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Via E-mail: atrygestad@crsi.org

March 20, 2020

Ms. Amy Trygestad, P.E.
Director of Codes and Standards
Concrete Reinforcing Steel Institute
933 Plum Grove Road
Schaumburg, Illinois 60173

Re: Technical Review Comments on
Durability of GFRP Bars Extracted from Bridges with 15 to 20 Years of Service Life
DFM SE No. 2019.04

Dear Ms. Trygestad:

At the Concrete Reinforcing Steel Institute (CRSI) Fall 2019 Technical Meeting, the CRSI - Durability Committee discussed a research report submitted to the Strategic Development Council (SDC) of the American Concrete Institute (ACI) on the durability of glass fiber reinforced polymer (GFRP) deformed reinforcing bars used in bridge decks. The objective of the research was to evaluate the long-term strength characteristics of GFRP reinforcing bars and their durability after being encased in bridge deck concrete for between 15 and 23 years. The bridges were in regions of the Unites States where they were exposed to a relatively hostile environment, that is, bridges where deicing salts were used on the decks.

The objective of the work performed for the CRSI Durability Committee is to have an independent third-party review the final report to the SDC of ACI and provide CRSI comments regarding the research findings. CRSI approved a proposal on December 3, 2019 for Donald Meinheit to perform the third-party review for CRSI.

Executive Summary of Report Review Findings

The research report submitted to the Strategic Development Council of the American Concrete Institute, dated June 1, 2019, lacks complete information for an unbiased independent review of the test data. Many of the test methods conducted appear to be experimental trials to see if the test method could imply information on the deterioration of in-service GFRP reinforcing bars used primarily in bridge deck structures. The most important aspect of the study, the mechanical properties of the GFRP reinforcing bar, were only examined on one of eleven bridges in the research study. Those 3 full-size bar tension test results were also obtained by unconventional methods leaving doubt about the conclusion that only 2 percent deterioration occurred over the 19 years of service life.

The review discussed in this letter found inconsistencies with respect to the reported tension test data, neglect of important observations on sawn coupons from full-size bars removed from one bridge, and lacked opinions on the usefulness of the testing methods performed on the GFRP bars that existed in concrete core samples.

Analyses made herein on the limited number of coupons sawn from full-size GFRP bars imply that there is deterioration greater than the reported 2 percent. However, comparison tests from pristine bars are not available to validate that finding.

Assuming that it is valid to compare coupon test results from the outside of the GFRP bar to the coupon from the center of the GFRP bar, a significant deterioration exists that was not reported. Deterioration in the GFRP bar strength of at least 10 percent and perhaps as much as 20 percent may have occurred.

Report Contents

Scope

The scope of the SDC study was to validate the performance of GFRP reinforcement in concrete structures and understand the long-term durability of GFRP reinforcement.

Bridges Sampled in Study

The SDC report summarizes the testing of concrete and GFRP reinforcing bar samples removed from bridges in states from Virginia westward to Denver. In total, 11 bridges were sampled in this SDC study. In Table 1, there is a brief summary of each bridge site, state in which the bridge is located, general characteristics of the bridge, year constructed, age when the SDC report was issued, and samples removed.

Table 1 – Bridges sampled

No.	Name (Bridge I.D.)	State	General characteristics	Year constructed	Age, years	Samples removed
1	Gills Creek (VA)	Virginia	3 spans, concrete deck on steel girders, Span "A" uses GFRP bars in top mat	2003	16	10 – 3.75 in. cores; 5 cores w/GFRP bars; 8 GFRP bars extracted
2	O'Fallon Park (CO)	Colorado	1 span, arch shape, box section, bottom soffit sampled	2003	16	10 – 3.75 in. cores; 5 cores w/GFRP bars; 9 GFRP bars and 1 steel bar extracted
3	Salem Avenue (OH1)	Ohio	5 spans, concrete deck on steel girders, 4 different GFRP systems used	1999	20	5 – 3.5 in. cores; 5 cores w/GFRP bars; 7 GFRP bars extracted
4	Bettendorf (IA)	Iowa	3 spans, concrete deck on prestressed girders, center span top mat of GFRP bars sampled	2001	18	6 – 3.75 in. cores 4 cores w/GFRP bars; 4 GFRP bars extracted
5	Cuyahoga County (OH2)	Ohio	2 spans, concrete deck on steel girders, both spans sampled, assuming top mat of GFRP bars sampled	2002	17	8 – 3.75 in. cores; 7 cores w/GFRP bars; 11 GFRP bars extracted
6	McKinleyville (WV)	West Virginia	3 spans, concrete deck on steel girders, all spans sampled, assumed that top mat of GFRP bars sampled	1996	23	5 – 3.75 in. cores; 4 cores w/GFRP bars; 10 GFRP bars extracted
7	Thayer Road (IN)	Indiana	5 spans, concrete deck on steel girders, top mat of GFRP bars sampled	2004	15	6 – 3.75 in. cores; 6 cores w/GFRP bars; 9 GFRP bars extracted
8	Roger's Creek (KY)	Kentucky	1 span, concrete deck on prestressed girders, GFRP bars in top mat of deck	1997	22	5 – 3.75 in. cores; 4 cores w/GFRP bars; 4 GFP bars extracted
9	Sierrita de la Cruz Creek (TX)	Texas	7 spans, concrete deck on prestressed girders, GFRP bars used in top mat of 2 spans, extracted 22-in. long #5 GFRP bars	2000	19	2 – 3.75 in. cores; 2 cores w/GFRP bars; 4 GFRP bars extracted; 3 – #5 bars 22-in. long
10	Walker Box Culvert (MO1)	Missouri	2-cell concrete box culvert, samples removed from cracks in top slab, #2 GFRP bars	1999	20	2 – 3.75 in. cores; 2 cores w/GFRP bars; 12 GFRP bars extracted
11	Southview (MO2)	Missouri	6-cell concrete box culvert, GFRP bars used in 4-cell widening, #3, #4, #5 #6 bars used and #3 GFRP prestress strand used	2004	15	10 – 3.75 in. cores (only 2 cores tested); 2 cores with GFRP bars; 3 GFRP bars extracted

