LONG-TERM DURABILITY OF FIBER-REINFORCED POLYMERS (FRPS) AND IN-SITU MONITORING OF FRP BRIDGE DECKS AT O’FALLON PARK BRIDGE

Yunping Xi
Sunyoung Chang
Andi Asiz
Yue Li

April 2004

COLORADO DEPARTMENT OF TRANSPORTATION
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The contents of this report reflect the views of the authors, who (are) responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Colorado Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.
Glass fiber reinforced polymers (GFRPs) were selected and used to build the bridge deck for O’Fallon Park Bridge in Denver, Colorado. This report contains two parts. The first part is an in-house experimental study on the durability of the selected GFRPs, and the second part is an on-site loading test for the behavior of one GFRP panel of the bridge and a long-term monitoring study of the panel. The influential parameters for the durability of GFRPs were reviewed, including freeze-thaw cycles, moisture penetration, deicing chemicals, alkali and acid attacks, and ultraviolet light. Experimental plans were carefully designed for the in-house durability study and the on-site loading test, as well as for the long-term monitoring of the bridge panel.

Every environmental parameter tested in the study resulted in a degradation of GFRPs to a certain extent. From the strength aspect, the worst degradation was a 35% reduction of tensile strength of the GFRP subjected to the ponding of 1M NaOH solution. From the stiffness point of view, the worst degradation was a 32% reduction of Young’s modulus of the GFRP subjected to the ponding of 3% Ca(Cl2) solution.

The strains due to the mechanical loading (a CDOT truck) are very small. Therefore, the structural design of the GFRP panel for O’Fallon Park Bridge is very conservative. Comparing the effect of environmental temperature with the effect of mechanical loading, it is very clearly that the effect of temperature is dominant. Therefore, in addition to the mechanical fatigue loading test performed in this project, a larger scale cyclic temperature test for the FRP panel is very necessary and important for evaluating the long-term performance of the panel.

**Implementation:**
The significant degradations in terms of the tensile strength and the stiffness must be considered in the specifications related to the structural design of bridge decks if the GFRP is to be used widely for bridge decks in the state of Colorado. The monitoring process of the bridge deck should be continued. The results obtained so far provide valuable information and can be compared to the strains that will be collected in the future to evaluate the long-term performance of the bridge deck.
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Yunping Xi, Sunyoung Chang, Andi Asiz, and Yue Li

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The Colorado Department of Transportation
Research Branch
4201 E. Arkansas Ave.
Denver, CO 80222
(303) 757-9506
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The writers would like to express their thanks to the Colorado DOT for continuous support and encouragement throughout this study, and specifically to Ahmad Ardani and Richard Griffin of CDOT Research Branch; Trever Wang, Ali Haraj, and Michael McMullen of CDOT Staff Bridge; Greg Lowery of CDOT Staff Materials; and Matt Greer of FHWA for their valuable suggestions and input.
EXECUTIVE SUMMARY

Fiber-reinforced polymers (FRPs) are increasingly being used as reinforcement in new concrete structures and as strengthening materials for the rehabilitation of existing concrete structures. Among various types of FRP materials, glass fiber reinforced polymers (GFRPs) were selected and used to build the bridge deck for O’Fallon Park Bridge in Denver, Colorado. Although much research has been done on the mechanical properties of FRPs, the overall long-term durability of GFRPs under severe environmental conditions has not been systematically evaluated. This is the major focus of the present report, which contains two parts. The first part is an in-house experimental study on the durability of the selected GFRPs, and the second part is an on-site loading test for the behavior of one GFRP panel of the bridge and a long-term monitoring study of the panel.

The influential parameters for the durability of GFRPs were reviewed, including freeze-thaw cycles, moisture penetration, deicing chemicals, alkali and acid attacks, and ultraviolet light. Experimental plans were carefully designed for the in-house durability study and the on-site loading test, as well as for the long-term monitoring of the bridge panel.

Every environmental parameter tested in the study resulted in a degradation of GFRPs to a certain extent. From the strength aspect, the worst degradation was a 35% reduction of tensile strength of the GFRP subjected to the ponding of 1M NaOH solution. From the stiffness point of view, the worst degradation was a 32% reduction of Young’s modulus of the GFRP subjected to the ponding of 3% Ca(Cl₂) solution.

For future work, it is suggested that the degradation of FRP should be tested with coupling effects. Due to coupling effects between moisture and elevated temperatures, the degradation could be accelerated by high diffusion rates. Additionally, the freeze-thaw, alkali attack, UV radiation, and moisture can be applied concurrently to see how the combinations of the influential parameters affect the degradation of the FRP specimens. For the ponding test, the
weights of specimens before and after ponding should be measured and compared. This is an important factor for measuring the moisture intake capacity of the GFRP specimens.

The strains due to the mechanical loading (a CDOT truck) are very small. Therefore, the structural design of the GFRP panel for O’Fallon Park Bridge is very conservative.

