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LIFE CYCLE COST ANALYSIS OF CFRP PRESTRESSED CONCRETE BRIDGES

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ABSTRACT

This paper presents a life cycle cost analysis of carbon fiber reinforced polymer (CFRP) reinforced concrete highway bridges. This study shows that despite the higher initial construction cost of CFRP reinforced bridges, they can be cost effective when compared to traditional steel reinforced bridges. The analysis considers the cost items of initial construction, maintenance, repair, rehabilitation and demolition activities and the associated user costs as determined by traffic volume, speed, operation and crashes. The analysis is performed for a 100-year service life. The cost information has been obtained from the literature, FHWA, and Michigan DOT. The most cost efficient alternative for side-by-side box beam bridges was a medium span CFRP bridge located in a high traffic area. Depending on traffic volume and bridge geometry, a probabilistic analysis revealed that there is greater than a 95% probability that the CFRP reinforced bridge will become the least expensive option between 20 and 40 years of service. The break-even year for the CFRP reinforced bridge is typically at the time of the first major repair activity, a shallow deck overlay, on the steel reinforced bridge.

1 INTRODUCTION

The first carbon fiber reinforced polymer (CFRP) bridge constructed in the United States was the Bridge Street Bridge over the Rouge River in the City of Southfield, Michigan. The three-span skewed bridge was opened to traffic in 2001 [1]. While many field and laboratory investigations have verified the effective structural performance of CFRP reinforced concrete members, a detailed life cycle cost analysis (LCCA) has not been performed to quantify when CFRP reinforcement becomes a cost-effective solution. This is a concern as the initial construction cost of a CFRP bridge is higher than the cost of a conventional bridge with steel reinforcement [2]. However, the reduced future repair costs for the CFRP bridge will offset the higher initial cost.

Life cycle cost analysis is considered an important investment decision tool in asset management. NCHRP Report 483 [3] presents a commonly accepted and comprehensive methodology for bridge LCCA. Results of a detailed LCCA allow transportation agencies to identify and quantify the economical long-term and short-term advantages and disadvantages of bridge alternatives.

The early applications of LCCA to bridge structures were in the evaluation of cost effectiveness of different treatment methods for specific deteriorating bridge components [4]. However, better LCCA models were needed that included the interrelationship between the infrastructure components in the highway network and the uncertainty in variables [5, 6]. Daigle and Lounis [7] presented such comprehensive LCCA of reinforced concrete bridges with different deck alternatives by taking into account all costs incurred by the owners and users from initial construction to demolition. LCCA has also been performed on several different bridge components constructed with fiber reinforced polymer [2,8-12]. However, the authors are not aware of published LCCA results for CFRP reinforced concrete bridges.

Bridge deterioration is driven by material deterioration, fatigue and overloading. In steel reinforced concrete bridges a major concern is deterioration due corrosion of the reinforcement and associated cracking of the concrete. Models for deterioration and crack initiation and propagation due to corrosion have been developed considering dimensional, material and deterioration parameters as random variables [13, 14]. The outcomes of these models are the probability for corrosion initiation, first cracking, and mean time and cost of failure.

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When evaluating alternatives the analyst considers the costs and timing of all future activities. Activities include routine and detailed inspection, maintenance, repair, rehabilitation, demolition, and reconstruction. As an addition or alternative to deterioration models, engineering judgment and historic data available from bridge management systems may be directly applied. Initiatives by the Federal Highway Administration (FHWA) are currently underway in gathering high quality bridge performance data under the Long Term Bridge Performance program. Detailed bridge performance data will enable improved life cycle cost analysis and hence asset management practices.

The initial value of the input parameters (variables) in the LCCA analysis is based on a best estimate. However, the value of each of these variables is likely to fall within a given range. NCHRP Report 483 [3] provides examples considering variable uncertainty. The outcome from such a probabilistic analysis may be the probability that the cost of one bridge alternative exceeds another, as a function of time.

NCHRP Report 483 [3] recommends the following user cost items associated with bridge activities to be included in LCCA: traffic congestion delays, traffic detours and delay-induced diversions, highway vehicle damage, environmental damage, and effects on businesses. Daigle and Lounis [7] and Kendall et al. [15] included the majority of these components in their integrated life cycle assessment analysis for bridge decks. The goal of this study is to determine if CFRP reinforced concrete bridges can be a cost effective design alternative to conventional steel reinforced concrete bridges. The objectives are to:

- Determine the life cycle cost of CFRP, epoxy-coated steel and black steel (with external corrosion resisting measures) reinforced concrete bridges.
- Determine the variables that highly influences the life cycle cost.
- Determine the probability that CFRP will be the most cost effective design alternative as a function of time.

