# DURABILITY OF GFRP BARS IN BRIDGES WITH 15 TO 20 YEARS OF SERVICE

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## ABSTRACT

Glass fiber reinforced polymer (GFRP) rebars have been implemented in concrete structures as a substitute for steel rebars due to their noncorrosive behavior. To validate their performance in concrete structures, a collaborative study between the University of Miami, Penn State University, Missouri University of Science and Technology and Owens Corning Composites investigated the durability of GFRP rebars extracted from eleven bridges with 15 to 20 years of service.

To investigate the durability of the GFRP rebars, 4 in.-diameter concrete cores were extracted from the bridges. A variety of tests were performed to evaluate the physical-chemical and mechanical conditions of the GFRP bars and their surrounding concrete. The results of DSC and fiber content were comparable to pristine values, while the results of the horizontal shear test were inconclusive. The results of SEM and EDS showed that bars from most bridges had no sign of physical or mechanical deterioration. Correspondingly, the results of a modified tensile test showed that bars in service for 17 years had a reduction in tensile strength of only 2.3%. This study provides positive indication on the long-term durability of GFRP bars as an internal reinforcement for concrete structures.

## INTRODUCTION

Glass fiber reinforced polymer (GFRP) rebars have been implemented in concrete structures as a substitute for steel rebars due to their noncorrosive behavior. In order to validate their performance in concrete structures, it is important to understand their long-term durability. A collaborative study between the University of Miami (UM), Penn State University (PSU), Missouri University of Science and Technology (M S&T) and Owens Corning Composites (OC) investigated the durability of GFRP rebars in eleven bridges with 15 to 20 years of service. The bridges investigated are located in the United States and are exposed to wet and dry cycles, freeze-thaw cycles and deicing salts; therefore, making them more prone to degradation.

To investigate the durability of the GFRP rebars, 4 in. (10 cm)-diameter concrete cores were extracted from the bridges. A variety of tests were performed to evaluate the physical, mechanical and chemical properties of the GFRP bars and the condition of the surrounding concrete. Carbonation depth, chloride penetration and pH tests were performed on the concrete. The extracted bars were tested for horizontal shear strength and tensile strength. The cross section of GFRP specimens were analyzed for scanning electron microscopy (SEM) imaging and energy dispersive X-ray spectroscopy (EDS) to observe any changes in their microstructure and composition. GFRP samples were also tested for fiber content, water absorption, moisture content and $T_g$ (differential scanning calorimetry (DSC)). The results of these tests were compared to data from pristine bars at the time of installation or to current standards when collected data was not available.

The objective of this study was to draw conclusions on the long-term durability of GFRP bars after at least 15 years in service. This paper presents how the study was conducted and its major findings. A report describing in details methodology and conclusions of the study is available at https://www.acifoundation.org/Portals/12/Files/PDFs/GFRP-Bars-Full-Report.pdf.

**SELECTED BRIDGES**

Eleven bridges in various locations across the U.S. were chosen for the investigation. Each of the bridges contains GFRP rebars in the deck or other location and has been in service for at least 15 years. These bridges are referred to as follows:

1. Gills Creek Bridge, Virginia (VA)
2. O'Fallon Park Bridge, Colorado (CO)
3. Salem Ave Bridge, Ohio (OH1)
4. Bettendorf Bridge, Iowa (IA)
5. Cuyahoga County Bridge, Ohio (OH2)
6. McKinleyville Bridge, West Virginia (WV)
7. Thayer Road Bridge, Indiana (IN)
8. Roger's Creek Bridge, Kentucky (KY)
9. Sierrita de la Cruz Creek Bridge, Texas (TX)
10. Walker Box Culvert Bridge, Missouri (MO1)
11. Southview Bridge, Missouri (MO2)

The location of the bridges is shown in Figure 1.


*Figure 1. Location of investigated bridges*

**SAMPLE EXTRACTION**

Concrete core samples of approximately 4 in. (10 cm) in diameter by 6 in. (15 cm) in length were extracted from the bridges. When possible, the targeted locations of extraction were areas with cracks and signs of environmental deterioration. Due to the inability to detect the GFRP bars, some concrete cores had GFRP samples shorter than 2 in. (5 cm) or no GFRP rebars at all. For this reason, to have a minimum of three samples per test, bars from the same bridge with the same nominal diameter were considered to be the same bar.