Comparing the effect of environmental temperature with the effect of mechanical loading, it is very clear that the effect of temperature is dominant. The maximum strain due to the mechanical loading is 226 microstrain, while the thermal strains in the winter are all higher than that. This means that the temperature variation is more important than the variation of mechanical loading. Therefore, in addition to the mechanical fatigue loading test performed in this project, a larger scale cyclic temperature test for the FRP panel is very necessary and important for evaluating the long-term performance of the panel.
IMPLEMENTATION STATEMENT

The significant degradations in terms of the tensile strength and the stiffness must be considered in the specifications related to the structural design of bridge decks if the GFRP is to be used widely for bridge decks in the state of Colorado.

The monitoring process of the bridge deck should be continued. The results obtained so far provide valuable information and can be compared to the strains that will be collected in the future to evaluate the long-term performance of the bridge deck.
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1. Long-Term Durability of Glass FRPs

1.1 Introduction

Fiber-reinforced polymers (FRPs) are increasingly being used as reinforcement in new concrete structures and as strengthening materials for the rehabilitation of existing concrete structures. The main advantages of FRPs are their lightweight, high strength, and non-corrosive features. Among several types of FRP materials available, glass fiber reinforced polymers (GFRPs) were selected and used to build the bridge deck for O’Fallon Park Bridge in Denver, Colorado. The details on the bridge design and structural analysis of bridge decks can be found elsewhere. (Camat and Shing 2004).

Much research has been done on the mechanical properties of FRPs, and FRP bridge decks have been used in several states in the United States. However, the overall long-term durability of the materials under severe environmental conditions has not been systematically evaluated. This is the major focus of the present report. In order to assess the durability behavior of FRPs in a reasonable period of time, various accelerated aging tests were employed in this study to investigate the deterioration of mechanical properties of GFRP plates in service environments.

1.2 Influential Parameters for the Durability of FRPs

Freeze-thaw cycles

The FRP materials are subjected to freeze-thaw cycles in cold region environments. The influence of freeze-thaw cycles may change the material properties of the FRP. Microcracks and voids in the polymer matrix can occur in FRP materials during a freeze-thaw cycling due to the mismatch of the coefficients of thermal expansion (CTE) of fibers and resin. Because of CTE mismatch and the appearance of the cracks, thermal fatigue can be induced between the fibers and matrix. (Tannous and Saadatmanesh 1998) Dutta (Dutta 1988) reported that the FRPs subjected to 150 cycles between -40 °C and +23.4 °C exhibited a 10% reduction in the tensile
strength. Gangarao and Vijay (Gangarao and Vijay 1997) reported that GFRPs with seven resin types exhibited a 6% loss in tensile strength when exposed to freeze-thaw cycles in a period of 141 days. The same GFRPs when exposed to alkali conditioning showed a 49% loss in tensile strength.

**Moisture penetration**

Moisture diffusion into an epoxy matrix and the susceptibility of the glass fibers to water causes changes in thermophysical, mechanical and chemical characteristics of FRPs. (Jones 1999; Shen et al., 1976) Moisture in the resin weakens the Van der Walls force between the polymer chains, and results in a significant degradation of the FRP material’s Young’s modulus, strength, and glass transition temperature. The swelling stress induced by the moisture uptake can also cause matrix cracking and fiber-matrix debonding (Hayes et al., 1998). GFRPs are particularly sensitive to the influence of moisture content. Hayes et al. (Hayes et al., 1998) reported that the tensile strength and Young’s modulus of glass/vinyl ester laminate was reduced by 26% due to wetting/drying cycles at 45°C after 30 days. Bank et al. (Bank et al., 1998) conducted moisture exposure tests on E-glass/vinyl ester rods that were immersed in water at 40°C and 80°C. The flexural strength of the material was reduced by 85% and 55% at 40°C and 80°C, respectively. Porter and Barnes (Porter and Barnes 1998) exposed a FRP specimen to air at 100% RH at temperatures of 93°C and 23°C for 200 days. Reductions in the tensile strength of the E-glass/vinyl ester laminate were 40% and 25% at 93°C and 23°C, respectively. Verghese et al. (Verghese et al., 1998) studied the effects of moisture uptake and temperature on mechanical properties of FRP materials.

