EFFICIENT SERVICE LIFE EXTENSION OF BRIDGES THROUGH RISK-BASED LIFECYCLE MANAGEMENT AND HIGH-PERFORMANCE CONSTRUCTION MATERIALS: EMPHASIS ON CORROSION-RESISTANT STEEL

This document is a technical summary of the U.S. Department of Transportation report, *Efficient Service Life Extension of Bridges Through Risk-Based Lifecycle Management and High-Performance Construction Materials: Emphasis on Corrosion-Resistant Steel,* Report CIAM-UTC-REG6 (Report Date: September 30, 2020)

INTRODUCTION

The main goal of this project was to establish an effective lifecycle bridge management framework for novel maintenance actions based on high-performance construction materials. To counteract the detrimental effects of steel corrosion, the application of high-performance construction materials will emphasize the use of corrosion-resistant steel, a material locally available in Pennsylvania. This steel, referred to as A709-50CR (formerly known as A1010), is an innovative, low-cost stainless steel developed and produced by ArcelorMittal, a Pennsylvania-based steel manufacturer.

Specifically, the objectives of this project were:
(a) to investigate and model the corrosion behaviors of both conventional carbon steel and corrosion-resistant steel,
(b) to evaluate the lifecycle cost impact of steel bridges with conventional carbon steel and corrosion-resistant steel,
(c) to assess the lifecycle risk of steel girder bridges repaired with A709-50CR, and
(d) to conduct risk-based lifecycle maintenance optimization under uncertainty.

A four-girder bridge model based on a steel bridge located in Montgomery County, Pennsylvania was studied to investigate the potential benefit of using A709-50CR for girder replacements. The bridge is a single-span, simply supported highway bridge carrying Cedar Hill Road and intersecting PA 309. The geometrical dimensions of the bridge are shown in Figure 1(a). The cross-section of the bridge superstructure and one of its girders are presented in Figure 1(b) and Figure 1(c), respectively.

METHODOLOGY

Optimal maintenance solutions associated with girder replacement using either A709-50CR or carbon steel girders were obtained herein through optimization processes. Corrosion modeling was considered to obtain time-variant girder resistances as well as time-variant correlation coefficients among girder resistances. Performance functions of girders were established based on AASHTO specifications (AASHTO 2017). System reliability analysis was then conducted to obtain time-variant system reliability profiles. Failure consequence evaluation was conducted to obtain time-variant risk profiles. Genetic algorithm was utilized to determine the optimal maintenance solutions for individual bridges.

In this study, failure of a girder was controlled by either flexural or shear failure, and thus modeled by a series model with two components. For a multi-girder bridge, excessive deflection causing the failure of bridges may only occur when several adjacent girders reach their ultimate limit states. Therefore, the system model for the multi-girder superstructure takes the form of several parallel-series subsystems connected with each other in series. Each subsystem consists of several adjacent girders. The system model is shown in Figure 2.

