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LIFE CYCLE COST ANALYSIS OF CFRP REINFORCED CONCRETE BRIDGES

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Introduction

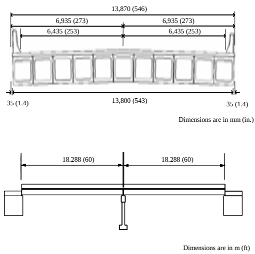
This study shows that despite the higher initial construction cost of Carbon Fiber Reinforced Polymer (CFRP) reinforced bridges, they can be cost effective when compared to traditional steel reinforced bridges.
Life cycle cost analysis (LCCA) is an important investment decision tool.
LCCA methodology: 1. Establish design alternatives 2. Determine activity timing 3. Estimate costs (agency and user) 4. Compute life-cycle costs 5. Analyze the results.

Objectives

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.

Bridge Cross-Section and Elevation

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 each case, three reinforcing alternatives were considered: (a) black (without epoxy-coating) steel reinforcement with cathodic protection; (b) epoxy-coated steel reinforcement; and (c) CFRP reinforcement.



Detailed LCCA Results of the medium-span with high-traffic-above and high-traffic-below

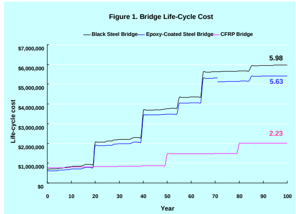
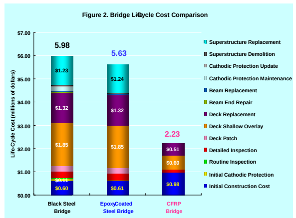
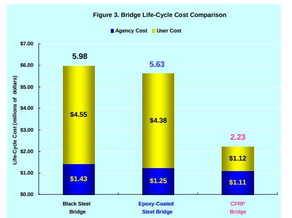


Figure 1 illustrates the yearly changes in total cost. The initial construction cost of the CFRP bridge is higher. However, in year 20, the steel bridges cumulative cost exceeds the cost of the CFRP bridge.

Figure 2 illustrates the final life-cycle costs (LCC) of all the alternatives by cost category. The total LCC are $5.98 million for the bridge with black steel reinforcement, $5.63 million for the bridge with epoxy-coated steel reinforcement, and $2.23 million for the bridge with CFRP reinforcement.

Figure 3 illustrates the final life-cycle costs (LCC) of all the alternatives by entity. The most significant contributor to LCC is user cost, which contributes from 50% to 78% of the total project cost for the different alternatives.





Probabilistic Analysis

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

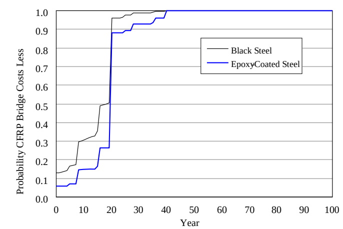
Random Variables

	Description
Agency Costs	
X(1)	Bridge construction
X(2)	Deck patch
X(3)	Deck shallow overlay
X(4)	Deck replacement
X(5)	Beam end repair
X(6)	Beam replacement
X(7)	Cathodic protection maintenance
X(8)	Cathodic protection upgrade
X(9)	Superstructure demolition
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

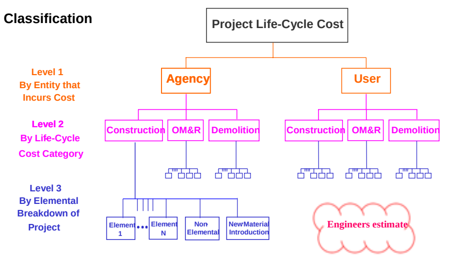
Results Summary

Case	Year when the probability that CFRP costs less is ≥ 0.95	
	Black Steel	Epoxy-Coated Steel
Long Span		
ML	40	40
MH	36	40
HH	20	28
HL	40	40
Medium Span		
LL	40	40
LH	20	36
ML	20	35
MH	20	20
HL	20	20
HH	20	20
Short Span		
LL	40	55
LH	20	25
ML	20	20

Probability Cost Distribution



Classification



Agency and User Costs

Agency costs include material, personnel, and equipment costs associated with operation, maintenance and repair (OM&R), demolition, and replacement. The cost of OM&R includes activities as shown in the "Activity Timing" graphs.
User cost is taken as the sum of travel time costs, vehicle operating costs, and crash costs.