## GFRP AND CONCRETE TESTS

To maximize the use of the small samples of GFRP bars for durability testing, an inventory for these samples was created. The capability of each laboratory was also evaluated to distribute the samples and tests along the collaborators. The capability of each laboratory is shown in Table 1 and the distribution of GFRP samples per test and laboratory is shown in Table 2.

The GFRP tests performed during this study were: fiber content, water absorption, differential scanning calorimetry (DSC), horizontal shear, scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDS), moisture content and modified tensile strength test. As long-term durability of GFRP rebars is related to the surrounding environment, tests to evaluate the condition of the concrete were also part of this study. The tests performed on concrete were: chloride penetration, carbonation depth and pH. The concrete tests allowed for observation of the concrete condition at the depth of the reinforcement, and, therefore, how such conditions may affect the durability of GFRP rebars.

*Table 1. Collaborators' capabilities*

| GFRP Tests | University/Company | | | |
|---|---|---|---|---|
| | UM | MS&T | PSU | OC |
| Fiber Content | x | x | x | x |
| Glass Transition Temperate (DSC) | | x | x | x |
| Scanning Electron Microscopy (SEM) | x | x | | x |
| Energy-Dispersive X-ray Spectroscopy (EDS) | x | x | | x |
| Interlaminar Shear | x | x | | |
| Water Absorption | x | x | x | |
| Direct Tension | x | | | |

*Table 2. Distribution of bridge samples*

| Bridge | Fiber Content | Moisture Absorption | DSC | SEM/EDS | Horizontal Shear | Tension |
|---|---|---|---|---|---|---|
| IA | UM | UM | S&T | UM | UM | |
| OH2 | S&T, PSU, OC | PSU | S&T, PSU, OC | OC | S&T | |
| VA | UM, OC | UM | S&T, OC | OC | | |
| CO | UM, PSU | PSU | PSU | UM | UM | |
| OH1 | UM | UM | S&T | UM | UM | |
| WV | OC, PSU | PSU | PSU | OC | UM | |
| IN | UM, OC, PSU | PSU | PSU | OC | UM | |
| KY | S&T, OC | | S&T | OC | | |
| TX | UM | | UM | UM | UM | UM |
| MO1 | UM | | UM | UM | UM | |
| MO2 | UM | | UM | UM | UM | |

## GFRP TEST RESULTS

The bars were cleaned of any adhered concrete and were cut with a water-cooled diamond saw to the size needed for each test. The bars were pre-conditioned for 48 hours inside the oven at a temperature of 104°F (40°C) before tests were performed, in order to ensure the same conditions between different laboratories.

Tests were performed in accordance with ASTM standards when possible. The results of the tests were compared to data collected at the time of bar installation or to current standards when data was not available.

A summary of each test performed and its results is presented below.

### Fiber Content

Two methods of fiber content were used in this study: burn-off technique in accordance with ASTM D2584 (1) and an acid wash technique. The acid wash technique used the procedure outlined on ASTM D2584 (1) and followed an acid wash to remove any fillers. This technique was performed at Owens Corning and allows for a more accurate measurement of the fiber content.

Fiber content was performed at every laboratory and GFRP bars from all eleven bridges were tested. Except for Roger's Creek Bridge, all bars presented an average fiber percentage by volume higher than 70%, which is the minimum required by ASTM D7957 (2) for quality control and certification of GFRP rebars**.** The results of the fiber content are shown in Table 3.

*Table 3. Fiber content results*

| Bridge | No. of Samples | Average Fiber Content (%) | Standard Deviation (%) |
|---|---|---|---|
| Gills Creek | 6 | 72.1 | 1.78 |
| O'Fallon Park | 6 | 72.9 | 1.75 |
| Salem Ave. | 3 | 72.5 | 0.06 |
| Bettendorf | 3 | 73.3 | 1.29 |
| Cuyahoga County | 15 | 76.4 | 2.47 |
| McKinleyville | 3 | 76.1 | 3.35 |
| Thayer Road | 3 | 76.5 | 1.79 |
| Roger’s Creek | 5 | 67.7 | 1.08 |
| Sierrita de la Cruz Creek | 9 | 76.4 | N/A |
| Walker Box Culvert | 4 | 82.8 | N/A |
| Southview | 4 | 73.4 | N/A |

**Water Absorption**

Water absorption was performed in accordance with ASTM D570 (3) at UM and PSU. The bars were cut into samples of approximately 0.5 in. to 1 in. in length and immersed in distilled water at 122°F (50ºC). The samples tested were from the following bridges: Gills Creek, O’Fallon Park, Salem Ave., Bettendorf Bridge, Cuyahoga, McKinleyville and Roger’s Creek.