Laboratory Tests Conducted

Testing Laboratories - The testing of samples was a collaborative effort by several universities and a GFRP manufacturer. The program was led by representatives of the University of Miami. Listed in Table 2 are the laboratories that participated in the study.

Table 2 – Collaborating test laboratories

Laboratory	Abbreviation	Contributor 1	Contributor 2	Contributor 3
University of Miami	UM	Vanessa Benzecry	Janna Brown	Antonio Nanni
Missouri University of Science and Technology	MST	Ali Al-Khafaji	John J. Meyers	
Pennsylvania State University	PSU	Rudy Haluza	Charles E. Bakis	
Owens Corning Composites	OC	Ryan Koch	Mala Nagarajan	

Tests Conducted – Several different tests were performed on the GFRP reinforcing bars and on the concrete core samples removed with the embedded GRFP bars. The listing of the tests, the laboratory conducting the test, and the bridge where the samples were removed are summarized in Table 3.

Table 3 – Test and distribution of test samples

Laboratory test	University/Manufacturer			
	UM	MST	PSU	OC
GFRP Tests				
	Bridge Identification (see Table 1)			
Fiber Content	VA,CO, OH1,IA, IN,TX, MO1,MO2	OH1,KY	OH2,CO, WV	OH2,VA, WV,IN,KY
Water Absorption	VA,IA, OH1		CO,OH2, WV,IN	
Moisture Content			CO,OH2	
Differential Scanning Calorimetry(DSC) and Modulated Differential Scanning Calorimetry (MDSC)	TX,MO1, MO2	VA,OH1, IA,OH2, KY	CO,OH1, WV,IN	VA,OH2
Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)	CO,OH1, IA,TX, MO1,MO2			VA,OH2, WV,IN,KY
Constituent Volume Content (image analysis)			CO	
Horizontal Shear Strength	CO,OH1, IA,WV,IN, TX,MO1, MO2	OH2		
Full-size Tensile Strength and Modified Tensile Strength	TX			
Concrete Tests				
Chloride Penetration Depth	VA,CO, OH1,IA, OH2,WV, IN,KY,TX, MO1,MO2 (Assumed)			
Chloride Ion Content		OH2		
Carbonation Depth	IA,OH2, VA,CO, OH1,MO1, MO2 (Assumed)			
pH	VA,CO, OH1,IA, OH2,WV, IN,KY,TX, MO1,MO2	OH2		

A summary of the tests performed on the GFRP samples, number of samples in the database, and number of bridges sample is listed in Table 4.

Table 4 – Summary of GFRP tests conducted

Test	ASTM Number	Number of Samples Tested	Number of Bridges
Fiber Content	D7957	64	11
Constituent Volume by Image Analysis	None given	3	1
Water Absorption	D570	35	8
Moisture Content	D5229 Procedure D	8	2
DSC & MDSC	D7957	65	11
Scanning Electron Microscopy (SEM)	None given	23	11
Energy Dispersive X-ray Spectroscopy (EDS)	None given	20	9
Horizontal Shear	D4475 Modified	22	7
Tension tests from TX bridge			
Full-size bar test	ASTM 7205	10 "pristine" bars 4 "vintage" bars	1
Modified bar sample (3 extracted bars; an unknown number of pristine bars were used for coupons)	None given	9 extracted coupons 10 pristine coupons	1

Summary of Reported GFRP Test Results

Fiber content – Numerous samples were tested. The fiber content, including remnant filler, by the current ASTM D2584 should be greater than 70 percent. One bridge sample, KY-Rogers Creek, one of the older installations (1999), had a fiber content slightly less that the ASTM D2584 specified value.

