

# Life-Cycle Cost Analysis of Reinforced Concrete Bridge Decks with Conventional and Corrosion Resistant Reinforcement

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**Abstract.** Reinforced concrete (RC) bridge decks suffer from corrosion-induced damage due to aggressive environmental conditions or de-icing chemicals. Significant expenditures are typically required to conduct routine maintenance and repairs of affected RC bridges. Compared to conventional steel reinforcement (i.e. black rebar), corrosion resistant reinforcement is initially more expensive but provides longer service life. In this paper, corrosion-induced cracking time, traffic delays associated with bridge deck maintenance, and the environmental impact associated with these activities are integrated into a probabilistic framework to investigate the life-cycle cost of RC bridge decks with conventional and corrosion resistant reinforcement. Monte Carlo simulation is implemented to quantify the probabilistic life-cycle cost of the bridge deck. Preliminary results obtained from this project show that corrosion resistant reinforcement has lower life-cycle cost compared to conventional reinforcement. The indirect cost associated with traffic delays accounts for over 50% of the total life-cycle cost for the investigated case study.

## 1 Introduction

Reinforced concrete (RC) bridges are fundamental components of the surface transportation system. To mitigate the effects of aggressive environmental conditions or de-icing chemicals, routine maintenance and replacement activities are applied to RC bridges to ensure satisfactory structural performance. Due to the significant cost of these activities, material selection decisions should be made based on life-cycle cost analysis (LCCA) instead of initial construction cost alone. Indirect costs including traffic delays and environmental impact should be integrated into the LCCA.

In a typical bridge system, the deck is the most susceptible component to experience corrosion. Conventional steel reinforcement in RC bridge decks has been shown to have poor corrosion resistance in aggressive environments [1, 2]. In order to extend the service life of bridge decks, corrosion resistant reinforcement such as galvanized rebar [3] and martensitic microcomposite formable steel (MMFX) rebar [4] have been proposed as alternative choices. Despite the higher initial cost of these corrosion resistant reinforcement alternatives, less subsequent maintenance and lower indirect costs could lead to a more economical bridge from a life-cycle cost perspective. Soliman and Frangopol [5] evaluated the life-cycle cost of a steel bridge using conventional and corrosion-resistant steel. The study shows the advantages of corrosion-resistant steel in reducing the life-cycle cost of steel bridges.

This paper presents preliminary results of LCCA to compare the performance of RC bridge decks constructed with conventional steel reinforcement to that of decks with corrosion resistant reinforcement. Black rebar and MMFX reinforcement are chosen to illustrate this method. Direct costs including initial construction and subsequent repair activities, and indirect costs, including traffic delay and environmental impact, are considered. Monte Carlo simulation is adopted to account for the uncertainties associated with these costs.

## 2 Life-cycle cost analysis

LCCA provides a mechanism for evaluating the costs related to all aspects of a structure throughout its service life. These costs can be divided into two categories: direct and indirect. The direct cost includes the initial engineering and construction costs, in addition to the cost and maintenance activities (e.g., materials, routine maintenance, repair/patching, rehabilitation and replacement) [6]. The indirect cost includes aspects such as economic and social impact of traffic delay on road network users and businesses as well as environmental impact due to increased emissions and pollution resulting from repair activities. These indirect aspects tend to have a vital influence on life-cycle cost [7]. In this paper, three main modules are integrated to evaluate the life-cycle cost of RC bridge decks: (a) corrosion time analysis of different rebar types which determines the frequency of maintenance and replacement, (b) estimation of traffic delays due to bridge maintenance

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activities, and (c) environmental impact of traffic delays arising from bridge interventions.

## 2.1 Corrosion cracking time

The time to corrosion-induced cracking of RC decks can be divided into corrosion initiation and propagation periods [8]. The corrosion initiation and propagation periods depend on the chloride exposure, type of reinforcement, and deck geometry. The time to corrosion cracking of black and MMFX rebars can vary widely due to their different corrosion resistant characteristics.