The coupling effect between moisture uptake and temperature is quite complex because a change of temperature can result in a change of diffusion coefficient of FRPs. As a result, the rate of moisture uptake may increase or decrease depending on the orientation of temperature changes. (Verghese et al., 1998) In the literature, the results of degradation of mechanical properties of FRPs obtained by different research groups showed a wide range of deviation.
**Deicing chemicals**

Large amounts of deicing salts are used on bridges during the winter season to control snow and ice. Since FRPs are non-corrosive materials, the deicing chemicals cannot trigger any corrosion damage to the FRPs, though they may have other adverse effects on the fibers, such as degradation of stiffness and strength if the fibers are inappropriately coated and shielded by the resin matrix during the production process. Saadatmanesh and Tannous (Saadatmanesh and Tannous 1997) conducted extensive tests for eight different GFRP rebars by immersing them in three different salt solutions at 25°C for six months: 3% NaCl, 7% NaCl+CaCl₂ (2:1), and 7% NaCl+MgCl₂ (2:1). It was found that the vinyl ester provides a better protection against chloride than polyester and aramid do, and that the carbon tendons have a much better resistance to salt attacks than that of E-glass and AR-glass rebars. Gangarao and Vijay (Gangarao and Vijay 1997) observed the strength and stiffness reductions up to 17% for four different GFRP plates with E-glass fibers immersed in a 4% salt solution for 220 to 240 days at room temperature.

**Alkali attack**

One of the main concerns about the use of FRP products is what the durability in alkaline environments will be, such as the pore solution of concrete. Because of the chemical attack on the glass fibers and because of the concentration and growth of hydration products between individual filaments, the strength and stiffness of FRP materials can be reduced significantly in concrete environments. (Murphy et al., 1999) The durability of FRP materials in the alkaline environment is strongly dependent on resin types and the manufacturing processes. Coomarasamy and Goodman (Coomarasamy and Goodman 1997) conducted tests on different glass fibers containing two types of resin (polyester and vinylester resin). FRP specimens were subjected to an alkaline solution of pH 13.5 at 60°C for eleven weeks. The tensile strength reduction of the polyester type specimens was over a wide range from 7 ~ 80%, and the vinylester type had a tensile strength reduction of 45%. It was shown that GFRPs with polyester resin formed a gel-like material which swelled, followed by blistering and disintegration of the resin. Uomoto et al. (Uomoto et al., 1997) conducted a durability test on GFRPs submerged in a
Na(OH)$_2$ solution at 40°C for 120 days. GFRP specimens experienced a reduction of tensile strength of up to 70%.

_Ultraviolet light_

FRPs may be degraded by weathering effects, particularly by ultraviolet (UV) light. Ultraviolet photons from the natural solar radiation cause photo-oxidative reactions that can alter the molecular chain of polymers and produce microcracking in the polymer. Thus, UV radiation can deteriorate the durability of GFRP. (Singh et al.) In order to investigate the influence of ultraviolet light on FRPs, Rahman et al. (Rahman et al. 1998) conducted some tests on IM7/997 carbon/epoxy composite laminates. A 9% reduction in the transverse strength was evidenced after 1000 hours of exposure to ultraviolet radiation. Surface microcracking and chemical degradation of the epoxy were observed. Sasaki et al. (Sasaki et al., 1997) reported a 40% reduction in the tensile strength of FRPs after exposure to sunshine for 42 months. Kato et al. (Kato et al 1997) conducted the test using ultraviolet rays on GFRP rods for 1250 exposure cycles (102 minutes in dry condition and 18 minutes in wet condition). An 8% reduction in the tensile strength was measured at the 0.2MJ/m$^2$ ultraviolet radiation intensity.

1.3 Experimental Plan

The objectives of the experimental study were to assess the effects of the above mentioned environmental conditions on mechanical properties of GFRPs, specifically on Young’s modulus and tensile strength of the selected GFRP. In this study, the modulus of elasticity (in psi units) is taken as the highest slope of straight line from initial point of the stress-strain curve. The tensile strength of the material is calculated by dividing the maximum applied load by the initial undeformed cross-sectional area of the specimen.

1.3.1 Specimen preparation
The GFRP laminated plates were provided by Kansas Structural Composites, Inc. The plates were cut into small pieces in rectangular shapes by the company. Vinylester was used for matrix material of the specimens. The average width, length and thickness of the specimens are 0.96 in, 9.0 in and 0.14 in, respectively.

1.3.2 Conditioning of specimens

Prior to the testing of specimens for the mechanical properties, the specimens were pretreated by subjecting them to various environmental conditions. This process, referred to as the conditioning of the specimens, is designed to generate deterioration of GFRP materials similar to that experienced in a service environment. After the GFRP specimens were conditioned, the mechanical properties of the conditioned GFRP specimens were evaluated and compared to the GFRP specimens without the conditioning.

Freeze-Thaw Cycles

ASTM C666 (Standard Test Methods for Resistance of Concrete to Rapid Freezing Thawing) was used in the present study for the freeze-thaw conditioning of GFRP specimens, although the testing procedures specified by ASTM C666 were originally designed for the durability of concrete. An environmental chamber manufactured by Russells Technical Products was used for the freeze-thaw conditioning. It is shown in Figure 1.

Figure 1. The environment chamber used in the project
The specimens were subjected to a temperature variation ranging between -20°F (-29°C) to 68°F (20°C), over 8 cycles per day with a one-hour hold at -20°F and a 20-minute hold at 68°F. Figure 2 shows the temperature cycles graphically for a 12-hour period. The specimens were exposed to 300 total freeze-thaw cycles (750 total hours of exposure).