Constituent volume contents by image analysis - Image analysis of a sample from one bridge determined that the fiber content was, on average, 20 percent less than that determined by the ASTM D2584 burn-off test.

Water absorption – Water absorption test results showed significant variability. Measured weight gains were from nearly nothing to above 2 percent.

Moisture content – Only two bridges were evaluated for GFRP bar moisture content. The measured weight gain, at equilibrium moisturegain, was only about 0.5 percent. This data might be inaccurate because the samples were not sealed in containers after they were extracted. Therefore, ambient moisture conditions could have influenced the final test results.

Differential and Modified Scanning Calorimetry (DSC & MDSC) – The DSC and MDSC tests are used to evaluate the glass transition temperature, T_g. The glass transition temperature is the temperature when the internal polymeric bonds start to change from solid to a more flexible condition. Above the T_g, the bond between the glass fibers in the bar decreases. In 5 of the 11 bridges studied, the T_g was above the current ASTM standard for GFRP reinforcing.

Scanning Electron Microscopy (SEM) – Examination of the GFRP under high magnification was intended to find physical damage to the glass fibers. Some physical damage of the sample fibers showed damage caused by the sample preparation (cutting and polishing). Anticipated damage, deterioration, is usually observed at the periphery of the cross section. However, the researchers did not indicate that the deterioration was found on the periphery and only estimated the deterioration was less than 0.15 percent. The deterioration observed was much less than would be anticipated by accelerated durability test methods.

Energy Dispersive X-ray Spectroscopy (EDS) - Energy Dispersive X-ray Spectroscopy examined the chemical composition of the elements in the GFRP bar. The researchers' analysis of the EDS plots showed that there was no change in the chemical composition or distribution of the chemicals from currently available pristine bars. No change in the internal chemistry implies that the GFRP bars have not reacted chemically with the concrete that has encased them, but this may depend upon where the sample was taken. Only for one bridge, the Sierrita de la Cruz Creek Bridge, did the report state that the EDS focused on the edge, periphery, of the bar. No indication was given regarding the location of the EDS plots for the other 7 bridges. Owens Corning evaluated 3 bridge samples and reported numerical values of results either from a "central fiber" or a "non-intact fiber". In those three cases, the numerical values of the chemical elements did not change from the central fiber to the non-intact fiber.

Horizontal shear – The fiber orientation is longitudinal to the GFRP bar axis. Perpendicular to the longitudinal axis, there is no fiber to hold the bar from splitting longitudinally. The GFRP bar should never see a shear stress that could split the bar longitudinally. However, this horizontal shear stress test is a convenient measure of how well the fibers are bonded transversely. This test, therefore, represents a reasonable quality control test that can be done on a small sample and potentially evaluate if there has been any deterioration of the GFRP bar. Twenty-two tests were performed for 7 of the 11 bridges. One of the bridges, Sierrita de la Cruz Creek Bridge, was the bridge where tensile samples were removed.

The magnitude of the measured horizontal shear strengths was consistent with current manufacturers data for GFRP reinforcing bars. The measured values for the extracted bars from cores varied from 4316 psi to 6809 psi. The horizontal shear strength of the Sierrita de la Cruz Creek Bridge samples was slightly above the average measured horizontal shear strength.

Tension on GFRP samples – Only one of the 11 bridges sampled had full-size GFRP bars removed that were longer that the diameter of the extracted core. Three full-size GFRP bars with a length of maybe 22 in. were removed from the Sierrita de la Cruz Creek Bridge (TX). In report section 4.1.8.1 the researchers state that 22-in long extracted samples and virgin, new, GFRP bars were cut into coupons. The bar size extracted appears to be that of a bar with cross-sectional area of 0.31 square inches, that is, a No. 5 bar.

Construction records for this bridge also contained four tests on full-size No. 5 GFRP bars used in the construction the bridge in 2000. This construction record test data is designated as "vintage" GFRP bar data. The report does not indicate the source of the new "pristine" bars only to say that the pristine bars were from the same manufacturer as the bars removed from the bridge.

The researchers decided that the extracted GFRP bars from the Sierrita de la Cruz Creek Bridge were not adequate to place in a testing machine and test as full-size bars. Therefore, a modified tensile test specimen was used. The modified coupon cut the extracted bars from the bridge into three parts: a left, a center, and a right coupon. Each of these coupon samples from the extracted GFRP bars was about 10-in long and had a cross-sectional area of about 0.045 square inches. A total of 9 test samples were made in this fashion.

