

ENVIRONMENTAL EFFECTS ON TENSILE PROPERTIES OF FRP LAMINATES MADE USING WET LAY-UP METHOD

Mohammadreza Tavakkolizadeh¹ and Hamid Saadatmanesh²

¹ Jackson State University, Jackson, Mississippi, USA

² The University of Arizona, Tucson, Arizona, USA

ABSTRACT

The demand for Fiber Reinforced Plastics (FRP) in rehabilitation of infrastructures is increasing. New techniques utilize the lightweight, high strength and formability of FRP fabrics and laminates in various retrofitting projects. This paper presents the results of a study on the long-term behavior of different types of FRP laminates made using the wet-lay-up technique. A total of 150 specimens were prepared using one type of epoxy and two different types of fabrics. Unidirectional fabrics made from glass and carbon, were used in this study. The samples were exposed to nine different environments. These environments were simulated using four different chemical solutions with pH of 12.5, 10, 7 and 2.5, and substitute seawater. In addition, four chambers for exposure to ultraviolet radiation, temperature of 60°C, temperature of 50°C with 95% relative humidity and soil with 25% moisture content and active microorganisms were considered. Uni-axial tension tests were performed on the samples after 6000, 12000 and 20000 hours of exposure as well as on control samples, and tensile properties were measured for each specimen. The results showed a significant loss of strength and ultimate strain for glass fiber reinforced plastics (GFRP) in solutions, especially in high pH values, while carbon laminates showed very little loss of mechanical properties.

INTRODUCTION

Fiber Reinforced Plastics (FRP's) are increasingly attracting the attention of civil engineers because of their unique properties for retrofitting of structures. The excellent tensile strength, lightweight, resistant to electrochemical corrosion and formability of FRPs make them materials of choice for repair and retrofit of structures. These materials have been used in different engineering fields such as aerospace, automotive, marine, chemical, etc. for many years, and in general, they have shown good long-term behavior. The methods of fabrication and quality control in civil engineering projects, however, are quite different from those in aerospace or defense industry. In addition, the FRP used in civil engineering projects are exposed to different environments than those in other fields of engineering. Therefore, in order to address the rising concerns about the long-term performance of FRP in civil engineering projects, durability of these materials and change in their mechanical properties with time must be investigated.

Several investigators have addressed the durability of FRP materials. Most of the research was concentrated on the effect of the moisture and temperature on FRP tendons, rebars, pultruded sections and laminates made with standard vacuum bagging procedures and under controlled-temperature curing cycles for periods of less than a year. The results of such studies have been used initially to answer some of the concerns of structural engineers. However, since durability of FRP materials is significantly affected by their manufacturing process and quality control used during construction, studies are needed to address durability issues specifically for the type of projects involving the wet-lay-up procedure and the environments in civil engineering applications.

PREVIOUS WORK

As it mentioned before, the existing database on long-term durability of composite laminate could not address all the concerns of practicing engineers. The manufacturing processes of the composite used in these researches were different than the wet-lay-up technique, which is the most common method used in civil engineering projects. The environments considered in most of these studies were not addressing all of civil engineering interests. In addition, most of these studies considered fairly short periods of exposure that may not satisfy the long-term concerns of structural engineers. The existing research on the durability of FRP structural elements can be categorized in four groups:

Laminates

In a study conducted by Springer¹, environmental effects on glass fiber reinforced polyester and vinylester composites were investigated. They exposed three different composite laminates to humid air (50% and 100% RH), saturated NaCl solution, diesel fuel, lubricating oil, antifreeze and gasoline at two temperatures of 23°C and 93°C for six months. They obtained the tensile and shear properties of the laminates by conducting uniaxial tension and short beam shear tests. The following conclusions were drawn from testing of over 600 specimens:

Specimens exposed at 93°C showed the highest loss of mechanical properties (~19%) in solutions as compared to those exposed at 23°C (~6%). The vinylester based laminates showed less degradation (~9.5%) compared to the polyester based laminates (~14.5%). Among all of the environments, antifreeze, saturated salt, gasoline and 100% RH showed the strongest effect on the specimens after 6 months exposure with the average loss of 28%, 22%, 15% and 13%, respectively.

