the way they are carried out is well known in advance.

Bridge maintenance can be defined as the work needed to preserve the intended load carrying capacity of the bridge and to ensure the continued safety of road users. It does not include any work leading to the refinement of the existing structure, whether by strengthening to carry heavier loads, by widening or by vertical realignment of the road surface. It also excludes any damage done by the laying of utility services.

Maintenance in general can be divided into two types on the basis of their functions. The two are as follows

2.2.1 Preventive Maintenance

Preventive maintenance can be defined as the work done on an asset to prevent deterioration of that asset. Whenever possible, the work is done promptly as soon as any incipient defects or conditions that may lead to defects, are detected. This is probably the best way to delay or even avoid the more expensive repair and rehabilitation work. Examples of preventive maintenance may be impregnation or sealing of concrete to reduce frost damage or reinforcement corrosion, waterproofing of the concrete when the inspection indicates that water is seeping through the structure.

It is a well known fact that as soon as the bridge is put into place and opened for traffic, deterioration starts. These deteriorations that develops are gradual and slow, and there is a general tendency on the part of the inspectors to ignore it momentarily. These distresses and deterioration that seems innocuous have the tendency to develop into big problems. Preventive maintenance is the correction of these problems.

Regular and effective preventive maintenance is the hallmark of any good management strategy. Preventive maintenance often is termed expensive in some countries. This shortsighted approach often leads to serious problems and some times major repairs or rehabilitation needs to be done, which are often more expensive than preventive strategy.

2.2.2 Corrective Maintenance

In corrective maintenance process, the deteriorations are identified and corrective actions are taken in accordance with the type and severity of the problems as well as cost effectiveness (Foo et al. 1995)

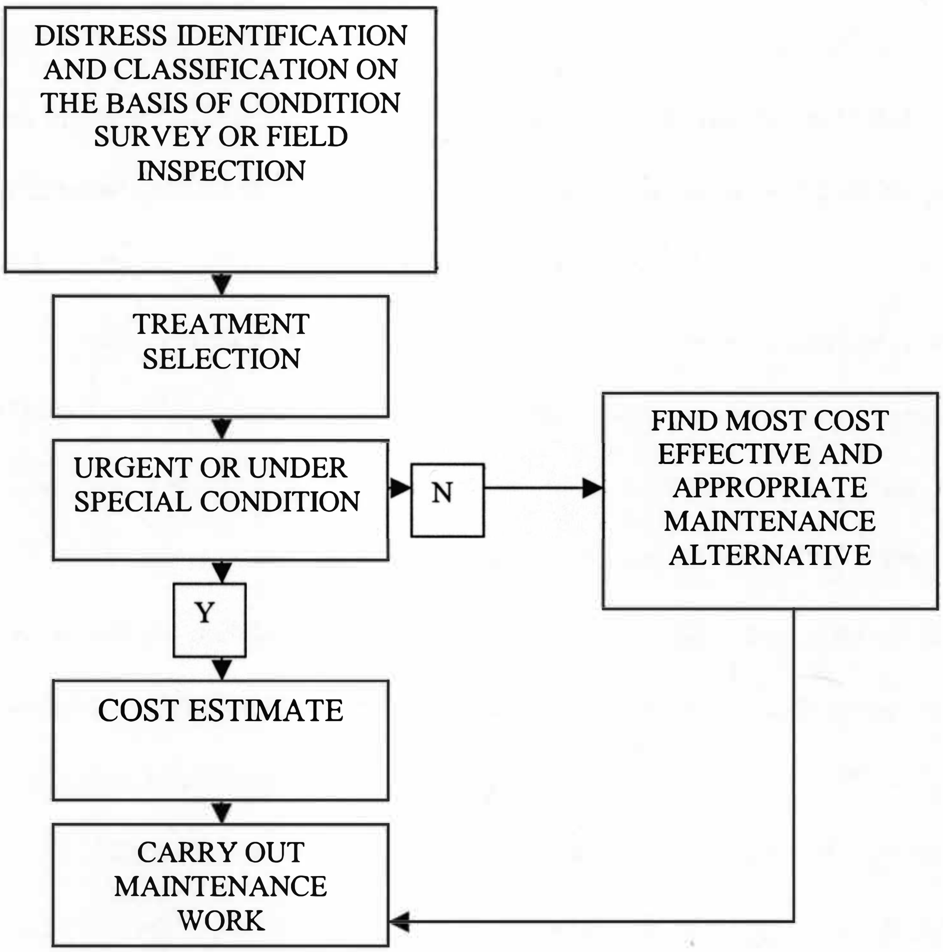

Figure 2.1: Essential Elements of a Corrective Maintenance Program

Figure 2.1 Outlines the essential elements of a good corrective maintenance program in a schematic way. The process begins by the identification of the problem. The problem or the distress is identified on the basis of either condition survey or field inspection. In the next step the most appropriate repair and rehabilitation strategy is selected. The repair method is selected after a close examination of the problem. For example if the crack isolated centerline crack, then no action is taken. Cracks that are more than 6 mm in width are repaired by sealing. Once the repair method is selected, the cost is estimated. At this stage it is decided that, whether the repair is needed urgently or under special conditions that only suits the repair method already selected. If the answer is yes then the already selected repair method is approved and repair work is carried out as planned. If the answer to this question is NO then the selected repair method is evaluated with other alternatives and the one that is most cost effective is selected.

2.3 Categories of Maintenance

Maintenance of any asset is a very vast field and it comprises of various activities. Bridge maintenance in general can be classified into the following categories.

2.3.1 Ordinary Maintenance

These are the general activities that are carried out on the bridge in order to keep it away from problems. These activities may include cleaning the bridge and drainage system, localized repair of surfacing, repair of traffic damages to parapets

2.3.2 Specialized Maintenance

This kind of repair mainly falls into two categories. Firstly, the work for which there is, from experience, a high expectation that it will become necessary during the life span of some bridges. Examples of this kind may be painting of steel work, localized patching of concrete, replacement of joints and bearings. Secondly, work that is unpredictable, such as correction of pile settlement.

Pavement maintenance involves field inspection, identifying existing problems, and selecting the most effective remedial measure to correct the deficiencies. Regular inspection and minor repairs prevent to reduce the occurrence of subsequent major problems (Foo et al. 1995).

Bridge maintenance activities are mostly more or less the same as mentioned above. Traditionally an Inspector is assigned to go and visit the bridge, which is reported to be in distress. The bridge Inspector uses his or her instincts and experience to assess the extent of the problem and give recommendations about its repair and rehabilitation. Lately there has been great improvement in the assessment of bridge deck conditions. Traditional means of finding distresses like chain drag and other methods are replaced by sophisticated equipments like Ground Penetrating Radar (GPR) and impact echo methods. The introduction of these new technologies has made the job of bridge inspectors fairly easy. Although these new inspection equipments are much accurate but their availability is still an issue. Moreover it also requires skilled workforce, which is not always available.

There is a possibility that the Inspector may overlook some details of the problem and thus may end up taking a wrong decision. Artificial intelligence, which is a branch of computer science, has the ability to develop programs and softwares that take data from the Expert and preserve it in a knowledge base. The program has the ability of processing this data through its inference mechanism. In other words once developed, these programs can act like a Bridge Inspector, taking data from the user and then reaching to a conclusion.

2.4 Chapter Summary

Chapter two began by outlining few common problems that are found in concrete bridge decks. This chapter mainly discussed maintenance. Various types and forms of maintenance were discussed. Corrective and preventive maintenance were explained. A general model about the maintenance strategy of a construction asset was discussed to give the reader an idea of the process of maintenance.

CHAPTER THREE

CONCRETE BRIDGE DECK PROBLEMS

3.1 Introduction

Concrete bridge decks are affected by a variety of problems. In this chapter three main problems with bridge decks are discussed in detail.

Cracking plagues new as well as old concrete. It is a very common problem. Several types of cracks can occur in a bridge deck, and the size of cracks may vary from micro cracks to wider full depth cracks. They may reduce structural strength and may allow chloride ions to infiltrate into the deck and begin the process of corrosion. Many steel-reinforced concrete bridges are subject to corrosion from chloride ions. Corrosion is a very serious problem in colder areas where the snowfall is heavy in winters. The third problem that will be discussed in this chapter is delamination. Delamination is the separation of concrete and steel layers from one another inside the bridge deck.

3.2 Concrete Problems

Generally concrete is considered to be very durable but there are problems that can deteriorate it to a very great extent. This material has been used for centuries. However, it is always exposed to deteriorating environment that weaken it strength and shortens its life expectancy.

Concrete deteriorates for many reasons, such as poor design, poor placement, chemical attack, snowplow damage, chloride ion intrusion resulting in corrosion, poor air entraining resulting in freeze-thaw damage, overloading and fatigue.

3.2.1 Cracking

Cracking is probably the most common problem associated with concrete, especially bridge decks. Cracks can vary from various sizes and shapes. Even the most minute and small cracks called "micro cracks " have the ability to develop with time, and ultimately result in more serious problems.

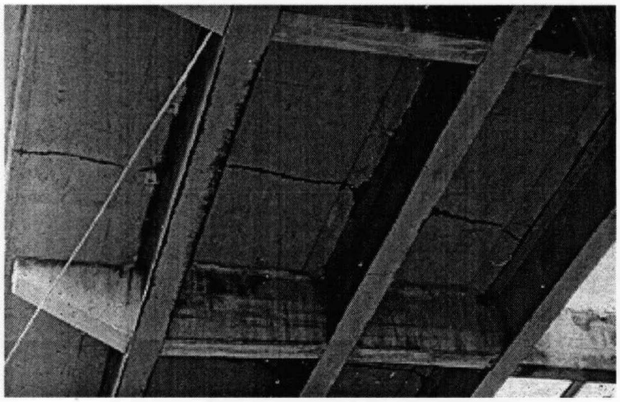

Figure 3.1: Cracked Deck

Figure 3.1 shows a deteriorated bridge deck. The deck shows a thick crack, which is uniform throughout the width of the deck.

Cracks in concrete occur when a restrained mass of concrete tends to change volume. (Saadeghvaziri 2002). Volume changes depend upon various factors like the constituent components, ambient temperature and humidity. Construction practices such as curing procedures, pouring sequences, and form type can also affect deck cracking. Cady et al. (1971), in their study of 249 bridge in Pennsylvania, have shown that the bridge decks constructed by certain contractors have more transverse deck cracking than other decks in the study and concluded that construction practices plays a major role in cracking of concrete bridge cracking.

Cracking can also occur in new concrete that has just been placed. Increased cracking in newly constructed concrete highway bridge decks has been reported in recent years. This is a concern since cracks can cause bar corrosion and concrete deterioration, resulting in decreased service life (khossorow et.al 1997).

Plastic shrinkage is the type of concrete shrinkage that occur if the rate of evaporation exceeds the rate at which water rises to the top of the surface. This type of shrinkage that can result in cracking, depends mostly on the ambient temperature and the temperature of the concrete itself. Wind speed and air humidity is also a factor in the increase or decrease of this kind of shrinkage cracks.

Fresh concrete has the tendency of subsidence during its finishing and bleed period. Although one of the secondary purpose of the horizontal steel provided is to resist this subsidence, but the down side of these is the development of cracking over and parallel to the rebar provided.

Curing is basically an endothermic reaction, which results in the release of heat of hydration. This initial temperature rise and tendency to expand do not induce residual compressive stresses in concrete because of its extremely low plastic modulus of elasticity (khossrow et.al 1997). The concrete when hardens and start to cool down reaches its ambient temperature. Longitudinal beams restrain the shrinkage and hence produce transverse cracking in the beams. This kind of cracking is called cracking produced by thermal shrinkage.

Drying shrinkage is the kind of shrinkage cracks that comes into effect after curing is complete. Basically the concrete due to the environmental effect releases the original water mix.

Autogenous shrinkage is the concrete shrinkage that occurs without even the loss of water. This kind of shrinkage occurs at low w/c ratios and significantly increases with the use of silica fume, high range water reducing admixtures and finer cement (Saadeghvaziri 2002).

The causes of cracking are more or less the same as of spalling, with the addition of drying shrinkage and structural distress. Under the effect of drying shrinkage, tension develops on the surface of the concrete as the volume of the concrete decreases as the concrete cures and water gets dissipated from the surface. These cracks may range from singular cracks to craze or map cracking in deep members.

3.2.2 Delamination

A Delaminated bridge deck is that which, when struck with a hammer or a steel rod, gives off a hollow sound, indicating the existence of a nearby laminated-fracture near the surface. The phenomenon of laminar separation in the concrete bridge deck is called Delamination.

Delamination is one of the most serious and wide spread problems that are usually associated with concrete bridge decks. Mostly this phenomenon is caused by poor bonding between the steel and concrete, excessive cracking which helps corrosive ions to infiltrate into the bridge decks. This problem is wide spread in areas where de-icing salt is used as a deicing method to keep the roads and bridges clear of snow and ice in winters. These harmful ions corrode the steel and make it to increase in the volume, which ultimately result in the breakage of the bond between the steel and concrete. The major cause of delamination is the expansion resulting from corrosion of reinforcing steel due to the intrusion of chloride ions. It occurs with either repeated chloride deicer application or continued exposure to marine environment. Inadequate cover over reinforcing steel will reduce the time to start of corrosion.

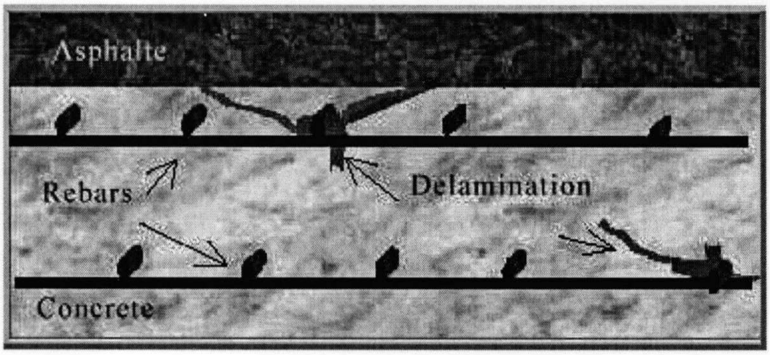

Figure 3.2: Delamination in Concrete Bridges

As we can see in the above figure 3.2, a concrete slab is covered with an asphalt coating. As the reinforcement steel corrodes, it expands and creates a crack or surface fracture plan in the concrete at, or just above the level of reinforcement. The fracture plan, or delamination, may be localized or may extend over a substantial area (Rhazi 2001).

Vehicular fires that may be ignited by accidents on the bridges or any other factor may also be the cause of delamination.

3.2.3 Corrosion

Corrosion is one of the major problems facing bridge engineers today. This can be illustrated by the fact that almost 40 percent of the steel produced each year is used to replace corroded metal (Emmons et al. 1997).

One of the basic purposes of providing cover over and under reinforcement is to protect the steel from detrimental environmental conditions. Concrete is highly alkaline which leads to a thin grey passive layer around the rebar. This thin film if broken by one reason or another leads to the corrosion, this may be caused by free chlorides at the reinforcement or by carbonation.

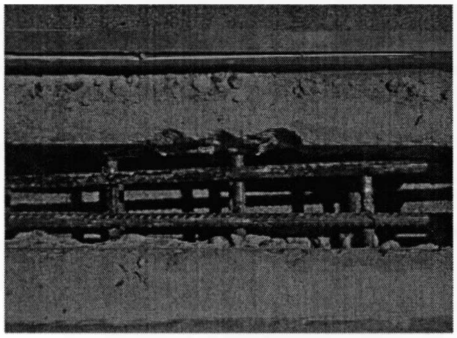

Figure 3.3: Corrosion in Concrete

Figure 3.3 shows a severely corroded bridge deck. The rebars are exposed and are corroded (Olek 1996)

Corrosion of iron is an electrochemical process, commonly known as half-cell reactions. Electrochemical oxidation takes place at anode and reduction takes place at the cathode. Iron is oxidized into ferrous ion at the anode. The ferrous ions are converted to 2Fe(OH)3 through a series of reactions and produce rust (Iyer et al. 2002).

Corrosion is basically an electro chemical process that results due to the breakage of passive layer. The non-corroding area becomes cathode and the area where the film is broken becomes the anode. This completes the circuit. It is the natural tendency of the metals in fluids that if two metals are connected by any conducting element, corrosion is going to take place in the metal with lower potential

Corrosion in steel is a very complex phenomenon, which involves a series of chemical reactions; the extent of the reactions may vary depending upon the environmental exposure as well as material characteristics. The general model or the sequence of events is as follows.

In general, the iron (Fe) atoms pass into solutions as positively charged (Fe+2) hydrated ions at the anodic side and the liberated electrons flow through the metal to cathodic sites, where dissolved oxygen is available to capture and consume them.

Concrete has a high PH environment. In this situation hydroxide (OH-) is abundant in the solution. Hydroxide ion may react with iron at the steel surface to create ferrous hydroxide [Fe(OH)2]. This can be termed as an anodic reaction. At the same time at an alternate location on the steel surface, dissolved oxygen(O2) reacts with water (H2O) and electrons released by the anodic reaction to form hydroxide (OH-). This is actually cathodic reaction. Together, the anodic and the cathodic reactions form a corrosion cell. Further the reaction of Fe(OH)2 with water and oxygen results in transformation to the insoluble corrosion product, specifically hydrated iron oxide compound in the solution, which accumulate in small pore spaces and interfacial zones around the steel. The iron oxide may be ferric oxide (Fe2O3) or magnetite or both. Many other ions exist in concrete pore solution and exact composition of steel varies.

One other form of corrosion may be termed as carbonation induced corrosion. It is a process in which carbon dioxide diffuses into the concrete from the air. Carbon dioxide dissolves into the pore water to form carbonic acid and also reacts with calcium hydroxide, to produce calcium carbonate. This kind of corrosion is not very common in the United States. This phenomenon increases with the age of the structure, especially in situation if the structure is exposed to environment containing high concentrations of carbon dioxide. Poor quality concrete with porous internal structure is more susceptible to the above-mentioned problem. Carbonation is a slow process in saturated concrete but increases strongly when the internal humidity increases up to 70 percent.

Another reasons of corrosion may be chloride. Chlorides can get into the concrete from mixing water, curing water, de-icing salt or surrounding soil. Chloride ions that diffuse into the concrete to the steel surface can disrupt the passive layer and induce corrosion, even in high PH environment. Chloride ions may reacts with iron compounds in the passive layer to create iron chloride complex. The iron chloride later on reacts with hydroxide ion within the surrounding concrete to form ferrous hydroxide (Fe(OH)2). The existing iron hydroxide continues the development of corrosion products and chloride gets released to further reacts with passive layers. There might be numerous corrosion cells present with in the concrete member at the same time. Localized corrosion has anode and cathode adjacent to one another with in the same metal surface. Corrosion in which anode and cathode reactions occur at the distant locations on the same or on different bars or metal elements that are electrically continuous. One of the forms of micro cell corrosion is called pitting. In this kind of corrosion, the corrosion starts as pitting in highly localized areas of great chloride concentration and/or inclusions in the steel surface or passive layer. Pitting continues until anodic areas are large enough to resemble or revert to general corrosion conditions.

The process of chloride-induced corrosion is influenced by many factors, such as moisture content, chloride content as well as chloride resistivity. For this kind of corrosion to occur in the concrete the chloride must reach the bar by breaching the passive layer. It has been noted that chloride displaces hydroxide in an ion exchange process at the steel concrete interface. The hydroxide is gradually removed by chloride thus causing localized reduction in solution PH.

3.3 Chapter Summary

Chapter three talked about the three main problems with bridge decks. The three problems i.e. Delamination, cracking and corrosion were discussed. Various forms and types of cracking were discussed. The phenomenon of corrosion was discussed in detail.

CHAPTER FOUR

REPAIR AND REHABILITATION STATERGIES

4.1 Introduction

Bridge deck repair and treatment is a very costly and major job to be done. Bridge maintenance should be done after carefully examining the problem, and selecting the best repair method and materials. Bridge inspection comes out to be a very important tool in carrying out the required bridge maintenance. Broadly speaking the bridge inspection should include more or less the following steps and stages.

1. Classification of the type of defect;
2. Evaluation of the risk of further deterioration
3. Determination of probable causes
4. Selection of suitable remedies and repairs.

In most cases the remedial work is carried out into two phases, first applying the temporary work and then applying the more definitive and the permanent treatment strategy. Monetary consideration is one of the pivotal criteria that need to be taken into account. Some of the most important factors that need to be looked into before committing into a repair and rehabilitation project are as follows.

- The nature, extent and severity of the defect;
- The danger which it constitute to the traffic and to the bridge surface itself
- The extent to which the repair operations will disrupt smooth traffic flow
- The financing means availability.

It should be kept in mind that temporary maintenance can only slow down the further deterioration, but will not eliminate the cause. Such repairs are generally less costly for the moment, but may prove to be more costly in the long run. Visual examination is normally considered enough to decide about such repair procedures.

The aim of definitive or permanent repair is to correct the cause of the defect. Although it is expensive at the onset, but the results are likely to be fully satisfactory, as long as they are on the correct assessment of the problem. It is generally advisable that visual inspection be supplemented by a more in depth study of the problem and their solution.

4.2 Objectives of Repair

In repairing a defected bridge deck, the primary objective is to restore the material to its original shape and conditions by using a material that will ensure structural integrity, durability and composite behavior. In addition to the above, the repair material should match the existing concrete in appearance and color. The choice of the material should not be at random and should satisfy some of the most important criteria set by experts. Some of the points that need to be kept in mind are as follows (Brinckerhoff 1993).

4.2.1 Strength and Durability

The material that is selected for the repair should be at least as strong as the existing material of construction. If this condition is not met, the durability of the repaired structure may go into question. Almost all of the repair materials used in the construction industry do meet this requirement.

4.2.2 Compatibility

Various important chemical and physical properties such as heat of hydration, modulus of elasticity, and the coefficient of thermal expansion should be compatible. It should also be made sure that the chemical properties of the repair material should not decrease the alkalinity of the existing structure.

4.2.3 Shrinkage

It should be made sure that the repair material that is selected for the job shall not shrink more than the expected or the anticipated amount. Extensive shrinkage may induce cracks in the repaired area. Shrinkage cracks at the interface of the old and new material signify week bond between the two of them. Most of the repair materials that are available do satisfy this condition.

4.2.4 Constructibility

Constructibity issue is often neglected because of complacency. It should be noted that some material get preference over other material just because of the environment or location. For example pneumatically applied concrete is ideal for the repair of the underside of the concrete beam, where the formed or trowelled concrete may be impossible to apply. Unless applied in a special way the cement based mortars may not be applied underwater.

4.2.5 Ease & Safety of Application

It should be kept in mind that certain materials are more difficult to apply than certain other materials. For example epoxy material are more sensitive to temperature and they have less pot life. This means that dealing with these materials necessitates the swiftness of operation. Some material might be intrinsically harmful. For example resin-based polymers needs special care when they are applied in close and confined areas because of their odor and low flash point.

4.2.6 Cost

This is one of the most important factors that are kept in mind before venturing upon any rehabilitation or repair strategy. Cost is very important because most of the time the decision to do or not to do the repair depend upon the availability of funds. The importance of cost factor is further illustrated by the fact that the choice between various alternatives is dependent upon their costs. For example regular cement based mortar cost less than the other non-shrinkage materials, and therefore might be preferred over epoxy mortars because of its reduced cost.

4.3 Typical Deck Repair Procedures

The repair of concrete bridge depends on the extent and depth of deterioration. The various deck repairs can be classified into three main categories (Brinckerhoff 1993).

