ASCE

# Durability Assessment of 15- to 20-Year-Old GFRP Bars Extracted from Bridges in the US. I: Selected Bridges, Bar Extraction, and Concrete Assessment

Vanessa Benzecry[1]; Ali F. Al-Khafaji[2]; Rudy T. Haluza[3]; Charles E. Bakis, A.M.ASCE[4]; John J. Myers, F.ASCE[5]; and Antonio Nanni, F.ASCE[6]

**Abstract:** Glass fiber–reinforced polymer (GFRP) bars have been used in concrete structures as an alternative to steel bars due to their noncorrosive behavior. However, due to the lack of full understanding of long-term performance, their use as internal reinforcement is still limited. To evaluate the durability of in-service GFRP bars under natural exposure, a collaborative project including four organizations investigated the conditions of GFRP bars and their surrounding concrete from bridges with 15–20 years of service. The aim of Part I of a two-paper series is to describe the bridge structures, methods of extraction, and the results of concrete testing, wheras Part II focuses on GFRP bar performance. The extracted bars were tested for physical, mechanical, and chemical properties, and the surrounding concrete was evaluated for chloride penetration, pH, and carbonation depth at the level of reinforcement. Results showed that carbonation and chloride may have reached the depth of the GFRP bars. This paper discusses the process of extraction of the bars, including the location and type of the selected bridge, and the concrete tests performed in terms of procedure, results, and observations. **DOI: 10.1061/(ASCE)CC.1943-5614.0001110.** *© 2021 American Society of Civil Engineers.*

**Author keywords:** Bridges; Concrete durability; Concrete tests; Glass fiber–reinforced polymer; Reinforced concrete.

## Introduction

The use of fiber-reinforced polymer (FRP) bars in civil infrastructure has emerged due to their high strength, corrosion resistance, and low density of the material (Van Den Einde et al. 2003). The first use of FRP bars in a vehicular bridge in the United States occurred in 1996, where glass FRP (GFRP) bars were used in the concrete deck of the McKinleyville Bridge in West Virginia (Kumar et al. 1997). In the early 2000s, influenced by infrastructure degradation, research and government agencies implemented GFRP bars in the deck of several bridges with the objective to eliminate corrosion and increase durability.

In addition to traffic loads, bridge decks are commonly exposed to thermal effects (e.g., high temperatures and freeze–thaw cycles), which are known to influence the durability of concrete and steel reinforcement. The main cause of deterioration in reinforced concrete (RC) bridges is corrosion of steel reinforcement (Zhou et al. 2015) induced by carbonation and chlorides that are derived from the application of deicing salts (Cady and Weyers 1983). Carbonation reduces the pH of concrete, and as a result, it weakens the passivity of embedded steel bars (Chen et al. 2018). Chloride penetration can cause chemical reactions with components of the cement paste and trigger corrosion of steel reinforcement when ions reach the bar level (Xi et al. 2018). Consequently, due to their noncorrosive properties, GFRP bars have emerged as an alternative to steel reinforcement.

Although proven to be noncorrosive, GFRP bars may be susceptible to degradation by a variety of factors, including high temperature, moisture absorption, and alkaline environments (Al-Salloum et al. 2013). A variety of studies in the literature focuses on the durability of GFRP bars, and some studies suggest that GFRP bars are negatively affected by concrete due to the high alkalinity of its pore solution (Dejke and Tepfers 2001; Chen et al. 2006). The alkaline solution can chemically attack the glass fibers and damage the fiber–resin interface due to the growth of hydration products (Micelli and Nanni 2004; Robert et al. 2009). To determine the durability conditions of the GFRP bars, laboratory tests to evaluate the physical, chemical, and mechanical properties of the bars are generally performed. These tests are discussed in detail in Part II of this two-paper series (Al-Khafaji et al. 2020).

Many researchers have recorded a loss in the properties of the bars when exposed to an alkaline environment. For instance, Davalos et al. (2012) recorded the tensile strength reduction of 40% for GFRP bars embedded into the concrete after 120 days of exposure to water at 60°C, and Benmokrane et al. (2017) recorded between 13% and 21% of reduction in interlaminar shear strength for GFRP bars after

[1]Ph.D. Candidate, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Miami, 1251 Memorial Dr., Coral Gables, FL 33146 (corresponding author). Email: v.benzecry@umiami.edu

[2]Ph.D. Candidate, Dept. of Civil, Architectural and Environmental Engineering, Missouri Univ. of Science and Technology, 1401 N. Pine St., Rolla, MO 65409. Email: aa7n6@mst.edu

[3]Ph.D. Candidate, Dept. of Engineering Science and Mechanics, Pennsylvania State Univ., 212 Earth-Engineering Science Bldg., University Park, PA 16802. ORCID: https://orcid.org/0000-0002-8455-9738. Email: rth5095@psu.edu

[4]Distinguished Professor, Dept. of Engineering Science and Mechanics, Pennsylvania State Univ., 212 Earth-Engineering Science Bldg., University Park, PA 16802. ORCID: https://orcid.org/0000-0002-6834-5318. Email: cbakis@psu.edu

[5]Professor, Dept. of Civil, Architectural and Environmental Engineering, Missouri Univ. of Science and Technology, 1401 N. Pine St., Rolla, MO 65409. Email: jmyers@mst.edu

[6]Professor and Chair, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Miami, 1251 Memorial Dr., Coral Gables, FL 33146. ORCID: https://orcid.org/0000-0003-2678-9268. Email: nanni@miami.edu

Note. This manuscript was submitted on June 16, 2020; approved on October 30, 2020; published online on January 23, 2021. Discussion period open until June 23, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Composites for Construction***, © ASCE, ISSN 1090-0268.

**Table 1.** Information from the bridges

| Bridge | Rain, mm (in.) | Snow, mm (in.) | Sunny days | Estimated freeze–thaw cycle duration (days) | Year built | Bar type | Bar location | Concrete cover, mm (in.) |
|---|---|---|---|---|---|---|---|---|
| Bettendorf | 940 (37) | 711 (28) | 205 | 90 | 2003 | N/A | Top | 63.5 (2.5) |
| Cuyahoga | 991 (39) | 1,473 (58) | 163 | 90 | 2003 | E-glass fiber and vinyl-ester resin | Top and bottom | 63.5 (2.5) |
| Gills Creek | 1,143 (45) | 279 (11) | 214 | 75 | 2003 | E-glass and vinyl-ester | Top | 57 (2.2) |
| McKinleyville | 991 (39) | 584 (23) | 162 | 75 | 1996 | E-glass and polyester. Type 1: sand coated. Type 2: nonsand coated | Top and bottom | 44.5 (1.8) |
| O'Fallon | 432 (17) | 1,524 (60) | 245 | 200 | 2003 | N/A | Top and bottom | 38 (1.5) |
| Roger's Creek | 1,168 (46) | 203 (8) | 190 | 80 | 1997 | N/A | Top | 63.5 (2.5) |
| Salem Ave. | 1,016 (40) | 432 (17) | 176 | 90 | 1999 | N/A | Top | 70 (2.8) |
| Sierrita de la Cruz Creek | 533 (21) | 381 (15) | 259 | 110 | 2000 | E-glass and vinyl-ester | Top | N/A |
| Southview | 1,168 (46) | 330 (13) | 193 | 90 | 2004 | N/A | Top and bottom | N/A |
| Thayer Road | 991 (39) | 584 (23) | 184 | 95 | 2004 | E-glass and vinyl-ester | Top | 38 (1.5) |
| Walker Box | 1,168 (46) | 330 (13) | 193 | 90 | 1999 | E-glass and polyester | N/A | N/A |