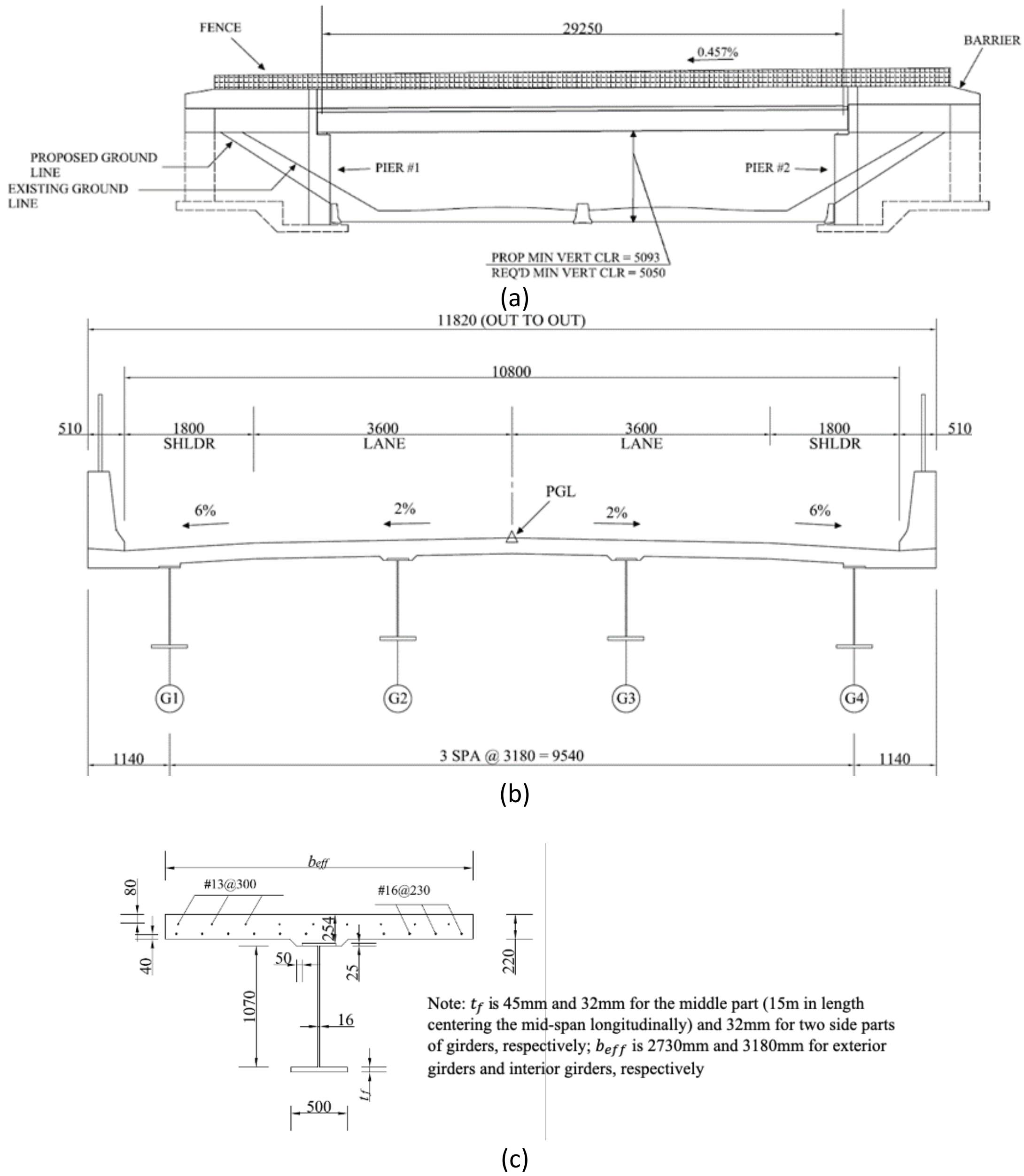


Figure 1. Schematic of Montgomery bridge: (a) elevation, (b) typical section, and (c) girder cross-section (all dimensions are in millimeters).

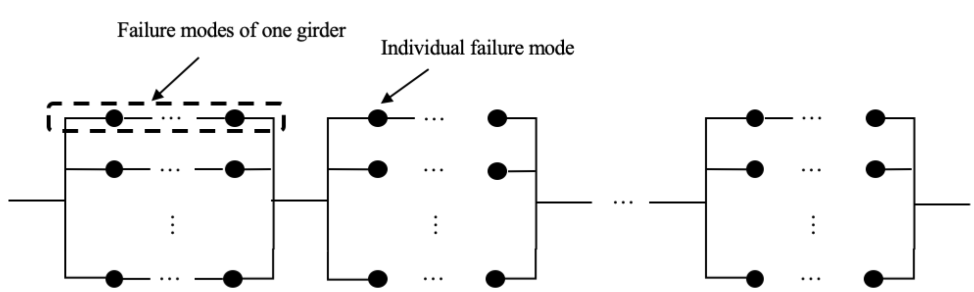


Figure 2. General system configuration for reliability analysis of bridge superstructure.

DATA SUMMARY

Table 1. Corrosion rate data of carbon steel plates.

