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GFRP Bar Reinforced Concrete Bridge Deck: Stress in GFRP Bar under Ultimate Design Loads

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Abstract: In current ACI 440.1R-06 design guideline, an environmental reduction factor (ERF) is specified to account for long-term durability of GFRP bar used in reinforced concrete structures. Such ERF factor is still lack of confidence to concrete industry prior to deliberate calibrations with in-field real time data. In this paper, a parametric study on the design of GFRP bar RC bridge deck per ACI 440 guideline is presented to investigate the stress level in GFRP bar under ultimate design loads per AASHTO LRFD Specifications. Results show that tensile stress in GFRP under ultimate design loads is always less than 25% of GFRP guaranteed tensile strength f^*_{fu}, which is much lower than the design strength per as specified in ACI 440 Guideline (i.e., 0.7 f^*_{fu}). It showed that GFRP bar RC bridge deck as designed in accordance with ACI 440 guideline could give sufficient safety margin.

Introduction

Modern bridges are mainly categorized into two types: steel bridge and steel-concrete bridge. Attentions have been heavily given to the steel corrosion problem that took place in either type bridge after certain period of field service, due to its significant impact on the structural serviceability as well as the public safety [1]. In 2001, the U.S. Federal Highway Administration (FHWA) released a 2-year study on the direct costs associated with metallic corrosion showing an overall annual $276 billion cost due to corrosion, among which the annual direct cost in infrastructure category is $22.6 billion [1]. In this regard, exploration of the corrosion prevention has been hotly carried out through various experimental studies and field tests in the past decades. Feasible solutions, such as cathodic protection method, epoxy-coated steel reinforcement, are asserted to be in-effective in corrosion control from the field application feedbacks. Therefore, in recent years fiber reinforced polymer (FRP) was recommended as an alternative due to its non-metallic characteristic. Among the available FRPs (i.e., CFRP, GFRP, AFRP), GFRP is more attractive to be used in concrete construction industry since it is more economical than others. To date, several design codes/guidelines for GFRP RC structures have already been published to provide guidance of appropriate use of GFRP bar in concrete structures [2,3,4]. Nevertheless, as a new technology, several issues are still needed to be justified, e.g., long-term durability under environmental exposure with or without sustained loading.

Recently, Huang (2010a, 2010b, 2011a) proposed an approach to determine more accurate ERF by taking the application temperature and humidity into account [5,6,7]. This matter was taken further by Huang (2011b) to investigate the combined effects of 20% sustained load and concrete environmental effects on GFRP durability in moist concrete, which showed a significant reduction in GFRP tensile strength [8]. In recognition of this, Huang (2011c; 2011d) looked into the design of GFRP RC bridge deck and revealed that serviceability (i.e., cracking) always control the design while the actual sustained stress in GFRP bar are in between 3-7%, which indicated GFRP bar could have much better durability in field bridge deck than that observed in lab with 20% sustained loading [9,10].

In order to have more in-depth understanding of the behavior of GFRP in concrete bridge deck, this paper aims to investigate the stress level in GFRP bar in RC bridge deck under ultimate design loads in accordance with AASHTO LRFD Design Specification, from which the research results could provide a good assessment on the GFRP long-term safety issue.

Design of GFRP Bar RC Bridge Deck

Figure 1 shows a typical section for a bridge superstructure. The loadings on bridge deck are mainly composed of dead load (DL) and traffic live load (LL) [11].

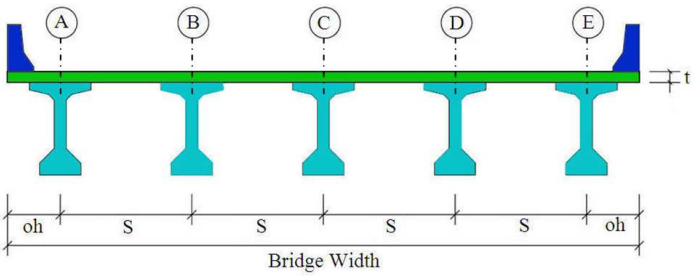


Fig. 1 Typical Bridge Cross Section

DL for a bridge deck typically includes deck own weight and non-structural superimposed attachments, such as barrier, future wearing surface. In practical design, superimposed loads are often distributed evenly in transverse direction for analysis purpose. Positive and negative flexural moment for interior deck under those distributed loads are conservatively calculated as to be $M=wL^2/10$. Assume that barrier w_b=520lb/ft (774 kg/m), stay-in-place form w_{SIP}=10psf (0.48MPa) and future wearing surface w_s=25psf (1.2MPa). Normal weight concrete (w_c=150pcf (2403kg/m^3)) with 28 day compressive strength of 27.6 MPa is used for the bridge deck. The LL effect on bridge deck is determined from AASHTO LRFD Specification Table A4-1, which has already taken the multiple presence factors and dynamic load allowance into account [11]. Table 1 summarizes the load combinations at different design phases.