5,000 h exposed to a simulated concrete alkaline solution at 60°C. Most of the available literature on the durability of GFRP bars, however, is based on accelerated laboratory tests and analytical models that may present conditions harsher than field exposure (Benmokrane et al. 2002; Chen et al. 2007; Robert et al. 2009). As an exception, Mufti et al. (2007) analyzed the chemical composition of GFRP bars removed from bridges in Canada using laboratory techniques, such as scanning electron microscopy and energy-dispersive X-ray, optical microscopy, differential scanning calorimetry, and infrared spectroscopy. It was concluded that the GFRP bars suffered no chemical changes during 5–8 years of field exposure. Consequently, additional field investigation of the long-term durability of GFRP bars is needed for the widespread use of this material.

To provide new information on the durability of in-service GFRP bars with field exposures, a collaborative project including the University of Miami (UM), Penn State University (PSU), Missouri University of Science &Technology (M S&T), and Owens Corning Composites (OC) investigated in 2017–2018 the conditions of concrete and GFRP bars extracted from 11 bridges with 15–20 years of service in several regions of the United States. The bridges were exposed to aggressive environmental conditions including deicing salts, wet and dry cycles, and freeze–thaw cycles. Concrete cores of 102 mm diameter, most containing pieces of GFRP bars, were extracted from the bridges.

As the long-term durability of the GFRP bars is related to the bar environment (Nkurunziza et al. 2005), evaluating the condition of the concrete is essential. Thus, in the current investigation, chloride penetration, pH, and carbonation depth were evaluated to describe and further detail the environment surrounding the bars. The GFRP bars were evaluated for fiber content, moisture content, water absorption, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), glass transition temperature (TA), short bar shear (SBS), modified tensile test, and constituent volume contents by image analysis (CVC). Part I of this two-part series describes the 11 bridges selected for evaluation, the core locations, the procedure for acquiring specimens for testing, and the results from the concrete tests. Part II contains the test procedures and results from the bar tests.

## Selected Bridges

Eleven bridges with 15–20 years of service are included in the investigation from geographically dispersed and environmentally varying locations across the United States. Nine of the investigated bridges contain GFRP bars in the deck, while two bridges contain GFRP at other locations. Descriptions of the bridges and locations of the extracted cores are given in this section. Table 1 presents a summary of the most relevant information from the bridges to assist in the interpretation of the test results.

### Bettendorf Bridge (Iowa)

The Bettendorf Bridge was completed in May 2003. It was built using funds provided through the Federal Highway Administration's (FHWA) Innovative Bridge Research and Construction (IBRC) program. The bridge extends 53rd Avenue over Crow Creek in Bettendorf, Iowa, and is exposed to approximately 90 freeze–thaw cycles per year (Haley 2011). It is a 52.9-m (173.6-ft) three-span bridge, as shown in Fig. S1 (Wipf et al. 2006). The bridge was the widest FRP-reinforced concrete deck at the time of construction, measuring 30 m (98.7 ft) wide. It was also the first FRP bridge deck in the United States to use composite action with prestressed concrete girders (Lee et al. 2009).

The concrete deck system is made of three different material combinations. The west span deck is constructed with cast-in-place (CIP) concrete reinforced with epoxy-coated steel, the middle span deck is made of CIP concrete reinforced with GFRP bars, and the east deck is made of pultruded FRP panels (Wipf et al. 2006). The GFRP bars used in the middle span deck were placed on the top mat (Nanni and Faza 2002). Six concrete cores were extracted from the middle span bridge deck, as shown in Fig. S2.

### Cuyahoga County Bridge (Ohio 2)

Miles Road Bridge No. 178, also known as the Cuyahoga County Bridge, was a rehabilitation project completed in October 2003. This project was funded by the FHWA's Transportation Equity Act for the 21st Century—IBRC Grant, administered through the Ohio Department of Transportation. This rehabilitation project consisted of rebuilding the bridge deck with GFRP-reinforced concrete and also implemented a monitoring system to collect strain, temperature, and deflection data (Eitel 2005).

The Cuyahoga County Bridge is located in the Southeastern Lake Erie snow belt in Ohio and is exposed to approximately 90 freeze–thaw cycles per year (Haley 2011) and heavy application of deicing salts. The bridge consists of two spans of 13.7-m (45-ft)-long and an 11.6-m (38-ft)-wide deck (Eitel 2005). The original bridge was built in 1956 and consisted of five steel girders with a 229-mm-thick (9-in.) steel-reinforced concrete deck with a 76-mm (3-in.) asphalt overlay. This bridge has the first deck on a multispan vehicular bridge to be entirely reinforced with GFRP bars. The GFRP bars used in this bridge were made of E-glass fibers and vinyl-ester resin (Eitel 2005).

The Cuyahoga County Bridge is shown in Fig. S3. The plan and section views are shown in Fig. S4. Eight concrete cores were extracted from the Cuyahoga County Bridge deck, as shown in Fig. S5.

### Gills Creek Bridge (Virginia)

Gills Creek Route 668 Bridge was completed in July 2003. This bridge was part of a project to investigate the durability and effectiveness of GFRP bar reinforcement in concrete decks. It was a project between the Virginia Department of Transportation, the Virginia Transportation Research Council, and the Virginia Polytechnic Institute and State University, funded by the FHWA IBRC program (Phillips et al. 2005).

The bridge is located in Franklin County, Virginia, and is exposed to approximately 75 freeze–thaw cycles per year (Haley 2011). It is a 52-m (170-ft) three-span steel girder bridge that crosses over Gills Creek, as shown in Fig. S6. The bridge has a width of 9.2 m (30.3 ft), and its Spans A, B, and C measure 13.7 m (45 ft), 24.4 m (80 ft), and 13.7 m (45 ft), respectively. The reinforced concrete bridge deck has a minimum thickness of 203 mm (8 in.) between the girders and 229 mm (9 in.) at the overhang, as shown in Fig. S7 (Phillips et al. 2005).