**Wetting and Drying Cycles**

In order to investigate the effects of wetting/drying cycles on the durability of the GFRP, two specimens were immersed in a water bath at room temperature for 30 minutes, then pulled out of the bath and hung in the air for 30 minutes. The wetting/drying cycles were repeated 2,160 times over 90 days. The testing apparatus is shown in Figure 3.
Deicing Chemicals

The influence of deicing chemicals such as magnesium chloride (Mg(Cl)$_2$), calcium chloride (Ca(Cl)$_2$), and sodium chloride (NaCl) on the behavior of FRP materials was investigated. Both long-term ponding tests and long-term cyclic wetting/drying tests in the chloride solutions were carried out. For the ponding test, a total of 15 specimens were immersed in the solutions of three deicing chemicals. The deicer solutions were Mg(Cl)$_2$ of 3%, Ca(Cl)$_2$ of 3%, and NaCl of 3%. The ponding tests were continued at room temperature for 90 days, as shown in Figure 4. For the cyclic wetting/drying test in the chloride solutions, a total of 12 specimens were tested using the same apparatus shown in Figure 3. The three different solutions of the deicing chemicals were used in the bath instead of water.
Alkaline and Acid Attack

Alkaline and acid attacks to GFRPs were simulated by using sodium hydroxide solution (1M NaOH) and hypochloric acid (1M HCl). A total of 4 specimens were submerged in the alkali and acid solutions respectively for 90 days at room temperature in the same manner as shown in Figure 4.

Ultraviolet Radiation

A standard ultraviolet (UV) resistance test based on ASTM G53 was used to simulate the weathering effect, particularly the deterioration of GFRPs caused by sunlight. The testing cycles are specified in ASTM D 5208. Three specimens were exposed to the cyclic fluorescent ultraviolet radiation in an environmental chamber for 90 days based on the Cycle C procedure of ASTM D 5208. The temperature in the chamber was kept at 50°C. The test chamber and the ultraviolet light are shown in Figure 5.
Figure 5. Ultraviolet Radiation Apparatus

Figure 6. Experimental setup for uniaxial tension test of a GFRP specimen
1.3.3 Uniaxial tension tests

The uniaxial tension test was carried out after the conditioning of the specimens was complete in order to investigate the degradation of the GFRPs exposed to environmental conditions. The uniaxial tension tests were performed on a Series 10,000 Bench UTM (Tinius Olsen Machine), as shown in Figure 6. The machine was equipped with a 10,000 lb load-cell. The specimens were inserted between the two grips of the testing machine and then loaded in tension until fracture occurred. To prevent any possible slip during loading, lateral pressure was applied at the grips. The tensile load was applied in the longitudinal direction, as shown in Figure 6. The specimens were subjected to uniaxial loading in tension with a displacement rate of 10 in/min. The load P and the elongation of the specimens were recorded. After the nominal stress and nominal strain were calculated, the Young’s modulus and the tensile strength of the specimens were obtained.

1.4 Experimental Results

(1) Failure pattern

All GFRP specimens failed in a very brittle manner under uniaxial tensile loading, as shown in Figure 7. The explosive failure occurred at the midpoint of the specimens. The failure pattern was consistent for all GFRP specimens with and without the environmental conditioning.
(2) The influence of freeze-thaw cycles

The specimens were subjected to 300 freeze-thaw cycles totaling 750 hours of exposure with the temperature ranging from 20°F (-29°C) to 68°F (20°C). Figure 8 shows the tensile stress-strain response of the GFRP specimen after the freeze-thaw cycling test.

![Figure 8. Tensile stress-strain curves of a GFRP bar after the free-thaw cyclic testing](image)
The stress-strain curve of the GFRP specimen maintained a nearly linear progression up to the failure point.

The Young’s modulus of the GFRP specimens was reduced by 18% after the freeze-thaw conditioning, and the tensile strength was reduced by 10%, as shown in Table 1. The reduction in Young’s modulus could be induced by the thermal fatigue.

The controlled GFRP bar exposed to room temperature at 78.8°F and relative humidity at 35% is used for the comparison of mechanical properties. The degraded tensile strength and Young’s modulus of the controlled GFRP bar were 15 ksi and 1074.4 ksi, respectively.

### Table 1. Mechanical properties of GFRP specimens after the freeze-thaw cyclic testing

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate Tensile Strength (ksi) [Reduction (%)]</th>
<th>Young’s Modulus (ksi) [Reduction (%)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled</td>
<td>15.1</td>
<td>1074.4</td>
</tr>
<tr>
<td>Freeze-Thaw</td>
<td>13.5 [10]</td>
<td>878.1 [18]</td>
</tr>
</tbody>
</table>

(3) The influence of wetting/drying cycles in water

After 90 days of wetting/drying conditioning, the Young’s modulus and tensile strength of the GFRP specimens were reduced by 4% and 27%, respectively, as shown in Table 2.

