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Maintenance, Repair and Rehabilitation (MR&R) Practice for Concrete Bridge Decks

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Abstract

Over the years, existing bridges have had various degrees of maintenance to extend the service life. As the existing bridges continue to deteriorate, however, each Department of Transportation (DOT) of the United States of America faces increasing demands on the limited funds available for bridge maintenance. Therefore, it is very important for State Department of Transportations to establish Maintenance, Repair, and Rehabilitation (MR&R) strategies for bridge structures such that funds get allocated for appropriate maintenance over the service life. This paper identifies the state-of-art and the state-of-practice of MR&R actions and the use of MR&R strategies in concrete bridge decks. In addition, a questionnaire survey was conducted to identify the type and timing for MR&R actions as well as existing MR&R strategies taken in concrete bridge deck by each DOT. This paper also presents the results of the survey.

Keywords: Bridge Decks, Maintenance, Repair, and Rehabilitation (MR&R) Action, Type and Time of MR&R Action, Questionnaire

1. INTRODUCTION

As existing bridges continue to deteriorate, each DOT faces increasing demands on the limited funds available for bridge maintenance. Bridges last much longer than paved highways. A bridge requires both preventive maintenance (planned maintenance) and corrective maintenance (unplanned maintenance) throughout its service life before being entirely replaced.

The focus of bridge engineering has, in the last few decades, slowly been changing from the design of new bridges to the maintenance, rehabilitation, and upgrading of existing bridges. This is in part due to the high structural deterioration rates that have been observed in some structures and the functional loss that has often occurred due to increasing traffic volumes (Brito and Branco 1998). As the U.S bridge inventory continues to age, the cost of maintaining it at an acceptable safety level continues to increase. The current annual maintenance cost of all U.S bridges has been estimated at $3 billion per year (Chase and Washer 1997). In recent years, a number of bridge management systems have been developed with the purpose of prioritizing the necessary maintenance. The basic principle on which some of these systems have been based is that an optimum network level maintenance strategy can be determined by recording the present condition states of the structures and their elements and then using deterioration prediction models related to different maintenance systems (Das 1999). It is very important for State Departments of Transportation to establish strategies with regard to maintenance, repair, and rehabilitation (MR&R) of bridges. However, the MR&R strategy for bridges typically receives too little consideration in bridge management systems.

The main objective of this paper is to the identify state-of-art and state of practice of Maintenance, Repair and Rehabilitation (MR&R) actions and the use of MR&R strategies in concrete bridge decks. This paper briefly introduces how bridges fail or deteriorate as well as two modes of bridge failure: namely, structurally deficient and functionally obsolete, in order to understand Maintenance, Repair, and Rehabilitation (MR&R) actions performed on a bridge. This paper also identifies existing MR&R actions and MR&R strategies taken in concrete bridge decks by State Departments of Transportation (DOT) particularly (i) the type of the MR&R actions and (ii) the timing for the MR&R actions.

As part of the present study, a questionnaire survey was carried out to determine the state-of-practice of concrete bridge deck maintenance and to document the experience of bridge maintenance engineers or inspectors. The survey questionnaire was mailed to each DOT to identify the type and timing for the MR&R actions and the existing MR&R strategies taken in concrete bridge decks.

2. FAILURE MODES OF BRIDGES

A bridge deficiency is defined as a defect in a bridge component or member that makes the bridge less capable or less desirable for use. To understand MR&R actions taken in bridges, one needs to understand how bridges fail or deteriorate. Therefore, it is important to understand clearly how components such as deck, superstructure, and substructure deteriorate in existing bridges. Although engineers are not in agreement about specific failure details and sequences, they usually agree on the primary locations and causes of bridge failures as illustrated by Ramey and Wright (1996). The Federal Highway Administration (FHWA) defines two modes of bridge failure; structurally deficient and functionally obsolete. If one of the three load carrying component (deck, super or substructure) of a bridge receives a condition rating (CR) of less than five on a scale of 0 – 9, then the bridge is considered to be “structurally deficient”. The structurally deficient mode of failure relates to condition of the bridge to its as-build conditions. “Functionally obsolete” means there is something unsatisfactory with the bridge geometry (for example, vertical clearance, width, railing or shoulders). The functionally obsolete mode of bridge failure is as the name implies, i.e., the bridge becomes obsolete relative to present standards (Ramey and Wright 1996).

3. MAINTENANCE, REPAIR, AND REHABILITATION ACTIONS IN BRIDGES

A bridge in good condition does not cost as much to maintain as compared to one in bad condition. Bridge maintenance can be delayed due to constraints such as availabilities of funds, competing priorities, and political considerations however the cost of repairing a structure increases significantly.

The repair of bridges often has been a reactive activity, initiated only when deterioration threatens the safety or tolerance of the public. Now, influenced by Bridge Management Systems (BMS), owners are beginning to emphasize cost-effective proactive strategies from the start, when the bridge is new. According to the American Association of State Highway and Transportation Officials (AASHTO 1993), "bridge management helps engineers and decision makers determine when and where to spend bridge funds so as to enhance safety, preserve existing infrastructure, and serve commerce and the motoring public." The BMS software being most commonly used in the United States of America is PONTIS and BRIDGIT.

