

LONG TERM DURABILITY OF CARBON FRP COMPOSITES APPLIED TO RC BRIDGES: STATE STREET BRIDGE ON INTERSTATE 80

Jaron T. Reay[†], Chris P. Pantelides[†],
Lawrence D. Reaveley[†], Terry A. Ring*

[†]Department of Civil and Environmental Engineering,

*Department of Chemical and Fuels Engineering,

University of Utah

Salt Lake City, Utah 84112

ABSTRACT

The purpose of this research was to determine through destructive and non-destructive testing the long-term durability of the carbon fiber reinforced polymer (CFRP) composite system, used as a seismic retrofit of State Street Bridge on Interstate 80. Non-destructive testing was conducted by installing various sensors and instruments at critical locations of the bridge bents, and monitoring the daily measurements. Destructive testing was performed on several different types of CFRP composite test specimens, including CFRP composite tensile coupons, CFRP composite rings, CFRP confined concrete cylinders, and CFRP bond test specimens. Further evaluation methods included thermographic imaging, implemented to detect any voids within the CFRP composite retrofit system, and chemical evaluation of new and aged core samples of the CFRP composite system and substrate. An evaluation of the environmental and ageing effects on the CFRP composite based on the collected data and test results is presented.

KEY WORDS: Carbon Fiber, Durability, Rehabilitation/Reconstruction/Retrofit

1. INTRODUCTION

Several field application studies of FRP materials that have been performed thus far have been limited to visual inspections, and have not provided the type of real-time durability data needed to better understand the effects of environmental conditions on FRP materials. (1) Accelerated testing of Carbon Fiber Reinforced Polymer (CFRP) composites has provided some information regarding composite durability, but there is a genuine need for obtaining durability data from

actual field applications to confirm and validate accelerated testing methods and results. (2) Because of the characteristics of Utah's bridges and the local climate, the State Street Bridge at Interstate 80 in Salt Lake City provides a natural test site for a CFRP composite application. The complete seismic retrofit of this bridge using CFRP composites provided a unique opportunity to perform both destructive and non-destructive long-term durability studies of the CFRP composite system. The scope of this project includes daily data collection from various instruments applied to the retrofitted bridge, strength and chemical testing of both in-situ and isolated laboratory CFRP specimens, and analysis of the collected data and results.

The overall objective of the project is to study the in-situ degradation of strength and modulus of elasticity of CFRP composites applied to R/C concrete bridges as a seismic retrofit system. Specifically, the following objectives are the focus of the project:

1. Evaluate the long-term reduction in strength and modulus of elasticity of the CFRP composite due to environmental factors such as changes in temperature, alkalinity, chlorides, UV light and freezing / thawing cycles.
2. Evaluate the long-term degradation of bond strength between the CFRP composite and the concrete using mechanical and chemical testing, and thermographic imaging.
3. Evaluate the long-term effect of the CFRP composite retrofit on the strength and structural characteristics of the R/C Bridge using strain gauges.
4. Develop a reduction factor to be used in the design of CFRP composites, which incorporates the information gathered from the long-term monitoring of State Street Bridge.

In order to achieve the objectives stated above, several instruments were installed during the construction phase of the retrofit on the east and west bridge bents supporting the eastbound traffic of Interstate 80 over State Street. The instruments include 100 strain gauges (both embedded in the CFRP composite and applied to the outer surface), four thermocouples, two relative humidity / temperature sensors, and six tilt meters. An automated data acquisition system was installed on-site to take measurements from each sensor at regular time intervals. The collected data is sent through a wireless Ethernet communication system to the University of Utah to be stored and analyzed. In addition, several CFRP composite test specimens have been constructed and stored at various locations for future destructive testing. Twelve CFRP composite patches (two layers of 406x406 mm composite) were attached to the side of the bent cap, to be used for tensile coupon testing. Rectangular plates and CFRP composite cylinder rings, prepared during the construction phase, were also used for tensile testing. They are stored in three different locations: on top of the bent cap of State Street Bridge, inside a cage located at ground level between two columns of the bridge, and in an isolated area of the Structures Laboratory at the University of Utah. The purpose of having three different locations is to compare the results from the testing to determine which environmental conditions have the greatest effect on CFRP composite durability. Additional test specimens include twelve concrete blocks with strips of CFRP composite on two sides, which are used to perform composite-to-concrete bond tests, and 150mm x 300mm CFRP composite confined concrete cylinders. These specimens are also stored in the three locations mentioned above. Testing of each type of specimen is performed at six-month intervals.

Much has been learned through the analysis of data collected by the data acquisition system and from destructive testing. The results indicate that environmental conditions do have an effect on the durability of the FRP composite. Strain in the composite is generally increasing, and all types of destructive testing but one indicate that the test specimens stored in the laboratory have a higher strength value than those stored in the field. Ageing of the epoxy resin is also an issue affecting the durability of the FRP composite, specifically the quality of the composite-to-concrete bond. However, the amount of data available for analysis is still limited, and the destructive test results are only beginning to show trends. Therefore, it is difficult to predict future strength and modulus value trends to an acceptable degree of certainty. Hence, further testing, monitoring of the instruments and analysis of the provided data is continuing.

2. INSTRUMENTATION

The type of data that would be needed to properly evaluate the long-term effects of the environment on the CFRP composite guided the choice of sensors to be used. Critical locations at the bridge bents, where the retrieved data would be most meaningful, were selected, and the specific location for each sensor was determined. The total work plan for the instrumentation of the bridge involved installing 100 strain gauges (both embedded in the CFRP composite and applied to the outer surface), four thermocouples, two relative humidity / temperature sensors, and six tilt meters. Each sensor was then connected to an automated data acquisition system, which takes readings from each sensor at a specified time interval. A wireless Ethernet connection from the University of Utah to the data acquisition system allows the collected data to be downloaded. The installation of these sensors and instruments occurred both during and after the application of the CFRP composite to the State Street Bridge bents. The following describes the location of each sensor, when the instruments were installed, and the applicability of the data provided by that type of sensor.