Steel Name	Exposure Condition	Corrosion Rates (μm/year)
Mild steel	Marine	36[a]
Mild steel	Marine (roof of Washington Hotel by the shore of Limon Bay)	12[b]
Unalloyed carbon steel (Cu 0.03 to 0.10 %, P < 0.07 %)	Kure Beach (250-m lot), North Carolina (eastern marine)	21.7[c]
	Point Reyes, California (western marine)	11.9[c]
Mild steel	Barcelona	20.4[d]
	Cadiz	12.5[d]
	Cabo Negro	45.3[d]
	Alicante (30-m lot)	48.3[d]
	Alicante (100-m lot)	8.4[d]
Carbon No.45	Block Island, Rhode Island	242.7[e]
	Kure Beach (250-m lot)	118.0[e]
Carbon steel	Kure Beach (250-m lot)	171.0[f]
		142.1[g]
		81.8[h]
Carbon steel	Kure Beach (250-m lot)	71.9[i]
Carbon steel	Point Reyes, California	76.8[j]
Carbon steel	Kure Beach (200-m lot)	20.7[k]

Note: (a) Based on Kucera and Mattson (1982); (b) Based on Southwell and Bultman (1975); (c) Based on Knotkova et al. (2012); (d) Based on Morcillo et al. (1995); (e) Based on Copson (1960); (f) Reference 9 in Albrecht and Hall, Jr. (2003); (g) Reference 11 in Albrecht and Hall, Jr. (2003); (h) Reference 12 in Albrecht and Hall, Jr. (2003); (i) Based on ASTM Committee B-3 (1959); (j) Based on Melchers (2007); (k) Based on FHWA (2011).

Table 2. Corrosion rate data of stainless steel plates.

Environment	Steel Type	Corrosion Rate	Corrosion Rate Ratio
Rural	Mild steel	22μm/year[a]	-
	AISI 410	0.03μm/year[a]	1.36×10^{-3}[a]
Urban	Mild steel	53μm/year[a]	-
	AISI 410	0.04μm/year[a]	7.55×10^{-4}[a]
Marine	Mild steel	36μm/year[a]	-
	AISI 410	0.04μm/year[a]	**1.11×10^{-3}**[a]
Marine (Kure Beach 250-m lot)	Mild steel	23.69μm/year[b]	-
	11.6% Cr steel	0.64μm/year[b]	**0.027**[b]
	12.2% Cr steel	0.32μm/year[b]	**0.0135**[b]
Marine (Kure Beach 200-m lot)	Carbon steel	20.7μm/year[c]	-
	A709-50CR	1.10μm/year[c]	0.0534[c]

Note: (a) Based on Kucera and Mattson (1982); (b) Based on Knotkova et al. (2012) and Schmitt and Mullen (1968); (c) Based on FHWA (2011). The data used to fit a distribution appear in bold.

EVALUATION RESULTS

An exponential distribution with a mean of 0.067 mm/year was used to model the annual corrosion rate of carbon steel plates (see Table 1). Due to limited data for A709-50CR, a uniform distribution was assumed for the corrosion rate ratio between A709-50CR and carbon steel. The lower and upper bounds of this ratio were determined using the data in Table 2. The coating life of a bridge was inferred from NBI data. The coating life thus obtained was modeled by a lognormal distribution with a mean of 15.3 years and a standard deviation of 5.3 years.

Monte Carlo simulation with 10^5 samples of each of the random variables involved in structural resistance calculation was conducted to depict the time-variant uncertainties in structural capacities. The results of time-variant flexural capacities are shown in Figure 3 for an exterior girder made of carbon steel and A709-50CR, respectively. Similar results can be obtained for shear capacities. Five candidate distributions were used to fit the samples of structural capacities including Gumbel, Weibull, Gamma, lognormal, and normal distributions. AIC criteria (Akaike 1998) were adopted to seek the best distribution to describe the uncertainties of load-carrying capacities. Normal distributions were found to be the best model for all shear and flexural capacities except for shear capacities of interior girders, in which case the normal distribution was the second-best model next to Weibull distribution. Therefore, normal distributions were used to represent all flexural and shear capacities in reliability analysis. The correlation coefficients among girder resistances were also determined through Monte Carlo simulation.