New pristine bars were also cut into coupons with the same length, about 10 inches, and cross-sectional area, 0.045 square inches. However, for these 10 samples no record exists of where the test samples for the pristine coupons came from within the bar cross section, that is, there were no left, center, and right designations. It is also unclear how many full-size bars were used to make the pristine coupon samples. All the coupon test values were included in one average which then represented the strength of either the extracted GFRP bars and the strength of the pristine GFRP bars.

The researchers' assessment of deterioration of the embedded GFRP bars is based on the following logic:

- The average strength of new pristine coupons, *Average Pristine GFRP Coupon*, is compared to the average strength of new pristine full-size GFRP bars, *Average Pristine GFRP Bar*. These tests establish the relative difference between pristine full-size bars and coupons cut from pristine full-size bars. Percent difference in these two strengths is equal to (1 - [*Average Pristine GFRP Coupon / Average Pristine GFRP Bar*]). This letter report will refer to this Change Between Pristine Coupons and Pristine Full-size bars as the value A.
- The average strength of extracted GFRP bar coupons, *Average TX GFRP Coupon*, is compared to the average strength of the vintage GFRP bars, *Average Vintage GFRP Bar*. These tests establish the relative difference between full-size vintage bars and coupons cut from full-size bars removed from the bridge, which were from the same production lots. Percent difference in these two strengths is equal to (1 - [*Average TX GFRP Coupon / Average Vintage GFRP Bar*]). This letter report will refer to this Change Between Extracted Coupons and Vintage Full-size bars as the value B.

In each case, the percent difference compares coupons to full-size bars. If the in-service difference is compared to the bars that did not see service, a measure of deterioration can be made. Therefore, if B is greater than A, there is potentially some deterioration, and if B is less than A, the supposition is there is no deterioration.

Using the test values in Tables 20, 21, and 22 in the report, the researchers concluded that B was greater than A and, therefore, after 19 years of service there was 2.1 percent deterioration of the in-service GFRP bars.

Summary of Reported Concrete Test Results

Carbonation depth – Carbon dioxide in the air can react with calcium hydroxide, $Ca(OH)_2$, in the concrete to form calcium carbonate, $CaCO_3$. The formation of calcium carbonate reduces the pH of the concrete and can affect the passivity the concrete provides embedded steel reinforcing bars. Freshly broken concrete sprayed with phenolphthalein, a pH indicator, does not change the color of concrete where the concrete is carbonated but changes the color to pink where the concrete is not carbonated.

Table 5 lists the results of the carbonation tests. Carbonation depths varied from none to as deep as 1 inch for the Sierrita de la Cruz Creek Bridge.

Chloride penetration – The depth of chloride penetration into the concrete from the exposed surface was measured by spraying onto a freshly cracked surface a silver nitrate solution. In zones where chlorides penetrated the concrete, the silver nitrate does not change the color of the concrete. Results are listed in Table 5.

Those bridges in regions where deicing salts are typically used showed some chloride penetration. Chloride penetration depths of 2.5 inches were measured on the Cuyahoga County bridge.

Chloride-ion content – Water soluble chloride tests were conducted on only two samples from one bridge, the Cuyahoga County bridge. This is the same bridge that had the greatest chloride penetration tests result; however, no significant chloride ion content was measured in the concrete. Results are listed in Table 5.

Concrete pH – The majority of the pH tests were conducted similar to the carbonation test where the entire freshly broken surface is sprayed with phenolphthalein indicator solution and the surface color is compared to a color-range palette to imply the pH of the concrete.

Two of the bridges had pH as low as 10 at the level of the reinforcing bar: McKinleyville (WV) and Roger's Creek (KY). The Roger's Creek bridge had pH measurements that ranged from 7 to 13. Results are listed in Table 5.

Table 5 – Summary of tests on concrete

No.	Name (Bridge I.D.)	Carbonation		Chloride penetration		Chloride-ion content		pH	
		Depth, in.	No. of tests	Depth, in.	No. of tests	Percentage	No. of tests	Ave.	No. of tests
1	Gills Creek, Virginia (VA)	None	3	<1/2	3			12.2	6
2	O'Fallon Park, Colorado (CO)	1/ 2 – 3/4	3	<1	3			12.1	2
3	Salem Avenue, Ohio (OH1)	None	2	1.5	1			11.6	6
4	Bettendorf, Iowa (IA)	< 1/4	3	1	3			12.1	6
5	Cuyahoga County, Ohio (OH2)	< 1/4	3	1 – 2.5	3	Insignificant	2	12.2	9
6	McKinleyville, West Virginia (WV)	NA		<1	1			10	3
7	Thayer Road, Indiana (IN)	NA		Minor	1			12	3
8	Roger's Creek, Kentucky (KY)	NA		None detected	1			10	3
9	Sierrita de la Cruz Creek, Texas (TX)	3/4 - 1	?	NA				11.5	3
10	Walker Box Culvert, Missouri (MO1)	None	1	None detected	1			11.5	3
11	Southview, Missouri (MO2)	None	1	None detected	1			11.5	NA

Review Comments on Report Test Results

Several different types of test were performed on removed core and GFRP samples attempting to evaluate if the embedded GFRP reinforcing bars deteriorated while in concrete due to the alkaline nature of the concrete or the environmental exposure to moisture, chlorides, or cracking.