The bridge considered in this study is a side-by-side concrete box beam bridge with transverse post-tensioning. The bridge length variables are short, medium and long span. The traffic variables are high, medium and low volume on and below the bridge. The LCCA includes costs for: initial construction, inspection, repair and maintenance, demolition, and replacement and the associated user costs. The performance of the alternatives must meet the same standards throughout the service life. To reflect this, an activity timing plan for each alternative was developed based on the structural conditions of different real-life bridges and common Michigan DOT bridge maintenance practices. A sensitivity analysis was used to determine the variables which significantly influence the life cycle cost. Finally, a probabilistic LCCA was conducted to account for cost uncertainties. The scope of this paper excludes user costs associated with environmental damage, business effects and optimization of maintenance interventions.

2 DETERMINISTIC ANALYSIS

The application of LCCA used in this study follows the methodology set fourth FHWA [16] and implemented in the NCHRP Report 483 [3]. The steps are:

- Establish design alternatives
- Determine activity timing
- Estimate costs (agency and user)
- Compute life-cycle costs
- Analyze the results.

Each of these steps will be discussed below.

2.1 Design Alternatives

The LCCA study considered the geometry of an existing precast prestressed side-by-side steel reinforced concrete box beam bridge with transverse post-tensioning, for which the original construction drawings were available from Michigan DOT (MDOT). The bridge is located in Oakland County in South East Michigan and it carries South Hill Rd over Interstate Highway I-96. At this location South Hill Rd has two lanes with shoulders while I-96 has three lanes in each direction. The bridge is composed of two 122.4 ft simple spans for a total length of 245 ft. The deck slab has a width of 45 ft and a horizontal skew of 66°. The slab is 6 in. thick with a single layer of reinforcement, and is cast in place over eleven side-by-side precast prestressed box beams. The beams have a cross-sectional area of 48 in.× 48 in. (Figure 1). The 122.4 ft long simple span is designated the “long span” case, while a short span (45 ft) and a medium span (60 ft) bridge were also considered. For these cases the structural members of the long span bridge were redesigned for these new lengths according to the current Michigan Bridge Design Manual [17] based on the current AASHTO LRFD Bridge Design Specifications. The medium and short span beams have cross-section area of 36 in.× 28 in. and 36 in. × 20 in., respectively. The original bridge was designed per the 1999 Michigan Bridge Design Manual [18], which was based on AASHTO (1998) LRFD Bridge Design Specifications.

Moreover, as traffic volume has an impact on user costs, different traffic volumes were considered in various combinations both on and below each bridge span. Traffic above each bridge (two lanes) was taken as a low volume (initial annual average daily traffic (AADT) of 1,000) and a high volume (initial AADT of 10,000) case, with an annual growth rate of 2% and limited to a maximum AADT of 26,000. Below bridge initial AADT values considered are given in Table 1, with an annual growth rate of 1%. The short, medium, and long span bridges are assumed to span 4, 6, and 8 lanes of traffic below, respectively. These span and traffic combinations result in a total of 13 bridge cases. The study matrix is shown in Table 2.

For each of these 13 cases, three reinforcing alternatives were considered; the focus of this study: (a) black (without epoxy-coating) steel reinforcement with cathodic protection; (b) epoxy-coated steel reinforcement; and (c) CFRP reinforcement. The CFRP bridge is designed based on ACI 440 design guidelines [19, 20] such that the CFRP bridge has the same flexural and shear capacity as the steel reinforced bridges.

2.2 Activity Timing

As suggested by FHWA [16], the analysis period must be long enough to include a major rehabilitation action and at least one subsequent rehabilitation action for each alternative. To satisfy this requirement for all alternatives, the LCC analysis period is taken up to 100 years. Furthermore, the projected repairs and rehabilitation actions are scheduled such that the overall bridge performance, at any time, is the same for all of the alternatives. According to MDOT, current steel-reinforced highway bridges have an expected service life of about 65 years with a minimum of three deck restoration projects throughout the service lifetime. It is assumed that the superstructure replacement will take 5 months and the road below the bridge will be open for traffic execpt during weekend demolition and beam installations.

In order to maintain the same performance level, different operation, maintenance and repair (OM&R) strategies are defined for each bridge. The OM&R strategies in this study are based on MDOT practices on the time interval for inspection of the traditional bridge, time frequency for deck-related maintenance work, frequency for beam-related maintenance work, and time for superstructure replacement and demolition. Based on the OM&R strategies of existing CFRP bridges in Japan [21, 22] and Canada [23], the CFRP bridge is expected to require a deck shallow overlay and deck replacement only once during its service life. An activity timeline for the bridges is shown in Figure 2. The activity timing schedule is similar for the black steel and epoxy-coated steel bridge aside from the activities associated with cathodic protection.

