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INDIANA DEPARTMENT OF TRANSPORTATION
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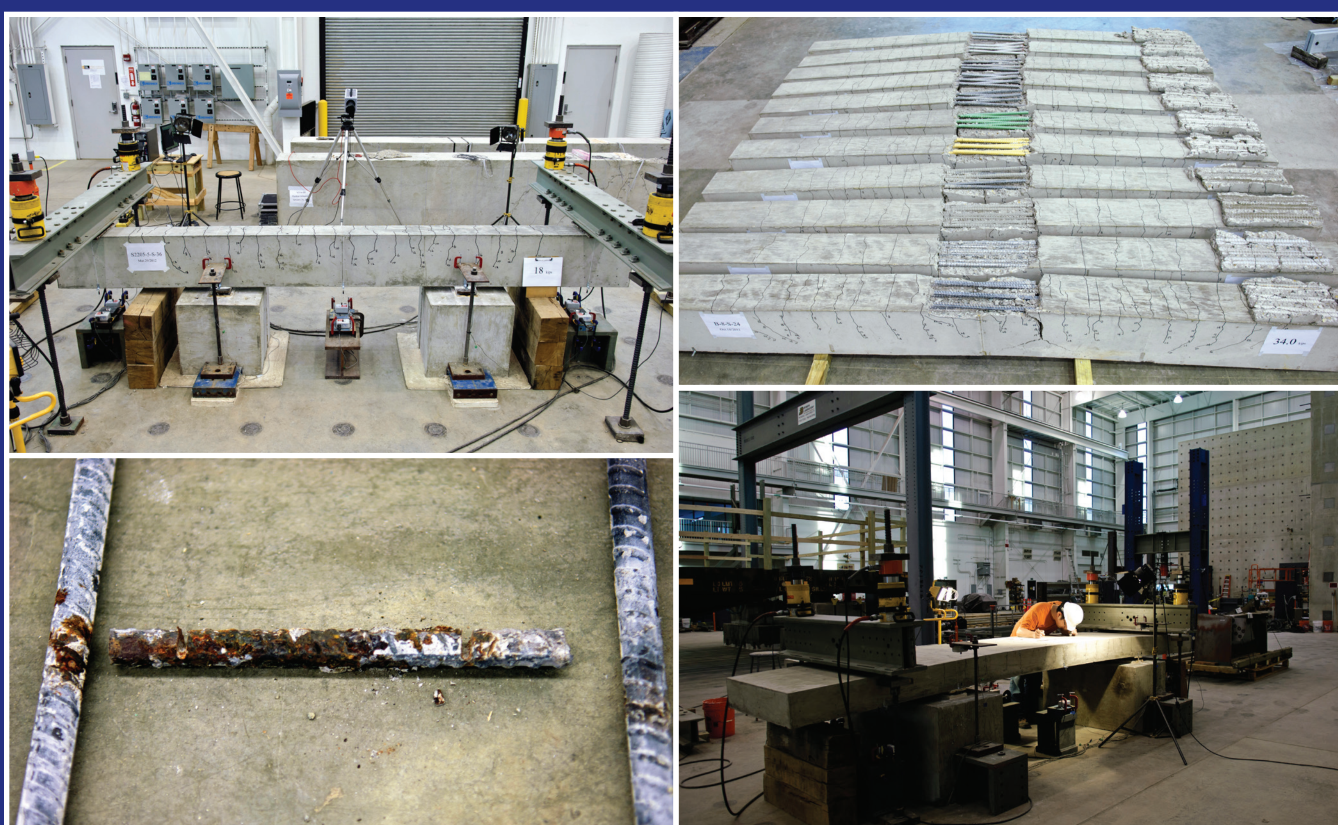
Increasing Bridge Deck Service Life

Volume II—Economic Evaluation



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16. Abstract

Deterioration of bridge decks is a primary factor limiting the lifespan of bridges especially in cold climates where deicing salts are commonly used. While controlling deck cracking or decreasing the permeability and porosity of concrete can improve performance and service life, chloride and moisture ingress as well as cracking cannot be eliminated. Full-depth cracks which are caused by restrained shrinkage allow for corrosive conditions at early ages for both the top and bottom reinforcement mats. Therefore, the use of corrosion-resistant reinforcement is essential to mitigate deterioration of bridge decks. The objective of this research program to examine the efficacy of using alternative materials in a bridge deck from both technical and economic perspectives. For the technical evaluation (Volume 1), a three phase experimental investigation was conducted considering a wide range of corrosion-resistant reinforcing materials. These materials included stainless steels, microcomposite steel, and coated steels considering a variety of metallic and nonmetallic coatings. The first phase evaluated the bond between corrosion-resistant reinforcement and concrete using lap splice tests. The second phase evaluated the cracking behavior of slabs reinforced with corrosion-resistant reinforcement. Finally, the third phase evaluated corrosion resistance under uncracked and cracked conditions using macrocell test specimens. Transverse steel was also tied to the longitudinal steel to simulate actual bridge deck conditions. Recommendations are provided on development and splice lengths for both conventional black and corrosion-resistant reinforcing steel, control of cracks widths, as well as the selection, design, and construction of corrosion-resistant reinforcement. For the economic evaluation (Volume 2), a decision support methodology and associated spreadsheet tool for robust analysis of the cost-effectiveness of alternative material types for bridge deck reinforcement was developed. The two evaluation criteria are agency and user costs, and the input data that influence this criteria include the deck service life, material process, discount rate, detour length, and bridge size. The methodology incorporates analytical techniques that include life cycle analyses to evaluate the long-term cost and benefits of each material over the bridge life; Monte Carlo simulation to account for the probabilistic nature of the input variables; stochastic dominance to ascertain the probability distribution of the outcome that a specific reinforcement material is superior to others; and analytical hierarchical process to establish appropriate weights for the agency and user costs. The study methodology is demonstrated using a case study involving three reinforcement material alternatives: traditional (epoxy-coated) steel, zinc-clad steel, and stainless steel. Through this study, it is demonstrated that the use of corrosion-resistant reinforcing materials can significantly increase bridge deck life, reduce agency and user costs associated with bridge deck rehabilitation and maintenance, and thus lower the financial needs for long-term preservation of bridges.

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EXECUTIVE SUMMARY

INCREASING BRIDGE DECK SERVICE LIFE: VOLUME II—ECONOMIC EVALUATION

Introduction

Deterioration of bridge decks is a primary factor limiting the lifespan of bridges, especially in cold climates where deicing salts are commonly used. Research has been previously performed to mitigate deterioration by controlling deck cracking using improved design methods, such as bar spacing and cover requirements, or by decreasing the permeability and porosity of concrete through the use of high performance concrete. While these methods can improve performance and extend service life, chloride and moisture ingress, as well as cracking, cannot be eliminated. Full-depth cracks that are caused by restrained shrinkage allow for corrosive conditions at early ages in both the top and bottom reinforcement mats. Therefore, corrosion of the reinforcing steel ultimately occurs. However, the service life of the deck has the potential of being significantly improved if corrosion resistant reinforcement is used.

While epoxy-coated reinforcement has become standard practice to improve corrosion resistance, this reinforcement type is not immune to corrosion. Its performance is highly dependent on the condition of coating. The coating can be damaged even with special care during manufacturing, transportation, and construction. Therefore, the use of other corrosion reinforcing materials has significant potential to provide improved performance. The objective of this research program was to examine the efficacy of using alternative materials in a bridge deck from both technical and economic perspectives. Technical criteria include bond strength, cracking performance, and corrosion resistance, while economic criteria comprise agency and user costs associated with construction, replacement, and rehabilitation over the life cycle.

Findings

Volume I: Technical Evaluation

The technical evaluation was conducted in three phases and considered a wide range of corrosion resistant reinforcing materials. These materials included stainless steel (316LN, Duplex 2205, Duplex 2304, XM-28), MMFX II microcomposite steel, and coated steel (epoxy, dual-coated zinc and epoxy (Z-bar), hot-dipped galvanized, and zinc-clad).

Bond Strength

The bond strength of corrosion resistant reinforcing materials was tested to ensure that current design procedures for the calculation of splice and development lengths are appropriate. Stainless-steel, MMFX II microcomposite, hot-dip galvanized, and Zbar (dual-coated) reinforcing bars have bond strengths comparable to black bars. Coated bars other than galvanized and dual-coated have reduced bond strengths. Epoxy-coated bars had on average 11% less bond strength than black while un-plated zinc-clad and tin-plated zinc-clad bar had on average 18% and 26% less bond strength than black bars, respectively. Modification factors were developed for development and splice length calculations when other bar types are used. The test data were also combined with other data available in literature to construct a simple model for development and splice length calculations that consider a wide range of corrosion resistant bar types as well as confined and unconfined conditions.

Cracking Performance

Because the variations in the surface roughness of different corrosion-resistant reinforcement, cracking performance was evaluated by testing slab specimens. The effect of bar spacing and the effect of high reinforcement stresses that can be obtained by high-strength reinforcement (stainless steel or MMFX II) were evaluated. The bar types affected the spacing and width of primary cracks. For the control of crack widths, it is recommended that crack widths be calculated based on black bars and multiplying modification factors. Design code approaches can directly incorporate these factors to reduce the spacing of corrosion-resistant bars by dividing the black bar spacing by the modification factors. Epoxy-coated, galvanized, and MMFX II microcomposite reinforcing bars do not need modification. Recommendations are provided for the control of crack widths for the other bars evaluated in this study. Spacing of the reinforcement affected both crack spacing and crack widths. As the reinforcement spacing increased, the number of primary cracks decreased and the crack spacing increased. This trend is consistent with previous test results. Crack spacing and crack width, however, did not increase significantly after spacing of the reinforcement became greater than 12 in. For design purposes, the crack spacing can be considered to be constant for bar spacing greater than 12 in. For a given stress, this results in the same crack widths for spacings greater than 12 in. In addition, crack widths of high-strength bars (stainless steel and MMFX II) that have a roundhouse stress-strain curve will increase nonlinearly at high stresses (>80 ksi). However, the crack widths of high-strength bars can be conservatively calculated using the model for conventional black bars up to bar stresses of 80 ksi.

Corrosion Resistance

While all uncracked specimens showed relatively very low currents at 503 days of exposure, several cracked specimens demonstrated high corrosion activity, which was electronically measured by the macrocell test and confirmed by visual examination through an autopsy of the specimen. Autopsy results demonstrated that the longitudinal steel (secondary reinforcement in a bridge deck) corroded at the intersection with the transverse steel (primary reinforcement in a bridge deck) while the transverse reinforcement corroded over its entire length. The transverse steel, typically located parallel to the cracks, was under direct chloride exposure over its entire length while the longitudinal steel had direct exposure only at the location of the cracks. When corrosion-resistant chromium-based reinforcing steel was used in the top mat and black bars were used in bottom mats, a galvanic couple resulted where the bottom black steel corroded to protect the top corrosion-resistant reinforcement. This galvanic couple occurred because the cracks in the macrocells were formed full depth where chlorides can easily reach the bottom black bars from the first day of testing. This condition is realistic as bridge decks have full-depth cracks that are formed at early ages (<28 days) due to restrained shrinkage. Both the electrical current measurements and autopsy results demonstrated that mixing reinforcement where black bars are provided in the bottom mat is detrimental to corrosion resistance. Specimens that were tied with black ties indicated more corrosion than specimens with plastic ties. In addition, tying reinforcing steel with dissimilar metallic materials resulted in galvanic coupling. When stainless steel ties were used to connect black reinforcement, increased damage of the black bars resulted. In addition, black ties used to connect stainless bars resulted in crevice corrosion and pitting of the stainless steel bar. Only similar metallic or inert (plastic) materials should be used to tie reinforcement.

Volume II: Economic Evaluation

The study developed a systematic framework for evaluating these alternative reinforcing materials on the basis of their life-cycle cost. Case studies involving different scenarios of bridge and operating characteristics were used to demonstrate the methodological framework, and to develop nomograms (decision support charts) for the material selection. On the basis of the results of the analysis and the case studies, it is recommended that deck reinforcement material for any future INDOT bridge deck design should be selected only after carrying out a life-cycle cost analysis among other considerations; such analysis should be preceded by establishment of the decision contexts and, consequently, values of the identified input parameters for the life-cycle cost analysis. From a general perspective, it is recommended that INDOT considers for inclusion in its bridge design or rehabilitation manual, the decision to support nomograms that specify the conditions at which each material is optimal from a life-cycle perspective.

Nevertheless, avenues exist that could be addressed or explored further to fine-tune the selection process for appropriate deck reinforcement material alternative for any specific bridge project. First, mathematical models describing the time-dependent, chloride-induced corrosion deterioration processes could be incorporated to provide more precise estimates of the life-cycle activity profiles for each material type.

Secondly, the laboratory experiments carried out as part of this research (see Volume I of the report) could be followed by full-scale field studies. For this, it is recommended that a few bridge reconstruction or deck replacement projects should be selected from INDOT's long-range plan or bridge program through an experimental design; for these bridges or decks, INDOT should apply the three material types in a controlled experimental setting. The costs (initial construction and subsequent maintenance), work durations, and the physical condition and service lives of the bridges or decks having each alternative material should be closely monitored and recorded over several decades. Doing this would validate or refine the assumptions made in this study. The experimental design could include climatic region (northern and southern Indiana), highway classes, traffic volume, and bridge size.

Implementation

Based on the research conducted in the technical evaluation, a number of recommendations were developed that address the selection and design of corrosion-resistant reinforcing bars and are appropriate for adoption into the INDOT Bridge Design Manual. First, guidance is provided to assist in the selection of corrosion-resistant reinforcement based on the duration of testing completed in this study. Extended corrosion exposure is required to provide improved estimates as well as differentiation of the materials. It is recommended that both the top and bottom mats of the bridge deck be constructed of the same reinforcing material. Mixing of reinforcing material causes galvanic corrosion. It is recommended that reinforcement be tied with only inert (plastic) ties or ties made of the same material as the reinforcing bar to avoid galvanic coupling between tie material and reinforcement. Second, design recommendations are provided for the calculation of development and splice lengths including modification factors required for the use of corrosion-resistant reinforcement. It was found that stainless-steel, MMFX II, hot-dipped galvanized, and Zbar perform similarly to black bars and do not require modification. Finally, design recommendations are provided for the control of cracking and the calculation of crack widths. The control of cracking is also of importance, even with the use of corrosion-resistant reinforcement, and is essential for durability of the bridge deck.

Based on the research conducted in the economic evaluation, a software tool, RM-LCCA, was developed that can be used by INDOT and design consultants. The economic evaluation methodology presented in this study provides a platform to assess the life-cycle costs of different types of bridge deck reinforcement materials based on their corrosion resistance as well as their economic efficiency. The analysis outcome from the RM-LCCA electronic tool can help bridge engineers and practitioners identify the optimal reinforcement alternative for a given bridge on the basis of its expected service life, schedules for rehabilitation and deck replacement, and the accompanying costs to the highway agency and bridge users. The service life of a bridge deck, even for the same reinforcement alternative, can change due to factors such as increased loading, rapid changes in the surrounding environment, and upcoming new policy decisions that can affect the short-term and long-term service life of preservation treatments. For the estimated preservation years, the user can incorporate the probability that the treatment timings will be different from what is specified as the average. By running the tool several times for different values of the input variables, the user can simulate the outcome corresponding to different combinations of the input variables. It is envisioned that as the benefits of corrosion-resistant reinforcement alternatives are tested and become recognized, their demand will increase, leading to higher production and lower unit prices.

CONTENTS

1. INTRODUCTION

Past research has shown that the key factor in bridge deck deterioration and subsequent deck failure is corrosion of the embedded reinforcement elements. For bridges located in cold-climate regions where deicing salts are applied to control wintertime snow and ice, season, the chlorides from these salts migrate through the concrete cover to reach the reinforcement level and destroy the protective passive film of the steel reinforcement. Once the passive layer is destroyed, the corrosion process initiates and propagates through the material, and as the corroded material builds up, it increases in volume and thus generates high tensile stresses that eventually lead to irreversible structural damage including concrete cracking, delamination, and spalling.

A number of treatments aimed at to mitigate chloride migration by reducing the porosity of concrete has been experimented; however, these have had only very limited success because they tend to create problems related to early age shrinkage cracking. The other option, namely, the use of corrosion-resistant reinforcement materials in bridge deck design and construction has been found to potentially reduce the rate of bridge deck deterioration and enhance bridge deck service life. Corrosion-resistant reinforcement materials include epoxy-coated steel, stainless steel, clad steel, fiber-reinforced polymer bars, MMFX reinforcements, and carbon fiber bars. These materials have different prices and effectiveness (in terms of corrosion resistance), thus, it is necessary to conduct life-cycle cost analysis for each of material alternative to identify the most cost effective choice.

Against this background, this research seeks to develop a systematic approach for reinforcement material type selection to mitigate the pervasive and widespread problem of bridge deck corrosion. In doing so, this study seeks to establish the values of the selection criteria that elaborate the conditions at which the different materials become most cost effective. The study also examines the impact of the probabilistic nature of input variables on the relative cost-effectiveness of each material type. Also, a case study is used to demonstrate the methodological framework: traditional (epoxy-coated carbon) steel, clad stainless steel, and stainless steel are evaluated as possible reinforcements for bridge decks.

This study assumes that the concrete is sound and also duly recognizes that the material service life, which corresponds to different rehabilitation profiles, is a key factor in bridge investment decisions and that the scheduled rehabilitation cost, timing, and effectiveness are highly influential in the evaluation outcome. For each material type, the expected length of service life and the timings for the repair or rehabilitation of a bridge deck over the service life, are specified based on previous studies.

The analytical techniques used include probabilistic life-cycle costing and multiple-criteria analysis, because rehabilitation frequencies and economic parameters such as interest rates and fuel prices are inherently uncertain in nature. LCCA enables a comparison of alternatives with different service lives, costs, and rehabilitation schedules. The Analytical Hierarchical Process (AHP) is used to establish the weights of the agency cost to the user costs of travel time and safety. The last part of the framework is a demonstration of the sensitivity analysis of the input variables in the reinforcement material type selection. The concept of stochastic dominance is used to identify the best alternative from a probabilistic, life-cycle perspective. A Microsoft Excel-based software tool (RM-LCCA) is developed during this study for bridge deck reinforcement material type selection and for quickly investigating the effect of varying the values of key inputs on the optimal choice. This tool will enable INDOT to tailor its reinforcement material choices to suit a particular bridge given its size, traffic conditions, and other external conditions associated with the economy (gas price, discount rate, etc.) and the prevailing relative prices of the reinforcement materials.

2. REVIEW OF LITERATURE

To acquire insight into the various issues associated with increasing bridge deck service life through the use of appropriate reinforcement material, an extensive literature review on the subject and related topics have been carried out. This chapter synthesizes the past research on bridge deck construction materials and their roles in deck corrosion. The properties of reinforcement materials, the mechanisms of reinforcement corrosion, propagation, and the current preventive practices have also been briefly discussed. Lastly, application of economic analysis is reviewed within a deterministic and stochastic framework by conducting probabilistic LCCA for the reinforcement material alternatives.

2.1 Reinforcement Corrosion

Bridge elements reach their terminal serviceability for a variety of reasons (e.g., deterioration, structural failure, corrosion, and load fatigue) (Estes & Frangopol, 2001). Corrosion is a natural phenomenon that occurs due to interactions between a material's properties and the environment. Chloride attack is a common initiator of corrosion and continues to be a major problem for reinforced concrete structures worldwide. The presence of chloride initiates the corrosion of bridge reinforcement, which results in rusting, cracking, spalling, and ultimately reduced load-carrying capacity (Liu & Weyers, 1998). Corrosion is particularly prevalent in marine environments or in climates where deicing chemicals are applied during the winter months. Due to the ingress of chloride from the sea water, the total life-cycle costs of bridges can increase as much as 1.5 times if the appropriate treatment is delayed (Tanaka, Kawano, Watanabe, & Nakajo, 2001). It has been estimated that the U.S. loses $8.3 billion per year on bridges alone due to corrosion (Koch, Brongers, & Tompson, 2002).

The effect of chloride exposure differs between steel and reinforced concrete bridges. Steel bridges corrode visibly due to direct chloride attack; reinforced concrete bridge elements, on the other hand, corrode internally and such corrosion is manifest through visible cracking and spalling on the concrete surface. Corrosion of the steel reinforcement occurs in two stages: the initiation (or incubation) period during which the chloride ions from deicing chemicals or marine environments travel through cracks in the concrete layer travel to the reinforcement level; and the active (or deterioration) stage during which the steel corrosion initiates and propagates (Fanous & Wu, 2000). The second stage, in turn, has two phases: (i) breakdown of the passive layer on the steel by the chloride ions (Broomfield, 2007; Gu, Beaudoin, Zhang, & Malhotra, 2001), and (ii) carbonation due to carbon dioxide reactions with the cement phase of the concrete (Bertolini, Elsener, Pedeferri, & Polder, 2004). In other words, when the chlorides diffuse to the depth of the reinforcing steel, they begin to attack the passive corrosion protection film on the surface of the steel reinforcement. This will not result in a decrease in the pH level, and the passive layer therefore will continually reestablish itself and prevent active corrosion (Pradhan & Bhattacharjee, 2009). However, when the concentration of the chlorides at the reinforcement reaches a threshold level, the passive layer breaks down and active corrosion initiates (Williamson, 2007). When the reinforcement corrodes, it increases in volume (by a factor of 3–6 (Ceran & Newman, 1992) and thus causes additional tensile forces due to the limited space it occupies, and this leads to concrete cracking, spalling and overall degradation (Broomfield, 2007; Fuhr & Huston, 1998).

The deck can be considered as the "roof" of the bridge. It is the element that is most exposed to rain, ice, salt, deicing chemicals, and direct traffic load impacts. Due to the influences of these external forces, the deck typically experiences spalling, cracking, corrosion, and delamination, and thus tends to have a relatively fast rate of deterioration compared to other bridge elements.

To reduce the rate of bridge deck deterioration due to corrosion, various techniques have been used at highway agencies. These range from techniques at the bridge design phase to those at the maintenance phase. For example the design could be made to have thicker cover or concrete or non-corrosive reinforcement, or a strict maintenance policy consisting of regular scheduled (preventive) and corrective preventive maintenance activities could be carried out to arrest the deterioration spiral. In the section below, a number of alternatives associated with the design-related techniques have been discussed.

2.2 Reinforcement Corrosion Prevention Approaches

There are two major categories of techniques for reducing chloride ingress into concrete bridge deck: (i) the barrier techniques, where a barrier is constructed at the concrete surface that inhibits or retards the rate of chloride ion ingress through the concrete, and (ii) selection of a reinforcement of a material type that is inert to chemical attack by the chloride ions (El-Reedy, 2008; Kepler, Darwin, & Locke, 2000).

