SUSTAINABILITY OF GFRP RC BRIDGE DECK: MATERIALS COST

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ABSTRACT

In the United States, reinforced concrete (RC) bridge decks have suffered from steel corrosion due to the enormous use of deicing salts for snow/ice removals in winter seasons. For the purpose of reducing/eliminating the steel corrosion, glass fiber reinforced polymer (GFRP) bars have been extensively researched as a promising substitute to the conventional steel reinforcement. Currently, the AASHTO has published the LFRD GFRP design guide specifications for GFRP RC bridge deck. However, the high initial material costs of GFRP bars still have been one of the most concerns hindering the wide use of GFRP bars in the concrete industry. This paper assessed the materials costs for GFRP RC bridge decks by a parametric study per AASHTO LFRD GFRP design guide specifications. Different deck thicknesses, girder spacings, and environmental reduction factors were considered in the study. The results from this paper could be used by bridge engineers in the preliminary design of new bridges with GFRP RC decks, or by decision makers in deck replacement projects with the option of GFRP RC decks.

Keywords: Bridge Deck, Concrete, Cost, GFRP Bar

1. INTRODUCTION

In the United States, there is a total area of $3.5\times10^8 m^2$ bridge decks, 86% of which are made of cast-in-place concrete decks[1]. The concrete bridge deck is directly exposed to environmental attacks, such as deicing salts used in North America, which have caused severe deck deteriorations resulting from steel corrosion[1]. Koch et al. (2002)[2] conducted a study on the corrosion costs for the Federal Highway Administration (FHWA), showing that an annual direct cost of corrosion for highway bridges is estimated to be $8.3 billion, consisting of $3.8 billion for the annual cost to replace structurally deficient bridges, $2.0 billion for maintenance of concrete bridge decks, $2.0 billion for maintenance of concrete substructures, and $0.5 billion for maintenance painting of steel bridges[2]. Life-cycle analysis estimates that indirect costs can be ten times greater than the direct cost of corrosion[2]. In this regard, resolving the steel corrosion problem in the bridge decks can not only extend the bridge service life, but also save dollars on the maintenance, repair, and rehabilitation.

In the past years, glass fiber reinforced polymer (GFRP) reinforcements have been recommended as a substitute to steel reinforcement due to its non-metallic characteristics[3]. In 2009, the American Association of State Highway and Transportation Officials (AASHTO) published the *LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings*[4] (noted as "AASHTO design guide" hereinafter), which is specifically for bridge deck application. Also, the American Concrete Institute published the ACI 440.1R-06, "G*uide for the Design and Construction of Structural Concrete Reinforced with FRP Bars"*, which has been widely used as a design reference in practice. Note that ACI recently update the ACI 440.1R-06 (2006)[3] to the ACI 440.1R-15 (2015)[5]. To date, GFRP bars have been successfully used in a number of demonstration bridge deck projects in the US and Canada[6,7]. However, the wide use of GFRP bars in concrete bridge decks has been hindered by concerns, such as the higher initial material costs of GFRP bars in contrast to steel reinforcements[8]. Therefore, it is necessary to conduct a comprehensive study on the costs analysis of GFRP reinforcements in bridge decks.

2. DESIGN OF GFRP BAR REINFORCED CONCRETE DECK PER AASHTO DESIGN GUIDE SPECIFICATIONS

The AASHTO design guide[4] and the ACI design guides[3,5] are quite similar in nature in terms of design method. For this specific research, only the AASHTO design guide[4] was used for deck designs. The following section summarized the deck design philosophy and design procedure in the AASHTO design guide[4].

For GFRP reinforced concrete, both over-reinforced section ($\rho_f>\rho_{fb}$) and under-reinforced section ($\rho_f<\rho_{fb}$) are allowed[4], where ρ_f is the reinforcing ratio, while ρ_{fb} is the balanced ratio, as can be calculated as follows.

$$\rho_f = \frac{A_f}{b\cdot d}$$

$$\rho_{fb} = 0.85\cdot\beta_1\cdot\frac{f_c'}{f_{fd}}\cdot\frac{E_f\cdot\varepsilon_{cu}}{E_f\cdot\varepsilon_{cu}+f_{fd}} \qquad \text{(AASHTO 2.7.4.2-2[4])}$$

Where f_{fd}= GFRP design strength, which is the product of an environmental reduction factor and the GFRP guarenteed tensile strength, f_{fu}, as below.

$$f_{fd} = C_E \cdot f_{fu} \qquad \text{(AASHTO 2.6.1.2-1}^4\text{)}$$

Where C_E= environmental reduction factor. The AASHTO guide specifies C_E=0.8 and C_E=0.7 for concrete element non-exposed and exposed to the earth and weather, respectively[4].