2.1 Strain Gauges The use of strain gauges is a common method of obtaining non-destructive data for the strength and structural characteristics of a structural element. For this application, the long-term change in strain at specific locations provides useful data for determining the strength degradation. Therefore, strain gauges were applied to all critical locations of the bridge bents in order to monitor them for any strength degradation. These locations include the bent cap-column joint, the bottom of one of the midspans of the bent cap between two columns, the CFRP composite U-strap connecting the column to the bent cap, the 360 degree completely wrapped CFRP composite stirrups, and the top and bottom regions of the columns. The CFRP composite layer in direct contact with the concrete was expected to see a different magnitude of strain than the final layer, so strain gauges were applied to both the first and last layers of the CFRP composite in each location; thus, the distribution of strain through the thickness of the composite could be obtained. The strain gauges were applied to the bridge bents throughout the construction period.

2.2 Thermocouples The use of thermocouples is a common method for measuring temperature changes. They are most useful because they are durable and can be embedded into concrete to find the internal temperature. In this application, it is important to know the temperature at all times because the CFRP composite is affected by even small temperature changes. It was decided that since other sensors would be monitoring the ambient air temperature, the

thermocouples would be embedded into the concrete. Therefore, the temperature change in the concrete and through the thickness of the composite could be monitored. Four thermocouples were embedded into the southeast bent: two on the south end, and two on the north end. The locations of the thermocouples are shown in Figure 1. They are labeled S1, S2, N1, and N2.

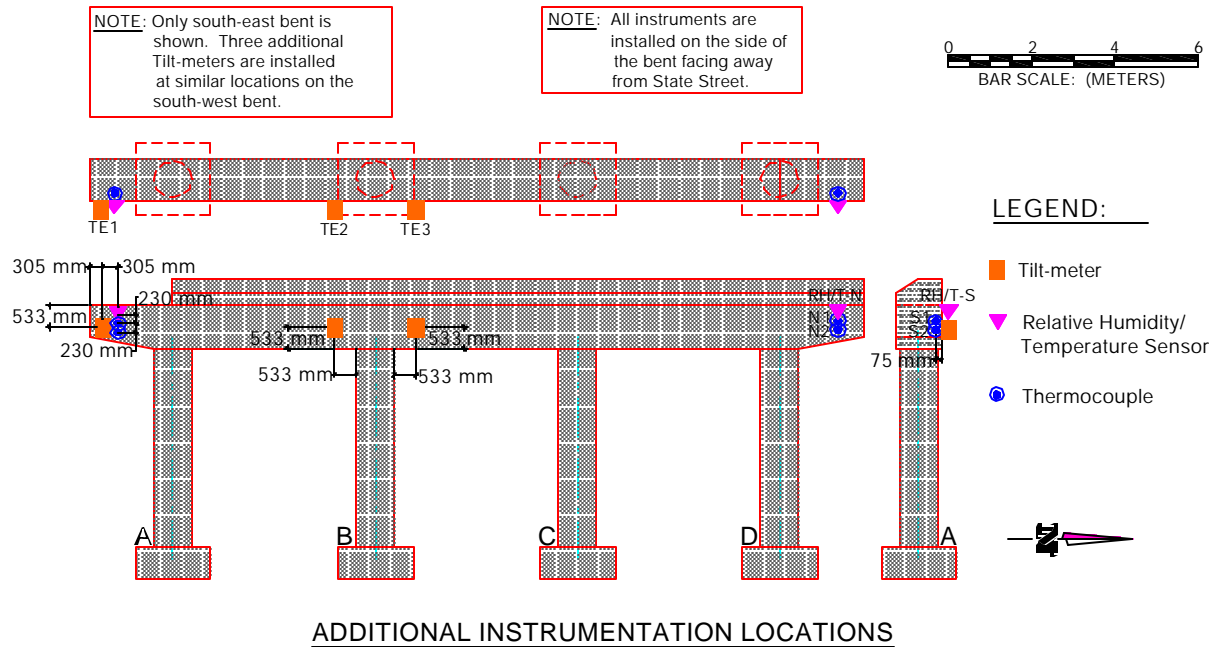


Figure 1. Sensor locations for the southeast bridge bent

2.3 Relative Humidity/Temperature Sensors Little is currently known about the effect that moisture and humidity have on CFRP composites in field applications. Laboratory studies have shown that the mechanical properties of FRP composite specimens are not affected by extended exposure to moisture. (3) However, moisture is known to affect the durability of reinforced concrete structures. Therefore, two relative humidity / temperature sensors were installed on the southeast bridge bent. They were mounted near the locations of the thermocouples, as shown in Figure 1, so the air temperature readings they provided could be compared to the internal temperature readings from the thermocouples, and a direct correlation between the readings could be established.

2.4 Tilt Meters Another variable that was monitored was the deflection of the bent at the cantilever ends and the midpoints between the columns of the bent cap. Since this is a field application open to the public, many of the traditional deflection measurement techniques were not possible. It was therefore decided that the best way to determine deflection patterns at these points would be to measure the rotation of the bent cap. Therefore, tilt meters were mounted at critical points to measure bent cap rotation. Three tilt meters were mounted on the southeast bent and three in similar locations on the southwest bent. The locations of the tilt meters are shown in Figure 1.

2.5 Data Acquisition System The data acquisition system, thermocouples, relative humidity / temperature sensors and tilt meters were installed on the bridge bents in January 2002. Two

separate dataloggers were installed at the bridge: one on the southeast bent and one on the southwest bent. The dataloggers were then programmed to automatically take readings from each sensor every three minutes, and report the average reading every 15 minutes. This translates into 96 recorded data points for each sensor every day. The dataloggers began recording data on January 19, 2002, and continue to do so at present. A wireless Ethernet system was installed in May 2002 to retrieve the stored data from the dataloggers. The data is transmitted from an antenna at the bridge site to a receiver at the University of Utah and is then downloaded to a computer.