4.3.1 Shallow Repair

Shallow repair is low budgeted repair, which is recommended when the depth of concrete repair is less than ¾ inches, and the rebars are not well exposed. In this method the deteriorated concrete is saw cut ¾ inches into regular shapes and is excavated either by pneumatic hammer or by hydrodemolition. The surface is cleaned and the repair material is applied and cured. When the repaired deck is to be overlayed later, the contractor may be given the option to fill the repair areas with overlay materials at the time of overlay.

4.3.2 Deep Repair

Deep repair is required when the deterioration has gone deeper than the top mat of the steel reinforcement. The deteriorated material is chipped off and removed. The reinforcing steel is exposed at least 1 inch from the concrete below it. The exposed bars are then thoroughly cleaned by sand blasting or hydrodemolaition. The reinforcing bars are also checked for any defects and are subsequently repaired. The repair material is poured once the bars are cleaned. A bonding agent may or may not be used in this process. It is not advisable to put in the bonding and repair material simultaneously. Since the repair is deeper there are chances that the variation in depth of the repair may induce shrinkage cracks along the periphery.

4.3.3 Total Deck Replacement

Deck replacement is treatment option with the highest initial cost and this should always be treated as a last resort. Both protective and non-protective treatments should be used to delay the bridge rehabilitation as long as possible. A bridge might have only localized delamination, corrosion and cracking. Therefore before going a head and doing this kind of repair process, due consideration must be given to all other available options. The below figure shows the deck replacement process in progress.

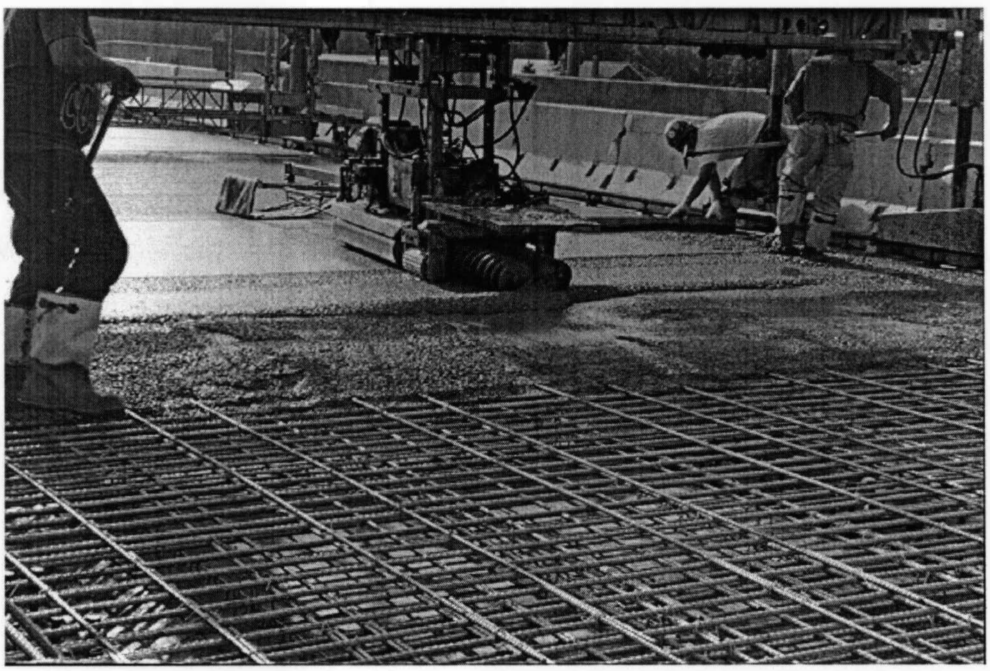

Figure 4.1: Total Deck Replacement

When the deterioration of the concrete is deep than half the depth f the slab itself, total deck replacement may be the better option. The deteriorated concrete is saw cut and removed, forms for the bottom surface of the deck slab are installed. The rest of the operation is more or less like that for deep repair.

Table: 4.1 Types Of Bridge Deck Repair Procedures

Depth of Deterioration	Repair Procedure in Practice
< than ¾ inches(19 mm)	Shallow Repair
> than the top mat of Rebars	Deep Repair
> than the half of slab's depth	Deck Replacement

4.4 Deck Treatment

Deck treatment is done if it is deemed necessary. Broadly speaking deck treatment can be broadly classified into three categories

4.4.1 Non-protective treatment

Non-protective treatment can also be termed as temporary treatment. Some of the most common of these temporary treatments are as follows.

Sealing

Sealing is a temporary remedy when

- There is cracking in the deck due to the slippage of the surface layers;
- There is cracking due to the movement of the thermal origin
- There are circular cracks due to the flattening of the blisters
- There is loosening of the surfacing at the concrete kerbs and joints.

Before applying the sealing coat, the cracks generally need to be widened and cleaned. Finally sealing is done with the product that has the following characteristics: good adhesive qualities especially with bituminous material, high elasticity so that it can extend without breaking and heat resistance.

Patching

Patching is generally considered as a temporary remedy when there is localized deformation, crazing or depression, and if there is cracking at the structural joints.

The damaged area is identified and the area is cleaned and excavated at 6-8 inches beyond the damaged area in all four directions. The opening is then filled out by placing the various layers having the same composition as those originally removed. The final layer should be fully compacted with due care, and it should be of bituminous material to ensure riding quality.

Patching can be done with cement based mortar or concrete. These are probably the most inexpensive materials used for this purpose. Cement based mortars are used for small size patching and concrete based mortars for comparatively bigger jobs. Depending on the requirement of the job various types of Portland cements can be used. Certain other admixtures can also be used fore special purposes. Such admixtures can be used to reduce the water cement ratio, to increase workability, to increase the strength or to accelerate the hardening of the concrete.

To prohibit the development of shrinkage cracks in the newly placed patching material, most engineers now prefer comparatively expansive materials in their concrete mixes. Prepackaged non-shrink quick setting mortars are such repair materials. These materials can provide along-lasting bond. Since these materials are comparatively expensive, they can be mixed with almost 50 % of their weight with pea gravel, with no marked reduction in their performance (Brinckerhoff 1993). Sika Top 122, Forsoc Patchroc are some of the commercially available material for this purpose.

Overlays

Maintenance of a deck that merely goes for an overlay without any water proofing membrane is called non-protective treatment. Non-water proofing overlay has the tendency to increase the life span of the structure. Under this treatment, the deck continues to deteriorate, resulting in even more structural defects. This new damage due to this kind of treatment tends to even increase the treatment later done to the deck.

Since this kind of treatment does not halt the deterioration, it should only be limited to temporary treatment. Asphalt overlays done like this is only good for keeping the deck in manageable situation until it can be replaced. For example patching of spalled areas with bituminous material is a kind of non-protective maintenance. This type of treatment will reduce the traffic impact loadings on the structure, however will almost do nothing to reduce or impede the ongoing deterioration in concrete. It is a general tendency of the concrete bridge deck to delaminate near the spalled area. This it can be said with surety that this kind of temporary repair tends to increased delamination, which is even a more serious problem than spalling. So it can be said that the asphalatic overlays are intrinsically porous and they, by themselves do not provide any effective seal. The porosity entraps salt-laden moisture, which in the absence of an effective deck sealer can even promote deck deterioration. In order to counteract this problem a multiple course penetration asphalt surface treatment, membrane or other deck sealers should always be applied prior to an asphaltic concrete overlay. One of the precautionary measures is to take a good look at the condition of concrete beneath the overlay. If the concrete below is deteriorated to a great extent, then all deteriorated and unsound material should be removed and replaced prior to the application of the overlay. This methodology may greatly help in minimizing the further deterioration of the concrete slab.

4.4.2 Protective treatment

Some of the protective treatments currently in practice are as follows

Protective Overlays

Asphalt overlays with waterproof membranes and concrete overlays are all protective treatment, extending deck services life. This kind of treatment though preferable has some down sides to it. For example repair material falling under this category are very sensitive to plastic deformation. So care should be taken not to use it on roadways and bridges that have very high traffic loads. Cracks that are narrower than 1/6 inch can be expected to be sealed and protected by overlays.

Protective overlays are much more expansive than non-protective overlays. One of the reasons for the application of this comparatively costly method of repair is that most of the bridge decks were constructed with out any protection against de-icing salts. Deck overlays serve the following purposes (Brinckerhoff 1993).

- It protects against the impact of heavy trucks and the further intrusion of de-icing salt, gasoline, acids, solvents and other contaminants.
- Prevents carbonations.
- Correct uneven surfaces due to wear and abrasion.
- Provide no-skid riding surfaces.

- Create a uniform appearance.

There are various kinds of overlays that are used by various departments of transportations. Some of the main types are as follows.

Latex Modified Concrete Overlay

After years of service, it's not unusual for Portland cement concrete (PCC) bridge decks to become permeable, allowing water and chloride ions from salt to penetrate. This can eventually cause corrosion in the deck's reinforcing steel. Aging decks also frequently suffer from poor skid resistance, poor ride quality, inadequate drainage, and deteriorated sections.

In many cases, highway agencies attempt to correct these problems by placing another layer of PCC on top of the original deck. Such overlays can add 30 years or more to the service life of a bridge, but the construction and curing time takes weeks, and sometimes even months. During that time, the bridge deck must be closed to traffic, which often is a major inconvenience to travelers and leads to increased congestion on other routes. And installing and maintaining concrete barriers and other traffic control and work zone safety measures is costly.

Latex modified concrete (LMC) has been used by various highway agencies to counter act public inconvenience and to provide an overlay that can seal the deck properly. Lately various department of transportations have been using very early strength (VES) latex modified PCC overlays to minimize public inconvenience. The bridge can be opened for public use after 8 hours of the overlay, which is very less as compared to conventional overlays.

LMC can be obtained by mixing cement mortar or concrete with styrene-butadiene latex. The mix that is obtained by this procedure is as successful as a concrete path or overlay.

The thickness normally specified for LMC by experts is 1-1/4 inches, but overlays as thick as 3 inches have been used in various cases. The shrinkage cracks are arrested by latex particles, forming an almost impermeable surface that successfully retards the intrusion of de-icing salts, acids, solvents, and other chemicals. To prepare the surface the thickness of 0.25 inches is scarified, cleaned with water and thoroughly wetted for one hour. The LMC should be mixed on site, in continuous mobile mixers. The placement temperature should range in between 45-85 degrees (Brinckerhoff 1993).

RSLMC (Rapid Set Latex Modified Concrete) is one of the commercially available materials for this purpose. This material is very fast setting and the bridge can be open for traffic in about 4 hours. The material is impervious to the various deteriorating agents and thus acts as a cover for the concrete against harmful agents. It is also economical because it can be installed at 25% to 35% cost savings over conventional concrete. The material is also one of the most low shrinkage materials available in the market.

Low-Slump Dense Concrete Overlay

Low-Slump Dense Concrete (LSDC) Overlay was developed by Iowa Department of Transportation. LSDC contains aggregates with maximum size of 0.5 inches with air entrainment additives. Silica is one of the major component of such a mix, which imparts hardness to the material. LSDC should be hard enough to stand surface wear.

LSDC is not known for its bonding abilities therefore they should be applied in conjunction with a bonding agent.

Bituminous Overlays

Lightly traveled and less salted bridges are repaired and rehabilitated by bituminous overlays. Once the surface spalls exceed a certain amount, it becomes evident that the corrosion in the steel has exceeded a certain acceptable extent. In this type of overlay the deteriorated parts are scarified and bituminous overlays are applied. Some times a coat of adhering materials is applied to ensure better bonding between the deck and the overlay. The bituminous concrete layer of 2-inch thickness is placed and rolled until the desired compaction is reached.

Fiber Reinforced Concrete Overlays

Fiber reinforced concrete is composed of conventional Portland cement containing discontinuous discrete fibers. Fibers are made from steel, plastic glass and other natural material. Steel fiber reinforced concrete (FRC) is widely used in bridge deck overlays lately because of the following reasons.

- High early strength
- High fatigue resistance
- Excellent crack control
- High durability

- Good bond development
- High strength and high toughness

SIFCON and SIMCON are the commercially available materials, which are made by infiltrating a high fiber volume fraction of discontinuous and continuous fiber mats.

Crack Repairs

Crack sealing also comes under protective treatment. Any sealant can be used from the wide variety of sealants available in the market. Extra care should be taken while selecting any sealant for cracks. The criterion is dependent upon the nature, location, and dimension of the crack as well as the importance of the structure. Some of the important points that must be kept in mind during the process of selection are as follows

- The compressive and shear strength must be adequate for the stresses applied to the material after the structure is open for use.
- The coeffient of thermal expansion of the resulting material should be similar to that of the original concrete to minimize stresses due to temperature.
- Low drying shrinkage is frequently necessary to minimize high bond line stresses between the patch material and the original concrete.

Some of the commercially available materials for this purpose are RESCON GEL ANCHOR and RESCON EPOXY BINDER LV. One of the advantages of using the latter is that it is a low modulus and low viscosity epoxy binder.

Cracks are one of the major causes of deterioration in concrete bridge decks. Concrete cracks are caused by many factors: shrinkage, improper placement or design problems, and uneven settlement. Some cracks may need extensive repair work than others. Crack that are formed by internal delamination and corrosion may need to dealt with completely different way than cracks due to shrinkage or due to excessive bending moments.

Cracks that can be termed as singular or cracks that have no regular pattern in shallow members can be treated by epoxy injection, flexible sealant, complete replacement, or encasement with reflective crack control. Cracks with a regular pattern or map cracking can be treated by either surface replacement or placement of bonded concrete.

Crack Repair with Epoxy Grouts

Cracks that range from 0.003 to 0.25 inches may be repaired with epoxy grouts. Epoxy grouts are used to fill up small cracks that are not very serious in their extent. Epoxy grouts, Epoxy resins and Polyester resins are some of the materials used.

Grouts basically consists of two or more chemicals that reacts to form a gel or foam as opposed to cement grouts that consists of suspension of solid particles in fluid.

The chemical reaction associated with epoxy and other chemical grouts causes the decrease in fluidity and tendency to solidify and fill voids in the bridge deck.

The advantage of this kind of repair material includes their use in moist environment, control of gelling time, and their application in very fine fractures and cracks. Some of the main disadvantages are high degree of skill needed, and the requirement that grouts should not dry out in service. Moreover some grouts are inflammable and therefore cannot be used in enclosed spaces (US Army Corps of Engineers 1995).

Grouting with Hydraulic Cement

This kind of grout material simply depends upon the hydration of Portland cement, Portland cement plus slag, or pozzolanas such as fly ash for strength gain. This kind of repair material and repair method may be used for the sealing of dormant cracks and to fill voids around and under concrete structures. Hydraulic cement has the tendency to disperse under pressure therefore it is not suited for 100% filling of the cracks. Practically the width of the crack the initiation point should be at least 0.25 inch for this material to be employed. These materials are generally less expensive than other types of grouts therefore; their use for large work is advisable.

Crack Repair with Resin by Gravity Feed

The topical application for crack repair uses a thin polymer resin to fill the cracks. In this method the resin settles by gravity, thus forming a polymer plug that seals out water, salt and other aggressive elements (Montani 2001).

Cracks can be repaired by gravity soak or gravity feed if they extend downward from a horizontal plane, are wider than 0.02 inches and deeper than 12 inches.

This kind of repair is mainly used for the cracks that are immovable by nature. Such cracks might be shrinkage cracks and settlement cracks. The basic objective of such repair is to reduce future deterioration caused by freeze-thaw action, corrosion and chemical and hazardous material attack on the reinforcing steel.

The second objective of such a repair method is the protection of the deck slab itself. Instead of gravity feeding each crack individually, the whole slab is flood coated with material so that it is sealed against any intrusion of harmful elements.

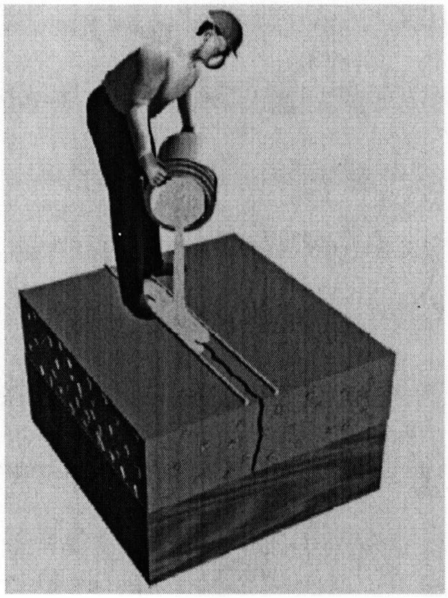

Figure 4.2: Gravity Feed with Resin

Gravity feed is not advisable for moving cracks. The materials are not known for acting as a flexible joint material. One of the main disadvantages of this kind of repair is that they cannot be viewed as a long-term repair method. The use of this method slows down the deterioration process but it certainly will not stop it indefinitely.

Crack and Spall Repair by Low Pressure Spraying

This method is very much similar to wet or dry shotcrete. The main difference is the velocity at which the material is pumped into the affected area. Due to the low pressure spraying of the material this method allows the spray nozzle to be much closer to the repair surface (Watson 2003). This makes it even more useful because it can reach very small and minute cracks and closed spaces.

Crack Repair by Injection

Cracks are also repaired by injection process. The material used for this purpose should have deep penetration of cracks, good chemical resistance, and excellent adhesive bonds and should confirm to ASTM-881 specifications.

Polymer are generally used for injection into the cracked deck having cracks as narrow as 0.05 mm. Epoxies are the most rigid systems used for structural repairs or "welding" of cracks to form a monolithic surface (US Army Corps of Engineers 1995). The technique for carrying out this repair method is to drill holes at close intervals along the crack, in some cases installing entry ports and injecting under pressure.

Various water repellent materials can be used to provide a chemically bonded protected barrier and long-term weather proofing protection. The material used should be good enough to resist the intrusion of salt and water, yet it should allow water vapors to pass through the treated surface. One of the market available products of this kind is SILANE 40%. One of the most common way of doing this is to have an overlay of 3 to 4 layers of resin and clean, dry, angular grained silica sand to provide a thick and relatively impermeable coating of material.

Sealers

This is another form of repair and rehabilitation. Sealers basically seal the surface of the concrete deck thus making it impervious. Some of the most widely used sealers are as follows. Sealers can be a very cost effective way to control cracking as well as excessive corrosion of uncoated reinforcing steel, steel with too little concrete cover, or steel embedded in concrete which exhibits hair line cracks. However, sealers are not considered as a cost effective way of inhibiting corrosion when applied to mature concrete of standard quality that utilizes other means of corrosion protection, such as epoxy coated, specialty overlays, etc. Also, care should be taken not to provide sealers below water line because these provide almost no protection when provided under submerged conditions.

There are two major types of sealers, which are coating and penetrating. Penetrating sealers are more preferable because they are better in blocking the ingress of water and chlorides. Moreover they are less expensive than coating sealers. Penetrating sealers has the ability of betting into the cracks and precipitating down to the reinforcement. They form bonds deep down which halts the ingress of various deteriorating agents. Coating sealers is normally applied when a good appearance is also the objective of the repair. These kinds of sealers are normally not used for heavy traffic areas because they can be easily abraded away by the heavy traffic.

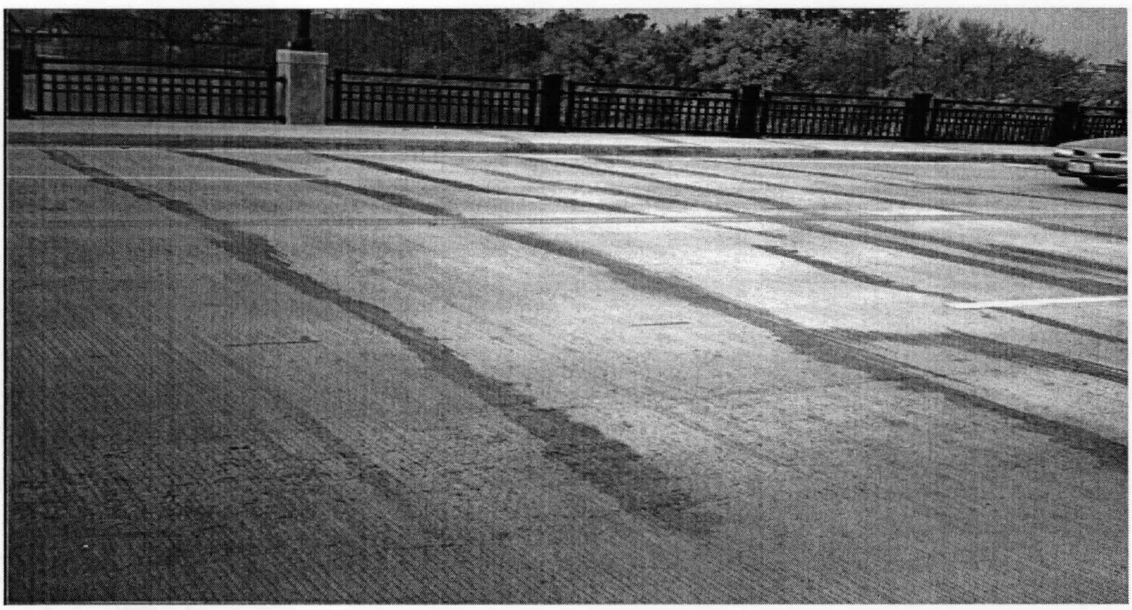

Figure 4.3: A Cracked Deck Sealed

The above figure shows a bridge deck, which has been sealed for cracks.

Epoxy Seals

Epoxy sealers are the most widely used materials for sealing of the deteriorated as well as repaired concrete bridge decks. They are very effective in preventing the penetration of the chemicals. The use of this method is generally discouraged in cases where encapsulated concrete may be exposed to freeze and thaw. This is because, the epoxy seals are completely waterproof, which in turn may trap moisture.

Penetrating Sealers

These sealers seal the concrete by penetrating it. These sealers known as silicon resins, polysiloxanes, silanes and stearates come in liquid form. The solvent or liquid part of the material acts as a transporter. Once the material is transported to the required area, the liquid part of the material vaporizes. Ideally the material has the ability of reaching the depth of ¼ inches (Brinckerhoff 1993).

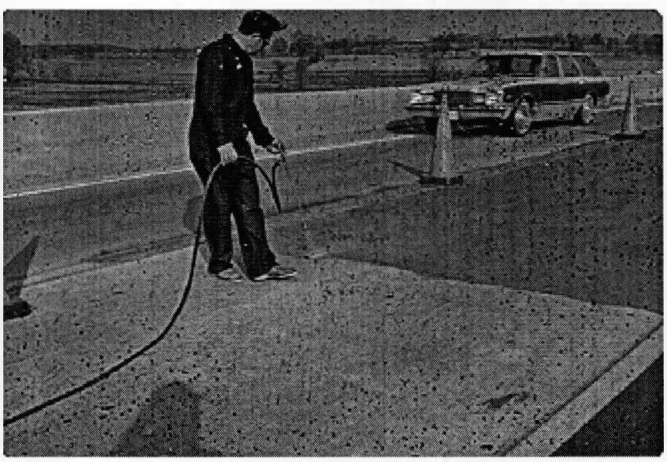

Figure 4.4: Deck Sealing

The above figure shows bridge deck sealing in progress. The most effective sealers known is silane, which forms a strong chemical bond with concrete. It nearly meets all the requirement of good sealers. Some of the distinguishing qualities of silanes are as follows.

- Resistant to alkalines and chlorides.
- Tack free finished surfaces.
- It does not trap up moisture
- Strongly resistant to water.

If the vehicular traffic is low and concrete wear of the surface is expected the be minimum, this repair method may be deemed preferable to more expensive overlays. However the use of these kind sealants is strongly discouraged if the wear and abrasion can be expected to be more than the thickness of the sealants itself.