2.3 Agency and User Activity Costs

Agency costs include material, personnel, and equipment costs associated with OM&R, demolition, and replacement. The total initial construction cost of the epoxy-coated steel reinforced bridge is estimated based on the general MDOT cost estimate scheme ($110 per bridge deck area). Costs of the two alternative bridges (black steel and CFRP) are based on the cost of the epoxy-coated steel reinforced bridge, accounting for the material cost differences. Material costs such as concrete, steel reinforcement, and CFRP are based on current (2009) estimates from MDOT and CFRP producers.

The cost of OM&R includes routine inspection, detailed inspection, cathodic protection, deck patch, deck shallow overlay, deck replacement, beam end repair, beam replacement, superstructure demolition, and superstructure replacement. These costs are based on MDOT estimations as well as other sources [21, 24, 25]

During construction and maintenance work, traffic in the work area is affected. Generally, traffic delays as well an increase in the accident rate results. The delay costs caused by construction work include the value of time lost due to increased travel time as well as the cost of additional vehicle operation. Therefore, user cost is taken as the sum of travel time costs, vehicle operating costs, and crash costs. Equations (1) - (3) are used to calculate these costs [9].

$$\text{Travel time costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times AADT \times N \times w \tag{1}$$

$$\text{Vehicle operating costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times AADT \times N \times r \tag{2}$$

$$\text{Crash costs} = L \times AADT \times N \times \left(A_a - A_n\right) \times c_a \tag{3}$$

Where L = length of affected roadway over which cars drive;
S_a = traffic speed during road work;
S_n = normal traffic speed;
AADT = annual average daily traffic, measured in number of vehicles per day;
N = number of days of road work;
w = hourly time value of drivers;
r = hourly vehicle operating cost;
c_a = cost per accident;
and A_a and A_n = during construction and normal accident rates per million vehicle-miles, respectively.

The annual average daily traffic (AADT) value for each year of the analysis period is estimated based on the initial AADT and estimated traffic growth rates (given above for each case). Growth rate is limited by maximum AADT, as calculated from the free flow lane capacity of the roadways on and below the bridge [26). Other parameter values are taken from the available literature [8, 27-30]. Values for each of the other variables are shown in Table 3.

2.4 Total Life Cycle Costs

The total project life cycle cost (LCC) is defined as the sum of all project partial costs. The total LCC is divided into agency and user costs. The LCC for each alternative must be conducted such that costs can be directly compared. Because dollars spent at different times have different present values (PV), the projected activity costs cannot simply be added together to calculate total LCC. Rather, future costs can be converted to present dollar values by considering the real discount rate and then summed to calculate LCC as:

$$\mathrm{LCC} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{4}$$

where

C_t = sum of all costs incurred at time t;

r = real discount rate for converting time t costs;

T = number of time periods in the study period.

The real discount rate reflects the opportunity value of time and is used to calculate both inflation and discounting at once. The relationship between real discount rate, nominal discount rate, and inflation rate is:

$$r = \left[(1+d)/(1+i)\right] - 1 = (d-i)/(1+i) \approx d - i \tag{5}$$

where

r = real discount rate

d = nominal discount rate (also called interest rate, funding rate)

i = inflation rate

The initial construction cost occurs in year 0 while the first year after bridge construction is defined as year 1. The costs associated with any subsequent activity are presented in terms of present value considering the real discount rate. The real discount rate is taken as 3% [16].

2.5 Results

A typical result is given in Table 4 and Figure 3, which is for the medium span (60 ft) bridge with a high level of traffic volume both on and below. For this case, two lanes pass under each of the two 60 ft spans. Table 4 presents the details for the final costs at 100 years, while Figure 3 illustrates the yearly changes in total cost.

Referring to Figure 3, the initial construction cost of the CFRP bridge is higher than the traditional steel bridges. However, in year 20, when the first significant deck repair occurs on the steel bridges, their cumulative cost exceeds the cost of the CFRP bridge. As shown in Table 4, the final life-cycle costs are $5.98 million for the bridge with black steel reinforcement, $5.63 million for the bridge with epoxy-coated steel reinforcement, and $2.22 million for the bridge with CFRP reinforcement. These results are also illustrated in Figure 4. The most significant contributor to LCC is user cost, which contributes from 50% to 78% of the total project cost for the different alternatives. It can be noted that the LCC of the steel reinforced bridges are about three times the LCC of the CFRP reinforced bridge. Furthermore, the agency life-cycle cost is reduced by 12% if CFRP reinforcement is selected over epoxy-coated reinforcement, and by 23% if CFRP is selected over black steel. The economic benefit is achieved from the reduced maintenance requirements associated with CFRP (no corrosion-associated deterioration; see Fig. 2).