The bridge deck span A was reinforced with M19 (#6) GFRP bars on the top mat and epoxy-coated M13 and M19 (#4 and #6) steel bars on the bottom mat, as shown in Fig. S7. The remaining two spans were reinforced with epoxy-coated steel bars (Phillips et al. 2005). The GFRP bars were made of E-glass fibers and vinyl-ester resin. Ten concrete cores were extracted from Gills Creek Bridge deck span A, as shown in Fig. S8.

### McKinleyville Bridge (West Virginia)

The McKinleyville Bridge was built in 1996. It was the first FRP-reinforced concrete vehicular bridge in the United States (Kumar et al. 1997). The project was developed through the Constructed Facilities Center—West Virginia University in cooperation with FHWA and the West Virginia Department of Transportation—Division of Highways (Shekar et al. 2003).

The bridge crosses Buffalo Creek in Brooke County (District 6), West Virginia, and is exposed to approximately 75 freeze–thaw cycles per year (Haley 2011). It consists of three spans with a maximum span length of 22.3 m (73 ft), as shown in Fig. S9, having a total length of 54.9 m (180 ft) and a deck width of 9 m (29.5 ft). The bridge was designed for HS-25 loading, and it is estimated that 150 vehicles cross the bridge per day over the two lanes. The bridge deck is 229-mm (9-in.) CIP concrete with two types of GFRP bars: one type was made of E-glass fibers with polyester resin, and the other type was sand coated made of E-glass fibers with isophthalic unsaturated polyester resin (Shekar et al. 2003). The GFRP bars were used as top and bottom reinforcement. Six concrete cores were extracted from the McKinleyville Bridge deck, as shown in Fig. S10; however, only five concrete cores were received.

### O'Fallon Park Bridge (Colorado)

The O'Fallon Park Bridge, shown in Fig. S11, was completed in 2003. This bridge was part of a project to investigate the feasibility of the use of FRP in highway bridge decks. The construction was developed through a collaboration between the City and County of Denver, the Colorado Department of Transportation (CDOT), and FHWA, and it was funded by the FHWA IBRC program (Camata and Shing 2005). This bridge is located west of the city of Denver and is exposed to approximately 200 freeze–thaw cycles per year (Haley 2011).

O'Fallon Park Bridge has a total length of 13.34 m (43.75 ft) and a width of 4.95 m (16.25 ft). The bridge deck is a GFRP deck supported by five reinforced concrete risers built over an arch. The arch is made of concrete reinforced with GFRP bars, with M19 (#6) GFRP bars at the top mat and M22 (#7) GFRP bars at the bottom mat. The bridge is mainly used for pedestrian traffic and occasional small vehicles, but it was designed for H-25-44 loading for maintenance and/or emergency vehicles (Camata and Shing 2005). Six concrete cores were extracted from the bottom of the bridge arch, near the waterline, as shown in Fig. S12. Some cores were broken and resulted in multiple pieces, and, therefore, 10 cores were recorded in the inventory.

### Roger's Creek (US-460) (Kentucky)

Roger's Creek Bridge was built in 1997. This bridge is the US-460 Bridge over Roger's Creek in Bourbon County, Kentucky, and is exposed to approximately 80 freeze–thaw cycles per year (Haley 2011). Its superstructure consists of a deck over simply supported prestressed concrete girders for a length of 11.1 m (36.5 ft) and a width of 11 m (36 ft), as shown in Fig. S13. The bridge deck is partially reinforced with GFRP and steel bars. The GFRP reinforcing bars are placed as the top mat over an area that measures $2.7 \times 4.7$ m ($9 \times 15.5$ ft) and runs over three supporting girders (Harik et al. 2004). Six concrete cores were extracted from Roger's Creek Bridge deck, as shown in Fig. S14.

### Salem Ave. Bridge (Ohio 1)

The Salem Ave. Bridge was a retrofit project completed in 1999. This project was part of a study to understand the effectiveness of replacing concrete decks with FRP deck panels through the IBRC program (Project OH-98-05) and the Ohio Department of Transportation (Mertz et al. 2003). The Salem Ave. Bridge consists of a pair of parallel bridges located on State Route 49 in Dayton, Ohio, and exposed to approximately 90 freeze–thaw cycles per year (Haley 2011). The bridges are 207.3 m (680 ft) long and cross the Great Miami River, as shown in Fig. S15. The bridges consist of built-up steel stringers with five spans of 39.6 m (130 ft), 41.8 m (137 ft), 44.2 m (145 ft), 41.8 m (137 ft), and 39.6 m (130 ft). The deck of the original bridge, built in 1952, was retrofitted with four different FRP deck systems for one of the twin bridges, while the second bridge was retrofitted with only one deck system (FRP-4) (Reising et al. 2001).

The investigated bridge was retrofitted with an FRP-4 deck system, which is a hybrid system that consists of a concrete deck poured over pultruded GFRP panels reinforced with GFRP tubular sections and additional GFRP reinforcing bars (Reising et al. 2001). The GFRP bars were placed at the top longitudinally and transversally. Six concrete cores were extracted from the bridge deck, as shown in Fig. S16; however, only five concrete cores were received.



J. Compos. Constr., 2021, 25(2): 04021007

### Sierrita de la Cruz Creek Bridge (Texas)

The Sierrita de la Cruz Creek Bridge was a replacement project completed in 2000. The bridge, shown in Fig. S17, is located on State Highway 1061, approximately 50 km (30 mi) northwest of Amarillo, Texas (Gooranorimi and Nanni 2017), and is exposed to approximately 110 freeze–thaw cycles per year (Haley 2011). The replacement was performed due to the bridge being structurally deteriorated and obsolete. The new design consists of seven spans, 24.1 m (79 ft) long and 14.3 m (45 ft) wide, supported by six prestressed concrete Texas Type *C* I-beams (Phelan et al. 2003).

The replacement project included M16 (#5) and M19 (#6) GFRP reinforcing bars made of E-glass fibers and vinyl-ester resin. The GFRP bars were placed in the top mat of the deck of the two southernmost spans (Spans 6 and 7). The other five spans used epoxy-coated steel bars, including Spans 1 and 2, which are symmetric with Spans 6 and 7, as shown in Fig. S18. Witness bars were also embedded in the bridge overhang during construction; these were M16 (#5) GFRP bars with 15.9 mm (0.63 in.) of cover (Gooranorimi et al. 2016). Five concrete cores and three witness bars were extracted from the overhang of the Sierrita de la Cruz Creek Bridge deck. The cores were extracted from locations near the bridge guardrail, as shown in Fig. S19. Fig. S20 shows the location of the extracted witness bars.