Epoxy Resins

Almost all of the above problems can be alleviated by a variety of Epoxy Resin compounds. Basically these compounds consist of two liquid components. One component is the resin itself while the other component is the hardening agent. Both of these materials are non reactive separately. They are mixed based on the recommendations of the manufacturers. Some of the most common uses of this group of materials are;

- Protective Overlays
- Water proofing
- Patching compound
- Crack and joint sealers

- Adhesive material for bond development
- Grouting agent

The inclusion of latex in concrete may also be used to reduce the w/c ratio and with this development the long-term properties of hardened latex concrete will be similar to conventional concrete with the same cement content. However the chloride ion ingress into the latex modified concrete will be reduced.

Methyl methacrylate polymer has almost the same properties as any other Epoxy resin. The monomer can penetrate dried in-place concrete and strengthen it after polymerization.

4.5 Chapter Summary

This chapter discussed the various repair methods and materials available for bridge deck problems. Various repair methods and materials were discussed with their relative advantages and disadvantages. The literature review about these methods and materials can be summarized in the below table.

Table 4.2 Summary of Repair Methods and their Relative Advantages and Disadvantages

Repair Method	Condition to Use	Advantages/ Disadvantages
Do Nothing	When repair is not needed. When funds are not available to carry out the repair and the bridge has deteriorated to such an extent that repair needs to be done.	A- since replacement is necessary, money is not wasted in useless repairs. D- The bridge remains to be inconvenience for public until it is replaced
Replacement	When the deterioration is beyond rehabilitation.	A- Money is not wasted on useless repairs
Non- Protective Sealing (bitumen, cement based mortar, concrete	When the deterioration depth ¾". When cracks are due to the slippage of surface area, movement of thermal origin or flattening of blisters. When there is loosening of the surfacing at the concrete kerbs and joints.	A-It is a good alternative to the more expensive protective sealing. D- Non- protective sealing is not completely waterproof. It may be a temporary remedy to the problem but it may further deteriorate the problem.
Non –Protective Patching (bitumen, cement based mortar, concrete)	When deterioration depth < ¾". When there is localized deformation, crazing or depression. When there is cracking at the structural joints.	A-It is a good alternative to the more expensive protective patching. D- Non- protective patching is not completely waterproof. It may be a temporary remedy to the problem but it may further deteriorate the problem
Non-Protective Overlay	When funds are not available to have protected overlay. When the bridge is to be replaced later on. When architectural appearance is desired.	A-It increases the life span of the structure. A- It keeps the deck in a manageable situation until it is replaced. A- less expensive than other type D- deck continues to deteriorate.
Protective LMC Overlay	When protective overlay is required. When is immediate reopening of the bridge is a priority.	A-It enhances the life span of the bridge deck. A- the curing time is very less. D- It is not advisable to use this material in a heavy traffic bridge because of its sensitivity to plastic deformation.
Protective LSDC Overlay	When protective repair is required. It is not known for its bonding qualities therefore it should be used in conjunction with other bonding agents.	A- This kind of overlay is very hard and therefore and stands surface wear. D- It is not known for its bonding abilities therefore it should be applied in conjunction with a bonding agent.
Protective FRC Overlay	When protective repair is required. When high early strength is required. When high fatigue resistance is required. When high durability is required.	A- High early strength, high fatigue resistance, excellent crack control, high durability. D- Expensive than LMC overlays.

Epoxy Grouting (Epoxy Resins, Polyester Resins)	Cracks that range from 0.003-0.25in When work is not in a confined space	A- They can used in moist situations. A-It can be applied in very fine fractures and cracks. D- Skilled labor is required. D- Grout should not dry in service. D- These grouts are inflammable.
Hydraulic Cement Grouting (Portland cement plus slag or pozzolonas)	When the crack width ≥ 0.25 in When the cracks are dormant. To fill voids under or around concrete structures. It is used for large works because is less expensive.	A- Since it is less expensive than other grouts, their use of large works is advisable. D- It has the tendency to disperse under pressure. D- Only can be employed in cracks that have the width of at least 0.25 inches.
Gravity Feed Resin (Epoxy or polymer resin)	When the crack width > 0.02 in When crack depth > 12 in. When there are shrinkage or settlement cracks.	A- It has the ability to seal deep cracks. A- Best to be used for shrinkage and settlement cracks. D- Chances of wastage of the material are high.
Polymer Injection	When crack width ≤ 0.05 in	A- It can used for very small and minute cracks.
Low Pressure polymer spraying	When the cracks size is very small and minute	A- It can used for very small and minute cracks.
Penetrating and coating sealers	When the rebars used in the structure are plain When the rebars are not specialty bars Should never be provided under submerged or excessively moist conditions. When protection and appearance is the objective at the same time.	A- Effective mechanism to control cracks. A- Effective in the treatment of excessively corroded decks. D- It cannot be provided below water line. D- Not useful to be used on deck that has Epoxy coated or any other specialty bars in the deck.

CHAPTER FIVE

DECISION SUPPORT SYSTEM FOR BRIDGE MAINTENANCE

5.1 Introduction

Decision Support systems, or knowledge-based systems are receiving greater attention from building industry to aid in decision-making process in areas such as diagnostics, design repair and rehabilitation. Although decision support systems, a segment of artificial intelligence, has been in existence since 1970's, the construction has been slow in utilizing this technology to solve real world problems (Kaetzel et al. 1991). Experts believe that several reasons for this slow acceptance are

- User attitude
- Constraints in acquiring knowledge about a subject
- Lack of ease to use development tools

The expert functions can be defined as software imitating intelligence in solving tasks on the basis of data and knowledge stored in computer memory (Bien, 1999). Decision support systems are not an alternative to bridge inspectors, in fact it is a support system to the bridge inspectors. It is merely to check, confirm and authenticate the decision made by inspectors.

Knowledge based systems or expert systems can be used to model human reasoning and decision-making process. Fully developed systems are capable of accepting facts from the users, processing these facts, and delivering solutions that are close to the solutions that would have been offered by human experts (Foo et al. 1995).

A successful decision support system is the one that mimic the way an expert would apply his problem solving abilities in making recommendations of drawing a conclusion, with degree of accuracy (Kaetzel et al. 1995). One of the main differences between decision support systems and ordinary computer programs is that the former is equipped with an inference engine. In other words a decision support system can almost think like a human being and give its recommendations.

Different authors have defined decision support systems differently. 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). Although this definition seems to be a little exaggerated but it still recognizes two important components of a decision support system i.e. a knowledge base and an inference engine.

According to another author a decision support system consists of a knowledge base which represents acquired knowledge in a certain format, an inference engine which make inferences based on knowledge base, and a user interface which interacts with user and presents inference results (Miyamotto 1997).

A decision support system is a computer program designed to simulate the problem-solving behavior of a human who is an expert in a narrow domain or discipline. A decision support system is normally composed of a knowledge base, inference engine, and the end user interface.

5.2 Characteristics of a Decision Support System

A decision support system resembles a computer program in many ways yet it has some of its specific characteristics that differentiates it from conventional computer programs

- The expertise and knowledge used to solve engineering problems can be represented by symbolic terms rather then numerical or explanatory terms.
- The knowledge represented is transparent and the process that is used to represent that knowledge is also transparent. Transparency means that the implementation language does not make the knowledge obscure.
- Decision support systems use the tacit knowledge or compiled knowledge or heuristics. Heuristics is the study or knowledge of procedures that are incapable of proof.

Programs that have one or all of the above characteristics can be called decision support in general terms.

5.3 Architecture of a Decision Support System

The architecture of a decision support system is explained by the following figure (Maher 1984). The knowledge is acquired from the expert and stored in the knowledge base. The inference mechanism controls the functions with in the expert system. Context is a smaller knowledge base, which is initially empty but is quickly populated by the inference engine using the knowledge base once the expert system starts its function.

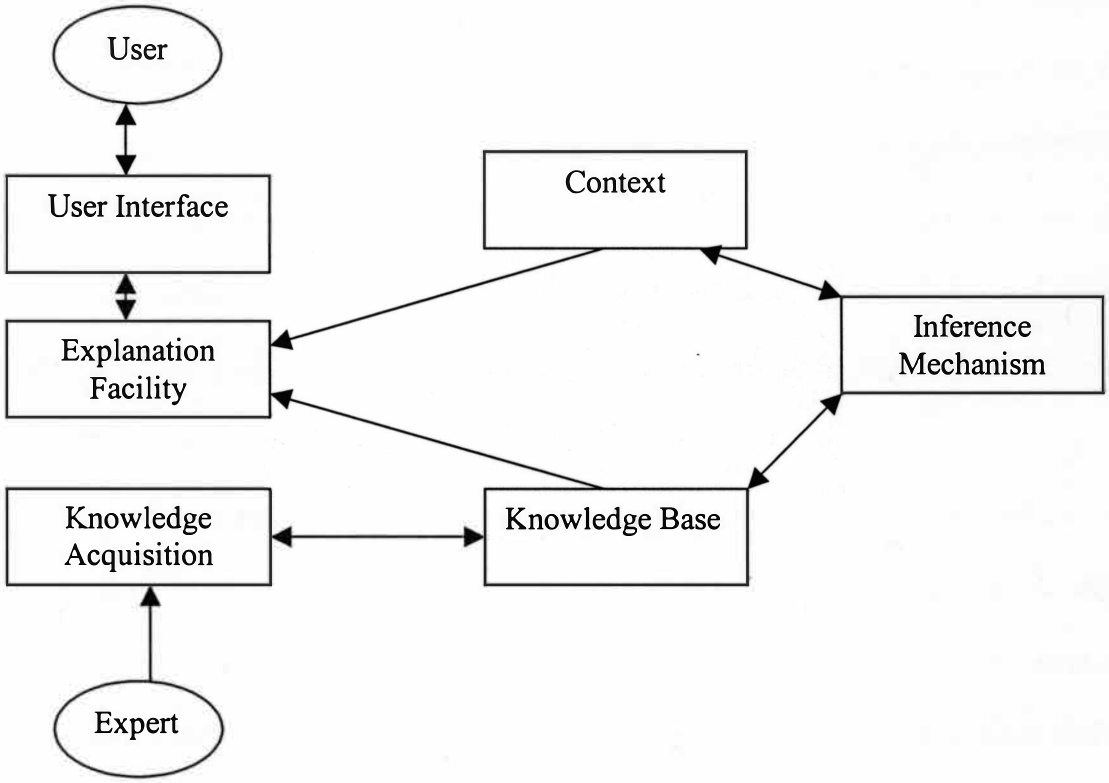

Figure 5.1: Architecture of a Rule Based Decision Support System

Decision support system can be broadly classified into three main components. However, there are a few more components of a decision support system, which get used to make the decision support system more users friendly and elaborate.

5.3.1 Knowledge Base

Knowledge base can be called as the heart of a decision support system. It is that part of a decision support system that contains facts and information about the problem on hand. It also contains the heuristics associated with the domain in the decision support system is applied. The facts are represented as declarative knowledge and the heuristics takes the form of the rules.

The knowledge base of the decision support system is normally composed of factual and heuristic knowledge. Factual knowledge is the knowledge that can be found in books, journals, and literature. It is the knowledge that is endorsed and agreed upon by most of the knowledgeable people in a particular field. Heuristic knowledge on the other hand is less rigorous, more experiential, more judgmental knowledge of performance. This kind of knowledge is practically opposite to the factual knowledge because it is mostly concerned to the individual having it. "It is the knowledge of good practice, good judgment, and plausible reasoning in the field. It is the knowledge that underlies the art of good reasoning (Engelmore 1993).

For example, the knowledge base about structural design would contain facts about an object. One example of the fact, or object is the beam. A beam could be represented in the knowledge base as structural component with characteristics and attributes including length, depth, loads etc. The rules that are related to the design of this structural member are based on heuristics, experience and functional relationship. For example, if the length of the beam is more than 40 feet the material that could be used is steel. In case of slabs if the length to width ratio is less than 1.5 then the slab is a two-way slab. The knowledge base should be very clear transparent and easy to modify. Engineering is basically a very mercurial field therefore, the knowledge base should be transparent so that it can be updated to cope with changing situations.

5.3.2 Context

The context is the part of the decision support system that contains the knowledge about the problem currently being solved. In the beginning, the context contains the information that defines the parameters of the problem but as the decision support system reasons about the given problem, the context expands and contains the information generated about the decision support system to solve it. For example, a context in a decision support system to select the appropriate liner for hazardous waste site initially contains information about the site and nature of the waste to be stored. The context would expand as the problem solving process progresses to include information about potential liners for the given site and certainty factor associated with each liner reflecting relative appropriateness. The context is basically a declarative form of the current state of problem the decision support system is solving.

5.3.3 Inference Mechanism

Inference mechanism is that part that contains the control information. The context is modified and expanded by the inference mechanism.

For example, if the desired out come is to find out the best welding technology among various alternatives. In this case the potential technologies are checked individually, using input data to verify the validity of the technologies been considered. Strictly speaking this approach is called backward chaining; the possible solutions are tried using the given data to determine which solution is the best.

5.3.4 Explanation Facility

The explanation facility within a decision support system shows how elaborate an decision support is. It varies from trace of execution to the ability to respond to questions about the reasoning process used to develop a solution.

Knowledge in many cases is incomplete and vague. This vagueness is reinforced by the inclusion of heuristics that are necessarily not credible. It is human nature that if the answer to the question is insufficient or unconvincing we tend to stress on explanation, if the explanation or logic is plausible and convincing we tend to believe in the out come. The same is true for an expert system; therefore, explanation facility is an integral part of any good decision support system.

For example if a decision support system is develop to diagnose problem s with pumps the user may ask the expert system "why do we need to know the type of pump?" The decision support system may reply by explaining the current state of the reasoning process that indicates that the information is necessary. Another type of explanation might be the one that explains how a solution was determined. For example the user may ask," how do you know that the motor is malfunctioning?" and the decision support system will provide the decision made to reach that conclusion.

5.3.5 Knowledge Acquisition Facility

This is an additional facility that helps in entering knowledge into the knowledge base or more generally the database. This facility more or less acts as an editor, and the knowledge is entered in the form that is in consonance with the software in which the decision support system is implemented.

5.3.6 User Interface

The user interface in the case of a decision support system goes beyond the traditional definition of the user interface of computer programs. A part from being highly interactive, perhaps with 'HELP' facilities, a decision support system's user interface needs the transparency of dialogue, whereby some form of an explanation facility indicates the inference, or reasoning, process used.

The most beneficial use of the decision support systems in construction industry is probably in diagnostic, repair and rehabilitation. It helps engineers and inspectors in identifying the distress, finding out the cause and recommending the solutions. The importance of decision support systems is increasing because of cuts in highway budgets and increasing emphasis on maintenance, dearth of professional and experienced inspectors, and advances in data gathering methods. Knowledge base should be kept as small as possible because the smaller the knowledge base, the lesser would be the number of rules and the easier would be to change and modify the knowledge base and the rules. Smaller database or knowledge base is typical of the decision support systems used by the construction industry. Visual knowledge such as graphics, diagrams and drawings are increasingly used by decision support system. This new introduction has two-pronged effect on the decision support systems developed lately. Firstly, it enhances the attraction of the decision support system and makes it more users friendly to use. Secondly, and most importantly it can reduce the interaction between end user and the decision support system by eliminating certain unnecessary questions.

5.4 Types of Decision Support Systems

Basically decision support systems can be divided into two types namely object based and rule based decision support systems.

5.4.1 Rule Based Decision Support System

The majority of decision support systems that are being produced recently are rule-based. These kinds of decision support systems have gained popularity because they are easy to use and modify. The kind of decision support system that is based on rules is called rule-based expert system. Rules represent IF condition 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)

If freeze thaw conditions are anticipated and

The normal size of the aggregate is 3/8 in

Then The percentage of entrained air should be 7.5

These kinds of decision support systems are basically in a question and answer format. The user enters the answers to the questions asked by the computer. The software uses its own inference engine to give meaning to the information and select an answer.

In order to find the best answer or solution the computer will either employ a back ward or forward chaining procedure. In the forward chaining procedure the computer uses information provided by the user, treats them like established facts and attempts to reach the goal by evaluating conditions that relate to the facts. A system uses forward – chaining strategy if it is working from an initial state of known facts to a goal state. Bottom-up, data driven, and antecedent-driven are terms equivalent to forward chaining. This kind of strategy is most beneficial when there are a lot of solutions and very few input data. Some time it may become cumbersome because it may be wasteful to require as input data all the possible facts for all conditions; sometime this is either not possible or feasible. Since forward chaining is driven or triggered by facts, it is known as goal driven. In the forward chaining inference procedure, there may be several solution sets of rules possible in reaching the goal. The consequence of one being true may infer that another rule is true (Kaetzel et al. 1991).

Back ward chaining procedure is intrinsically different from forward chaining procedure in many respects. A system is said to be using back ward chaining procedure if it assumes a goal or hypothesis and reasons and inquire back to known data or facts to support or discount the assumed hypothesis. Top-down, goal-driven, and hypothesis –

driven are the names that can be used for the backward chaining procedure. If the known facts do not hold the hypothesis true, then the preconditions that are needed for the hypothesis are set up as sub-goals. This check and balance procedure continues until the original hypothesis is either completely rejected or accepted with the help of the known facts. If the case is negative then the system may pursue the validity of other hypothesis. For example, for the floor system design problem, a backward chaining-chaining strategy assumes an alternative two dimensional horizontal system and determines whether it is appropriate for the current situation or not.

5.4.2 Object Based Decision Support System

This is a much more logical way of building a decision support system. In this system the knowledge is grouped in a way an expert normally think about knowledge. Objects are identified by classes and instances. Below is a figure that shows the basic architecture of an object-based decision support system.

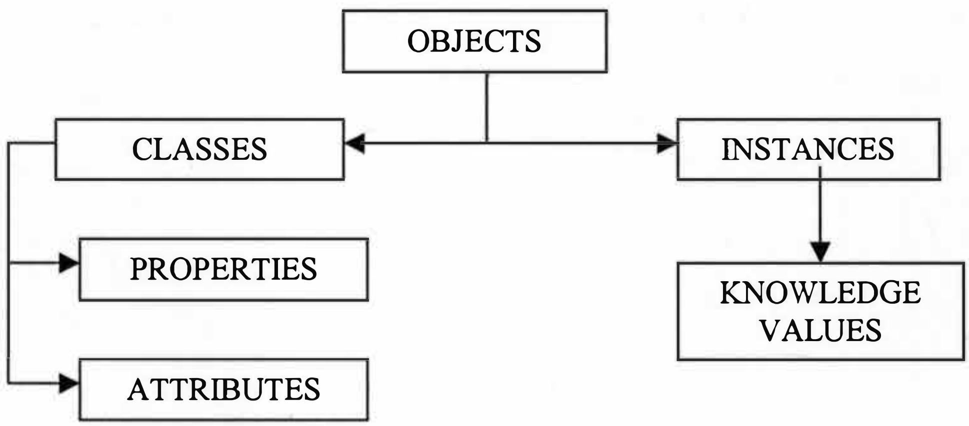

Figure 5.2: Object Base Decision Support System

As evident from the above flow chart, the class component represents objects properties and attributes. The instances represent the knowledge value. For example, a class called distress may be established, this class may be further divided into subclasses for material related distresses and in-service related distresses (Kaetzel et al.1991).

Expert systems have been successfully applied to the design of structural elements and structures. For example an expert system has been developed in India by the name of TALLEX, which is developed in for tall buildings. This expert system has been validated for tall building around the world.

Another type of expert system that is used extensively for the identification of distresses, and suggestion for their repair. This expert system serves the purpose of assisting building engineers and inspectors to modify and renovate buildings. Below is given a structural framework established for diagnosis and suggestion for repair method for cracking in brick masonry (Krishnamoorthy, 2000).

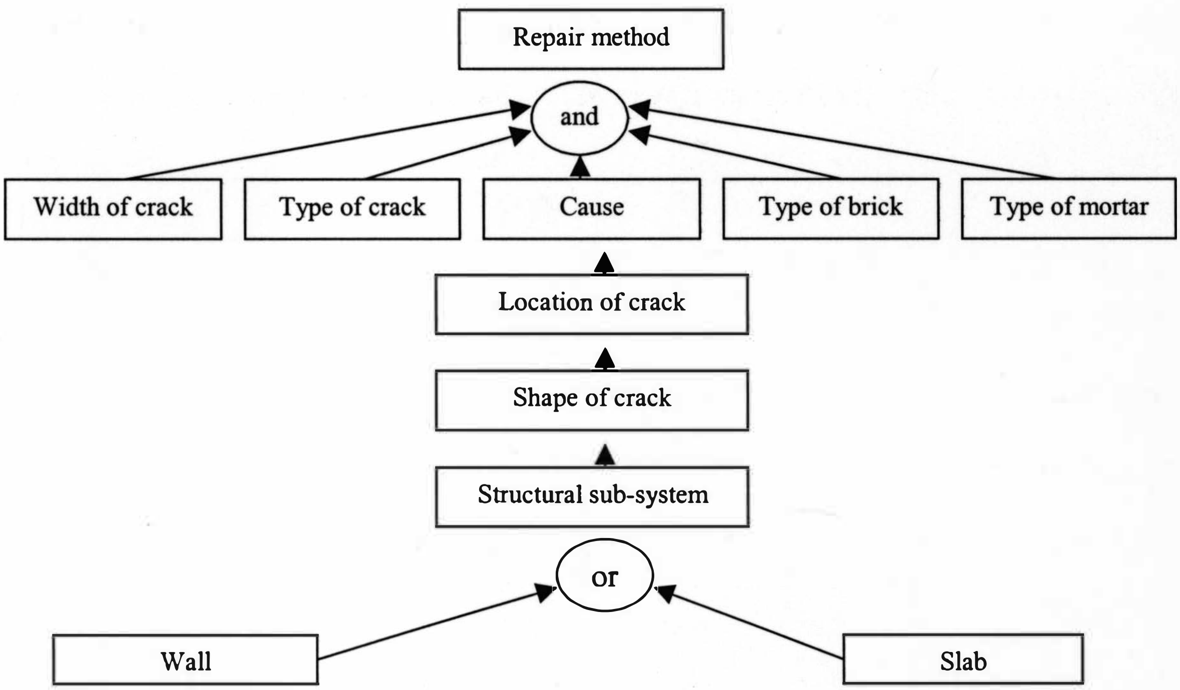

Figure 5.3: Block Diagram for Repair Methods for Cracking in Brick Masonry

Apart from the rule based and object based decision support systems, there is another type of decision support system that blends the characteristics of both rule based and case based decision support systems. This type of decision support system is called hybrid-type decision support system.

5.5 Chapter Summary

This chapter familiarized the reader with decision support systems in general. Different types of decision support systems were discussed with their relative advantages and disadvantages. The architecture of a decision support system was explained with the explanation of its various components. The soft ware that will be used in the development of this decision support system is EXSYS Professional, which is a rule-based decision support system developmental shell. This software has the ability to use both forward and backward chaining mechanisms.

CHAPTER SIX

TOOLS FOR BUILDING DECISION SUPPORT SYSTEMS

6.1 Introduction

The development of a decision support system can be accomplished in various ways. Artificial intelligence, which is a branch of computer science, has made galloping strides in the past few decades. Unlike the early eighties and nineties, various tools have been developed to develop decision support systems. This chapter discusses the various tools that are available to develop decision support systems.

Decision support systems are developed using various tools that are available to us. Broadly speaking the available tools for building decision support systems can be classified into the following three categories.