In another study conducted by Hexcel Corporation² the effects of ozone (at 60°C), salt water, fresh water, alkaline soil (pH=8.5~10.5), high temperature (60°C) and UV radiation on the tensile properties of GFRP laminates were investigated. The laminate, which was made of 920 gr/m² glass fabric, had an average thickness of 2 mm. Laminates, after 1000 hours of exposure, did not show any significant degradation of their tensile properties.

Rebars and Tendons

In two studies conducted at The University of Arizona³, the effect of different environmental exposure on E-glass FRP rebars, pan-based carbon FRP-tendons and aramid FRP-tendons was investigated. They tested the specimens after exposure to seven different solutions, ultraviolet radiation and freeze-thaw cycles. The solutions considered were fresh water (at 25°C and 65°C), alkaline (pH of 12 at 25°C and 65°C), acidic (pH of 3 at 25°C), sea-water (3.5% NaCl at 25°C) and deicing salt (7% NaCl +CaCl₂ and NaCl +MgCl₂ at 25°C). After six months of exposure, they tested the specimens in uniaxial tension and reported a relatively higher strength loss in alkaline (~18%) and deicing salt (~17%) solutions compared to fresh water (4%), sea-water (8%) and acidic (5%) solutions. In addition, they reported less degradation in Vinylester based rebars (~10%) in comparison to polyester based ones (~16%). They also observed that the loss of strength in smaller rebars (~16%) were much higher than the larger diameter rebars (~9%). Meanwhile, they pointed out a limited change in tensile modulus of the FRP rebars as a result of the exposure. Their test results after 1 year of exposure, showed almost no degradation for carbon tendons. In case of the aramid tendons, excellent freeze-thaw and fresh water immersion durability was observed. The acidic solution had the most significant effect on aramid tendons

and caused 8% drop in strength, while for the rest of the environments, an average of 5% loss in tensile strength was reported.

Pultruded Sections

Gomez⁴ investigated freeze-thaw durability of Pultruded fiberglass composites. They considered two different pultruded laminates with polyester and vinylester matrix. They reported an average reduction in flexural properties of 26% and 20% for vinylester and polyester based laminates, respectively. The reduction in flexural properties of laminates only exposed to solution was 9% and 5% for the vinylester and polyester based laminates.

In another study by Bank⁵, the accelerated aging of vinylester based glass pultruded rods was addressed. For specimens immersed in water, they reported flexural strength losses of 14% to 45% for the temperatures of 40°C to 80°C, respectively. In the case of alkaline solutions, only 30% ammonia solution appeared to have had a measurable effect on the properties. The humid environment did not affect the properties either.

Overwraps

Twelve different composite overwrap systems made with E-glass and carbon fiber in epoxy, polyester and vinylester matrices were considered by Steckel⁶ in a durability study. The exposures included 100% relative humidity at 38°C, salt water, alkaline solution with pH of 9.5, temperature of 60°C and freeze-thaw cycles. Uniaxial tension tests were performed on 19 mm wide straight coupons with 5 cm long tab with a 7° taper. Short beam shear tests were conducted with a length/thickness ratio of 6~7. The specimens were tested after 3000 hours of exposure. Generally, most specimens showed very good durability in the environments tested. However, only one glass system showed significant reduction in tensile strength (15%) in 100% RH, and one carbon system showed large reduction in shear strength (25%~35%).

EXPERIMENTAL STUDY

In order to investigate the effects of environmental exposure on the mechanical properties of FRP laminates as prepared in a typical civil engineering application, uniaxial tension tests were performed. Composite laminates made from fabrics made of different materials with similar weave patterns were tested after exposure to various simulated aggressive environments. Tensile properties such as ultimate strength, modulus of elasticity and ultimate strain were measured for each sample after specific exposure time. By comparing the mechanical properties of the exposed specimens to those for control specimens, the effect of different environments on the composite laminates made using wet-lay-up procedure (typically used in civil engineering applications) was determined.