### Table 2. Mechanical properties of GFRP specimens after wetting/drying cycles in water

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate Tensile Strength (ksi) [Reduction (%)]</th>
<th>Young’s Modulus (ksi) [Reduction (%)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled</td>
<td>15.1</td>
<td>1074.4</td>
</tr>
</tbody>
</table>
The stress-strain curve of the GFRP specimen after wetting/drying cycles in water is shown in Figure 9.

![Stress-strain curve](image)

Figure 9. A tensile stress-strain curve of a GFRP specimen after wetting/drying cycles in water

(4) *The influence of deicing chemicals (the Ponding Test)*

After the ponding test of the three deicing chemical solutions, the tensile strengths of the GFRP specimens were reduced significantly ranging from 12% to 16%, as shown in Table 3.

Table 3. Mechanical properties of GFRP specimens exposed to deicing chemicals (Ponding Test)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Young’s Modulus (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Reduction (%)]</td>
<td>[Reduction (%)]</td>
</tr>
<tr>
<td>Controlled</td>
<td>15.1</td>
<td>1074.4</td>
</tr>
<tr>
<td>Mg(Cl₂) 3%</td>
<td>13.2 [13]</td>
<td>797.5 [26]</td>
</tr>
<tr>
<td>Ca(Cl₂) 3%</td>
<td>13.2 [12]</td>
<td>850.2 [21]</td>
</tr>
<tr>
<td>NaCl 3%</td>
<td>12.7 [16]</td>
<td>768.8 [28]</td>
</tr>
</tbody>
</table>
The reductions of Young’s modulus were significant, from 21% to 28% as shown in Table 3. In terms of each individual deicer, NaCl has the strongest effect on the tensile strength of GFRP specimens, which is 16%, and the strongest effect on Young’s modulus, which is 28%. The ultimate tensile strengths and Young’s modulus exposed to each deicing chemicals are compared in Figure 10.

Figure 10. Comparison of mechanical properties of GFRP specimens exposed to deicing chemicals (the ponding test) (a) Ultimate tensile strength; and (b) Young’s modulus
*(5) The influence of deicing chemicals (Cyclic wetting/drying test)*

Long-term durability tests were conducted for GFRP specimens cyclically exposed to the three deicing salts: Mg(Cl₂) 3%, Ca(Cl₂) 3%, and NaCl 3%. The results of the experiments are shown in Table 4.

Table 4. Mechanical properties of a GFRP bar exposed to deicing chemicals (Cycling test)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate Tensile Strength (ksi) [Reduction (%)]</th>
<th>Young’s Modulus (ksi) [Reduction (%)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled</td>
<td>15.1</td>
<td>1074.4</td>
</tr>
<tr>
<td>Mg(Cl₂) 3%</td>
<td>13.4 [11]</td>
<td>773.1 [28]</td>
</tr>
<tr>
<td>Ca(Cl₂) 3%</td>
<td>14.7 [2]</td>
<td>726.5 [32]</td>
</tr>
<tr>
<td>NaCl 3%</td>
<td>11.5 [24]</td>
<td>768.8 [28]</td>
</tr>
</tbody>
</table>

The reductions of Young’s modulus by cyclic exposure of deicing chemical were more significant than ponded exposure, from 28% to 32% as shown in Table 4. In terms of each individual deicer, NaCl has the strongest effect on the tensile strength of GFRP specimens, which is 24%; Ca(Cl₂) has the strongest effect on Young’s modulus, which is 32%. The ultimate tensile strengths and Young’s modulus exposed to each deicing chemicals are compared in Figure 11.
Figure 11. Comparison of mechanical properties of a GFRP bar exposed to deicing chemicals (Ponding test) (a) Ultimate tensile strength; and (b) Young’s modulus

*The influence of alkaline and acid attack*

The exposure of the GFRP bar to 1M NaOH resulted in a decrease in tensile strength of 35% and a decrease of 28% in the Young’s modulus as shown in Table 5. The tensile strength and Young’s modulus were reduced up to 6% and 25% by the acid attack (1M HCl). Based on the test results, the tensile strength of the GFRP bar was not seriously
reduced, but a 25% reduction in Young’s modulus was observed by the exposure of 1M HCl acid attack, shown in Table 5.

Table 5. Mechanical properties of GFRP specimens exposed to alkaline attack

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>[Reduction (%)]</th>
<th>Young’s Modulus (ksi)</th>
<th>[Reduction (%)]</th>
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<td>773.9 [28]</td>
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*The influence of ultraviolet radiation*

To investigate the influence of cyclic sunlight exposure to the GFRP, an ultraviolet radiation test was conducted. A considerable reduction in both the tensile strength and Young’s modulus as a result of ultraviolet radiation was observed. The reduction for tensile strength was 22% and the Young’s modulus was reduced by 29%. The results are listed in Table 6.