### Southview Bridge (Missouri 2)

The Southview Bridge was an expansion project completed in 2004. The bridge is located in Rolla, Missouri, over Carter Creek and is exposed to approximately 90 freeze–thaw cycles per year (Haley 2011). The bridge has an overall length of 12 m (40 ft), as shown in Fig. S21. It was originally a one-lane bridge using conventional four-cell steel RC box culverts. It went through a widening in 2004, which included the construction of an additional lane and a sidewalk (Holdener et al. 2008). As a demonstration project to apply the use of FRP bars and tendons, the new deck was made of FRP prestressed/reinforced concrete, including M19 (#6) GFRP bars at the top and bottom mat, M13 (#4) GFRP bars for temperature and shrinkage, and M10 (#3) CFRP bars as the prestressing tendons, as shown in Fig. S22. The 254-mm (10-in.)-thick concrete deck is continuous on three conventional RC walls as for the existing structure (Fico et al. 2006). The extension of the deck plus a 2-m (6.6-ft)-wide conventional RC sidewalk on the opposite side extended the overall width of the bridge from 3.9 m (12.8 ft) to 11.9 m (39.0 ft). Ten concrete cores were extracted from the Southview Bridge deck, but only two cores were available for this specific study. Fig. S23 shows the location of the extracted cores.

### Thayer Road Bridge (Indiana)

The Thayer Road Bridge replacement project was completed in 2004. The bridge is located on Thayer Rd. crossing I-65 Newton County, Indiana, and is exposed to approximately 95 freeze–thaw cycles per year (Haley 2011). The bridge, shown in Fig. S24, was designed for 60-km/h (40-mph) traffic of cars and trucks and consists of five spans of 12.1 m (39.8 ft), 19.4 m (63.5 ft), 23.7 m (77.8 ft), 19.4 m (63.5 ft), and 12.2 m (40 ft), respectively, summing up to a total length of 86.6 m (284 ft) with a 10.5-m (34.5-ft)-wide deck. The project was a collaboration of the Indiana Department of Transportation and Purdue University and involved the replacement of a concrete deck. The deck is supported by seven wide-flange steel girders and is reinforced with GFRP bars on the top mat and epoxy-coated steel on the bottom mat, as shown in Fig. S25 (Frosch and Pay 2006). The GFRP bars were made of E-glass fibers and vinyl-ester resin. Six concrete cores were extracted from the Thayer Road Bridge deck, as shown in Fig. S26.

**Fig. 1.** Gills Creek Bridge core sample.

### Walker Box Culvert Bridge (Missouri 1)

The Walker Box Culvert Bridge replacement project was completed in 1999. The bridge is located on Walker Avenue in Rolla, Missouri (Gooranorimi et al. 2017), and is exposed to approximately 90 freeze–thaw cycles per year (Haley 2011). The original bridge became unsafe to operate due to excessive corrosion of the steel pipes (Nanni 2001). To replace the original bridge, GFRP bars made of E-glass fibers and polyester resin were used to reinforce the concrete box culvert. The new bridge, shown in Fig. S27, is 11 m (36 ft) wide, consisting of 18 box culverts that are 1.50 × 1.50 m (4.92 × 4.92 ft) with a thickness of 150 mm (5.9 in.) (Wang et al. 2018). The RC boxes were entirely reinforced with M6 (#2) GFRP bars prebent and cut to size by the manufacturer (Alkhrdaji and Nanni 2001). Six concrete cores were extracted from the Walker Box Culvert Bridge. The extracted cores were taken from the bottom of the two culverts, as shown in Fig. S28.

## Sample Extraction

To extract the concrete cores from the bridges, a barrel of 102 mm (4 in.) in diameter was used. The targeted locations for core extraction were, when possible, areas with cracks or signs of environmental deterioration. No nondestructive method for identifying bar location is yet available. As a result, some concrete cores had no GFRP bars, and others had GFRP bars shorter than 51 mm (2 in.). An extracted core with a short bar is shown in Fig. 1.

## Sample Inventory and Distribution

Upon receipt of the concrete cores at UM, an inventory of all specimens was compiled. The concrete cores were measured and approximate GFRP bar lengths and concrete cover were determined. The core specimens are identified using a two-part identification scheme NN_C*x*, where NN = state abbreviation of the bridge's location; and C*x* = the *x*th core number.

For the GFRP bars, a three-part identification scheme is used, NN_C*x*_B*x*, where NN = abbreviation of the bridge's location; C*x* = *x*th core number; and B*x* = *x*th bar number. In cases where more than one specimen from a certain bar was tested, an extra (-*x*) suffix is used to identify the specimen number.

Once the inventory was compiled at UM, the cores were placed in sealed plastic bags for storage until testing or distribution to other laboratories. Consequently, a plan for carrying out the concrete and GFRP tests among the project partners was developed. Most concrete tests were performed at UM, while the GFRP tests were divided based on the testing capabilities of each laboratory.

## Challenges and Solutions

One challenge in testing was the relatively small number of specimens that could be tested due to the limited number of cores that could be extracted, the small length of bars embedded in the cores, and the difficulty of locating GFRP bars prior to drilling the cores. The extracted bars, with the exception of witness bars extracted from the Sierrita de la Cruz Creek Bridge, had a maximum length of 95 mm (3.75 in.). The aim of the investigation was to run three repetitions for each material property. For GFRP tests that required bar lengths of 25 mm (1 in.) or less, the bars were cut to the required dimension so that a minimum of three test replicates could be achieved with one bar. For other tests, however, in order to achieve a minimum of three replicates per test type, multiple bars of the same size extracted from the same bridge were assumed to have had identical exposure conditions.

Another challenge during this study was the lack of data on most of the materials at the time of installation. No information on the original concrete mix designs could be obtained. Thus, no comparison was made between the concrete quality before and after in-service exposure. In addition to the lack of information on concrete mixtures, the cores were not sealed hermetically upon extraction from the bridges, which may have affected some concrete properties such as moisture content.

## Concrete Tests Procedure

### Chloride Penetration Depth

Chloride penetration is a major concern in concrete structures with steel reinforcement because it can accelerate corrosion. GFRP bars, on the other hand, have been reported to be highly resistant to chloride ions (Zhou et al. 2018). To evaluate the chloride penetration depth of the extracted concrete cores and understand how chloride presence may have influenced the durability of reinforcement, the calorimetric method using silver nitrate ($AgNO_3$) was employed. According to Meck and Sirivivatnanon (2003), this method was popularized by Otsuki et al. (1992) and Collepardi (1995). In this method, a 0.1 N $AgNO_3$ solution is sprayed on a freshly broken concrete surface, where chloride ions are present. The silver ions react with the chloride ions and form a white precipitate, and in areas containing few or entirely free of chloride ions, a brown precipitate forms (Yuan et al. 2008). Additionally, there is a distinguished boundary between the white and brown regions.

Although this method can be influenced by many factors such as the sprayed volume and concentration of $AgNO_3$ solution, which can result in high variability (Meck and Sirivivatnanon 2003; He et al. 2012), chloride penetration resistance varies significantly with concrete mixture. For instance, increasing fly ash and fly ash fineness and reducing the water-to-binder ratio can increase the chloride penetration resistance (Chindaprasirt et al. 2007).