3. INSTRUMENTATION DATA ANALYSIS RESULTS

Analysis of the collected data indicates that on a daily basis, temperature has the greatest effect on the strain in the composite. Figure 2 shows typical strain measurements taken over a seven-day period, from two strain gauges located on the bottom of the bent cap at the midspan. CFRP composite has a negative coefficient of thermal expansion, which means that as the temperature rises, the composite contracts and the strain decreases; as the temperature decreases, the composite expands and the strain increases. The sample data of Figure 2 shows this pattern for each day. The strain peaks at about 7:00 am, and as the temperature rises throughout the day, the strain decreases. The valleys occur at about 5:00 pm, and as the temperature decreases, the strain increases once more. In most cases, the change in strain from peak to valley due to temperature change is less than 80 microstrain. This is small compared to the ultimate tensile capacity of the CFRP composite material, which is approximately 13,000 microstrain.

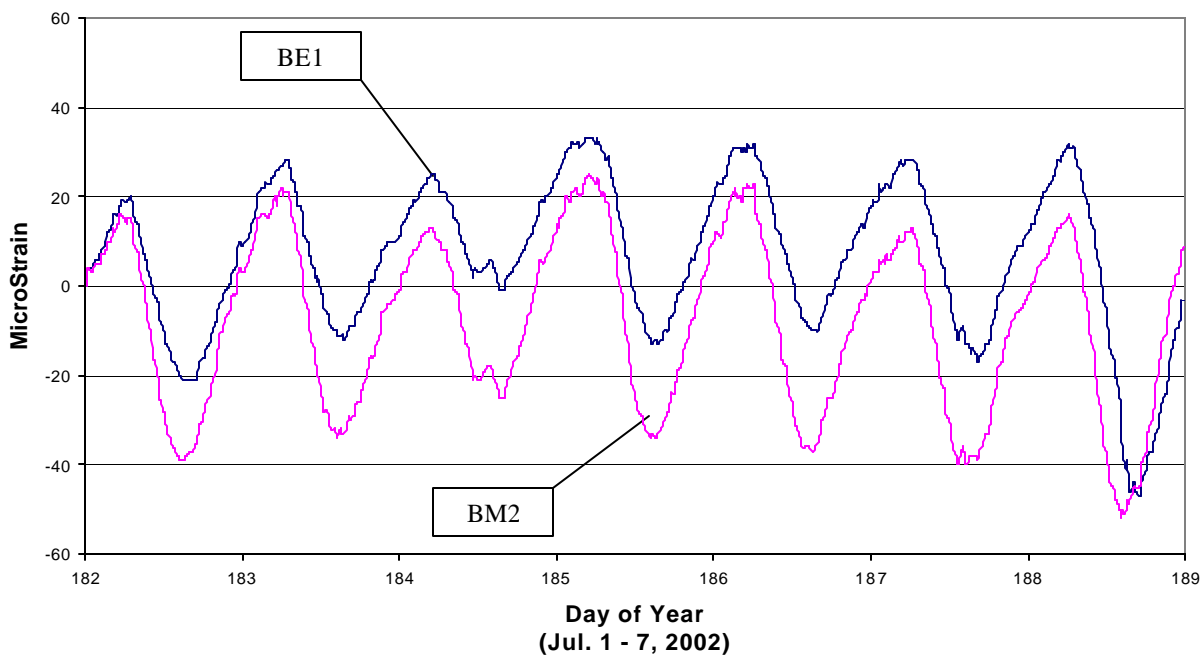


Figure 2. Data recorded from southeast bent strain gauges

Although temperature has the greatest effect on daily strain in the composite, the strain at each gauge location is generally increasing. Figure 3 shows the average monthly strain measurements of several randomly chosen strain gauges, plotted against temperature over a two-year period. The general increase in strain over time, regardless of temperature, is apparent, increasing to an average of over 600 microstrain. The average strain reading of all strain gauges increased from 320 microstrain in July 2002, to 785 microstrain in July 2003. This general increase in strain readings indicates that other factors are contributing to the strain in the CFRP composite, in addition to temperature.

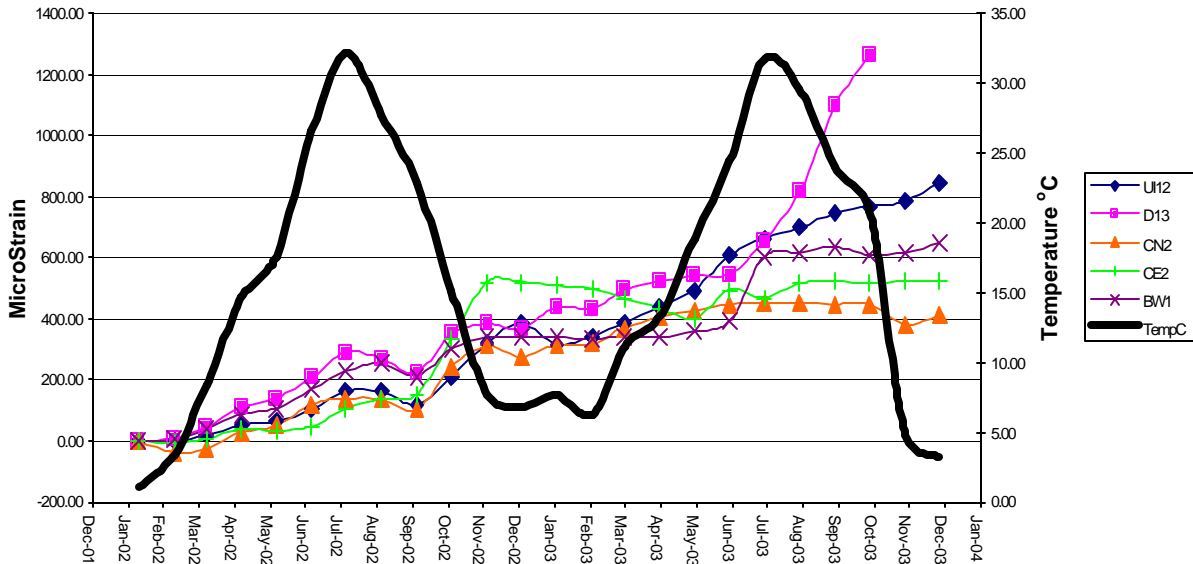


Figure 3. Average monthly strain vs. average monthly temperature

Humidity was also a variable that was considered as a possible influence on composite strain, but no discernable pattern or link could be found in the data between change in strain and humidity. However, humidity may be an important factor when considering other durability issues such as epoxy resin ageing, and bond strength between the FRP composite and concrete.