2.2.1 The Barrier Technique

The barrier techniques prevent or slow down the ingress of water, oxygen, and chloride ions into the concrete and thereby protect the reinforced concrete from corrosion damage. Some highway agencies have modified their design standards to include thicker cover requirements for decks and the use of low-permeability concrete, both of which can increase the chloride diffusion time through the concrete and subsequently enhance the deck service life (Williamson, 2007). Corrosion inhibitors (anodic and cathodic) are the chemical substances that can be added to concrete at the time of mixing. They can be effective in decreasing the corrosion rate of the reinforcement by forming a protective film around the reinforcement without reducing the concentration of the corrosive agent (Monticelli, Frignani, & Trabanelli, 2000). Deck sealers are solvents or water-based liquids applied to the deck surface after construction of the deck or at any time of bridge life, to form a finite impermeable layer that prevents the chloride penetration into the concrete (Weyers, Prowell, Sprinkel, & Vorster, 1993). Cathodic protection is an electrochemical technique that prevents the initiation of corrosion by cathodically polarizing the reinforcement to increase its potential by applying a low current. Installing a sacrificial anode (made of zinc, for example) in the deck is also an example of cathodic protection: in serving as an anode, zinc (a less noble metal compared to steel or iron) creates an environment where the steel reinforcement becomes the cathode, and thus prevents the reinforcement from corroding (Whiting, Nagi, & Broomfield, 1996): by applying a temporary anode and external electric potential on the deck surface, the chlorides are extracted from the deck. To repair carbonation-induced corrosion, re-alkalization of a deck can be carried out (Constantinou & Scrivener, 1997). Other barrier techniques seclude the use of high performance concrete (HPC), a standard technique used to slow down chloride ingress, as the lower water/cement ratio of HPC and its typical admixtures make it denser and superior in strength compared to regular concrete (Neville & Aïtcin, 1998).

The above techniques, however, can only delay chloride ingress into concrete and do not ensure a complete, long-term protection of the reinforcement steel from chloride-induced corrosion. Thus, the barrier techniques, in and of themselves, do not present a permanent panacea of the problem of corrosion. Concrete decks do and will crack due to different types of loading, fatigue, and distress; and poor workmanship and inadequate mix proportions, as well as vehicle collisions with bridge elements, are among other reasons for cracking in concrete decks (Cope, 2009). Chlorides and water can and do directly access the reinforcement through cracks wider than 0.3 mm, regardless of the cover depth or the admixtures used in the concrete (Koch et al., 2002). Thus, a more direct technique compared to the barrier technique is needed to help resist corrosion.

2.2.2 The Reinforcement Material Technique

The reinforcement material technique involves the use of chloride-resistant materials. The application of materials such as epoxy-coated steel and stainless steel have gained industry acceptance over the last several years in a bid to combat the corrosion problem. Epoxy-coated steel has often been considered a suitable alternative for carbon steel as it is capable of serving as a thin barrier between chlorides and the steel surfaces. In the early 1980s, epoxy-coated reinforcement (ECR) started becoming widely used as a corrosion prevention technique as it is found to inhibit the penetration of water and prevent chlorides from contacting the reinforcement. ECR, with its small additional expense and substantial increase in service life, became a viable reinforcement material option for highway agencies. A complex fabrication process led to irregularities in production, however, which resulted in coating "holidays" during the fabrication process. Coating damage during transportation and construction also accelerate the absorption of moisture that often leads to de-bonding of the coating from the steel and subsequent pitting corrosion (Manning, 1996; Williamson, 2007). Good quality epoxy coatings and best construction practices help prevent corrosion initiation. However, once initiated, the corrosion in epoxy-coated bars often progresses at a rate similar to carbon steel reinforcements.

As explained in greater detail in Volume 1 of this report, non-traditional materials such as stainless steel have proven to be potentially resistant to corrosion and can be economical for use. Stainless steel material consists of nickel, molybdenum, and at least 10.5% chromium to enhance the chloride-induced corrosion resistance and mechanical properties of the steel. Austenitic and austenitic-ferritic (duplex) type stainless steel is most often used as an alternative for carbon steel (Bertolini et al., 2004). The chromium oxide passive layer enables the corrosion rate of stainless steel reinforcement to be at least 50 times lower than carbon steel in a chloride-contaminated environment (Markeset, Rostam, & Klinghoffer, 2006; Nürnberger & Beul, 1999; Ping, Elliot, Beaudoin, & Arsenault, 1996). However, the initial cost of stainless steel reinforcement is several times more than that of carbon steel so the former may generally be considered more cost-effective mostly for bridges that tend to be affected frequent and/or extended closures or that are located in highly corrosive marine environments. Stainless steel clad (SSC) is a composite material that helps reduce the reinforcement cost because there are essentially carbon steel cores that provide the necessary physical and mechanical strength while maintaining the superior corrosion resistance properties of the stainless steel bars. Research studies have shown that SSC bars can be used as direct substitutes for ECR (Clemeña, Kukreja, & Napier, 2003). The price of SSC bars is generally lower than that of solid SS reinforcement, and the corrosion rate of SSC is much lower than that of carbon steel (Kepler et al., 2000). However, similar to ECR, improper bonding between the cladding in the SSC bars (Mietz, 1997) will lead to exposure of the mild steel in the concrete making it vulnerable to corrosion (Darwin, Kahrs, & Locke, 2002).

In recent years, to provide better corrosion resistance at a comparatively lower cost, other corrosion-resistant alloys have been used as viable alternatives for concrete reinforcement. MMFX reinforcement, for example, exhibits four to eight times lower corrosion resistance compared to uncoated reinforcement, and a one-third to two-thirds lower corrosion rate. MMFX also has a high corrosion threshold of 5.36 lb/yd^3 with a corrosion rate of 0.024 mil/year so the first repair therefore is projected to be after approximately 52 years of service life. Some limitations of MMFX include the reduction in its ductility at ultimate load levels and bond strength, with further study suggested by the authors. Overall, MMFX has higher yield strength, better corrosion resistance, and lower life-cycle costs than ECR (Clemeña & Virmani, 2003; Hansson, Pourasee, & Jaffer, 2007). Other novel reinforcement materials include galvanized steel reinforcement (GSR) and fiber-reinforced plastic (FRP) reinforcement. However, the rapid corrosion of GSR in wet cement makes it a less viable option, and FRP's rapid failure at the end of its service life is a major limitation of that material (Cope, Bai, Samdariya, & Labi, 2011). Carbon-fiber reinforcement is a relatively novel non-metallic reinforcement.

2.3 Evaluation of Reinforcement Alternatives

In evaluating a new reinforcement material as an alternative to traditional material, it is imperative to compare their physical/mechanical and economic properties. The physical properties include tensile strength, loading factors, and workability; and the economic properties include their prices ($/lb).

The physical properties of a reinforcement material translate into (a) the time needed for placement of the reinforcement during construction and hence the user costs associated with the bridge downtime; (b) the longevity of the concrete element (in this case, the bridge deck) and thus determines the service life or the analysis period which is a key input in any life-cycle cost analysis of the alternative materials. Alternative reinforcement materials having similar strength values will not significantly influence the deck design. Therefore, in any economic analysis of these new materials, there is no need to include any additional cost of the bridge design man-hours.

Stainless steel or clad stainless steel are superior to traditional carbon steel in workability and ease of reinforcement placement. For example, ECR must be stored away from direct sunlight, fabric or cloth straps must be used in transportation of the reinforcement, proper instruments must be used in cutting the reinforcement, and care must be taken in installation so the epoxy coating is not scratched or marred (INDOT, 2011). On the other hand, the main precaution for installing solid or clad stainless steel reinforcement is that the tie wires, bands, and lifts also must be made of stainless steel to prevent galvanic corrosion (NXI, 2008).

A number of laboratory tests have been conducted to test the corrosion rates of alternative reinforcement materials. In 2008, a 96-week corrosion-testing program of different reinforcement materials in concrete slabs is conducted by FHWA to simulate corrosive marine environments and the application of winter deicing chemicals. The results indicated that the slabs containing stainless steel reinforcement exhibited no damage while both the uncoated carbon steel and the epoxy-coated carbon steel reinforcement exhibited pronounced cracking and rust staining. An accelerated screening test measured the polarization resistance and weight loss of the reinforcements due to the wet-dry cycles of a saline solution over an 84-day period (Hartt, Powers, Lysogorski, Liroux, & Virmani, 2007). The results confirmed that solid stainless steel exhibited the best performance and traditional carbon steel performed the worst. Further, clad reinforcement with no visible defects showed results close to the solid stainless steel results, while the performance of clad reinforcement with visible defects is similar to traditional carbon steel (Hartt et al., 2007). This testing program also confirmed that a large variability exists for clad stainless steel reinforcement, which is dependent on proper manufacturing. Xi (2004) performed an evaluation of various corrosion protection systems of bridges in Colorado. Also, as part of the current project, Purdue University tested at least eight different reinforcement material types for bridge decks over a 3-year period. The results of that experiment are presented in Volume 1 of this report.

The relatively high cost of stainless steel precludes its widespread use as a reinforcement material. On average, both clad and solid stainless steel cost far more than carbon steel. But this price differential could be explained by scale economies of material production: a relatively lower volume of stainless steel production, due to its low-scale use, has led to a paucity of manufacturers of stainless steel reinforcement. With the current fluctuating economic conditions and volatile steel prices, it is difficult to find a consistent price for steel across many different sources. However, the price differential between traditional carbon steel, clad and solid stainless steel reinforcing has been fairly consistent. Most sources state that solid stainless steel generally costs three to five times more than traditional carbon steel while clad stainless steel is two to three times costlier than traditional carbon steel. Clad stainless steel is less expensive than solid stainless steel; and this price differential is an important consideration in any cost-effectiveness analysis geared towards the identification of the optimal reinforcement material choice. It is hypothesized here that the higher initial cost of stainless steel is offset by its longer service life (and concomitant benefits) relative to traditional carbon steel.

2.4 Bridge Deck Service Life

In general, the service life of a bridge deck may be divided into three sub-phase periods (Phases I, II, and III): design and construction, service, and post-service, respectively. At the design phase (I), the initial investments are made in the design, material selection, and construction of the deck. The total cost incurred during this phase is referred to as the initial cost of construction (Bakis et al., 2002). When a bridge officially opens to traffic, Phase II (service) begins. The costs in Phase II may include preventive maintenance costs, user costs such as vehicle operating costs, safety costs, and travel-time savings (Sinha & Labi, 2007). When a bridge becomes structurally deficient, it enters Phase III, at which time rehabilitation and replacement activities will occur and the associated user costs will become the major costs (Jacobs, 1992). A bridge reaches the end of its service life when it is permanently closed to traffic. As a result, the total costs of a bridge over its lifetime, is the sum of the initial cost of construction is the cost occurring during the deck's service life, and the cost occurring during the post-service life duration.

Most bridges in Indiana typically have reinforced concrete decks, which, on average, require replacement or rehabilitation every 20 to 25 years after construction or replacement (Labi, Rodriquez, & Sinha, 2008). The timing and intensity of deck rehabilitation and reconstruction activities are influenced by factors including chloride exposure, traffic loading, climatic severity, corrosion rates and threshold of the reinforcement, and available funding. These parameters themselves are stochastic in nature, but their average values could be established for specific bridge deck designs and types.

The base timeline service life is for carbon steel (10 years). Due to the widespread use of epoxy-coated carbon reinforcement in bridge decks, the service life increases fourfold with a service life of 40 years. FRP shows a considerable increase in service life of 65 to 90 years (Boyd, 1997); and it has been estimated that solid stainless steel has a service life of 75–120 years while clad stainless steel, 75–100 years.

2.5 Analysis Techniques

The analysis to select a material for bridge deck reinforcement and thus to increase the bridge deck service life can be carried out using either deterministic or probabilistic approaches. A deterministic approach estimates the life-cycle cost for a bridge deck using an average value for the various input parameters. On the other hand, a probabilistic approach incorporates the stochastic nature (a range rather than a fixed value) of each input variable into the estimation of the life-cycle cost for alternative reinforcement materials. A deterministic approach to the problem cannot address all variations and will result in a significant difference between the theoretical computation and the actual estimations. Thus, the current research developed a Microsoft Excel-based software tool (Reinforcement Material-Life-Cycle Cost Analysis, RM-LCCA) which uses Monte Carlo statistical techniques to allow the analyst to integrate the input parameter variability into the estimation of life-cycle cost and subsequent selection of reinforcement alternatives.

Risk analysis is a part of every decision made by engineers. A bridge planner/engineer constantly faces uncertainty, ambiguity, and variability in decision-making. The current age is one of unprecedented access to information, nevertheless, it is impossible to predict the future with absolute certainty. To accommodate the practical reality of uncertainties in analyzing inputs and hence, outputs, Monte Carlo Simulation (MCS) can be used. Using MCS, the analyst can present all the possible outcomes of decisions based on the input variables and their associated uncertainties. The impact of the risks can be assessed, thereby allowing for better decision-making under uncertainty. MCS is a mathematical technique that allows users to account for risks in the quantitative analysis of a problem by generating suitable random numbers and observing that fraction of the numbers which obeys some property or properties (Weisstein, 2006). In this study, MCS takes into account the stochastic nature of the input variables by randomly selecting numerical values based upon a known distribution. For example, the average annual daily traffic (AADT) is often normally distributed, therefore, the range of possible values for AADT can be defined by the mean and standard deviation of the AADT data. Once the distribution has been identified, random occurrences of AADT that ultimately and collectively follow this distribution and its parameters (the mean and standard deviation) can be generated and used as an input in the life-cycle cost analysis of the reinforcement material alternatives.

Stochastic dominance (SD) is an intuitive analytical tool that can be used in decision-making to show the superiority of one cumulative distribution of the life-cycle cost (for a given material type) over those of other material types. The concept of stochastic dominance has been extensively used in different disciplines including finance, operations research (Levy, 1992), and psychology (Heathcote, Brown, Wagenmakers, & Eidels, 2010). The SD test is non-parametric in nature, thus eliminates the chances of model misspecification (Heyer, 2001). Out of all n^{th}-degree criteria, first-degree stochastic dominance (FSD) and second-degree stochastic dominance (SSD) are most useful in identifying reinforcement alternatives. In this research, the cumulative distribution functions of the EUAC of total cost are used to develop optimal decisions for reinforcement material type selection between alternatives A_i and A_j. Briefly, if the cumulative probability distribution function of A_i lies below that for A_j without intersecting, then it is called first-order stochastic dominance (FSD). Which mean that we would prefer alternative A_j; and the high probability and lower cost of A_j make it more preferable. Graphically, FSD is a very strong form of dominance, which exists when the cumulative distribution functions of alternatives do not intersect. If they do cross, then the second-order stochastic dominance (SSD) will be useful. In the main report (see Appendix) the mathematical function of stochastic dominance and its applications have been discussed in this study.

LCCA for bridge management systems has gained more recognition in the past decades. Popular bridge management systems such as PONTIS, BRIDGIT, and IBMS use LCCA in their internal algorithmic frameworks. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the National Highway System Designation Act of 1995 encouraged consideration of life-cycle cost in the design and engineering of highway assets. In the context of this study, LCCA is used to minimize the total cost associated with bridge deck construction, rehabilitation, and replacement, as well as user costs such as traffic delays and vehicle-operating costs. It allows the comparison of different reinforcement alternatives with different service lives. The differences in service lives are resulted from the differences in reinforcement material longevity and the associated frequencies, intensities of maintenance and rehabilitation over the service lives. Several state agencies determine a weight for the user costs while computing LCCA. It is clear that inclusion of the user costs (benefits to users) can result in increasing an agency's financial implications (Lamptey, Ahmad, Labi, & Sinha, 2005). To avoid bias due to the different activity profiles and hence service lives associated with the different reinforcement materials, this study used the life-cycle EUAC as the criterion for economic evaluation.

The Analytical Hierarchy Process (AHP) is an important concept that can be used in decision-making involving multiple criteria such as the decision of selecting an appropriate bridge deck reinforcement material on the basis of criteria including agency cost, longevity (service life), and user cost. AHP can align multiple criteria in an ordered hierarchy and assess the relative importance of a criterion, compare the alternatives for each criterion, and finally determine an overall ranking of the different alternatives based on the criteria (Dweiri & Al-Oqla, 2006). For complex multi-criteria decision-making (MCDM) situations, different criteria are expressed in different dimensions or units. Examples of such dimensions include tangible and intangible costs and benefits. AHP provides assistance in solving this type of problem (Triantaphyllou & Mann, 1995). Thomas Saaty (1980; 2008) developed this widely used and popular tool that deals with complex multiple decision criterion problems in a logical and simple manner (Elkarmi & Mustafa, 1993). AHP is based on expert opinion and experience (Cheng & Li, 2001) and uses a fundamental scale of absolute numbers that has been validated by physical and decision problem experiments (Saaty, 1980, 2008). It converts individual preferences into ratio scale weights that can be combined into a linear additive weight for each alternative. The AHP results can be used to compare and rank alternatives and, which assists the decision-maker in making a choice. To examine the influence of different weights, a range of weights sets can be considered in multiple-criteria analysis.

3. STUDY METHODOLOGY

3.1 Introduction

This chapter describes the steps for the analysis. These steps consider the reinforcement material alternatives, their associated service lives, the bridge deck parameters, traffic, and other inputs and utilize deterministic and stochastic analysis methods. There are several steps and sub-steps necessary for the alternative evaluation methodology. This methodology is implemented by developing a Microsoft Excel-based software tool (RM-LCCA) to analyze the alternatives for bridge deck LCCA in a deterministic or stochastic manner. In the probabilistic analysis, the tool has the capability to simulate different distribution profiles.

To perform a Monte Carlo simulation, it is necessary to specify the probability distribution of the input variables, from which outcomes can be generated based on the prescribed probability distribution of the inputs. In this research study, the uncertainties associated with each input variable are made to follow at least one of four probability distributions: uniform, normal, lognormal, and triangular. In order to generate the distribution profiles of the variables and to enable precise and quick analysis, Visual Basic algorithms are written for the RM-LCCA tool. Random numbers with the known probability distribution functions (PDF) are generated from the transformation of the standard uniformly distributed random numbers. The cumulative distribution functions are obtained by integrating the probability distribution functions; and to generate the distribution profiles, a minimum of two inputs are required. For the uniform and triangular distributions, a range of variables is required; and for the normal and lognormal distributions, the mean and standard deviations are required.

Due to the complexity of decision-making, the stochastic nature of the inputs, and the large number of data utilized in the simulations, it is important to choose the number of samples/iterations required to provide a nearly accurate solution or to increase the probability of doing so. An increase in the sample size or the number of iterations will result in a more accurate estimate, but this approach is not feasible for an entire range of data. For given distribution parameters, it has been observed that 10,000 or above iterations can provide a good estimate of the service life prediction for a given alternative reinforcement.

3.2 Input Variables for Life-Cycle Cost Estimation

The various input parameters can be grouped as follows: the reinforcement material type, the bridge deck features, and the economic factors. The reinforcement material-related parameters are based on the costs and effectiveness (expected service life) associated with each reinforcement type. The deck parameters are related to the physical dimensions of the deck and the features or activities associated with the deck, such as the traffic volume and the treatment durations and costs. The economic criteria include the discount rates for the various costs and the parameters that affect the travel behavior of road users. The probability distribution functions of these input variables are the key pieces of information required in Monte Carlo simulations to assess the life-cycle cost associated with each of numerous combinations of the input variables. From another perspective, the input variables can also be placed in two categories: generic and material-specific variables. Material-specific variables are directly influenced by different reinforcement alternatives, whereas generic variables are external factors that may influence the selection of alternative reinforcement materials. The methodology presented in this study uses generic variables one-by-one to explain the impact of change for a specific bridge deck under analysis.

The next set of input variables consists of the project duration for construction and the preservation activities. As discussed in the previous section, the project duration has a direct impact on user costs. The longer the duration, the longer the delay, resulting in higher user costs associated with the project. The traffic volume (vehicles per day) is also an important variable. The detours and work zones associated with a bridge project either provide alternative longer routes or reduce the traffic flow and speed through the work zone, resulting in higher user travel time and delay costs. The other input variables to compute the initial construction cost include the bridge dimensions (e.g., length and width). The unit price of the reinforcement alternatives and their service lives in years are other input variables. Changes in material prices could influence the analysis outcomes in terms of the relative life-cycle cost-effectiveness of the alterative materials. Economic factors also influence the choice of deck reinforcement materials. This study identified five main economic input variables as significant contributors to the life-cycle cost of bridge construction and preservation. Based on FHWA recommendations, a 4% mean discount rate value is selected (Walls & Smith, 1998) but for purposes of the uncertainty analysis, is varied stochastically within a given range. Other input variables in the user cost calculation include the vehicle occupancy, minimum hourly wage, average fuel economy, and price of vehicle fuel.

3.3 Estimation Approach: Life-Cycle Cost Analysis (LCCA)

In this study, LCCA is used to evaluate the competing alternative reinforcement options for increasing bridge deck service life. LCCA incorporates the initial and discounted future agency costs and the user costs to identify the best long-term value of an alternative solution (Hawk, 2003; Walls & Smith, 1998).

3.4 Reinforcement Material Selection and Associated Service Life

In LCCA, the first step is to establish the initial assumptions and to select reinforcement alternatives for analysis. This involves a determination of alternatives worthy of consideration. Section 2.5 discussed in detail the initial decision criteria for selecting the reinforcement alternatives on the basis of their physical, technical, and economic properties. In general, reinforcing materials that exhibit similar physical properties to the traditional material are analyzed in this study. These alternatives are more expensive compared to traditional material but exhibit superior resistance to chloride-induced corrosion.

While a great deal of specific reinforcement impact analysis for bridge deck service life has been conducted in the past, this research provides an analysis methodology and electronic tool that can be used for deterministic and probabilistic LCCA for currently available and future reinforcement materials. In this study, the tool is used for evaluating traditional epoxy-coated steel, solid stainless steel, and clad stainless steel.

After identifying the reinforcement materials, the second step is to determine the activity profiles for the bridges whose decks would be reinforced using each material under consideration. The activity profiles include all of the treatments to the bridge over its entire life, from initial construction to the end of the useful service life of the deck. The occurrences of rehabilitation and the deck replacement timings differ for these alternatives, for example, the rehabilitation cycle for Indiana bridges for carbon steel is generally 20 years, whereas the first rehabilitation for clad steel occurs around 40 to 45 years of service life (Labi et al., 2008; NXI, 2008).

The activity profile or schedule for a traditional bridge is normally based on historical rehabilitation records of typical bridges and. For the bridges in Indiana and this study, these profiles are based on the Indiana Bridge Management System (Sinha, Labi, McCullouch, Bhargava, & Bai, 2009) and FHWA research (Yunovich, Thompson, Balvanyos, & Lave, 2001). The service life profile is estimated based on laboratory testing and literature sources (FHWA, 1998; NXI, 2008). The differences in bridge preservation schedules across the alternatives translate into differences in the costs incurred by the agency and users over the bridge life.

3.5 Life-Cycle Cost Estimates

Step three involved determining the life-cycle costs associated with each reinforcement material type. Life-cycle cost estimation can be divided into three components: the initial (agency) construction costs, the rest-of-life preservation (rehabilitation and deck replacement) costs borne by the agency, and the rest-of-life user costs. The agency costs refer to the expenditures incurred by an agency in providing and maintaining a bridge deck, which consist of the construction and preservation costs over the life-cycle of a bridge deck, where the preservation costs include the costs associated with rehabilitation or reconstruction of the bridge decks; the initial cost of construction includes the costs of advance planning, preliminary engineering, final design, right-of-way acquisition, and construction. Preservation costs include all of the costs to rehabilitate and reconstruct a bridge deck throughout its lifetime.