Test Variables

The effects of several parameters on the durability of FRP laminates were examined. Nine simulated aggressive environments were considered: (1) Fresh water, (2) Saturated calcium hydroxide, Ca(OH)₂, solution (pH of 12.5), (3) Saturated Ca(OH)₂ solution (pH of 10.0), (4) Hydrochloric acid, HCl, solution (pH of 2.5), (5) Simulated seawater, (6) Moist alkaline soil with micro organisms, (7) Dry air at temperature of 60°C, (8) Air temperature of 50°C and relative humidity of 95%, and (9) Ultraviolet radiation. Two different types of fabrics were used: (1) Unidirectional glass, G-U and (2) Unidirectional carbon, C-U, as shown in Figure 1. For designation of different fabrics, letters G stood for E-glass and C stood for pan-based carbon,

while U represented unidirectional. The exposure time played an important role in the degradation process. Three different exposure times of 6000, 12000 and 20000 hours were considered.

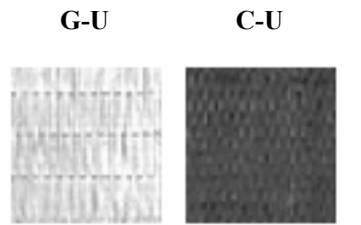


Figure 1: Different Types of Fabrics

Materials

Epoxy: A two-component epoxy was used as the matrix for preparing the coupons. The mixing ratio of the epoxy was two-part resin (bisphenal A based) to one-part hardener (polyamine based) by volume. It had a pot life of 45 minutes and full a cure time of 7 days at 25°C.

Fabrics: Two different unidirectional fabrics were used in the study. The fabrics were made of E-glass and pan-based carbon. Various characteristics of these fabrics are listed in Table 1.

Table 1: Characteristic of Different Fabrics

Designation	Orientation	Fiber Type	Style	Weight (gr/m ²)	Glass Content (Vol.)	Glass Content (Wt.)
G-U	Unidirectional	Glass	Sticky String	400	1	1
C-U	Unidirectional	Carbon	Sticky String	350	0	0

Environments

In order to expose the composite coupons to aggressive conditions similar to those in the civil engineering applications, nine different environments were simulated using chemical solutions following ASTM specification. These environments are listed in Table 2.

Table 2: Properties of Aggressive Environments

Designation	Temperature	Humidity	pH	Remark	ASTM
W-S- ALK	Ambient	N/A	12.5		C 581
W-W-ALK	Ambient	N/A	10.0		C 581
W- NEUT	Ambient	N/A	7.0		C 581
W-S-ACID	Ambient	N/A	2.5		C 581
OCIEN	Ambient	N/A	7.25		D 1141
SOIL	Ambient	N/A	10.5	MC = 25 ~ 30 %	D 3083
HEAT-D	60°C	RH = 0 ~ 5 %	N/A		D3045
HEAT-M	50°C	RH = 95%	N/A		D 4585
UV-RAD-D	Ambient	RH = 5 ~ 10 %	N/A	UV-A (340 nm)	G 53
RH = Relative humidity; MC = Moisture Content; nm = 1×10^{-9} m					

Solutions: Distilled water with neutral pH of 7 was used to simulate exposure to fresh water. Saturated calcium hydroxide, $\text{Ca}(\text{OH})_2$, solutions with pH of 10 and 12.5 were used to simulate exposure to hydrating cement and other alkaline environments. The alkaline solutions were prepared by dissolving $\text{Ca}(\text{OH})_2$ in distilled water until saturation. Then NaOH solution was added to control the pH as needed. Acidic solution was used to simulate exposure to low pH environments such as that encountered in sewer pipes and wastewater treatment facilities. The solution was prepared by the addition of diluted hydrochloric acid, HCl, to distilled water until reaching the pH of 2.5. Substitute ocean water with pH of 7.25 was used to simulate exposure to marine environment. The major ingredients of this solution were NaCl (24.53 g/L), MgCl_2 (5.20 g/L), Na_2SO_4 (4.09 g/L), CaCl_2 (1.16 g/L), KCl (0.695 g/L) and NaHCO_3 (0.201 g/L). The pH of the solutions was monitored weekly with an electronic pH meter with a resolution of ± 0.1 . The adjustment to the solutions was made after ± 0.2 deviations in pH. All solutions were replaced with new ones every two months to prevent contamination and change in their chemical composition.