To determine the presence of chlorides in the concrete cores and to observe if chlorides reached the depth of the GFRP bars, the concrete cores were split to expose a fresh surface and compressed air was used to remove dust particles from this surface. The silver nitrate solution was sprayed onto the surface and allowed to dry. The chloride penetration depth was measured with a ruler, as the lighter color indicates areas of chloride penetration, and a darker color indicates areas not affected by chlorides. At least three exposed surfaces were tested for samples from each bridge.

### Carbonation Depth

Carbon dioxide that penetrates the surface of concrete can react with alkaline components in the cement paste. The chemical reaction of $Ca(OH)_2$ and calcium–silicate–hydrate (C–S–H) with $CO_2$ forms $CaCO_3$ and water (Chang and Chen 2006). As a result, the pH value of the pore solution decreases, destroying the passivity of embedded steel reinforcement bars (Chang and Chen 2006). For GFRP bars, on the other hand, carbonated concrete was found to be less aggressive than noncarbonated concrete (Rajput and Sharma 2017). The most common method to determine the depth of carbonation is by using a phenolphthalein indicator solution. This method was carried out by spraying the solution over a fresh-cut concrete surface and then monitoring the change in surface color. The solution mixture has 1% phenolphthalein, 70% ethyl-alcohol, and 29% distilled water per volume ratio. The concrete turns shades of purple when pH is above 9 and remains colorless when pH is below 9 (Chang and Chen 2006).

### pH

The pH of ordinary portland cement concrete is generally between 12.5 and 13, but deterioration mechanisms such as chloride ingress and carbonation can decrease the pH of concrete (Behnood et al. 2016). Behnood et al. (2016) show that even with nearly zero concentration of chloride ions near the bars, a concrete pH level of less than 11 in the area of the steel bars can initiate corrosion. Although a low pH is detrimental for steel, some researchers suggest that the high pH of concrete can reduce the durability of GFRP bars (Chen et al. 2006).

To measure the pH of the concrete from the selected bridges, cores from each bridge were tested at three or more different locations. Two different procedures were used: one according to Grubb et al. (2007) and the other one by using a rainbow indicator. The Grubb et al. (2007) procedure was used in cores from eight bridges to determine the pH at various depths. Cores were split and then drilled to collect 5 g (77 grains) of concrete dust for each test. Split cores were drilled at three varying depths from 13 mm (0.5 in.) below the surface of the concrete to 13 mm (0.5 in.) above where the GFRP bar had been located. The concrete dust was then mixed with 10 mL (0.34 oz.) of fresh distilled water at a temperature of 23°C (73.4°F). The mixture was stirred for 30-s intervals three times over 7 minutes and then filtered through No. 40 filter paper. A calibrated pH probe was then used to read the pH of the mixture.

The rainbow indicator procedure was used in the evaluation of specimens from three bridges: Roger's Creek, Thayer Road, and McKinleyville Bridges. This procedure is very simple and consists of spraying a rainbow indicator (Germann Instruments, Evanston, Illinois) on a fresh concrete surface. The concrete cores were cut to expose a fresh surface, dust was removed with



J. Compos. Constr., 2021, 25(2): 04021007

**Table 2.** Concrete tests results

| Bridge | Average Chloride penetration, mm (in.) | Highest Chloride penetration observed, mm (in.) | Highest observed carbonation depth, mm (in.) | Average pH |
|---|---|---|---|---|
| Bettendorf | 19 (0.8) | 25 (1.0) | 19 (0.8) | 12.1 |
| Cuyahoga | 38 (1.5) | 64 (2.5) | 25 (1.0) | 12.2 |
| Gills Creek | 8 (0.3) | 13 (0.5) | 51 (2.0) | 12.2 |
| McKinleyville | 0 | 0 | 0 | 10 |
| O'Fallon Park | 13 (0.5) | 13 (0.5) | 38 (1.5) | 12.1 |
| Roger's Creek | 0 | 0 | 0 | 10 |
| Salem Ave. | 38 (1.5) | 64 (2.5) | 76 (3.0) | 11.6 |
| Sierrita de la Cruz Creek | 0 | 0 | 38 (1.5) | 11.5 |
| Southview | 0 | 0 | 0 | 11.5 |
| Thayer Road | 0 | 0 | 0 | 12 |
| Walker Box Culver | 0 | 0 | 0 | 11.5 |

compressed air, and the indicator was sprayed on the concrete surface. Once the indicator dried, changes in color could be observed on the concrete surface. This color indicated the pH value according to the color pallet.

## Concrete Tests Results

### Chloride Penetration Depth

Chloride penetration testing was performed in 10 of the 11 bridges (excluding Sierrita de la Cruz Creek). The difference in the color of the concrete due to silver nitrate was difficult to identify in some of the specimens. For instance, for the McKinleyville, Roger's Creek, Thayer Road, Southview, and Walker Box Bridges, no chloride penetration was observed. All other bridges presented chloride penetration, varying from approximately 6 mm (0.25 in.) to 64 mm (2.5 in.). The worst case of chloride penetration, approximately 64 mm (2.5 in.), was observed in concrete specimens from the Cuyahoga and Salem Ave. Bridges. Table 2 shows the average and the highest chloride penetrations for each bridge.

The chloride penetration observed in the extracted cores appeared to be due to the deicing salt applications, as four out of the five bridges that showed chloride presence had the highest amount of snow per year. In terms of its effect on the extracted GFRP bars, the Cuyahoga Bridge that presented chloride penetration reaching the level of reinforcement also showed a significant reduction in shear strength and a glass transition temperature ($T_g$) lower than required by the latest ASTM standard (ASTM 7957/D7957M, ASTM 2017) (Al-Khafaji et al. 2020). A reduction in the shear strength would be indicative of fiber–matrix interface degradation (Benmokrane et al. 2015), and a reduction in $T_g$ would be indicative of resin degradation. However, these results could also be due to other factors such as the high moisture absorption rate (1.52%) observed for the Cuyahoga Bridge (Al-Khafaji et al. 2020).

In this study, the lack of information on the concrete mixes does not allow a comparison between results. To understand the obtained results, values from other studies in the literature can be considered. In the study of Xi et al. (2018), for example, the bridge decks exposed to deicing salts presented chloride ingress at a depth of 50 mm (2 in.). However, the percentage of chloride by concrete weight can be minor and possibly not detected when using silver nitrate solution. The chloride content at 50 mm appears to increase with the concrete age. For example, for a bridge deck with 14 years of service, chloride concentrations of 0.061% at a depth of 50 mm (2 in.) were observed, while for a bridge deck of 21 years of service, 0.065% chloride penetration was observed at the same depth (Xi et al. 2018).

The observed chloride penetration using silver nitrate may indicate a high enough level of chloride content to break the passive layer of the steel reinforcement. The observed chloride penetration at 64 mm (2.5 in.) would have reached the reinforcement and cause corrosion initiation for steel reinforcement.