### 2.1.1 Initiation period

Initiation period describes the time required for surface chloride ions to penetrate into the deck and cause the concentration of ions on the steel rebar surface to reach a critical value. Once chloride ion concentration exceeds this critical value, the steel rebar begins to corrode, and the deck enters the propagation period. This critical value is the surface chloride threshold which is determined by material properties of the rebar [9]. Considering the diffusion of chloride ions, the RC surrounding the rebar is modeled as a concrete cylinder with the steel rebar in its center as shown in Figure 1. Under this assumption, Fick's second law [10] is adopted to evaluate the corrosion initiation time  $T_i$ . Given the chloride threshold  $C_r$  of a certain rebar type, the corrosion initiation time  $T_i$  can be computed as

$$T_i = \frac{C^2}{4D_c \left( \text{erf}^{-1} \left( 1 - \frac{C_r}{C_0} \right) \right)^2} \quad (1)$$

where  $C_0$  ( $\text{kg}/\text{m}^3$ ) is the surface chloride concentration;  $D_c$  ( $\text{mm}^2/\text{yr}$ ) is the diffusion coefficient;  $t$  is time of diffusion;  $C$  ( $\text{mm}$ ) is concrete cover depth; and  $\text{erf}()$  is the statistical error function.

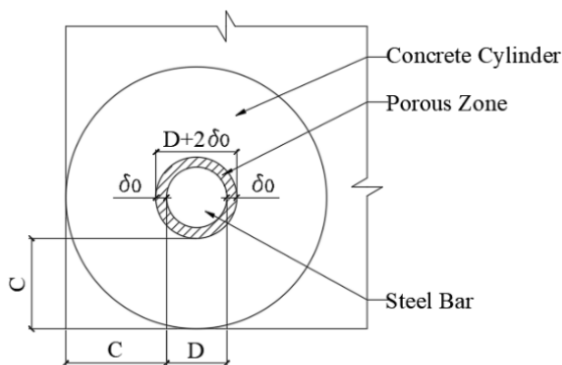


Fig. 1. Deck section model.

### 2.1.2 Propagation period

Propagation period represents the time required for the concrete to develop cracks after steel bars begin to corrode. The presence of a porous zone around the steel rebar is responsible for extending the propagation period

[11]. Rust needs to fill this zone first before generating enough pressure on the concrete cover to cause cracking. The propagation time can be calculated as [11]

$$T_{cr} = \frac{\rho_s z F \left( \frac{2C_{cr} k}{D} + \delta_0 \right)}{M \left( \frac{1}{\gamma \beta} - 1 \right) i} \quad (2)$$

$$k = \frac{(1 + \nu + \Delta)(D + 2\delta_0)(1 + \varphi_{cr})}{2E_c}, \quad \Delta = \frac{(D + 2\delta_0)^2}{2C(C + D + 2\delta_0)}$$

where  $\rho_s$  is the density of steel ( $7.85 \text{ g}/\text{cm}^3$ );  $z$  is the ionic charge (2 for  $Fe \rightarrow Fe^{2+} + 2e^-$ );  $F$  is Faraday's constant (96,500 As);  $M$  is the atomic mass of iron (56);  $f_{cr}$  is the concrete tensile strength;  $\beta$  is the ratio of mass density of rust to mass density of the original steel (0.5) [12];  $\gamma$  is the ratio of molecular mass of steel to molecular mass of rust; and  $i$  ( $\text{A}/\text{cm}^2$ ) is the current density;  $D$  ( $\text{mm}$ ) is the diameter of rebar;  $\delta_0$  ( $\mu\text{m}$ ) is the thickness of porous zone;  $E_c$  is the elastic modulus of concrete; and  $\varphi_{cr}$  is the concrete creep coefficient considered herein as 2.35 ([13]. Based on the previous discussion, the total corrosion cracking time  $T$  is given by

$$T = T_i + T_{cr} \quad (3)$$

## 2.2 Traffic delay estimation

Reduced speed, queuing and crashes are common occurrences in work zones. Traffic delay estimation must consider the average daily traffic (ADT), hourly delay, reduced speed limits in work zones and queuing. Denoting the maintenance duration as  $d$  (days) and aggregating the hourly traffic delay, the total traffic delay time due to maintenance  $TL$  is

$$TL = d \times ADT \times \sum_{i=1}^{24} D_{Ti} \quad (4)$$

where  $D_{Ti}$  is the traffic delay time per vehicle in the  $i$ th hour considering vehicle queuing [14]. Traffic delay cost due to maintenance  $C_{TL}$  can be estimated as [15]

$$C_{TL} = [c_w O_c (1 - T) + (c_c O_t + c_g) T] \times TL \quad (5)$$

where  $c_w$  ( $\$/h$ ) is the average wage per hour;  $c_c$  ( $\$/h$ ) is the average compensation per hour for truck drivers;  $c_g$  ( $\$/h$ ) is the time value of the goods transported in a cargo;  $O_c$  and  $O_t$  are average occupancies for cars and trucks; and  $T$  is the truck percent of ADT expressed as a decimal. Due to the uncertainties associated with these input variables, it is essential to conduct the LCCA probabilistically.