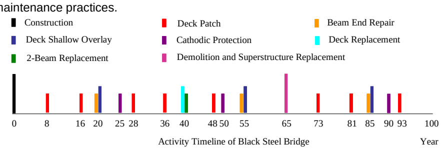
User Cost Related Values

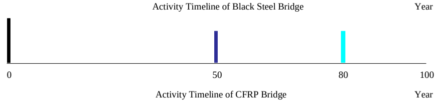
* Below the bridge

Parameter	Value
Length of affected roadway (L)	0.5-2 miles
Number of days (N)	4 hours – 5 months
Normal driving speed (S_n)	45 mph
Traffic speed during road work (S_a)	30 mph
Normal driving speed (S_n*)	70 mph
Traffic speed during road work (S_a*)	45 mph
Hourly driver cost (w)	$13.61
Hourly vehicle operating cost (r)	$11.22
Cost per accident (C_a)	$99,560
Accident rate during road work (A_a)	2.58%
Normal accident rates (A_n)	1.56%

Activity Timing

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.





Routine and detailed inspection per Federal Highway Administration (FHWA)

Results of Parametric Study (millions of dollars)

*N/C: Not considered

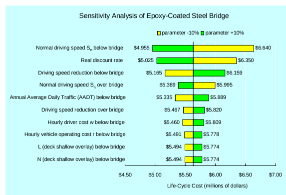
	Reinforcement Type	Initial construction cost	Life-Cycle Cost					
			HH	HL	MH	ML	LH	LL
Long Span	Black Steel	1.21	8.31	6.97	7.18	5.83	N/C*	N/C
	Epoxy-Coated Steel	1.23	7.98	6.79	6.84	5.65	N/C	N/C
	CFRP	2.25	3.87	3.64	3.61	3.39	N/C	N/C
Medium Span	Black Steel	0.60	5.98	4.78	4.72	3.53	3.42	2.23
	Epoxy-Coated Steel	0.61	5.63	4.59	4.37	3.33	3.07	2.03
	CFRP	0.98	2.23	2.01	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

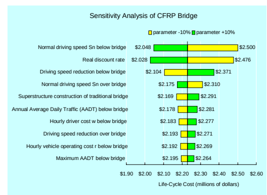
HH: High-traffic-below and high-traffic-above
HL: High-traffic-below and low-traffic-above
MH: Medium-traffic-below and high-traffic-above
ML: Medium-traffic-below and low-traffic-above
LH: Low-traffic-below and high-traffic-above
LL: Low-traffic-below and low-traffic-above

AADT above the bridge are initially 1,000 (low) and 10,000 (high) with 26,000 maximum. AADT below the bridge are initially 10,000 (low) and 30,000 (medium) with 120,000 maximum for short-span bridges; initially 20,000 (low), 60,000 (medium) and 100,000 (high) with 200,000 maximum for medium-span bridges; and initially 100,000 (medium) and 140,000 (high) with 250,000 maximum for long-span bridges.

Sensitivity Analysis

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 the following two figures for the ten most influential parameters.
In the figures, 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.





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Conclusions and Future Directions

The LCCA of prestressed concrete side-by-side box beam bridges shows that bridges constructed with CFRP reinforcement will become more cost effective than steel reinforced concrete bridges as time increases. The project findings 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. **4.** The probabilistic analysis confirmed deterministic results and showed 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.

Side-by-side concrete box beam bridges were considered. This analysis could be applied to other types of bridges such as an AASHTO beam bridge. Furthermore, due to different maintenance conditions of the bridges and other influential factors, a different activity timing could be applied to the bridges, which could affect results.