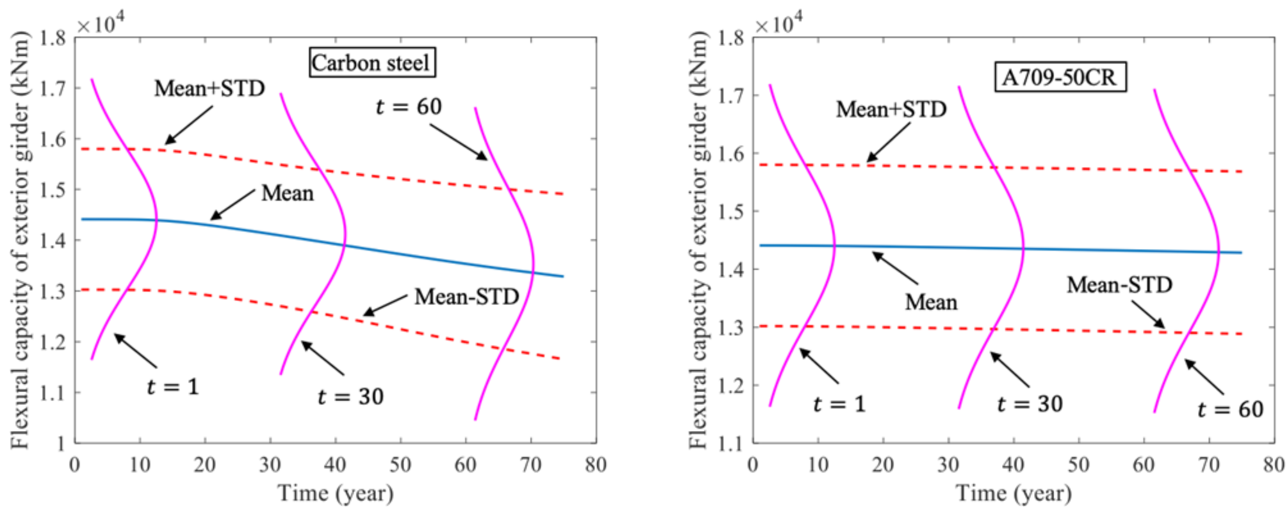


Figure 3. Time-variant flexural capacity of steel girders made of (a) carbon steel and (b) A709-50CR.

Based on the system model in Figure 2, the failure of the bridge superstructure was considered herein due to the failure of two adjacent girders. Figure 4 shows the annual system reliability/risk profiles for bridges made of carbon steel and A709-50CR. Based on the annual risks, the lifecycle risk of bridge failure can be calculated. It can be seen that A709-50CR can effectively enhance the lifetime reliability of steel bridges and mitigate the lifecycle failure risk.

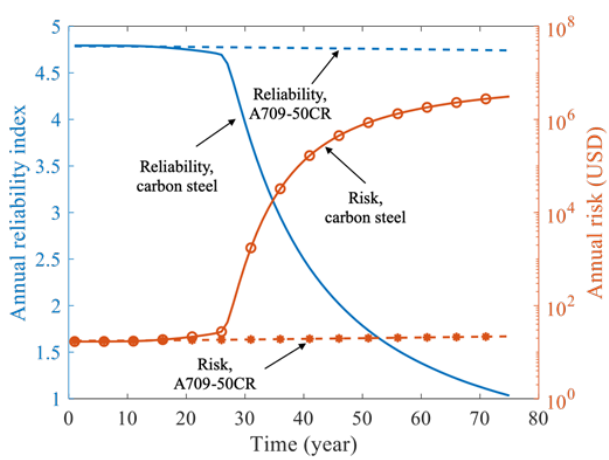
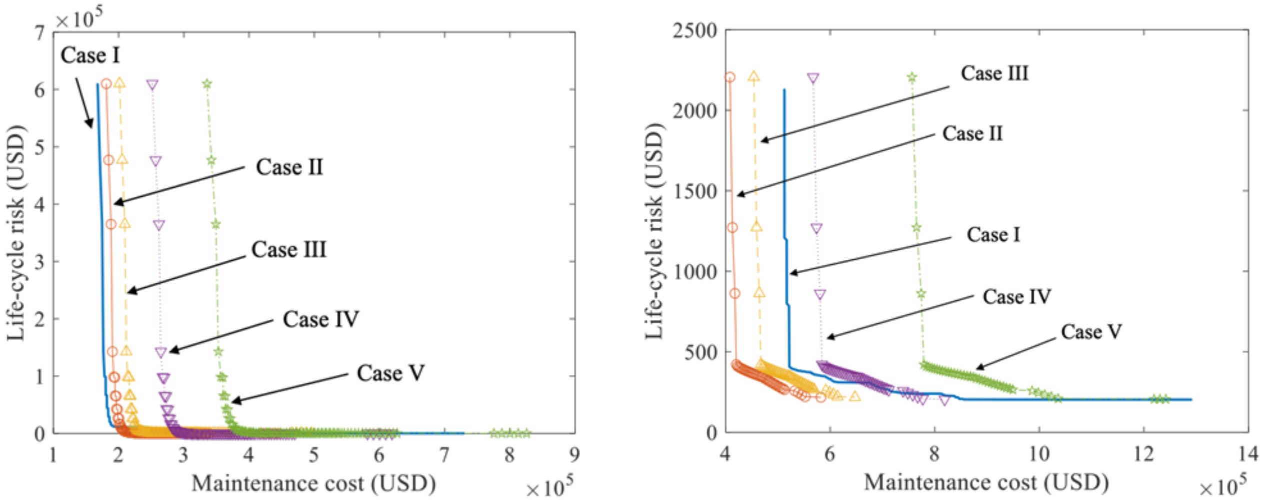