During bridge construction or rehabilitation, users experience delays, lower safety, and higher vehicle maintenance expenditures associated with detours or work zones, which can be quantified in monetary terms to represent the adverse impacts of work zones or detours. Often the monetary costs borne by the user are important and therefore, the inclusion of this cost category appears logical and necessary; the weighting scheme is also necessary since the user costs typically greatly outweigh the agency costs. The inclusion of user cost considerations bring in a multiple-criteria dimension to the evaluation problem, thus necessitating the use of analysis tools such as multiple criteria analysis and AHP.

In this study, the unit bridge deck replacement and rehabilitation contract costs have been established from historical data and calculated using the average costs ($/ft^2) of bridge decks. The historical data are the as-built costs of past bridge contracts in Indiana where the main motivation is deck replacement or rehabilitation; and the preservation costs used in this study are reflective of the current practices in Indiana. It is noted that the initial costs and preservation costs can differ across regions due to different climate, loading, or other factors, but the uncertainties in costs can be overcome by using probabilistic analysis.

User costs are commonly due to the reduced user safety and increased travel time caused by deficient bridges and associated detours or work zones during construction activities. For the purposes of this research study, it is assumed that for a given bridge, there are no differences in functional or structural capacity for each material alternative, thus, any difference in the user costs are delay costs only due to the work zones associated with their different life-cycle profiles. User costs include direct and indirect costs such as loss of time and additional fuel if a detour or work zone is used. The sum of the costs incurred due to additional travel time and additional fuel consumption yielded an estimate of the user costs due to delay. The source of the equations used for calculating the costs of additional travel time and fuel due to bridge work zones is Chitturi, Benekohal, and Kaja-Mohideen (2008).

Also, it is assumed that the placement practices for different reinforcement alternatives are similar and require a similar project execution duration, which validates the assumption that for a given work zone, the work zone user cost does not vary by material alternatives. However, the frequency of work zones differs across the material types. Therefore, the overall user costs will differ in the case of varied work zone frequencies over the service life, which means that more frequent work zones lead to longer user delays and, subsequently, higher user costs. The importance of the user costs consideration has been highlighted by various state agencies and organizations.

In life-cycle cost estimation, the user costs usually far exceed the agency costs, and identifying the relative weight of the agency costs to the user costs always remains a critical issue. There is no consensus in the literature regarding the relative weight between agency cost and user cost, and the weighting approach therefore is often based on expert opinion. Weighting is influenced by various circumstances, such as different work scenarios, locations, and past experiences. As such, in various past studies, researchers are unable to address the relative weight issue. With this in mind, the present research uses stochastic variation in the agency to user cost weights to determine the impact on alternative selection. These weights in practice are outcomes of either surveys or expert opinion. Therefore, AHP is adopted to address this situation. Since no fixed quantitative weights are available for agency to user costs, AHP allows highway agencies and decision-makers to identify the weights with minimal life-cycle cost estimation for alternative evaluation.

After establishing the activity profiles, other input variables and the associated uncertainties, as probability distribution functions, are determined in order to estimate the associated costs. This study proceeds to conduct LCCA with EUAC using Monte Carlo simulation to generate the cumulative distribution functions of the EUAC for the alternative reinforcement materials. The NPV evaluation reflects the value of the project (all present and future cash flows and discount amounts) at the time of the base year of the analysis, which may be consider as the year of decision-making. Periodic routine maintenance is considered independent of the bridge reinforcement material so it is assumed that it would not affect the reinforcement selection; thus, the routine maintenance costs are therefore not considered in the NPV calculations. The same is with salvage cost, which is not included in the case study. The NPV equation provided some initial indication of the amount of capital needed for the lifetime of the bridge.

Monte Carlo simulation allows for the probabilistic description of EUAC on the basis of several different random combinations of input variables that have individual probability distributions. In the case study, the uncertainty of the input variables is governed by normal distributions, and the final EUAC computation is generated on the cumulative distribution profiles for the alternative reinforcement materials. The methodology presented in this study uses AHP to determine the weights for the agency and user costs.

3.6 Stochastic Dominance for Alternative Selection

To evaluate the alternative reinforcement materials over the life cycle and against the background of uncertainty in the input variables, the theory of stochastic dominance is used. For a given project, in the case study, the levels of the input attributes are varied with a given range of variance to calculate the "simulated" life-cycle cost. The output for this analysis generated the cumulative distribution functions of the agency, user, and total costs for each reinforcement material type. The stochastic dominance concept can help the decision-maker assess, in a more robust fashion, the relative superiority of alternative reinforcement material types on the basis of the cumulative distribution of their simulated life-cycle costs.

4. CASE STUDY AND DATA ANALYSIS

The methodology presented in this study enables a reinforcement material selection decision to be made in uncertainty situations where the input variables are probabilistic. This chapter examines the impacts of the considered reinforcement alternatives on the probabilistic lifetime cost savings for a give individual project of known characteristics. This analysis is conducted for new construction projects, however, it is noted that the rest-of-life cost analysis can also be carried out for existing bridges using the same framework.

The RM-LCCA tool is capable of evaluating more than two material options and considers the initial bridge construction costs and subsequent preservation activities. In this study, three different reinforcement alternatives are analyzed: traditional or epoxy-coated carbon steel (CS), clad stainless steel (CSS), and solid stainless steel (SS). The stochastic analysis results are presented in the Appendix to compare the life-cycle cost of alternative deck reinforcement types.

4.1 Deterministic Scenario

For the case study, two bridges are identified to demonstrate the utility of the methodology and the impact of alternative reinforcement materials on their service lives and budgets: (i) a large bridge with high traffic volume and (ii) a small bridge with low traffic volume. These bridges are assumed to be built using traditional steel as their deck reinforcement material. Bridges under construction can either have specified detour routes or require its users to travel through the work zone at a reduced speed; the two bridges in this case study involved detours.

Using the input data, the life-cycle agency and user costs are determined and the EUAC calculated for each bridge. For the deterministic (certainty) scenario, the analysis results suggest that the EUAC is the lowest for bridge with solid stainless steel deck reinforcement, followed by clad stainless steel, and highest for traditional carbon steel. Equal weights of agency cost to user cost are considered for this probabilistic analysis. The results include plots of the cumulative distributions of the EUAC of the agency costs, user costs, and total costs for each of the two bridges, which demonstrate the importance of the life-cycle agency cost over the user cost for small-scale bridge projects. Also, the results show that it is critical to consider these relative weights in the evaluation of the total life-cycle cost for the reinforcement material selection. It is suggested that the agency costs can be an effective measure to evaluate alternative reinforcement for small-scale projects only, whereas both agency and user costs become important to evaluate larger projects as one such project can impose costs on a large group of users.

4.2 Stochastic Scenario

As discussed in the previous chapters, the input variables for estimating bridge life-cycle costs are typically deterministic but usually occur within certain ranges and may follow some probability distributions. There are a large number of possible influential input variables. For all of these input variables, it is assumed, based on the certainty value, that the variance in the normal distribution is 10% of the mean value. The software tool has the capability to choose a specific variance with the input parameters. The unit cost for bridge rehabilitation and deck replacement is based on the literature review (Yunovich et al., 2001); and these numbers were generated randomly according to the assumed distribution. The concept of stochastic dominance is used to identify and assess the extent of the superiority of one alternative over others. The concept involves a comparison of the probability distributions of the costs or benefits of two alternatives (Clemen, 1996). For instance, if an alternative A stochastically dominates another alternative B, then, even though not all of the possible values of A are better than any value of B, for a certain given level, the probability that A is better than the given level is equal or greater than the probability that B is greater than the given level. Then, obviously, A is better than B. In the context of this research, the cumulative probability distribution for EUAC is used to assess the stochastic dominance across the alternatives. It is seen that, for a given EUAC, the probability exists that stainless steel achieves an EUAC equal to or greater than that for clad stainless steel and traditional steel. These results suggest that, at each EUAC level, the probability that the cost is less than a given value for the stainless steel alternative is equal to or greater than that for clad stainless steel and traditional steel alternatives. Thus, from the perspective of superiority in terms of the EUAC, the stainless steel alternative stochastically dominates the other two alternatives. In the cases where clear dominance is not obviously visual, then the area bounded by the cumulative distribution functions can be used to measure the superiority of the reinforcement alternatives. The trapezoidal rule is applied to measure the area bounded by the two curves. For the given two bridge cases, the superiority of both clad stainless and stainless steel reinforcement over traditional steel for bridges #1 and #2, are observed.

The concept of first-order stochastic dominance is then used to evaluate the superiority of stainless steel over clad stainless steel and traditional steel for bridge #1. The graphs developed in this research that show second-order stochastic dominance (computing area bounded by functions), suggest that the clad stainless and stainless steel is superior to the traditional steel. It is observed that for a certain range of input variables, the traditional steel becomes a superior choice compared to stainless steel, particularly when the weight of agency cost dollar far exceeds that of the user cost. The analysis results also suggest that within the range of input data used, clad stainless steel is always a preferable choice to traditional steel, irrespective of the relative weights between agency cost and user costs; also, for a certain limit of EUAC, clad stainless steel is a superior alternative to stainless steel. However, from the second-order stochastic dominance view, it is clear that stainless steel is a preferable choice to clad stainless steel, albeit with a margin that is small compared to the superiority of stainless steel over traditional steel.

From the EUAC analysis results, it is observed that for bridge #1(small bridge and low traffic volume), the agency cost far exceeded the user cost. The opposite is observed for bridge #2 (large bridge and high traffic volume). Thus, for bridge #1, the agency cost alone could be used to determine the relative feasibility of the alternative reinforcement materials, a clear first order dominance is exhibited by bridge #1. However, the concept of agency to user weights becomes important for large high-volume bridges such as bridge #2. The total EUAC analysis results are presented for the weighted user costs for bridges #1 and #2.

4.3 Sensitivity Analysis

Sensitivity analysis with weighted user costs and discount rates is carried out to determine how these variables influence the alternative reinforcement selection. First, agencies do not follow any clear-cut policy or guideline regarding the relative weights of user cost and agency cost, stochastic as well as different fixed weights for user cost are analyzed in order to examine the outcomes of these weights. Second, the discount rates influence decision-making in life-cycle costing which hinges on the time value of money. The user costs directly reflect the inconvenience experienced by road users due to repeated bridge rehabilitation and construction. Past research has established that work zones are the second largest contributor to non-recurring delay on freeways and principal arterials (Yunovich et al., 2001). This study focuses on the agency and the user cost estimation to assess the feasibility of alternative reinforcement. The user costs are further classified into the cost for additional travel time (TC) and the vehicle operating cost (VOC). AHP is used to assess the weights for deterministic scenarios for these two costs to give a final total life-cycle cost value.

Due to the uncertainty associated with the discount rate, it is useful to study the impact of varying the discount rate on the analysis outcome. Thus, the sensitivity of the EUAC to different levels of the discount rate ranging from 2% to 10% is analyzed. The stochastic EUAC results are calculated with only the agency cost in consideration for both bridges #1 and #2. The resulting stochastic dominance charts suggest that for each of the discount rates considered, stainless steel is a preferable option to clad stainless steel and traditional steel. Nevertheless, the band of cumulative distribution of the EUAC of the total costs for clad stainless steel shrinks with an increase in the discount rate. In other words, for higher discount rates, the relative attractiveness of clad stainless steel decreases, whereas stainless steel still remains an attractive choice.

5. SUMMARY, DISCUSSION, AND RECOMMENDATIONS

Many state highway agencies are investing a significant portion of funds in bridge infrastructure preservation in response to the deterioration of the bridge deck and other bridge elements. Such deterioration has increased drastically in the last decade as many bridges in U.S. are approaching the end of their service lives. Bridge decks deteriorate due to the loadings and a corrosive climate. Every year, billions of dollars are spent to address bridge deck cracking, delamination, and scaling. Deck repair or replacement becomes necessary in addition to strengthening the bridge structure in the case of severe cracking (Minor, White, & Busch, 1988). The literature review of this study concludes that preventive measures are more cost-effective than repair/restoration measures. For example, repairing a damaged bridge deck will cost five to ten times more than installing some form of preventive measure (Rostam, 1991). As mid-service life preventive treatment has been proven to be cost-effective in reducing corrosion-induced damage, bridge planners and designers can enhance their tasks by assessing the life-cycle cost of corrosion-reducing reinforcement alternatives for new bridges.

Several studies have been conducted to assess the life-cycle cost of individual reinforcement alternatives from both the material and the economic evaluation perspective and have demonstrated the associated benefits and costs. To further extend the service life of infrastructure, several novel reinforcing material types have been adopted (or at least are undergoing experimentation) by individual highway agencies.

The methodology presented in this study provides a platform to assess the life-cycle costs of different types of bridge deck reinforcement materials based on their corrosion resistance as well as their economic efficiency. The analysis outcome from the RM-LCCA electronic tool developed in this study can help bridge engineers and practitioners identify the optimal reinforcement alternative for a given bridge on the basis of its expected service life, schedules for rehabilitation and deck replacement, and the accompanying costs to the highway agency and bridge users. The service life of bridge deck, even for the same reinforcement alternative, can change due to factors such as increased loading, rapid changes in the surrounding environment, and upcoming new policy decisions that can affect the short-term and long-term service life of preservation treatments. For the estimated preservation years, the tool incorporates the probability that the treatment timings will be different than what is specified as the average. By running the tool several times for different values of the input variables, the user can carry out Monte Carlo simulation of different combinations of the input variables.

In sum, this study compares the costs, benefits, and cost-effectiveness of different reinforcement material types using the concept of first-order and second-order stochastic dominance. Two bridges from Indiana (one small in size, low-volume and the other large in size, high-volume) are used for the case study to assess the relative stochastic superiority of stainless steel, clad stainless steel, or traditional steel using a multi-criteria approach. Based on all of the analysis, it is determined that solid stainless steel is a superior alternative to clad stainless steel and traditional carbon steel for two extreme bridge cases. The case study is presented to showcase the methodology.

New and more efficient materials are becoming available for bridge construction. Even though they have higher initial costs, they often lead to drastic reductions in life-cycle cost, particularly when user costs are considered in the analysis. Where the agency cost only is considered for LCCA analysis, the projected costs of these materials are exceptionally high due to low production and adaptability in the market at the early stages and, consequently, low economy of scale. It is envisioned that as the benefits of the newer reinforcement alternatives are tested and become recognized, their demand will increase, leading to higher production and lower unit prices as a result.

There is a number of software tools that carry out life-cycle cost estimation for bridge projects. Such tools address issues of corrosion initiation, propagation, and subsequent cracking based on chloride-induced corrosion. Examples of such software tools are STADIUM concrete analysis and Life-365. These tools are basically built for decision support regarding concrete treatments such as installing a barrier or a water membrane. On the basis of the chloride diffusion principle, most of these tools tend to predict service life very well but are less successful in carrying out detailed economic analysis of the use of reinforcement materials. RM-LCCA, which is developed in this study, provides a platform where different alternative reinforcement materials can be evaluated for their life-cycle costs and benefits.

The methodology, software tool, and case study developed in this study yield intuitive and interesting results. However, there are areas that should be addressed to make the evaluation even more comprehensive. Mathematical models describing the time-dependent chloride-induced corrosion deterioration processes could be incorporated in the tool. These models would enable designers to be more confident about assumptions of the timings of rehabilitation actions and the overall life cycle of the bridge deck and the bridge itself. The capability of including specific models involving the initiation and progression of corrosion, cracking, and spalling could greatly enhance the reliability of the prescribed activity profiles for each reinforcement material type.

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APPENDIX A: FULL REPORT

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1. INTRODUCTION

1.1 Background and Problem Statement

At the current time, highway agencies are grappling with the ever-increasing rates at which bridge elements approach their design lives vis-à-vis limited funding for maintenance. This is a critical issue for agencies, particularly in the face of higher user expectations, greater traffic loads, and limited staff. As such, agencies are seeking to construct highway infrastructure that are expected to last longer with minimal frequency and intensity of rehabilitation and maintenance during their service lives. Opportunities for doing this exist for bridges, a critical part of overall highway infrastructure system. As of 2009 in the U.S., the average bridge age is 43 years; 42% of bridges have reached their average life expectancy, and another 35% will reach this age within the next 20 years; also, only 23% of existing bridges are relatively younger in age (FHWA, 2009; see Figure 1.1). Every year, billions of dollars' worth of work is carried out to address bridge deck cracking, delamination, and scaling; and deck repair or replacement becomes necessary in addition to strengthening the bridge structure in the case of severe cracking (Minor, White, & Busch, 1988). Also, significant amounts are expended on preventive measures (Rostam, 1991).

In recent years, numerous strategies have been proposed or adopted to enhance bridge deck service life in a cost-effective manner. A number of bridge management systems have been developed for supporting cost-effective decisions for construction, maintenance, rehabilitation, and replacement work (Hawk & Small, 1998; Lauridsen, Bjerrum, Andersen, & Lassen, 1998; Thompson et al., 1998). These investment decision frameworks are based on life-cycle costing, and the prime objective is to identify and implement the best possible strategy that ensures an adequate level of service for the lowest possible life-cycle cost to achieve a certain minimum level of performance or maximum life-cycle benefits to be earned for a given budget level (Frangopol & Furuta, 2001; Thoft-Christensen, 1995). Life-cycle cost analysis (LCCA) is defined by the Federal Highway Administration (FHWA) as a process for evaluating the total economic worth of a usable project by analyzing the initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs as well as user costs, over the life of the project (FHWA, 1998). It is worth noting that the timings, costs, and effectiveness of the maintenance, rehabilitation, or replacement of a specific bridge deck are characterized by a large degree of variability and hence, uncertainty, because they depend on a variety of factors including the type of material used and the environmental conditions. Therefore, the concept of uncertainty needs to be considered in the life-cycle cost analysis.

Past research has shown that the key factor in bridge deck deterioration and subsequent deck failure is corrosion of the embedded reinforcement elements. In cold-climate regions, deicing salts are applied to control snow and ice during the winter season. The chlorides from these salts migrate through the concrete cover to reach the reinforcement level and destroy the protective passive film of the steel reinforcement. Once the passive layer is destroyed, the corrosion process initiates and propagates. As the corrosion products accumulate, they generate high tensile stresses which eventually lead to irreversible structural damage including concrete cracking, delamination, and spalling (Hartt, Powers, Lysogorski, Liroux, & Virmani, 2007; Yunovich, Thompson, Balvanyos, & Lave, 2001).

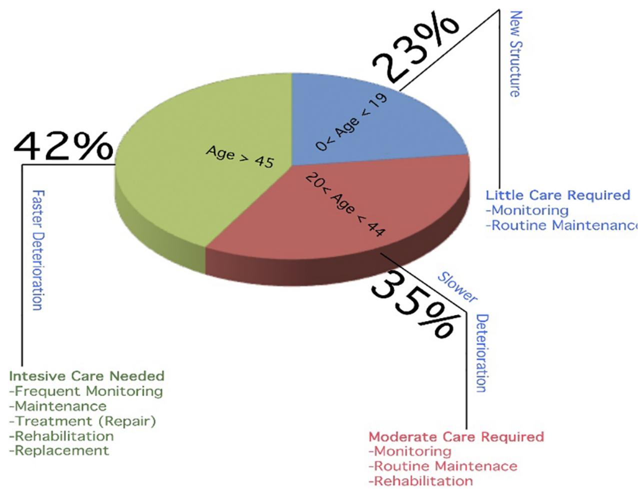

Figure 1.1 Deterioration rates and preservation needs by age group (FHWA, 2009).

Various treatments aimed at arresting corrosion by reducing the porosity of concrete to mitigate chloride migration have only very limited success because such treatments create problems related to early age shrinkage cracking. The use of corrosion-resistant reinforcement materials in bridge design can potentially reduce the rate of bridge deterioration and enhance bridge deck service life. There are numerous materials for this purpose, such as epoxy-coated steel, stainless steel, clad steel, fiber-reinforced polymer bars, MMFX rebars, and carbon fiber bars. These materials have different costs and effectiveness and therefore need to be evaluated by analyzing all their respective agency and user costs over their respective service lives.

1.2 Research Objective

The main objective of this research is to develop a systematic framework for reinforcement material type selection for a given bridge under prevailing conditions of traffic volume, bridge size, and other features associated with the bridge, the natural environment, and the economy. In doing so, this study examines the impact of the probabilistic nature of input variables on the relative cost-effectiveness of each material type. The framework is intended to facilitate identification of the conditions at which each material is most cost-effective. Another objective is to demonstrate the study methodology using a case study involving epoxy-coated steel, clad stainless steel, and stainless steel as alternative reinforcement materials for the bridge deck.

1.3 Overview of This Technical Report

This report first identifies the materials for bridge deck construction, discusses the common problems and treatments associated with these materials, and finally, focuses in detail on one specific category of these materials: deck reinforcement, on the basis of the assumption that the concrete is sound. It is recognized duly that the material service life, which corresponds to different rehabilitation profiles, is a key factor in bridge investment decisions and that the scheduled rehabilitation cost, timing, and effectiveness are probabilistic. The average timings for the repair or rehabilitation of bridge decks are specified using information from past studies. A large number of timing scenarios were evaluated in order to identify the cost-effective scenario that best reduces spending by reducing rehabilitation frequency, increasing bridge deck service life, and lowering life-cycle costs.

The analytical techniques used in the study include probabilistic life-cycle costing and multiple-criteria analysis (e.g., Analytical Hierarchical Process (AHP)). Since rehabilitation frequencies and economic parameters such as interest rates and fuel prices are inherently uncertain in nature, the LCCA is carried out while accommodating the stochastic behavior of the inputs. The output results are compared in term of the stochastic dominance of the cumulative distribution functions associated with different material alternatives. The LCCA enables a comparison of alternatives with different service lives, costs, and rehabilitation schedules. The AHP is used to evaluate the relative weights across the multiple criteria (agency and user costs). The last part of the framework is a demonstration of the sensitivity of the outcome (choice of the reinforcement material type) to different levels of the input variables.

A Microsoft Excel-based software tool (RM-LCCA) was developed as part of this study to serve as a decision support tool for INDOT for purposes of identifying the optimal type of bridge deck reinforcement material and for quick investigation of the effect of varying the levels of key inputs on the optimal choice. This tool will enable agencies to tailor their reinforcement material choices to suit any individual bridge at a specific location under specific traffic and other external conditions.

2. LITERATURE REVIEW

2.1 Introduction

To acquire insight into the various issues associated with increasing the service lives of bridge decks by appropriate selection of reinforcement material, an extensive literature review on the subject was carried out. This chapter synthesizes the past research on the main materials for bridge deck construction and their roles in deck corrosion; it also discusses the properties of reinforcement materials, the mechanisms of reinforcement corrosion, propagation, and the current preventive practices. Lastly, relevant past work on application of relevant analytical techniques including LCCA, AHP, and stochastic dominance, is reviewed.

Bridge superstructure and substructure (see Figure 2.1) are designed to carry and transmit loads. The beams and girders are intermediate members that transfer the live and dead loads of the superstructure to the sub-structural elements. As the "roof" of the bridge, the deck is the element that is most exposed to rain, ice, salt from the sea, spray or deicing chemicals, and traffic loading impacts. Under the influence of external forces such as salt and loading, bridge elements deteriorate continually. For example, a typical reinforced concrete bridge deck experiences spalling (Xanthakos, 1996), cracking (MacGregor & Bartlett, 2000), corrosion (Clear & Hay, 1973), and delamination. In certain cases, the timing decisions for bridge repair are aided by bridge instrumentation: sensors installed at strategic locations on the bridge provide tell-tales of defective conditions and thus alert the agency when there is a need for corrective maintenance, rehabilitation, or replacement (Benmokrane, El-Salakawy, El-Ragaby, & El-Gamal, 2007; Schmitt et al., 2009).