One future focus will be preventive maintenance (Roberts 2000). Preventive maintenance (PM) is to keep bridge components in their current condition rating. Though preventive maintenance can not lead to substantial improvement of condition rating in bridge components, it can prevent or delay deterioration of bridge components. Studies over the past twenty years have shown convincingly that appropriate bridge management activities, performed at the proper time, are cost-effective (Das 1999, Purvis 2000). Therefore, preventive maintenance is cost-effective whereas deferring maintenance results in increased costs over the life of the structure. In addition to preventive maintenance, bridge MR&R action includes corrective maintenance (CM) which is performed in order to improve the condition rating of the bridge and is based on actual need. Without corrective maintenance activities, bridge deterioration can lead to reduction in the loading capacity of the bridge, its closure, or in the worst case, catastrophic failure.

(1) Preventive Maintenance

Preventive maintenance can be defined as a planned strategy of cost-effective treatments that are applied at the proper time to keep bridge in good condition and to avoid more expensive costs in the future to rehabilitate or replace bridges and extend the useful life of a bridge. The old adage of "an ounce of prevention is worth a pound of cure" is most appropriate for cost-effective maintenance of highway bridges.

As shown in Fig.1, bridge MR&R actions taken in preventive maintenance can be divided into two types such as routine and minor repair maintenance. Each type also has two sub-groups: maintenance performed at specified intervals and maintenance performed on needed basis. The first sub-group includes cyclic servicing of bridges on a scheduled basis. The intervals will be variable depending on each DOT and the type of MR&R action. New York DOT, for example, has performed seven "cyclic" preventive maintenances that are simply based on elapsed time from a previous treatment. These kinds of cyclical maintenance consist of activities that bridge owners can perform as planned actions, in advance of critical need, to reduce the rate of deterioration of critical bridge elements. These activities are essential for a bridge to reach its maximum useful life and maintain its designed level of service. The seven items are shown in Table 1 (NYDOT 1997).

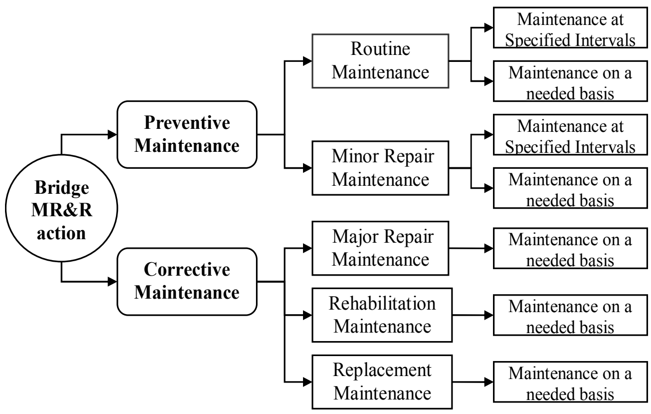

Figure 1. Classification of bridge MR&R actions

Table 1. Cyclic Preventive Maintenance in New York DOT

Action Items	Cycle
Bridge Cleaning	2 Years
Paint Bridge Steel	12 Years
Lubricate Bearing	4 Years
Seal Cracks in Wearing Surface	4 Years
Seal Concrete Deck	4 Years
Seal Concrete Substructures	6 Years
Replace asphalt wearing surface	12 Years

The activities of the first items (refer to Table 1) include such tasks as (Purvis 2000, Connecticut DOT 2002)

- (i) Cleaning deck, seats, caps, and salt splash zones,
- (ii) cleaning drainage system and opening drains,
- (iii) cleaning expansion joints,
- (iv) cleaning and lubricating expansion bearing assembly,
- (v) sealing concrete decks or substructure elements

Similarly, the second sub-group is performed corresponding to need identified by bridge inspectors. These activities include such tasks as (Purvis 2000) (i) resealing expansion joints, (ii) Painting of steel members, (iii) removal of debris (i.e., brush, pigeon guano, etc.) from sidewalk, safety walks, curbs, parapets, brush pigeon debris, etc., (iv) replace wearing surface, (v) extending or enlarging deck drains, (vi) sealing and patching of minor cracks in the floor or elsewhere, and (vii) correction of leakage (i.e., deck joint, scuppers, etc.)

It is also necessary to expand, formalize, and otherwise improve annual and other cyclic bridge preventative maintenance activities. Upper management should place a high priority on providing the funds and personnel necessary to adhere to scheduled maintenance activities (Ramey et al. 1997).

(2) Corrective Maintenance

In spite of even the most aggressive cyclical preventive maintenance, some deterioration or damage of a bridge will occur. The corrective maintenance is included in a traditional approach to bridge maintenance. Bridges were built and ignored if a safety problem was not reported until they became obsolete.