## 2.3 Environmental influence

Traffic delay caused by construction and maintenance activities will increase air pollution and emissions [16, 17]. Based on Soliman and Frangopol [5], the increase in

emissions  $E$  (kg) during the project duration can be estimated as

$$E = ADT \times L \times d \times [En_{d,c}(1 - T) + En_{d,t}T] \times \frac{En_{SD} - En_{SO}}{En_{SO}} \quad (6)$$

where  $En_{d,c}$  (kg/km) and  $En_{d,t}$  (kg/km) are the environmental metric per unit distance for cars and trucks, respectively, quantified herein as the carbon dioxide emissions per kilometer; and  $En_{SD}$  (kg/km) and  $En_{SO}$  (kg/km) represent the carbon dioxide emissions per kilometer at speeds  $SD$  and  $SO$ , respectively. The costs of carbon dioxide emissions  $C_E$  can be transferred into monetary value by

$$C_E = E \times c_{Env} \quad (7)$$

where  $c_{Env}$  (\$/ton) is the cost value of the environmental metric.

### 2.4 Life-cycle cost

The total life-cycle cost of a structure  $C_T$  can be computed as

$$C_T = C_{init} + \sum_{i=1}^n (C_{TLi} + C_{Ei}) \div (1 + r)^{y_i} \quad (8)$$

where  $n$  is the number of times maintenance will be performed during the service life;  $C_{TLi}$  and  $C_{Ei}$  are the traffic delay cost and environmental influence cost of  $i$ th maintenance, respectively;  $r$  is the discount rate of money, and  $y_i$  is the number of years used in discounting future costs of  $i$ th maintenance.

## 3 Illustrative example

### 3.1 Bridge properties

To evaluate life-cycle cost of RC bridge decks with black rebar and MMFX, a bridge model with span 32 m and deck area of 464.5 m<sup>2</sup> is studied. The bridge is assumed to have 2 lanes per direction. Other key variables and their descriptors are given in Table 1. Overlay is considered as the primary maintenance activity. Simulation results of corrosion cracking time are used to determine the deck replacement interval.

**Table 1.** Descriptors of variables associated with the bridge properties.

Variables	Value
Service life	100 (yrs)
Deck replacement duration	T <sup>a</sup> [95,100,105] (days)
Overlay application duration	T <sup>a</sup> [8,10,12] (days)
Overlay effective period	T <sup>a</sup> [9,10,11] (yrs)
Construction area	464.5 m <sup>2</sup> (5000 ft <sup>2</sup> )
Discount rate	0.02
Overlay cost	120.7 (\$/m <sup>2</sup> )
Construction cost	Black 1950.4 (\$/m <sup>2</sup> )

	MMFX	1987.0 (\$/m <sup>2</sup> )
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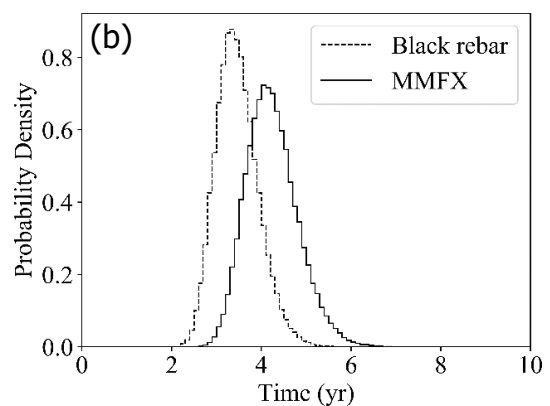
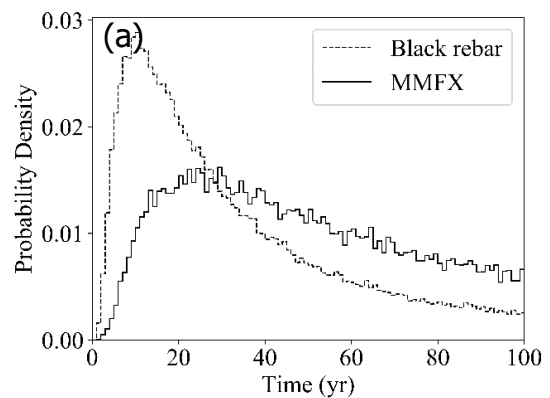
<sup>a</sup> Triangular distribution: [lower limit, mode, upper limit]

Monte Carlo simulation is used to draw samples from the probabilistic corrosion initiation time given by Equation 1. This process results in the probability density function (PDF) of the corrosion initiation time for both types of reinforcement as shown in Figure 2(a). Properties of black rebar and MMFX are shown in Table 2. The simulation results show that the black rebar has a shorter initiation time compared to MMFX.