6.2 General Purpose Programming Languages

This is probably the most time consuming method of developing decision support system. Practically the decision support system is made from scratch by using general purpose programming languages. Computer languages like Lisp, Fortran, Pascal and Prolog can be used for the development of such a system. Lisp is the most widely used language in the United States for this purpose because of the fact that Lisp is oriented towards symbolic computation; the programmer can code terms like "slabs" and "beams ". The Lisp program has the ability to manipulate these symbols and their relationships. Most Lisp systems can be interpreted and therefore has the ability to provide an interactive environment for the development of Lisp codes. The development of a decision support system is greatly augmented by the interactive environment provided by Lisp. The most commonly available dialects of Lisp are Maclisp and

Interlisp. Most of the time the choice between the two kinds of dialects is based upon availability rather than technical superiority.

6.3 General Purpose Representation Languages

These languages are specifically developed for knowledge management. These languages are helpful in the development of decision support system and knowledge based software. They are intrinsically preferable over the conventional languages because of the fact that they make the job of program developer very easy.

ROSIE is a rule based representation language. Rules may be entered in plain English-like syntax. The inference mechanism transfers these rules into the computer language and interprets them either sequentially or the user may specify an execution order. This execution order may be cyclic. A cyclic execution order is similar to the typical production system control, where the execution of a rule is triggered by conditions in the database (Maher 1984).

OPS5 is another rule based representation language designed for decision support systems. The knowledge base is termed as production memory and consists of production rules. Working memory is the name used for context and it contains elements with associated attribute-value pairs (Vianu 1996). Over the years OPS5 has become popular among decision support system developers. OPS5 stores data in working memory, and If-Then rules in production memory. Rules in OPS5 are completely independent of one another. They can be placed in production memory in any order. If the data in working memory match the conditions of a rule in production memory, the rule's actions take place. Possible actions include modifying the contents of working memory (which might then match the conditions of another rule), reading information from a file, displaying information on the screen, and calling external programs. In some versions of the language, a rule's actions can cause a new rule to be created, allowing the development of systems that learn.

OPS5's built-in inference mechanism, forward chaining, starts from a set of data in working memory and causes a sequence of rules to be applied until a goal is satisfied. The other prominent decision support system inferencing procedure is backward chaining, in which a goal to be achieved causes sub goals to be satisfied until a problem solution is found. Backward chaining can be implemented in OPS5 with some work.

6.4 Expert System Shells

A decision support system shell is simply an inference engine with an empty knowledge base. Some of these shells may also include an explanation facility. In the early days of knowledge engineering the shells were made by simply extracting the original knowledge base from a domain dependent decision support system. These frame works or " empty decision support systems " can be used for developing decision support systems that are more or less similar to the original decision support systems.

The use of an available empty decision support system can greatly help in the development of a decision support system. Nowadays most of the soft ware developers use shells for their decision support systems.

EXSYS professional is one such shell that can be used to develop interactive decision support system software for a variety of purposes. This software is very simple to use. The first step is to identify a problem that has many alternatives or solutions.

Suppose the problem is to track down and identify various items on a desk. The items may be telephone, computer, floppy disk, paper and pencil. A decision tree is made for all these items and then that decision tree is converted to rules that are the driving forces to the already built in inference engine. At every node in the decision tree the expert insert in a truth table that tells the decision support system how to interpret and answer the question. The truth table is also used by the explanation facility since it has the necessary information about the step in progress.

The above-mentioned truth tables are converted to rules by the programmer. The rules are then feed into the software. These rules decides the direction in which the user will go in the decision tree diagram, once the software starts minting data from him through a question answer session.

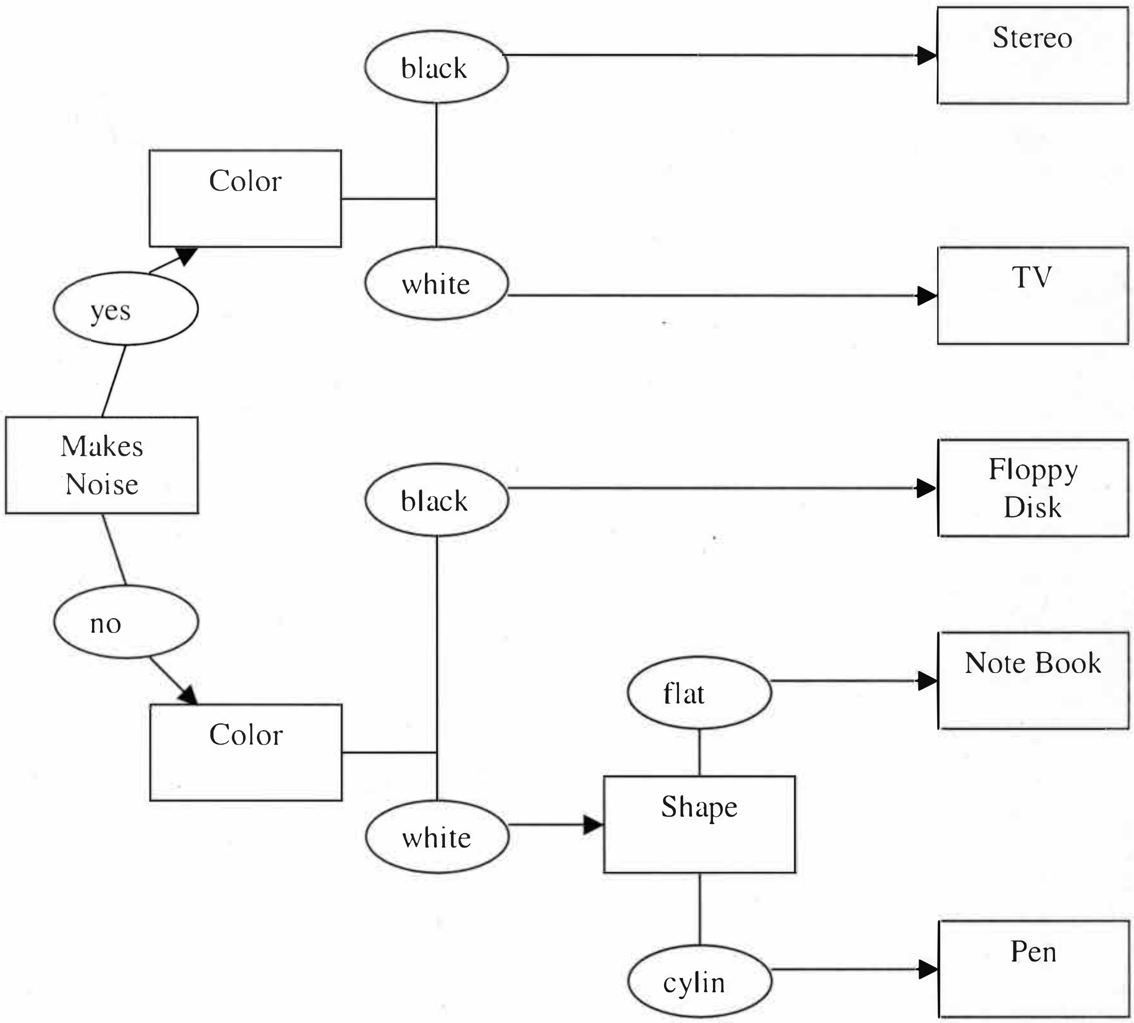

Figure 6.1: A Typical Tree Diagram

Now the above sample tree diagram may be converted into simple rules. For example

RULE # 1

IF

The item is noisy

And

The color is black

THEN

The item is a Stereo

RULE # 2

IF

The item is noisy

And

The color is white

THEN

The item is TV

RULE # 3

IF

The item is not noisy

And

The color is black

THEN

The item is Floppy disk

RULE # 4

IF

The item is not noisy

And

The color is white

And

The shape is flat

THEN

The item is Note Book

<u>RULE # 5</u>

IF

The item is not noisy

And

The color is white

And

The shape is cylindrical

THEN

The item is pen.

A good shell allows the knowledge engineer to concentrate on knowledge there fore make the decision support system more reliable and extensive. This is because of the fact that the shell automatically manages the knowledge, interface, the inference method, and the inference rules (intelligent system development). InstantTea, XpertRuleKBS, G2, K-Vision and JESS are some of the various available shells in the market.

6.5 Chapter Summary

This chapter discussed the various tools available for the development of decision support system. General-purpose programming languages, General-purpose representation languages, and expert system shells were discussed in detail. This chapter adds to the reader's understanding of decision support systems.

CHAPTER SEVEN

BRIDGE INSPECTION

7.1 Introduction

Bridge inspection can be termed as one of the most neglected area of construction and transportation engineering. Bridge inspection needs special attention because proper and prompt inspection can extend the life of the facility and thus save a lot of money for the bridge authorities and state governments. This chapter will explain the bridge inspection process, its components, types, and levels. Various Bridge Management systems (BMS), and coding systems will be discussed.

7.2 History of Bridge Inspection

The United States of America saw a great boom in bridge construction after the Second World War. Right from the beginning, little emphasis was placed on the inspection and repair procedures. This mentality on the part of bridge authorities changed dramatically with the catastrophic failure of Silver Bridge, at Mount Pleasant, West Virginia. This collapse put the inspection and repair of bridge in the limelight. "Federal Highway Act of 1968" was modified and development of a national bridge inspection standard was made an obligation upon the secretary of transportation.

The National Bridge Inspection Standard came into existence in 1971. The NBIS established policies regarding.

- Inspection procedures and methods
- The timing and frequency of inspections
- Inspection personal qualifications, selection and training
- Inspection reports and logs

- Maintenance of state bridge inventory.

Various manuals were developed in series for the strengthening of the NBIS. Subsequent manuals regarding bridge maintenance and inspection were modified and re-modified to cope with the changing situation and to accommodate new research.

The 1990's proved to be a turning point in the area of bridge management. Several states developed their own bridge management systems and started encouraging further research in this field. In 1991 the FHWA proposed and sponsored a bridge management system called "Pontis". This bridge management system software was adopted quickly and is one of the primary tools used for bridge management even up to this point in time.

The purpose of bridge inspection is to ascertain the current conditions of the bridge and predict the future deterioration. The inspection of the bridge allows the owner to rate the condition of the bridge, provide a continuous record of bridge condition, and help the authorities to decide whether to replace, rehabilitate or close down the bridge.

7.3 Levels of Inspection

Inspection is an organized procedures and it can only be helpful if and when done with certain guidelines. There are five levels of bridge inspection. (Bridge inspector reference manual 2002)

7.3.1 Initial Inspection

The initial inspection is an inspection that is done to access and evaluate the new bridge. This kind of inspection may also be done if the ownership of the bridge changes or if the bridge is widened or renewed. It is basically a fully documented investigation and is accompanied by load capacity ratings. This kind of inspection serves two of the most basic functions pertaining to bridge inspection. Firstly, it provides the structural inventory appraisal and secondly, it provides a standard or base line condition of the bridge and its related problems. It serves as a good means of comparing the conditions of the bridges at any later date.

7.3.2 Routine Inspection

Routine inspections are "planned inspections" that are carried out on regular basis. Readings and measurement are taken at fixed points in time to look for any deterioration with the passage of time and to evaluate and compare the existing conditions with the initial conditions. It is merely a check to ensure that the bridge is working in the way it was thought to work. Bridge deck and superstructures are checked for any distresses and deterioration. The areas that need to be closely monitored are those that have been identified by previous inspections.

7.3.3 Damage Inspection

Damage inspection is more or less an emergency inspection that is carried out to access the structural damage caused by any environmental or human factor. This kind of inspection should be concentrated to the reported problem. The inspector should come up with a prompt decision to either repair or close down the bridge momentarily so that no one is put at risk.

7.3.4 In-depth Inspection

An in-depth inspection is a kind of inspection that is carried out on any one, or all the structural members above or below the ground or water level to access the condition of the bridge. This may called as an intensified version of the routine inspection. In order to fully ascertain the deterioration of the structure, much more elaborate and sophisticated methods and equipment may be used. For example if the routine inspection reveals the possibility of delamination in the routine inspection, the same problem may be further investigated by various non-destructive methods. A good and thorough in-depth inspection may also give the inspector an idea about the remaining life of the bridge and the remedial measures to enhance the remaining life. For small bridges and culverts the in-depth inspection should include all the critical members of the bridge. For very large and complex bridges these inspections may be scheduled for defined members or group of members that need to be inspected in a timely manner.

7.3.5 Special or Interim Inspection

A special inspection is an inspection that is scheduled on the will and choice of the bridge owner. It is used to investigate a particular deterioration or deficiency such as an increases number of crack lines or severe settlement. These inspections are necessity driven and therefore are not very comprehensive and thorough.

7.4 Methods of Inspection

Engineers are called in to evaluate existing bridge decks far more than they are asked to design new decks. Of the about 667,000 bridges through out the United States most are inspected every two years, as required by law. Most of the departments of transportations have well composed manuals that act as a reference material for the inspectors. The manuals contain methods and information about inspecting and evaluating bridges from underwater components to the super structures.

7.4.1 Visual Inspection

This is the most basic kind of inspection that can be carried out by the bridge inspector. The inspector may visually inspect the concrete deck for deformation like cracking, spalling and peeling.

In general, the inspection of the bridge should begin with the visual field examination from top to bottom. A detailed visual examination will reveal cracking, spalling, corrosion of reinforcement. Flexure cracks may occur at the point of maximum bending moment usually at the mid point between the supports. Visual inspection may be used for the evaluation of cracks but delaminations and corrosion may need further examination.

7.4.2 Coring

Coring is probably the most important and most commonly used method of inspection. An engineer or an experienced inspector should be present at the time of coring to inspect the cores at the site and later on in the laboratory. The inside of the core should be inspected closely. This serves as a very good opportunity to track delamination and voids in the concrete decks. This also affords an opportunity to check the cover thickness and the condition of the rebar.

This is very important because most of the problem with bridge decks arise because of the insufficient thickness of concrete cover over the rebars. This also gives a very good indication of the homogeneity of the concrete material. For example if the coarse aggregate has settled down to the bottom, leaving the fine aggregate at the top, this shows the inspectors that the there was some problem with the pouring and curing sequence of the material.

Coring location should be selected at random, provided that to the minimum, one core is taken immediately behind a transverse roadway joint and, in the Snow Belt states, at the face of the curb and other locations, where salt laden runoffs tend to accumulate (Bridge decks 1997).

The number of cores to be taken is determined on the spot as necessity arises. For example if an experienced engineer thinks that there might be some problem with the concrete, he may take some more cores to make himself sure of the problem. It tells the engineer that whether the problem is a local problem or it ranges all through out the bridge deck.

The cores are documented for future investigations.

Cores may be taken to the laboratory for some standard laboratory tests and then evaluated against the initial test results of the bridge decks. Some of the widely used test on cores may be compressive strength, air content and chloride content. Chloride content determination is very vital in Snow Belt areas. Coring is comparatively less expensive method and may inhibit the use of more expensive non-destructive evaluation of the bridge deck.

7.4.3 Non-destructive Evaluation

Non-destructive evaluation of concrete is one of the most reliable methods of bridge deck inspection. It means to evaluate the bridge deck with out taking cores or disturbing the bridge structure. Chain drag is one of the most widely used and less expensive methods for decks that are not covered with any kind of overlay. Sounding can also be done by hitting the critical areas with the hammer. The hollow sounds indicate the existence of delaminations and voids.

These two methods are used when money is the issue because they are less expensive and needs very little supervision from experienced inspectors.

The Ground penetrating radar (GPR), Impact echo and Thermograph are the three most advanced methods of bridge deck evaluation. Thermograph mapping is generally used for bridge decks that are not covered with overlays, because the inclusion of overlays affects its authenticity. The GPR is probably the best method that can be used for this purpose. This equipment traces the areas of extensive delaminations and voids by the reception of the waves that are sent into the material from a mobile unit.

7.5 Bridge Management Systems

Bridge management systems have come a long way during the past five decades. The collapse of Silver Bridge in 1968 initiated the national bridge inventory (NBI) and made biennial inspection on all bridges supported by federal aid mandatory. The failure of Mianus River Bridge and Schoharie Creek Bridge further intensified the need for a good bridge management system (Sanford et. al 1999).

The NBI records and evaluates the condition of a bridge by mainly gauging three major key components of a bridge i.e. the deck, the superstructures and the substructures. These components of the bridge are assessed on the scale from 0 to 9 with zero being the worst and 9 being the best condition state. This rating system is not uniform within all the states. For example the New York state department of transportation has a rating system as follows.

Table 7.1 Condition Rating (NYDOT)

1	Totally deteriorated, Failed condition
2	In between state 1 and 3
3	Seriously deteriorated, not functioning as desired by design
4	In between state 3 and 5
5	Some deterioration, but functioning as originally designed
6	In between state 5 and 7
7	New condition, no deterioration
8	Not applicable
9	Condition or existence not known

The above-mentioned rating system is more or less subjective and does not provide with definite condition of the bridge state. It provides a vague idea of the severity of the problem but fail to quantify the deterioration. This shortcoming adversely effect the effectiveness of the NBI rating in determining the correct state of deterioration and hence the repair and rehabilitation methods.

The normal rule in New York department of transportation is that condition 3 and lower may need substantial rehabilitation and repair work where as condition 3 and above may be improved with regular maintenance (Fundamentals of Bridge Management and Inspection 1997).

The Colorado department of transportation has a somewhat different ranking system. This ranking system has been modified to fit into Pontis format. This ranking system is much more improved and clarified. Bridge elements are categorized into five condition states (Pontis Bridge Inspection Coding Guide 1998).

Table 7.2 Condition Rating (CDOT)

Condition State 1	The surface of the deck has no repaired areas. No spalls or delaminations. No visible wear.
Condition State 2	Spalls/Repaired areas/Delaminations exists. Combined distressed area is 2 % or less of the total deck area.
Condition State 3	Spalls/Repaired areas/Delaminations exists. Combined distressed area is 10% or less of the total deck area.
Condition State 4	Spalls/Repaired area/Delaminations exists. Combined distressed area between 10% to 25 %.
Condition State 5	Spalls/Repaired areas/Delaminations exists. Combined distressed area is more than 25%

Pontis includes many innovative features. The condition data included in the system are more detailed than the requirements of the NBI. The bridge is divided into individual elements, or sections of the bridge, which are comprised of the same material and can be expected to deteriorate in the same manner. The condition of each element is reported according to a condition state, which is a quantitative measure of deterioration. The condition states are defined in engineering terms and are on a scale from 1 to 5 for most elements.

Pontis also views bridge deterioration as probabilistic, recognizing the uncertainty in predicting deterioration rates. The system models deterioration of the bridge elements as a Markov process. Pontis automatically updates the deterioration rates after historical inspection data are gathered.

The present practice of repair and rehabilitation of bridge deck is done primarily with pontis. Most of the states use pontis as bridge management system. This software can assist the highway agencies in arranging and analyzing their repair and rehabilitation data and economic factors and making smart decisions about maintaining and rehabilitating their infrastructure. One of the biggest advantages of using this software is that it allows its user to look into the future and show those making funding decision how much to be invested in bridges to minimize the long-term preservation costs. The bridge management system can be divided into two main types:

- Project level
- Network level

Project level Bridge Management Systems (BMS) can be distinguished from network level bridge management systems in the following ways (Thompson et.al 2003).

- Network level bridge management systems focuses on the uniform combination or groups of bridges, while project level bridge management systems focuses on just one bridge at a time.
- The primary modes of presentation at network level are list of bridges and network wide summaries, while the primary modes at the other type are the list of elements and the need on one particular bridge, and prediction of future condition and performance of that bridge.

- The network level focuses on what many bridges may have in common, while the project level BMS focuses on the unique situation of each bridge.
- Network level uses techniques such as simulation, that are suitable for automating decisions over large group of bridges, while project level uses techniques that provide quick feed back on large number of bridge-specific decision variables.
- At the network level, each bridge contributes probabilistically, in at least a small way, to the expected value of funding requirements during the programming horizon. At the project level, only a few bridges are realistically considered for implementation: the scope of the work is deterministic and estimated cost most certain, even though the deterioration and benefits are still probabilistic.

Network level bridge management systems are most widely used these days. Project level Bridge Management Systems (BMS) on the other hand are relatively new and less known for its use by various departments of transportations.

It can be inferred from the above bullets that project level and network level bridge management systems are different. But at the same time it can be said that they are complementary and they can be used to come up with an even more elaborate and better bridge management systems. They are linked: the network level contributes predictive models (e.g., deterioration and life cycle costs) needed by the project level to evaluate possible outcomes of the decisions; the project level produces a set of candidate projects, with cost and benefits, that can be used in a network level priority setting and budgeting analysis and decisions.

Pontis, as already discussed is a purely network level bridge management system. It is being used by the departments of transportation through out the United States for decisions regarding the prioratizitation of major rehabilitation projects.

The objective of this thesis is to come up with a project level bridge management system (decision support system), which can be later modified and updated to be used in conjunction with the network level bridge management systems.

7.6 Inspection Forms

The bridge inspection forms that are currently being used in the various departments of transportations are very general. For example the Michigan department of transportation uses a form (Appendix H1) that rates the bridge components according to the NBI ratings. NBI rating, which is mandatory from federal highway administration is used by almost all of the DOT's. The form as you can see in the Appendix H, rates the various components of the bridge (0-9).

These forms do not say anything about the individual problems in the concrete bridge deck. For example the NBI rating form (Appendix H) has a section for the bridge deck, which gives information only about the surface of the bridge deck. The bridge inspector rates the bridge deck surface and suggest a repair method on the basis of his inspection.

The NBI and the Michigan Department of Transportation's forms are very good for any network specific bridge management system (BMS), but it needs to be modified to be used in a project level bridge management system (BMS). The other way would be to attach an auxiliary form to the existing NBI rating form. This auxiliary form should have details about the individual problems in concrete bridge deck. One such form (Appendix H) was developed during this thesis.

7.7 Chapter Summary

This chapter began by discussing the history of bridge inspection followed by the levels, types, and methods of inspection. The bridge rating systems of the state of New York and Colorado was also discussed. The difference between project level and network level Bridge Management Systems (BMS) was discussed in details.

CHAPTER EIGHT

DEVELOPMENT OF THE DECISION SUPPORT SYSTEM

8.1 Introduction

Decision support system or Knowledge based expert system is a system that incorporates the intellectual qualities of an expert with the capabilities of a computer to improve the quality of decisions. It is basically a computer-based support system for management decision makers who deal with semi-structured problem (Turban et.al 2001).

One of the main requirements for the development of any decision support system is that the problem selected should be well understood and the solutions should be universal so that the support system can be validated by almost any one. In other words, problems that cannot be solved by human brain cannot be solved by a decision support systems.

The development of this decision support system can be divided into the following stages.

- Investigating the three main problems normally found in the bridge decks.
- Investigating the repair and rehabilitation strategies.
- Development of the expert system.

One of the main revelations of the study was that major differences were found to exist between the repair and rehabilitation strategies found in the literature and the one found to be in practice. As opposed to literature review, the repair processes through out the United States were found to be mostly identical. The knowledge base for this decision support system was made from input both from literature and experts in the field.

This chapter focuses on the development of the decision support system and will explain the stages of the development of this decision support system. This chapter mainly discusses the process of making the knowledge base, decision tree and then subsequently the rules, which are the building blocks of the decision support system.

8.2 Knowledge from the Literature

The first step in the development of this decision support system was to get input from the literature. Literature was well searched for repair methods and rehabilitation processes. There were many repair methods and strategies for the problems of corrosion, delamination and cracking. Since the choice of the repair methods depends on the extent of the problem, therefore effort was made to develop criterions for the selection of particular repair methods. These criteria were later used for the development of tree diagram and more importantly, the rules. The decision tree that was developed at the beginning, also proved to be very helpful in the development of the questioner that was sent to the experts in the field of bridge management and maintenance.

