EVALUATION OF FRP REBAR REINFORCED CONCRETE BRIDGE DECK SUPERSTRUCTURE

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Abstract

Discussed in this paper is a theoretical evaluation of Fiber Reinforced Polymer (FRP) rebar concrete bridge deck design options coupled with long-term field performance monitoring of the constructed bridge. The theoretical evaluation of design options are based on numerical simulations of structural behavior to provide a predictive capability that is able to assess the composite structural response and long term behavior including effects of thermal factors and response to impact loading. The computational design is complemented by experimental evaluation and monitoring tools. The monitoring sensors include utilizing long-gage fiber optic sensors to give insight into the structural response of both the concrete decks and composite steel beams. The long-gage fiber-optic sensors capture measurements across the entire length of the instrumented components offering high resolution and accuracy as well as long-term stability. The intent of this work is for the simulation results to enable integration of Non-Destructive Evaluation (NDE) methods for in-service evaluation of concrete structures with computational interpretation of health signals collected from critical locations of the bridge superstructure.

Introduction

With many of today’s bridge superstructures deteriorating at such a rapid rate, there is a need to develop new superstructures that can last longer and stand up to the effects of both greater loading and harsh environmental conditions. In recent decades; civil engineers have started to implement Fiber Reinforced Polymer (FRP) rebar in bridge superstructures to replace common steel reinforcement. A material once used primarily in the automobile and aerospace industries is now used for many bridge structures around the world. FRP rebar is commonly found in the form of glass, carbon, aramid, and hybrid (carbon and glass mix) to make up what is called the fibers of the material. The fibers are pulled thru a resin dye, by the pultrusion process, to bind the fibers together and allow them to jointly carry the load. With the strength of two to three times that of steel, FRP usually meets the ultimate strength requirements of a bridge deck. However, while FRP has a much higher ultimate strength than steel, it possesses a much smaller modulus of elasticity which leads to a reduction in the stiffness of the material. This stiffness reduction causes greater deflection in the structure which leads to induced cracking. The various types of FRP rebar have different properties that in turn affect the behavior with the interaction between the resin and concrete matrix.

Because the process of using FRP in bridge structures is relatively new, there are still some uncertainties as to the interaction between the two materials. As a result, monitoring of the superstructure is desirable and the use of embedded long-gage fiber-optic sensors offer the opportunity to monitor continuously, accurately and over a long period after the deployment of the structure. Like FRP material, fiber-optic sensors are relatively new in their implementation into civil structures. The many advantages of using fiber-optic sensors include their small size which allows them to be embedded in concrete providing precise readings for such measurements, strain (though measurement of displacement) and temperature. They are also durable and immune from any electromagnetic interference. With their high sensitivity, many of the sensors can be combined along a single fiber and routed to a single point to reduce the number of fibers needed (Merzbacher et al., 1995).

The remainder of this paper will focus on a bridge design undertaken by the authors in White Creek New York, which implements FRP reinforced concrete deck and FOS located at critical points throughout the superstructure to monitor the performance of the new structure. The design considerations included bridge geometry, loading, concrete deck crack width, main FRP reinforcement bond strength, thermal effects on the interaction between concrete and FRP for temperature reinforcement and placement of fiber-optic sensors.
Preliminary Design

The Bridge in consideration for this paper is located in White Creek New York on county road 68 crossing Little White Creek. The existing bridge is a simple span structure spanning approximately 34.5 feet in length and with an effective deck width of 28 feet. The structure is skewed at an angle of 29 degrees. The current timber deck sits on seven W24X76 steel girders spaced at 4 ft and are integrated into the abutments. For the replacement bridge, the new deck is to be designed using Carbon Fiber Reinforced Polymer (CFRP) rebar with normal strength concrete (NSC) while keeping the same bridge dimensions. Spaced 6 feet center to center, W24 steel girder sections will be used to keep a similar profile to the original structure due to the clearance requirements between the water and the bottom flange of the girder. HS25 truck loading is the design loading used in the calculations as specified by Washington County Department of Public Works.

Serviceability and Crack Control

Due to the CFRP rebar’s high ultimate strength value and low modulus of elasticity, serviceability, instead of strength, requirements control the design of the bridge deck. This in turn produces a deck which is more flexible and thus either the deflection or the crack width controls the design. In the calculations of the moments taken by the main reinforcement, the live load moments were calculated using AASHTO 3.24.3.1 multiplied by 30 percent for impact effect. This impact factor helps control any excessive vibrations caused from moving loads, as well as any increased stresses above static loads (Taly, 1998). The dead load moments taken into consideration were from the slab and the guide railing load (200 lb/ft). Due to crack width control, a recommended maximum width of 0.01 inch set forth by American Concrete Institute (ACI) 340-350 family of codes on bridge and other structures exposed to corrosive environments, is the design limit when considering spacing layout for the main reinforcement. To calculate the crack width of reinforced concrete the Faza-Gangarao (1993) equation is used:

\[
W = \frac{2A f_{cfc} f_r}{\mu_{cfc} E_{cfc} \pi D}
\]  
(Eq.1)

where:
- \( W \) = Crack width
- \( A \) = Area of concrete around bar in tension
- \( f_{cfc} \) = Carbon Fiber Composite (CFC) rebar stress
- \( f_r \) = Rupture strength of concrete
- \( E_{cfc} \) = Young’s modulus of CFC
- \( D \) = Rebar Diameter