The variables that have the highest influence on the life cycle cost were determined with a sensitivity analysis. The sensitivity analysis results for the medium span, high traffic case are shown on the tornado chart in Figure 5 for the ten most influential parameters. In the figure, each variable is perturbed 10% up or down from its original (best estimate) value, and the resulting LCC is reported. The intersection of the x and y-axes provide the original life-cycle cost of the bridge. The ten most significant variables are: normal driving speed (S_n) below the bridge; real discount rate (r); driving speed reduction (S_n-S_a) below the bridge; AADT below the bridge; hourly driver cost (w) below the bridge; hourly vehicle operating cost (r) below the bridge, number of days (N) of deck shallow overlay work below the bridge, length of affected roadway (L) below the bridge for the deck shallow overlay work, superstructure construction unit cost, and maximum AADT below the bridge. The same variables were found to be most significant for the epoxy-coated reinforcing bridge.

The ten most significant variables for the CFRP were slightly different (Figure 5 (b)). These are: normal driving speed (S_n) below the bridge; real discount rate (r); driving speed reduction (S_n-S_a) below the bridge; superstructure construction unit cost; AADT below the bridge; number of days (N) of deck shallow overlay work below the bridge; length of affected roadway (L) below the bridge for the deck shallow overlay work; hourly driver cost (w) below the bridge; CFCC prestress strand unit price; and hourly vehicle operating cost (r) below the bridge.

As derived from Table 5, the initial construction cost of the CFRP reinforced bridge is 84%, 60%, and 65% more than the corresponding long, medium, and short span steel reinforced bridges, respectively. This indicates that CFRP reinforcement is most cost-effective in terms of initial construction cost for medium and short span bridges.

In all cases, as traffic volume increases, the CFRP bridge becomes more cost-effective. This is because maintenance-related user cost differences between the CFRP and steel reinforced bridges are magnified. Therefore, the medium span bridge with high traffic levels below and above was found to be most cost-effective for CFRP.

3 PROBABILISTIC ANALYSIS

A probabilistic analysis was performed to evaluate the probability that CFRP is the most cost effective solution throughout the analysis period.

3.1 Random Variables

All major cost items were taken as random variables (RVs), except for the agency cost associated with inspection, which was taken as deterministic. A list of RVs appears in Table 6. This resulted in nine agency and eight user cost RVs. RV means were taken as the deterministic cost values, while coefficients of variation (COV) were taken from the available literature, as described below. Insufficient data were available to obtain distributions, so RVs are assumed normal.

Agency cost statistics can be divided into two categories: construction costs and repair/maintenance costs. Construction cost COVs were based on an analysis of bridge and building project cost variances [31, 32], where repair and maintenance cost COVs were taken from Florida DOT bridge repair cost records [33]. Travel time cost COV was based on an analysis of USDOT-compiled data [34], while vehicle operating cost COV was computed from average operating costs of different types of vehicles [29, 35]. COV of vehicle crash costs was taken from FHWA-compiled data of crash geometries pertinent to bridge work sites [36].

3.2 Analysis and Results

Monte Carlo Simulation (MCS) was used to simulate cumulative bridge costs each year. For each of the 13 comparison cases, 100,000 simulations per bridge per year were used, for 30 million simulations per case considered. This large number of simulations is needed to adequately estimate the upper and lower tails of the probability graph (Figure 6), which presents a typical result (medium span, low traffic volume below and high traffic above). The figure gives the probability that the cumulative yearly discounted cost of the black steel and epoxy-coated reinforcement bridges will exceed the cost of the CFRP reinforced bridge. As time progresses, the probability that CFRP will become the cheapest option increases. Up to year 20, there is a low probability that this will occur, given the high initial cost of CFRP relative to the other options. However, at year 20, after the first deck shallow overlay for the steel bridges, the trend reverses where now CFRP has a 0.88 (compared to epoxy-coated) to 0.96 (compared to black steel) probability of being the cheapest option. At year 40, there is less than a 1 in 10,000 probability that CFRP will be a more expensive option for this case.

A summary of all results is presented in Table 7. Here, the probability that CFRP will be the least expensive option by year 20 is given, as well as the year for which CFRP is expected to have a 0.95 or greater probability of being the cheapest option. Similar to the deterministic results, as traffic volume increases, CFRP becomes more cost effective. The table also shows that the medium span lengths are most cost efficient, where there is greater than a 0.90 probability that CFRP will be the least expensive option by year 20 for most of these cases. Conversely, the cases for which CFRP are least cost effective are the short span with low traffic on and below; the medium span with low traffic on and below; the long span with medium traffic below and low traffic above; and the long span with high traffic below and low traffic above. The first case, short span with low traffic below and above, is the least cost-effective case. Here, the epoxy-coated reinforced bridge is more likely to be cost effective than CFRP until year 28, at which time the CFRP has only a 0.51 probability of being cheapest. For this case, not until year 55 does CFRP have a 0.95 probability of being less expensive than the epoxy-coated alternative.