As explained in the fourth chapter, the following repair methods were found to exist in the literature.

Table 8.1 Repair Methods and their Selection Criterion

S No	Repair Method or Material	Criterion for Selection
1	Do Nothing	-When no repair is needed. -When "do nothing" is a better option than repair because of monetary or any other reason -When the bridge deck is beyond repair.
2	Replacement	-When the deterioration is beyond rehabilitation.
3	Non-Protective Sealing (bitumen, cement based mortar, concrete)	-When the deterioration depth < ¾". -When cracks are due to the slippage of surface area, movement of thermal origin or flattening of blisters. -When there is loosening of the surfacing at the concrete kerbs and joints.
4	Non-Protective Patching (bitumen, cement based mortar, concrete)	-When deterioration depth < ¾". -When there is localized deformation, crazing or depression. -When there is cracking at the structural joints.
5	Non-Protective Overlay (bituminous overlay)	-When funds are not available to have protected overlay. -When the bridge is to be replaced later. -When architectural appearance is desired.
6	Latex Modified Concrete Overlay (Mixture of cement mortar or concrete with styrenebutadiene latex)	-When protective overlay is required. -When is immediate reopening of the bridge is a priority.
7	Low Slump Dense Concrete Overlay (Air entraining additives with silica)	-When protective repair is required. -It is not known for its bonding qualities therefore it should be used in conjunction with other bonding agents.
8	Fiber Reinforced Concrete Overlay (Conventional Portland cement containing discontinuous discrete fibers)	-When protective repair is required. -When high early strength is required. -When high fatigue resistance is required. -When high durability is required.
9	Epoxy Grouting (Epoxy resins, Polyester resins)	-Cracks that range from 0.003-0.25in -When work is not in a confined space
10	Hydraulic Cement Grouting (Portland cement plus slag or pozzolonas)	-When the crack width ≥ 0.25 in -When the cracks are dormant. -To fill voids under or around concrete structures. -It is used for large works because is less expensive.
11	Gravity Feed Resin (Epoxy or polymer resin)	-When the crack width > 0.02 in -When crack depth > 12 in. -When there are shrinkage or settlement cracks.
12	Polymer Injection	-When crack width ≤ 0.05 in
13	Low Pressure Polymer Spraying	-When the cracks size is very small and minute
14	Penetrating and Coating Sealers	-When the rebars used in the structure are plain -When the rebars are not specialty bars -Should never be provided under submerged or moist conditions. -When protection and appearance is the objective at the same time.

8.3 Tree Diagram for Decision Support System

There are various ways and approaches to build a decision support system. Some developers prefer backward chaining while other stick with forward chaining. Some use modular systems with blackboards; other prefers large single module systems. As long as the system give the correct answers, no system is better than the other one. But some types of problems necessitate the use of a particular type of system to be adopted.

One of the most convenient methods for building a decision support system is to draw a decision tree for the problem on hand. This method is very useful for inexperienced programmers because they can make rules out of the tree diagram fairly easily.

Based on the literature review, a tree diagram was developed for this decision support system. Each branch in the tree goes to a group of choices. Figure 8.2 shows a general tree diagram for the decision support system, which was developed in this studty. Only one of the braches is shown for clarity, the other two branches are exactly identical. The tree diagram gave us an idea for the questionnaire that was sent to experts throughout the country. Nodes within the tree are most important. These nodes direct the rules. In other words, at each node the program makes a choice among the various paths available. Based on the rule fired the inference engine selects the appropriate path.

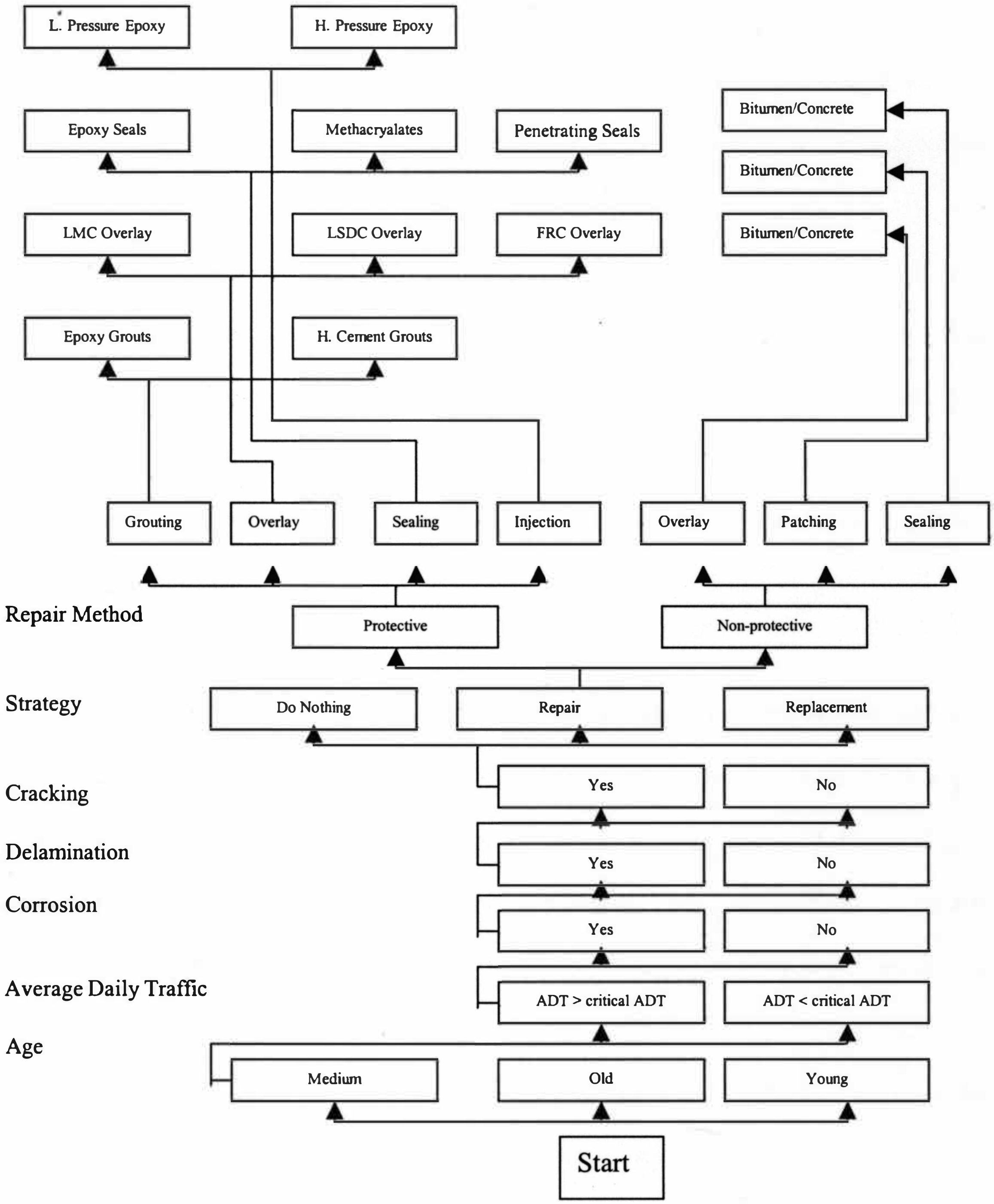

Figure 8.1: Branch of the Diagram for Decision Support System for Bridge Maintenance

The above tree diagram can be called as a theoretical model for the development of the decision support system for Bridge Maintenance. The tree is developed by extending one of its branches. The above-mentioned tree is general, and the other branches will be identical because it is going to lead to the same repair methods. The above tree diagram proved to be very helpful in developing the rules and making the questionnaire.

8.4 Development of the Questionnaire

The development of the questionnaire (Appendix F) was the trickiest part of all. Every possible effort was made to make the questioneer as simple as possible. Past experiences proves that cumbersome and confusing questioneer gets very little feedback from the people in the field. The main issues that were targeted by the questioneer were as follows.

8.4.1 Cost

Any decision support system would be very authentic if it can take the cost into consideration before it reaches a conclusion. An expert while making a decision about a repair method keep the cost factor in his mind, but this knowledge is tacit and cannot be quantified. This was proved correct by the questioneer survey, when almost all of the experts did say yes to the question " do you keep cost factor in mind?" But no one answered the auxiliary question, "how?"

The question is that do they base their decision on the cost or simply they consider the cost when they reach the conclusion. They argument seems to be trivial when we talk about an expert making a decision. But consider a decision support system making the decision. Since it is software, it has to be programmed in a certain way. It can be programmed in such a way that after having a question and answer session with the user it gives a repair method with its cost. The user may simply reject or accept the option on the basis of its cost. The other method is to program the decision support system in such a way that it ask a question about the cost in the question answer session. Based on the answer from the user the software gives its recommended repair option. The second method is preferable but there are two main hindrances.

- Variables such as cost should be initialized at a certain value. The experts from the survey did not come up with any concrete answer, so that we could quantify the cost factor.
- Cost factor can only be drawn into the tree and made a factor in the decision, if all problems with bridge decks are investigated. This decision support system only covers three problems. Bridge decks normally have a lot of problems.

8.4.2 Repair Methods & Materials

The second objective of the questioneer was to find out the current practices in bridge management. The experts were asked questions about the kind of repair methods and materials they use in different scenarios. The feedback about this point was very good. Expert through out the country explained in detail, the kind of strategies they use in bridge management.

8.4.3 Inspection

Experts in the field were asked about the kind of instruments and methods that they use for inspection. It was revealed that the old method of chain drag is still predominantly used for the detection of delamination and voids. Most of the people said that, their organizations either don't have the advanced instrument like GPR, or they don't have the manpower to use them. This is crucial to the future of bridge management because the good use of advanced instruments can help a lot in good bridge management.

The feedback about corrosion also revealed some interesting practices. Almost all of the replies suggested that no standard way of accessing and quantifying corrosion of deck rebars is in place. The decision about repair is, most of the time dependent upon naked eye inspection.

Out of the 50 questioneers sent, only 11 came with a response. Although the number of feedbacks was not significant, it did give us enough information for our decision support system.

The Results from the survey can be summarized in the following tables.

Table 8.2 Results from the Survey (Coding & Rating)

Coding & Rating	% of the responses	Comments
NBIS	37.5	It represents the percent of experts who use NBIS as the only coding and rating system.
PONTIS	12.5	It represents the percent of experts who use Pontis rating system as the only rating system.
Others	37.5	It represents the percent of experts who use departmental practices in addition to the mandatory NBIS rating system.

Table 8.3 Results from the Survey (Delamination Inspection)

Equipment or Method	% of Response	Comments
Chain Drag	63	The traditional methods of visual inspection followed by chain drag.
Visual & Coring	12	Visual inspection followed by coring.
Chain Drag with additional investigation	25	Although Methods like GPR, Infrared are used but their use is not very common

Table 8.4 Results from the Survey (Repair Methods & Materials for Delamination & Corrosion)

Delamination & Corrosion			
Low		Severe	
Patching	37%	Patching	0%
Patching & Overlay	63%	Patching & Overlay	0%
Replacement	0%	Replacement	100%

Table 8.5 Results from the Survey (Corrosion Inspection)

Equipment or Method	% of Responses	Comments
Visual Inspection	87	It is the most common way of detecting and inspecting corrosion.
Half cell method	0	WSDOT tried it in the 1980's but later abandoned it.
Others	13	In addition to visual inspection some experts use chain drag, coring e.t.c.

Table 8.6 Results from the Survey (Repairs for Cracking)

Cracking			
Low		Severe	
Replacement	0%	Replacement	13%
Sealing	50%	Sealing	0%
Sealing & Overlay	50%	Sealing & Overlay	87%

8.5 EXSYS Professional

The expert system was developed using EXSYS Professional. EXSYS Professional is basically a decision support system development tool, which has an inbuilt inference engine. It is very good for the development of small sized decision support systems. Rule editor is the main component of EXSYS Professional. Rules are made in rule editor, which can later be modified and edited using the same.

8.5.1 Components of EXSYS Professional

EXSYS Professional has many features that make it easier and preferable to use. Some of the main features and components of EXSYS Professional are as follows.

Knowledge base

Qualifiers, choices and variables essentially make up the knowledge base. The knowledge base is the data that is feed into the system by an expert. It is the most important part because the whole system depends upon this. The more reliable and authentic the knowledge base would be, the more reliable and authentic the final product would be.

Qualifiers

Qualifiers are basically multiple-choice questions. Many factors in decision-making process can be best expressed in multiple-choice lists. Qualifiers can be added into the knowledge base through a command.

Figure 8.2: EXSYS Professional Editor Qualifiers List

To add a new qualifier click on “Rule” on the EXSYS Professional Editor front page. Click on the qualifier list in the pull down menu. A window will appear, showing all the existing qualifiers, if any. Any existing qualifier can be edited from this window. To add a new qualifier click on the “new qualifier”.

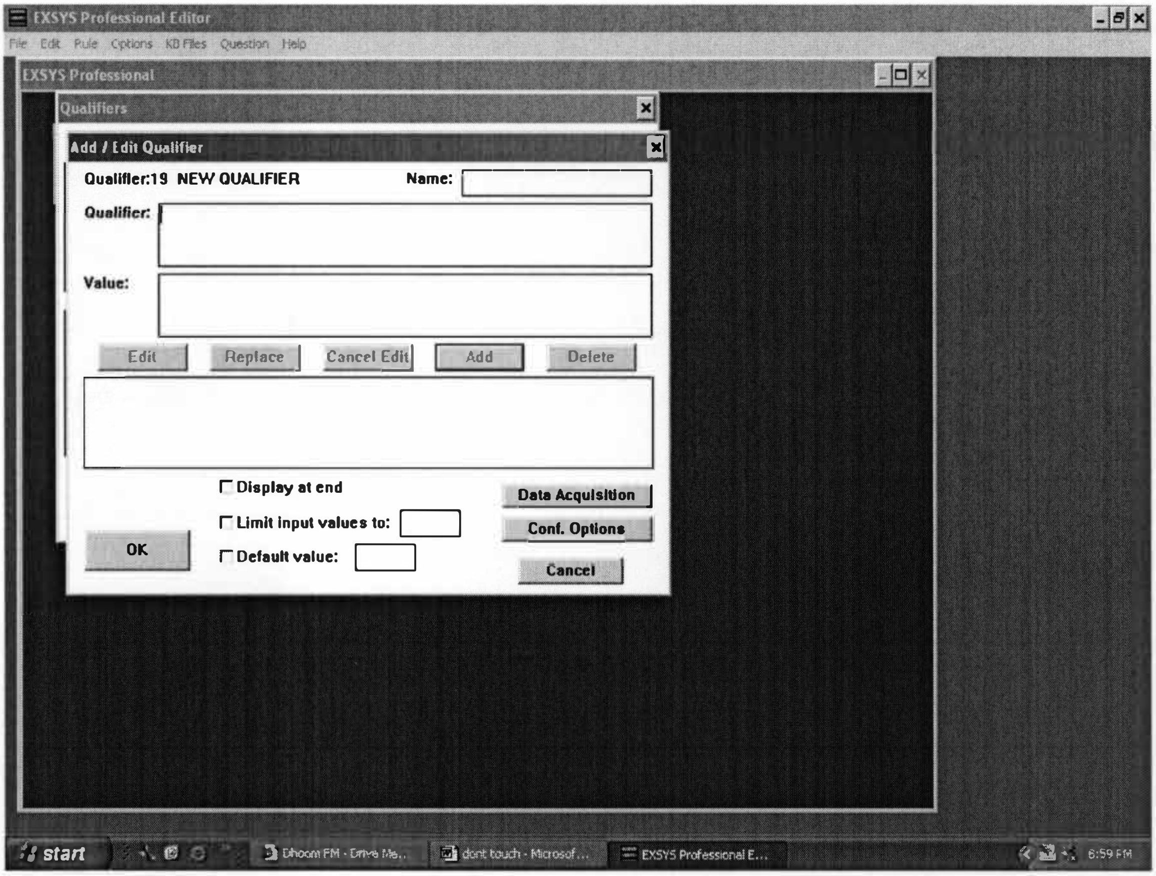

Figure 8.3: EXSYS Professional Editor New Qualifier

Qualifier and their associated values are multiple type lists. Typically, a qualifier is the part of the sentence up to, and including the verb. "Values" are the possible completion of the sentence that the user is able to select among. The values can be limited to a certain number. For example if the qualifier is "The color of the car is" the values could be red, green and blue. All the three values are entered and then added by the "add" button. If the programmer wants the user choice of the values limited to a certain value, he can put 1 for "limit input value to". This way the user will be limited to choose one value i.e. either blue, green red for this qualifier. Once all qualifiers and their values are selected press "OK" and save your work.

Choices

When a new knowledge base is started, the system asks the programmer to put in the choices. Choices are basically the answers that the decision support system provides at the end of the run. For example, the repair methods that were studied in the previous chapters will make up the list of choices for this expert system. Choices can be entered at the beginning as well as at any time during the development of knowledge base.

To enter choices, click on "Rule" on the EXSYS Professional Editor front page. Click "Choice list" and the existing choice list will pop up.

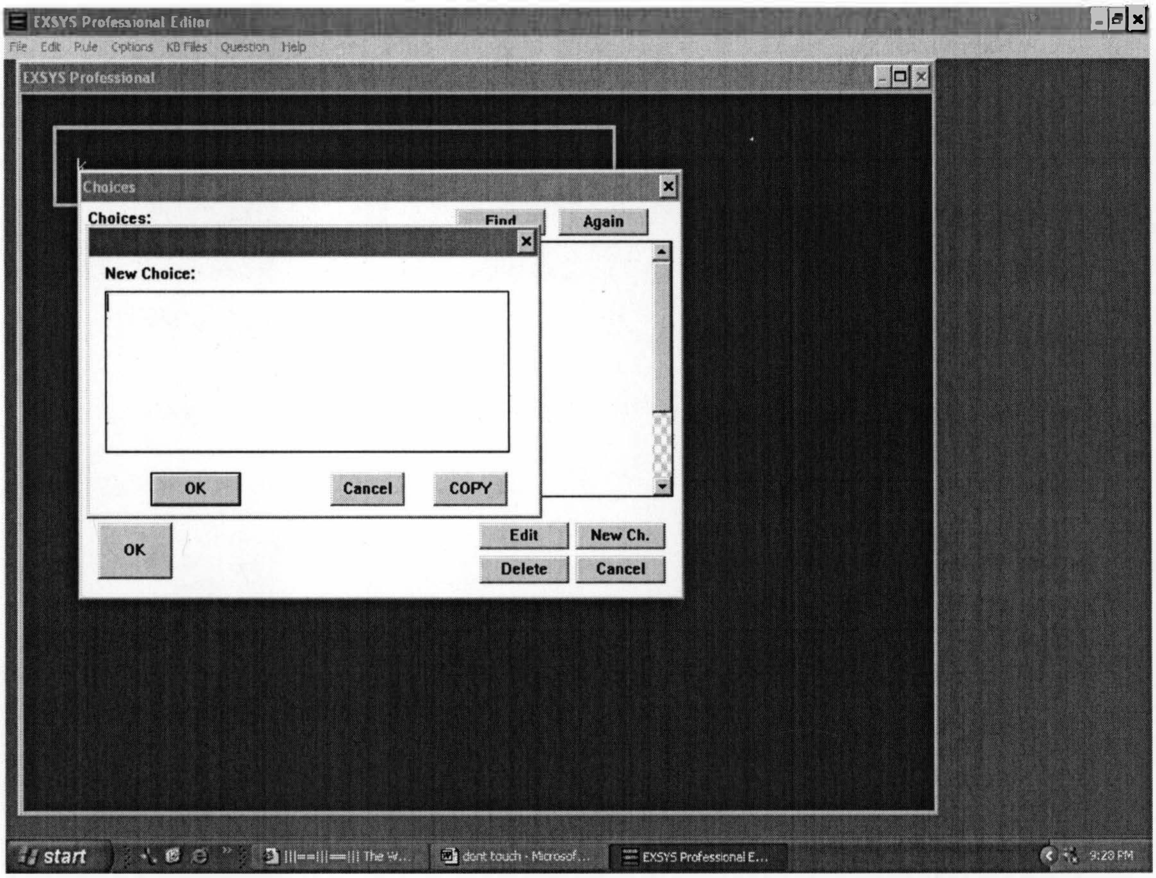

Figure 8.4: EXSYS Professional Editor Choices List

New choices can be entered into this window. Once done with all the choices, press "OK" and save your work.

Variables & Mathematical Expressions

Variables and mathematical expressions can be used for a variety of purposes in EXSYS Professional. A variable is any string of alphanumeric characters, including spaces, enclosed in brackets. A variable can only contain letters, digits or spaces. For example [Number of bridge decks] would be a legal variable, where as [# of bridge decks] would be an illegal variable. To enter a new variable, click on "Rule" on the EXSYS Professional Editor front page. Click on "Variable List" and click on "New Variable."

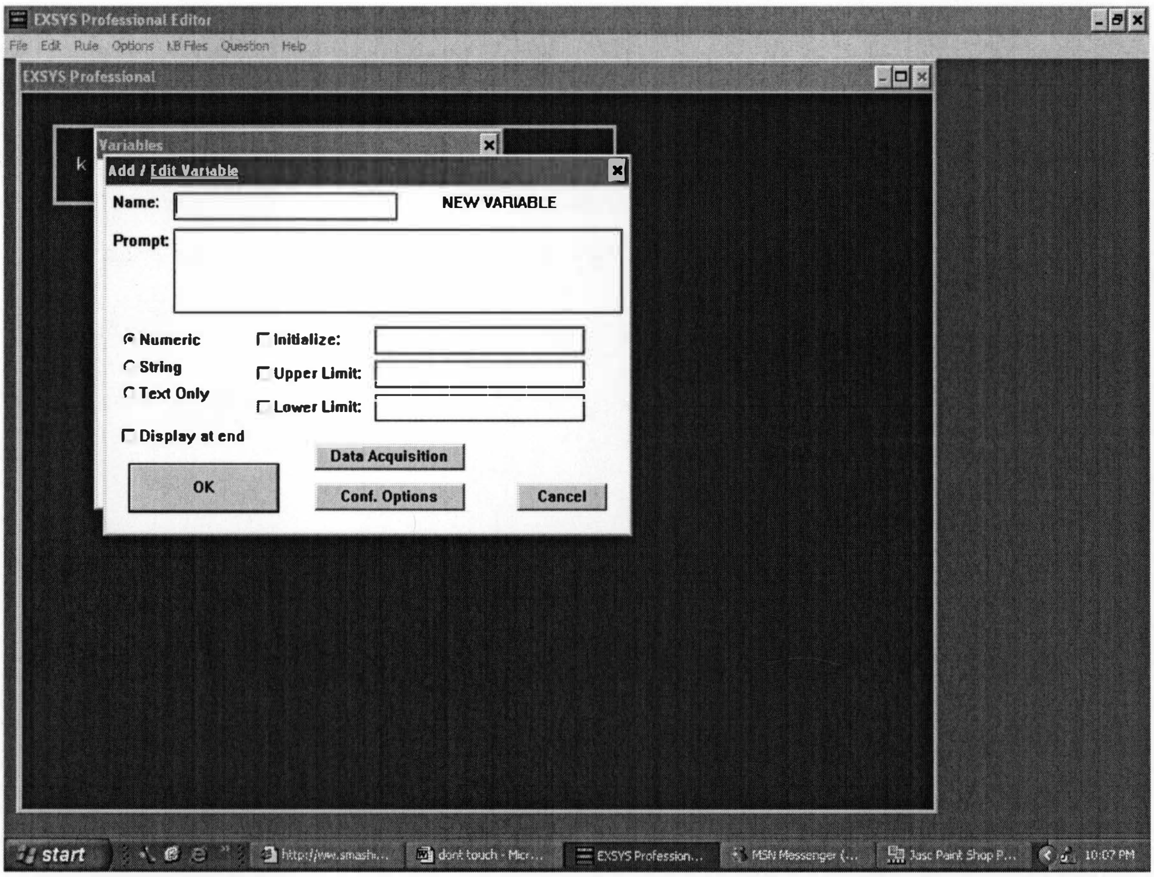

Figure 8.5: EXSYS Professional Editor Variables List

As shown in the above figure a variable can be a numeric variable, string variable or text only variable.