Table 6. Mechanical properties of GFRP bar exposed to ultraviolet radiation

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<tr>
<th>Condition</th>
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<th>Young’s Modulus (ksi)</th>
<th>[Reduction (%)]</th>
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1.5 Suggestions for Future Research

Experimental results were obtained in this study for a systematic assessment of long-term durability behaviors of GFRP, specifically the extent of strength reduction and stiffness reduction of GFRPs under various simulated service environments. The information is very important for bridge design engineers, contractors, and state transportation agencies for the selection, construction, and maintenance of FRP materials used in bridge structures. It is important to note that the present study did not intend to investigate specific deterioration mechanisms of GFRPs that are responsible for the strength and stiffness reductions under the testing environments. From the material science and material engineering points of view, more studies are needed to investigate the changes of chemical composition and the microstructure of the GFRP materials caused by the environmental parameters, which is absolutely important for further improving the performance of the GFRPs, as well as for developing new materials.

For the ponding test, the weights of specimens before and after ponding should be measured and compared. This is important evidence for measuring the moisture intake capacity of the GFRP specimens.

The accelerated testing environments should be correlated with actual environmental conditions. For example, the testing environment should be created so that the number of months or years of applications of deicing salts is equivalent to a one-month period of 3% NaCl solution cyclic wetting/drying conditioning. This is not an easy task, but will be very useful for practical applications.
2. In-situ Monitoring of the GFRP Deck Panel

2.1 Introduction

In May 2003, the O’Fallon Park Bridge was built over Bear Creek in Denver Mountain Parks in the state of Colorado. The bridge is 41’-3 7/16” long and about 16’ wide. The new bridge is composed of six GFRP honeycomb composite deck panels of 16’ 3” length and 7’-31/2” width. The FRP Honeycomb (FRPH) panels were constructed by Kansas Structural Composites, Inc (KSCI) and are shown in Figure 12.

![Figure 12. Fiber-Reinforced Polymer Honeycomb (FRPH) Sandwich Panels](image)

The bridge was designed by ASSHTO LRFD Bridge Design Specification (1998) with Interim Specifications, City & County of Denver Standard Specifications (1999), Colorado DOT Standard Specifications (1999), and ACI 440.1R-01 “Guide for the Design and Construction of Concrete Reinforcement with FRP Bars.” The bridge is designed for Type 3 Colorado Posting Vehicle with Impact Factor 10%. (The bridge is capable of supporting an AASHTO HS-25 load,
1, 500, 000 pounds). Permanent fiber optic sensors were embedded into Panel 6 during the manufacturing of the panels. A plan view and the dimensions of the bridge are sketched in Figure 13. Design details can be seen in Reference 21.

A load test using a CDOT dump truck was performed on the bridge on August 20, 2003 to evaluate the behavior of the bridge deck panel. Strains in the panel were measured for four static load cases and temperature effect on the FRPH panels to monitor the performance of the bridge. Strains were also measured on February 17, 2004 for the temperature effect.

![Figure 13. The bridge in O’Fallon Park, Denver, Colorado](image)

**2.2 Installation of Fiber Optic Sensors**

Due to their high accuracy, small size, fast response, non-electric (immunity to electromagnetic and radio-frequency interference) and lightning surcharges, fiber optic sensors (strain gages) were applied to monitor structural responses of a FRPH panel at the O’Fallon Park Bridge. A typical fiber optic sensor can be seen in Figure 14.
A Fabry-Perot fiber optic strain sensor was chosen in the project. When a gage is bonded to a substrate, a strain variation in the axial direction of the strain gage will produce a variation of the cavity length, which can be converted into a numerical strain value. A total of twenty strain sensors were embedded at Panel 1 (seen in Figure 13) longitudinally and transversely so that various load effects could be observed, including dead loads, live loads, snow loads and wind loads. The gages were permanently installed as shown in Figure 15 so that long-term effects due to settlement and creep can also be monitored over time. The detail of placement of fiber optic sensors on the panel is shown in Figure 16.
Figure 16. The locations of fiber optic sensors in the FRPH panel
The monitoring system is illustrated in Figure 17. The fiber optic cables were used to connect the sensors with the digital logger called DMI Multi-Channel Fidel Data Logger. The readout in terms of strain values can be displayed directly on the Window-based data acquisition software called FISO Software.

(a) The data acquisition system
(b) The ditch for embedding fiber optic cables
(c) The data logger

Figure 17. Installation of the fiber optic strain gage monitoring system
2.3 In-situ Monitoring of the Bridge Decks

2.3.1 Results of truck loading test

A loading test was performed using an empty CDOT dump truck to determine the FRPH deck panel behavior for the actual live load, as shown in Figure 18.

Figure 18. Load test for the bridge (a CDOT dump truck)
The axle loads of both the front axle and rear axle are provided in Figure 19.