4 SUMMARY AND CONCLUSIONS

This paper presents a life cycle cost analysis of prestressed concrete side-by-side box beam bridges. The LCCA shows that bridges constructed with CFRP reinforcement will become more cost effective than steel reinforced concrete bridges.

Specific results are:

1. Traffic volume on and below the bridge significantly affects the life cycle cost. The cost effectiveness of the CFRP reinforced bridge is greatest when located in an area with high traffic volumes.
2. The CFRP reinforced medium-span bridge is generally most cost-efficient.
3. The four variables that have the highest influence on LCCA in this study are: traffic speed on the roadway below; real discount rate; speed reduction during construction; and traffic volume. This was found for all bridge alternatives. Which additional variables are significant depend on the bridge case considered.
4. The probabilistic analysis confirmed deterministic results. It was found that there is greater than a 0.54 probability that CFRP will be the most cost-effective option by year 20 for all cases considered, except for a short span with low traffic on and below the bridge. It was

found that for seven of the thirteen cases considered, there is greater than a 0.90 probability that CFRP will be the most cost-effective option by year 20.

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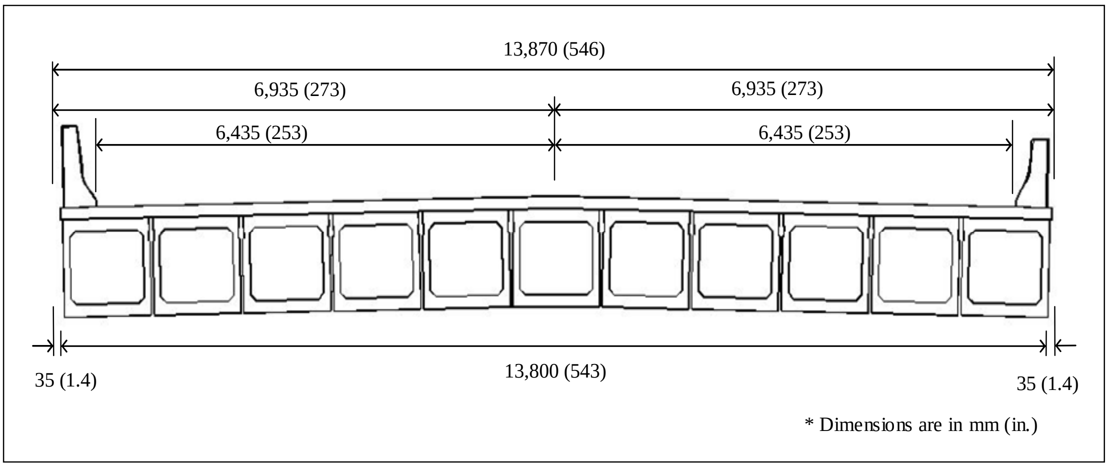


FIGURE 1: Bridge Cross-Section. Original drawing.