Numeric variables are stored as floating point numbers and are handled in algebraic expressions. If the variable is considered to be a numeric variable, its value will be floating point value. Numeric variables are used in algebraic expressions for testing. Only numeric variables can have upper and lower bounds and initial values. The following would be legal numeric variables.

- [Number of bridges] > [7]
- [T] + [Z] >= [P]/5

The values of the numeric variables can be fixed at a certain value, for example [COST OF REPLACEMENT OF THE BRDGE DECK] is a variable whose initial value can be fixed to [500]. If this variable is used in a rule;

If the cost of replacement is more than available funds then "do nothing."

The decision support system will compare the input "available funds" to this variable which is initialized to "500", and fire the rule.

If the variable is handled as a string, its value will be text and not a floating-point value. This can be very useful for names or other text information. When the user will be asked for the value of string variable, the text input will be taken as the string value of the variable.

String variables can be used in the "IF" part of the rule. The following would be a valid string variable:

[P] = "This is a beam"

This string variable would be true, if the string value of the variable would be "This is a beam." However, the following would not be a legal string variable:

[P] = 25

This expression is flawed because it is comparing a string variable with a numeric value. String variables can also be used in the "THEN" part of the rule. In this case the value assigned must be another string variable or a string enclosed in double quotes. For example the following would be a valid string variable:

[P] is given the value "BEAM"

Data for a string variable can also be acquired from an external program. This external program can also be a dat. file that is made within the expert system.

Text only variables are those variables that have no associated value. They appear in the "THEN" part of the rule. The text that is associated with the variable will be displayed as a note in the rule.

Rules

"Rules" is that component of the decision support system, which directs or controls the inference mechanism. Based on the input from the user appropriate rules get fired, and a conclusion reached.

A rule can be built by creating conditions in the IF, THEN, and ELSE part of the rule. A new rule can be made or any existing rule can be edited through the rule editor. The IF, THEN, and ELSE part of the rule is made up of the existing lists of variables, choices, and qualifiers. EXSYS Professional will ask the programmer to name the new qualifier, choice or variable if it is not selected from the existing lists. This feature is particularly helpful in the case of variables, since there is always a chance to set the variable for different values.

A new rule is made in EXSYS Professional by clicking on "Rule" in the EXSYS Professional front page.

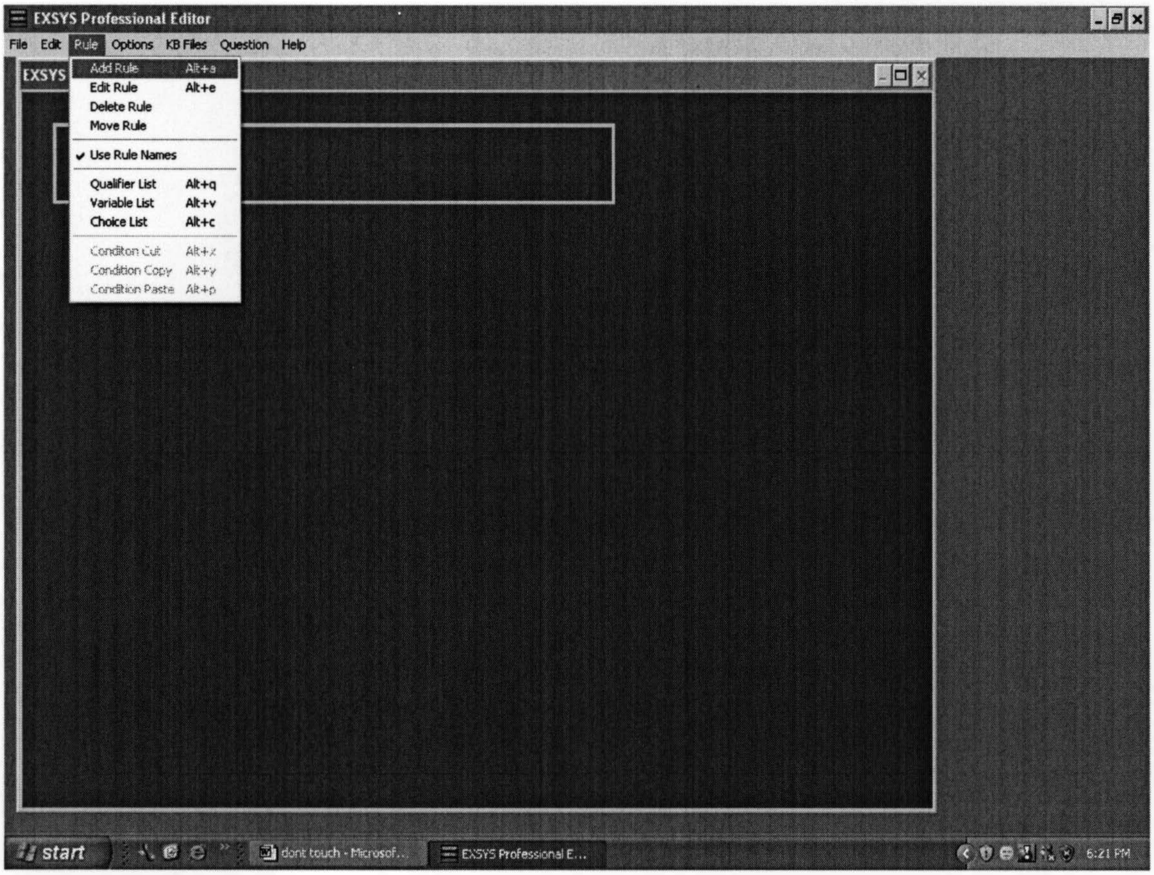

Figure 8.6: EXSYS Professional Rule Editor

Once "Add Rule" is clicked a window will appear that will have "IF" and "THEN" blocks.

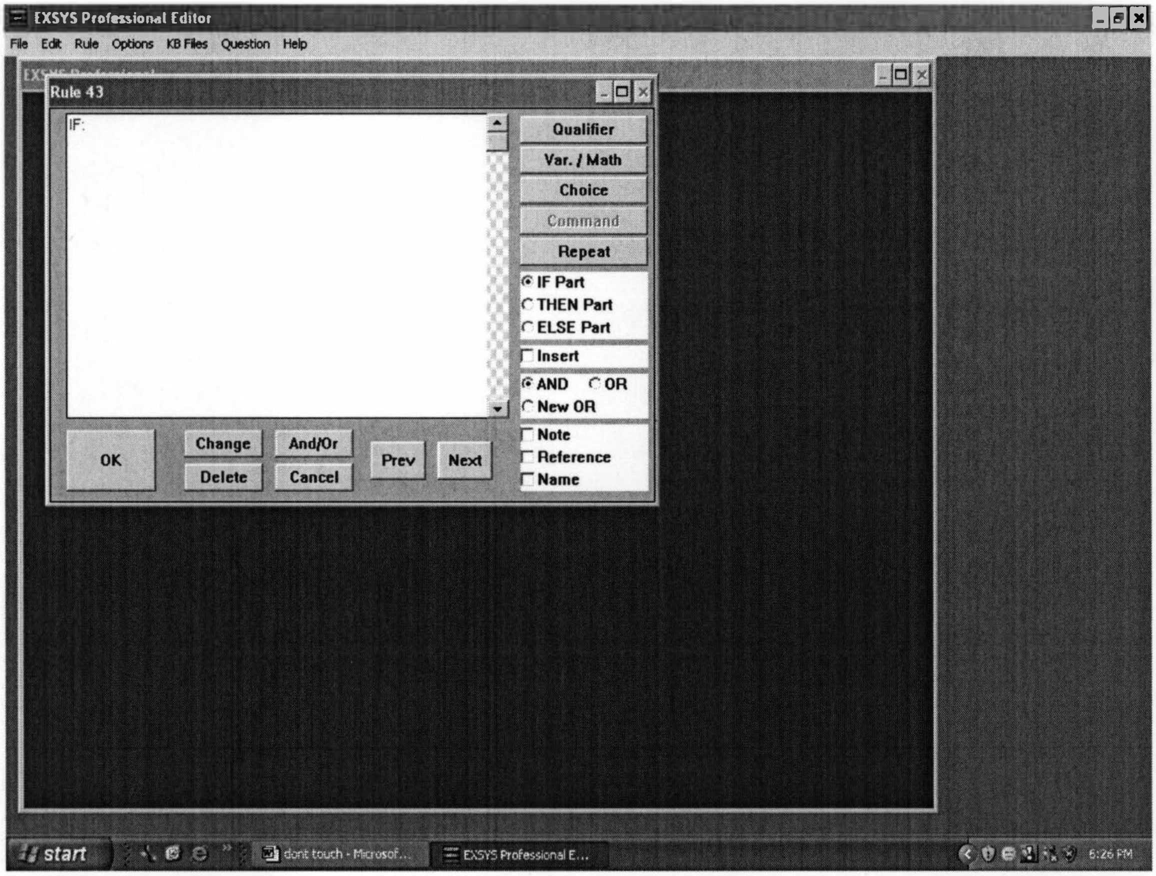

Figure 8.7: EXSYS Professional Rule Editor: Adding a Rule

If you want to build the "IF" part of the rule using a qualifier. Click on the "Qualifier" tab, the complete list of qualifiers with its values will be displayed. Once the appropriate variable is clicked, the values will also be highlighted. The "IF" part can be completed by choosing, the appropriate value with the qualifier and clicking "OK."

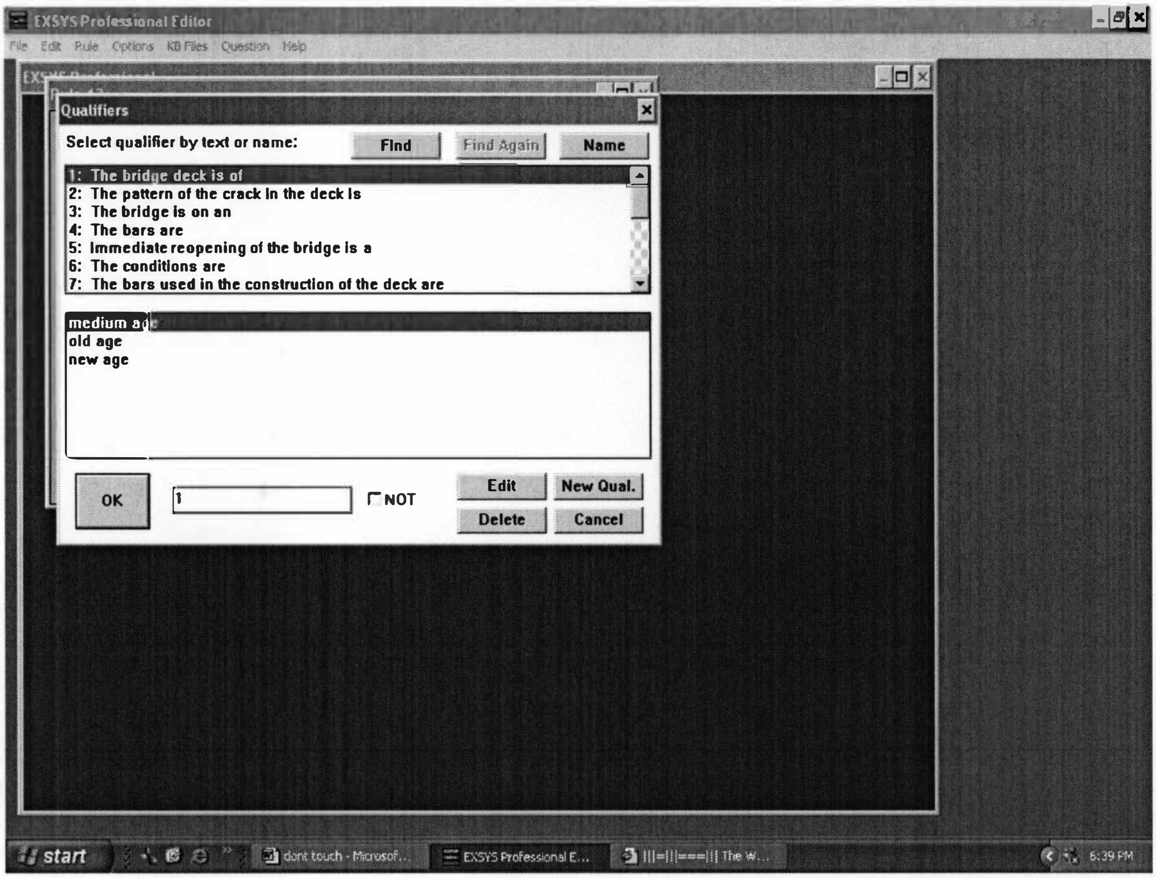

Figure 8.8: EXSYS Professional Rule Editor: Adding the IF Part

The "NOT" option available in the above window is a very powerful tool, that can be used in the creation of the rules. Qualifier number 6, in the above window states; "The conditions are." This qualifier has the values "moist" and "dry." So the "IF" statements could be; "The conditions are moist", or "The conditions are dry". THE "NOT" option when used, would make the "IF" part as; "The conditions are NOT moist. The advantage is that we don't have to make any more qualifiers for this condition, and four statements out of two values.

The same procedure can be used for adding variables, or choices in the "IF" part of the rule. Simple decision support systems normally does not require the usage of choices, or variables in the "IF" part of the rule.

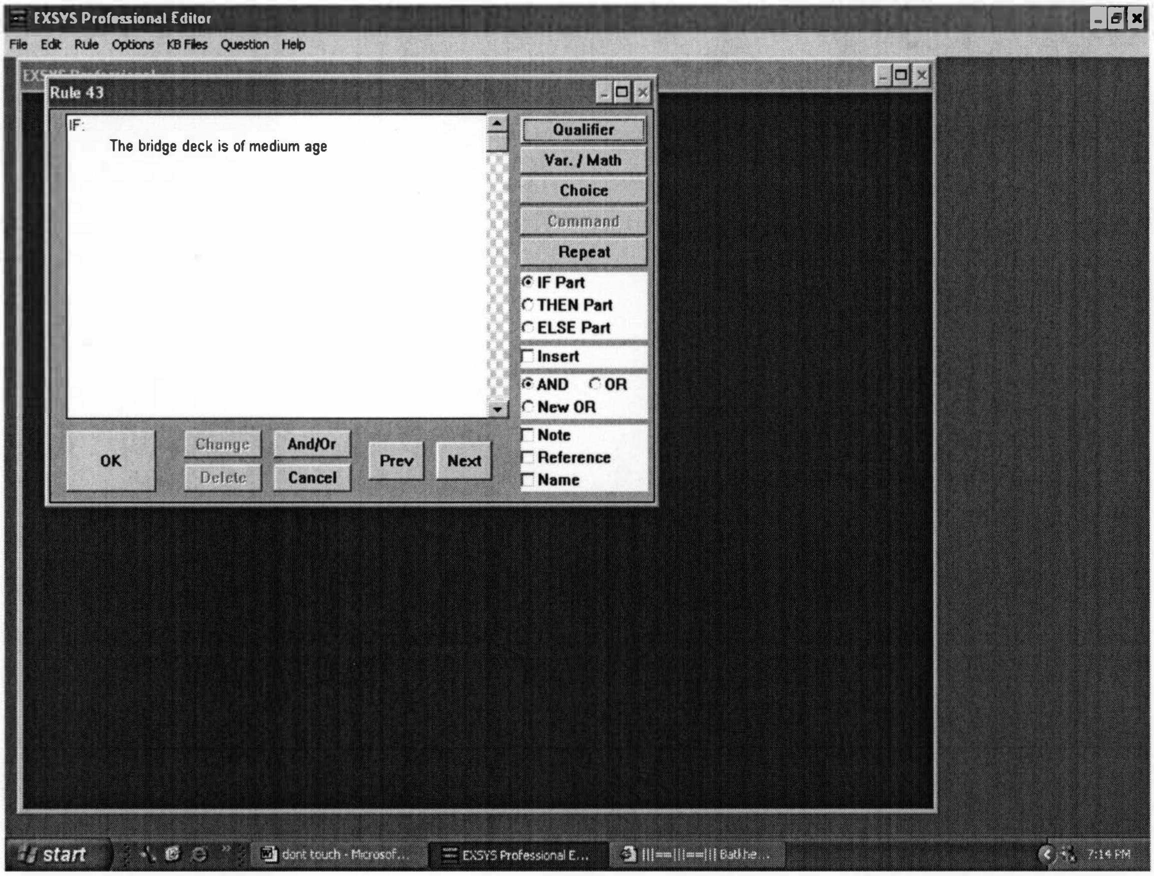

Figure 8.9: EXSYS Professional Rule Editor: The IF Statement

More statements can be added in the "IF" part, by clicking on the variable, choice, or qualifier. The statements will add up in the "IF" part with the word "and" in the beginning of each statement. Statements in the "IF' part can be connected with "OR" with each other. If the two statements are connected with an "AND" the rule will be true if both parts of the statements are true. If the two statements are connected with an "OR" the rule will be true if any of the parts is true. The "OK" tab is selected, once the "IF" part of the rule is completed.

To make the "THEN" statement, click on the "THEN" tab. The "THEN" part of the rule may be made of variable, choice, or qualifier. The same process is repeated for the "THEN" and " ELSE" part.

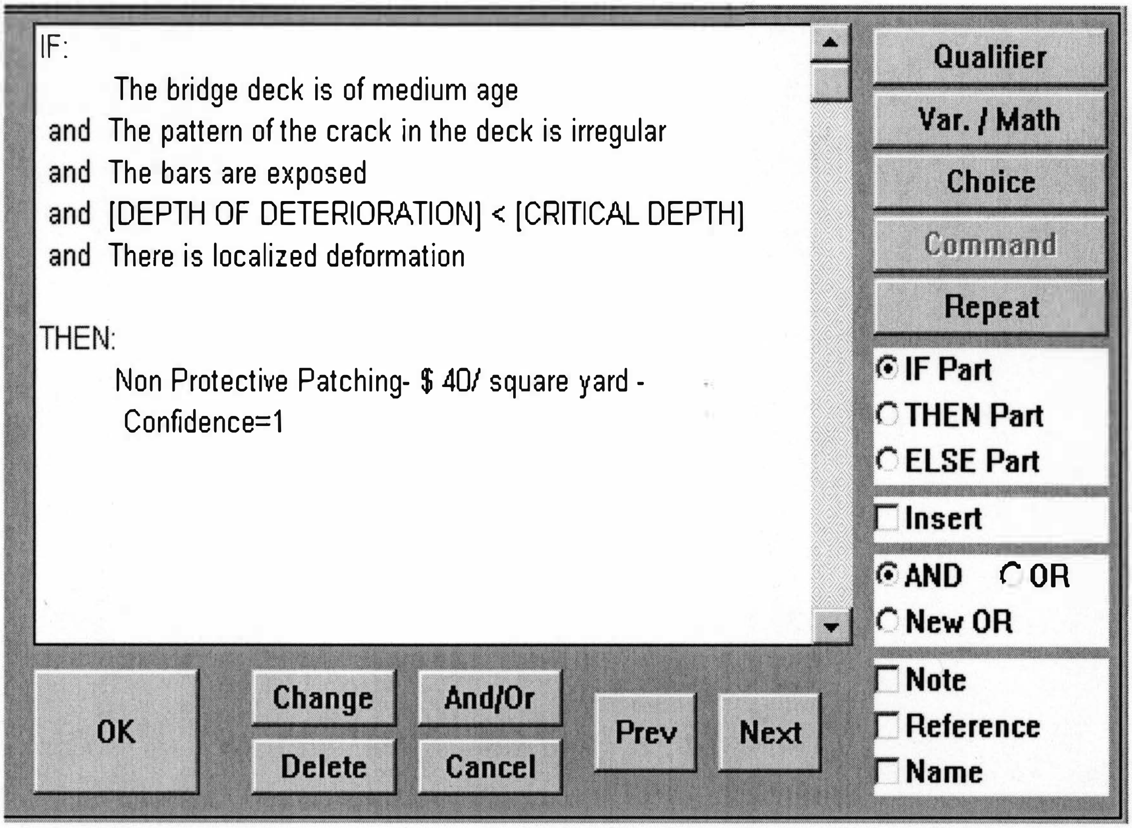

Figure 8.10: EXSYS Professional Rule Editor: Completed Rule

Once the rule is completed, click "OK" and move on to the next rule.

Parameters

When a new knowledge base is started the system asks the programmer to set the parameters for the decision support system. Most of these parameters can be changed later on except of the confidence mode. The decision support system will not move forward, until and unless these parameters are set in advance. A brief description of these parameters are given below.

Subject

Every decision support system should have a unique subject. This subject is displayed on the system title screen. The subject title cannot be more than 200 characters.

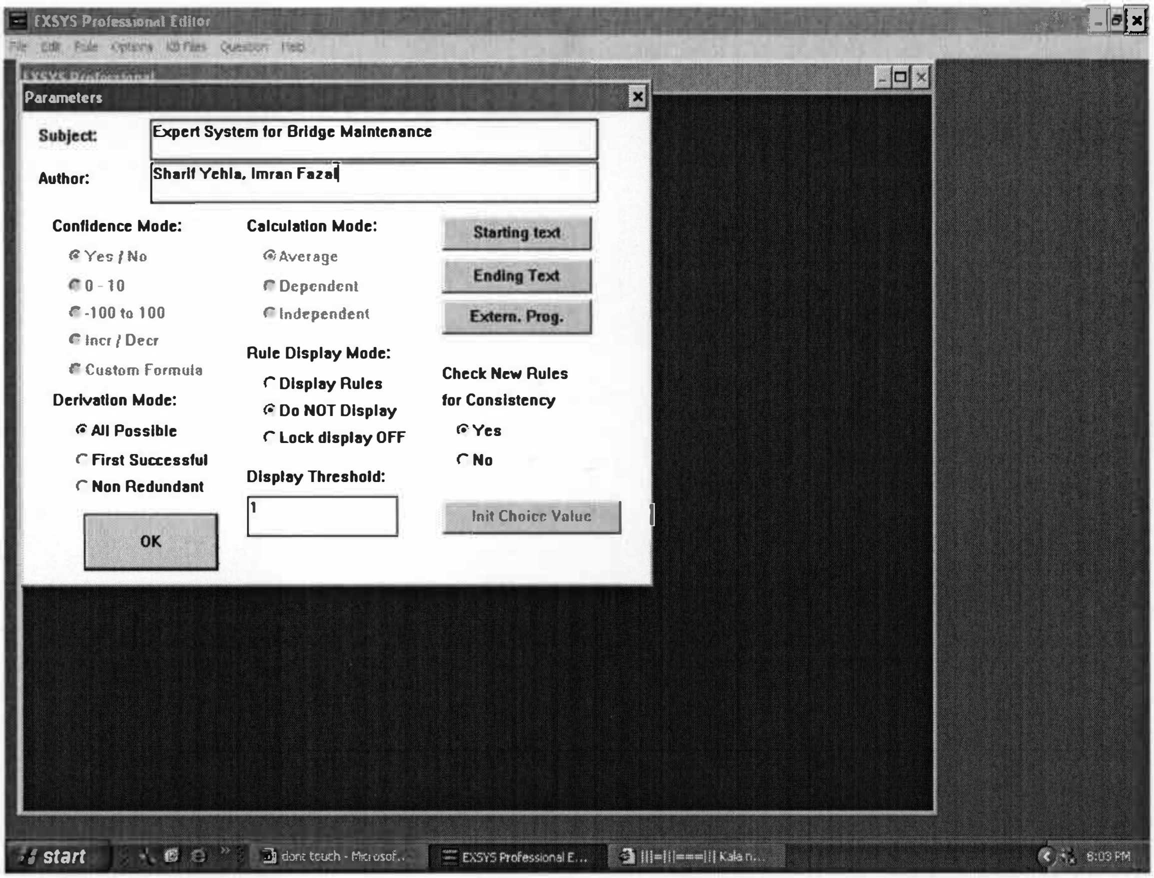

Figure 8.11: EXSYS Professional Rule Editor: Parameters

Author

Like the subject, the program asks for the author's name. The author's name should also be less than 200 characters in length. The author's name is also shown on the title screen. The decision support system will not move forward until the author's name is entered.