Table 2. Corrective Preventive Maintenance in New York DOT

Action Items	Description	Selection Criteria
Repairing asphalt wearing surface	Remove and replace damaged portions of wearing surface and membrane waterproofing	Consider this treatment for any bridge with an asphalt-cement wearing surface and wearing-surface condition rating less than 5.
Repairing concrete deck	Remove and replace damaged portions of structural concrete deck and reinforcing steel	Consider this treatment for any bridge with a structural-deck condition rating less than 5.
Repairing/ Replacing joints	Repair or remove and replace deteriorated or damaged sections of joint systems, including surrounding concrete. Perform this work on all types of joint systems, as required.	Consider this treatment for any bridge with a joint-system condition rating less than 5.
Repairing/ Replacing Steel members	Repair or replace deteriorated or damaged steel sections	Consider this treatment for any bridge with steel elements having a condition rating less than 5, for any member damaged while is service. Steel bridge members exhibiting cracking also need repair.
Repairing/ Replacing Bearings	Jack structure and repair or replace non-functioning bearing systems or system components for all types of bearings, as required.	Consider this treatment on any bridge with a bearing condition rating less than 5.
Repairing/ Replacing concrete substructures	Remove and replace damaged portions of substructure concrete and reinforcing steel	Consider this treatment for any ridge condition rating less than 5 for substructure elements (i.e., seat & pedestals, backwalls, stems, footing & piles, wingwalls, pier columns, pier caps, pier cap beams).
Repairing Erosion/ Scour	Repair undermined foundations and/or scoured or eroded stream channels with concrete, stone fill, or rip-rap.	Consider this treatment for any bridge with an erosion or scour condition rating less than 5.

As shown in Fig.1, major repair, rehabilitation, and replacement maintenance are included in corrective maintenance for bridge MR&R action. Each type has only one sub-category unlike preventive maintenance which is maintenance performed on an as needed basis. Corrective maintenance needs are based on logic related to the condition rating of various bridge elements, as well as the overall condition rating of the bridge. Corrective maintenance includes all items of painting, repairing existing structures, replacement of defective parts, units or sections and all other operations pertinent to restoring structures to either their original condition and capacity or to a safe and usable condition, possibly with limited capacity. It also includes the correction of conditions affecting stream flow and channel alignment and the repair of eroded or scoured areas adjacent to the structure (Connecticut DOT 2002, NYDOT 1997). The selection criteria and description of corrective maintenance taken in New York is presented in Table 2.

4. MR&R ACTIONS ON CONCRETE BRIDGE DECKS

As shown in Fig.1, bridge MR&R actions can be categorized into five kinds of maintenance: Routine Maintenance, Repair Maintenance (minor and major repair), Rehabilitation Maintenance, and Replacement Maintenance. Each maintenance type has at least one sub-category. The classification of MR&R actions taken in bridges can be adapted to the main bridge elements; deck, superstructure, and substructure. However, the bridge deck is an important part of the bridge and it is directly subjected to cyclic loading and harsh environmental conditions. Furthermore, concrete decks are more widely used than steel decks and they need maintenance more frequently (Liu et al. 1997). As indicated in the study by Saito and Sinha (1990), two major rehabili-tation groups for bridges are deck reconstruction and deck replacement. Deck reconstruction means that part of the deck is repaired by shallow or deep patching. Deck replacement consists of the replacement of the entire deck with a completely new one. They are the groups most frequently used to identify rehabilitation work by the state bridge inspectors (Saito and Sinha 1990).

The increase in trucking loads, use of lighter more flexible designs, and various environmental impacts all combine to make concrete decks highly susceptible to deterioration. Related to rehabilitation and maintenance are issues concerning the construction details of a bridge. The design of a highway bridge should focus not only on the ability of the structure to resist design loads but also on its ability to function over a long period of time with minimal maintenance and repair operations.

Table 3. Overall Maintenance of Concrete Bridge Decks

Preventive Maintenance	Routine Maintenance	Bridge Cleaning / Snow and Ice removal
	Minor Repair	Cracking / Scaling / Patching / Spalling / Sealing
Corrective Maintenance	Major Repair	Cracking / Scaling / Patching / Spalling / Sealing/ Cathodic Protection
	Rehabilitation	Increased Slab Thickness and cover
	Replacement	Cast-in-place deck / Precast reinforced concrete deck / FRP deck

There are a variety of construction, rehabilitation, and maintenance methods employed to increase the useful service lives of concrete bridge decks. Some methods can be employed at the initial construction of the deck while others represent remedial measures taken after deterioration has set in. As discussed earlier, there are two kinds of MR&R actions related to concrete bridge decks; CM and PM. The justification for corrective maintenance is that without it the bridge would be unsafe. The justification for preventive work is cost related: if it is not done on time, it will cost more at a later stage to keep the bridge deck condition from becoming critical (Frangopol et al. 1997). Based on literature review, various types of MR&R actions are summarized in Table 3. For more details on various MR&R actions refer to Tonias (1995), Connecticut DOT (2002), NYDOT (1997), and Hong (2003).