**Table 2.** Descriptors of variables associated with corrosion initiation time.

Variables	Probability Distribution Function
$C_o$	Gamma: $\alpha = 3.56, \beta = 1.25$ (kg/m <sup>3</sup> ) <sup>a</sup>
$C$	Lognormal: $\mu = 51, \sigma = 10$ (mm)
$D_c$	Gamma: $\alpha = 1.42, \beta = 27.05$ (mm <sup>2</sup> /yr) <sup>a</sup>
$C_r$	Black Normal: $\mu = 0.944, \sigma = 0.189$ (kg/m <sup>3</sup> ) <sup>b</sup>
	MMFX Normal: $\mu = 2.436, \sigma = 0.487$ (kg/m <sup>3</sup> ) <sup>b</sup>

<sup>a</sup> Zemajitis [18]; <sup>b</sup> Darwin et al. [19]



**Fig. 2.** Probability density function of (a) corrosion initiation time, and (b) corrosion propagation time.

The PDF of corrosion propagation time for each rebar type is established using Monte Carlo simulation based on Equation 2. The resulting PDFs are shown in Figure 2(b). Descriptors of the corrosion propagation model input variables are given in Table 3. The propagation model variables included in Equation 2 are similar for both rebar types, except for the current

density  $i$  [20]. Simulation results show that the black rebar has a propagation life with a mean value of 3.46 years and standard deviation of 0.47 years. For the MMFX, the mean propagation life is 4.24 years and the standard deviation is 0.58 years.

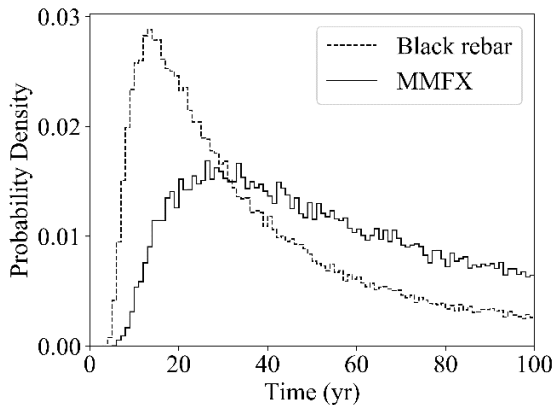
**Table 3.** Descriptors of variables of the corrosion propagation model.

Variables	Probability Distribution Function	
$C$	Lognormal: $\mu = 51, \sigma = 10$ (mm)	
$D$	$T^a$ : [15, 15.5, 16] (mm) <sup>b</sup>	
$\delta_0$	$T^a$ : [10, 15, 20] ( $\mu\text{m}$ ) <sup>b</sup>	
$\gamma$	$T^a$ : [0.523, 0.573, 622] <sup>b</sup>	
$i$	Black	0.422 ( $\mu\text{A}/\text{cm}^2$ ) <sup>c</sup>
	MMFX	0.3448 ( $\mu\text{A}/\text{cm}^2$ ) <sup>c</sup>

<sup>a</sup> Triangular distribution: [lower limit, mode, upper limit]

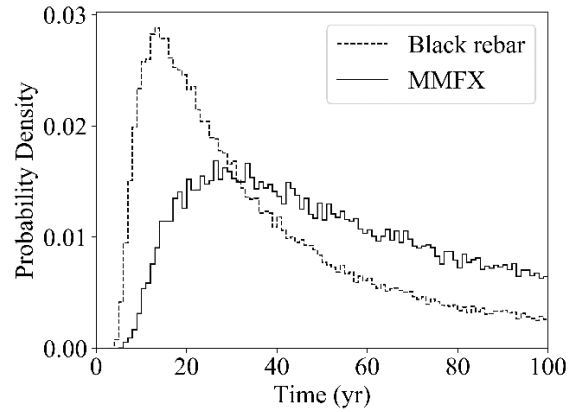
<sup>b</sup> El Maaddawy and Soudki [11] <sup>c</sup> Nikoo et al. [20]

Based on previous analysis, the PDF of the corrosion cracking time of RC bridge decks constructed with different rebar types can be established as shown in Figure 3. The corrosion cracking time for the decks constructed using black rebar has a higher possibility of a shorter service life compared to those using MMFX. Accordingly, the use of corrosion resistant reinforcement can reduce the frequency of maintenance activities and its associated indirect cost.