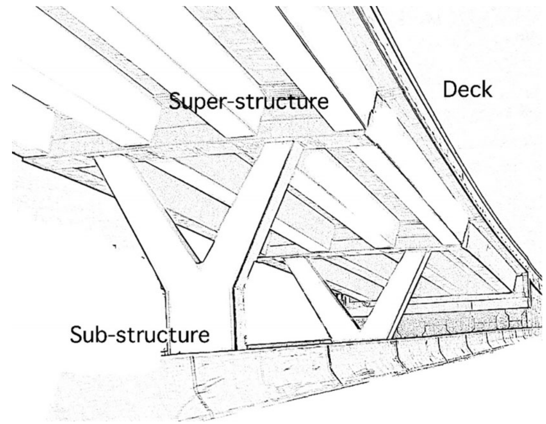

Figure 2.1 Structural elements of a typical highway bridge

2.2 Reinforcement Corrosion and Preventive Measures

Bridge elements reach their terminal serviceability for a variety of reasons that include deterioration, structural failure, and load fatigue (Estes & Frangopol, 2001). Corrosion occurs due to interaction between a metallic material and the environment. The presence of chloride initiates the corrosion of bridge reinforcement material, resulting in rusting, cracking, spalling, and ultimately reduced load-carrying capacity of the deck (Liu & Weyers, 1998). Thus, as stated in Chapter 1 of this appendix, chloride attack is a key deterioration factor and continues to be a major problem for concrete structures worldwide, particularly in marine environments or in climates where deicing chemicals are applied during the winter months. At coastal areas, due to the ingress of chloride from the saline environment, the total life-cycle cost of a bridge can be as much as 1.5 times that of its non-coastal counterpart, particularly if the appropriate treatment is delayed (Tanaka, Kawano, Watanabe, & Nakajo, 2001). It has been estimated that overall, the U.S. loses $8.3 billion per year on bridges alone due to corrosion (Koch, Brongers, & Tompson, 2002).

2.2.1 Reinforcement Corrosion

The effect of chloride exposure differs between steel and reinforced concrete bridges. Steel bridges visibly corrode due to direct chloride attack; on the other hand, reinforced concrete bridges corrode internally which is then manifest

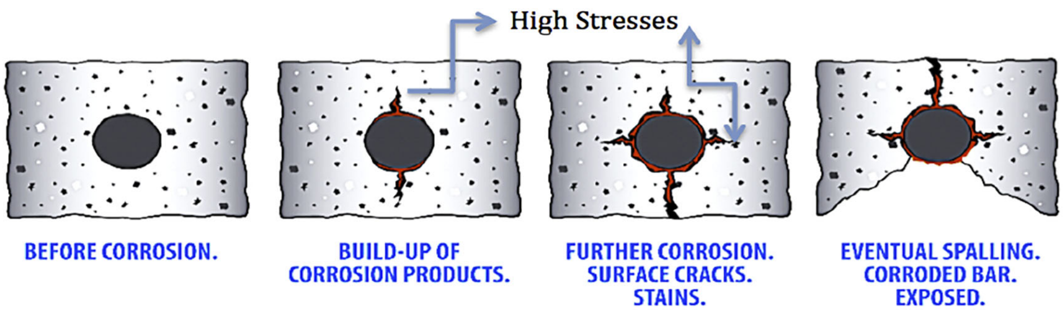

Figure 2.2 Corrosion propagation in steel rebar and concrete spalling (source: http://www.frpdistributors.com/).

outwardly in the form of cracking and spalling. The corrosion of steel reinforcement takes places in two stages: the initiation or incubation period in which chloride ions travel to the rebar level and the active or deterioration stage in which corrosion of the steel initiates and then propagates (Fanous & Wu, 2000). The corrosion of steel occurs through the following mechanisms: (i) breakdown of the passive layer on the steel by the chloride ions (Broomfield, 2007; Gu, Beaudoin, Zhang, & Malhotra, 2001), and (ii) carbonation due to carbon dioxide reactions with the cement phase of the concrete (Bertolini, Elsener, Pedeferri, & Polder, 2004).

When the chlorides diffuse to the depth of the reinforcing steel, they begin to attack the passive film of the corrosion protection products present on the surface of the steel. This will not result in a decrease in the pH level, and the passive layer therefore will continually reestablish itself and prevent active corrosion (Pradhan & Bhattacharjee, 2009). However, when the concentration of the chlorides at the reinforcement reaches a threshold level, the passive layer on the steel reinforcement surface breaks down and active corrosion initiates (Williamson, 2007). The corrosion of the reinforcement in turn causes concrete degradation due to additional tensile forces exerted by the corroding steel; and as steel corrodes, the volume expands by a factor of 3–6 (Ceran & Newman, 1992), and these forces cause concrete cracking and, eventually, spalling (Broomfield, 2007; Fuhr & Huston, 1998). Figure 2.2 illustrates the stages of this mechanism: chloride ingress, stress development, and concrete cracking and spalling.

There are two major strategies for bridge decks to arrest or retard corrosion: (i) the barrier method: construction of a barrier at the concrete surface that stops or slows down the travel of chloride ions through the concrete (Type 1), and (ii) selection of a reinforcement material that is inert to chemical attack by the chloride ions (Type 2) (El-Reedy, 2008; Kepler & Locke, 2000). We discuss these in the next section. Figure 2.3 shows the treatments currently available that can be applied to prevent or mitigate bridge deck corrosion.

2.3 Corrosion Protection Systems Type I

The first type of corrosion protection is to establish a barrier that prevents the chloride ions from reaching the reinforcement. For doing this, depending on the condition of the concrete or steel, an agency may increase the cover-depth requirements for decks or use low-permeability concrete,

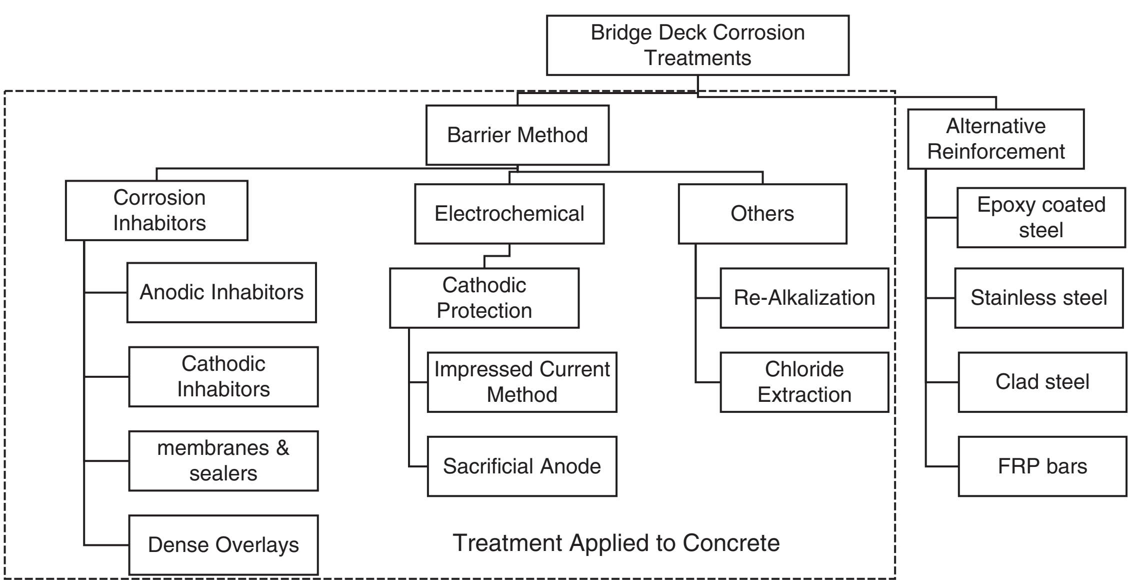

Figure 2.3 Bridge deck corrosion treatment strategies (Olek, 2010).

both of which increase the chloride diffusion time through the concrete and subsequently enhance the deck service life (Williamson, 2007).

Barrier methods prevent the ingress of water, oxygen, and chloride ions into the concrete and protect reinforced concrete from corrosion damage. These treatments are for direct application to bridge decks or concrete. Deck sealers are either solvents or water-based liquids applied to the deck surface that create a finite impermeable layer to prevent the penetration of chloride into the concrete (Weyers, Prowell, Sprinkel, & Vorster, 1993). Corrosion inhibitors are chemicals added to the concrete mixture during construction of the deck to ensure a sufficient concentration of the inhibitor at the depth of the reinforcement (Williamson, 2007). They decrease the corrosion rate of the rebar by forming a protective film around the rebar without reducing the concentration of the corrosive agent (Monticelli, Frignani, & Trabanelli, 2000). In the electrochemical method, cathodic protection is widely used. Cathodic protection prevents the initiation of corrosion by cathodically polarizing the reinforcement to increase its potential by applying a low current. Installing a sacrificial anode such as zinc in the deck is also an example of cathodic protection. Zinc, a metal less inert compared to steel or iron, will act as the anode thereby making the steel reinforcement act as the cathode, thereby not allowing the reinforcement to corrode (Whiting, Nagi, & Broomfield, 1996). By applying a temporary anode and external electric potential on the deck surface, the chlorides are extracted from the deck. To repair carbonation-induced corrosion, re-alkalization of a deck can be carried out (Constantinou & Scrivener, 1997). To reduce the rate of chloride ingress, the use of high performance concrete (HPC) is the standard technique; HPC's lower water/cement (w/c) ratio and admixtures make it denser and superior in strength (Neville & Aïtcin, 1998).

The above-describe barrier techniques can only delay chloride ingress into concrete and do not ensure the protection of the reinforcement steel from chloride-induced corrosion. The practical reality is that concrete deck cracks due occur due to a variety of reasons that include loading, fatigue, distress, poor workmanship, inadequate mix proportions, vehicle collision with bridge elements, among others (Cope, 2009). Thus, no matter how extensive barrier techniques are used, chlorides and water will ultimately access the reinforcement through cracks, particularly those wider than 0.3 mm (Koch et al., 2002). Thus, an alternative or a complement to the barrier techniques is the use of inert material for the reinforcement. We discuss this in the next section.

2.4 Corrosion Protection Systems Type II

Reinforcement materials such as epoxy-coated steel and stainless steel have gained industry acceptance over the last several years to combat the corrosion problem. Epoxy-coated steel has long been considered a viable alternative for carbon steel as the epoxy had successfully extended the element lives by serving as a barrier between the attacking chlorides and the steel surfaces. To achieve a very long service life, materials that are inherently immune to chloride attack are needed. Thus, materials such as stainless steel became promising options. Some other alloy materials, such as MMFX rebars, have shown themselves to be potentially very resistant to corrosion and can be economical for use. The next sub-section discusses different reinforcement materials in use and their associated benefits and limitations.

2.4.1 Epoxy-Coated Rebar

In the early 1980s, epoxy-coated rebar (ECR) started becoming widely used as a corrosion prevention method as it was found to inhibit the penetration of water and prevent chlorides from contacting the rebar. ECR, with its relatively little additional expense and observed substantial increase in service life, became a viable reinforcement material option for highway agencies. However, it became increasingly clear that its complex fabrication process led to irregularities in production, resulting in "coating holidays" that developed during the fabrication process. Also, damage to the coating during transportation and construction leads to absorption of moisture that in turn causes de-bonding of the coating from the steel and subsequent pitting corrosion (Manning, 1996; Williamson, 2007). Good quality epoxy coatings and best construction practices help prevent corrosion initiation; however, once initiated due to any of the above-mentioned reasons, the corrosion in epoxy-coated bars often progresses at a rate similar to carbon steel rebars.

2.4.2 Stainless Steel Rebar

Stainless steel rebar is composed of nickel, molybdenum, and at least 10.5% chromium to enhance the steel's mechanical properties and its resistance to chloride-induced corrosion. Austenitic and austenitic-ferritic (duplex) type stainless steel is most often used as an alternative for carbon steel (Bertolini et al., 2004). Due to the passive chromium oxide layer, the corrosion rate of stainless steel rebar is at least 50 times lower than that of carbon steel in a chloride-contaminated environment (Markeset, Rostam, & Klinghoffer, 2006; Nürnberger & Beul, 1999; Ping, Elliott, Beaudoin, & Arsenault, 1996). On the other hand, the initial cost of stainless steel rebar is several times more than that of carbon steel so it is typically considered more cost-effective only at severely corrosive marine environments or where it is sought to drastically minimize bridge downtime (and hence, the associated user costs) where traffic volumes are very high.

2.4.3 Stainless Steel Clad Rebar

Stainless steel clad (SSC) bars are stainless steel tubes with a carbon steel core. This composite material helps reduce the cost of the reinforcement by mostly using the relatively less expensive carbon steel that provide the necessary physical and mechanical strength while maintaining the superior corrosion resistance properties of the stainless steel material on its outer layer. Research studies have shown that SSC bars can be used as direct substitutes for ECR (Clemeña, Kukreja, & Napier, 2003). It has been stated in the literature that the cost for SSC bars is lower than that of solid SS rebar and their corrosion rate is twofold lower than that of carbon steel (Kepler & Locke, 2000). However, similar to ECR, improper bonding between the cladding in the SSC bars (Mietz, 1997) will lead to exposing the mild steel in the concrete and subsequent corrosion will progress (Darwin, Kahrs, & Locke, 2002).

2.4.4 Alloy Reinforcement (MMFX)

In recent years, corrosion-resistant alloys have been used as viable alternatives for concrete reinforcement in a bid to provide superior corrosion resistance at a relatively lower cost. Table 2.1 provides details on some of these materials. MMFX rebar, for example, exhibits four to eight times lower corrosion resistance compared to uncoated rebar, and a one-third to two-thirds lower corrosion rate. MMFX also has a high corrosion threshold of 5.36 lb/yd^3 with a corrosion rate of 0.024 mil/year so the first repair therefore is projected to be after approximately 52 years of service life. Some limitations of MMFX include the reduction in its ductility at ultimate load levels and bond strength, with further study suggested by the authors. Overall, MMFX has higher yield strength, better corrosion resistance, and lower life-cycle costs than ECR (Clemeña & Virmani, 2003; Hansson, Pourasee, & Jaffer, 2007).

Other relatively novel reinforcement materials include galvanized steel rebar (GSR) and fiber-reinforced plastic (FRP) rebar. However, the rapid corrosion of GSR in wet cement makes it a less viable option, and FRP's rapid failure at the end of its service life is a major limitation of that material (Cope, Bai, Samdariya, & Labi, 2011). Carbon-fiber reinforcement is a relatively new non-metallic material for reinforcement.

2.5 Evaluation of Reinforcement Alternatives

In evaluating a new reinforcement material as an alternative to traditional epoxy-coated carbon steel, a comparison of the physical/mechanical and economic properties of the reinforcement material is imperative. The physical properties include tensile strength, loading factors, and workability; and the economic properties include price.

Stainless steel and clad stainless steel are generally considered superior to traditional (epoxy-coated carbon) steel in workability and ease of reinforcement placement. For example, ECR must be stored away from direct sunlight, fabric or cloth straps must be used in transportation of the reinforcement, proper instruments must be used in cutting the rebar, and care must be taken in installation so the epoxy coating is not scratched or marred (INDOT, 2011). For solid or clad stainless steel reinforcement, the main precaution during installation is that the tie wires, bands, and lifts also must be made of stainless steel to prevent galvanic corrosion (NXI, 2008).

A number of laboratory tests have been conducted to test the corrosion of alternative reinforcements. A 96-week corrosion-testing program of different rebar materials in concrete slabs was conducted by FHWA in 2008 to simulate corrosive marine environments and the application of winter deicing chemicals. The results indicated that the slabs containing stainless steel rebar exhibited no damage while both the uncoated carbon steel and the epoxy-coated carbon steel rebar exhibited pronounced cracking and rust staining. An accelerated screening test measured the polarization resistance and weight loss of the reinforcements due to the wet-dry cycles of a NaCl solution over an 84-day period (Hartt et al., 2007). The results confirmed that solid stainless steel performed the best and traditional carbon steel performed the worst. Further, clad rebar with no visible defects showed results that were similar to that found for solid stainless steel, while the performance of clad rebar with visible defects was similar to that of the traditional carbon steel (Hartt et al., 2007). This testing program also confirmed that there is a large variability regarding the effectiveness of clad stainless steel reinforcement due to the large influence of the quality of its manufacture. Xi (2004) performed an evaluation of various corrosion protection systems of bridges in Colorado. Also, as part of the current project, at least eight different reinforcement material types for bridge decks over a 3-year period were tested at Purdue University's Bowen Laboratory. The results of that experiment are presented in the main volume of this report.

The relatively high cost of stainless steel precludes its widespread use as a reinforcement material. On average, both clad and solid stainless steel cost far more than carbon steel. However, the issue of scale economies is worthy of consideration. A relatively lower volume of stainless steel production, due to its low-scale use, has led to a paucity of manufacturers of stainless steel reinforcement. With the current fluctuating economic conditions and volatile steel prices, it is difficult to find a consistent price for steel across many different sources. However, the price differential between traditional carbon steel and clad and solid stainless

TABLE 2.1
Performance details of two alloy-based reinforcement materials

Alloy Type	Composition	Corrosion Initiation Time Ratio*	Cost Ratio*
MMFX-2 (ASTM A615 Grade 75)	Low carbon, low chromium micro-composite steel	2	2–4 times
2101LDX (ASTM A955-98)	1.5% Ni, 21% Cr	7	
3Cr12	3% Ni, 12% Cr	1.6	

Source: Hansson et al. (2007).
*Compared to traditional (carbon) steel.

steel reinforcing has been fairly consistent. Most sources state that solid stainless steel generally costs several times more than carbon steel while clad stainless steel is more costly than traditional carbon steel. These price differentials are important considerations in any cost-effectiveness analysis that seeks to identify the optimal reinforcement material. It is hypothesized here that the higher initial cost of stainless steel is offset by its longer service life (and concomitant benefits) relative to traditional carbon steel. It has been suggested in the literature that the service life of a two-layer, solid and clad stainless steel rebar potentially can be twice that of traditional epoxy-coated carbon steel.

2.5.1 Bridge Deck Service Life

In general, the service life of a bridge deck may be divided into three phases: design and construction, service, and post-service. At the design phase (I), the initial investments are made in the design, material selection, and construction of the deck. The total cost incurred during this phase is referred to as the initial cost of construction, C_{INT} (Bakis et al., 2002). When a bridge officially opens to traffic, Phase II (service) begins. The costs (C_{SL}) in Phase II may include preventive maintenance costs, user costs such as vehicle operating costs, safety costs, and travel-time savings (Sinha & Labi, 2007). When a bridge becomes structurally deficient, it enters Phase III, at which time rehabilitation and replacement activities will occur and the associated user costs will become the major costs, C_{PSL} (Jacobs, 1992). A bridge reaches the end of its service life when it is permanently closed to traffic. Thus, the total costs of a bridge over its lifetime, C_T can be expressed as:

$$C_T = C_{INT} + C_{SL} + C_{PSL} \tag{2.1}$$

where C_T represents the total cost over the bridge deck life-cycle, C_{INT} is the initial cost of construction, C_{SL} is the cost occurring during the deck's service life, and C_{PSL} is the cost occurring during the post-service life duration.

Table 2.2 presents the three sub-phase periods and the associated costs of a bridge deck during its service life, as well as possible causes of bridge deck failure or structural deficiency.

Most bridges in Indiana typically have reinforced concrete decks that, on average, require replacement or rehabilitation every 20–25 years after construction or replacement (Labi, Rodriguez, & Sinha, 2008). Figures 2.4 and 2.5 illustrate a typical chloride-based bridge deck service life profile and a treatment profile during a deck life cycle, respectively. The frequency and intensity of deck rehabilitation and reconstruction activities depend on factors such as the chloride exposure, traffic loading, corrosion threshold of reinforcement, and available funding). These parameters themselves are stochastic in nature, but an average value can be defined for specific bridge deck types. Table 2.3 shows the mean estimated service life for different rebar selections.

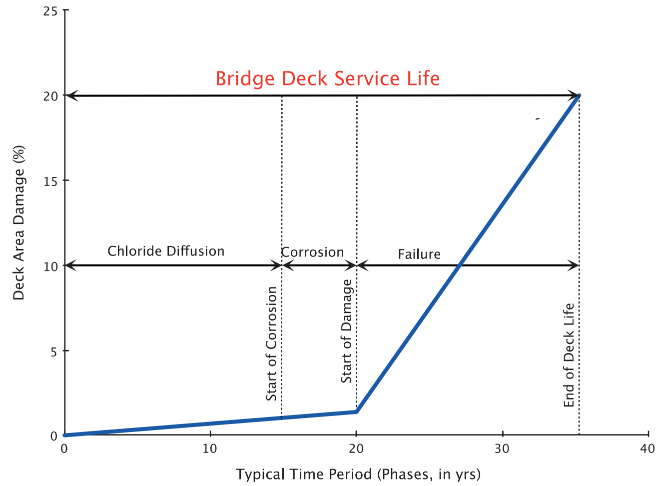

Figure 2.4 Bridge deck corrosion with service life.

As the table indicates, the base timeline service life is for uncoated carbon steel (10 years). Due to the widespread use of epoxy-coated carbon reinforcement in bridge decks, the service life increases fourfold with a service life of 40 years. FRP shows a considerable increase in service life of 65–90 years (Boyd, 1997); and solid stainless steel has an estimated service life of 75–120 years while clad stainless steel has an estimated service life of 75–100 years.

2.6 Analysis Techniques

The process for selecting the deck reinforcement material can be carried out on the basis of conditions that are either deterministic or probabilistic. A deterministic approach

TABLE 2.2
Bridge deck phases, failure causes, and associated costs

Cost (CT)	CINT	CSL	CPSL
Phase	**Design and Construction**	**Service**	**Post-service**
Possible causes for bridge deck deterioration	Budget constraints, economical and political (non-tech) issues and policy change Estimation and construction error	Budget constraints, economical and political (non-tech) issues and policy change Traffic growth Environmental corrosion	Budget constraints, economical and political (non-tech) issues and policy change Traffic growth Environmental corrosion

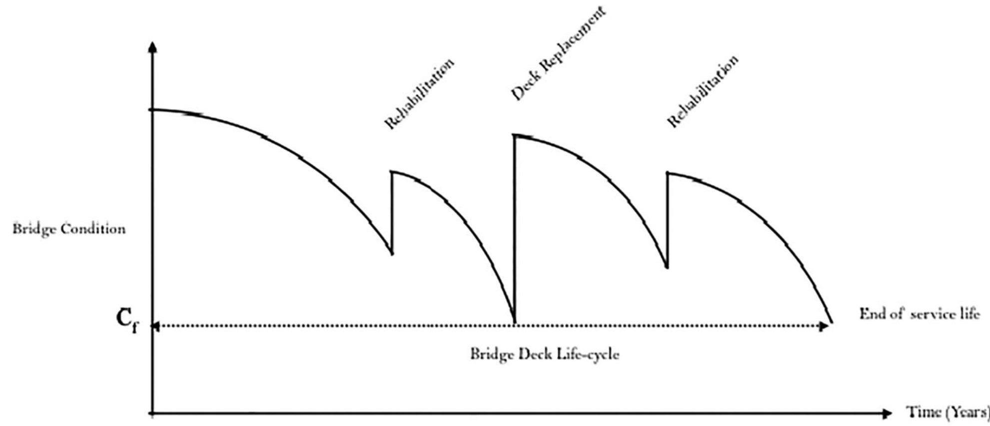

Figure 2.5 Typical bridge deck service life profile (Cope, 2009).

estimates the life-cycle cost for a bridge deck using an average value for the various input parameters. A probabilistic approach, on the other hand, incorporates the stochastic nature of the input variables into the estimation of the life-cycle cost. A deterministic approach to the problem cannot address all variations and will typically result in a significant difference between the theoretical computation and the actual output. Thus, the current research developed a Microsoft Excel-based software tool (Reinforcement Material-Life-Cycle Cost Analysis, RM-LCCA) which uses techniques that allow for the integration of input parameter variability into the estimation of life-cycle cost and subsequent selection of reinforcement alternatives.