Depending upon their location on the bent cap, tilt meters translate a negative deflection as either a positive or a negative rotation. As shown in Figure 4, each tilt meter shows a change in rotation from April to July of 2003. These rotations all translate into negative deflections. It is unknown why these rotations exist. Temperature change was considered, but as the temperature decreased, the rotations did not return to zero, making temperature change an unlikely explanation. Although the reason for the rotations is unknown, the magnitude of the rotations is small enough to be considered negligible. The largest changes in rotation translate into a deflection at the midspan of approximately 0.01 mm, and a deflection at the cantilever end of about 0.008 mm.

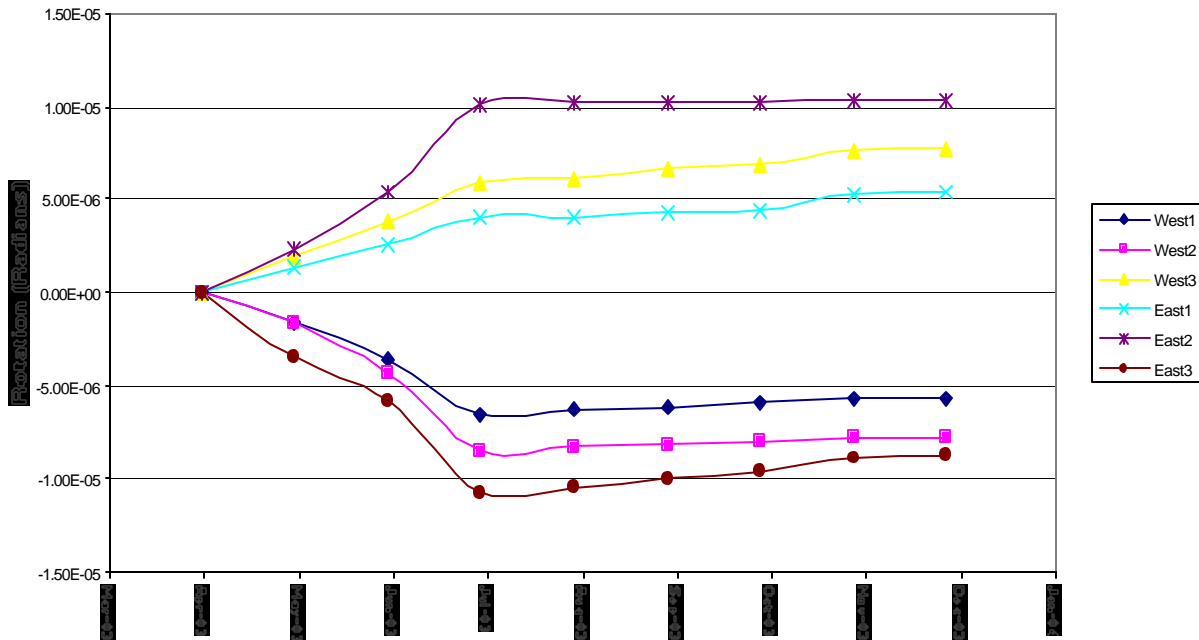


Figure 4. Tilt meter change in rotation

Daily tilt meter degree of rotation generally remains within $\pm 2.0 \times 10^{-6}$ radians, which indicates a deflection at the midspan of less than 0.005 mm, and a deflection at the cantilever end of less than 0.004 mm. Figure 5 shows that the tilt meters experience the greatest rotations between 3:00 pm and 6:00 pm when the traffic is heaviest, which is as expected.