5. QUESTIONNAIRE SURVEY

For the purpose of this study, a questionnaire survey was conducted to determine the state of practice of MR&R actions and the use of MR&R strategies in concrete bridge decks. The survey questionnaire was designed along the various types of maintenance shown in Table 3. Three questions were asked of bridge engineers or inspectors of each DOT to be answered based on available data and/or subjective opinion (Refer to Table 4): (i) *Has your state implemented MR&R strategy to extend the life of concrete bridge decks? (ii) What kinds of MR&R actions were mostly taken in concrete bridge decks in your DOT? and (iii) When are the various MR&R actions taken in concrete bridge decks after bridge construction?*

Table 4. Matrix used in Questionnaire Survey

Maintenance		MR&R action	Year
Routine maintenance	☐	Bridge Cleaning	FA: ___ FT: ___
	☐	Snow and Ice Removal	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
Repair Maintenance	☐	Crack Maintenance	FA: ___ FT: ___
	☐	Sealing	FA: ___ FT: ___
	☐	Scaling	FA: ___ FT: ___
	☐	Patching/Spalling	FA: ___ FT: ___
	☐	Cathodic Protection	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
Rehabilitation Maintenance	☐	Increased Slab Thickness and Cover	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___
Replacement Maintenance	☐	Cast-in-place deck	FA: ___ FT: ___
	☐	Precast reinforced concrete deck	FA: ___ FT: ___
	☐	FRP deck	FA: ___ FT: ___
	☐	Other(Specify) ___	FA: ___ FT: ___

Table 5. 49 DOTs responding or not responding to the questionnaire survey

DOT	R or Nr	DOT	R or Nr	DOT	R or Nr
Washington	√	Oregon	×	California	√
Nevada	√	Idaho	√	Montana	×
Wyoming	√	Utah	×	Arizona	×
Colorado	√	New Mexico	√	North Dakota	√
South Dakota	×	Nebraska	×	Kansas	×
Oklahoma	√	Texas	√	Minnesota	√
Iowa	√	Missouri	√	Arkansas	√
Louisiana	×	Wisconsin	×	Illinois	√
Michigan	×	Indiana	√	Kentucky	√
Tennessee	√	Mississippi	√	Ohio	√
Alabama	√	Georgia	√	Florida	√
Virginia	√	West Virginia	√	South Carolina	×
North Carolina	×	Pennsylvania	×	New York	√
Vermont	√	Maryland	√	Delaware	×
New Jersey	√	Connecticut	√	Rhode Island	×
Massachusetts	×	New Hampshire	√	Maine	√
District of Col.	√				

In Table 4, "FA" means the age when the First Application of MR&R actions were takes in concrete bridge decks and "FT" means the Frequency Thereafter. The phrase "MR&R action", as used throughout this study, refers to all actions taken to extend the life cycle of a bridge.

A discussion of the response to each part of the questionnaire is presented in the subsequent sections. The questionnaire survey was mailed to 49 DOTs except for Alaska, Hawaii, and Puerto Rico DOT. Responses from 33 out of 49 DOTs (67%) were received. Table 5 lists the responding DOTs.

6. TYPE AND TIMING OF MR&R ACTIONS TAKEN IN CONCRETE BRIDGE DECKS BY THE DOTS

As indicated in the previous subsection, a questionnaire survey was used to identify the type of MR&R action taken in concrete bridge decks by each DOT. As shown in Figure 2, in case of routine maintenance; "bridge cleaning" was undertaken in concrete bridge decks by 22 DOTs and "Snow & Ice Removal" was under taken by 28 DOTs that responded to the questionnaire survey. Other routine maintenance, such as "expansion joint repair" and "Handrail maintenance & repair" were done by 3 DOTs and 1 DOT, respectively.

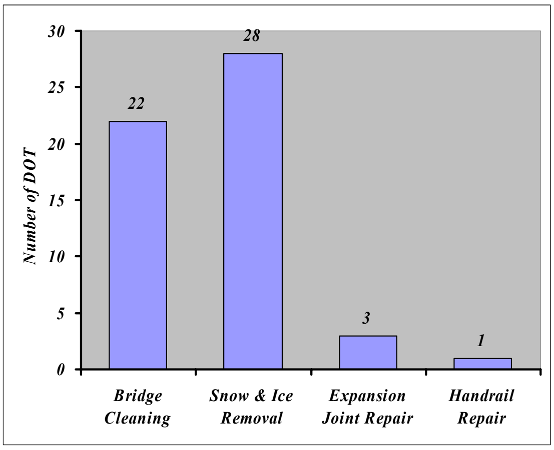

Figure 2. Frequency of Routine Maintenances taken by DOTs

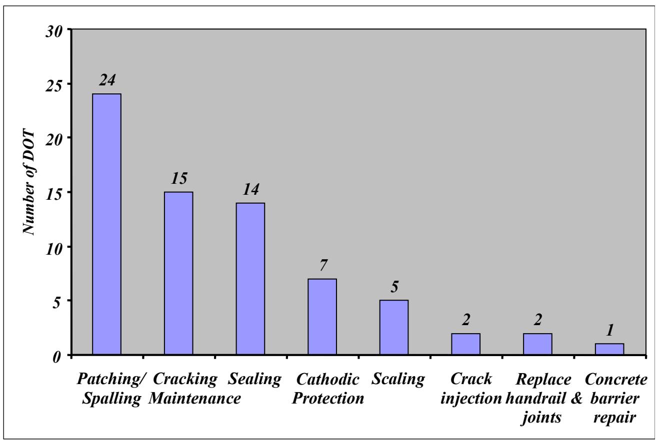

Figure 3. Frequency of Repair Maintenances taken by DOTs

As shown in Figure 3, in the case of repair maintenance, 'Patching/Spalling' has been under taken in concrete bridge decks by 24 DOTs. Whereas ‘Cracking Maintenance’, ‘Sealing’, ‘Cathodic Protection’ and ‘Scaling’ have been done by 15, 14, seven and five DOTs respectively. The cathodic protection has mostly been used experimentally on a few bridges. For the Nevada DOT and New Hampshire DOT, the ‘Cathodic Protection’ has been installed on one and three bridges respectively. In addition to these, the other types of repair maintenance were identified as ‘Crack Injection’, ‘Replacing Handrail and Joints’, and ‘Concrete Barrier Repair’.