For flexural design, when $\rho_f < \rho_{fb}$, the nominal flexural strength M_n is calculated with AASHTO Eq. 2.9.3.2.2-3.

$$M_n = A_f f_{fd} (d - \frac{\beta_1 c_b}{2}) \qquad \text{(AASHTO 2.9.3.2.2-3}^4\text{)}$$

$$c_b = (\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fd}}) \cdot d \qquad \text{(AASHTO 2.9.3.2.2-4}^4\text{)}$$

When $\rho_f > \rho_{fb}$, the nominal flexural strength M_n is calculated with AASHTO Eq. 2.9.3.2.2-1.

$$M_n = A_f f_f (d - \frac{a}{2}) \qquad \text{(AASHTO 2.9.3.2.2-1}^4\text{)}$$

Where "a" is the depth of equivalent rectangular stress block that can be calculated with AASHTO 2.9.3.2.2-2 below.

$$a = \frac{A_f \cdot f_f}{0.85 \cdot f_c^{'} \cdot b} \qquad \text{(AASHTO 2.9.3.2.2-2}^4\text{)}$$

f_f is the effective strength in GFRP bar at the strength limit state, which cannot exceed the GFRP design strength, as follows.

$$f_f = (\sqrt{\frac{(E_f \varepsilon_{cu})^2}{4} + \frac{0.85 \beta_1 f_c^{'}}{\rho_f} E_f \varepsilon_{cu}} - 0.5 E_f \varepsilon_{cu}) \leq f_{fd} \qquad \text{(AASHTO 2.9.3.1-1}^4\text{)}$$

In LRFD design approach, a resistance factor is specified and applied to the nominal flexural resistance for obtaining the factored flexural resistance. Depending the reinforcement ratio, different resistance factors, ϕ, are used to account for structural ductility, as shown in AASHTO Eq. 2.7.4.2-1.

$$\phi = \begin{cases} 0.55 & \text{for } \rho_f < \rho_{fb} \\ 0.3 + 0.25 \dfrac{\rho_f}{\rho_{fb}} & \text{for } \rho_{fb} < \rho_f < 1.4 \rho_{fb} \\ 0.65 & \text{for } \rho_f > 1.4 \rho_{fb} \end{cases} \qquad \text{(AASHTO 2.7.4.2-1}^4\text{)}$$

Thus, the factored flexure resistance can be obtained for the strength limit state, as follows.

$$M_r = \phi \cdot M_n \quad \text{(AASHTO 2.9.3.2.1-1[4])}$$

Due to the low stiffness of GFRP bar as compared to steel rebar, a check for the serviceability of GFRP RC elements shall be executed. To avoid creep rupture of GFRP bar under sustained loadings, or failure due to fatigue loading, the stress levels, f_{fs}, in GFRP bars are limited in the AASHTO design guide[4]. f_{fs} is recommended not exceeding 20% of the GFRP design strength, as shown in AASHTO Eq.2.7.3-1.

$$f_{fs} \leqq 0.2 f_{fd} \quad \text{(AASHTO 2.7.3-1[4])}$$

Where,

$$f_{fs} = \frac{n_f d(1-k)}{I_{cr}} M_s \quad \text{(AASHTO 2.7.3-2[4])}$$

$$k = (\sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f) \quad \text{(AASHTO 2.7.3-3[4])}$$

$$I_{cr} = \frac{1}{3} d^2 k^3 + n_f A_f d^2 (1-k)^2 \quad \text{(AASHTO 2.7.3-4)}$$

In AASHTO Eq. 2.7.3-2, M_s shall be calculated with the load combination at Fatigue or Service I limit states, which can be obtained from the AASHTO LRFD[9] Table 3.4.1-1.