### Carbonation Depth

Concrete cores from all 11 bridges were tested for carbonation depth. Most specimens presented some carbonation near the surface, but others such as McKinleyville, Roger's Creek, Southview, Thayer Road, and Walker Culvert presented no carbonation at all. This could be due to the degree of relative humidity of the specimens. According to the study of Chang and Chen (2006), phenolphthalein indicator changes color (to white) when the area is fully carbonated (the level of carbonation is above 50%), which happens when the relative humidity is above 50%. Carbonation above 50% presents an opportunity for corrosion of steel reinforcement. Steel reinforcement would be unlikely to corrode in the bridges with less than 50% carbonation.

Some bridges presented significant depth of carbonation reaching into the central volume of the concrete core and possibly reaching the reinforcement. These results were consistent with the results from Sagues et al. (1997), where 18 bridges with 16–59 years of service were investigated for carbonation. Sixteen of the 18 bridges studied by Sagues et al. (1997) presented carbonation. The average carbonation depth was approximately 10 mm (0.4 in.) and some bridges presented carbonation depth as high as 50 mm (2 in.).

Table 2 shows the highest carbonation depth observed for each bridge. All bridges that presented the chloride penetration also presented the carbonation. The bridges that presented from the highest to the lowest carbonation depth are Salem Ave., Gills Creek, O'Fallon Park, Sierrita de la Cruz Creek, Cuyahoga, and Bettendorf. Half of these bridges also presented GFRP bars with a high volume of water retention. For some bridges, O'Fallon Park, Salem Ave., and Sierrita de la Cruz Creek, the depth of carbonation may have reached the reinforcement. Although carbonated concrete is considered a less aggressive environment than noncarbonated concrete, these bridges still presented a reduction in the GFRP bar shear strength. The bar physical and chemical composition, on the other hand, presented no signs of deterioration from SEM and EDS tests (Al-Khafaji et al. 2020). If these bridges had been reinforced with steel bars, the observed carbonation depth could have resulted in corrosion initiation.

### pH

All 11 bridges were tested for pH. Out of the 11 bridges, eight were tested according to the procedure from Grubb et al (2007), and three bridges were tested using the rainbow indicator.

The bridges presented pH extreme values as low as 7 and as high as 13 with an average between 10 and 12. The lowest average pH value observed was 10 for the Roger's Creek and McKinleyville Bridges, the two oldest bridges in the investigation. On the other hand, the highest average pH was 12.2 for Cuyahoga and Gills Creek Bridges. The pH values observed during this test were consistent with the values obtained by Grubb et al. (2007), who recorded a pH value of approximately 10.5 for a 20-year-old specimen and a 12 pH value for a 2-month-old specimen.

The average results for each bridge can be observed in Table 2. Most bridges presented high pH, above 11.5, which according to some authors would be detrimental to FRP bars (Ceroni et al. 2006; Demis et al. 2007). However, based on the results obtained in Al-Khafaji et al. (2020), no direct correlation between GFRP bar degradation and pH was identified. The condition of the GFRP bars from the McKinleyville and Roger's Creek Bridges that presented an average pH of 10 was comparable to the bars from the other bridges with higher pH. On the other hand, a pH lower than 11 would be representative of corrosion initiation of steel reinforcement even with a low presence of chloride ions near the bars (Behnood et al. 2016).

## Conclusions

Concrete cores with embedded GFRP bars were extracted from 11 bridges with 15–20 years of service to investigate their performance and durability. The investigated bridges are located across the United States and exposed to varying environmental conditions (e.g., deicing salts, wet and dry cycles, and freeze–thaw cycles) that influence the durability of reinforced concrete structures. Experiments were performed on the concrete to evaluate its condition and its influence on the durability of in-service GFRP bars. The concrete tests included chloride penetration depth, carbonation depth, and pH tests. The results were compared with the information given from the bridges and to the results obtained in Part II of this two-part series of paper. The following observations were made:

- Carbonation was observed in most concrete cores. Some bridges presented carbonation depth larger than 38 mm (1.5 in.), which may indicate that carbonation reached the GFRP bars.
- Chloride penetration tests were performed on specimens from 10 bridges. In some bridges, no chloride penetration was observed; in the worst case, chloride may have reached the reinforcement at about 64 mm (2.5 in.) depth. The chloride penetration observed in the bridges suggests that it was due to the application of deicing salts.
- Concrete pH values were recorded on the specimens from all bridges. Most bridges presented relatively high pH, above 11, which according to the literature (Ceroni et al. 2006; Demis et al. 2007) are conditions detrimental to GFRP bars. The two oldest bridges in the investigation presented an average pH of 10, an indicator of corrosion initiation for steel reinforcement. No correlation between pH and degradation of GFRP bars could be concluded.

The work presented in this paper is relevant to the interpretation of the test results on GFRP samples extracted from the cores and discussed in Part II of this two-paper series (Al-Khafaji et al. 2020).

## Data Availability Statement

All data, models, or codes generated or used during the study appear in the published article.

## Acknowledgments

The authors are grateful to the Strategic Development Council (SDC) of the American Concrete Institute (ACI) and NSF Industry/University Center for the Integration of Composites into Infrastructure (CICI) at the University of Miami under Grant No. NSF-1916342 for providing the funding that allowed the extraction of the cores and the distribution of specimens to four laboratories for the performance of the tests and the Tier 1 ReCAST University Transportation Center for supporting a portion of the laboratory testing and evaluation. Similarly, the authors acknowledge the collaboration and help provided by the state and local authorities that have jurisdiction on the selected bridges for allowing this research to take place. Several other individuals provided technical support to this endeavor. In particular, the authors thank Jason Cox of Missouri S&T, and Ryan Koch, Bryan Barragan, Doug Gremel, Mala Nagarajan, and Nelson Yee of Owens Corning Infrastructure Solutions. The opinions and findings expressed in this paper are those of the authors and do not necessarily reflect those of the sponsor.

## Supplemental Materials

Figs. S1–S28 are available online in the ASCE Library (www.ascelibrary.org).

## References

Alkhrdaji, T., and A. Nanni. 2001. "Design, construction, and field-testing of an RC Box Culvert Bridge reinforced with GFRP bars." In *Proc., 5th Int. Symp. on Fiber-Reinforced Polymer Reinforcement for Concrete Structures*, edited by C. Burgoyne, 1055–1064. London: Thomas Telford.

Al-Khafaji, A., R. T. Haluza, V. Benzecry, M. J. John, C. E. Bakis, and A. Nanni. 2020. "Durability assessment of 15–20 years old GFRP bars extracted from bridges in the USA—part 2: GFRP bar assessment." *J. Comp. Constr*.

Al-Salloum, Y. A., S. El-Gamal, T. H. Almusallam, S. H. Alsayed, and M. Aqel. 2013. "Effect of harsh environmental conditions on the tensile properties of GFRP bars." *Composites, Part B* 45 (1): 835–844. https://doi.org/10.1016/j.compositesb.2012.05.004.