The ASTM D7957 (2) stablishes a limit of 0.25% of water absorption at 24-hr. and 1% for long-term water absorption. The long-term immersion duration (i.e., time to saturation) varied among bar types and sizes, as the measurements had to continue until the increase in weight (shown by three consecutive measurements over a period of two weeks), be on average less than 1% of the total increase in weight.

Bars from the majority of the bridges tested presented less than 0.25% of absorption gain at 24-hr. while at the long-term immersion, some samples presented a weight increase of up to 2%. The results are shown in Table 4.

*Table 4. Water absorption results*

| Bridge | Number of Samples | Average 24-hr Immersion (%) ≤ 0.25 | Weight Change at Equilibrium (%)≤ 1.0 | Length of Saturation (days) |
|---|---|---|---|---|
| Gills Creek | 3 | 0.58 | 1.57 | 179 |
| O’Fallon Park | 3 | 0.01 | 0.33 | 133 |
| Salem Ave. | 5 | 0.10 | 0.30 | 85 |
| Bettendorf | 3 | 0.54 | 2.16 | 179 |
| Cuyahoga | 4 | 0.19 | 1.47 | 133 |
| Roger’s Creek | 3 | 0.05 | 0.16 | 77 |

Note: Average 24-hr immersion should be less than 0.25% and weight change at equilibrium should be less than 1.0%

### Horizontal Shear

Due to the length of the extracted GFRP coupons, bars from only eight bridges could be tested for horizontal shear. These bridges included: O'Fallon Park, Bettendorf, Salem Ave., Cuyahoga, McKinleyville, Thayer Road, Sierrita de la Cruz Creek and Southview. The bars were tested in accordance with ASTM D4475 (4) at UM and S&T. However, due to the coupons' length, modifications of the test set-up were implemented while testing bars from Bettendorf and Cuyahoga bridges. Therefore, these results could not be used for evaluation. The results of the horizontal shear test for Sierrita de la Cruz and Southview yielded a higher shear strength than that from pristine bars at the time of installation. The results of the other bridges were also in compliance with current standards. The average result for each bridge is shown in Table 5.

*Table 5. Horizontal shear results*

| Bridge | Nominal Diameter | Number of Samples | Average Apparent Shear Strength, psi (MPa) |
|---|---|---|---|
| O'Fallon Park | #7 | 2 | 6115 (42) |
| Salem Ave. | #6 | 3 | 6459 (45) |
| Cuyahoga | #6 | 3 | 4316 (30) |
| McKinleyville | #3 | 3 | 5214 (36) |
| Thayer Road | #5 | 3 | 6809 (47) |
| Sierrita de la Cruz Creek | #5 | 5 | 6047 (42) |
| Southview Bridge | #6 | 3 | 6340 (44) |

### Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) measures the heat flow into small pieces of bar in a sealed aluminum pan, relative to an empty pan, during a constant rate of temperature change from one limit to another. The changes in heat flow are used to assign a glass transition temperature ($T_g$).

Bars from nine bridges were tested: Bettendorf, Cuyahoga, Gills Creek, O'Fallon Park, Salem Ave., Sierrita de la Cruz Creek, Walker Box and Southview. The test was performed in accordance with ASTM E1356-08 (5) and $T_g$ was assigned by drawing three tangents to the total heat flow curve, finding the middle value of total heat flow between the two points where the tangents intersect, and identifying the temperature corresponding to the middle value of total heat flow. This value is known as the mid-point temperature, $T_m$ in ASTM1356-08 (5). The results were compared to the limit stablished by ASTM D7957 (2) that specifies a $T_g$ higher than 212ºF (100°C). Most bars tested yielded a $T_g$ higher than 212ºF (100°C); however, bars from three bridges (i.e., Cuyahoga, Gills Creek and O'Fallon Park) yielded $T_g$s of 198 (92), 207 (97) and 176ºF (80°C), respectively. The results of each bridge is shown in Table 6.