2.6.1 Monte Carlo Simulation Method

Bridge planners and engineers constantly face uncertainty, ambiguity, or risk (variability) in decision-making. Monte Carlo Simulation (MCS) is a mathematical technique that helps account for risk in the quantitative analysis of a problem. This is often done by generating suitable random numbers and observing that fraction of the numbers that obeys some property or properties (Weisstein, 2006). Using MCS, the probability of each possible outcome can be ascertained, and the best reinforcement material in terms of the life-cycle cost, under the most likely conditions, can be determined. Such a quantitative statement of the uncertainty can help the agency assess the risks associated with the decision problem and thus facilitates more informed and more robust decision-making. In this study, MCS takes into account the stochastic nature of the input variables by randomly selecting numerical values based upon a known distribution. For example, the average annual daily traffic (AADT) is normally distributed; therefore, the range of possible values for AADT can be defined by the mean and standard deviation of the AADT data set. After the probability distribution for each input variable has been identified, randomly generated values for each variable can be obtained; the developed distribution, rather than the average or default single value, then serves as the input for the life-cycle cost analysis; the outcome is the relative attractiveness of the alternative materials in terms of the probability distribution of their life-cycle costs.

TABLE 2.3
Bridge deck mean service life for different reinforcement material types

Reinforcement Material	**Estimated Mean Service Life (Years)**
Carbon steel rebar	10
Epoxy-coated rebar	40
Fiber-reinforced plastic bars	65–90
Solid stainless steel rebar	75–120
Clad stainless steel rebar	75–100

Sources: Ceran & Newman (1992), NXI (2008), Yunovich et al. (2001).

2.6.2 Stochastic Dominance

Stochastic dominance (SD) is an intuitive analytical tool that can be used in decision-making that can show the superiority of one cumulative distribution (developed from the MCS probability distributions) compared to the cumulative distributions of other alternatives. The concept of stochastic dominance has been used extensively in disciplines including finance, operations research (Levy, 1992), and psychology (Heathcote, Brown, Wagenmakers, & Eidels, 2010). The SD test is non-parametric in nature, thus eliminating the chances of model misspecification (Heyer, 2001). Out of all n^{th} degree criteria, first-degree stochastic dominance (FSD) and second-degree stochastic dominance (SSD) are most useful in identifying reinforcement alternatives.

In this research, the cumulative distribution functions of the EUAC of total cost are used to develop optimal decisions for reinforcement material type selection between any two alternatives, say A_i and A_j. Briefly, if the cumulative probability distribution function of A_i lies below that for A_j without intersecting, then it is called first-order stochastic dominance (FSD). We will be measuring costs so $A_i > A_j$ would mean that we would prefer alternative A_j; and lower cost of A_j and its higher probability make it more preferable. Graphically, FSD is a very strong form of dominance, which exists when the cumulative distribution functions of alternatives do not intersect. If they do cross, then the second-order stochastic dominance (SSD) will be useful. Chapter 3 of this Appendix discusses the mathematical

TABLE 2.4
AHP scale for pair-wise comparison

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favor one over the other
5	Much more important	Experience and judgment strongly favor one over the other
7	Very much more important	Experience and judgment very strongly favor one over the other
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise between any two choices is needed

Source: Saaty (2008).

function of stochastic dominance and its adoption in the current study.

2.6.3 Life-Cycle Cost Analysis (LCCA)

LCCA for bridge management systems has gained more recognition in the past decades; and popular bridge management systems (BMS) such as PONTIS, BRIDGIT, and the Indiana Bridge Management System (IBMS) use LCCA in their analyses and decision-making processes. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the National Highway System Designation Act of 1995 encouraged consideration of life-cycle cost in the design and engineering of highway assets.

In this study, LCCA was used to minimize the total cost associated with bridge deck construction, rehabilitation, and replacement, as well as the user costs associated with traffic delays and vehicle-operating costs. It allows for the comparison of different reinforcement alternatives with different longevities (and hence, service lives) and different activity profiles (maintenance/rehabilitation frequencies and intensities). In computing LCCA, some state agencies or research efforts explicitly or implicitly specify a weight for the user cost (Lamptey, Ahmad, Labi, & Sinha, 2005). LCCA can be measured in terms of net present value (NPV), internal rate of return (IRR), or equivalent uniform annual cost (EUAC). In this study, we use EUAC to express the life-cycle cost due to the different service lives of each material type.

2.6.4 Analytical Hierarchical Process (AHP)

AHP is an important concept that can be used in decision problems that involve multiple (two or more) criteria. AHP can align multiple criteria in an ordered hierarchy and assess the relative importance of a criterion, compare the alternatives for each criterion, and finally determine an overall ranking of the different alternatives based on the criteria (Dweiri & Al-Oqla, 2006; Triantaphyllou & Mann, 1995). AHP is based on expert opinion and experience (Cheng & Li, 2001) and uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments (Saaty, 1980). Thomas Saaty developed this widely used and popular tool that deals with complex multiple decision criterion problems in a logical and simple manner (Elkarmi & Mustafa, 1993). AHP converts individual preferences into ratio scale weights that can be combined into a linear additive weight $w(a)$ for each alternative a. Table 2.4 shows the AHP scale for pairwise comparison. The results can be used to compare and rank alternatives and, hence, can assist the decision maker in making a choice. To examine the influence of different weights, stochastic weights can be considered in multiple-criteria analysis.

2.7 Chapter Summary

This chapter provided a review of the literature on reinforcement corrosion and prevention and the mitigation strategies used by various agencies, and the various analytical methodologies that can be used in identifying the most cost-effective material reinforcement option.

3. STUDY METHODOLOGY

3.1 Introduction

This chapter describes the steps for the analysis (Figure 3.1). These steps consider the reinforcement alternatives, associated service lives, deck parameters, traffic, etc. and utilize deterministic and stochastic analysis methods. First, an overall life-cycle cost methodology was established to assess each material type. The relative weights of the multiple criteria (user and agency costs) were established using AHP. This methodology was implemented by developing a Microsoft Excel-based electronic tool (RM-LCCA). Then, recognizing that each input factor in the LCCA is inherently probabilistic, the LCCA was made more robust by carrying out Monte Carlo simulation of the LCCA using the probability distributions of the input factors. The concept of stochastic dominance was then used to interpret the resulting cumulative distributions of the life-cycle cost.

3.2 Life-Cycle Cost Analysis (LCCA)

In this study, LCCA was used to evaluate the competing reinforcement options for increasing bridge deck service life. LCCA incorporates the initial and discounted future agency costs and the user costs to identify the best long-term value of an alternative solution (Walls & Smith, 1998). (Table 3.5 presents the LCCA inputs.)

3.2.1 Reinforcement Selection and Associated Service Life

In LCCA, the first step is to establish the initial assumptions and to identify the alternatives for the analysis.

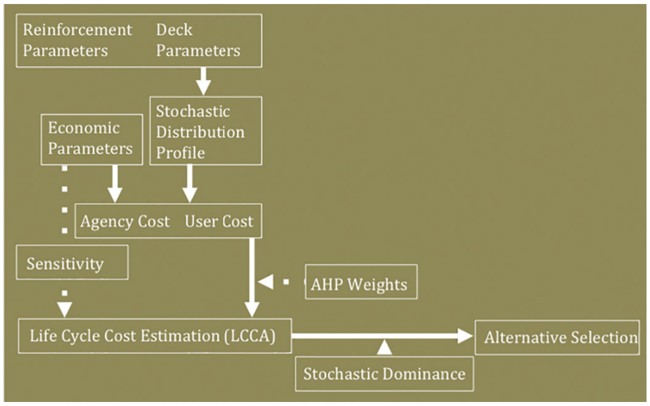

Figure 3.1 Study framework flow diagram.

Section 2.5 discussed in detail the initial selection criteria for the reinforcement materials for the analysis, and these are based on their physical properties and economic characteristics. In general, the reinforcement materials that were considered in this study exhibit very different prices and longevities but otherwise similar physical properties (for example, strengths) and technical features (for example, site preparations).

After identifying the reinforcement materials, the second step was to establish the activity profiles for the bridges with the different materials for their deck reinforcement. The activity profiles included all of the treatments to the bridge over its entire life, from initial construction to the end of the useful service life. Table 3.1 presents the rehabilitation and deck replacement schedules for bridges with specific types of reinforcement material. The timings of rehabilitation and the deck replacement differ across these alternatives; for example, the rehabilitation cycle for Indiana bridges for carbon steel decks is generally 20 years (Sinha, Labi, McCullouch, Bhargava, & Bai, 2009), whereas the first rehabilitation for clad steel is estimated to occur at approximately 40–45 years of service life (NXI, 2008).

The activity profile or repair schedule for a traditional bridge is typically established by expert opinion or historical rehabilitation records. For Indiana and this study, these profiles were based on information from the Indiana Bridge Management System (Sinha et al., 2009) and FHWA research (Yunovich et al., 2001); and the service life profile was estimated based on laboratory testing and literature sources (FHWA, 1998; NXI, 2008). The differences in bridge

TABLE 3.1
Mean activity profile for bridge life-cycle after construction

Alternative Reinforcement Activity	Epoxy-Coated Steel	Clad Stainless Steel	Stainless Steel
First rehabilitation	20	45	45
First deck replacement	45	75	–
Second rehabilitation	60	–	75
Estimated service life (year)	75	100	100

Source: Cope (2009).

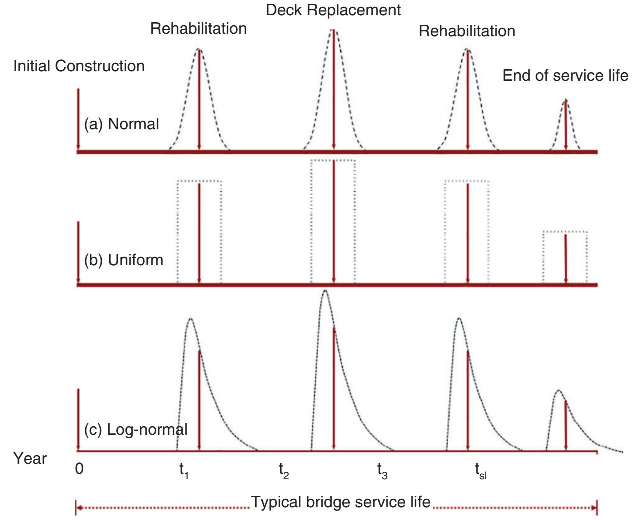

Figure 3.2 Illustration of probabilistic variation in bridge preservation activity profile.

preservation activity profiles or schedules across the material alternatives translate into differences in the overall life-cycle costs incurred by the agency and users over the bridge life.

A typical probabilistic activity profile for a bridge in its service life is shown in Figure 3.2, where distribution represents the probability of occurrence of rehabilitation, and replacement and the arrow represent the mean time in years found in the literature.

3.2.2 Cost Estimates

Step three involved determining the costs associated with the various alternatives. Cost estimation can be divided into three components: initial construction costs (which are borne by the agency), preservation (rehabilitation and deck replacement) costs that are borne by the agency, and user costs. Thus, the agency costs consist of the construction and preservation costs over the life-cycle of a bridge deck; and the preservation costs include the costs associated with rehabilitation or reconstruction of the bridge deck. During bridge construction or rehabilitation, users experience delays, lower safety, and higher vehicle maintenance expenditures associated with detours or work zones, which can be quantified in monetary terms to represent the adverse impacts of work zones or detours. The inclusion of user cost considerations infuses a multiple-criteria dimension to the evaluation problem. Often, the overall monetary value of the user costs greatly outweighs that of the agency costs; therefore, application of some relative weighting is often needed to avoid bias generated by the excessive level of user costs.

3.2.3 Agency Costs

Agency cost, in the problem context, refers to the expenditures incurred by an agency in providing and maintaining a bridge deck. The initial cost of construction includes the costs of advance planning, preliminary engineering, final design, right-of-way acquisition, and construction. Most of these costs are common across the alternatives and thus may not need to be included in the analysis. The preservation costs include all of the costs to rehabilitate and reconstruct a bridge deck throughout its lifetime. The statistical model developed by Saito, Sinha, and Anderson (1990), which can be used for aggregate estimation of the bridge replacement cost, is as follows:

$$BRTC = 1.155 \times BL^{0.903} \times DW^{0.964} \quad (3.1)$$

Where, $BRTC$ is the total bridge construction cost in thousands of dollars for all bridge types (1985 constant dollars); BL is the bridge structure length in ft.; and DW is the out-to-out bridge deck width in ft. A factor of 2.12 was used to convert 1985 constant dollars into 2012 constant dollars (FHWA, 2012).

For a bridge using a material for deck reinforcement other than traditional steel, the additional cost of the bridge due to the use of more expensive material (relative to traditional steel) is given by (P_{Alt} (P_T) $\times$ W_D. Thus, the initial construction costs for a bridge using a given reinforcement material type is given by:

$$AC^{Alt}_{initial} = BRTC + (P_{Alt} - P_T) \times W_D \quad (3.2)$$

Where, $AC^{Alt}_{initial}$ is the bridge construction/replacement cost for a given deck reinforcement material type; P_T is the unit price of traditional steel (\$/lb); P_{Alt} is the unit price of given reinforcement material type; and W_D is the weight (in lbs) of the bridge deck reinforcement.

In this study, the unit bridge deck replacement and rehabilitation contract cost values were established from historical data and calculated using the average costs (\$/ft^2) of bridge decks. Average costs were used because most of the statistical models produced to date do not segregate projects for which corrosion of the bridge decks is the main incentive for reconstruction. By using the average cost values, one can be more certain that other costs due to structural insufficiency or other construction problems are not included. Equations 3.1 through 3.5 were used to compute the agency costs for the reinforcement materials.

$$AC^{T}_{Deck\ replacement} = BL \times DW \times C_{DP} \quad (3.3)$$

$$AC^{Alt}_{Deck\ replacement} = BL \times DW \times C_{DP} + (P_{Alt} - P_T) \times W_D \quad (3.4)$$

$$AC_{Deck\ rehab} = BL \times DW \times C_{DR} \quad (3.5)$$

Where, $AC^{T}_{Deck\ replacement}$ deck replacement cost for traditional carbon steel deck; $AC^{Alt}_{Deck\ replacement}$ is deck replacement cost for a given reinforcement material type; C_{DP} is the unit cost of deck replacement, in \$/ft^2; and C_{DR} is the unit cost of deck rehabilitation, in \$/ft^2.

The historical data utilized were the as-built costs of Indiana bridge contracts where the main motivation was deck replacement or rehabilitation; and the preservation costs used in this study are reflective of the current practices in Indiana. It is noted that the initial costs and preservation costs can differ across regions and specific bridges due to different climate, loading, or other factors; in probabilistic analysis, such cost uncertainty are addressed.

Figure 3.3 presents the bridge rehabilitation treatments in the life-cycle activity profiles and the costs (as well as the cost

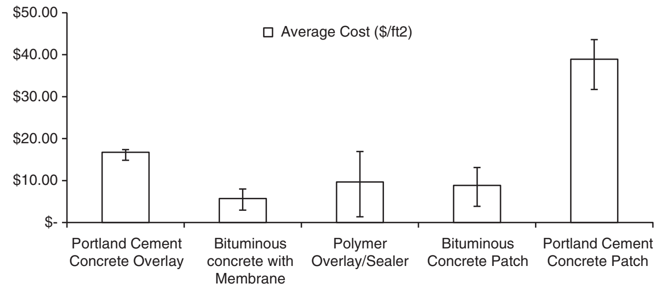

Figure 3.3 Rehabilitation cost comparison (in 2012 dollars).

ranges for purposes of probabilistic analysis) (Schnell & Bergmann, 2008). For our case study, a Portland cement concrete overlay was used because (1) it is considered an appropriate treatment to rejuvenate the wearing surface and to repair any cracking or spalling damage, and (2) it is generally difficult to predict, from a general planning perspective, the frequency or severity of areas needing patching for analysis and forecasting procedures. It was also assumed that the treatment life of these rehabilitation treatments is similar across the different alternatives.

3.2.4 User Costs

User costs are commonly due to the reduced safety and increased travel time of road users arising from structurally deficient or functionally obsolete bridges, and the detours or work zones associated with construction or rehabilitation activities. For the purposes of this study, it was assumed that the bridge under investigation has no functional or structural problems so any difference in user costs are only the delay costs due to the work zones associated with their different life-cycle profiles. User costs also include direct and indirect costs such as loss of time and additional fuel if the bridge preservation involves a detour or work zone. The sum of the costs incurred due to additional travel time and additional fuel consumption yields an estimate of the user costs due to delay. The equations used for calculating the costs of additional travel time and fuel due to bridge work zones are as follows (Chitturi, Benekohal, & Kaja-Mohideen, 2008):

$$UC^{workzone}_{TTC} = \left(\frac{BL}{Speed_{workzone}} - \frac{BL}{Speed_{normal}}\right) \times ADT \times T \times Unit_{VOT} \quad (3.6)$$

$$UC^{detour}_{TTC} = \left(\frac{DL}{Speed_{DL}}\right) \times ADT \times T \times Unit_{VOT} \quad (3.7)$$

$$UC^{detour}_{VOC} = DL \times ADT \times T \times Unit_{VOC} \quad (3.8)$$

$$Unit_{VOT} = Vehicle\ \ occupancy \times Minimum\ \ hourly\ \ wages \quad (3.9)$$

$$Unit_{VOC} = \frac{Fuel\ \ Cost(\$)}{Fuel\ \ Economy\ (miles\ \ per\ \ gal)} \quad (3.10)$$

Where, DL is the detour length; ADT is the average daily traffic; T is the project duration in days; $Unit_{VOT}$ is the unit value of travel time ($/hr); $Unit_{VOC}$ is the unit vehicle operating cost ($/vehicle-mile); $Speed_{DL}$ is the travel speed in the detour zone; $Speed_{workzone}$ is the travel speed in the work zone; and $Speed_{normal}$ is the travel speed in a normal operation period (that is, when the bridge is not undergoing any repair).

The daily user cost due to a bridge work zone is calculated as the sum of the constituent costs of delay and VOC. It is assumed that the placement efforts (man-power and time) for the different reinforcement materials do not differ significantly from each other and thus the work duration for a specific instance of construction or deck replacement is same across the alternatives. Therefore, the life-cycle user cost will differ across the alternatives only in terms of the number of work zones over the service life (in other words, the frequency of deck replacement over the service life); this means that more frequent work zones lead to longer user delays and, subsequently, higher user costs.

As we have explained earlier in this chapter, in life-cycle cost analysis, the calculated user cost typically far exceeds the agency cost, and implicit or explicit relative weighting between the two criteria is carried out to avoid bias in the LCCA outcome. However, identifying the relative weight remains a critical issue. There seems to be no consensus in the literature regarding the actual relative weight between agency cost and user cost, and this weighting therefore is often based on expert opinion. Weighting is influenced by various circumstances, such as different work scenarios, locations, and past experiences. As such, in various past studies, researchers were unable to address the relative weight issue. In this study, AHP was used to help establish the relative weights.

After establishing the activity profiles and the input variables and their respective probability distribution functions, this study proceeded to carry out Monte Carlo simulation to generate the cumulative distribution functions of the life-cycle cost (in terms of the EUAC) for each reinforcement material type. The EUAC was calculated from the NPV (the value of all the present and future cash flows and discount amounts at the base year of the analysis). The NPV provided some initial indication of the capital needed for construction and rehabilitation over the bridge lifetime. The intensity of annual routine maintenance was considered independent of the bridge reinforcement material type and thus was not considered in the life-cycle costing. Also, it was assumed that for salvage value or disposal costs are equal across the material alternatives.

EUAC was used instead of NPV for the life-cycle cost analysis because EUAC is useful for comparing alternatives with different service lives and allows a direct comparison between the annualized costs of bridge decks reinforced with alternative reinforcement materials.

$$EUAC_{RM} = \left[\sum\nolimits_{j,k,l} \propto (AC) + \beta(TTC) + \gamma(VOC)\right] \times \left[\frac{r \times (1+r)^n}{(1+r)^n - 1}\right] \tag{3.11}$$

Where, RM is reinforcement material alternative; AC is the sum of the present worth of the agency cost of initial construction, rehabilitation, and deck replacement; TTC and VOC are the sum of the present worth of the travel time cost and vehicle operating cost of detours or work zones for initial construction, rehabilitation, and deck replacement; $\propto$, β, and γ are the weight factors assigned to AC, TTC, and VOC, respectively; j, k, and l are the initial construction, rehabilitation, and deck replacement activities occurring in bridge service life respectively; r is the discount rate; and n is the bridge service life (years).

Monte Carlo simulation allows for the probabilistic description of EUAC on the basis of several different random combinations of input variables that have individual probability distributions. In our case study, the uncertainty of the input variables was governed by normal distributions, and the final EUAC computation was generated on the cumulative distribution profiles that were generated for the alternative reinforcement material types. Figure 3.1 shows the flow diagram for the analysis steps.

3.2.5 Analytical Hierarchical Process Methodology

The methodology presented in this study uses AHP to determine the relative weights between the agency and user costs. The AHP procedure is explained as follows (Saaty, 2008):

Step 1: Determine the problem and goals. Develop a hierarchical structure [goals-criteria-sub-criteria-alternatives]. Assuming there are n criteria (factors) to consider, the construct of a pair-wise comparison weight matrix, if the relative weights are already known:

$$A = (a_{ij})_{n\times n} = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{pmatrix} \tag{3.12}$$

$$here,\ \ a_{ii} = 1,\ \ a_{ij} = \frac{1}{a_{ji}},\ \ (i,j = 1,2,\dots,n)$$

Use this matrix form to determine eigenvalues:

$$\underline{A\omega} = \lambda\underline{\omega}$$

So $\underline{\omega}$ is an *eigenvector* of matrix A corresponding to *eigenvalue* λ.