Figure 4. Time-dependent risk profiles.

Based on the material cost data, the initial cost of one A709-50CR girder is 7.9% higher than that of a carbon steel girder. Considering the potential volatility of A709-50CR cost, three additional cases were analyzed, where the cost of an A709-50CR girder is assumed to be 20%, 50%, and 100% higher than that of a carbon steel girder. The optimization objectives are to minimize the lifecycle maintenance cost and lifecycle risk. Two different annual reliability index thresholds were set for the girders, namely 2.0 and 3.5, respectively. The optimal Pareto fronts associated with these two annual reliability index constraints are shown in Figure 5. Overall, for both constraints, using A709-50CR for maintenance can save lifecycle cost when the safety requirement is strict, and this advantage exists as long as the cost of A709-50CR girders is below 1.5 times the cost of carbon steel girders.



(a) (b)

Note: Case I = carbon steel; Case II = A709-50CR (market cost); Case III = A709-50CR (cost assumed to be 1.2 times that of carbon steel); Case IV = A709-50CR (cost assumed to be 1.5 times that of carbon steel); Case V = A709-50CR (cost assumed to be 2.0 times that of carbon steel).

Figure 5. Risk-based optimal Pareto fronts.

CONCLUSION AND IMPLEMENTATION

- Based on the literature review on the corrosion behavior of A709-50CR and other types of martensitic stainless steel with similar chemical composition, it was found that the corrosion rate of A709-50CR is much lower than that of carbon steel when exposed to the same type of environment. For bridges under atmospheric corrosion in a marine environment, the corrosion rate of A709-50CR is about 0.1-2.7% of that of carbon steel. The high corrosion resistance of A709-50CR indicates no painting/repainting and other corrosion-related maintenance actions are needed for A709-50CR girders.
- When the acceptable lifecycle risk is low (or the reliability threshold is high), using A709-50CR for girder replacement can yield lower lifecycle cost. This comparative advantage is significant based on the market data of A709-50CR and carbon steel costs and can still be pronounced even when the cost of an A709-50CR girder is about 50% higher than that of carbon steel. When the cost of A709-50CR is even higher, the cost-effectiveness of using A709-50CR for girder replacement starts to diminish. Similarly, when the acceptable lifecycle risk is high (or the reliability threshold is low), carbon steel becomes cheaper than A709-50CR for girder replacement.
- When the target lifecycle risk is low, using A709-50CR steel can lead to a lower maintenance budget for the management of bridge network compared with using carbon steel to conduct replacement. The target risk level at which using carbon steel or A709-50CR for steel bridge replacement is equally cost-effective is contingent upon multiple factors, such as the failure consequence of the bridges in the network and the failure probabilities of each bridge, among others. The user equilibrium estimation approach adopted may also have an impact on this specific target risk level.
- To provide more accurate predictions on lifecycle cost and performance of steel bridges, future research is still needed to reduce the uncertainties associated with the corrosion rate of carbon steel and the corrosion rate ratio of A709-50CR to carbon steel. Due to galvanic corrosion at the interface between carbon steel and A709-50CR, caution should be taken when using A709-50CR in existing carbon steel bridges. This corrosion mechanism can be mitigated by detailing measures such as adding nonmetallic filler plates.

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