ASTM. 2017. *Standard specification for solid round glass fiber reinforced polymer bars for concrete reinforcement*. ASTM D7957/D7957M. West Conshohocken, PA: ASTM.

Behnood, A., K. Van Tittelboom, and N. De Belie. 2016. "Methods for measuring pH in concrete: A review." *Constr. Build. Mater.* 105: 176–188. https://doi.org/10.1016/j.conbuildmat.2015.12.032.

Benmokrane, B., A. H. Ali, H. M. Mohamed, A. ElSafty, and A. Manalo. 2017. "Laboratory assessment and durability performance of vinyl-ester, polyester, and epoxy glass-FRP bars for concrete structures." *Comp. Part B: Eng.* 114: 163–174. https://doi.org/10.1016/j.compositesb.2017.02.002.

Benmokrane, B., F. Elgabbas, E. A. Ahmed, and P. Cousin. 2015. "Characterization and comparative durability study of glass/vinylester, basalt/vinylester, and basalt/epoxy FRP bars." *J. Compos. Constr.* 19 (6): 04015008. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000564.

Benmokrane, B., P. Wang, T. M. Ton-That, H. Rahman, and J.-F. Robert. 2002. "Durability of glass fiber-reinforced polymer reinforcing bars in concrete environment." *J. Compos. Constr.* 6 (3): 143–153. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:3(143).

Cady, P. D., and R. E. Weyers. 1983. "Chloride penetration and the deterioration of concrete bridge decks." *Cem. Concr. Aggregates* 5 (2): 81–87. https://doi.org/10.1520/CCA10258J.

Camata, G., and B. Shing. 2005. "Evaluation of GFRP honeycomb beams for the O'Fallon park bridge." *J. Compos. Constr.* 9 (6): 545–555. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:6(545).

Ceroni, F., E. Cosenza, M. Gaetano, and M. Pecce. 2006. "Durability issues of FRP rebars in reinforced concrete members." *Cem. Concr. Compos.* 28 (10): 857–868. https://doi.org/10.1016/j.cemconcomp.2006.07.004.

Chang, C., and J. Chen. 2006. "The experimental investigation of concrete carbonation depth." *Cem. Concr. Res.* 36 (9): 1760–1767. https://doi.org/10.1016/j.cemconres.2004.07.025.

Chen, Y., J. F. Davalos, and I. Ray. 2006. "Durability prediction for GFRP reinforcing bars using short-term data of accelerated aging tests." *J. Compos. Constr.* 10 (4): 279–286. https://doi.org/10.1061/(ASCE)1090-0268(2006)10:4(279).

Chen, Y., J. F. Davalos, I. Ray, and H. Kim. 2007. "Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures." *Compos. Struct.* 78 (1): 101–111. https://doi.org/10.1016/j.compstruct.2005.08.015.

Chen, Y., P. Liu, and Z. Yu. 2018. "Effects of environmental factors on concrete carbonation depth and compressive strength." *Materials* 11 (11): 2167. https://doi.org/10.3390/ma11112167.

Chindaprasirt, P., C. Chotithanorm, H. T. Cao, and V. Sirivivatnanon. 2007. "Influence of fly ash fineness on the chloride penetration of concrete." *Constr. Build. Mater.* 21 (2): 356–361. https://doi.org/10.1016/j.conbuildmat.2005.08.010.

Collepardi, M. 1995. "Quick method to determine free and bound chlorides in concrete." In *1st RILEM Workshop on Chloride Penetration into Concrete*, edited by L.-O. Nilsson and J.-P. Ollivier Saint Remy-les, 10–16. Chevreuse, France: Np.

Davalos, J. F., Y. Chen, and I. Ray. 2012. "Long-term durability prediction models for GFRP bars in concrete environment." *J. Compos. Mater.* 46 (16): 1899–1914. https://doi.org/10.1177/0021998311427777.

Dejke, V., and R. Tepfers. 2001. "Durability and service life prediction of GFRP for concrete reinforcement." In *Proc., 5th Int. Conf. on Fiber-Reinforced Plastics for Reinforced Concrete Structures*, 505–516. Cambridge, UK: Thomas Telford Publishing.

Demis, S., K. Pilakoutas, and E. Byars. 2007. "Durability of fibre reinforced polymers in concrete-procedures for reduced alkalinity exposures." In *Proc., 8th Int. Symp. on Fiber-Reinforced Polymer Reinforcement for Concrete Structures*, 534–535. Patras, Greece: University of Patras.

Eitel, A. 2005. "Performance of a GFRP reinforced concrete bridge deck." Ph.D. thesis, Dept. of Civil Engineering, Case Western Reserve Univ.

Fico, R., N. Galati, A. Prota, and A. Nanni. 2006. *Southview bridge rehabilitation in Rolla, Missouri*. Rep. No. UTR 103. Rolla, MO: Center for Infrastructure Engineering Studies Univ. Transportation Center Program, Univ. of Missouri–Rolla.

Frosch, R. J., and A. C. Pay. 2006. *Implementation of a non-metallic reinforced bridge deck, Vol. 2: Thayer Road Bridge*. Publication No. FHWA/IN/JTRP-2006/15-2. West Lafayette, IN: Joint Transportation Research Program, Indiana Dept. of Transportation and Purdue Univ.

Gooranorimi, O., T. Bradberry, E. Dauer, J. Myers, A. Nanni, and R. C. Tier. 2016. *FRP reinforcement for concrete: Performance assessment and new construction: Volume I: Sierrita De La Cruz Creek bridge*. No. RECAST UTC# 00042134-04-103A. Rolla, MO: RE-CAST Tier-1 Univ. Transportation Center.

Gooranorimi, O., J. Myers, and A. Nanni. 2017. "GFRP reinforcements in box culvert bridge: A case study after two decades of service." In *Concrete pipe and box culverts*, ASTM STP1601, edited by J. J. Meyer, and J. Beakley, 75–88. West Conshohocken, PA: ASTM.

Gooranorimi, O., and A. Nanni. 2017. "GFRP reinforcement in concrete after 15 years of service." *J. Compos. Constr.* 21 (5): 04017024. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000806.

Grubb, J. A., H. S. Limaye, and A. M. Kakade. 2007. "Testing pH of concrete." *Concr. Int.* 29 (4): 78–83.

Haley, J. S. 2011. "Climatology of freeze–thaw days in the conterminous United States: 1982–2009." Master's thesis, Dept. of Geography, Kent State Univ.

Harik, I. E., P. Alagusundaramoorthy, V. Gupta, C. Hill, and C. C. Chiaw. 2004. *Inspection and evaluation of a bridge deck partially reinforced with GFRP rebars*. Rep. No. KTC-04-21/FRPDeck-1-97-1F. Lexington, KY: Kentucky Transportation Center.