Alkaline Soil: In order to simulate exposure to alkaline soil containing microorganism, compost soil was prepared using commercial potting soil and natural fertilizers. The moisture content of the mix was kept between 25 to 30 % (by weight) by adding water periodically. Lime was added to the soil to keep the alkalinity around pH of 10.5. Cotton strips were used to monitor the biological activity in the mix. A 70% drop in the tensile strength of cotton strips in one week was an indication of satisfactory biological activities. Soil samples were replaced every month to insure the high level of biological activity.

Chambers: The effects of hot-dry and hot-moist climates were measured in two separate chambers. In the first chamber, the temperature was kept at 60°C with presence of minimal moisture. In the second chamber, the temperature was kept at 50°C with the relative humidity of 95%. The temperature was kept at $\pm 1^\circ\text{C}$ from the target value by using a heating element and a thermostat. The relative humidity was kept at $\pm 2\%$ by providing adequate evaporation surface for water containers in the chamber. In the third chamber, the effect of sunlight exposure was

studied. A series of 15 Watt Black Light Fluorescent tubes were used to simulate ultraviolet radiation between 300 and 400 nm with a peak of 340 nm and intensity of 30×10^{-6} J/sec/cm². Tubes and specimens were 25 cm apart from each other. In all chambers, miniature fans were circulating air to achieve uniform environments.

Sample Preparation

Two different types of FRP laminates were manufactured using the wet-lay-up technique without heat and pressure treatments. The laminates were 25 × 50 cm made of one layer of fabric. Fabrics, after saturation with epoxy, were placed between two layers of Mylar sheets. Excessive air bubbles were bled out of the laminate along with extra epoxy using a putty knife and a 12 cm wide roller. Laminates were then placed between two 2-mm thick glass plates on a level surface. The laminates were kept under 1 kPa pressure for 24 hours and then the Mylar sheets were peeled off. The laminates were kept inside the laboratory under ambient temperatures for 6 more days before being cut into strips with dimensions of 2.5 × 40 cm. The edges of the coupons were smoothed, using 100-grit sandpaper on a flat surface. The exact dimensions and weight of each coupon were measured using a caliper and a digital scale. The resolution of the caliper and scale were ±0.025 mm and ±0.01 gr, respectively.

Experimental Setup

Certain mechanical properties of the composite laminates were sensitive to their thicknesses. Considering the unavoidable variation in the thickness of the coupons made with this technique, twelve coupons were selected randomly as control specimens. The rest of the coupons were then placed in specified environments and their behaviors were monitored over time. A total of 9 coupons for each laminate were placed in each environment in order to be tested at three different times. For each laminate, twelve control specimens were kept inside the lab under ambient conditions and were tested with the first batch of exposed coupons after 6000 hours. Each set of exposed coupons were washed with fresh water and kept inside the laboratory under ambient condition for seven days to dry out, and then their weights were measured. The uniaxial tension tests were performed following ASTM D 3039 using an MTS-810 test machine and MTS-647 hydraulic wedge grips.

During previous experiments, SurfAlloy flat wedges had shown that they could yield desirable results without using tabs on the coupons for gripping purposes. This simplified the test setup considerably. The axial deformation was monitored using an MTS-632.12E-24 extensometer with a gage length of 25.4 mm and accuracy of 10 microstrain as shown in Figure 2. The load was measured by an MTS-661.20E-03 load cell with a capacity of 100 kN. Displacement controlled loading was used with a rate of 0.025 mm/sec. The values of the load and strain were recorded every second and the data were analyzed using spreadsheet software.

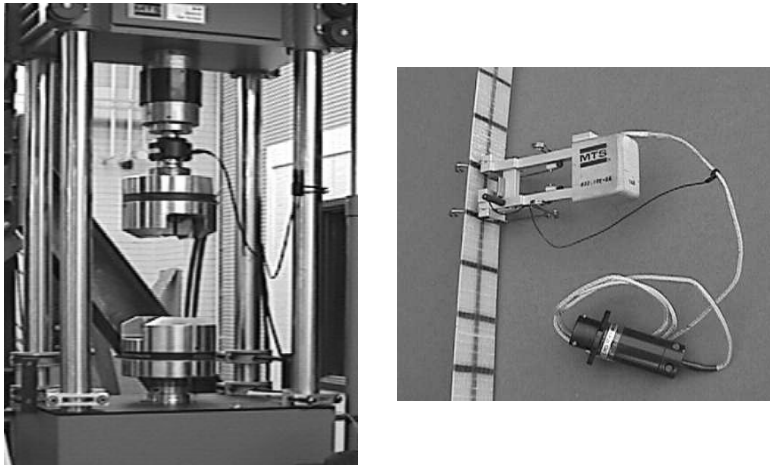


Figure 2: Universal Testing Machine and Extensometer Mounted on a Typical Specimen