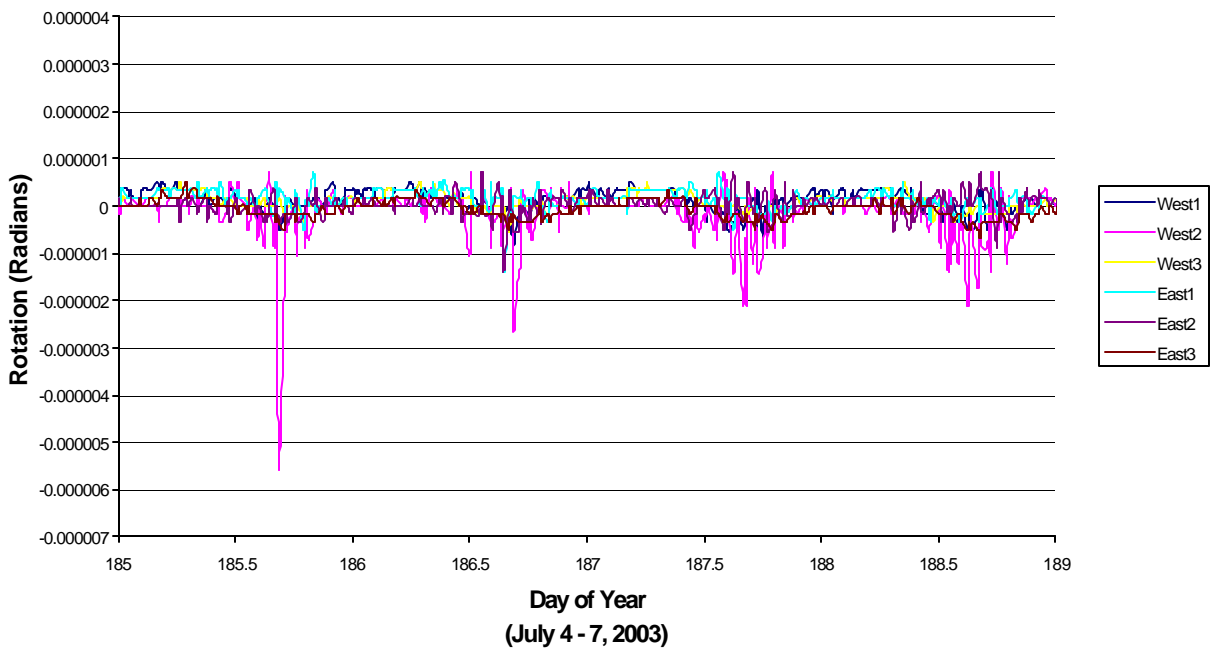


Figure 5. Data recorded from tilt meters

4. DESTRUCTIVE TEST RESULTS

The most direct way to monitor the degradation of strength and modulus of elasticity of CFRP composites applied to the State Street Bridge is through destructive strength tests of various types of specimens. The specimens are tested at six-month intervals in order to monitor the change in strength over time. Four types of specimens were prepared during the construction phase of the project: CFRP composite tensile coupons, CFRP composite rings, CFRP confined concrete cylinders and CFRP bond test specimens.

4.1 CFRP Composite Tensile Coupons The first type of specimen is a tensile coupon, used to determine the tensile strength of the CFRP composite. This information relates to the composite on the beam cap, specifically the U-straps and 360 degree completely wrapped stirrups. The tests are performed in accordance with ASTM D3039-00 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. (4) The test is performed using tensile coupons from two different kinds of specimens. The first kind is a CFRP composite patch (two layers of 400x400 mm composite), which was attached to the side of the bent cap on State Street Bridge. Half of the patch is covered with a UV protective coating, and the other half is uncovered in order to determine what effect, if any, the coating has on the composite. The second kind of tensile test specimen is a CFRP composite panel (two layers of 355x355 mm composite) made during the construction phase of the project. A number of tensile coupons from these panels were tested on a weekly basis throughout construction of both the east and west bents for quality control purposes. The average stress from these tests was 1190 N/mm^2 with a standard deviation of 118 N/mm^2 . The remaining panels were stored at three different locations: on top of the bent cap at the State Street Bridge, inside a cage located at ground level between two columns of the State Street Bridge, and in an isolated area of the Structures Laboratory at the University of Utah. The purpose of having three different locations is to compare the results from the testing to determine which environmental considerations have the greatest effect on CFRP composite durability. Each round of testing involves tensile coupons cut from one panel from each of the three storage locations, and from both sides of one patch from the side of the bent cap on the State Street Bridge, providing five categories of specimens for comparison. The results from the tests performed thus far indicate that the ultimate strength in every group but one is increasing. The increase in ultimate strength for each group ranges from 3% to 16%, except for the Bent Top Panels, which show an ultimate strength decrease of 12% over the last 18 months. Each group showed a decrease in ultimate strain, ranging from 30% to 33%. The laboratory panels had the highest overall strength. The complete results from the tests are given in Table 1.

Specimen Category	Specimen Age (months)	Average		Average		%Change in Stress from Baseline	%Change in Strain from Baseline
		Ultimate Stress (N/mm ²)	Standard Deviation (N/mm ²)	Ultimate Strain (%)	Average Modulus (E) (N/mm ²)		
Baseline Panels	0	1193	118	1.24	NA	-	-
Lab Panels	18	1236	43	1.30	79834	3.57	4.84
	24	1250	93	0.87	92848	4.78	-30.14
	30	1383	108	0.84	100218	15.92	-32.53
Cage Panels	6	1117	90	1.26	80315	-6.34	1.61
	12	1245	71	0.94	96064	4.36	-23.92
	18	1349	96	0.84	90639	13.06	-32.10
Bent Top Panels	18	1337	58	1.29	91555	12.11	3.76
	24	1226	80	0.92	87510	2.80	-25.94
	30	1196	94	0.84	88822	0.22	-32.58
Painted Patches on Bent Cap	24	1167	40	0.89	87508	-2.15	-28.11
	30	1229	104	0.87	88272	3.00	-30.00
Unpainted Patches on Bent Cap	18	1027	74	1.14	79903	-13.95	-8.06
	24	1165	98	0.83	89427	-2.31	-32.93
	30	1242	100	0.86	82305	4.08	-30.97

NA = Not Available

Table 1. Test results from CFRP composite tensile coupons

4.2 CFRP Composite Rings The second type of test specimen was created for a hoop strength test. This test provides information on the CFRP strength representing applications such as circular columns. Throughout the construction phase of the project, CFRP composite cylinders were made by wrapping 500 mm diameter, 610 mm tall stainless steel drums with five layers of the CFRP composite. After the composite had cured, the cylinders were removed from the drums, and taken to the three different storage locations mentioned earlier. Testing of the rings was performed according to ASTM D2290-00. (5) The cylinders were cut into 25 mm rings, then placed in a split-ring test fixture, which expands the ring at a constant rate until failure occurs. The test fixture records the load (stress), and strain gauges measure the strain. In preliminary testing, the strain along the circumference of the rings was evenly distributed throughout the entire test. For that reason, it was decided that only two strain gauges were needed to monitor strain in the rings, and the measured strain would be representative of the strain around the entire ring. The results from the tests performed thus far have been tabulated and are shown in Table 2. Each group of rings exhibited a drop in strength over a one-year period, ranging from 2% to 32%. The strength and modulus (E) values of the field specimens are comparable to the lab specimens of the same age. The ultimate strain of each group fluctuates with time, indicating a possible connection to temperature changes. Overall, the ultimate strain of each group has decreased, exhibiting drops from 10% to 16%.