In addition, the minimum requirement for flexural tensile reinforcement shall be checked with AASHTO Eq. 2.9.3.3-1, as follows.

$$A_{f,\min} \geq \max(0.16\sqrt{f_c^{'}};0.33)\frac{bd}{f_{fd}} \quad \text{(AASHTO 2.9.3.3-1[4])}$$

The maximum crack width shall also be checked in accordance with the AASHTO design guide, as shown in AASHTO Eq. 2.9.3.4-1 below.

$$w = 2\frac{f_{fs}}{E_f}\beta k_b \sqrt{d_c^2 + \frac{s^2}{4}} \leqq 0.02\text{in.} \quad \text{(AASHTO 2.9.3.4-1[4])}$$

In summary, the GFRP RC bridge decks shall be designed by satisfying the strength limit state, the maximum crack width, the minimum reinforcement requirements, and the creep/fatigue rupture limit[4]. Table 1 showed the AASHTO design requirements and the corresponding load combinations.

Table 1 Load combinations for different limit states

Limit states	AASHTO Requirements[4]	Load combinations[9]
Flexural resistance	$M_u < \phi M_n$	1.25DC+1.5 DW +1.75LL
Creep rupture	$f_{fs}<0.2f_{fd}$	1.0DC+1.0 DW +LL
Fatigue rupture	$f_{fs}<0.2f_{fd}$	0.75LL
maximum crack width requirements	w < 0.02 in.	1.0DC+1.0 DW +1.0LL
Minimum requirement for reinforcement	$A_{f,\min} \geq \max(0.16\sqrt{f_c^{'}};0.33)\frac{bd}{f_{fd}}$	NA

3. PARAMETRIC DESIGN OF GFRP RC DECK

Fig.1 showed a schematic diagram of deck slab reinforcements in a transverse section. The transverse bars are the main reinforcements in the deck, while the longitudinal reinforcements are shrinkage and temperature reinforcements. In this study, clear concrete covers of 1.0'' were used for both top and bottom GFRP bars.

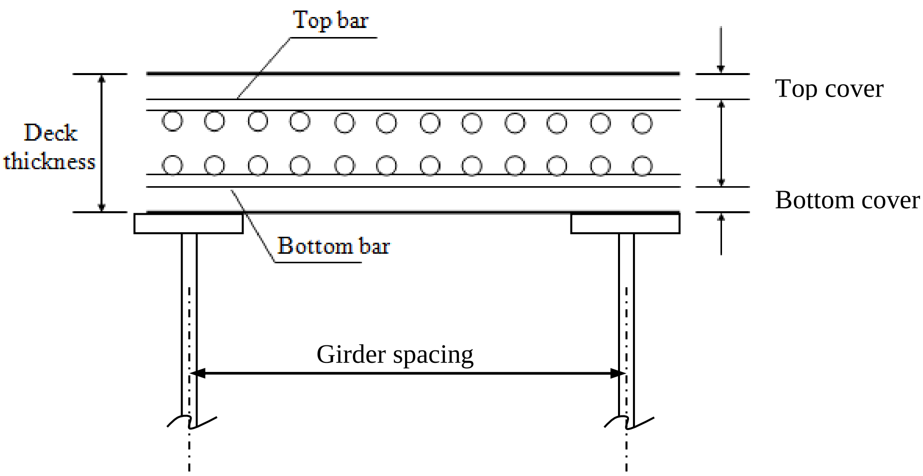


Fig. 1 Schematic diagram of deck slab reinforcements in a transverse section

The transverse reinforcements were designed by satisfying the strength and service limits as shown in Table 1. The area of longitudinal shrinkage and temperature reinforcements provided in each direction in each face of the concrete component can be computed by AASHTO Eq. 2.11.5-1[4].

$$\rho_{f,st} = 0.0018\frac{60ksi}{f_{fd}}\frac{E_s}{E_f} \qquad \text{(AASHTO Eq. 2.11.5-1}^4\text{)}$$

Where $\rho_{f,st}$ = the ratio of GFRP shrinkage and temperature reinforcement area to gross concrete area[4]; E_s=modulus of elasticity of steel reinforcement, ksi; E_f= modulus of elasticity of GFRP reinforcement, ksi. Note that $\rho_{f,st}$ need not exceed 0.0036[4].

3.1 DESIGN PARAMETERS

This research intended to investigate the material costs of GFRP RC decks by parametric study per AASHTO design guide[4]. Different deck thicknesses, girder spacings, and environmental reduction factors were considered in the study, as follows.