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<th>Rear axle with dial tires</th>
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<td>10,000 lb</td>
<td>15,000 lb</td>
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</table>

Figure 19. The axle load of the CDOT truck

The strains were recorded in twenty channels both in the longitudinal and lateral directions. Data were collected with an acquisition rate of 3 seconds and acquisition average interval of 0.05 seconds. Four load cases were performed to measure strains at the top and bottom of the FRPH panel. The truck was positioned so that only the rear axle with dial tires was located on the desired locations. Once the truck was positioned, strains were recorded. The readings were also taken before the load was applied and used as the reference strains.
Case 1: Loading at Section A-A on the shoulder

For the loading test 1, the rear axle of the truck was loaded at the location shown in Figure 20. Figure 21 shows the microstrain distributions in Section A-A (see Fig. 16).

Figure 20. The location of the rear axle in the loading test 1

Figure 21. Microstrain distributions in Section A-A
Case 2: Loading at Section B-B on the shoulder

For the loading test 2, the rear axle of the truck was loaded at the location shown in Figure 22. Figure 23 shows the microstrain distributions in Section B-B (see Fig. 16).

Figure 22. The location of the rear axle in the loading test 2

Figure 23. Microstrain distributions in Section B-B
Case 3: Loading at Section A-A in the midspan

For the loading test 3, the rear axle of the truck was loaded at the location shown in Figure 24. Figure 25 shows the microstrain distributions in Section A-A (see Fig. 16).

Figure 24. The location of the rear axle in the loading test 3

Figure 25. Microstrain distributions in Section A-A

3' 5"
Case 4: Loading at Section B-B in the midspan

For the loading test 4, the rear axle of the truck was loaded at the location shown in Figure 26. Figure 27 shows the microstrain distributions in Section B-B (see Fig. 16).

Figure 26. The location of the rear axle in the loading test 4

Figure 27. The microstrain distribution in Section B-B
2.3.2 Temperature effect

The FRPH panels are subjected to significant variations of environmental conditions during the initial fabrication process and the service period. Among the many environmental conditions, temperature effect is a very important one. To monitor the effect of temperature variation on the internal strain/stress of the panel, two readings were taken, one in the summer and one in the winter. The strains were measured continuously for 110 minutes from 9:30 a.m. to 11:10 a.m. on September 12, 2003 and for 120 minutes from 10:00 a.m. to 12:00 p.m. on February 17, 2004. Temperatures were measured from the top surface and the bottom surface of the panel. The temperature readings of the top surface were taken in the wearing surface (gravel overlay, 1/2”), and the temperatures of the bottom surface were taken from underneath the precast concrete arch near the sensor locations. The temperature profiles are shown in Figure 28, and the strain variations are shown in Figures 29, 30, and 31.

![Temperature profiles at the top and bottom surfaces of the panel](Figure 28)

Figure 28. Temperature profiles at the top and bottom surfaces of the panel (September 12, 2003 and February 17, 2004)
In Figure 28, the surface temperature is higher than the bottom temperature in the summer, which is due to the direct, heavy sunshine in the summer. The surface temperature is lower than the bottom temperature in the winter, which is due to the relatively stagnant air under the arch of the bridge, and there is no direct cold wind.

Figure 29. Longitudinal microstrains versus time in the top of the panel due to the temperature effect
Figure 30. Longitudinal microstrains versus time in the bottom of the panel due to the temperature effect
In Figure 31, the strains from gage 6 in the summer, and the strains from gage 1 in the winter look abnormal. Taking the gage 1 as an example, the strains of gage 1 during the reading period were quite stable, about 2400 µε. Using the Young’s modulus of unexposed GFRP specimen, 662 ksi (see Table 5), the corresponding stress is about 1600 psi, which is only about 10% of the ultimate strength of the unexposed specimen. Therefore, the gage 1 may have recorded the actual strain in the location. More readings are needed in the future.
3. Conclusions and Recommendations

3.1 Durability of GFRPs

The effect of environmental conditions on the long-term durability of GFRPs was investigated by systematic durability testing. Several environmental parameters were considered in this study, including freeze-thaw effects, moisture effects (continuous ponding and cyclic wetting/drying), deicing chemicals (continuous ponding and cyclic wetting/drying), alkaline and acid attacks, and natural sunlight exposure (UV light). The degradation of mechanical properties of GFRPs was determined in terms of tensile strength and Young’s modulus.

Every environmental parameter tested in the study resulted in a degradation of GFRPs to a certain extent. From the strength aspect, the worst degradation was a 35% reduction of tensile strength of the GFRP subjected to the ponding of 1M NaOH solution. From the stiffness point of view, the worst degradation was a 32% reduction of Young’s modulus of the GFRP subjected to the ponding of 3% Ca(Cl₂) solution.

In general, these degradations may be attributed to the chemical reactions in the polymer matrix and microcracks developed in the matrix, as well as in the matrix/fiber interface. In particular, each influential parameter has its own damage mechanism(s) and must be studied separately.