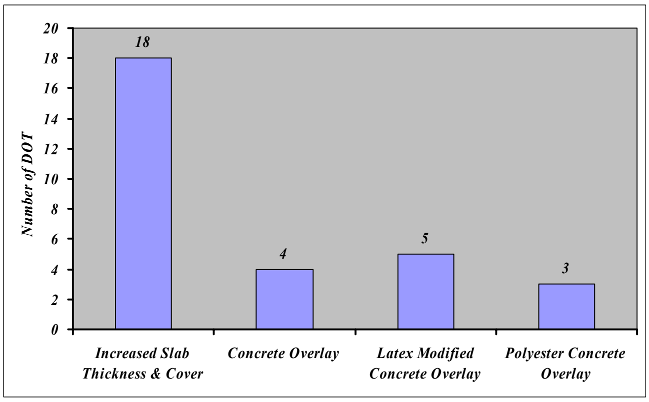

Figure 4. Frequency of Rehabiliation Maintenances taken by DOTs

As shown in Figure 4, in case of rehabilitation maintenance, 18 DOTs have used “Increased Slab Thickness and Cover.” Fairly few DOTs have used ‘Latex Modified Concrete (LMC) overlay’ (five DOTs) and ‘Polyester Concrete Overlay’ (three DOTs) beyond ‘Regular Concrete Overlay (four DOTs)’ to maintain wearing surface. ‘Latex Modified Concrete’ is considered as the key to modern bridge deck repair that enhances the ability of an overlay to adhere to an existing concrete slab and resists thermal forces by temperature fluctuations (Tonias 1995). The other type of rehabilitation maintenance like ‘Eliminating Unnecessary Deck Drains’ and ‘Extending Tubes’, were done by Illinois DOT.

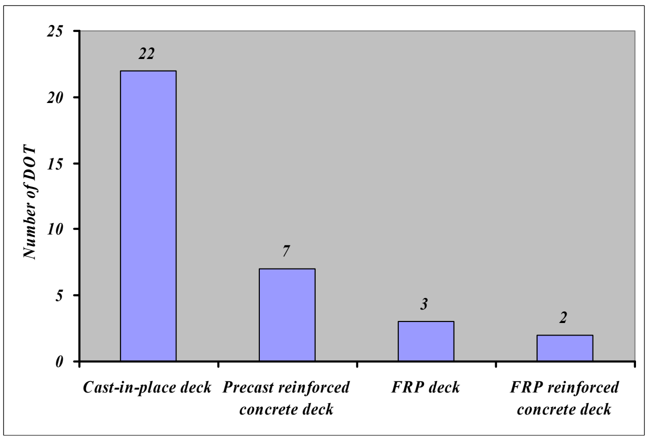

Figure 5. Frequency of Replacement Maintenances taken by DOTs

For replacement maintenance of concrete bridge decks, ‘Cast-in-place deck’ has been used by the majority (22 DOTs) as shown in Figure 5. Seven DOTs have used “Precast reinforced concrete deck.” “FRP deck” and “FRP reinforced concrete deck” were implemented by three DOTs and two DOTs, respectively (Refer to Fig.5).

The results of the questionnaire survey show that most DOTs have performed routine maintenance at specified intervals. ‘Bridge cleaning’ was performed mostly every one or two years. ‘Snow and ice removal’ was generally done every year except for Florida DOT. In most of the DOTs, however, it was done on an as needed basis. In addition to the routine maintenance, MR&R actions were performed on an as needed basis while some DOTs have performed MR&R actions at specified intervals.

In this paper, the type of MR&R action and timing for the MR&R actions taken by Missouri DOT are presented as an example in Table 6. For additional information on MR&R actions taken by 23 DOTs refer to Hong (2003).