From a structural engineering design standpoint, the most important issue is: was there any difference in the mechanical properties of the GFRP bars after years of service as compared to the mechanical properties of the GFRP bars when the bridge was constructed.

Unfortunately, mechanical properties in tension were only evaluated on 1 of the 11 bridges. Horizontal shear strength, another mechanical property, was evaluated on 7 of the 11 bridges. The horizontal shear tests values were reported consistent with the horizonal shear value of modern GFRP bars.

The tests on the GFRP bars and on the concrete assist in establishing characteristics that may promote deterioration. However, these tests did not appear to provide any significant insight into whether deterioration of the GFRP bar occurred or not.

Comments on GFRP Test Results

Fiber content – Assuming the fiber content met the original ASTM specification when the bridge was constructed, there does not appear to be a decrease in fiber content due to embedding the GFRP bar in concrete. It is unclear why the image analysis testing had a smaller fiber content than the burn-off test. The report did not provide an explanation. All the fiber contents effectively met the ASTM D7957 requirements.

Water absorption – Samples from eight bridges were tested for water absorption. Water absorption results were highly variable. ASTM D7957 established a maximum limit of 1 percent absorption. Three of the 8 bridge samples exceeded this weight change limit at the equilibrium state. No tests were conducted on the Sierrita de la Cruz Creek Bridge for relative comparison to changes in mechanical properties.

Moisture content – The report states that 5 of the 11 bridges had samples tested for moisture content. The report appendix only list results for 2 of the bridges. Apparently, the other samples were still under test when the report was prepared. Moisture content was reported as a weight change upon being subjected to drying at 176 degrees F. The ASTM D7957 specifies a maximum of 1 percent water absorption. All reported test results had moisture contents less than 1 percent. No tests were conducted on the Sierrita de la Cruz Creek Bridge for relative comparison to changes in mechanical properties.

Differential and Modified Scanning Calorimetry (DSC & MDSC) – All 11 bridges were tested for the glass transition temperature, T_g, of the polymeric binder used in the GFRP bar. The minimum glass transition temperature from ASTM D7957 is 212 degrees F. Six of the 11 bridges were found to have glass transition temperatures, T_g, less than the recommended minimum.

Scanning Electron Microscopy (SEM) – Scanning electron microscope visual examination of magnified images by the researchers showed that fibers adjacent to voids in the adhesive binder appeared to be damaged. This damage could have been the result of the preparation process and not the result of any deterioration from the environment. Deterioration of GFRP fibers typically appears at the periphery of the bar. The researchers do not report they found deterioration at the periphery.

Energy Dispersive X-ray Spectroscopy (EDS) – These tests showed no apparent signs on deterioration as the chemical elements detected did not change from the distribution of those of a pristine GFRP bar.

Horizontal Shear – Horizontal shear stress is a mechanical property of the GFRP bar, and testing for the horizontal shear strength might provide an indication that the binders in the GFRP bar had deteriorated. Samples from seven bridges were tested including samples from the Sierrita de la Cruz Creek Bridge. The measured values of the horizontal shear strength were "consistent" with horizontal shear strengths listed on current product data sheets. The Sierrita de la Cruz Creek Bridge horizontal shear test results were above average.

Tension on Full-size GFRP Bars and Modified GFRP Bar Coupon Samples – The method the researchers used to determine if the GFRP bars had deteriorated on one bridge are logical. However, the actual calculated values of maximum stress using the listed area and maximum load are different than what is reported in Appendix VI and the Appendix VI values are not the same as in Tables 20 and 21 of the research report. Additionally, test sample 1L from one of the Sierrita de la Cruz Creek Bridge extracted bars, is ignored because it was reported to have failed at the reduced cross section grip-tab junction. The table in Appendix A of this letter lists all the tensile test results and the maximum stress calculated and maximum stress listed in Appendix VI of the research report. On average, the coupon strength from the Sierrita de la Cruz Creek Bridge is about 3 percent higher than reported in the research report, and, on average, the pristine coupon is about 3 percent lower than reported in Table 20

Independent calculations using the data in Appendix A and using the procedure outlined by the researchers shows the following results, see Table 6.