Specimen** Category	Specimen Age (months)	Average Ultimate Load (kN)	Average Ultimate Stress (N/mm ²)	Average Ultimate Strain (%)	Average Hoop Modulus (E) (N/mm ²)	% Change in Stress from Baseline*	% Change in Strain from Baseline*	
Lab Rings	A	12	250	1261	1.26	99216	-	-
	A	18	274	1240	1.45	81507	-1.70	14.76
	B	24	234	1356	1.21	111666	-	-
	B	30	219	1123	1.49	87733	-17.21	23.34
	B	36	204	922	1.09	82741	-32.02	-9.77
Cage Rings	C	12	244	1296	1.24	102127	-	-
	C	18	207	1223	1.56	98871	-5.60	26.21
	C	24	208	1258	1.08	114623	-2.97	-12.62
Bent Top Rings	D	24	255	1189	1.27	97292	-	-
	D	30	242	1055	1.47	76541	-11.28	16.43
	D	36	224	981	1.07	91339	-17.49	-15.48

* Baseline is taken as the results of the first test performed on that group, regardless of specimen age.

** Two different cylinders (A and B) were used to provide the rings for the Lab group tests. Only one cylinder (C) was used to provide all of the rings for the Cage group tests, and only one (D) was used for the rings for the Bent Top group tests.

Table 2. Test results from CFRP composite rings

4.3 CFRP Confined Concrete Cylinders The third type of test specimen is a 150mm x 300mm concrete cylinder wrapped in one layer of CFRP composite with a 150 mm overlap. These cylinders are used in compression tests, and represent the additional column compressive strength and strain provided by the confinement of the composite. The 28-day concrete strength was approximately 24 N/mm². Each cylinder was instrumented with strain gages to measure hoop strain, and an LVDT to measure axial strain. The test is performed on three cylinders from each storage location, and the average results are calculated. Table 3 shows the average strength values for each specimen category from the tests performed to date. The test results show that the initial increase in the stress capacity of the cylinders is nearly three times that of the stress capacity without the CFRP composite confinement. However, after the six-month time interval between tests, each group of specimens experienced a decrease in strength capacity, ranging from 3.5% to 13%. The Bent Top cylinders showed the largest decrease. Ultimate strain capacity in the Bent Top specimens showed a decrease as well, in both radial (-22%) and axial (-3%) strain. Specimens from both the Laboratory and Cage groups showed increases in ultimate strain, ranging from 10% to 21% in radial strain, and 0.7% to 11.5% in axial strain.

Specimen Category	Specimen Age (months)	Average Ultimate Stress (N/mm ²)	Average Ultimate Radial Strain (%)	Average Ultimate Axial Strain (%)	% Change in Stress from Baseline	% Change in Radial Strain from Baseline*	% Change in Axial Strain from Baseline*
Lab Cylinders	12	69.17	1.33	1.38	-	-	-
	18	63.02	1.46	1.39	-8.89	9.77	0.72
Cage Cylinders	12	70.77	1.25	0.96	-	-	-
	18	68.33	1.51	1.07	-3.45	20.80	11.46
Bent Top Cylinders	12	72.62	1.41	1.50	-	-	-
	18	63.06	1.10	1.45	-13.16	-21.99	-3.33

* Baseline is taken as the results of the first test performed on that group, regardless of specimen age.

Table 3. Test results from CFRP composite confined concrete cylinders

4.4 CFRP Bond Test Specimens The fourth type of specimen was prepared to perform bond tests. This type of test is intended to determine if any debonding between the CFRP composite and the concrete occurs over time. In addition, any degradation of the bond can be measured. The preparation of these specimens involved twelve 150mm x 150mm x 300mm concrete blocks. One side of each block received water blasting surface preparation, which was used for the surface preparation of the State Street bridge bents as well. All other sides were wire brushed to remove any loose particles. One layer of CFRP composite was then placed on the water blasted side, and another layer was placed on one of the wire brushed sides of each block. The blocks were then stored in the three different storage areas mentioned earlier; i.e. in the Structures Laboratory, in the cages at State Street Bridge, and at the top of the bent cap of State Street Bridge. The bond test was performed in accordance with ASTM D 4541-95 Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers. (6)

Results from the bond tests are shown in Table 4. They indicate that initially, the average bond strength to the water blasted side of the concrete block was 45% stronger than the wire brushed side. However, after the six-month time period between the first two tests, the water blasted side showed a significant loss of strength, ranging from 25% to 35%, whereas the wire brushed groups showed only a 4% to 15% loss in bond strength. It has been determined that the reason for this behavior is because of epoxy resin deterioration. Initially, the epoxy resin strength was greater than the tensile strength of the concrete, so the tensile concrete strength controlled the test results. After 12 months, the epoxy resin had deteriorated to the extent that its strength was no longer greater than the tensile strength of the concrete, so the bond strength controlled the results. It is important to note that even with the epoxy resin degradation, the water blasted side continues to exhibit an average of 24% higher bond strength than the wire brushed side. The results also show that the Laboratory specimens generally perform better than the field specimens, indicating that environmental factors do affect CFRP composite-concrete bond strength.

Specimen Category	Specimen Age (months)	Water Blasted			Wire Brushed		
		Average Bond Strength (N/mm ²)	Standard Deviation (N/mm ²)	% Change in Strength from Baseline*	Average Bond Strength (N/mm ²)	Standard Deviation (N/mm ²)	% Change in Strength from Baseline*
Lab Blocks	6	7.51	1.47	-	5.41	1.41	-
	12	5.38	1.83	-28.35	5.27	1.53	-2.55
	18	5.86	1.03	-22.02	4.75	1.03	-12.10
	24	5.65	1.24	-24.77	5.20	1.17	-3.86
Cage Blocks	6	7.44	0.97	-	5.24	1.92	-
	12	5.99	1.22	-19.44	5.10	1.09	-2.63
	18	5.31	1.03	-28.70	4.34	0.76	-17.12
	24	5.41	1.03	-27.30	4.48	0.76	-14.45
Bent Top Blocks	6	8.06	0.26	-	5.24	1.15	-
	12	4.63	1.46	-42.56	4.20	1.06	-19.74
	18	4.89	0.96	-39.32	3.72	0.83	-28.95
	24	5.24	0.93	-35.00	4.48	0.76	-14.45

* Baseline is taken as the results of the first test performed on that group, regardless of specimen age.