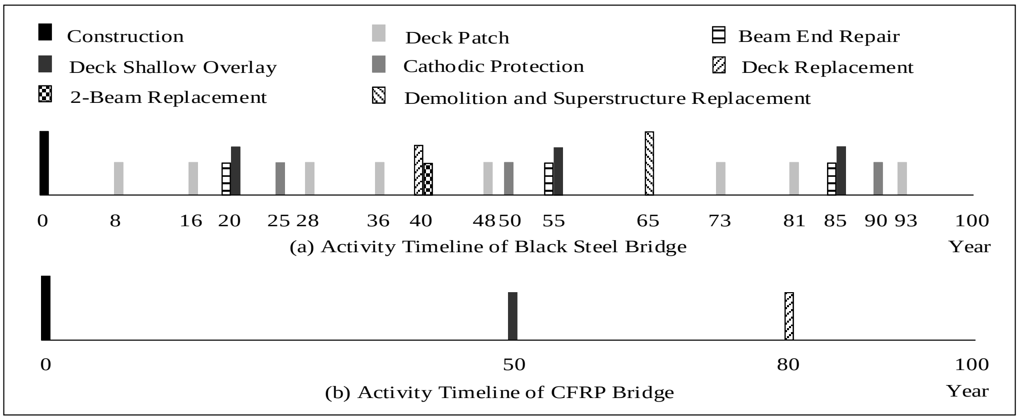


FIGURE 2: Activity Timeline

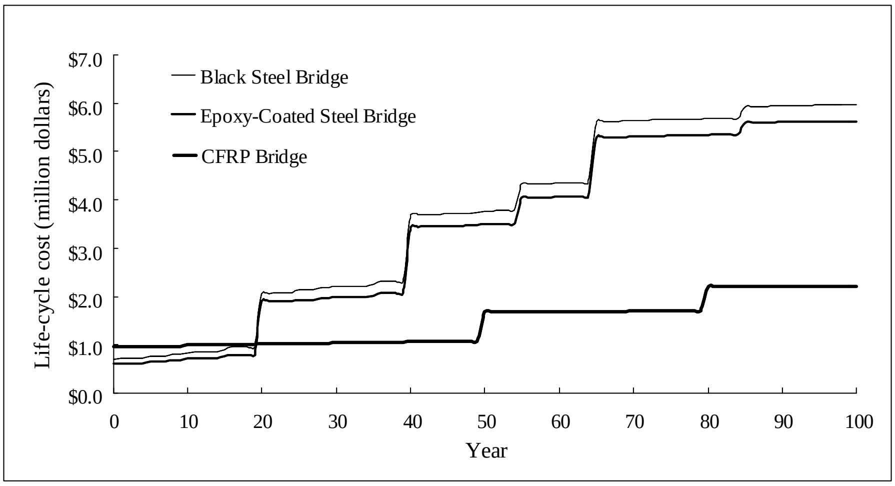


FIGURE 3: Bridge Life-Cycle Cost vs. Year Chart

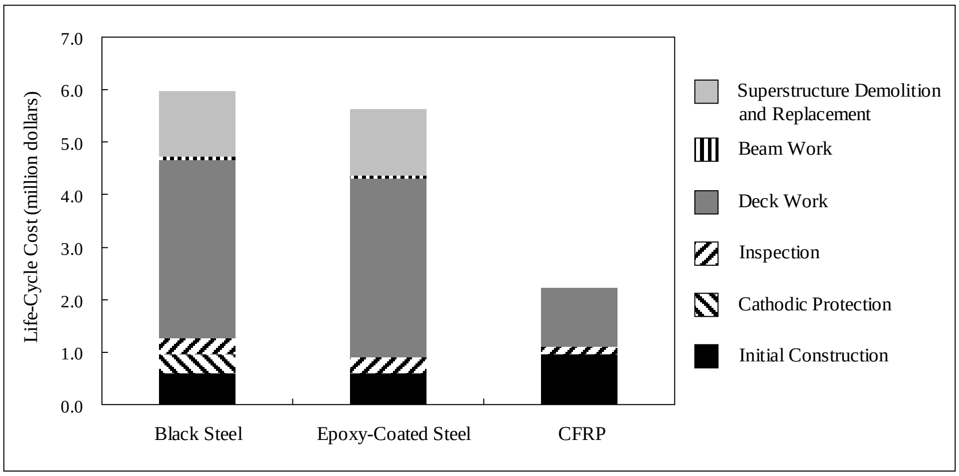
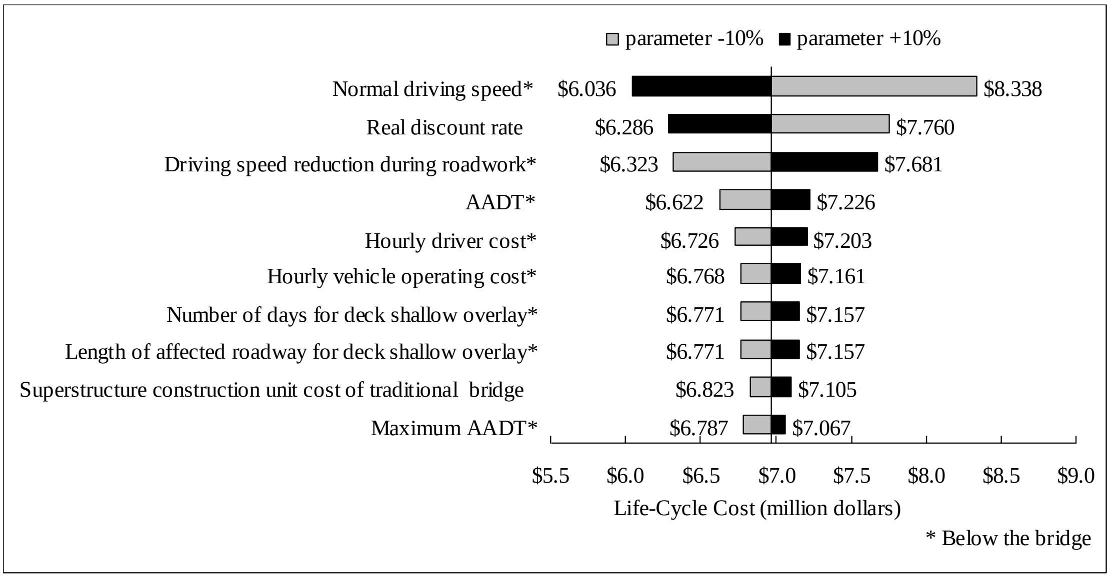
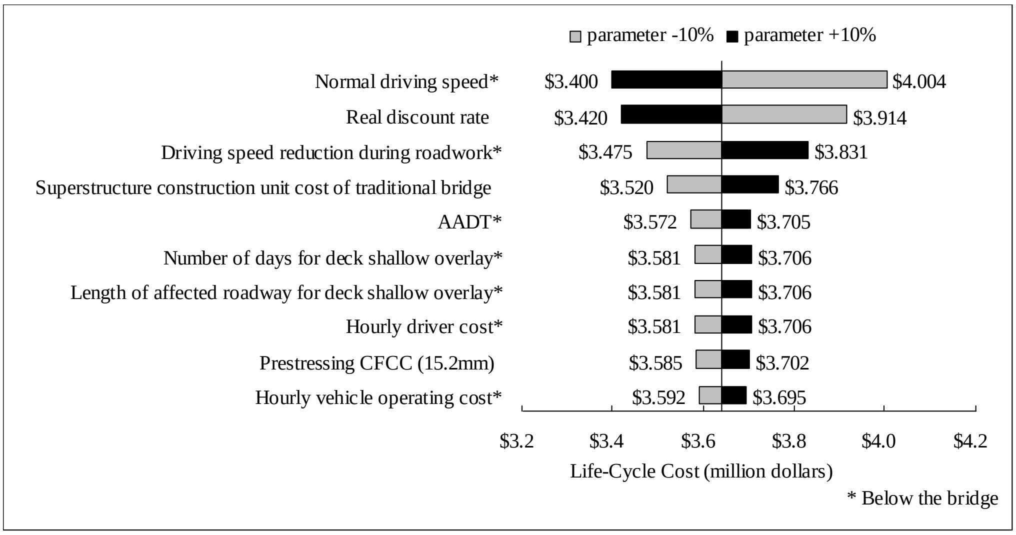