Table 6 – Estimate of long-term deterioration amount

<table>
<tr><th>Sample type</th><th>Source</th><th>Average Maximum Stress* (psi)</th><th>Number of tests</th><th>Coefficient of Variation, percent</th><th>Difference between pristine coupon and pristine full-size bars</th><th>Difference between in-service coupon and vintage full-size bars</th></tr>
<tr><td>Full-size</td><td>Pristine new bars</td><td>119,318</td><td>10</td><td>2.55</td><td rowspan="2">18.1
(A)</td><td></td></tr>
<tr><td>Sawn coupons</td><td>Pristine new bars</td><td>97,757
(96,997)</td><td>10</td><td>9.85</td><td></td></tr>
<tr><td>Full-size</td><td>Vintage</td><td>113,840</td><td>4</td><td>6.06</td><td></td><td rowspan="2">20.7
(B)</td></tr>
<tr><td>Sawn coupons</td><td>In-service</td><td>90,271
(90,110)</td><td>9</td><td>10.01</td><td></td></tr>
</table>

*Values in italics are the average stress in Table 21 of the research report

The *Change Between Extracted Coupon and Vintage Full-size Bar* (B) is greater than the *Change Between Pristine Coupon and Pristine Full-size Bar* (A) so there is an implied deterioration of 2.6 percent.

An alternate way of assessing potential deterioration is to compare ratios of pristine coupons/pristine bars to in-service coupons/vintage bars. By calculating the ratio of the pristine coupon to the pristine bar, a sense of the strength reduction from using coupons as part of the testing procedure is estimated. Once this ratio is known, the in-service coupon strength can be converted to an equivalent in-service bar strength and then be compare it to the vintage bar strength.

Table 7 summarizes this second approach. It is noted that the ratios of the coupon to full-size bar for each case are nearly the same (0.82 to 0.79). The magnitude of these ratios implies two things: a) the coupon testing method should give lower test results, and b) if the ratios were close to 1.0 there would likely be no deterioration of the GFRP in-service bars. Using this simplified approach, the deterioration is estimated to be 3.2 percent, not much different than the 2.6 percent using the researchers' method of assessment and the revised values of maximum stress.

Table 7 – Alternate estimate of long-term deterioration amount

Sample type	Source	Average Maximum Stress (psi)	Ratio pristine coupon to pristine full-size bar	Ratio of in-service coupon to vintage full-size bar
Sawn coupons	Pristine new bars	97,757	97,757/119,318 = 0.82	
Full-size	Pristine new bars	119,318		
Sawn coupons	In-service	90,271		90,239/113,840 = 0.79
Full-size	Vintage	113,840		
Deterioration estimate	90,271 / 0.82 = 110,181		1 – [110,181 / 113,840] = 0.0321 x 100 = 3.2%	

The sawn coupon test procedure has not been validated but was a means for the researchers to assess the bar strength for the GFRP samples removed from the Sierrita de la Cruz Creek Bridge. Not discussed in the report is the variation of the test results by location of the coupon sample, that is, left, center, and right. GFRP bars deteriorate from the outside toward the center. The researchers averaged all the in-service coupon tests to obtain an average strength of the in-service GFRP bar discarding one test due to the location of the failure. However, if the discarded test, 1L, actually represents deterioration of the GFRP bar it should be included in the sample database. The left and right coupon averages when compared to the center coupon average are anywhere from 10 to 20 percent less that the center. This fact opens the question whether the GFRP bars deteriorated more than the calculations in Tables 6 and 7 imply. Test results in Table 8 summarize this observation.

Table 8 – Coupon tests from Sierrita de la Cruz Creek Bridge analyzed by location in original bar sample

Bar Sample No.	Left	Center	Right
1	67457	93034	95779
2	90771	100336	87064
3	74353	99591	81238
Average	77527	97654	88027
Percentage change from center	77527/97654 = 0.79		88027/97654 = 0.90

Comments on Concrete Test Results

Carbonation depth – Carbonation depth is an important characteristic for steel reinforced concrete. Its usefulness for GFRP reinforced concrete is not as important other than to make a comparison to concretes reinforced with steel. There was nothing too surprising about the carbonation depth data. It appears normal except for the Sierrita de la Cruz Creek Bridge where the carbonation depth approaches 1 inch. This is an unusually high carbonation depth for a concrete that is only 19-years old. However, not knowing anything about the aggregates, mixture design, and concrete strength, there is no clear cause for this unusual carbonation depth. The other carbonation depths look normal.

Chloride penetration and Chloride-ion content – These two measurements are coupled. The chloride penetration test only tells how deep the chlorides penetrated and not the magnitude of the chloride-ion amount. The report also does not indicate if the penetration depth has a chloride threshold needed for the surface to indicate chloride. Only one bridge had both the chloride penetration and chloride-ion content tested. The chloride-ion test implied an insignificant amount of chloride existed whereas the chloride penetration test indicated chlorides penetrated 1 to 2 inches from the top surface of the deck slab. The location of the chloride-ion test sample in the extracted core is not identified. It is questionable if any conclusions regarding durability can be gleaned from these two tests.