Step 2: Multiply the elements of every row and take the n[th] power to compute the geometric mean:

$$\begin{pmatrix} b_{11} \\ \vdots \\ b_{nn} \end{pmatrix} \quad here,\ \ b_{1j} = 1_{1j}a_{1j}\dots a_{1n}\ \ \overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{3.13}$$

$$(where,\ \ i = 1,2,\dots,n)$$

Step 3: Now the normalized weights are as shown:

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n} \overline{w_i}} \tag{3.14}$$

On the basis of AHP, Figure 3.4 demonstrates the goal, criteria, and alternative selections. The overall goal is

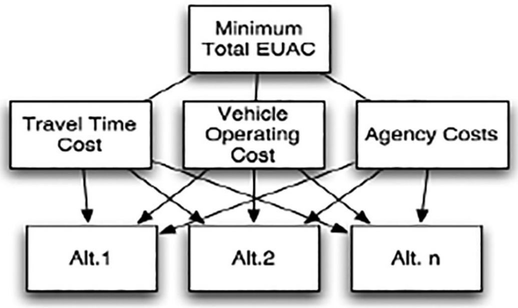

Figure 3.4 Hierarchy for alternative reinforcement selection for bridge deck.

minimizing the total EUAC, and the criteria are the agency and user costs (travel time and vehicle operating costs). The presented methodology does not directly evaluate alternatives based on AHP and stops the AHP process only at the point where it identifies the normalized weights for the criteria shown in Figure 3.4. These weights further are used with the output of Monte Carlo simulation and analyzed for their stochastic dominance.

3.3 Values of the Input Variables

The next set of input variables contains the project duration for construction and the preservation activities. Project duration has a direct impact on user costs. The longer the duration, the longer the delay, resulting in higher user costs associated with the project. The traffic volume (vehicles per day) is also an important variable. The detours and work zones associated with a bridge project either provide alternative longer routes or reduce the traffic flow and speed through the work zone, resulting in higher user travel time and delay costs. The other input variables to compute the initial construction cost include the bridge dimensions (e.g., length and width). The unit price of the reinforcement alternatives and their service lives in years are other input variables. Changes in material prices could influence the cost-effectiveness of the materials. Table 3.2 presents the input variables and the mean values for each variable.

Economic factors also influence the life-cycle cost of deck reinforcement materials. This study identified five main economic input variables as significant contributors to the life-cycle cost of bridge construction and preservation. The factors and their default values are identified in Table 3.3. Based on FHWA recommendations, a 4% mean discount rate value was selected (Walls & Smith, 1998). The vehicle occupancy, minimum hourly wage, average fuel economy, and cost of fuel are also used in the user cost calculation. The mean values of the variables are shown in Table 3.3 (Chitturi *et al.*, 2008; U.S. Department of Energy, 2009). The mean values included in Table 3.3 can be considered close to the average values in Indiana under present market scenarios.

TABLE 3.2
Material-related variables and mean values

Reinforcing Material	Mean Cost ($/lb)	Mean Service Life (yr)
Epoxy-coated steel	$1.20	40
Clad stainless steel	$3.02	100
Solid stainless steel	$3.60	100

Sources: NXI (2008) and Yunovich et al. (2001) in 2012 constant dollars.

TABLE 3.3
Economic-related variables and mean values

Economic Input Variable	Mean Value
Discount rate	4%
Number of passengers per vehicle	1.8
Minimum hourly wage	$13.43
Average fuel economy	23 mpg
Cost of fuel	$3.75/gal

Sources: Chitturi et al. (2008), U.S. Department of Energy (2009).

3.4 Distribution Functions

For the Monte Carlo simulation of the life-cycle cost of each material alternative, it is necessary to specify the probability distribution of each input variable. In this research study, the uncertainties in the input variables were characterized using any one of four distributions: uniform, normal, lognormal, and triangular.

In order to generate the distribution profiles of the variables and to enable precise and quick analysis, random numbers with the known probability distribution functions (PDF) were generated from the transformation of the standard uniformly distributed random numbers. Table 3.4 presents the mathematical forms of the PDFs. The cumulative distribution functions were obtained by integrating the probability distribution functions. To generate the outcome distribution profiles, a minimum of two inputs are required. For the uniform and triangular distributions, a range of variables was required; and for the normal and lognormal distributions, the mean and standard deviations were required.

The inverse transformation method was used to generate random numbers between 0 and 1 for the uniform and triangular distributions while the Box-Muller transformation and the inverse of Box-Muller were used for the normal and lognormal distributions. The inverse transformation method uses the inverse of the PDF and converts a random number between 0 and 1 to a random value for the input distribution. The process can be mathematically described as follows:

For a continuous random variant X, following a probability distribution function f, let F be the cumulative probability distribution function (CDF) for the variant X, which is continuous and strictly increasing in (0,1). Let F^{-1} denote the inverse of the function F, which is often called the inverse CDF function. Then, a randomly generated number U = (0,1) will used to generate a random number $X = F^{-1}(\mathrm{U})$ from the PDF f.

Due to the complexity of decision making, the stochastic nature of the inputs, and the large number of data utilized in

TABLE 3.4
Probability distribution function formulations

Distribution	Probability Distribution Functions	Comments
Uniform	$f_X(x) = \begin{cases} \frac{1}{b-a} & a \le x \le b \\ 0 & otherwise \end{cases}$	X uniformly distributed in [a, b]
Triangular	$f_X(x) = \begin{cases} \frac{2 \times (x-a)}{(m-a) \times (b-a)}, & a \le x \le m \\ \frac{2 \times (x-b)}{(m-b) \times (b-a)} & m \le x \le b \\ 0 & otherwise \end{cases}$	X with a triangular distribution of T [a, m, b], where a & b = minimum and maximum value of X respectively, m = the mode value of X
Normal	$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} exp^{\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]}, \quad -\infty \le x \le \infty$	X with mean μ and standard deviation σ
Log Normal	$f_X(x) = \begin{cases} \frac{1}{\sigma\sqrt{2\pi y}} exp^{\left[-\frac{(\ln y-\mu)^2}{2\sigma^2}\right]} & 0 \le y \le \infty \\ 0 & otherwise \end{cases}$	Y = e^X, where X is a normal distributed random variable with mean μ and standard deviation σ

the simulations, it is important to choose the number of samples/iterations required to provide a nearly accurate solution or to increase the probability of doing so. An increase in the sample size or the number of iterations will result in a more accurate estimate, but this approach is not feasible for an entire range of data. For given distribution parameters, it has been observed that 10,000 or above iterations can provide a good estimate of the outcome (life-cycle cost) for a given reinforcement material type.

3.4.1 The Probability Distributions of the Input Variables

Figure 3.5 presents the various input variables for the life-cycle analysis. As mentioned in an earlier section of this chapter, these variables are related to the reinforcement material type, the bridge activity profile, traffic features, detour characteristics, and economic factors. The reinforcement material variables include the material price and the expected service life associated with it. The deck-related variables include the deck physical dimensions, and the traffic-related variables include the traffic volume. The economic variables include the discount rate and the gas price. Other variables include the rehabilitation and maintenance costs and contract durations. Table 3.5 presents the assumed nature of the probability distribution function for each input variable. The input variables can be placed in two categories: generic and material-specific variables. Material-specific variables are the variables that depend on each reinforcement material alternative, such as the material price; on the other hand, the generic variables are external factors that are independent of the material alternatives, for example, detour length. The probability distribution functions of these input variables were the key inputs for the Monte Carlo simulations to develop the life-cycle cost distributions for each alternative reinforcement material.

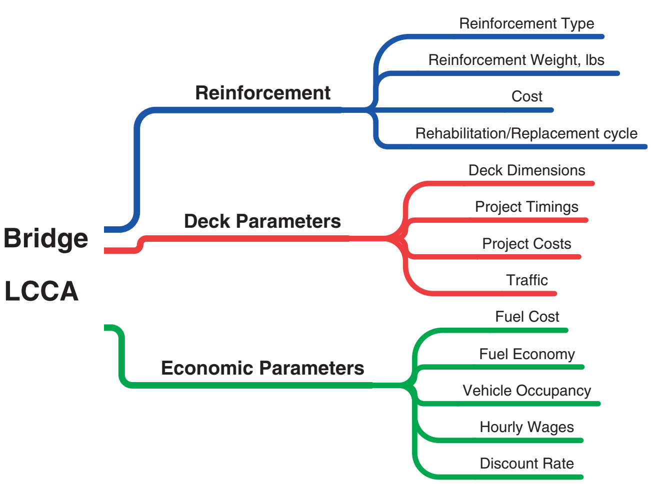

Figure 3.5 Input variables for the Monte Carlo simulation of life-cycle cost.

3.5 Stochastic Dominance for Alternative Selection

To evaluate the alternative reinforcement materials on the basis of the life-cycle simulation outcomes (that is, the resulting probability distributions of the life-cycle cost for each material type), the theory of stochastic dominance was used. For a given material type scenario in the case study, the level of input attributes were varied with a given range of interaction to calculate the "simulated" outcome (that is, the life-cycle cost). Also, the output for this analysis includes the individual cumulative distribution functions of the life-cycle agency cost, life-cycle user cost, and total life-cycle costs, for each reinforcement material type. The stochastic dominance concept can help the decision-maker assess the relative superiority of alternative reinforcement material types on the basis of the cumulative distribution of their simulated life-cycle costs.

TABLE 3.5
Characteristics of the input variables for the Monte Carlo simulation of life-cycle costs

Input Variables	Type of Variable (material specific (M) or generic (G))	Nature of Probability Distribution	Units
Cost of alternative reinforcement	M	Normal	$
Weight of reinforcement per square foot	M	Normal	lb/ft2
Unit bridge deck rehabilitation cost	M	Normal	$/ft2
Unit deck replacement cost	M	Normal	$/ft2
First rehabilitation year	M	Normal	# of years
Second rehabilitation year	M	Normal	# of years
Deck replacement year	M	Normal	# of years
End of service life	M	Normal	# of years
Discount rate	G	Uniform	%
Vehicle occupancy	G	Uniform	Pass./vehicle
Fuel cost	G	Uniform	$/gal
Hourly wage	G	Uniform	$/hour
Fuel economy	G	Uniform	miles/gal
Construction duration	M	Normal	Days
Rehabilitation duration	M	Normal	Days
Deck replacement duration	M	Normal	Days
Average annual daily traffic (AADT)	G	Uniform	#
Detour length	G	Uniform	Miles
Detour speed	G	Uniform	Mph
Work zone length	G	Uniform	Miles
Work zone speed	G	Uniform	Mph

Figure 3.6 exhibits four hypothetical scenarios of the cumulative distribution function of the costs of two alternatives (in our case, two material types) F and G. These are herein considered to explain the stochastic dominance concept in the four scenarios: (a) equal dominance of F and G; (b) dominance of F over G; (c) identifiable dominance, where there is switching of dominance between F and G; and (d) non-dominance, which is an advanced case of (c) where multiple switching occurrences make it difficult to identify which alternative is dominant.

Decision-makers seek to maximize their expected probability (E_{EUAC}) to choose between alternatives F and G. Equation 3.15 shows that F is definitely dominant over G.

$$E_{EUAC}[p(EUAC_F)] - E_{EUAC}[p(EUAC_G)] \geq 0 \qquad (3.15)$$

$$\text{with } p(EUAC_F) - p(EUAC_G) \geq 0 \qquad (3.16)$$

Alternative F is uniformly preferred to alternative G under increasing EUAC preference (F dominates G) under first-order stochastic dominance. This can be written as Equation 3.17 and is explained graphically in Figure 3.7.

$$F_G(p) - F_F(p) \geq 0 \text{ for all } p \text{ with Eq.3.8 holds true} \qquad (3.17)$$

Typically, where the decision criterion is the outcome of simulation, there are several levels of the outcome that may occur for each alternative. As such, the decisions to select one of several alternatives are not easy to make and involve complexity because one alternative may be superior at some level of the outcome but inferior at another level of the outcome. In our study, the outcome is the EUAC. To address this issue, the second-order stochastic dominance method can be used. This is referred to as the risk aversion method for alternative selection. Second-order stochastic dominance can be written as Equation 3.18 and is explained graphically in Figure 3.8.

$$\int_{\min F \text{ and } G}^{p} [F_G(p) - F_F(p)]dp \geq 0 \quad \text{for all } p \text{ with Eq.3.8 holds true} \qquad (3.18)$$

Figure 3.8 depicts the two cumulative distribution functions that intersect and, consequently, result in a situation where neither alternative is uniformly superior at every level of EUAC. Figure 3.8 (a) exhibits the superiority of alternative F for a certain range of EUAC. Figure 3.8 (b) shows that the expected savings in selecting alternative F is depicted by the sum of the positive and negative areas bounded by the cumulative distribution functions of F and G.

To assess the superiority of alternative F over alternative G, the area bounded by the cumulative distribution functions is measured. The trapezoidal method was applied to compute the area bounded by two distributions curves, as shown in Figure 3.9 and represented in Equation 3.19. Figure 3.9 exhibits the coordinates of one trapezoid among all n numbers of trapezoids considered for evaluating the area bounded by the functions of F and G.

$$Area = \frac{1}{2}\sum_{i=1}^{n-1}(X_{i+1} - X_i) \times [\{F(X_{i+1}) - G(X_{i+1})\} + \{F(X_i) - G(X_i)\}] \qquad (3.19)$$

Where, X represents the EUAC values, functions F and G are the upper and lower bound functions, and n is the total number of trapezoids considered to estimate the area.

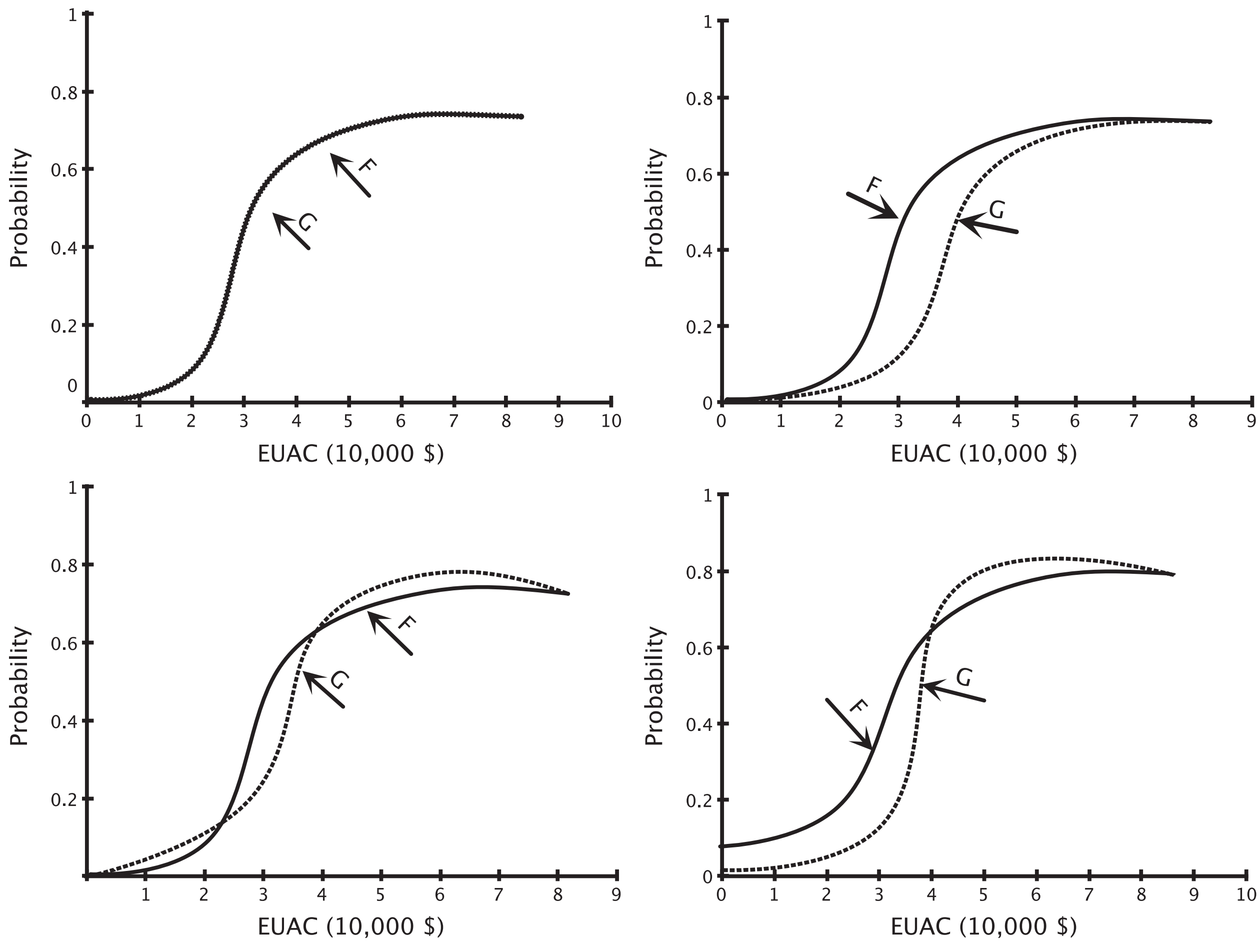

Figure 3.6 Stochastic dominance interpretation for two hypothetical cumulative distributions (Heathcote et al., 2010).

3.6 Chapter Summary

This chapter outlined the basic LCCA procedure in this study. After identifying the alternatives for analysis, the appropriate activity profiles (which are indicators of the frequency of rehabilitation in bridge deck life) and their associated probability distribution functions, were established. Mathematical formulations to measure stochastic dominance were developed and explained. This chapter also provided the methodology and mathematical framework for

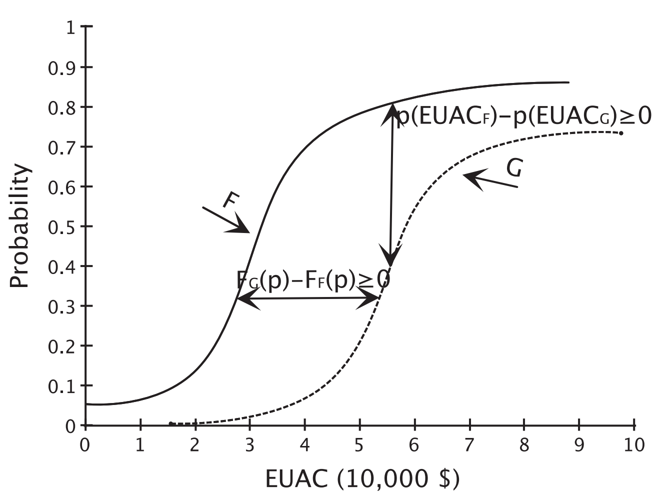

Figure 3.7 First-order stochastic dominance: condition for alternative selection.

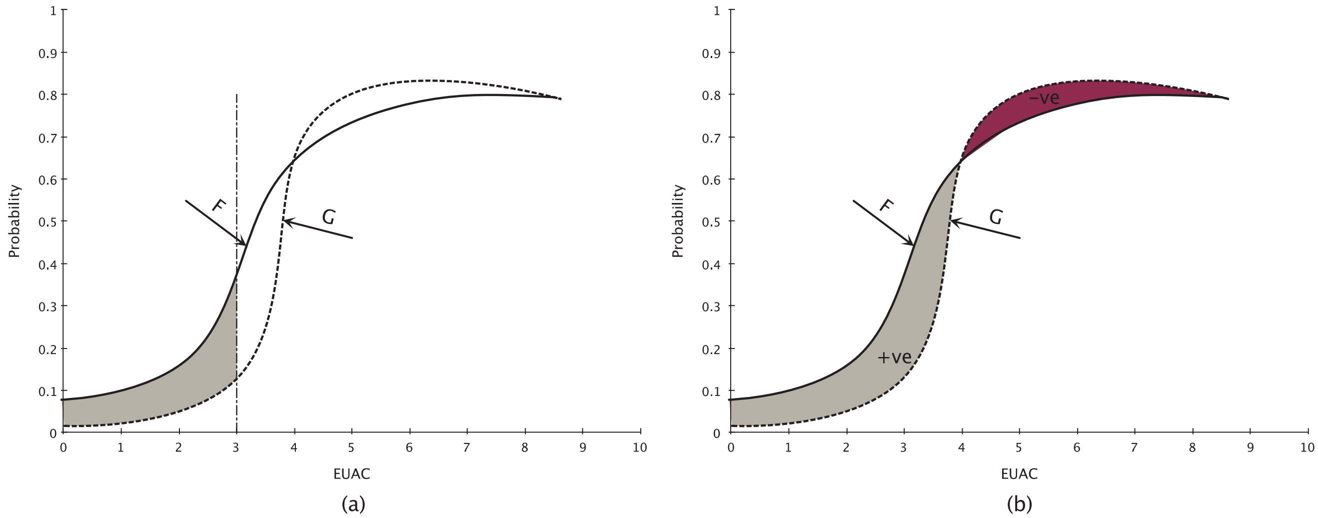

Figure 3.8 Second-order stochastic dominance for (a) any given EUAC and (b) entire range of EUAC.

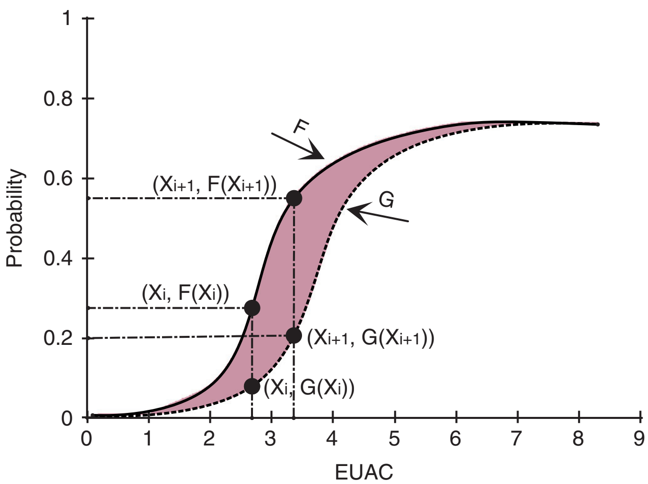

Figure 3.9 Evaluating stochastic dominance using the area bounded by the cumulative distribution functions.

the LCCA analysis and how the best material was identified on the basis of stochastic dominance.

4. CASE STUDY AND DATA ANALYSIS

4.1 Introduction

The methodology presented in this study enables a decision to be made in certainty or uncertainty situations where the input variables are probabilistic. This chapter examines the impacts of the considered reinforcement alternatives on the life-cycle cost of individual projects. This analysis was conducted for new construction; however, it is noted that mid-service life strategy implementation for existing bridges can also be carried out using the same framework.

In this case study, three different reinforcement alternatives were analyzed: epoxy-coated steel (CS), clad stainless steel (CSS), and solid stainless steel (SS). The deterministic results of the analysis are presented in the Exhibit section of this Appendix. For the stochastic analysis, greater discussion is necessary to facilitate comprehension; thus, most of this chapter is devoted to explaining the results of the stochastic analysis that compare the probabilistic life-cycle costs of alternative deck reinforcement material types.

For the deterministic analysis, graphs were provided to show the analysis results involving the two bridges for the variation of EUAC (agency cost) to the discount rate, the price ratio of the material relative to traditional steel, bridge deck replacement project duration, and the bridge size (see Figures E.1–E.8 in the Exhibit). Also, multiple case studies were analyzed and used to develop a set of decision support graphs or nomograms (see Figures E.9–E.12 in the Exhibit) that could be used by the agency for identifying the optimal reinforcement material type under a given set of conditions related to the bridge, traffic, economy, and other factors.