Confidence Mode

There are five-confidence modes from which we can select for the expert system. Broadly speaking, confidence mode system assigns the extent of confidence to the choice that we select in any rule. There might be some cases, in which the choices cannot be selected with complete confidence. Therefore, the most logical and obvious YES/NO confidence mode system cannot be used for every decision support system. The five confidence modes systems are explained below.

YES/NO System

If the choices in the decision support system do not need any probabilistic estimates, the Yes/NO (0-1) is the best system to select. This system is comparatively very easy to use since the first rule that fires for a choice sets the value to 1 for Yes or 0 for No. No intermediate values can be assigned for the choices.

This kind of confidence system is very good for selecting choices from a list, an automated questionnaire, or other systems which contain choices that can be definitely answered with a "yes" or "no".

0/10 System

The confidence mode is from 0 to 10 in this system. It is used for problems whose outcomes are may not be categorized as absolute "Yes" or "No". An assignment of 0 locks the value for the choice at "No", while the assignment of 10 locks the value for the choice at "Yes". This system is not only capable of selecting or rejecting a choice but can also allow intermediate values to indicate choices that may be appropriate.

For example, repair method, LMC overlay was in three rules which fired with confidence level 3,7,8; repair method, FRC overlay was in two rules which fired with confidence level 6 and 10; and repair method, Bituminous overlay was in one rule with the confidence level of 4. The expert system will show three results with the following average confidence levels.

- Choice 2: 10 (because of the presence of absolute yes in the answers)
- Choice 1: 6 (the average of the three numbers)

- Choice 3: 4

The decision support system will recommend FRC overlay for repair, followed by the other two methods.

–100 to +100 System

In this system, values can be assigned to choices in the range of –100 to +100. This system provides more range to the user compared to 0-10 system. One of the drawbacks in this system is that absolute yes and no cannot be used. This system is best suited to problems whose outcomes are essentially probabilistic. This system is also best if independent or dependent probability is required.

Increment/Decrement System

In this system values are either added to, or subtracted from the total points for a choice. A rule can add or subtract as much as 100 points from the total for a choice. This system differentiates among possible outcomes that might provide identical results using the other systems.

For example if one choice gets the value 3,3,3 and the other receives 3,3 the 0-10 system will average the values and will consider both choices as equal. Unlike 0-10 system, this system will prefer choice one over choice two because the final score for choice one would be 9, and the final score of choice two would be 6.

Custom Formula System

This is by far the most difficult and cumbersome of the confidence systems. This is not recommended for the beginners. This should only be used when the other confidence systems are not feasible to use. This system allows the developer to write his own formulas for the combination of confidence values.

Calculation Mode

This radio button will only come into effect if and only if the –100 to +100 confidence mode is selected. The calculation mode selects how the values assigned to choices in the –100/+100 system will be combined. Any of three options average, dependent probability, and independent probability can be selected.

Threshold Level for the Display of the Results

This parameter determines, which choices will be displayed in final screen. The decision support system makes its choice, dependent on the final score. This value can be adjusted based on the type of problem and confidence mode used in a particular decision support system.

Display Rule Mode

This mode determines whether the rules will be displayed at the end of the run or not. If the "Display Rule" mode is selected, then all the rules that fires will be displayed at the end of the run automatically. If the second option is selected the user can always check the rules by using the "HOW" option at the end of the run. Rules cannot be examined if the third option is selected.

Starting & Ending Texts

The programmer can enter starting and ending text to be displayed at the beginning and the end of the run. This is an extra feature of EXSYS Professional, which makes it look more complete and effective.

External Program

The system can call an external program to be run at the end or start of the run. The external program can be a database, spreadsheet, or a power point presentation.

Printing the Knowledge Base

The whole knowledge base can be printed with a simple command in EXSYS Professional. To print the knowledge base, select print from the file menu. It will allow you to print the knowledge base either to the disk file or to the printer.

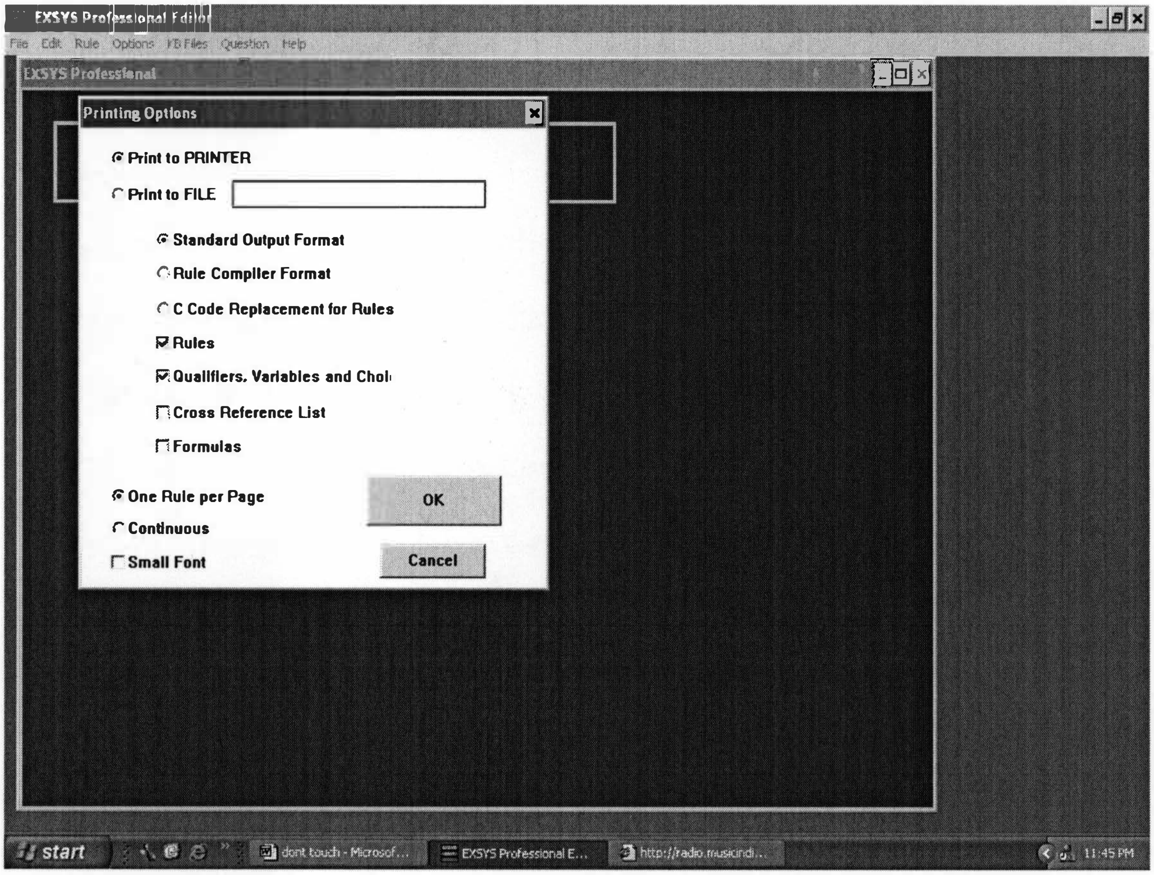

Figure 8.12: EXSYS Professional Editor: Printing the Knowledge Base

The various options in printing can be changed using this window. It is always advisable to copy the knowledge base to the disk file and then print it.

8.6 Development of the Decision Support System

This decision support system was developed using EXSYS Professional. The complete name of the decision support system is "Decision Support System for Bridge Maintenance. In addition to the decision support system, auxiliary files were also made, which shows the repair methods in detail. These auxiliary files can be retrieved after the run is completed.

8.6.1 Confidence Mode for the Decision Support System

Confidence mode is one of the most important parameters. It is very difficult to change the confidence mode once the development of the decision support system is begun. It can only be changed through the rule complier. The confidence mode selected for this decision support system was 0-10. This confidence mode was selected because of the following reasons:

- It is the most user-friendly confidence mode system.
- The problem selected, had clear and mutually exclusive choices (repair methods).
- The choices did not have any probabilistic calculations in them.

8.6.2 Qualifiers for the Decision Support System

The qualifiers were based on the feedback from questionneer survey as well as the literature review. It was made sure that all possible scenarios are included. This is also very important part because qualifiers make a big bulk of the questions that will be asked from the user. The total number of qualifiers was 18 (Appendix A).

8.6.3 Choices for the Decision Support System

As explained above, choices are the results of the run. The total number of choices used in this decision support system was 20 (Appendix B). This means that there are a total of 20 possible outcomes that this decision support system can give to the user. There are certain scenarios in which the decision support system suggests more than one choice at the end of the run. This is because the in certain cases experts have to choose between two closely competing methods of repair. Since the confidence mode is 0-10, the repair methods have the same confidence. In such case the repair method can ultimately be decided upon the cost of the repair.

8.6.4 Variables for the Decision Support System

The total number of variables used in this decision support system was 11 (Appendix C). The initial values, upper limits, and the lower limits for the variables were set based on the literature review.

8.6.5 Rules for the Decision Support System

The total number of rules used in this decision support system was 42 (Appendix D). All of the rules were checked for consistency among each other. It was sure that the rules have correct order since the firing of rules sometimes should be in the right sequence for backward chaining.

8.6.6 Run

The decision support system can be run by pulling down the "Option" menu, and then clicking "Run". A sample scenario is run below for display purposes.

Let us suppose that a bridge deck after inspection has the following information to the user.

- The bridge deck is of young age (0-10) years.
- The bars are fully exposed and rusted.
- Delamination is 40% of the total deck area.
- Funds for the repair or replacement are available.

Let us run the decision support system to find out the repair and rehabilitation strategy for the above case.

Once the run option is activated, the following window will appear.

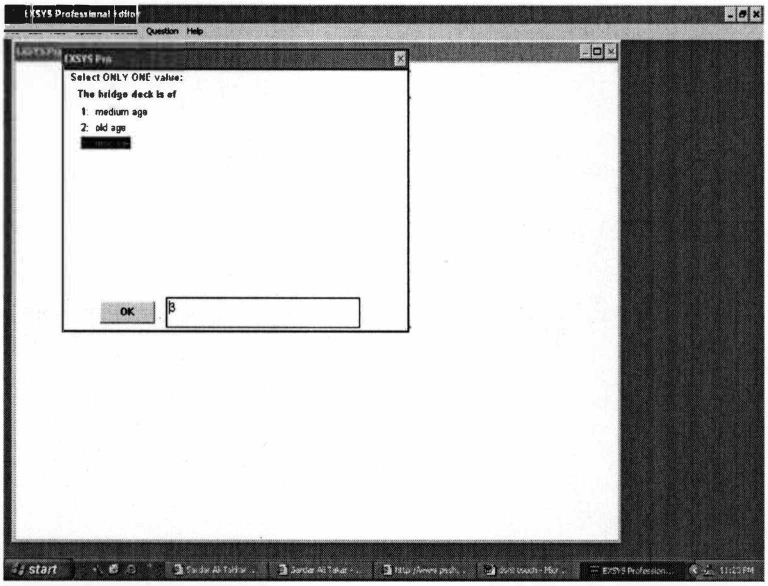

Figure 8.13: Run "Step 1"

Clicking on option 3 will pop up the following window.

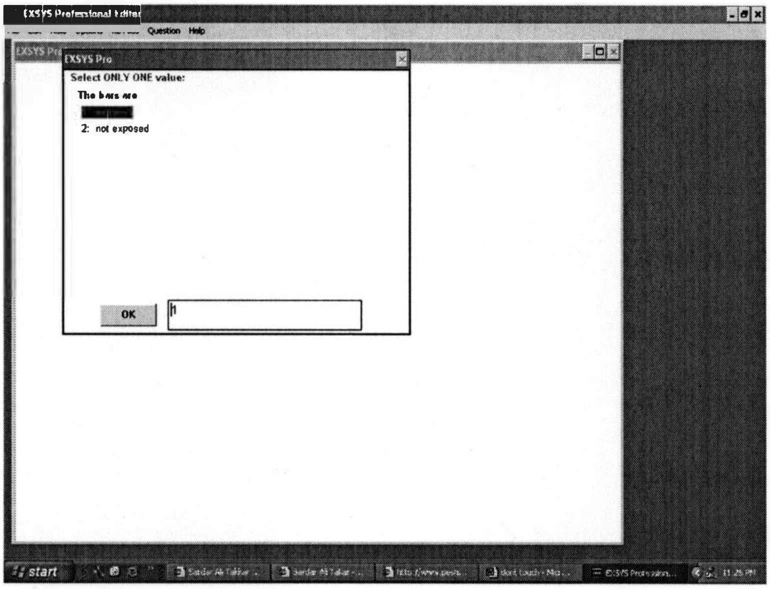

Figure 8.14: Run “Step 2”

Clicking on option 1 will bring on the following window.

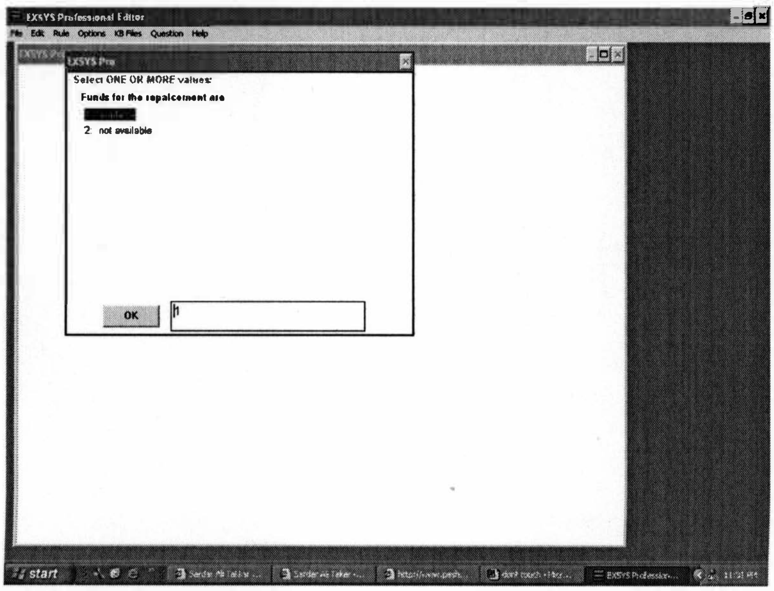

Figure 8.15: Run “Step 3”

Clicking on option 1 will bring the following window.

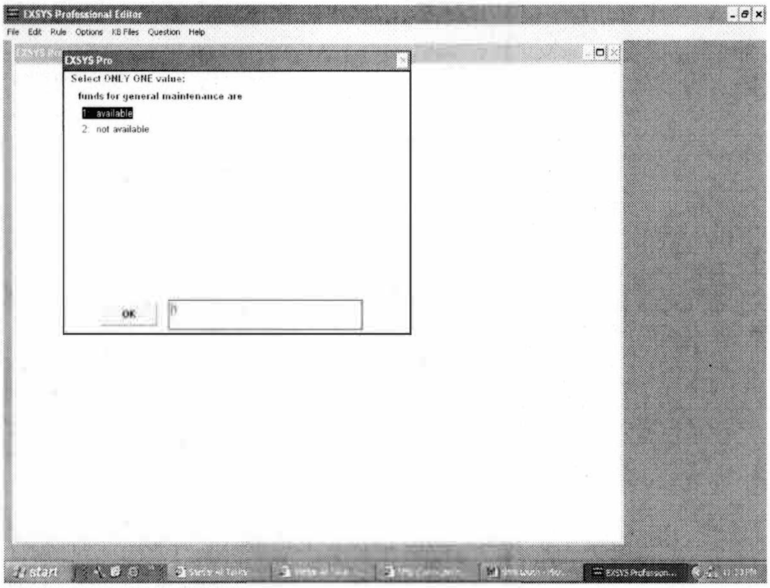

Figure 8.16: Run "Step 4"

Clicking on option 1 will bring the following window.

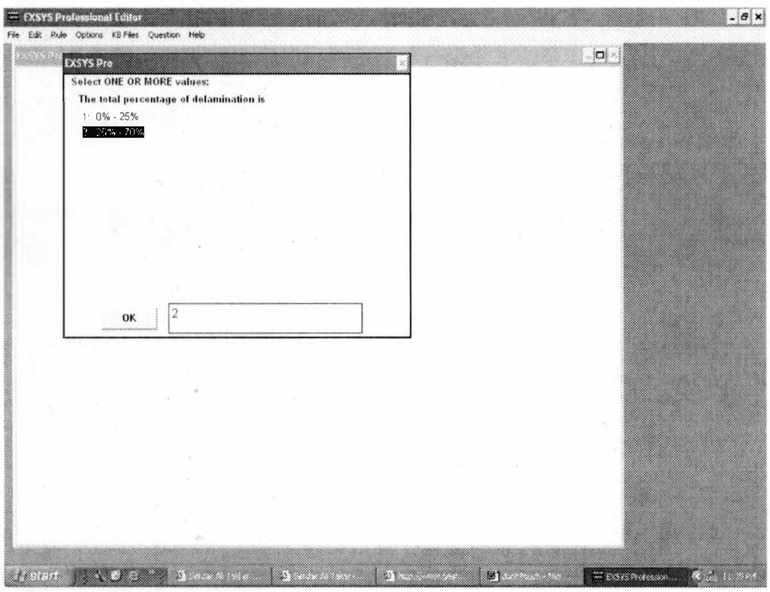

Figure 8.17: Run "Step 5"

Clicking on option 2 will bring the repair method suggested.

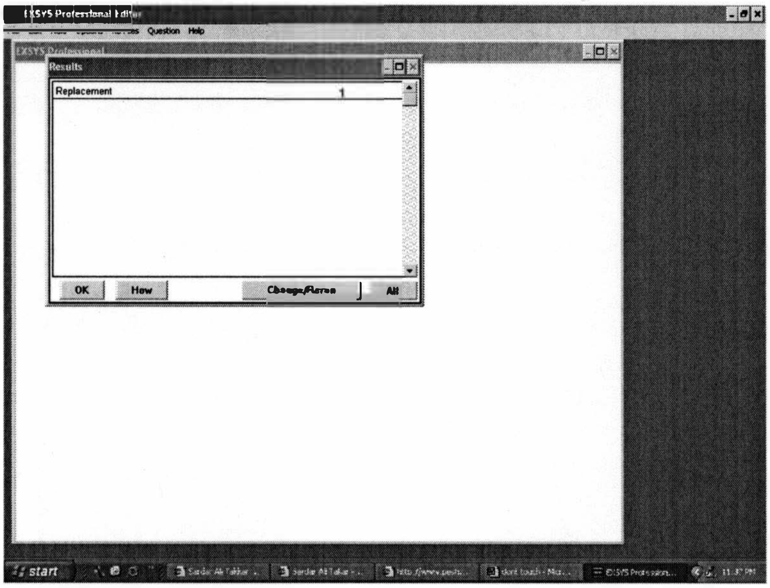

Figure 8.18: Run "Step 6"

This window shows that replacement is the best option. The user can ask the decision support system why this conclusion was reached, by click the repair method suggested, followed by the "HOW" button. The decision support system will show the rule(s), which directed the system to the suggested decision.

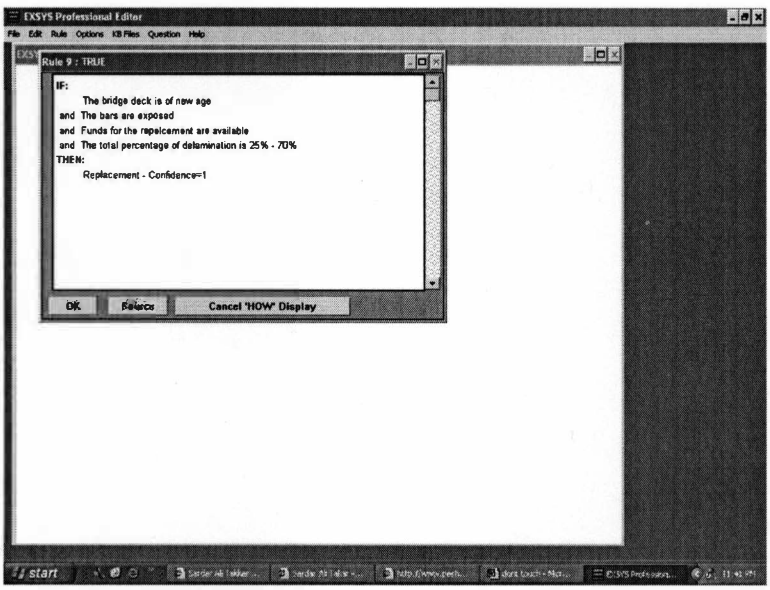

Figure 8.19: Run "Step 7"

8.7 Chapter Summary

This chapter discussed the development of the decision support system. The "Tree Diagram" was explained. The questioneer and the main points it sought to exploit were also discussed. The bulk of the chapter explained the various components of "EXSYS Professional". Rules, qualifiers, choices, and variables that were used in the decision support system were explained. Running the soft ware for a short and selected scenario concluded the chapter.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

The transportation infrastructure in the United States has been deteriorating over the past few decades. It is generally believed that maintenance of the transportation infrastructure is lagging behind the deterioration rate. Bridges are one of the key elements of the transportation infrastructure in the United States. Bridge decks are susceptible to deterioration because of its main function and location within the bridge components. Deterioration in the bridge deck impedes the usefulness of the bridge and can be a reason to human and business losses.

The traditional means of bridge deck inspection and repair are faulty and can some time add up to the deterioration rather than decreasing it. Repair is carried out on the basis of the data received from the inspection reports and logs. The bridge inspector consults these logs and reports and tries to reach an optimal decision about the repair and rehabilitation procedure. This decision-making acumen comes from the bridge inspector's intuition and experience. The decision-making knowledge is mostly tacit and is very difficult to codify.

The objective of this thesis was to codify the decision making process by the bridge inspector. The product of this research will be a decision support system for bridge maintenance.

This decision support system was made for the problems of cracking, corrosion, and delamination. The three problems with concrete bridge decks were thoroughly investigated in literature. The research can be broadly classified into three main stages.