By equating the first moment of concrete area in compression about the neutral axis (N.A), to the first moment of CFC area multiplied by modular ratio \( n = E_{cfc}/E_{concrete} \) as shown in Figure 1 and equation. 2, the stress in the rebar can be determined.

\[
\frac{b(kd)^2}{2} + nA_{cfc} (kd) - nA_{cfc} d = 0
\]  
(Eq.2)

Figure 1: Slab design effective cross-section with concrete above NA in compression and rebar in tension
There are many different solutions based on different design parameters. The number of bars, thickness of slab, size and location of bars, bond strength between the concrete and rebar as well as the concrete strength all play a key role in the determination of the maximum crack width. Bar spacing is a critical factor in any bridge deck design. In evaluating this particular structure, bar spacing ranging from 4 to 6 inches center to center for slab thicknesses of 9 to 12 inches were studied. Figure 2 shows the crack widths for different designs considered with a concrete compressive strength of 4,000 psi and bond strength of 220 psi. Figure 2 shows that when there is a decrease in the spacing of the rebar, the crack width is smaller. Likewise when the slab thickness increases, the crack width reduces. A key parameter, bond strength, is not well known and a conservative value of 220 psi is used for the design.

![Figure 2: Crack width based on thickness, and bar spacing for 220 psi bond strength in Normal Strength Concrete (4000 psi)](image)

**Bond Strength**

Perhaps the greatest uncertainty associated with a FRP rebar bridge deck is the bond strength between the concrete and CFRP rebar due to its relatively new application in the structural world. When designing to reduce the crack width in the concrete, the bond strength is among the key factors. The number of studies relating the bond strength between concrete and composite rebar are limited. With no absolute value for bond strength, it is difficult to select a value that will be appropriate for the design; thus, due to this uncertainty, a conservative value is selected. The main factors that contribute to bond strength include: concrete strength, bar diameter, mechanical properties and surface deformations and texture of the rebar. As the concrete strength increases so does the bond strength, whereas an increase in bar diameter decreases bond strength. It is noted that research performed by Cosenza et al. (1997) determined that deformed (ribbed or indented) FRP and steel rebar contain similar ultimate bond strengths, however when composite rebar is coated with sand instead of braided deformations, it possesses greater bond strength and improved stiffness.
Thermal Effects

While the primary reinforcement will carry the live and dead loads of this deck, the temperature reinforcement will also see loading from changes in temperature. In a traditional steel reinforced concrete deck, when the concrete is under intense heat or cold conditions, it will expand or contract respectively. Because steel and concrete have approximately the same coefficients of thermal expansion ($5.5 \times 10^{-6}/^\circ F$), they expand or contract together, creating minimal stresses at the interface. The thermal expansion coefficient of CFRP rebar is near zero, which means that it is not affected by temperature changes, i.e., it will not elongate or shorten due to heat or cold. Meanwhile, the concrete wants to expand or contract under the same temperature changes, thus producing stresses at the interface which cause internal forces in both materials. Figure 3 along with Equation 3 illustrate the behavior of these materials when subjected to changes in temperature.

![Diagram of forces acting on concrete and composite rebar due to temperature change]

**Figure 3: Forces acting on concrete and composite rebar due to decrease in temperature**

\[
(F \frac{L}{AE} + \alpha L \Delta T)_{CFR} = (F \frac{L}{AE} + \alpha L \Delta T)_{concrete}
\]

(Eq. 3)

where:
- $A$ = Area of CFC or concrete
- $E$ = Modulus of Elasticity
- $L$ = Length
- $F$ = Force in CFC or Concrete (equal and opposite)
- $\alpha$ = Coefficient of Thermal Expansion
- $\Delta T$ = Change in Temperature

The compatibility equation (Eq.3) is known as the Element Force-Temperature-Deformation equation (Craig, 1999). A temperature increase will cause the concrete to expand but the rebar is unaffected and will pull the concrete back in compression. On the other hand when subjected to a temperature cooling, the force exerted in the concrete becomes positive. This is because when there is a decrease in temperature, the concrete will want to shrink however the CFRP rebar will not allow it to, creating tensile forces in the concrete. Thus the temperature effects need to be taken into account to assure that the stress in the concrete does not exceed the rupture strength of the concrete.