4.2 Bridge Selection and Input Parameters

Two bridges were identified to demonstrate the developed methodology: (i) a large high-volume bridge and (ii) a small low-volume bridge (see Table 4.1). Bridge construction can either have specified detour routes or require its users to travel through the work zone at a reduced speed; the two bridges in this study used detours instead of partial lane closures.

As discussed in previous chapters, the input variables for estimating bridge life-cycle costs are typically deterministic but typically occur within certain ranges and may follow some probability distributions. There are a large number of possible influential input variables, and all of those considered for uncertainty analysis in this study are listed in Table 4.1; for such input variables, it is assumed that the variance in the normal distribution was 10% of the mean value. Deterministic and stochastic analyses were carried out and their results are presented in subsequent sections of this chapter.

TABLE 4.1
Input variables and their probability distributions

Input Variables	Bridge #1	Bridge #2
Bridge type	Prestressed concrete beam	Prestressed concrete beam
Bridge length (ft)	168	3507
Total deck width (ft)	22	89.67
Traditional steel price ($/lb)	N (1.15, 0.12)	
Clad stainless steel price ($/lb)	N (2.90, 0.29)	
Stainless steel price ($/lb)	N (3.46, 0.35)	
Rehabilitation unit cost ($/SF) (for traditional steel deck)	N (19.02, 1.90)	
Deck replacement unit cost ($/SF) (for traditional steel deck)	N (54.51, 5.45)	
Service life of bridge with traditional steel deck	N (75, 7.5)	
Service life of bridge with clad stainless steel deck	N (100, 10)	
Service life of bridge with stainless steel deck	N (100, 10)	
First rehabilitation for bridge deck with traditional steel	N (20, 2)	
Second rehabilitation for bridge deck with traditional steel	N (40, 4)	
Deck replacement for bridge deck with traditional steel	N (60, 6)	
First rehabilitation for bridge deck with clad stainless steel	N (45, 4.5)	
Deck replacement for bridge deck with clad stainless steel	N (75, 7.5)	
First rehabilitation for bridge deck with stainless steel	N (45, 4.5)	
Second rehabilitation for bridge deck with stainless steel	N (75, 7.5)	
Discount rate	4%	
AADT	141	113410
Reinforcement per square feet of deck area (lb/sq-ft)	N (8.5, 0.9)	
Detour length	3	3
Detour speed (mph)	N (45, 5)	N (45, 5)
Minimum hourly wages ($)	13.43	
Vehicle occupancy	1.8	
Fuel cost ($/gal)	3.75	
Fuel economy (miles/gal)	23	

Note: All monetary values in the table are in 2012 US dollars.
Where *N (a, b), N* represents the normal distribution, *a* is the certainty value of the input parameter, and *b* is the variance associated with *a*.

4.3 EUAC Results

Based on the input variables, the life-cycle agency and user EUAC values were computed for each of the two bridges. The results of the deterministic analysis show that the EUAC is the lowest for solid stainless steel, followed by clad stainless steel, and, lastly, traditional carbon steel.

Figure 4.1 represents the cumulative distributions of the EUAC of the agency costs, user costs, and total costs for each of the two bridges. Figures 4.1(a) and 4.1(c) show the influence of bridge size in determining the evaluation outcome whereas Figures 4.1(b) and 4.1(d) show the influence of the relative weights (between agency and user cost) in determining the evaluation outcome. Figure 4.1 suggests that for small-size bridges, the agency cost alone can be used to effectively decide on the choice of reinforcement material type; however, for large bridges, both the agency and user costs are needed to make such a decision.

The concept of stochastic dominance is used to identify and assess the extent of the superiority of one alternative over others. The concept involves a comparison of the probability distributions of the costs or benefits of two alternatives (Clemen, 1996). For instance, if an alternative A stochastically dominates another alternative B, then, even though not all of the possible values of A are better than any value of B, for a certain given level, the probability that A is better than the given level is equal or greater than the probability that B is greater than the given level. Then, obviously, A is better than B. In the context of this research, the cumulative probability distribution for EUAC is used to assess stochastic dominance. It is seen that, for a given EUAC, the probability exists that stainless steel achieves an EUAC that is equal to or greater than that for clad stainless steel and traditional steel. These results suggest that, at each cost level, the probability that the cost is less than a given value for the stainless steel alternative is equal to or greater than that for clad stainless steel and traditional steel alternatives. Thus, from the perspective of superiority in terms of the life-cycle cost (EUAC), the stainless steel alternative stochastically dominates the other two alternatives. In cases where clear dominance is not obviously visual, then the area bounded by the cumulative distribution functions can be used to measure the superiority of the reinforcement alternatives. The trapezoidal rule was applied to measure the bounded area. For the given two bridge cases, the use of Equations 3.10 and 3.11 yielded a positive sign, which is indicative of the superiority of both clad stainless and stainless steel reinforcement over traditional steel for bridges #1 and #2.

4.4 Sensitivity Analysis

Sensitivity analysis with weighted user costs and discount rates was carried out to determine how these variables

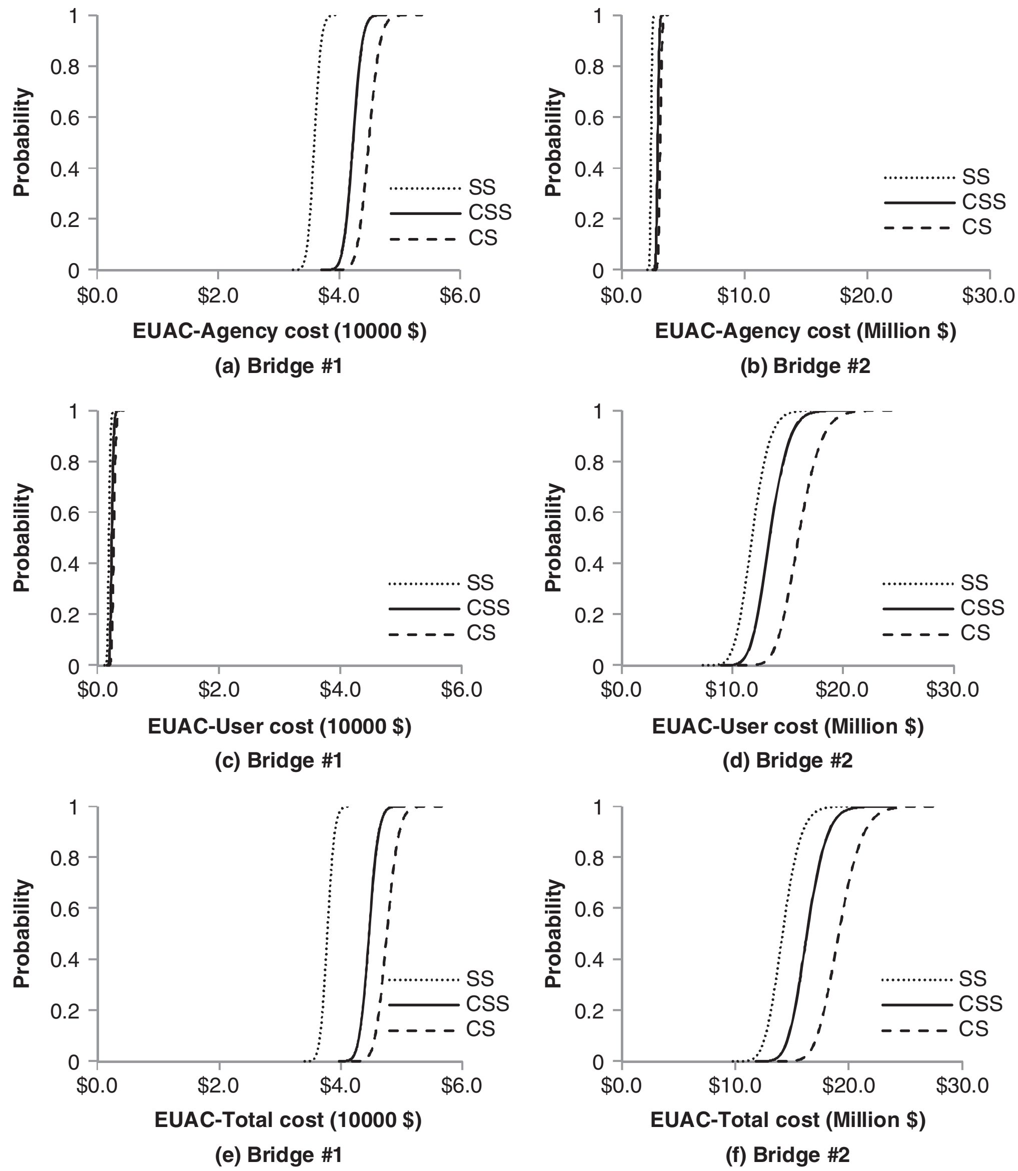

Figure 4.1 Cumulative cost distribution analysis for bridges #1 and #2 with equal weights of agency to user cost.

influenced the alternative reinforcement selection. First, agencies do not follow any clear-cut policy or guideline regarding the relative weights of user cost and agency cost. Therefore, different scenarios of weight ratios for user cost were analyzed in order to examine the influences of the relative weights on the evaluation outcome. Second, the discount rate can influence decision making that is based on life-cycle costing because LCCA output hinges on the time value of money.

4.4.1 Sensitivity of EUAC to User Cost

As discussed earlier in this report, the user costs directly reflect the inconvenience experienced by road users due to repeated bridge rehabilitation and construction. Past research has established that work zones are the second largest contributor to non-recurring delay on freeways and principal arterials (Yunovich et al., 2001). This study uses both the agency and user costs to evaluate the reinforcement materials. The user costs were further classified into the cost for additional travel time (TC) and the vehicle operating cost (VOC). AHP was used to assess the weights for deterministic scenarios for these two costs to give a final total life-cycle cost value. The AHP analysis matrix provides the weights to each criteria, the formulation of which is shown in Equation 4.1.

$$Total\ \ Cost = \alpha \times (AC) + \beta \times (TC) + \gamma \times (VOC) \qquad (4.1)$$

$$where,\ \ \alpha + \beta + \gamma = 1 \qquad (4.2)$$

To assess stochastically the impact of the relative weight on the evaluation outcome, random numbers were

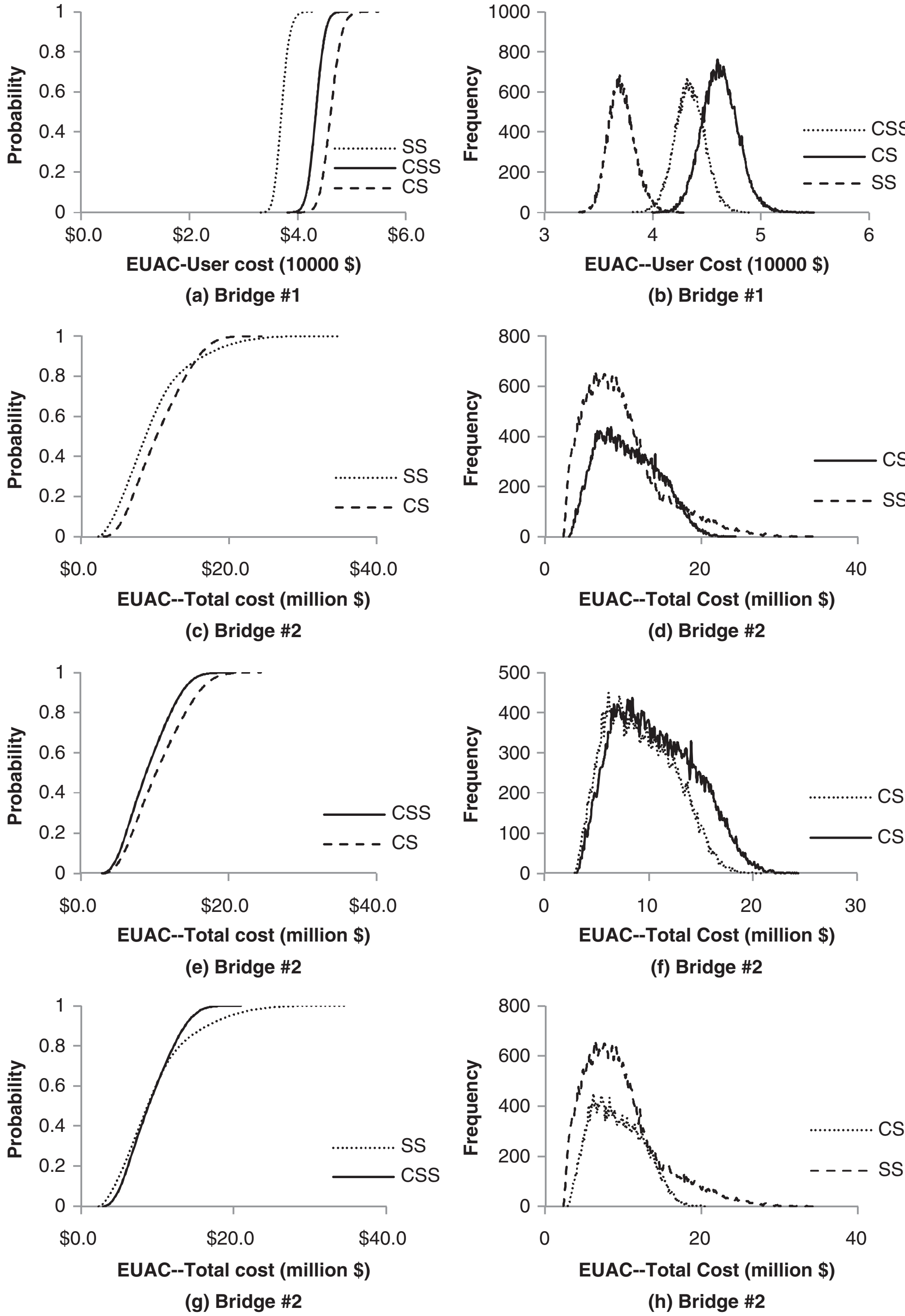

Figure 4.2 Cumulative cost distribution analysis for bridges #1 and #2 with stochastically varied ratio of agency cost to user cost weights.

generated for α, β, and γ with the constraint of Equation 4.2. The results (in terms of the life-cycle costs in terms of EUAC) for each bridge are shown in Figure 4.2.

First-order stochastic dominance can be used to evaluate the superiority of stainless steel over clad stainless steel and traditional steel for bridge #1 as shown in Figure 4.2(a). The second-order stochastic dominance was estimated by calculating the area bounded by the curves in Figures 4.2(c) and (e); the result is suggestive of the superiority of clad stainless steel and stainless steel over traditional steel. Figure 4.2(c) also suggests that, within a certain some range of the evaluation outcome (EUAC), traditional steel is a better choice compared to stainless steel; plausibly because those simulation runs that assigned a high weight to the

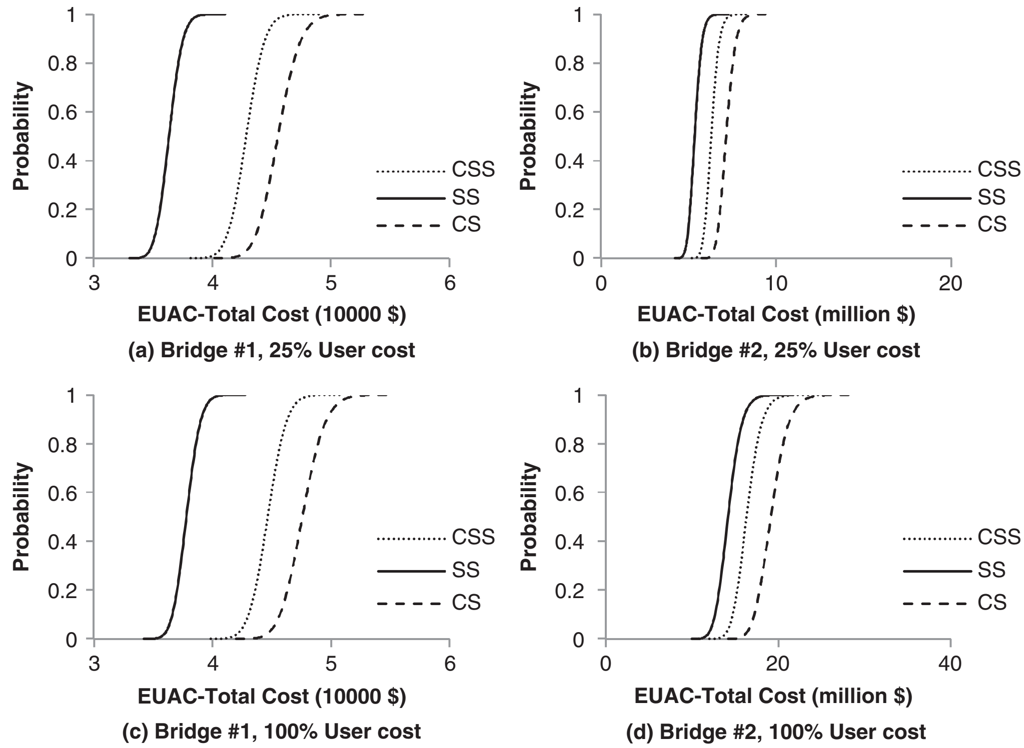

Figure 4.3 Variation of EUAC-total cost for bridges #1 and #2 with relative weight between agency and user costs.

agency cost relative to the user cost. Figure 4.2(e) shows that clad stainless steel is always a preferable choice to traditional steel, irrespective of the relative weights between agency cost and user costs. Within a certain some range of the expected evaluation outcome, clad stainless steel is a superior alternative to stainless steel as depicted in Figure 4.2(g). However, from the perspective of second-order stochastic dominance, stainless steel is clearly a preferable choice to clad stainless steel, albeit with a margin that is small compared to the superiority of stainless steel over traditional steel.

From the EUAC analysis results shown in Figure 4.1, it is observed that for bridge #1(small bridge and low traffic volume), the agency cost was far more influential compared to the user cost. The opposite was observed for bridge #2 (large bridge and high traffic volume). Thus, for bridge #1, the agency cost alone could be used to determine the choice of the alternative reinforcement materials; a clear first order dominance was exhibited by bridge #1. However the concept of agency to user weights becomes important for large high-volume bridges such as bridge #2. Figure 4.3 shows the total EUAC analysis results for the weighted user costs for bridges #1 and #2.

4.4.2 Sensitivity of EUAC to Discount Rate

Due to the uncertainty associated with the discount rate, it is useful to study the impact of varying the discount rate on the analysis outcome. Thus, the sensitivity of the EUAC to the discount rate varying from 2–10% was analyzed. The stochastic EUAC results were determined with only the agency cost in consideration for both bridges #1 and #2. The stochastic dominance charts in Figures 4.4 and 4.5 suggest that for each of the discount rates considered, stainless steel is a preferable option to clad stainless steel and traditional steel. Nevertheless, the band of cumulative distribution of the EUAC of the total costs for clad stainless steel shrinks with an increase in the discount rate. In other words, for higher discount rates, the relative attractiveness of clad stainless steel decreases, whereas stainless steel still remains an attractive option.

4.5 Results of the Deterministic Analysis

As discussed in earlier sections of this chapter, decision-making for selecting an appropriate reinforcement material can be carried out using deterministic or stochastic analysis. In deterministic analysis, it is possible to assess the changes in the evaluation outcome in response to changes using sensitivity analysis. Thus, in this study, graphs were provided in the Exhibit at the end of this Appendix to show the analysis results involving the two bridges for the variation of EUAC (agency cost) to the discount rate, the price ratio of the material relative to traditional steel, bridge deck replacement project duration, and the bridge size (see Figures E.1–E.8 in the Exhibit).

Also, multiple case studies were analyzed and used to develop a set of decision support graphs (see Figures E.9–E.12 in the Exhibit) that could be used by the agency for choosing the best reinforcement material type under a given set of conditions related to the bridge, traffic, economy, and other factors. Figure E.9(a) presents the DSS chart for traffic volume and detour length and Figure E.9(a) presents the DSS chart for the detour length and bridge length. From Figure

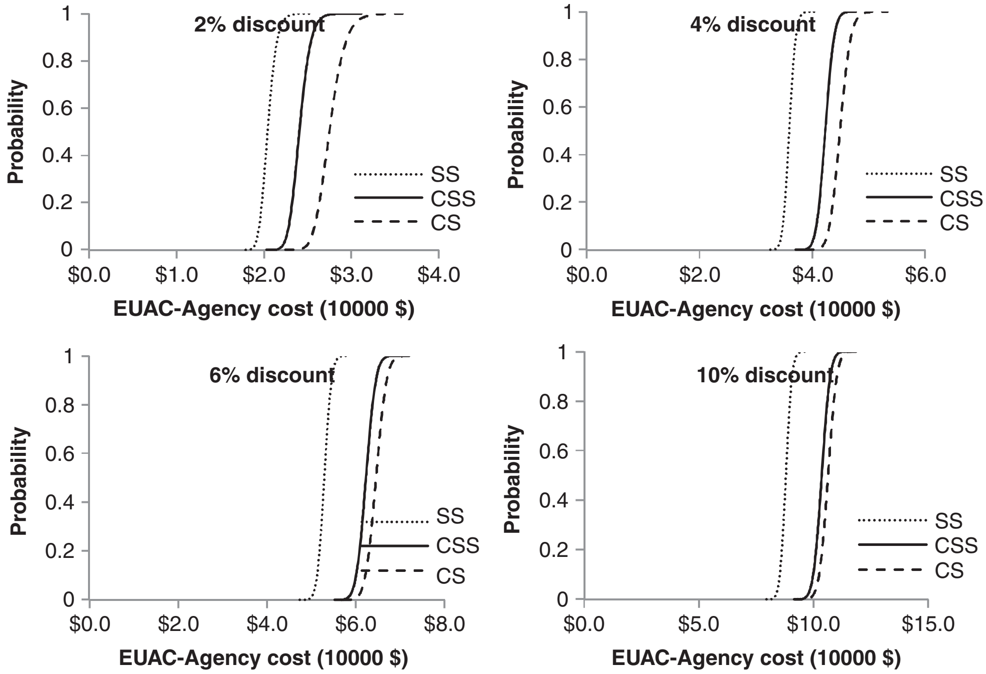

Figure 4.4 Variation of EUAC-total cost for bridge #1 with discount rate.

E.9, it can be seen that with a fixed bridge length, (1) under high traffic volumes, solid stainless steel causes least life-cycle cost; (2) under moderate traffic volumes, clad stainless steel causes least life-cycle cost; (3) under small traffic volumes, carbon steel causes least life-cycle cost; (4) under long detour lengths, clad stainless steel causes least life-cycle cost; (5) under short detour lengths, carbon steel causes least life-cycle cost.