- Four different deck thicknesses: 7in., 8in., 9in., and 10in.
- Seven different girder spacings: 6ft, 7ft, 8ft, 9ft, 10ft, 11ft, and 12ft
- Two different environmental reduction factors: 0.7 and 0.8

<u>Dead loads:</u> Per AASHTO LRFD design specifications[9] and AASHTP GFRP design guide[4], dead loads (DL) for a GFRP bridge deck shall include deck itself, future wearing

surface, stay-in-place formwork, and barriers[4,9]. Table 2 shows the unit weights for each category.

Table 2 Unit weights for the deck dead loads[4,9]

	Concrete for deck	Barrier/each	stay-in-place formwork	future wearing surface
Unit weight	0.150 kcf	520plf	10psf	25psf

The above dead loads were treated as evenly distributed loadings on the deck [9,10]. Thus, $M=wL^2/10$ was used to calculated the positive and negative flexural moments in the deck[10]. Note that only interior deck is discussed in this study.

Live loads: Live load (LL) effect on bridge deck is determined by the AASHTO LRFD Specification Table A4-1, which has incorporated the multiple presence factors and dynamic load allowance[9].

Material Properties: Normal weight concrete with 4ksi compressive strength (28-day) was used in this study. The material properties of GFRP bars are taken from the ACI documents[3,5,11], as shown in Table 3.

Table 3 GFRP Bar Materials Properties[3,5,11]

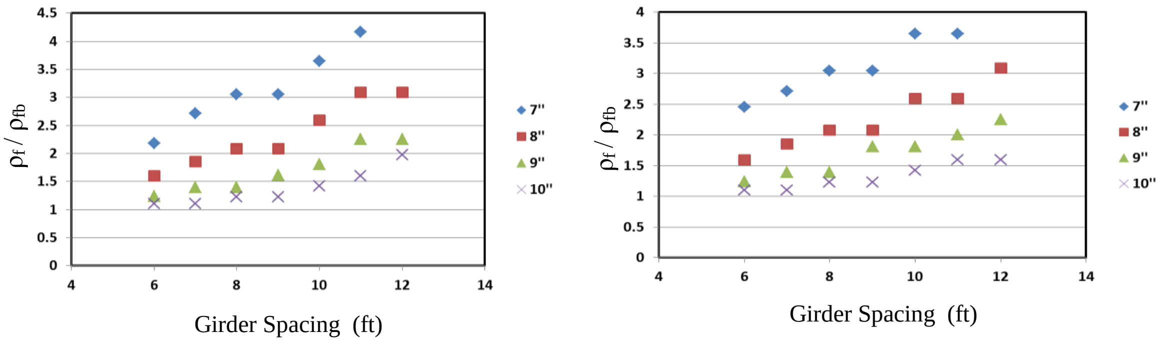
GFRP bar size	d_b (in.)	A_f (in.^{2})	f_{fu} (ksi)	E_f (ksi)
#4	0.500	0.20	100	5946.5
#5	0.625	0.31	95	5946.5
#6	0.750	0.44	90	5946.5
#7	0.875	0.60	85	5946.5
#8	1.000	0.79	80	5946.5
#9	1.128	1.00	75	5946.5

3.2 PARAMETRIC STUDY AND RESULTS DISCUSSIONS

With the aforementioned design procedure and design parameters, a total of 108 bridge decks were designed for different deck thicknesses, girder spacings and environmental reduction factors.

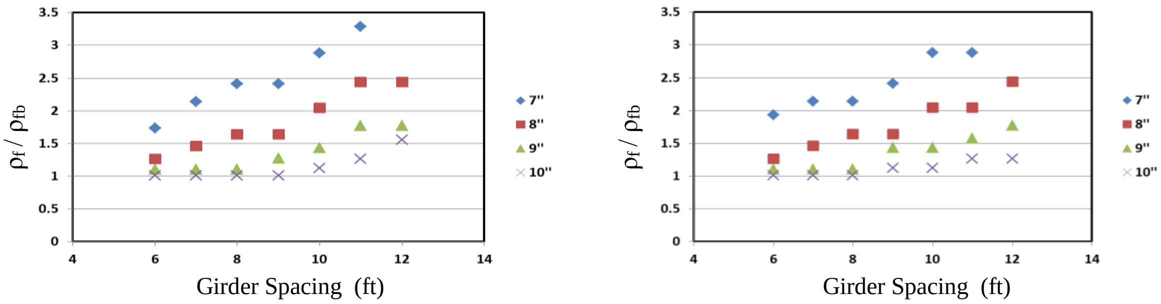
- The transverse bars were designed to meet the strength, creep/fatigue rupture, minimum reinforcement, and maximum crack width requirements. Note that over-design is avoided in this study, for example, the design gives a crack width slightly less than 0.02in if the maximum crack width governs, or the design gives a M_r slightly larger than M_u if the strength governs
- The longitudianl bars were designed based on AASHTO Eq. 2.11.5-1

Fig. 2 and Fig. 3 showed the data plots for ρ_f / ρ_{fb} for the transverse reinforcements with respect to the girder spacing for various deck thicknesses. The legends as shown on the figures represent the deck thicknesses.