Table 4. Test results from CFRP composite-concrete bond test blocks

5. THERMOGRAPHIC IMAGING

Because of indications of epoxy resin degradation from both the bond test results and CFRP composite ring test specimens, it was necessary to investigate whether or not the CFRP composite applied to the State Street Bridge was experiencing similar degradation. Such degradation would lead to delamination and the formation of voids. Voids in the CFRP composite prevent the full tensile/confinement strength from being utilized, creating weak points. Thus it is important to locate and eliminate any voids in the CFRP composite system.

Thermographic imaging has been used in several past studies as a method of detecting localized bond flaws and voids. (7) In July 2003 several thermographic images were taken at various locations containing possible voids on the southeast bent of the State Street Bridge. When the selected area is evenly heated, properly bonded areas conduct the heat into the concrete. Voids cannot conduct heat into the concrete, and therefore show up as “hot spots” in a thermographic image. Several voids of varying size and shape were discovered within the CFRP composite system. However, it was unknown if these voids formed because of epoxy resin deterioration over time, or if they were the result of careless application of the CFRP composite to the bridge during retrofit construction. Therefore, additional thermographic images were taken six months later to determine if any changes had taken place. Voids formed as a result of epoxy resin deterioration would continue to increase in size over time, and possibly damage the surrounding CFRP composite. If the epoxy was not deteriorating, the voids would remain the same size and shape they were at the time the first images were taken. Figure 6 shows a thermographic image of a void discovered in one of the columns, which clearly shows up as a “hot spot” within the heated area of the column. The left image was taken in July 2003. The right image was taken

five months later in December 2003. Figure 7 shows the same images using a different color palette in order to enhance the visible shape of the void. It appears that the lower-right side of the void has increased in size, indicating probable epoxy resin deterioration. All other voids discovered from images taken in July 2003 did not appear to have changed after the five-month time period. Under normal circumstances, it is recommended that any discovered voids be filled with epoxy resin to regain tensile strength in the FRP composite.