Figure E.10(a) presents the DSS Chart for the discount rate and bridge length and Figure E.10 (B) presents the DSS chart for the price ratio (ratio of

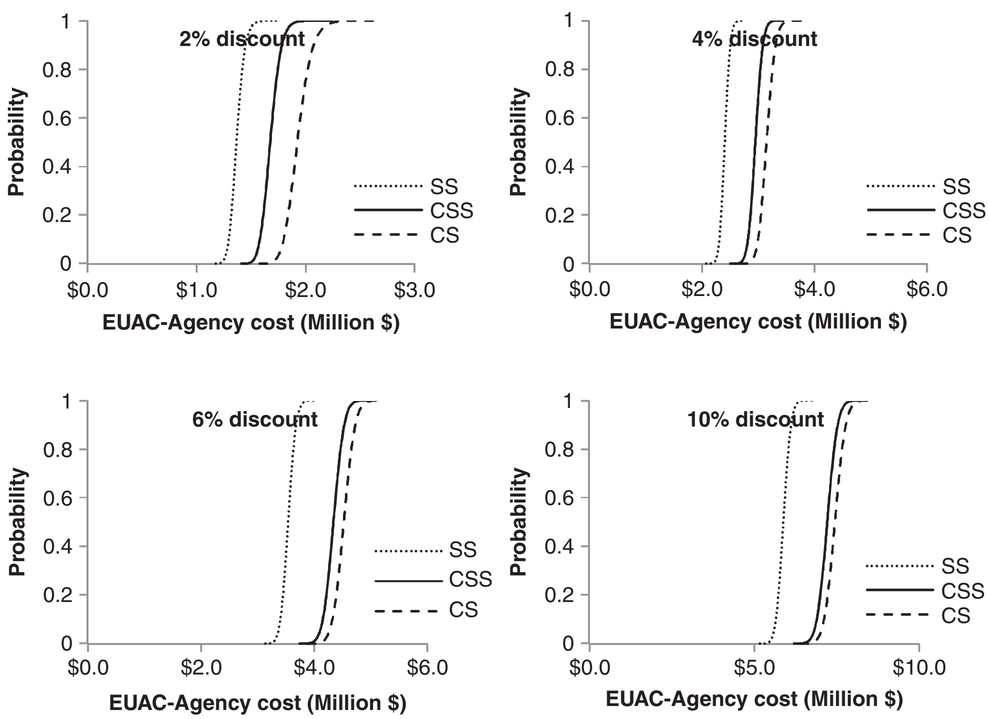

Figure 4.5 Variation of EUAC-total cost for bridge #2 with discount rate.

material price in $/lb to traditional steel price) and bridge length. From Figure E.10, it can be seen that: (1) with short bridge lengths and high discount rates, clad stainless steel causes least life-cycle cost; (2) with low discount rates, solid stainless steel causes least life-cycle cost; (3) with high discount rates, carbon stainless steel causes least life-cycle cost; (4) under very high user cost ratios, solid stainless steel causes least life-cycle cost; (5) under moderate user cost ratios, clad stainless steel causes least life-cycle cost; (6) under small user cost ratios, carbon steel causes least life-cycle cost.

Figure E.11 presents the DSS chart for fuel price and bridge length. From the figure, it can be seen that for a fixed bridge length, (1) under high fuel prices, clad stainless steel causes least life-cycle cost; (2) under low fuel prices, carbon steel causes least life-cycle cost.

4.6 Chapter Summary

This chapter demonstrated the methodology presented in this study to assess the deterministic and probabilistic life-cycle costing analysis for assessing different bridge deck reinforcement material alternatives. In the probabilistic part, the analysis was carried out to account for the stochastic nature of all the input variables and their concerted effect on the attractiveness across the material types. The concepts of first-order and second-order stochastic dominance were measured to assess the cost-effectiveness of alternative reinforcements. For the specific bridges chosen as case studies, the analysis outcomes suggest that generally, the most economically efficient reinforcement option is solid stainless steel, followed by clad stainless steel, and the least economically efficient option is traditional carbon steel.

5. SUMMARY, DISCUSSION, AND RECOMMENDATIONS

5.1 Summary and Conclusion

Bridge decks deteriorate due to loading and climatic severity, and state highway agencies continue to invest a significant portion of their funding in bridge infrastructure preservation in response to deterioration of the bridge deck and other bridge elements. Such deterioration has increased drastically in the last few decades as an increasing number of highway bridges in the United States approach the end of their service lives. Annually, billions of dollars' worth of work is carried out not only as preventive measures but also to address a variety of bridge deck problems including cracking, delamination, and scaling. In extreme cases, deck repair or even replacement is necessary. New and more efficient (corrosion resistant) materials are becoming available for bridge construction. Even though they have higher initial costs, these materials often lead to drastic reductions in life-cycle cost, particularly when user costs are considered in the analysis. It has been hypothesized that the use of corrosion resistant reinforcement materials can significantly reduce the number of times that a bridge deck is replaced and thus helps reduce or even avoid the agency and user costs associated with bridge deck replacement.

This study addresses this issue. The methodology presented in this study provides a platform to assess the life-cycle costs of different types of bridge deck reinforcement materials based on their corrosion resistance as well as their economic efficiency. The analytical framework developed in this study can help bridge engineers and practitioners to understand and identify a superior reinforcement alternative based on the prevailing conditions of bridge size, traffic volume, and other factors related to the economy. The reinforcement alternatives were compared by their first-order and second-order stochastic dominance over traditional reinforcement.

A case study was presented to showcase the developed methodology. Two bridges from Indiana (one small in size, low-volume and the other large in size, high-volume) were used for the case study to assess the relative stochastic superiority of stainless steel, clad stainless steel, or traditional steel using a multi-criteria approach. Based on all of the analysis, it was determined that solid stainless steel was a superior alternative to clad stainless steel and traditional carbon steel for two extreme bridge cases. It is envisioned that as the benefits of reinforcement alternatives are tested and become recognized, their demand will increase, leading to higher production and lower unit prices as a result.

5.2 Industry Outreach for RM-LCCA

There are a number of electronic tools that carry out life-cycle cost analysis for bridge projects, for example, STADIUM concrete analysis and Life-365. Because they were built basically to support concrete and relevant treatment such as installing a barrier or a water membrane, these tools address issues of corrosion initiation, propagation, and subsequent cracking based on chloride-induced corrosion and predict service life fairly well on the basis of the chloride diffusion principle. However, these tools are less successful in carrying out detailed economic analysis of bridge reinforcement materials. RM-LCCA, which was developed as part of this research study, provides an automated platform where different alternative reinforcement materials can be evaluated on the basis of their life-cycle costs and benefits.

5.3 Recommendations and Future Work

The study developed a systematic framework for evaluating these alternative reinforcing materials on the basis of their life-cycle cost. The RM-LCCA (Reinforcement Material-Life-Cycle Cost Analysis) was developed to automate implantation of the framework. Case studies involving different scenarios of bridge and operating characteristics were used to demonstrate the methodological framework and to develop nomograms for decision support. From the results of the analysis and the case studies, it is recommended that deck reinforcement material for any future INDOT bridge deck design should be selected only after a carrying out life-cycle cost analysis among other considerations; such analysis should be preceded by establishment of the decision contexts and consequently, values of the identified input parameters for the life-cycle cost analysis. From a general perspective, it is recommended that INDOT considers for inclusion in its bridge design or rehabilitation manual, the decision support nomograms that specify the conditions at which each material is optimal from a life-cycle perspective.

Nevertheless, there exist avenues that could be addressed or explored further to fine-tune the selection process for appropriate deck reinforcement material alternative for any specific bridge project. First, mathematical models describing the time-dependent chloride-induced corrosion deterioration processes could be incorporated to provide more precise estimates of the life-cycle activity profiles for each material type.

Secondly, the laboratory experiments carried out as part of this research (see Volume I of the report) could be followed by full-scale field studies. For this, it is recommended that a few bridge reconstruction or deck replacement projects should be selected from INDOT's long-range plan or bridge program through an experimental design; for these bridges or decks, INDOT should apply the three material types in a controlled experimental setting. The costs (initial construction and subsequent maintenance), work durations, and the physical condition and service lives of the bridges or decks having each alternative material should be closely monitored and recorded over several decades. Doing this can help validate or refine the assumptions made in this study. The experimental design could be designed carefully to include climatic region (northern and southern Indiana), highway classes, traffic volume, and bridge size.

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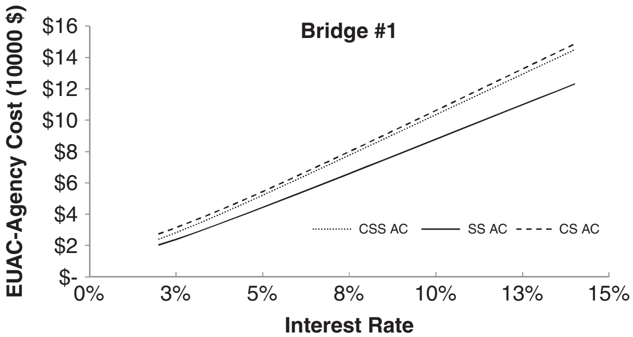


Figure E.1 Variation of EUAC-agency cost for bridge #1 discount rate.

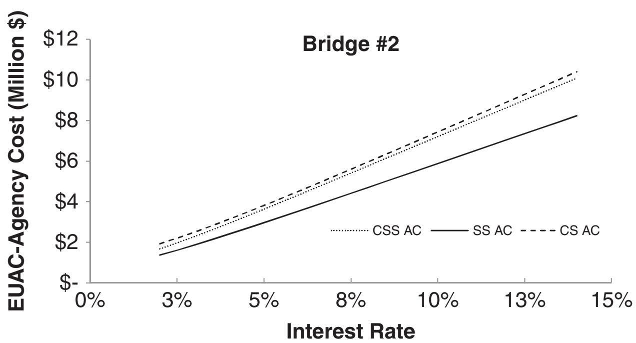


Figure E.2 Variation of EUAC-agency cost for bridge #2 discount rate.

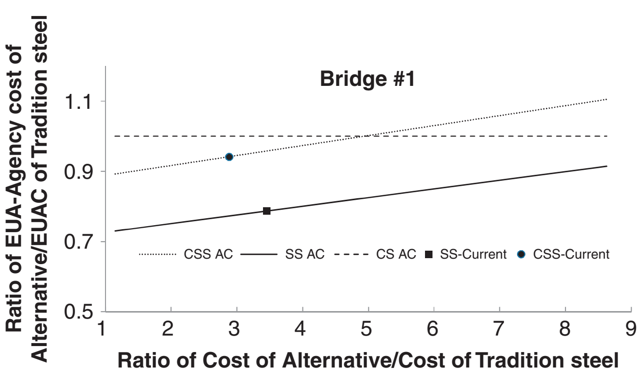


Figure E.3 Unit price analysis for bridge #1.

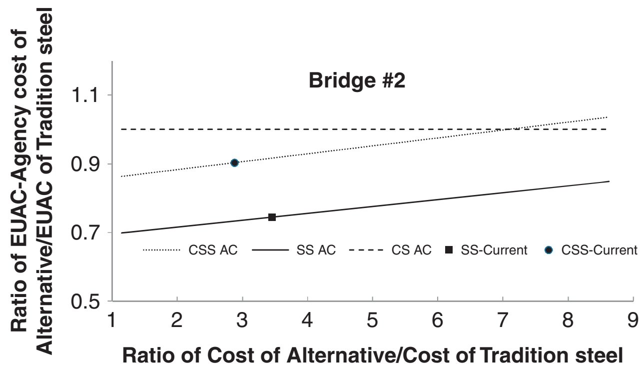


Figure E.4 Unit price analysis for bridge #2.

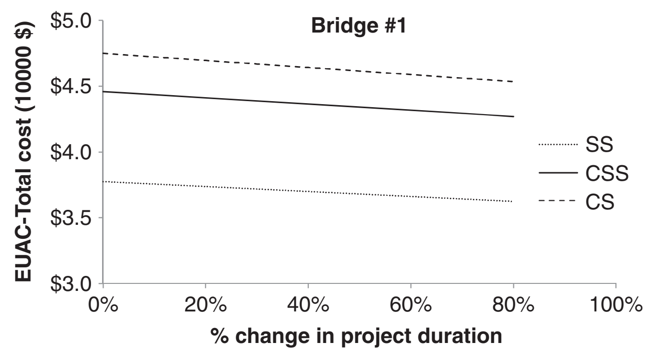


Figure E.5 Sensitivity in reduction in project duration for bridge #1.

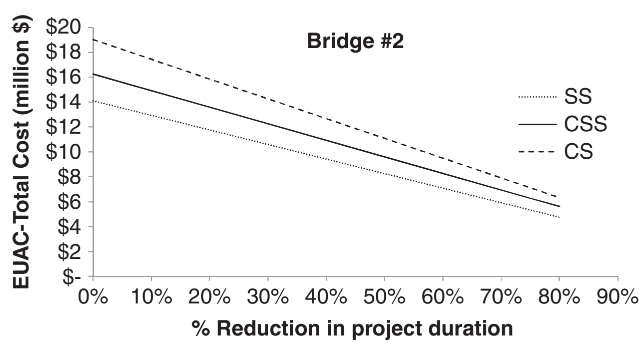


Figure E.6 Sensitivity in reduction in project duration for bridge #2.

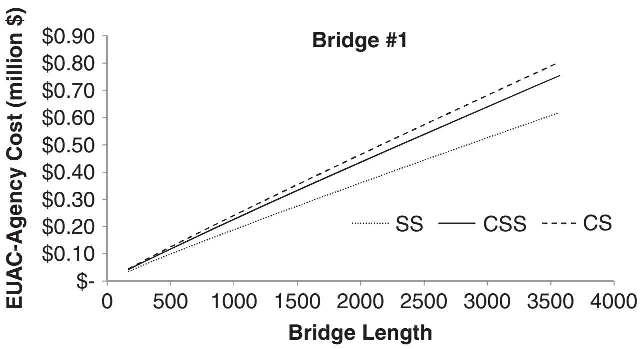


Figure E.7 Sensitivity in bridge size for bridge #1 for given AADT.

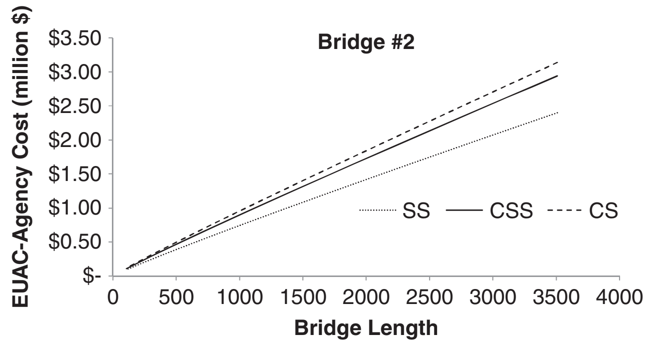
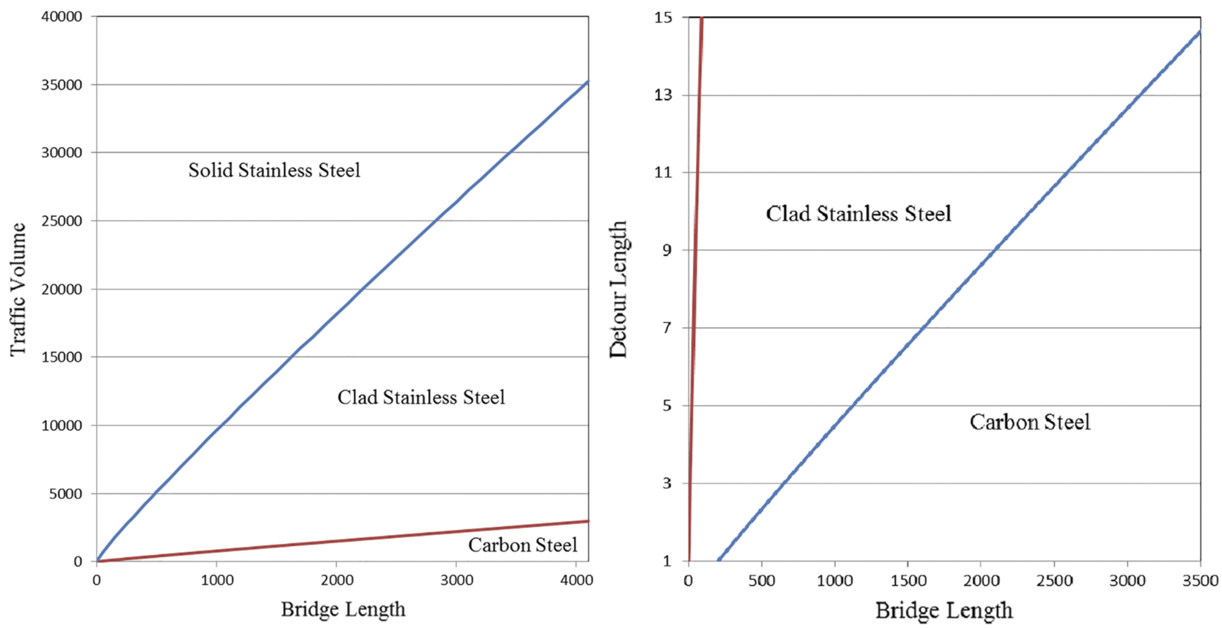


Figure E.8 Sensitivity in bridge size for bridge #2 for given AADT.



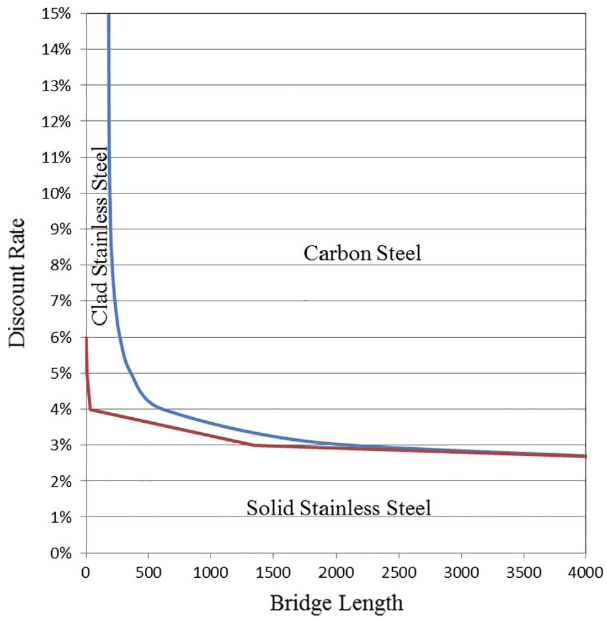
Parameter setting	
Total deck width (ft)	50
Detour length (mile)	3
Detour speed (mph)	45
Vehicle occupancy (person)	1.8
Weight ratio	1
Discount rate	4%
Fuel cost ($/gal)	3.75

(a)

Parameter setting	
Total deck width (ft)	50
Detour speed (mph)	45
AADT (vehicles per day)	500
Vehicle occupancy (person)	1.8
Weight ratio	1
Discount rate	4%
Fuel cost ($/gal)	3.75

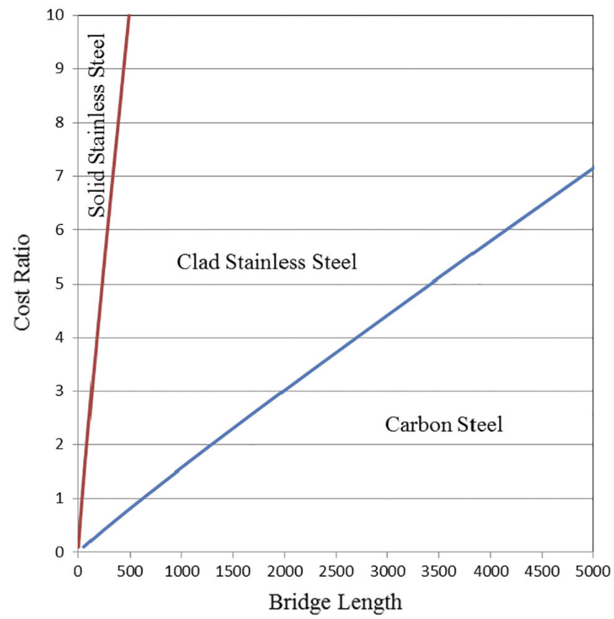
(b)

Figure E.9 Example DSS chart for (a) traffic volume and detour length (b) detour length and bridge length.



Parameter setting	
Total deck width (ft)	50
Detour length (mile)	3
Detour speed (mph)	45
AADT (vehicles per day)	500
Vehicle occupancy (person)	1.8
Weight ratio	1
Fuel cost ($/gal)	3.75

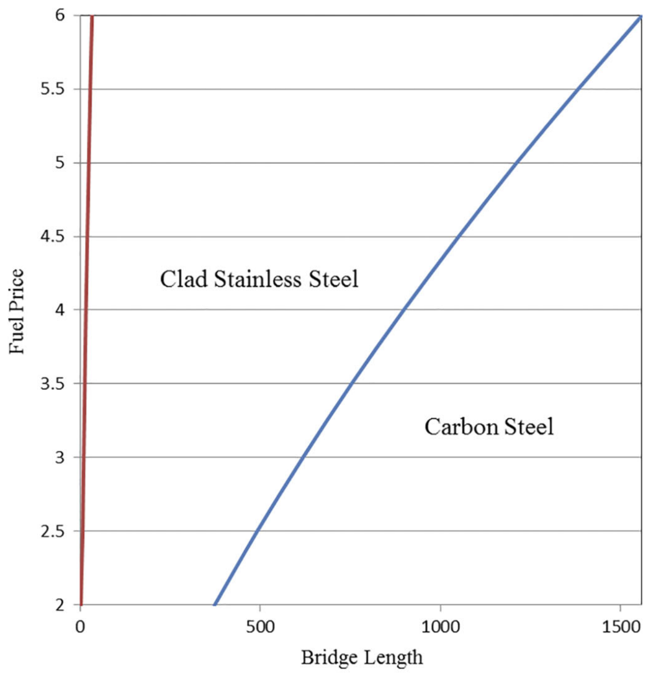
(a)



Parameter setting	
Total deck width (ft)	50
Detour length (mile)	3
Detour speed (mph)	45
AADT (vehicles per day)	500
Vehicle occupancy (person)	1.8
Discount rate	4%
Fuel cost ($/gal)	3.75

(b)

Figure E.10 Example DSS chart for (a) discount rate and bridge length (b) price ratio and bridge length.



Parameter setting	
Total deck width (ft)	50
Detour length (mile)	3
Detour speed (mph)	45
AADT (vehicles per day)	500
Vehicle occupancy (person)	1.8
Weight ratio	1
Discount rate	4%

Figure E.11 Example dss chart for fuel price and bridge length.

Activity Profiles	Year
Service life of bridge with traditional steel deck	65
Service life of bridge with clad stainless steel deck	75
Service life of bridge with stainless steel deck	120
1st rehabilitation for bridge deck with traditional steel	15
Deck replacement for bridge deck with traditional steel	30
2nd rehabilitation for bridge deck with traditional steel	40
1st rehabilitation for bridge deck with clad stainless steel	30
2nd rehabilitation for bridge deck with clad stainless steel	55
1st rehabilitation for bridge deck with stainless steel	40
2nd rehabilitation for bridge deck with stainless steel	85

Parameter setting	
Minimum hourly wages ($)	13.43
Fuel cost ($/gal)	3.75
Traditional steel price ($/lb)	1.15
Clad stainless steel price ($/lb)	2.9
Stainless steel price ($/lb)	3.46
Rehabilitation unit cost ($/sq-ft)	19.02
Deck replacement unit cost ($/sq-ft)	54.51
Reinforcement per square feet of deck area (lb/sq-ft)	8.5

Figure E.12 Other input data used in developing the example DSS charts shown in Figures E.9–E.11

APPENDIX B: RM-LCCA USER MANUAL

Appendix B is available for download at http://dx.doi.org/10.5703/1288284315517.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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