(CE=0.8, top bar) (CE=0.8, bottom bar)

Fig. 2 ρ_f / ρ_{fb} with respect to girder spacing and deck thickness



(CE=0.7, top bar) (CE=0.7, bottom bar)

Fig. 3 ρ_f / ρ_{fb} with respect to girder spacing and deck thickness

As can be seen, over-reinforced sections (i.e., $\rho_f / \rho_{fb} > 1.0$) are required for all the cases being explored. It can be observed that, for each specific deck thickness, the ratio of ρ_f / ρ_{fb} increased as the girder spacing increased. However, for each specific girder spacing, the ratio of ρ_f / ρ_{fb} decreased as the deck thickness increased. It should be noted that over-reinforced designing generally satisfies the deflection limit[4].

With the above parametric study, the bar sizes and spacings for the top and bottom reinforcements in both directions were obtained, which were then used to calculate the materials costs. In this study, the cost analysis was focused on the materials costs only. For easy comparisons between different decks, the unit costs per sq. ft deck were calculated for the above 108 cases. Fig. 4 showed a schematic diagram of the reinforcement details in a unit deck, namely, one square foot deck. The reinforcements consists of top and bottom bars in the transverse direction (main reinforcement), and top and bottom bars in the longitudinal direction (shrinkage and temperature reinforcement).

Based on Fig. 4, the costs for the reinforcements in a unit deck can be calculated as follows:

$$UCR = UP_{tt}\frac{12in.}{S_{tt}}\times 1' + UP_{tb}\frac{12in.}{S_{tb}}\times 1' + UP_{lt}\frac{12in.}{S_{lt}}\times 1' + UP_{lb}\frac{12in.}{S_{lb}}\times 1' \qquad \text{(Eq. 1)}$$

Where, *UCR*= unit cost for reinforcements in a unit deck, \$/ft^2; UP_{tt}= unit price of transverse top bar, \$/ft; UP_{tb}= unit price of transverse bottom bar, \$/ft; UP_{lt}= unit price of longitudinal top bar, \$/ft; UP_{lb}= unit price of longitudinal bottom bar, \$/ft; S_{tt}= spacing between transverse top bars, in.; S_{tb}= spacing between transverse bottom bars, in.; S_{lt}= spacing between longitudinal top bars, in.; S_{lb}= spacing between longitudinal bottom bars, in.

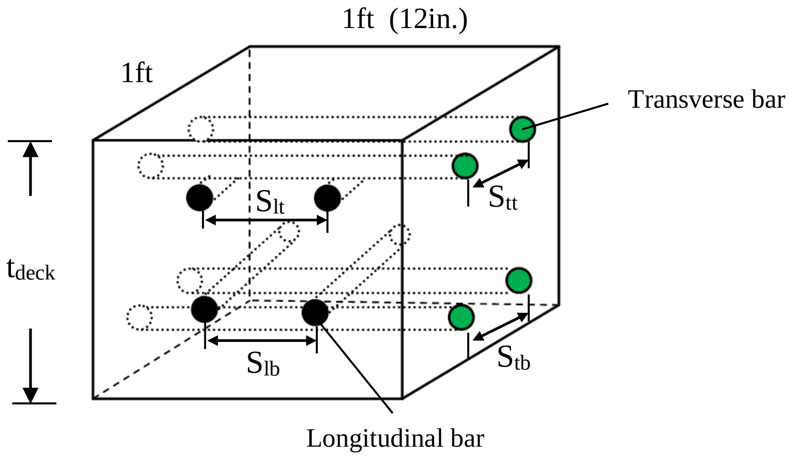


Fig. 4 Schematic diagram of the reinforcement details per unit deck

For the costs of concrete materials in a unit deck, it can be calculated as follows.