Table 6. Type and timing of MR&R action in Missouri DOT

Category	Type of MR&R actions	Timing for MR&R actions (Years)
Rehabilitation Maintenance	▪ Bridge cleaning (Done by Districts) ▪ Snow & Ice Removal (Done by Districts)	▪ **FA**: 1 **FT**: 1 ▪ **FA**: 1 **FT**: 1
Repair Maintenance	▪ Crack Maintenance (Done by Districts) ▪ Sealing (No longer use asphalt seal costs, seal cracks only may apply epoxy polymer overlay to bridge decks with NBIS rating 6 and above for preventive maintenance) ▪ Scaling (apply linseed oil when new and after open for a year. Have no scaling problems to speak of on new bridges built since 1970) ▪ Patching/Spalling (Done by Districts or by district let maintenance contracts.) ▪ Cathodic Protection (first bridge done in 1977, up to 130 decks in early 1990’s now down to about 90, have replaced some systems in last few years – 5 decks in 2001, letting 9 decks in Dec.2002 (place only on concrete superstructure bridges in metropolition areas in Kansas city and St. Louis), 2 experimental galvanic substructure applications.) ▪ Epoxy overlay	▪ **FA**: 1 **FT**: 5 ▪ **FA**: N/A **FT**: N/A ▪ **FA**: N/A **FT**: N/A ▪ **FA**: 15 **FT**: 2 ▪ **FA**: 20 **FT**: 15 ▪ **FA**: 15 **FT**: 15
Rehabilitation Maintenance	▪ Increased Slab Thickness and Cover (Seldom done, occasionally Asphalt Concrete overlay) ▪ Attaching additional longitudinal girders or steel plates (seldom done, trying experimentally FRP strengthening on off-system and secondary routes.) ▪ Our highest rehabilitation with out replacing deck is patching and adding Portland Cement Concrete (PCC) overlay (almost all done by construction project) ▪ 100% FRP deck, repairs and wearing surface ▪ FRP reinforced Portland Cement Concrete (PCC) deck	▪ **FA**: 25 **FT**: 10 ▪ **FA**: 25 **FT**: 50 ▪ No data ▪ **FA**: 28 **FT**: 50 ▪ **FA**: 28 **FT**: 28
Replacement Maintenance	▪ Cast-in-place deck (a few full deck replacements done by construction contract per year) ▪ Precast reinforced concrete deck ▪ FRP deck (Have some all FRP and FRP reinforced PCC bridges off-system (Non-state).) ▪ 100 % FRP deck and FRP reinforced PCC deck	▪ **FA**: 50 **FT**: 50 ▪ **FA**: 30 **FT**: 20 ▪ **FA**: 50 **FT**: 50 ▪ **FA**: 1 **FT**: 75

7. BRIDGE MAINTENANCE, REPAIR, AND REHABILITATION (MR&R) STRATEGY

Strategic decision making for bridge maintenance has become a major issue for the highway agencies because of the rapidly increasing requirements of bridge maintenance. The annual expenditure to replace, repair or rehabilitate the deteriorated components of the nation’s infrastructure is enormous. Since the budget available for bridge maintenance is limited, there is a growing need for the optimization of long-term MR&R strategy in order to minimize the total maintenance cost of bridges. The repair of bridges often has been a reactive activity, initiated only when deterioration threatens the safety or tolerance of the public. Now, influenced by BMSs, owners are beginning to emphasize cost-effective proactive strategies from the start, when the bridge is new (Roberts 2000). In a study by Liu et al. (1997), a maintenance strategy is defined as a plan specifying the set of maintenance methods used for a bridge system during a specific planning period. Optimal bridge management is defined as the minimization of life-cycle cost under system reliability constraints (Frangopol et al. 1997).

(1) MR&R strategy for concrete bridge decks

Several studies have investigated the optimum maintenance strategy for bridge decks. In a study by Jacobs (1992), a mixed-integer mathematical model is presented to optimally schedule long-term bridge deck rehabilitation and replacement activities. Markow suggested a life-cycle cost approach to decide the time and methods of improving bridge decks (Markow 1994).

The Genetic algorithm based optimization techniques for the maintenance strategies of a bridge deck system are developed in a study by Liu et al. (1997). In a study by Itoh and Liu (1999), a Genetic algorithm is modified to deal with the rehabilitation plan of bridge decks by minimizing the rehabilitation cost and deterioration degree at the same time (Itoh and Liu 1999). In a study by Estes and Frangopol (2001), a decision tree analysis is used to develop an optimum lifetime maintenance plan over the expected useful life of a deteriorating structure. The optimized strategy is revised and updated as new inspection information becomes available. The methodology is illustrated using a concrete bridge deck.

The selection of the optimum maintenance strategy is also a challenging task because a lot of feasible combinations increase exponentially with the number of bridges *N*, the planning period *T*, and the number of maintenance alternatives *M*. The number of all combinations of maintenance strategies is $M^{N \times T}$. If the relationships among bridge elements and among different bridges, the limited resources, and so on are taken into consideration in the selection of the optimum maintenance strategy, this selection will be even more complex. The problems one has experienced in the real-world can not be solved by simply using conventional mathematical planning techniques (Jacobs 1992). Furthermore, since the environmental and traffic conditions for each DOT are different, the timing and type of MR&R actions taken by each DOT are different.

The existing models do not facilitate development of individual MR&R strategies for each DOT (Hong 2003). Therefore, the development of optimal MR&R action scenarios suitable to each DOT is urgently needed for managing bridges effectively.

(2) Existing MR&R strategies taken in concrete bridge decks by the DOTs

Most of the DOTs have an individual MR&R strategy to extend the life of concrete bridge decks, but some DOTs are in the stage of developing a MR&R strategy. However, 12 DOTs among 33 DOTs responding to the questionnaire survey have not used MR&R strategy or do not have a formal strategy: Alabama, Arkansas, Connecticut, Iowa, Main, Mississippi, Nevada, New Mexico, Oklahoma, Texas, Virginia, and Wyoming DOT. The existing MR&R strategies taken by the 21 DOTs are summarized in this section.