FIGURE 4: Bridge Life-Cycle Cost Comparison



(a) Black Steel Bridge

FIGURE 5: Sensitivity Analysis Tornado Charts



(b) CFRP Bridge

FIGURE 5: Sensitivity Analysis Tornado Charts

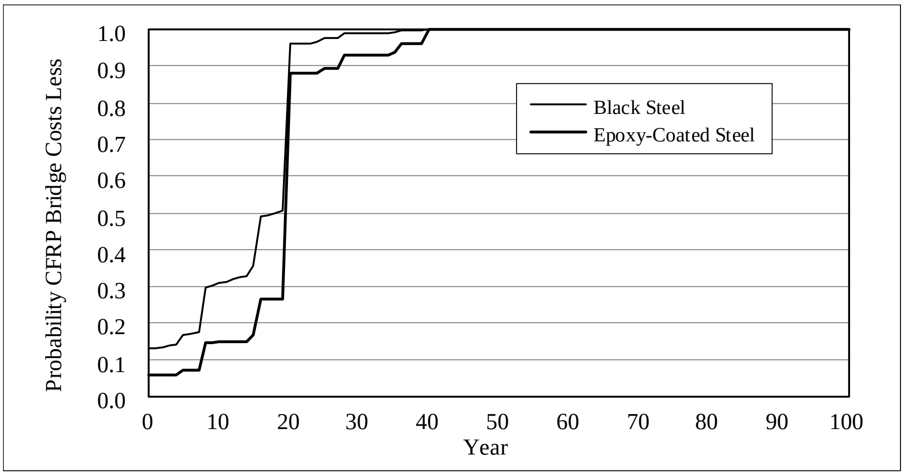


FIGURE 6: Probability Cost Distribution

TABLE 1: Below Bridge Initial AADT

	Below Bridge Traffic Volume*		
Bridge Span	Low	Medium	High
Short	10,000	30,000	N/C
Medium	20,000	60,000	100,000
Long	N/C	100,000	140,000

*Maximum AADT values are 120,000; 200,000; and 250,000 for the low, medium, and high traffic volumes, respectively. N/C = not considered.