$$UCC = UP_{con}\left[1'\times 1'\times \frac{t_{deck}}{12\frac{in}{ft}} - \left(\frac{A_{tt}\frac{12in.}{S_{tt}} + A_{tb}\frac{12in.}{S_{tb}} + A_{lt}\frac{12in.}{S_{lt}} + A_{lb}\frac{12in.}{S_{lb}}}{144in.^2}\right)\times 1'\right] \qquad \text{(Eq. 2)}$$

Where, UCC= unit cost for concrete material in a unit deck ((\$/ft^2); UP_{con}= unit price for concrete, \$/ft^3; t_{deck}= deck thickness, in.; A_{tt}= cross section area of one transverse top bar, in.; A_{tb}= cross section area of one transverse bottom bar, in.; A_{lt}= cross section area of one longitudinal top bar, in.; A_{lb}= cross section area of one longitudinal bottom bar, in.

Thus, the total material costs of a unit deck (i.e., UC) can be determined as below.

$$UC = UCR + UCC \qquad \text{(Eq. 3)}$$

As can be seen, in order to calculate the deck unit costs, the reinforcement details shall be available. Also, the unit prices for GFRP bars and concrete materials shall be provided. Table 4 showed the unit prices of GFRP bars[12].

Table 4 Unit price of GFRP bars[12]

bar size	#3	#4	#5	#6	#7	#8	#9
\$/ft	0.520	0.721	1.165	1.520	1.865	2.610	3.365

Regarding the concrete unit price, the National Ready Mixed Concrete Association (NRMCA) reported a national average price of \$93/yd^3 (or \$3.44/ft^3) for concrete mix as of 2013[13]. With the above price information, the deck unit costs can be computed, as exampled below.

Benmokrane et al. (2007) reported a demonstration project of GFRP bars in a 9'' thick RC deck slab of the Morristown Bridge built in Vermont, U.S[7]. The reinforcement details were reported as follows: transverse top and bottom bars: #6@4''; longitudinal top and bottom bars: top #6@6''[7]. By referring to Table 4, the unit price for a #6 GFRP bar is \$1.520/ft. Assume the unit price for concrete is \$3.44/ft^3, then, UCR and UCC can be calculated as follows.

$$UCR = \frac{\$1.52}{ft} \times \frac{12in.}{4in.} \times 1' + \frac{\$1.52}{ft} \times \frac{12in.}{4in.} \times 1' + \frac{\$1.52}{ft} \times \frac{12in.}{6in.} \times 1' + \frac{\$1.52}{ft} \times \frac{12in.}{6in.} \times 1' = \$15.20$$

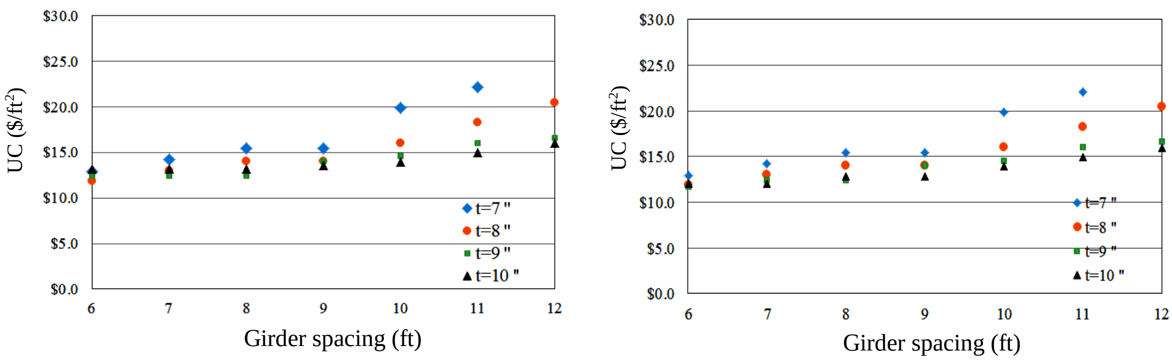
$$UCC = \frac{\$3.44}{ft^3}\left[1' \times 1' \times \frac{9in.}{12in./ft} - \left(0.44\frac{12}{4} + 0.44\frac{12}{4} + 0.44\frac{12}{6} + 0.44\frac{12}{6}\right) \times \frac{1'}{144in^2}\right] = \$2.48$$