- California: Caltrans (**Cal**ifornia **Trans**portation) has a fairly aggressive methodical program for bridge decks with early signs of cracking. Spalls are quickly repaired to prevent rebar corrosion. If deterioration progresses, polyester concrete overlays, partial deck replacements or deck on deck strategies are used.

- Colorado: CDOT has not yet developed a concrete bridge deck MR&R strategy, but is working on an overall bridge management system using AASHTO PONTIS Bridge Management software. CDOT has been inspecting using both FHWA NBI and PONTIS element inspection codes for over seven years. CDOT started some bridge deterioration modeling, but faced a problem because the new PONTIS version 4.0 and other versions do not have the capability to update their past PONTIS information. CDOT is now converting to the PONTIS 4.1 program and will now do all their bridge inspection reporting for National Bridge Inventory (NBI) and deterioration modeling on AASHTO PONTIS only. CDOT in general has not replaced decks unless the superstructure and substructure are in very good shape. In general, all three parts of a concrete deck bridge (deck, superstructure, and substructure) seem to deteriorate at about the same rate in Colorado. In general, CDOT Bridge Staff has recommended that water-proof membrane should be added to all concrete deck bridges that do not have water-proof membrane whenever possible such as when asphalt is going to be replaced. However, due to limited project funding, often this is not done. In the case of CDOT, the deck might be the major reason the bridge qualifies for MR&R work, but Colorado bridges generally deteriorate equally among their major components.

- District of Columbia: The District of Columbia has a preventive maintenance construction contract which has pay items for deck overlays, deck sealing and repairing partial and full depth holes in bridge decks. When deterioration is below certain threshold levels, a low slump or microsilica overlay is used. If the deterioration is more advanced, the deck is replaced.

- Florida: The DOT is implementing the AASHTO bridge management system called PONTIS. One element of this program has a MR&R strategy section which is used by the DOT.

- Georgia: GDOT routinely evaluates concrete decks through the bridge inspection program and rates them in accordance with NBIS. A major emphasis has been placed on the Interstate system since it has the highest volume of truck traffic that damages decks. When the condition rating reaches a "6" in a scale of 0 to 9, evaluation is made for sealing with an epoxy sealer. If the condition reaches a "5" evaluation for hydrodemolition and concrete overlay or partial replacement is made. If the condition rating drops to a "4" or less, evaluation for replacement of the deck or entire structure is made. Routine maintenance such as crack sealing and patching are performed as needed until the bridge reaches a condition rating of "5" usually within the first 25-30 years of deck life. After rehab, the process starts over.

- Idaho: When bridge decks deteriorate to a rating of 5 or less in a scale of 0 to 9, they become candidates for rehabilitation. Rehabilitation consists of water blasting of the top surface of the deck down to the reinforcement. All delamination is removed at that time. A silica fume wearing surface is placed over reinforcement to a minimum depth of 2½″.

- Illinois: The DOT has a program called "B-Smart" (Bridge Strategic Maintenance at the right time). This is a program that undertakes minor patching, scarification, and a concrete overlay on bridge decks before they require replacement. Typical criteria include a maximum 15% deck delamination, an NBIS Deck Rating of 5 or greater, a Superstructure Rating of 6 or greater, and Substructure Rating of 6 or greater.

- Indiana: Bridge cleaning (flushing drains) and snow removal is done annually as needed. Preventive maintenance to repair joints, patching concrete, etc., is conducted annually (one contract per district). Repair & rehabilitation through planning and programming for each bridge is conducted as required.

- Kentucky: Bridge Maintenance Crews located in their 12 highway district offices perform routine deck cleaning and patching. As the wearing surface deteriorates, contracts are let to replace it. Typically 1-1/4″ Latex Modified Concrete (LMC) is used.

- Maryland: As a deck deteriorates, a visual and/or non-destructive assessment is performed to best determine the necessary steps to maintain/improve its condition.

- Minnesota: Typically their strategy is to do nothing and repair or replace when performance falls below a certain minimum acceptable level. General guidelines provide that bridge decks that have 10% or more delamination should be repaired and overlaid with two inches of low slump concrete. Bridge decks with 40% or more delamination should be scheduled for replacement. However, application of these guidelines varies considerably across the state depending on traffic volumes and priorities. Most District maintenance staffs have a program to flush bridge decks annually, and some perform crack sealing on a five to seven years' cycle, but these practices vary also with concern for traffic delays or interference and with other work priorities.

- Missouri: An amount of money is set aside in the Maintenance budget for each District each year to be used for preventive maintenance of bridges. The amount is specified each year, split up among the ten District offices and the District decides how they will use it. Mostly projects are set up for sealing, patching, and overlaying of bridge decks to keep moisture and salt out of the concrete by using epoxy polymer overlays.