- The problems of corrosion, delamination, and cracking were studied thoroughly. Journal papers, books and DOT's manuals were consulted. The objective of the first part of the thesis was to familiarize the reader with the problems we are dealing with.
- The second stage was the probably the most important one. The objective of this part was to find answers to most of the questions that were raised by the literature review. The repair and rehabilitation strategies for the above-mentioned problems were studied. Based on the knowledge gained from the literature review about the three problems and their repair and rehabilitation strategies, a decision tree was built. This decision tree was used to develop a questionnaire, which was sent to bridge repair experts in various departments of transportations. The feedback from the survey was processed to get the required knowledge. The repair procedures from the literature and experts feedback were compared and a common criterion for repair was tried to come up with. This "common criteria" proved to be very beneficial in the development of the decision support system.
- Using the knowledge gained from the first two stages, a decision support system was developed for bridge maintenance. The decision support system was developed with an Expert System Shell called "EXSYS Professional". EXSYS Professional was preferred against various other available shells because it is very user friendly compared to most of the other shells. EXSYS Professional uses both backward and forward chaining processes.

9.2 Conclusions

The study reached the following conclusions.

9.2.1 Inspection Procedure

One of the main conclusions of the study was that the inspection practices and procedures are faulty and needs some restructuring.

- DOT's (Departments of Transportations) use different kind of forms for inspection purposes. These forms are very general. They rate the bridge components individually. This system of rating is not effective for the identification of the problem.
- The questionnaire survey revealed that delamination inspection is still done with chain drag despite the availability of modern equipments like the GPR and the thermograph.
- The questionnaire survey revealed that there is no standard procedure for the inspection of corrosion in concrete bridge decks. Half-cell method was used in the eighties but it has been abandoned for one reason or another.
- The questionnaire survey also revealed that the cost of repair differs considerably from one state to another.
- The questionnaire survey also revealed that naked eye inspection is the predominantly used for the inspection of cracking in concrete bridge decks. Moreover, the feedback showed that cracking is considered to be an absolute phenomenon and the cause of cracking is not tried to be investigated before reaching on a conclusion about the repair procedure. As opposed to this practice the literature review showed that different kinds of cracking, that may seem to be

identical, needs to be repaired in completely different ways. For example cracking due to design problems may need to be repaired in a completely different way from shrinkage cracks.

9.2.2 Cost

The study concluded the following about the cost of repair.

- Cost for the repair varies considerably through out the United States.
- Cost should be made a factor in the decision making process. It is only possible if we can initialize cost as a variable in the decision support system. In this decision support system the end choice is associated with the cost of the repair. Selection criterion for all of the bridge deck problems and their repair methods should be developed to drag the cost into the decision tree and to make it as a factor in the decision making process rather than an outcome of the decision making process.
- The feedback from the questionnaire showed that the cost factor is kept in mind before reaching a conclusion about the deck repair.
- Experts were not able to provide a concrete answer to the question "how do they use the cost factor in their decision making process"? In other words their answer was objective rather than subjective.

9.2.3 Bridge Management System

The ultimate goal of this study was to some how link this decision support system with other Network Level Bridge Management Systems. The study concluded the following in this regard.

- Pontis, which is used by most of the DOT's, is a Network Level Bridge Management System. Pontis takes a group of bridges and rates them, once repair funds becomes available the bridge with the highest ranking is taken out of the list and the whole list is updated. Pontis does not provide any information about the individual bridge because it is not project level Bridge Management System. Researchers consider this to be a loophole and they argue that Pontis should be linked with another project specific level Bridge Management System.

- This decision support system can serve the purpose of a project specific Bridge Management System, if it is extended to all the problems with concrete bridge decks.

Expert's input is very important and pivotal for the success of any decision support system. One of the main conclusions of the study was that the experts need to be interviewed rather than sent questionnaire. The reason is that knowledge about the bridge repair is subjective. The usual questionnaire survey does not serve the purpose because information required cannot be in yes/no format. Most of the time the experts find it tedious and laborious to answer the explanatory mode of the questionnaire.

9.3 Contributions

The main contributions from the author in this thesis are as follows.

- The development of the "Tree diagram for Decision Support System"
- The development and formatting of questionnaire, which was sent to experts through out the country in the field of bridge management.
- The development of the "Decision Support System for Bridge Maintenance."
- The development of the inspection form, which will be used to extract data for the running of this decision support system.

This decision support system has some limitations. These limitations are as follows.

9.4 Limitations

The limitations of this decision support system are as follows

- This decision support system can suggest repair method only for the problems of corrosion, delamination, and cracking.
- This decision support system needs specific data as an input, therefore should be used with specially made inspection forms.

9.5 Recommendations

The following are the recommendation and future research needs that can support and enhance this study.

- The scope of the study should be extended so that it can cover all of the bridge deck problems. Once a decision support system is good enough to suggest recommendation to any kind of bridge deck problem, it can be used in conjunction with any Network Level Bridge Management System.
- The inspection process and procedures should be changed through out the DOT's. Inspection equipments like GPR and Thermographs should be used to get a more accurate inspection data.
- The inspection forms are too general and they need to be made more specific. Some auxiliary forms needs to be used along with already in use inspections forms to run this decision support system. One such sample form is shown in Appendix F.
- Interviews rather than questionnaires should be used to get the input from the experts. The knowledge gained through interviews promises to be more accurate and extensive.

- Cost should be included as a factor in the decision-making process rather than a product of the process.

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APPENDIX A

List of Qualifiers

1. The bridge deck is of

- Medium age
- Old age
- New age

Maximum acceptable = 1

2. The pattern of the crack in the deck is

- Regular
- Irregular

Maximum acceptable = 1

3. The bridge is on an

- Interstate
- Internal road

Maximum acceptable = 1

4. The bars are

- Exposed
- Not exposed

Maximum acceptable = 1

5. Immediate reopening of the bridge is a

- Priority
- Not a priority
- Not sure

Maximum acceptable = 1

6. The conditions are

- Moist
- Dry

Maximum acceptable = 1

7. The bars used in the construction of the deck are

- Plain
- Specialty bars

Maximum acceptable = 1

8. External appearance of the deck is

- A factor in the decision
- Not a factor in the decision

Maximum acceptable = 1

9. Funds for the replacement are

- Available
- Not available

Maximum acceptable = 1

10. Skilled labor is

- Expensive
- Not expensive

Maximum acceptable = 1

11. The treatment should be

- Protective
- Non protective

Maximum acceptable = 1

12. There is surface cracking in the deck due to

- Slippage of the surface area
- Thermal change
- Flattening of blisters
- Loosening of the concrete at the kerbs and joints

Maximum acceptable = 1

13. There is

- Localized deformation
- Localized depression
- Cracking at structural joints

Maximum acceptable = 1

14 The total percentage of delamination is

- 0% - 25%
- 25% - 70%

Maximum acceptable = 1

15. The width of the crack is

- LESS THAN 0.003"
- 0.003-0.25"
- MORE THAN 0.25"

Maximum acceptable = 1

16. The depth of the crack is

- 0-6"
- 6-12"

Maximum acceptable = 1

17. Funds for general maintenance are

- Available
- Not available

Maximum acceptable = 1

18 Even at a higher cost high durability is

- Required
- Not required

Maximum acceptable = 1

APPENDIX B

List of Choices

1. Do nothing.
2. Replacement- $ 85 square ft.
3. Non Protective Sealing- $ 9.48/ square yard.
4. Non Protective Patching- $ 40/ square yard
5. Non Protective Overlay- Portland cement concrete overlay- $ 83.21/ square yard------- Bitumen concrete overlay- $ 24.62/ square yard.
6. Protective Epoxy Grouting-
7. Protective Hydraulic Cement Grouting.
8. LMC Overlay- $ 35 / square ft.
9. LSD.
10. FRC.
11. Low Pressure Spraying.
12. High Pressure Injections.
13. Penetrating Sealers: $ 5.45/ square yard.
14. Polymer Modified Cement Coating- $ 43.55/ square yard.
15. Gravity Sealing-$ 1.50 / square ft.
16. Coating Sealers.
17. Do Nothing - The Bridge needs to be replaced in the near future.

18. Do Nothing- The condition of the bridge is critical. The delamination is too high. The bridge should be closed for traffic if possible until funds are available.

19. Coating with Epoxy Resin.

20. Do Nothing- The Bridge needs to be repaired once the funds become available.

APPENDIX C

List of Variables

1. ADT

    Average Daily Traffic

  Numeric variable

2. CRITICAL ADT

    The Critical Average Daily Traffic

  Numeric variable

  Initialized to 10000.000000

3. TOTAL DELAMINATION

    The Total Delamination in Percentage

  Numeric variable

4. MILD DELAMINATION

    The Delamination, which is less than 25 %

  Numeric variable

  Initialized to 25.000000

5. SEVERE DELAMINATION

    The Delamination, which is 25%-50%

  Numeric variable

  Initialized to 50.000000

6. CRACK WIDTH

The Width of the Crack

Numeric variable

7. CRACK DEPTH

The Depth of the Crack

Numeric variable

8. MIN CRACK

The Minimum Crack Width

Numeric variable

Upper limit = 0.250000

Lower limit = 0.003000

9. MIN CRACK DEPTH

The Minimum Crack Depth

Numeric variable

Lower limit = 12.000000

10. DEPTH OF DETERIORATION

The Depth of Deterioration

Numeric variable

11. CRITICAL DEPTH

The Critical Depth

Numeric variable

Initialized to 0.750000

APPENDIX D

Rules

<u>RULE NUMBER: 1</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is surface cracking in the deck due to thermal change

THEN:

Non-Protective Sealing- $ 9.48/ square yard. – Confidence = 1

<u>RULE NUMBER: 2</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is surface cracking in the deck due to slippage of the surface area

THEN:

Non-Protective Sealing- $ 9.48/ square yard. - Confidence=1

<u>RULE NUMBER: 3</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is surface cracking in the deck due to flattening of blisters

THEN:

Non-Protective Sealing- $ 9.48/ square yard. - Confidence=1

<u>RULE NUMBER: 4</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is surface cracking in the deck due to loosening of the concrete at the kerbs and joints

THEN:

Non-Protective Sealing- $ 9.48/ square yard. - Confidence=1

<u>RULE NUMBER: 5</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is localized deformation

THEN:

Non-Protective Patching- $ 40/ square yard - Confidence=1

<u>RULE NUMBER: 6</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is cracking at structural joints

THEN:

Non-Protective Pathing- $ 40/ square yard - Confidence=1

<u>RULE NUMBER: 7</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is localized depression

THEN:

Non-Protective Patching- $ 40/ square yard - Confidence=1

RULE NUMBER: 8

IF:

The bridge deck is of new age

and The bars are not exposed

and Funds for the replacement are not available

and The total percentage of delamination is 0% - 25%

THEN:

Do nothing - Confidence=1

RULE NUMBER: 9

IF:

The bridge deck is of new age

and The bars are exposed

and Funds for the replacement are available

and The total percentage of delamination is 25% - 70%

THEN:

Replacement- $ 85 square ft. - Confidence=1

RULE NUMBER: 10

IF:

The bridge deck is of new age

and The bars are exposed

and Funds for the repalcement are not available

and The total percentage of delamination is 25% - 70%

THEN:

Do nothing - Confidence=1

RULE NUMBER: 11

IF:

The bridge deck is of old age

and [ADT] > [CRITICAL ADT]

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are available

THEN:

Replacement- $ 85 square ft. - Confidence=1

RULE NUMBER: 12

IF:

The bridge deck is of new age

and The bars are not exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is less than 0.003"

and The depth of the crack is 0-6"

THEN:

Do nothing - Confidence=1

RULE NUMBER: 13

IF:

The bridge deck is of new age

and The bars are not exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are not available

THEN:

Do Nothing- The condition of the bridge is critical. The delamination is too high. The bridge should be closed for traffic if possible until funds are available - Confidence=1

RULE NUMBER: 14

IF:

The bridge deck is of new age

and The bars are exposed

and funds for general maintenance are available

and The total percentage of delamination is 0% - 25%

THEN:

Non-Protective Patching- $ 40/ square yard - Confidence=1

RULE NUMBER: 15

IF:

The bridge deck is of new age

and The bars are exposed

and funds for general maintenance are not available

and The total percentage of delamination is 0% - 25%

THEN:

Do nothing - Confidence=1

RULE NUMBER: 16

IF:

The bridge deck is of new age

and The bars are not exposed

and Funds for the replacement are not available

and funds for general maintenance are available

and The total percentage of delamination is 0% - 25%

and The width of the crack is more than 0.25"

THEN:

Non-Protective Patching- $ 40/ square yard - Confidence=1

RULE NUMBER: 17

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are not exposed

and [DEPTH OF DETERIORATION] > [CRITICAL DEPTH]

THEN:

Non Protective Overlay- Portland cement concrete overlay- $ 83.21/ square yard------- Bitumen concrete overlay- $ 24.62/ square yard. - Confidence=1

RULE NUMBER: 18

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are exposed

and [DEPTH OF DETERIORATION] > [CRITICAL DEPTH]

THEN:

Non Protective Overlay- Portland cement concrete overlay- $ 83.21/ square yard------- Bitumen concrete overlay- $ 24.62/ square yard. - Confidence=1

RULE NUMBER: 19

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are exposed

and [DEPTH OF DETERIORATION] > [CRITICAL DEPTH]

THEN:

Non Protective Overlay- Portland cement concrete overlay- $ 83.21/ square yard------- Bitumen concrete overlay- $ 24.62/ square yard. - Confidence=1

RULE NUMBER: 20

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The width of the crack is less than 0.003"

and The total percentage of delamination is 0% - 25%

and Immediate reopening of the bridge is a not sure

THEN:

Low Pressure Spraying - Confidence=1

RULE NUMBER: 21

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The width of the crack is 0.003-0.25"

and The total percentage of delamination is 0% - 25%

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 22

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The width of the crack is 0.003-0.25"

and The total percentage of delamination is 25% - 70%

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 23

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The width of the crack is more than 0.25"

and The depth of the crack is 0-6"

THEN:

Protective Hydraulic Cement Grouting - Confidence=1

RULE NUMBER: 24

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The width of the crack is more then 0.25"

and the depth of the crack is 6-12"

and Funds for the replacement are not available

and The conditions are dry

THEN:

Gravity Sealing-$ 1.50 / square ft. - Confidence=1

RULE NUMBER: 25

IF:

The bridge deck is of medium age

and Immediate reopening of the bridge is a priority

and [DEPTH OF DETERIORATION] > [CRITICAL DEPTH]

and The bars are exposed

and The total percentage of delamination is 0% - 25%

and The pattern of the crack in the deck is regular

and The width of the crack is less than 0.003"

THEN:

LMC Overlay- $ 35 / square ft. - Confidence=1

<u>RULE NUMBER: 26</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The bars are exposed

and The total percentage of delamination is 25% - 70%

and The width of the crack is more than 0.25"

and Funds for the replacement are available

THEN:

Replacement- $ 85 square ft. - Confidence=1

<u>RULE NUMBER: 27</u>

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and Immediate reopening of the bridge is a priority and The bars are exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is more than 0.25"

and Even at a higher cost high durability is required

THEN:

FRC - Confidence=1

RULE NUMBER: 28

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The bars are not exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are available

THEN:

Replacement- $ 85 square ft. - Confidence=1

RULE NUMBER: 29

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The bars are not exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are not available

and The conditions are moist

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 30

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and The bars are exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is more than 0.25"

and The depth of the crack is 6-12"

and Funds for the replacement are not available

and The conditions are moist

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 31

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is regular

and Immediate reopening of the bridge is a not a priority

and The bars are exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is more than 0.25"

THEN:

LSD - Confidence=1

RULE NUMBER: 32

IF:

The bridge deck is of new age

and The bars are not exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is 0.003-0.25"

THEN:

Coating with Epoxy Resin - Confidence=1

RULE NUMBER: 33

IF:

The bridge deck is of new age

and The bars are not exposed

and The total percentage of delamination is 0% - 25%

and The width of the crack is more than 0.25"

THEN:

Coating with Epoxy Resin - Confidence=1

RULE NUMBER: 34

IF:

The bridge deck is of old age

and [ADT] > [CRITICAL ADT]

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are not available

THEN:

Do Nothing- The condition of the bridge is critical. The delamination is too high. The bridge should be closed for traffic if possible until funds are available - Confidence=1

RULE NUMBER: 35

IF:

The bridge deck is of old age

and [ADT] > [CRITICAL ADT]

and The total percentage of delamination is 0% - 25%

and funds for general maintenance are not available

THEN:

Do Nothing- The Bridge needs to be repaired once the funds become available - Confidence=1

RULE NUMBER: 36

IF:

The bridge deck is of old age

and [ADT] > [CRITICAL ADT]

and The total percentage of delamination is 0% - 25%

and funds for general maintenance are available

and The conditions are moist

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 37

IF:

The bridge deck is of old age

and [ADT] > [CRITICAL ADT]

and The total percentage of delamination is 0% - 25%

and funds for general maintenance are available

and The conditions are dry

THEN:

Protective Hydraulic Cement Grouting - Confidence=1

RULE NUMBER: 38

IF:

The bridge deck is of old age

and [ADT] < [CRITICAL ADT]

and The bars are exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are available

THEN:

Replacement- $ 85 square ft. - Confidence=1

RULE NUMBER: 39

IF:

The bridge deck is of old age

and [ADT] < [CRITICAL ADT]

and The bars are exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are not available

THEN:

Do Nothing- The condition of the bridge is critical. The delamination is too high. The bridge should be closed for traffic if possible until funds are available - Confidence=1

RULE NUMBER: 40

IF:

The bridge deck is of old age

and [ADT] < [CRITICAL ADT]

and The bars are not exposed

and The total percentage of delamination is 25% - 70%

and Funds for the replacement are not available

THEN:

Do Nothing - The Bridge needs to be replaced in the near future. - Confidence=1

RULE NUMBER: 41

IF:

The bridge deck is of old age

and [ADT] < [CRITICAL ADT]

and The bars are exposed

and The total percentage of delamination is 0% - 25%

THEN:

Non Protective Overlay- Portland cement concrete overlay- $ 83.21/ square yard------- Bitumen concrete overlay- $ 24.62/ square yard. - Confidence=1

RULE NUMBER: 42

IF:

The bridge deck is of old age

and [ADT] < [CRITICAL ADT]

and The bars are not exposed

and The total percentage of delamination is 0% - 25%

and funds for general maintenance are available

THEN:

Protective Epoxy Grouting- - Confidence=1

RULE NUMBER: 43

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is localized deformation

THEN:

Non Protective Patching- $ 40/ square yard - Confidence=1

RULE NUMBER: 44

IF:

The bridge deck is of medium age

and The pattern of the crack in the deck is irregular

and The bars are exposed

and [DEPTH OF DETERIORATION] < [CRITICAL DEPTH]

and There is cracking at structural joints

THEN:

Non Protective Patching- $ 40/ square yard - Confidence=1

APPENDIX E

HSIRB APPROVAL NOT NEEDED

Date: November 17, 2004

To: Yehia Sherif, Principal Investigator
Imran Fazal, Student Investigator for thesis

From: Amy Naugle, Interim Chair

Re: Approval not needed

This letter will serve as confirmation that your project "Development of a Decision Support System for Bridge Repair and Maintenance" has been reviewed by the Human Subjects Institutional Review Board (HSIRB). Based on that review, the HSIRB has determined that approval is not required for you to conduct this project because you are not asking for information about individuals. Thank you for your concerns about protecting the rights and welfare of human subjects.

A copy of your protocol and a copy of this letter will be maintained in the HSIRB files.

APPENDIX F

QUESTIONNAIRE

1. What guidelines and specifications do you follow for the inspection, repair and rehabilitation of concrete bridge deck in your organization?
2. How does the various departments of transportations (specially the DOT of your state) rank various bridge elements (0---------9)?

Delamination

3. How do you access (measure the extent and subsequently record in your forms) delamination in a concrete bridge deck?
4. What kind of equipment do you use for the inspection and assessment of delamination?
5. How would you categorize delamination on the basis of its severity (moderate, low, severe)?
6. Do you investigate the cause of delamination before deciding upon the repair method? Does the cause of the problem have any bearing on the repair strategy?
7. What repair methods do you use for the repair of various levels of severity (low, medium, high) of delamination in a concrete bridge deck. Please answer for both protected and un-protected deck?
8. What repair materials do you use in any selected repair technique and method?
9. What are the various factors that you take into account before deciding upon the repair methods for delaminated bridge deck? (For all three levels of severity)

10. How do you record delamination on your inspection forms and logs?
11. Do you investigate the cause of delamination before deciding upon the repair method? Does the cause of the problem have any bearing on the repair strategy?
12. Do you keep the cost factor in your mind before deciding upon the repair method?
13. What are the costs of various methods of repair of delamination?

Cracking

14. How do measure and access the extent of cracking on a concrete bridge deck?
15. What is the extent of bridge deck cracking, after which the deck becomes a candidate for any kind of repair strategy? (How do you decide upon the "do nothing" option in this case)
16. What the various methods of repair for concrete bridge deck cracking?
17. What kind of equipment do you use for the inspection of cracking?
18. Do the repair methods and materials vary with the type of concrete deck cracking? (Shrinkage cracking, flexural cracking etc.)
19. How do you classify cracking in concrete bridge deck? (High, low, medium, negligible)
20. Do you investigate the cause of deck cracking before deciding upon the repair methods and materials?
21. What are the costs of various methods and materials of repair for cracking?

Corrosion

22. How do you record the rate of corrosion in a concrete bridge deck?
23. What equipment and methods do you use for the inspection of corrosion in a concrete bridge deck?

24. How do you classify corrosion? (High, low, medium)

25. How do you repair or rehabilitate a concrete bridge deck with corrosion?

26. What are the various materials used for this purpose and what are their costs?

APPENDIX G

INSPECTION FORM FOR DECISION SUPPORT SYSTEM

<table>
<tr><td colspan="3">DOT Bridge ID</td><td colspan="3">NBI Bridge ID</td></tr>
<tr><td colspan="2">Location</td><td colspan="2">Latitude</td><td colspan="2">Longitude</td></tr>
<tr><td colspan="2">Year Built</td><td colspan="2">Year Reconstructed</td><td colspan="2">Bridge Area</td></tr>
<tr><td colspan="2">Bridge Type</td><td colspan="2">Deck Type</td><td colspan="2">NBIS Rating</td></tr>
<tr><td colspan="2">ADT</td><td colspan="2">Average ADT</td><td colspan="2">Critical ADT</td></tr>
<tr><td colspan="6">CORROSION</td></tr>
<tr><td colspan="3">Method of Inspection</td><td colspan="3">Are the bars Exposed</td></tr>
<tr><td colspan="3">Type of bars used</td><td colspan="3">Percentage of Corrosion</td></tr>
<tr><td colspan="6">CRACKING</td></tr>
<tr><td colspan="3">Method of Inspection</td><td colspan="3">Type of Cracking</td></tr>
<tr><td colspan="2">Pattern of Cracking</td><td colspan="2">Irregular</td><td colspan="2">Regular</td></tr>
<tr><td colspan="2">Crack width</td><td colspan="2">Crack length</td><td colspan="2">Crack depth</td></tr>
<tr><td colspan="6">DELAMINATION</td></tr>
<tr><td colspan="2">Method of Inspection</td><td colspan="2">% of Delamination</td><td colspan="2">Cause of Delamination</td></tr>
<tr><td colspan="6">GENERAL INFORMATION</td></tr>
<tr><td colspan="3">Average Temp.</td><td colspan="3">Average Precipitation</td></tr>
<tr><td colspan="2">Average humidity</td><td colspan="2">Frequency of icing</td><td colspan="2">Skilled labor</td></tr>
<tr><td colspan="6">Additional Information (if any)</td></tr>
<tr><td colspan="3">Inspected by</td><td colspan="3">Date</td></tr>
</table>