He, F., C. Shi, Q. Yuan, C. Chen, and K. Zheng. 2012. "$AgNO_3$-based colorimetric methods for measurement of chloride penetration in concrete." *Constr. Build. Mater.* 26 (1): 1–8. https://doi.org/10.1016/j.conbuildmat.2011.06.003.

Holdener, D., J. Myers, and A. Nanni. 2008. "An overview of composites usage in bridge facilities in the state of Missouri, USA." In *Int. Conf. and Exhibition on Reinforced Plastics*, 1–8. Mumbai, India: Np.

Kumar, S. V., H. K. Thippeswamy, and H. V. S. Gangarao. 1997. "McKinleyville bridge: Construction of the concrete deck reinforced with FRP rebars." In *Int. Composites Expo '97*. Nashville, TN: Composite Institute.

Lee, Y., T. Hosteng, U. Deza, J. S. Nelson, T. Wipf, B. Phares, D. Wood, and W. Klaiber. 2009. "Structural field testing and evaluation of two demonstration FRP deck bridges: Case studies on FRP panel deck bridge and temporary bypass bridge." In *TRB 2009 Annual Meeting*, 1–19. Washington, DC: Transportation Research Board.

Meck, E., and V. Sirivivatnanon. 2003. "Field indicator of chloride penetration depth." *Cem. Concr. Res.* 33 (8): 1113–1117. https://doi.org/10.1016/S0008-8846(03)00012-7.

Mertz, D. R., M. J. Chajes, J. W. Gillespie, D. S. Kukich, S. A. Sabol, N. M. Hawkins, W. Aquino, and T. B. Deen. 2003. *Application of fiber reinforced polymer composites to the highway infrastructure*. NCHRP Report 503. Washington, DC: Transportation Research Board.

Micelli, F., and A. Nanni. 2004. "Durability of FRP rods for concrete structures." *Constr. Build. Mater.* 18 (7): 491–503. https://doi.org/10.1016/j.conbuildmat.2004.04.012.

Mufti, A. A., M. Onofrei, B. Benmokrane, N. Banthia, M. Boulfiza, J. P. Newhook, B. Bakht, G. S. Tadros, and P. Brett. 2007. "Field study of glass-fibre-reinforced polymer durability in concrete." *Can. J. Civ. Eng.* 34 (3): 355–366. https://doi.org/10.1139/l06-138.

Nanni, A. 2001. "Relevant field Applications of FRP composites in concrete structures." *In Proc., Int. Conf. Composites in Construction*, edited by J. Figueiras, L. Juvandes and R. Furia. A. A. Balkema Publishers: Porto, Portugal.

Nanni, A., and S. Faza. 2002. "Design and construction of concrete reinforced with FRP bars: An emerging technology." *Concr. Int.* 24 (11): 53–58.

Nkurunziza, G., A. Debaiky, P. Cousin, and B. Benmokrane. 2005. "Durability of GFRP bars: A critical review of the literature." *Prog. Struct. Mater. Eng.* 7 (4): 194–209. https://doi.org/10.1002/pse.205.

Otsuki, N., S. Nagataki, and K. Nakashita. 1992. "Evaluation of $AgNO_3$ solution spray method for measurement of chloride penetration into hardened cementitious matrix materials." *Mater. J.* 89 (6): 587–592.

Phelan, R. S., W. P. Vann, and J. Bice. 2003. *FRP reinforcing bars in bridge decks field instrumentation and short-term monitoring*. No. FHWA/TX-06/9-1520-4. Lubbock, TX: Texas Tech Univ.

Phillips, K. A., M. Harlan, C. L. Roberts-Wollmann, and T. E. Cousins. 2005. *Performance of a bridge deck with glass fiber reinforced polymer bars as the top mat of reinforcement*. VTRC 05-CR24. Charlottesville, VA: Virginia Center for Transportation Innovation and Research.

Rajput, A. S., and U. K. Sharma. 2017. "Durability and serviceability performance of GFRP rebars as concrete reinforcement." *Indian Concr. J.* 91 (7): 51–60.

Reising, R. M. W., B. M. Shahrooz, V. J. Hunt, M. S. Lenett, S. Christopher, A. R. Neumann, A. J. Helmicki, R. A. Miller, S. Kondury, and S. Morton. 2001. "Performance of five-span steel bridge with fiber-reinforced polymer composite deck panels." *Transp. Res. Rec.* 1770 (1): 113–123. https://doi.org/10.3141/1770-15.

Robert, M., P. Cousin, and B. Benmokrane. 2009. "Durability of GFRP reinforcing bars embedded in moist concrete." *J. Comp. Constr.* 13 (2): 66–73. https://doi.org/10.1061/(ASCE)1090-0268(2009)13:2(66).

Sagues, A. A., E. I. Moreno, W. Morris, and C. Andrade. 1997. *Carbonation in concrete and effect on steel corrosion*. No. WPI 0510685. Tampa, FL: Univ. of South Florida.

Shekar, V., S. H. Petro, and H. V. S. GangaRao. 2003. "Fiber-reinforced polymer composite bridges in West Virginia." *Transp. Res. Rec.* 1819 (1): 378–384. https://doi.org/10.3141/1819b-48.

Van Den Einde, L., L. Zhao, and F. Seible. 2003. "Use of FRP composites in civil structural applications." *Constr. Build. Mater.* 17 (6–7): 389–403. https://doi.org/10.1016/S0950-0618(03)00040-0.

Wang, W., O. Gooranorimi, J. J. Myers, and A. Nanni. 2018. "Microstructure and mechanical property behavior of FRP reinforcement autopsied from bridge structures subjected to in situ exposure." In *Int. Congress on Polymers in Concrete*, 585–591. Cham, Switzerland: Springer.

Wipf, J. T., B. M. Phares, F. W. Klaiber, and U. Deza. 2006. *Evaluation of the Bettendorf Bridge, Iowa*. Final Rep. Ames, IA: Center for Transportation Research and Education, Iowa State Univ.

Xi, Y., Y. Jing, and R. Railsback. 2018. *Surface chloride levels in Colorado structural concrete*. Rep. No. CDOT-2018-05. Denver: Colorado Dept. of Transportation.

Yuan, Q., C. Shi, F. He, G. De Schutter, K. Audenaert, and K. Zheng. 2008. "Effect of hydroxyl ions on chloride penetration depth measurement using the colorimetric method." *Cem. Concr. Res.* 38 (10): 1177–1180. https://doi.org/10.1016/j.cemconres.2008.04.003.

Zhou, A., C. L. Chow, and D. Lau. 2018. "Structural behavior of GFRP reinforced concrete columns under the influence of chloride at casting and service stages." *Composites, Part B* 136 (Mar): 1–9. https://doi.org/10.1016/j.compositesb.2017.10.011.

Zhou, Y., B. Gencturk, K. Willam, and A. Attar. 2015. "Carbonation-induced and chloride-induced corrosion in reinforced concrete structures." *J. Mater. Civ. Eng.* 27 (9): 04014245. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001209.