- New Hampshire: To extend the life of concrete bridge decks, they have adapted sweep and washing, applying sealants to exposed concrete surfaces, pavement crack sealing, and snow & ice removal. They only have decks for single span structures because they are concerned about negative moment cracking. On these short small structures they spray apply a 50/50 % mixture of double boiled linseed oil and Siloxane while traffic is not on the structure. After appropriate cure time traffic is allowed to travel on the deck. They also use metal methaculate to seal cracks and construction joints.

- New Jersey: The Bureau of Structures Evaluation, NJDOT, has a bi-annual inspection cycle for all the state bridges. They have categorized the repairs needed on each structure as: (i) Emergency: Immediately, (ii) Priority I: Schedule for repair as soon as possible, (iii) Priority II: Within one-two months, and (iv) Priority III. In the cycle report, all types of repairs needed in both superstructure and substructures are included. The report also includes rehabilitation and replacement as a recommendation.

- New York: They are divided into eleven regions. Each region is responsible for developing the MR&R strategy for itself. The strategies used by the regions are based on the needs and funding levels of that region, and therefore vary from year to year within a region and vary from region to region within a year.

- North Dakota: Little or nothing is done to maintain decks until a project has been initiated for that bridge or until that stretch of highway has a project. At that time each bridge is evaluated to determine what should be done.

- Ohio: ODOT has a policy to perform preventive maintenance. The DOT has also established minimum level of service criteria that directs when bridges must be programmed for replacement or major rehabilitation. Suggested Preventive Maintenance (PM) strategies are out lined in the on line Bridge Preventive Maintenance Manual (http://www.dot.state.oh.us/preventivemaintenance/). Actual work being performed to date includes bridge cleaning. The minimum level of service is based upon NBIS inspection data which is the basis for the departments operational performance index (OPI).

- Tennessee: For new bridges, reinforcing steel is epoxy coated and has a 2.5″ concrete cover over the top mat in the bridge deck. For existing deck, a protective layer of material is added to the top of the concrete deck. These layers are either a 3.25″ asphalt overlay with a rubber membrane sandwiched between lifts of asphalt, or a reinforced 4.5″ concrete overlay. All overlays require the existing bridge decks to be repaired prior to overlay application. These overlays are commonly handled through rehabilitation type of projects, repair projects, and/or resurfacing projects involving several miles of roadway.

- Vermont: New decks are constructed using epoxy coated rebar and sheet membrane waterproofing between the concrete deck and 2.5″ of bituminous concrete pavement.

- Washington: Maintenance: Winter deicer applications as needed and repair deterioration as needed. Rehabilitation: Bridges with delamination of more than 2% deck area are repaired by applying a protective overlay. WSDOT has only replaced ten concrete bridge decks out of over 2600 bridges.

- West Virginia: The strategy includes thin HPC overlays, such as latex and Mircosilica overlays over new structures and to rehabilitate older decks that meet the necessary criteria. When the decks get to very poor condition, they are paved with asphalt to extend their life and minimize maintenance.

8. CONCLUSION AND SUMMARY

Currently, in the case of our country, the inspection timing of bridge structures has been absolutely regulated irrespective of deteriorated or damaged extent. The inspection timing of our country and OECD country is compared to Table 7.

Table 7. Comparison of inspection timing

Type of inspection	OECD	Japan	Republic of Korea
General inspection	One time per 1–2 year	Variable	At least two time per year
Major inspection	One time per 3–10 year	One time per 5–7 year	At least one time per two years
Special inspection	Inspection on a needed basis	Inspection on a needed basis	At least one time per five years

Engineers in-charge of bridge maintenance are difficult to determine whether bridge structures are defective or not due to lack of their professionalism on the performance of bridge structure. In addition, although there are a lot of data related to inspection, diagnoses, and MR&R actions, these data management has not been effectively or systematically performed. As compared to Unites State, the application of these data has been conspicuously low. Thus, in order to collect and manage systematically these data, Highway Bridge Management System (HBMS) has been established in 1999. However, these data related to bridge MR&R actions collected from the HBMS are not useful yet in terms of the application of these data.

Therefore, the purpose of this paper was to identify the state-of-practice of concrete bridge deck maintenance and to document the experience of bridge maintenance engineers or inspectors in the United States of America. The questionnaire was mailed to bridge management engineers or bridge maintenance engineers of 49 DOTs in order to identify the types of MR&R actions taken in concrete bridge deck by each DOT as well as the timing for the MR&R actions. A response from 33 DOTs out of 49 DOT was received.

In this study, the MR&R action was categorized into four parts: routine, repair, rehabilitation, and replacement maintenance. “Snow & ice removal” among routine maintenance was used most in concrete bridge decks, whereas “Patching/spalling” was used for repair maintenance, “Increased slab thickness and cover” for rehabilitation maintenance and “Cast-in-place deck” for replacement maintenance. However, many MR&R actions taken in concrete bridge decks have been performed on an as needed basis as indicated in the literature review. The timing when the MR&R actions have usually been taken differs for each DOT because of the variable environmental and traffic conditions of each DOT. MR&R strategies for concrete bridge decks have not been developed by 48 % of the DOTs responding to the questionnaire survey, suggesting a strong need for a tool that would assist these DOTs to establish a feasible and optimal MR&R strategy.

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