*Table 6. $T_g$ results*

| Bridge | Average *Tg* (°C) ≥ 100 | Average *Tg* (°F) ≥ 212 |
|---|---|---|
| Bettendorf | 109 | 228 |
| Cuyahoga | 92 | 198 |
| Gills Creek | 97 | 207 |
| O'Fallon Park | 80 | 176 |
| Salem Ave. | 108 | 226 |
| Roger's Creek | 100 | 212 |
| Sierrita de la Cruz Creek | 115 | 239 |
| Walker Box | 112 | 234 |
| Southview | 101 | 214 |

Note: Average $T_g$ should be more than 212°F (100°C)

**SEM/EDS**

Bars were cut with a water-cooled diamond saw into small samples of approximately 0.25 in (0.635 cm) and then mechanically polished with sand papers and sputter coated with gold to prepare for SEM imaging and EDS analysis. GFRP bars from all eleven bridges were tested for SEM and EDS at UM, S&T and OC. The SEM images focused on fibers located near the edge of the bar, as these are more likely to be damaged by external conditions.

Evidence of GFRP rebar fibers being negatively affected by the concrete environment after 15 years in service is minimal and less than expected or predicted by accelerated test methods. Physical damage on fibers was observed on the outer edge of some bars, typically near a void in the resin matrix. At times, damage is likely due to the specimen preparation procedure (saw cutting and polishing). Overall, it was estimated that approximately 0.05 to 0.12% of the total number of fibers was damaged.

The result of EDS analysis shows Si and Al (from glass fibers) and C (from the matrix) as the predominant chemical elements. An example of SEM image and EDS are shown in Figures 2 and 3.

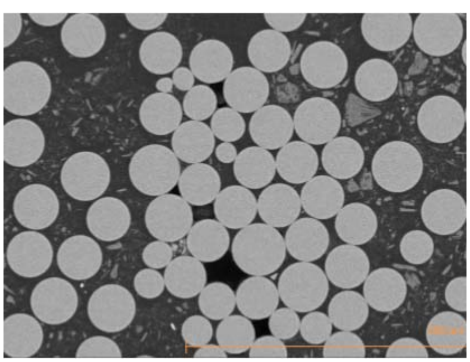

*Figure 2. Cuyahoga Bridge. No visually affected fibers*

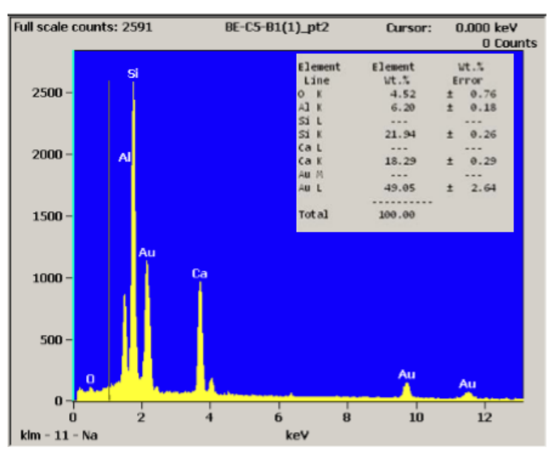


*Figure 3. Bettendorf Bridge EDS*

### Modified Tensile Strength

Witness GFRP rebars were extracted from Sierrita de la Cruz Creek, thus allowing for a modified tensile strength test. The modified tensile strength test used extracted bars cut into coupons of approximately 0.4in x 10 in. x 0.1 in. (11 mm x 254 mm x 2.5 mm) (width x length x thickness) from the left, center and right of the bar circumference, as shown in Figure 4 and 5. These thin laminates were also obtained from new bars. And full-size new generation virgin bars were also tested in tension in accordance with ASTM 7205 (6).

The results from the new generation virgin full-size rebars were compared to data from tensile tests performed in 2000 on bars used in Sierrita de la Cruz Creek. Consequently, a correlation factor between the coupon ultimate tensile strength and the full-sized ultimate tensile strength was calculated and used to interpret results. It was found that the extracted GFRP bars had a reduction in strength of 2.1% over 17 years of service, as shown in Table 7.