Table 1 Load combinations [2,11]

Design phases	Load combination
Ultimate limit state	M_u: $1.25M_{DC}+1.5\ M_{DW}+1.75M_{LL}$
Cracking requirement	M_s: $1.0M_{DC}+1.0\ M_{DW}+1.0M_{LL}$
Check for the creep rupture	M_{sus}: $1.0M_{DC}+1.0\ M_{DW}+0.2M_{LL}$

Design Requirements per ACI 440.1R-06 Design Guideline

GFRP material is a kind of brittle material without any yielding characteristic.Therefore, a failure by concrte crushing is desired for the structural ductility of GFRP bar RC flexural elements. In ACI 440 guideline, over-reinforced design ($\rho_f > \rho_{fb}$) is recommended, though, the under-reinforced design ($\rho_f < \rho_{fb}$) is permitted as well. ρ_f is the reinforcing ratio, while ρ_{fb} is the balanced ratio as calculated by ACI 440 Eq. (8-3) [2].

$$\rho_{fb} = 0.85 \cdot \beta_1 \cdot \frac{f_c^{'}}{f_{fu}} \cdot \frac{E_f \cdot \varepsilon_{cu}}{E_f \cdot \varepsilon_{cu} + f_{fu}}$$

Nominal Moment Capacity

In order to calculate the nominal flexural moment, the tensile stress of the GFRP bar at the ultimate state of the RC beam needs to be calculated first with ACI 440 Eq. (8-4d) (when $\rho_f > \rho_{fb}$), as follows.

$$f_f = \left(\sqrt{\frac{(E_f\varepsilon_{cu})^2}{4} + \frac{0.85\beta_1 f_c^{'}}{\rho_f} E_f\varepsilon_{cu}} - 0.5E_f\varepsilon_{cu}\right)$$

Then, by using ACI 440.1R-06 Eq. (8-5), the nominal flexural strength M_n can be determined as below.

$$M_n = \rho_f f_f (1 - 0.59 \frac{\rho_f f_f}{f_c^{'}}) b d^2$$

To account for the structural ductility, strength reduction factor Φ shall be applied to nominal moment M_n depending on the reinforcement ratio, as specified in ACI 440.1R-06 Eq. (8-7) as below.

$$\Phi = 0.55 \qquad \rho_f < \rho_{fb}$$

$$\Phi = 0.3+0.25\ \rho_f / \rho_{fb} \qquad \rho_{fb} < \rho_f < 1.4\rho_{fb}$$

$$\Phi = 0.65 \qquad \rho_f >= 1.4\rho_{fb}$$

Cracking Requirement

The calculation of crack width for FRP bar reinforced concrete members is recommended in ACI 440.1R-06 Eq. (8-9), as below.

$$w = 2\frac{f_s}{E_f}\beta k_b \sqrt{d_c^2 + (\frac{s}{2})^2} \qquad \text{Where, } f_s = \frac{M_s}{A_f d(1 - k/3)}$$

Check for Creep Rupture

Sustained stress in GFRP bar resulted from the sustained load combination is recommended as of not exceeding 20% of GFRP design strength [2]. Stress in GFRP under sustained loadings could be calculated as follows.

$$f_{sus} = \frac{M_{sus}}{A_f d(1 - k/3)}$$

Design Assumptions

Bridge decks with slab thickness varying from 203 mm to 279 mm are designed per unit width for girder spacing at 1.829m, 2.438m, 3.048m and 3.658m. GFRP bars are spaced at 100 mm on centers. A 38mm concrete clear cover is assumed for both the top and bottom GFRP bar.

For GFRP bar, the material property varies from the manufacturers. In this study, properties for GFRP bar are assumed on the basis of ACI 440.1R-06 as shown in Table 2, where f^*_{fu} is the guarenteed tensile strength.