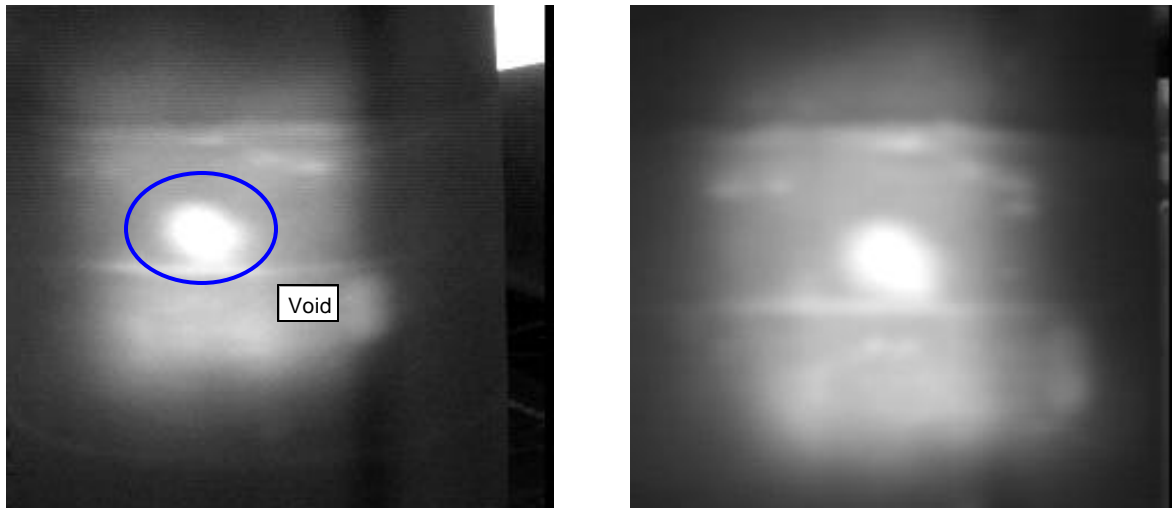


Figure 6. Thermal images of void in column-grayscale palette

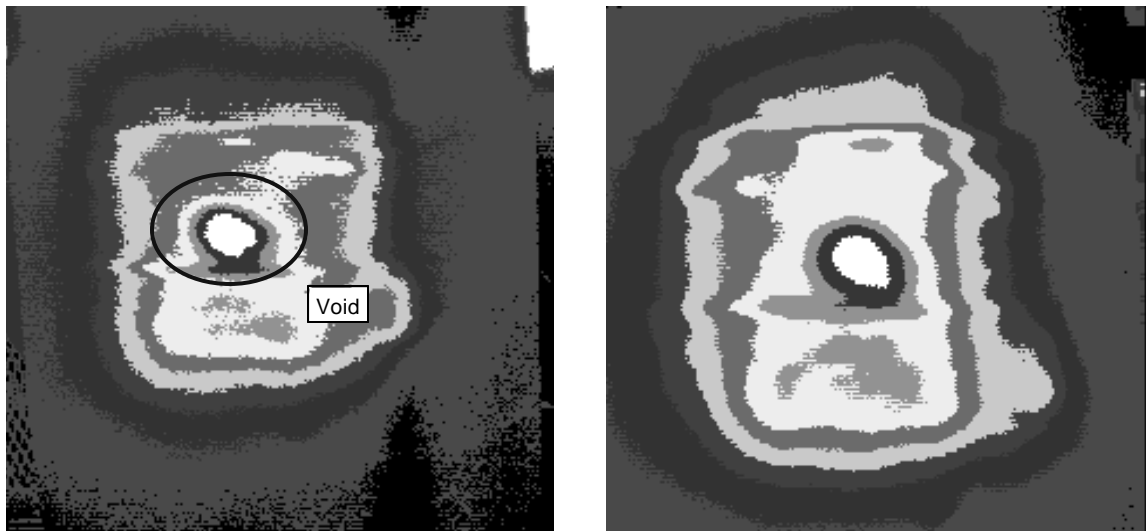


Figure 7. Thermal images of void in column-10 color rainbow palette

6. CHEMICAL TESTING

In the summer of 2001 two 19mm diameter core samples were taken from State Street Bridge for analysis and preservation as a baseline for ageing studies of the CFRP composite system and

coating applied to the bridge. Fourier transform Infrared spectroscopy was the quantitative analysis method used for determining chemical degradation of the CFRP composite system. Reflection spectra were taken from all four layers of the samples (UV protective coating, CFRP composite, adhesive and concrete) using a gold-coated mirror as a reflection background. The reflection spectra were transformed using a Kramer-Konig Transform to give the absorption response as a function of wave number.

In February 2003, a second set of core samples was taken from State Street Bridge. These samples were analyzed using the same quantitative analysis method as before. Substantial differences could be seen in the comparison between the new and aged core sample layers. The results from the comparison between the base samples and the aged samples are as follows.

First, the aged UV protective coating was heavily polluted with hydrocarbon/soot by products. The aged carbon fiber epoxy layer showed indications of a high degree of oxidation, which affects the carbon/epoxy interface causing the bond to become weaker. The aged adhesive sample produced drastically different spectra than the new adhesive sample. The differences indicate oxidation of the adhesive, and diffusion of cement minerals into the adhesive. Oxidation causes the adhesive to become brittle and crack. Diffusion of cement particles into the adhesive, which is most likely due to moisture flow, causes it to lose its elasticity and flexibility. Finally, the aged concrete sample did not show any significant changes from the base sample.

7. REMARKS AND PRELIMINARY CONCLUSIONS

Several patterns and trends have been observed from the bridge sensor data and the destructive test results, which have led to the formation of preliminary conclusions. The following are the preliminary conclusions made so far:

1. Temperature has a greater effect on the daily change in strain in the CFRP composite than any other variable, and definite patterns can be seen in the strain data as the temperature changes throughout each day. However, temperature is not the only environmental variable that affects the strain, as the strain in the composite is generally increasing over time.
2. Data from the tilt meters installed indicate that the rotation of the bent cap at the critical locations is small, as expected.
3. Destructive testing of CFRP composite tensile coupons, CFRP composite rings, and bond strength specimens indicates that the specimens stored in the laboratory generally have higher strength values than those of samples stored in the field, indicating that the environment does have an affect on CFRP composite tensile strength, bond strength and durability. Results from all four test types indicate that the top of the bent cap at State Street Bridge generally caused the largest degradation of strength and strain capacity. However, aging of the CFRP composite is also a major contributor to composite degradation. The ultimate tensile strain of CFRP composite coupons experienced an average drop in capacity of 32%, regardless of the specimen location. CFRP composite rings exhibited a drop in both ultimate hoop stress (from 3% to 32%) and strain (from 10% to 16%), regardless of the location of the specimen. CFRP confined concrete

cylinders showed a drop in compressive strength of 4% to 13%, regardless of the location. The bond strength from CFRP composite-concrete bond test blocks showed a drop in bond strength ranging from 25% to 35%, regardless of the specimen location.

4. Indications of epoxy resin deterioration were noted in two different instances, and led to the discovery of several voids in the CFRP composite system of the State Street Bridge. One void in particular appears to be the result of epoxy resin deterioration. This is the most significant durability concern noted thus far. Because test specimens are experiencing this deterioration regardless of environmental exposure, and it has been most prominently observed in only the oldest test specimens, it has been determined that the reason for this deterioration is epoxy resin ageing.
5. Chemical testing has shown indications of significant oxidation in the FRP composite and adhesive layers of the retrofit system. Oxidation of the epoxy and adhesive causes them to become brittle and crack, weakening the CFRP composite-concrete bond. Diffusion of cement particles into the adhesive was also apparent. This diffusion of cement particles into the adhesive is most likely due to moisture flow, and creates a loss in flexibility and elasticity, which also weakens the CFRP composite-concrete bond strength.
6. Further testing and data monitoring is required to accurately develop reduction factors for design with FRP composites. It is clear, however, that several reduction factors will be required, accounting for different strength variables and aspects of design, such as tensile strength, confinement, ageing, and bond strength.

7. REFERENCES

1. M.H. Teng, E.D. Sotelino and W.F. Chen, Journal of Composites for Construction, ASCE, **7** (2), 83 (2003)
2. A.H Cardon, et.al. in M. El-Badry, ed., Advanced Composite Materials in Bridges and Structures, The Canadian Society for Civil Engineering, Quebec, 1996, pp. 657-663
3. F. Micelli, L. De Lorenzis, A. La Tegola in K.H. Tan, ed., Proceedings of the Sixth International Symposium on FRP Reinforcement for Concrete Structures, World Scientific Publishing Co. Pte. Ltd., Singapore, 2003, pp. 795-804
4. American Society for Testing and Materials, ASTM Standards, **15.03** (15), 105 (2001)
5. American Society for Testing and Materials, ASTM Standards, **08.04** (8), 97 (2001)
6. American Society for Testing and Materials, ASTM Standards, **06.02** (6), 332 (2001)
7. O. Hag-Elsafi, J. Kunin and S. Alampalli, "In-Service Evaluation of a Concrete Bridge FRP Strengthening System/Report FHWA/NY/SR-03/139," March 2003.