The total unit cost for the concrete deck would be equal to \$17.68, as shown below:

$$UC = UCR + UCC = \$15.20 + \$2.48 = \$17.68$$

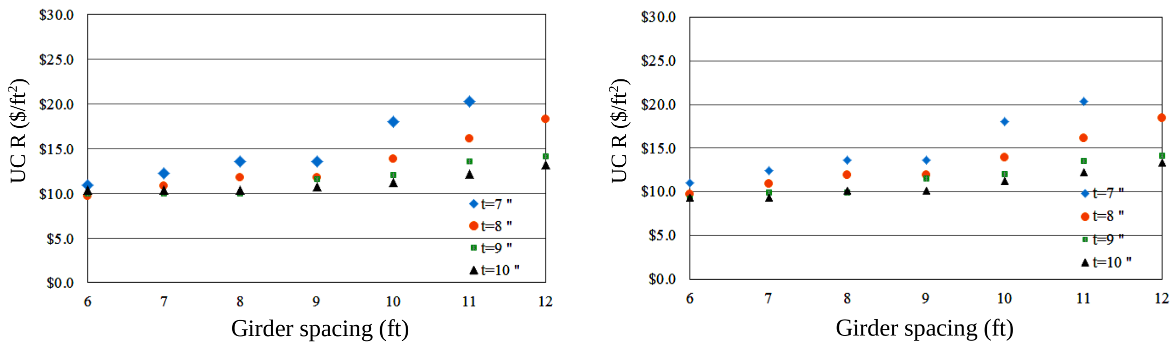
3.3 GFRP RC DECK UNIT COST CALCULATION

By repeating the above calculations for all the 108 cases explored in this study, the deck unit costs (UC) and costs for GFRP reinforcements (UCR) in a unit deck were calculated. Figure 5 showed the deck unit costs including the costs for both GFRP bars and concrete, while Figure 6 showed the costs for GFRP bars only.



(a) C_E=0.7 (b) C_E =0.8

Fig. 5 Unit costs of GFRP RC decks (GFRP+Concrete)



(a) C_E=0.7 (b) C_E =0.8

Fig. 6 Unit costs of GFRP RC decks (GFRP only)

As can be seen, the UC ranged from \$11.7/ft^2 to \$22.1/ft^2, while the UCR ranged from \$9.7/ft^2 to \$20.3/ft^2 for all the cases being explored. For each specific deck thickness, the unit cost increased as the girder spacing increased. For a specific girder spacing, the unit cost decreased as the deck thickness increased. In general, the unit cost increased slowly when the girder spacing is less than 10ft, after which it abruptly increased, especially for the 7’’ and 8’’ thick decks. When the girder spacing is larger than 10ft, the slab of 7’’ and 8’’ thickness are not recommended in practice. For decks spanning from 6ft to 10ft, the deck unit cost (i.e., UC) ranged from \$11.9/ft^2 to \$16.1/ft^2 for 8’’ decks, while it ranged from \$12.5/ft^2 to \$14.5/ft^2 for 9’’ and 10’’ decks. The differences of deck unit costs for 9’’ and 10’’ thick decks are very limited. It is also observed that the influence of environmental reduction factors on the deck unit costs is negligible.

In general, decks with lower girder spacings had less materials costs, however, it should be noted that increasing the girder spacing may reduce the number of girders which could pay off the increased deck costs. Thus, the overall costs of a bridge project shall be considered in the bridge preliminary design. In summary, the above results could be used by bridge engineers or decision makers in the process of bridge preliminary designs to achieve a cost-effective and sustainable design, or for the cost estimates of bridge deck replacement projects.

In order to justify the deck unit costs in Fig. 5, several real GFRP RC bridge decks were selected for comparison. Benmokrane et al. (2007) reported a performance evaluation of several GFRP RC deck slabs in Canada and the US, including Morristown Bridge (2002, USA), Cookshire-Eaton Bridge (2004, Canada), and Val-Alain Bridge (2004, Canada)[7].The GFRP reinforcement details were provided for these bridges, which were adopted to compute their deck unit costs (UC), as shown in Fig. 7.