The bond strength at the interface of the concrete and CFRP rebar is also affected by temperature. Studies (Katz et al., 1999; Juska et al., 2001) show that at very high temperatures, the properties of the composite rebar change. The resin matrix of the material becomes weaker as the temperature approaches the glass transition temperature ($T_g$), the point where the material becomes soft and viscous, reducing the bond strength considerably. However, because these temperatures are outside the realm of temperatures in this geographical area, this was not a major consideration in the evaluation of this bridge deck.

Sensor Placement and Structural Health Monitoring

Structural health monitoring of new bridges is critical to understanding the long-term operational cost and safety of the structures – this is particularly important when new and innovative construction materials and methodologies are employed. Knowledge of the bridge's health, load bearing capacity, and remaining life is the primary goal of any strategy of structural health monitoring. Understanding the condition of bridges is critical to the structural integrity and cost effectiveness of not only the structures themselves but also the transportation system as a whole. Employing new and innovative bridge construction materials and methodologies advance the state of practice in bridge engineering. However, an objective evaluation of the bridge status is needed in order to gain insight into the operational performance of the new bridge. In the long term, a properly designed structural health
monitoring system can not only verify the design parameters used but can also be used for life cycle monitoring. In turn the monitoring system can significantly reduce money spent on maintenance, repair and replacement as the years pass. The key is to have a combination of local and global monitoring systems.

Local sensors would be used for detailed monitoring the performance of key components of the new bridge. The method to be used in this bridge is to utilize long-gage fiber optic sensors to give insight into the structural response of both the concrete deck and steel beams, including measurements of pure deformation (average strain). The SOFO long-gage fiber optic measurement system offered by SMARTEC SA (Smartec SA, 2005) is considered as a viable system for measurements of deck strains. The SOFO deformation sensors essentially consist of an active fiber optic zone with a reference and measurement fiber that responds to changes in distance between the anchored ends (Fig. 4). The sensors are embeddable, allowing the measurement of deformation normal to the deck surface that may be produced by both axial (mainly due to temperature changes) and bending stresses. For the current research, fiber-optic sensors will be tied to the FRP rebar and embedded in the concrete deck. These sensors are connected to a reading unit placed on the structure that collects the data and sends it to a PC for further analysis.

![Fig. 4: Smartec SOFO standard deformation sensor (Smartec SA, 2005)](image)

Because they are long-gage, the sensors capture measurements across the entire length of the instrumented component and do not simply give a point reading. Being fiber optic, they offer high resolution and accuracy as well as excellent long-term stability. These gages have proven very successful in civil engineering applications because of their ease of installation and ruggedness, whether they are surface mounted or embedded in concrete. In order to perform the structural monitoring of various bridge components, it is necessary to place sensors only at critical locations of interest. The placement of sensors effectively divides up the bridge into discrete components which are monitored as a whole.

The fiber optic sensors measure the absolute deformation of each sensor in each segment, $\Delta L_i$. The average strain in each segment is taken as the ratio of measured deformation and the length of the sensor ($\varepsilon_i = \Delta L_i / L_i$). Once the strain, $\varepsilon_i$, in each segment is known, then the load in the segment is also known ($P_i = \varepsilon_i \cdot [AE_i]$) assuming that the composite $AE$ for the individual segments is known. For concrete decks, a composite $AE$ can be taken as $AE = A_cE_c + A_rE_r$, (where subscript ‘c’ refers to concrete and subscript ‘r’ refers to rebar) using the Rule of Mixtures. With the load ($P_i$) and deformation ($\varepsilon_i$) of each segment determined, the load transfer relationship of the component can then be calculated.

The fiber-optic sensors may also be mounted on the steel composite girders externally. The girders for this structure are integrated into the abutment creating a slightly different moment demand than the traditional simply supported structure. In an integral abutment design, the girders will experience end moments that are not seen in a simply supported case. The beams are restricted from moving horizontally and vertically as well as rotating. Due to this fixed condition, there are moments generated at the ends of the girders which may cause crack formations at the bridge approaches. Thus sensors may also be placed at or near the ends of the bridge to monitor any affects of the fixed condition.

**Conclusions**

Fiber Reinforced Polymer (FRP) rebar is a relatively new method of construction in today’s structures. In a superstructure bridge deck with FRP reinforcement serviceability (deflection) controls the design, therefore a recommended maximum crack width set by ACI of 0.01 inches is the limiting factor. This crack width is controlled by many aspects including: concrete strength, bar size and location, slab thickness, rebar properties, and bond
strength at the interface. Because this design method is new, there are a number of uncertainties in associated design parameters, including bond strength, and thus conservative values tend to be used for design. The use of long-gage fiber optic sensors can provide insight into the validity of the design parameters used by capturing measurements across the entire length of the instrumented components.

References


American Concrete Institute 340 and 350 families of codes.


Smartec SA, http://www.smartec.ch