Table 2 GFRP Bar Materials Properties

GFRP bar size	d_b (mm)	A_f (mm^2)	f^*_{fu} (MPa)	E_f (GPa)
13	12.7	129	700	41
16	15.9	199	660	41
19	19.1	284	620	41
22	22.2	387	585	41
25	25.4	510	550	41
29	28.7	645	515	41

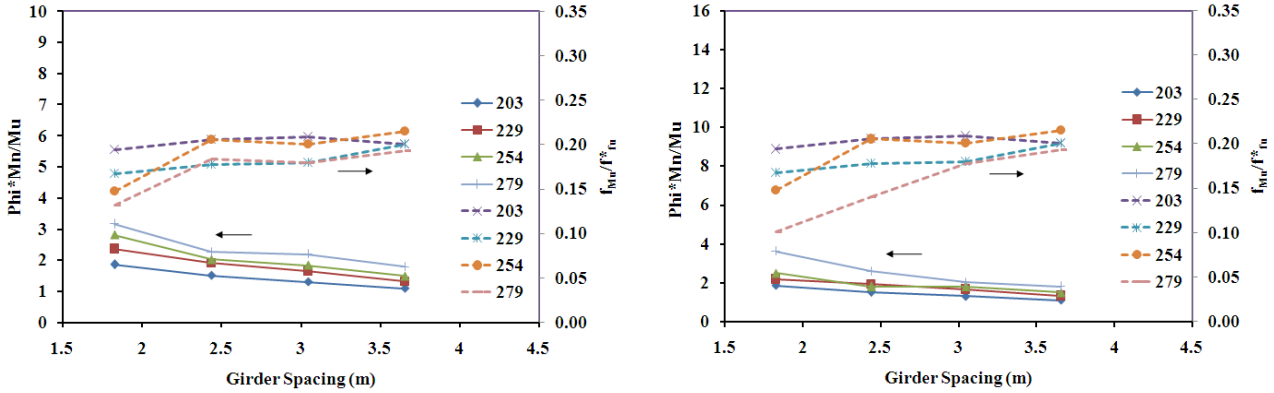
Per ACI 440 guideline, design stength of GFRP bar $f_{fu}=C_E f^*_{fu}$, where C_E is environmental reduction factor and is equal to 0.8 and 0.7 for applications not exposed and exposed, respectively, to weather and earth.

Stress Level of GFRP Bar in RC Bridge Decks

The stress level in GFRP under ultimate loads is calculated by taking the ratio of f_{Mu} / f^*_{fu}. Where f_{Mu} is determined as follows under assumption that concrete behavior elastically or nearly so.

$$f_{Mu} = \frac{M_u}{A_f d(1-k/3)}$$

Since top GFRP bars in bridge deck are more likely to be exposed to environmental attacks, stresses in top bars are investigated for both environmental reduction factors C_E= 0.8 and C_E= 0.7. Upon all the design requirements are met per ACI 440 design guideline, the values for flexural resistance (phi^*M_n), required strength (M_u), etc. for each case being studied are recorded for post-processing. Figure 2 shows the plots of GFRP stress level (f_{Mu}/f^*_{fu}) under ultimate design loads against different girder spacings for each deck thickness.



(a) C_E=0.8; Top bar (b) C_E=0.7; Top bar

Fig. 2 Stress level in GFRP bar in RC bridge deck under ultimate design loads

As can be seen, the stress in GFRP bar in RC bridge deck with different thickness, i.e., 203mm, 229mm, 254mm and 259mm, varies from approx. 0.10 f^*_{fu} to 0.25 f^*_{fu} depending on the girder spacing, regardless of the values for C_E . In general, narrow girder spacing gives lower stress level. This observation could be reflected by the ratio of flexural resistance (phi^*M_n) to the required strength (M_u) as shown in Fig. 2. It can be seen that the deck is more "over-reinforced" at smaller girder spacing which results in lower stress in GFRP bar. Per ACI 440 design guideline, environmental reduction factor C_E is recommended as of 0.8 and 0.7 for applications not exposed and exposed, respectively, to weather and earth. Therefore, the minimum design strength of GFRP bar should be equal to 0.7 f^*_{fu}, which is much higher than the stress of GFRP bar determined hereinabove under ultimate design loads. Hence, GFRP bar RC bridge deck could have sufficient safety margin during its targeted service lifetime, i.e. 75 years, if the design requirements per ACI 440 guideline are implemented.

Summary and Conclusions

A parametric study on the GFRP bar RC bridge decks is conducted per ACI 440.1R-06 design guideline to investigate the stress level in GFRP bar under ultimate design loads. On the basis of the study results in this paper, the following conclusions could be drawn:

- Difference of stress in the top GFRP bar in RC bridge deck from different C_E is limited.
- Stress levels in GFRP bar under ultimate design loads are approx. 10%-25% of GFRP guaranteed tensile strength depending on the deck thickness and girder spacing.
- For the application of GFRP bars to RC bridge deck, current ACI 440 design guideline could give sufficient safety margins.

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