Concrete pH – Concrete pH is a good indicator of how much passivation protection may exist for embedded steel reinforcing bars when in an aggressive corrosion environment. Other research, Trejo et.al.*, has reported that high alkalinity and moisture is an environment that is not good for GFRP bars. It is suspected that these pH measurements were made to show that steel would probably be corroding in most of these concrete environments and that the GFRP bar is not corroding.

*(David Trejo, Paolo Gardoni, and Jeong Joo Kim, Long-Term Performance of Glass Fiber-Reinforced Polymer Reinforcement Embedded in Concrete, ACI Materials Journal, Vol 108, Issue 6, Pgs. 605-613, November -December 2011)

Final Comments and Conclusions

General Comment on Research Report

The research report lacks complete information. It would have been informative to know if the sample bridges see traffic, see deicing salts, whether it ever had any maintenance, or if anyone dragged a chain to test for delaminations. The report is difficult to read because of poor editing. Consistency between the appendices and the report is lacking. Tension test results do not appear to be calculated correctly from the given information in the Appendix VI and data reported in Tables 20 and 21 are not in agreement with the as-listed data in Appendix VI. Therefore, it becomes unclear what the actual tensile stress values are because they cannot be independently verified. Coupon test results from the left and right were not compared to the center coupon. Coupons from pristine bars were treated in the same fashion except that there were 10 tests from an unknown number of pristine GFRP bara and no record exists of the location from where the 10 coupons were removed. It is unclear if the left, center, and right coupons from pristine bars behavior the same way the coupons that were removed for the Sierrita de la Cruz Creek Bridge. If the coupons behave differently, then the deterioration could be an order of magnitude greater than the research report calculates.

Comments on Usefulness of the Tests Conducted

Tables 4 and 5 of this letter lists and summarizes the tests conducted on the GFRP bars and surrounding concrete. An opinion of the usefulness of these tests in assessing the durability of embedded GFRP bars is summarized in Table 9.

Table 9 – Summary of test usefulness

<table>
<tr><th rowspan="2">Test</th><th rowspan="2">Researchers' conclusions</th><th colspan="2">Reviewer's opinion relative to providing durability information</th></tr>
<tr><th>Useful</th><th>Not useful</th></tr>
<tr><td>Fiber content</td><td>Meets ASTM specifications</td><td>X</td><td></td></tr>
<tr><td>Constituent Volume by Image Analysis</td><td>No conclusion related to other fiber content measurements</td><td></td><td>X</td></tr>
<tr><td>Water Absorption</td><td>Highly variable results</td><td></td><td>X</td></tr>
<tr><td>Moisture Content</td><td>Weight change less than expected</td><td></td><td>X</td></tr>
<tr><td>DSC & MDSC</td><td>Some GFRP bars had T_g less than expected</td><td></td><td>X</td></tr>
<tr><td>Scanning Electron Microscopy (SEM)</td><td>SEM showed small percentage of physical damage</td><td></td><td>X</td></tr>
<tr><td>Energy Dispersive X-ray Spectroscopy (EDS)</td><td>EDS showed no apparent signs of deterioration</td><td>X (good for quality control)</td><td></td></tr>
<tr><td>Horizontal Shear</td><td>Results consistent with current information data sheets; no deterioration apparent</td><td>X (easy test to run)</td><td></td></tr>
<tr><td>Full-size bar test</td><td rowspan="2">Report estimates 2% deterioration of GFRP bars</td><td>X (use longer full-size bars)</td><td></td></tr>
<tr><td>Modified bar sample</td><td></td><td>X (procedure not validated)</td></tr>
<tr><td>Carbonation depth</td><td>Irregular carbonation depth measured</td><td>X</td><td></td></tr>
<tr><td>Chloride penetration</td><td>Chlorides may have reached depth of GFRP reinforcing</td><td></td><td>X</td></tr>
<tr><td>Chloride-ion content</td><td>No comments made</td><td>X</td><td></td></tr>
<tr><td>Concrete pH</td><td>pH between 9 and 11 meeting expectations of the concrete</td><td>X</td><td></td></tr>
</table>

Comments on Tension Tests Conducted

It is unfortunate that several long GFRP bars, preferably 36-in long, were not removed from each bridge. Surely there are areas in all 11 bridges were the GFRP bars were not in tension. Sacrificing a full-size bar in several strategic location in each bridge could have provided much more important data regarding deterioration.

The report provides just the findings of a study on the durability of GFRP reinforcing bars embedded in the deck slab of a bridge. A variety of tests were conducted, perhaps with the hope that the tests would indicate something about the durability of in-service GFRP reinforcing bars after some 15 to 23 years of service. A conclusion section is provided, but it does not say much about how the testing helped determine the durability of the in-service GFRP reinforcing bars. My conclusion is that most of the testing was inconclusive and not useful relative in evaluating durability. The only tests that may have some bearing on durability are those that could have been used to compare the condition of the concrete in these bridges to concrete in other non-sampled bridges containing embedded steel reinforcement.