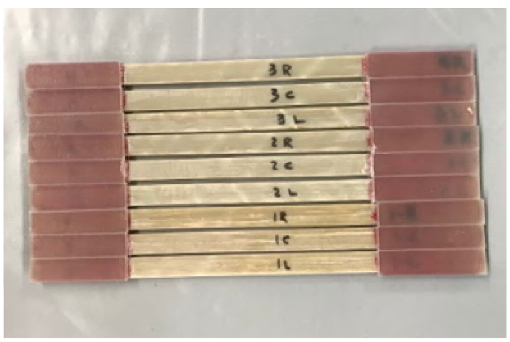

*Figure 4. Extracted bars cut into laminates*


*Figure 5. Extracted bar from the left being tested in tension*

*Table 7. Modified tensile test results*

| Sample | Full size Strength, psi (MPa) | Coupon Strength, psi (MPa) | Change Between Coupon and Full-size % |
|---|---|---|---|
| Pristine | 119,318 (823) | 96,997 (669) | 18.71 |
| Extracted bars | 113,840 (785)* | 90,110 (621) | 20.84 |
| Difference due to degradation % | | | 2.13 |

Note: * at the time of installation

## CONCRETE TESTS

### Chloride Penetration

The chloride penetration test consisted of applying a 0.1M silver nitrate solution to fresh broken concrete cores. Samples from all eleven bridges were tested for chloride penetration. The difference in the color of the concrete due to the silver nitrate was difficult to identify in some of the samples. For some bridges, no chloride penetration was observed in the samples and in the worst case, about 2.5 in (6.35 cm) of chloride penetration was observed, a depth exceeding the location of the reinforcement.

### Carbonation Depth

Carbonation depth was determined by using a phenolphthalein indicator solution sprayed over a freshly-cut concrete surface. The surface was monitored to observe any change in color. A surface turns pink when pH is above 9, and remains colorless when the pH is below 9. Concrete from eleven bridges were tested for carbonation depth. Most samples presented some carbonation near the surface, while others presented no carbonation. Sierrita de la Cruz Creek samples, however, presented significant depth of carbonation of about 1.5 in (3.8 cm).

### pH

For the pH test two procedures were used: the procedure outlined by Grubb et al. (7) and a rainbow indicator from Germann Instruments, Inc. The procedure by Grubb and co-workers consisted of extracting 0.03 oz. (1 g) of concrete powder from each core and then placing it inside a mixing pan. Next, a 0.03 oz. (1 g) of distilled water was added and mixed with concrete powder. After that, the pH was determined using measuring strips. The pH of the samples varied between 9 and 13. The lowest average pH was 10 for both Roger's Creek and McKinleyville bridges, while the highest average pH was 12.2 for both Cuyahoga and Gills Creek bridges. The results of each bridge are shown in Table 8.

*Table 8. Average pH*

| Bridge | Average pH | Bridge | Average pH |
|---|---|---|---|
| Bettendorf | 12.1 | Roger's Creek | 10 |
| Cuyahoga | 12.2 | Thayer Road | 12 |
| Gills Creek | 12.2 | Sierrita de la Cruz Creek | 11.5 |
| O'Fallon Park | 12.1 | Walker | 11.5 |
| Salem Ave | 11.6 | Southview | 11.5 |
| McKinleyville | 10 | | |

## CONCLUSIONS

A variety of tests were performed to assess physical-chemical and mechanical conditions of GFRP bars and their surrounding concrete from eleven bridges with 15 to 20 years of service. The results allow the evaluation of the long-term durability of GFRP reinforced concrete structures.

The results of fiber content were in accordance with ASTM 7957 (2), as well as the results of $T_g$ for most bridges. The results of moisture absorption and horizontal shear varied significantly among bridges and no specific conclusion could be drawn from these tests. The results of SEM and EDS showed minimal physical and chemical degradation. Furthermore, the results of modified tensile test for Sierrita de la Cruz Creek bridge also yield minimal reduction in tensile strength: 2.13% in 17 years of service.

The results of the concrete tests showed that most concrete samples had carbonation and chloride penetration near the surface and a few samples where chloride and carbonation reached the depth of the reinforcement. The pH of the concrete varied between 9 and 13, which is expected for the age of the samples.

Despite the challenge of working with a limited number of small samples, this study provides additional evidence to validate the long-term durability of GFRP rebars in concrete structures. The results of the tests were overall positive and indicated minimal degradation of GFRP after at least 15 years of service.

**ACKNOWLEDGMENTS**

This study was supported by the American Concrete Institute (ACI) Strategic Development Council (SDC). The full report is available at https://www.acifoundation.org/Portals/12/Files/PDFs/GFRP-Bars-Full-Report.pdf.

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