TABLE 2: Parameter Matrix

Traffic/bridge span variables		Short-span bridge (45ft)	Medium-span bridge (60ft)	Long-span bridge (122ft)
Low traffic below bridge	Low traffic above bridge	C	C	N/C
	High traffic above bridge	C	C	N/C
Medium traffic below bridge	Low traffic above bridge	C	C	C
	High traffic above bridge	N/C	C	C
High traffic below bridge	Low traffic above bridge	N/C	C	C
	High traffic above bridge	N/C	C	C

C: Considered, N/C: Not Considered

TABLE 3: User Cost Related Values

Parameter	**Value**
L	0.5-2 mile
N	4hours-5months
S_n	45mph
S_a	30mph
S_n*	70mph
S_a*	45mph
w	$13.61
r	$11.22
c_a	$99,560
A_a	2.58%
A_n	1.56%

* Below the bridge

L varies from 0.5 mile to 2 mile and N varies from 4 hours (routine inspection) to 5 month (superstructure replacement) based on different extend of activities. Values are acquired from MDOT experience and other different sources.[8, 9, 29, 36]

TABLE 4: Detailed Life-Cycle Cost Results of Three Alternative Bridges (million dollars)

Item	Black Steel	Epoxy-Coated Steel	CFRP
Initial Construction	0.60	0.61	0.97
Initial Cathodic Protection	0.11	----	----
Routine Inspection	0.02	0.02	----
Detailed Inspection	0.29	0.29	0.14
Deck Patch	0.23	0.23	----
Deck Shallow Overlay	1.85	1.85	0.60
Deck Replacement	1.32	1.32	0.51
Beam End Repair	0.01	0.01	----
Beam Replacement	0.04	0.04	----
Cathodic Protection Maintenance	0.19	----	----
Cathodic Protection Upgrade	0.06	----	----
Superstructure Demolition	0.02	0.02	----
Superstructure Replacement	1.23	1.24	----
Total Life-Cycle Cost	**5.98**	**5.63**	**2.22**
Responsible party	**Black Steel**	**Epoxy-Coated Steel**	**CFRP**
Agency	1.43	1.25	1.10
User	4.55	4.38	1.12
Total Life-Cycle Cost	**5.98**	**5.63**	**2.22**

TABLE 5: Parameter Study Results (million dollars)

Type of Reinforcement in the Bridge	**Condition of Case**						
	INITIAL	HH	HL	MH	ML	LH	LL
Long Span							
Black Steel	1.21	8.31	6.97	7.18	5.83	N/C	N/C
Epoxy-Coated Steel	1.23	7.98	6.79	6.84	5.65	N/C	N/C
CFRP	2.25	3.87	3.64	3.61	3.39	N/C	N/C
Medium Span							
Black Steel	0.60	5.98	4.78	4.72	3.53	3.42	2.23
Epoxy-Coated Steel	0.61	5.63	4.59	4.37	3.33	3.07	2.03
CFRP	0.97	2.22	1.99	1.90	1.67	1.54	1.31
Short Span							
Black Steel	0.45	N/C	N/C	N/C	3.28	3.14	1.66
Epoxy-Coated Steel	0.46	N/C	N/C	N/C	3.08	2.79	1.46
CFRP	0.75	N/C	N/C	N/C	1.44	1.30	0.99

N/C: Not Considered
INITIAL: Initial construction cost
HH: High-traffic-below and high-traffic above
HL: High-traffic-below and low-traffic above
MH: Medium-traffic-below and high-traffic above
ML: Medium-traffic-below and low-traffic above
LH: Low-traffic-below and high-traffic above
LL: Low-traffic-below and low-traffic above

TABLE 6: Random Variables

Agency Costs	Description	COV
X(1)	Bridge construction	0.20
X(2)	Deck patch	0.40
X(3)	Deck shallow overlay	0.40
X(4)	Deck replacement	0.20
X(5)	Beam end repair	0.60
X(6)	Beam replacement	0.20
X(7)	Cathodic protection maintenance	0.40
X(8)	Cathodic protection upgrade	0.40
X(9)	Superstructure demolition	0.20
User Costs		
X(10)	Deck patch	*
X(11)	Deck shallow overlay	*
X(12)	Deck replacement	*
X(13)	Superstructure replacement	*
X(14)	Cathodic protection maintenance	*
X(15)	Cathodic protection upgrade	*
X(16)	Routine inspection	*
X(17)	Detailed inspection	*

*COV varies for each RV per bridge case and is a function of travel time cost COV (0.12), operating cost COV (0.18), and crash cost COV (0.13).

TABLE 7: Results Summary

Case*	**Probability that CFRP costs less by year 20**		**Year when the probability that CFRP costs less is ≥ 0.95**	
	Black Steel	Epoxy-Coated Steel	Black Steel	Epoxy-Coated Steel
Long Span				
ML	0.67	0.59	40	40
MH	0.88	0.83	36	40
HH	0.96	0.94	20	28
HL	0.85	0.81	40	40
Medium Span				
LL	0.71	0.54	40	40
LH	0.96	0.88	20	36
ML	0.97	0.93	20	35
MH	0.999	0.99	20	20
HL	0.999	0.998	20	20
HH	>0.999	>0.999	20	20
Short Span				
LL	0.67	0.47	40	55
LH	0.99	0.94	20	25
ML	0.99	0.98	20	20

*See abbreviation key for Table 5.