**Fig. 3.** Corrosion cracking time of black rebar and MMFX.

The PDF of the daily traffic delay cost, based on Equation 5, is shown in Figure 4. The mean value and standard deviation of the traffic delay cost are 44,252 \$/day, and 4,235 \$/day, respectively. These results will be utilized to estimate the total life-cycle cost.



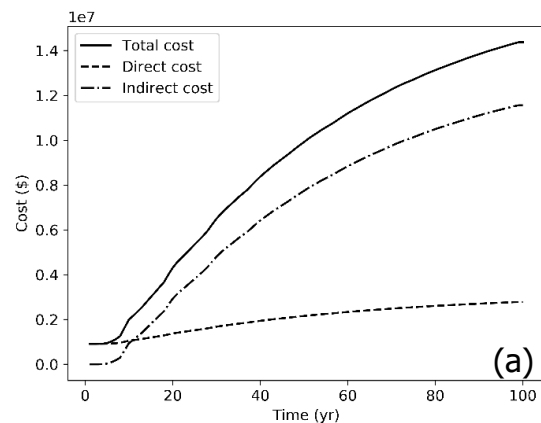
**Fig. 4.** Daily traffic delay cost.

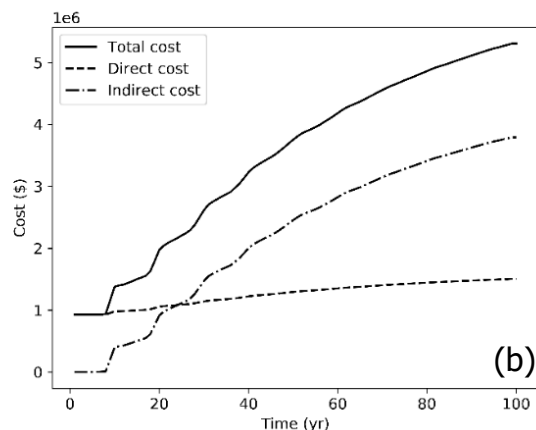
The environmental cost model variables are shown in Table 4 [16, 21, 22]. Preliminary simulation results indicate that the cost of environmental impact is relatively low compared to the cost of traffic delay. However, this result may change if a higher value for the cost of the carbon dioxide per ton (i.e.,  $C_{Env}$ ) is used.

**Table 4.** Descriptors of variables associated with environmental cost.

Variables	Probability Distribution Function
$En_{d,c}$	Lognormal: $\mu = 0.22, c.o.v = 0.2$ (kg/km)
$En_{d,t}$	Lognormal: $\mu = 0.56, c.o.v = 0.2$ (kg/km)
$En_{SD}$	0.379 (kg/km)
$En_{SO}$	0.298 (kg/km)
$C_{Env}$	Lognormal: $\mu = 26, c.o.v = 2.93$ (\$/ton)

The life-cycle cost of black rebar and MMFX including direct cost and indirect is shown in Figure 5. As shown, indirect aspects dominate the life-cycle cost and can account for over 50% of the total life cycle cost. As unit prices of the two materials will be characterized by its small influence on total life-cycle cost, corrosion resistant reinforcement has lower cost in all aspects compared to the black rebar. Based on preliminary results, it is concluded that corrosion resistant reinforcement is a more effective solution from a long-term perspective.





**Fig. 5.** Life-cycle cost of the investigated bridge for (a) black rebar, and (b) MMFX.

#### 4 Preliminary Conclusions

This paper presents the results of a probabilistic investigation to evaluate the life-cycle cost of RC bridge decks with conventional and corrosion resistant reinforcement. The life-cycle cost includes maintenance and replacement cost, traffic delay cost, and environmental cost. With estimation of the corrosion cracking time, traffic delay model, and environmental impact, the life-cycle cost of black rebar and MMFX are calculated and compared. The following conclusion are drawn:

1. Black rebar and MMFX have different corrosion cracking times. This is caused by the different chloride concentration thresholds and current density required to initiate and propagate the corrosion process.
2. Traffic delay cost appears to play a major role in the life-cycle cost of bridge decks and represents over 50% of total life cycle cost for the investigated case study.
3. Corrosion resistant reinforcement has a lower life-cycle cost compared to conventional reinforcement.

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