The significant degradations in terms of the tensile strength and the stiffness must be considered in the specifications related to the structural design of bridge decks if the GFRP is to be used widely for bridge decks in the state of Colorado.

For future work, it is suggested that the degradation of FRP should be tested with coupling effects. Due to coupling effects between moisture and elevated temperatures, the degradation could be accelerated by high diffusion rates. Additionally, the freeze-thaw, alkali attack, UV radiation, and moisture can be applied concurrently to see how the combinations of the influential parameters affect the degradation of the FRP specimens. For the ponding test, the
weights of specimens before and after ponding should be measured and compared. This is an important factor for measuring the moisture intake capacity of the GFRP specimens.

3.2 Monitoring of the Bridge Deck

The strains due to the mechanical loading are very small. Therefore, the structural design of the FRPH panel for O’Fallon Park Bridge is very conservative.

Comparing the effect of temperature (Figures 21, 23, 25, and 27) with the effect of mechanical loading (Figures 29, 30, and 31), one can see that the effect of temperature is clearly dominant. The maximum strain due to mechanical loading is 226 microstrain in Case 4, while the thermal strains in the winter are all higher than that. This means that the temperature variation is more important than the variation of mechanical loading. Therefore, in addition to the mechanical fatigue loading test performed in this project, a larger scale cyclic temperature test for the FRPH panel is very necessary and important for evaluating the long-term performance of the panel.

In the summer when the temperature rose from 70 °F to 95 F in about two hours, all gages showed increasing strain in tension in both longitudinal and transverse directions, which reflects the rapid thermal expansion. While in the winter, when the temperature stabilized on the top and bottom surfaces in the two-hour reading period, all gages showed large strains in compression in both directions, which is the result of thermal contraction. It should be noted that the strains are relative values based on the installation condition (taking the initial strains as the reference readings).

Strain gage 1 showed abnormal readings with very high compressive strain in the winter, compared with other strain gages. It may be due to a problem with the gage, or it may reflect the actual strain at the location. Future readings will confirm the condition of the gage.
The monitoring process of the bridge deck should be continued. The results obtained so far provide valuable information and can be compared to the strains that will be collected in the future to evaluate the long-term performance of the bridge deck.
4. References


APPENDIX A. UNIAXIAL TENSION TEST DATA FOR DURABILITY OF GFRP SPECIMENS

A.1 Conditioning: Room temperature at 78.8°F and 35% Relative Humidity (Controlled Specimen)

Ultimate tensile strength: 15.07 ksi
Elastic modulus: 1074.4 ksi
Stress-strain curve:

![Stress-strain curve graph](image-url)
A.2 Conditioning: Freeze-Thaw Cycles

Ultimate tensile strength: 13.5 ksi
Elastic modulus: 878.10 ksi
Stress-strain curves:

A.3 Conditioning: Wetting-Drying Cycles in Water

Ultimate tensile strength: 14.5 ksi
Elastic modulus: 785.47 ksi
Stress-strain curve:
A.4 Conditioning: Mg(Cl₂) 3% Ponding Test

Ultimate tensile strength: 13.16 ksi
Elastic modulus: 797.46 ksi
Stress-strain curve:

A.5 Conditioning: Ca(Cl₂) 3% Ponding Test

Ultimate tensile strength: 13.20 ksi
Elastic modulus: 850.24 ksi
Stress-strain curve:
A.6 Conditioning: NaCl 3% Ponding Test

Ultimate tensile strength: 12.73 ksi
Elastic modulus: 768.75 ksi
Stress-strain curve:

![Stress-strain curve for NaCl 3% Ponding Test](image)

A.7 Conditioning: Mg(Cl₂) 3% Cyclic Test

Ultimate tensile strength: 13.44 ksi
Elastic modulus: 773.05 ksi
Stress-strain curve:

![Stress-strain curve for Mg(Cl₂) 3% Cyclic Test](image)
A.8 Conditioning: Ca(Cl₂) 3% Cyclic Test

Ultimate tensile strength: 14.73 ksi
Elastic modulus: 726.45 ksi
Stress-strain curve:

A.9 Conditioning: NaCl 3% Cyclic Test

Ultimate tensile strength: 11.50 ksi
Elastic modulus: 768.75 ksi
Stress-strain curve:
A.10 Conditioning: 1M NaOH Ponding Test

Ultimate tensile strength: 9.78 ksi
Elastic modulus: 773.87 ksi
Stress-strain curve:

A.11 Conditioning: 1M HCl Ponding Test

Ultimate tensile strength: 14.13 ksi
Elastic modulus: 804.02 ksi
Stress-strain curve:
A.12 Conditioning: Ultraviolet Radiation Test

Ultimate tensile strength: 11.69 ksi
Elastic modulus: 763.92 ksi
Stress-strain curve:
## APPENDIX B. STRAIN HISTORY OF O’FALLON PARK BRIDGE DUE TO TEMPERATURE EFFECT

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