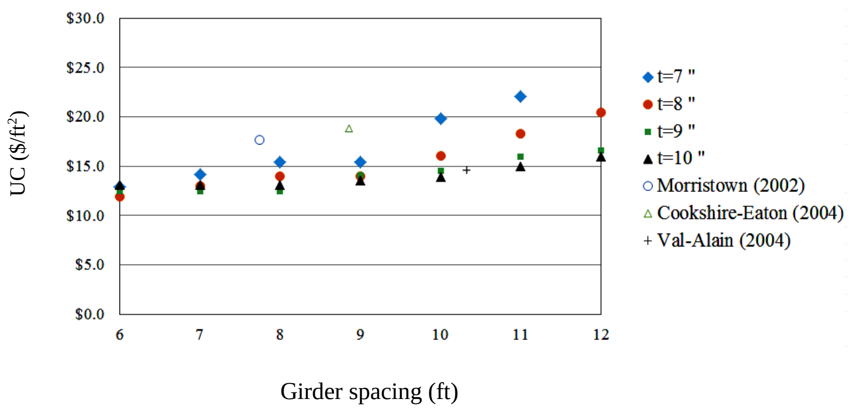


Fig. 7 Comparison of deck unit costs
(GFRP bar + Concrete)

As can be seen, the deck unit costs of the three bridges are in the same magnitude of that determined from the parametric study herein. The Morristown and Cookshire Bridges gave slightly higher costs, while the Val-Alain Bridge had a similar cost as that from this study. It should be noted that over-designs were intentionally avoided during the parametric study, which may explain why the deck unit costs from this paper were slightly lower than that of the Morristown and Cookshire Bridges.

Currently, epoxy steel reinforcing bars are popularly used in bridge decks with harsh environmental exposures, e.g. deicing salts. Assume the unit cost for epoxy steel bars is $0.7/lb [Ref.14], the material costs for epoxy steel RC bridge decks are computed, as shown in Figure 8.

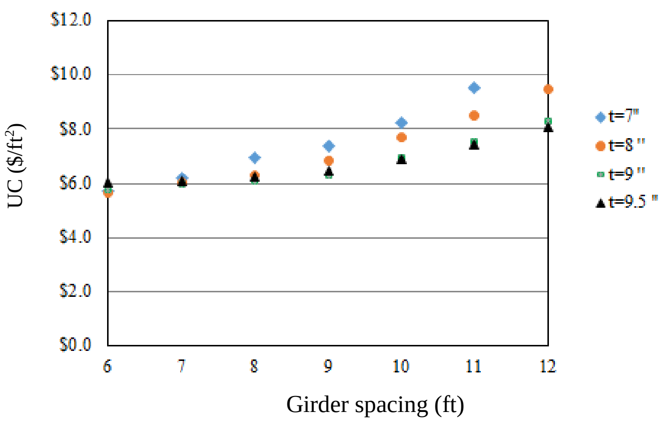


Fig. 8 Unit costs of epoxy steel RC decks
(Epoxy steel + Concrete)

As compared to the unit costs of GFRP RC bridge decks (see Figure 5), the unit costs of epoxy steel RC bridge decks are about half of the GFRP RC bridge decks. Since GFRP bars are non-corrosive, it could offer a lower life-cycle cost of GFRP RC deck as compared to epoxy steel ones. Also, GFRP bars are light in weight that could save dollars in construction labor costs. More research on life-cycle cost comparison between the steel decks and GFRP decks are under research by the authors.

4. CONCLUSIONS

In this paper, the materials costs for GFRP RC bridge decks were determined by a parametric study per AASHTO LFRD GFRP design guide specifications. Different deck thicknesses, girder spacings, and environmental reduction factors were considered. Based on the results in this study, several conclusions can be made:

- For a specific deck thickness, the GFRP deck unit cost increases as the girder spacing increases
- For a specific girder spacing, the GFRP deck unit cost decreases as the deck thickness increases
- The influence of environmental reduction factors (i.e. C_E=0.7, 0.8) on the deck unit costs is negligible
- The difference of deck unit cost for 9’’ and 10’’ thick deck is very limited
- For decks spanning from 6ft to 10ft, the deck unit cost (i.e., UC) ranged from \$11.9/ft^2 to \$16.1/ft^2 for 8’’ decks, from \$12.5/ft^2 to \$14.5/ft^2 for 9’’ and 10’’ ones, based on the reported unit prices of GFRP bars and concrete
- When the girder spacing is larger than 10ft, the 7’’ and 8’’ thick decks are not recommended

The above results could be useful for the bridge engineers in deck replacement projects or designs of new bridges with GFRP RC decks. More researches on the construction costs and life cycle costs of GFRP RC decks are undertaken by the author.

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