The key objective was to determine if the GFRP bars had deteriorated due to any cause. Yet only one of the 11 bridges had bar samples removed that were longer than the core diameter. Only reduced size coupon samples from 3 bars were tested. Making small coupons severely limited the effectiveness of the research in evaluating the full-size GFRP bar durability. Likewise, this is a very small database on which to base definitive conclusions. Longer removed bars tested in direct tension had the potential of providing much better and more meaningful data. Removing 22-in long GFRP bar samples from a bridge deck, although not the ideal length, seems long enough to test the full-size bar in a testing machine. Extracting full-scale bars on only one bridge was likewise not the best experimental testing decision.

Testing of the removed GFRP bar samples by making small strip coupons is a methodology that does not appear well founded scientifically. It is a method that has some rational, but the variability in the test results seems much higher that simply testing intact GFRP reinforcing bars. The report listed the coupon tests from in-service GFRP bars that were sliced from left or right of the center coupon. However, the report does not discuss the differences in the left and right results relative to the center coupon. A comparison of that data, done here, implies that the GFRP bar deterioration is more than indicated in the research report. Perhaps 5 times more than the research report implies, that is, 10 percent or more deterioration.

Considering the variability in the “coupon” test results, the method used to assess strength reduction, and the small differences in the reported percentages used to make a comparison, implying that the test data measurements are due to deterioration is suspect. Definitively saying that the deterioration is 2, 3, or 10 percent based upon these test results is very difficult because of the unvalidated method of making the test samples. The reported strength reduction opinion that only a 2 percent change from initial construction exists is probably unwarranted. A more rational engineering opinion, based upon the available left, center, right coupon testing of the bars removed from an existing bridge, is that the deterioration could be 10 percent or more. This would be my conclusion based upon the limited data.

Respectfully submitted,

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Donald F. Meinheit

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Appendix A

Tensile tests reported in Appendix VI of research report

Sample Number	Area, in^2	Peak Load, lbs	Calculated Maximum Stress, psi	Reported psi in Appendix VI	Calculated - Reported	Calculated/ Reported	Percent Difference
Sierrita de la Cruz Creek Bridge Coupons							
1L	0.0405	2732	67457	67442	15	100.022	2.19%
1C	0.0445	4140	93034	93118	-84	99.909	-9.05%
1R	0.0526	5038	95779	95747	32	100.034	3.39%
2L	0.0402	3649	90771	90689	82	100.091	9.06%
2C	0.0446	4475	100336	100215	121	100.121	12.11%
2R	0.0528	4597	87064	87131	-67	99.924	-7.64%
3L	0.0402	2989	74353	74386	-33	99.956	-4.40%
3C	0.0464	4621	99591	99434	157	100.157	15.74%
3R	0.0533	4330	81238	81188	50	100.062	6.19%
Pristine Coupon							
F1	0.0518	5696	109961	110014	-53	99.952	-4.78%
F2	0.0555	4609	83045	83094	-49	99.941	-5.89%
F3	0.0553	4894	88499	88488	11	100.013	1.25%
F4	0.0442	4538	102670	102772	-102	99.900	-9.96%
F5	0.0466	5321	114185	114108	77	100.067	6.71%
F6	0.0454	4065	89537	89583	-46	99.949	-5.09%
F7	0.0439	4110	93622	93740	-118	99.874	-12.60%
F8	0.0471	4609	97856	97934	-78	99.920	-8.00%
F9	0.0521	5207	99942	99929	13	100.013	1.34%
F10	0.0470	4618	98255	98265	-10	99.990	-0.99%
Pristine full-size bars							
1	0.31	37312	120361	120360	1	100.001	0.11%
2	0.31	38008	122606	122608	-2	99.999	-0.13%
3	0.31	35608	114865	114866	-1	99.999	-0.13%
4	0.31	37259	120190	120190	0	100.000	0.03%
5	0.31	38186	123181	123180	1	100.001	0.05%
6	0.31	35264	113755	113756	-1	99.999	-0.10%
7	0.31	37488	120929	120928	1	100.001	0.09%
8	0.31	37212	120039	120040	-1	99.999	-0.11%
9	0.31	36576	117987	117987	0	100.000	0.01%
10	0.31	36972	119265	119265	0	100.000	-0.04%
Vintage full-size bars							
1P	0.3068	35659	116229	116229	0	100.000	-0.02%
2O	0.3068	37519	122291	122291	0	100.000	0.03%
3O	0.3068	32693	106561	106561	0	100.000	0.03%
4O	0.3068	33833	110277	110277	0	100.000	0.00%