EVALUATION AND ANALYSIS OF THE RESULTS

The first step in analyzing the result was establishing an average value for the tensile properties of the control specimens. Initially, twelve values for each laminate were averaged and considered as the control values. After conducting a correlation analysis, it was observed that the values for the ultimate strength and the modulus of elasticity had a strong correlation with the thickness of the laminates. Therefore, a different approach for these two parameters was considered. A linear regression between the values of these two parameters and the laminate thickness was performed. In these cases, linear control functions replaced the control values. A summary of the averages (AVR), coefficients of variation (COV), and coefficients of correlation (COC) is presented in Table 3.

Table 3: Statistical Characteristics of Control Specimens

Designation	Ultimate Strength (MPa)			Modulus of Elasticity (GPa)			Ultimate Strain (%)		Load / width (KN/cm)	
	AVG	COV	COC	AVG	COV	COC	AVG	COV	AVG	COV
G-U	286.6	0.14	-0.72	20.3	0.08	-0.87	1.470	0.20	3.67	0.14
C-U	564.3	0.10	-0.63	56.1	0.07	-0.97	1.000	0.07	4.17	0.07

AVG = Average Value; COV = Coefficient of Variation; COC = Coefficient of Correlation

After establishing the control values and functions for different laminates, testing of coupons with 6000, 12000 and 20000 hours of exposure began. Three coupons were tested for different environments, exposure times and composite types. The ultimate tensile strength, tensile strain and tensile modulus of elasticity were measured for each laminate. In order to simplify the analysis, all the values for exposed specimens were normalized with respect to their corresponding control values (without exposure). The results are presented in Figures 3 through

12. The change in weight of the laminates in different environments was obtained by subtracting the dry weight of each coupon from the weight after exposure. The weight change results are presented in Table 4.

Freshwater (pH of 7.0)

Freshwater with a neutral pH did not have any significant effect on the modulus of elasticity of the laminates. The ultimate strength of G-U laminates reduced by 11%, 20% and 26% while the strain at failure declined by 19%, 37% and 32% after 6000, 12000 and 20000 hours, respectively. The carbon laminates displayed insignificant decrease in their ultimate strength and strain at failure.

Alkaline Solutions (pH of 10.0 and 12.5)

Alkaline solutions did not affect the modulus of elasticity of the laminates. The effect of these solutions on the other tensile properties of carbon-based laminates was also insignificant. However, glass based laminates lost significant portion of their tensile properties when subjected to alkaline solutions.

At pH of 10, the strength of G-U laminates reduced by 21%, 26% and 29% while the strain at failure declined by 32%, 42% and 38% after 6000, 12000 and 20000 hours, respectively.

At pH of 12.5, the strength of G-U laminates dropped by 6%, 58% and 58% while the strain at failure declined by 18%, 53% and 61% after 6000, 12000 and 20000 hours, respectively.

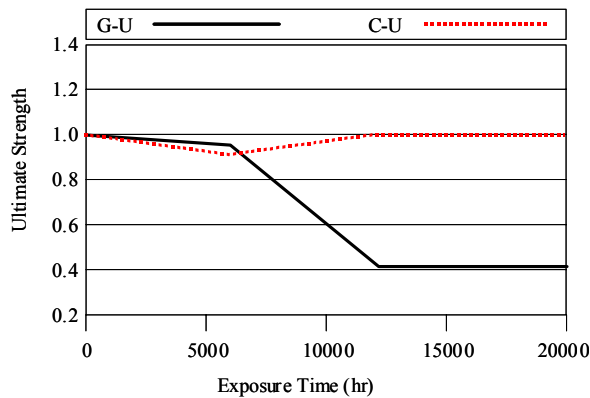


Figure 3: Normalized Values of Ultimate Tensile Strengths vs. Exposure Time for Laminates in Alkaline Solution (pH = 12.5)

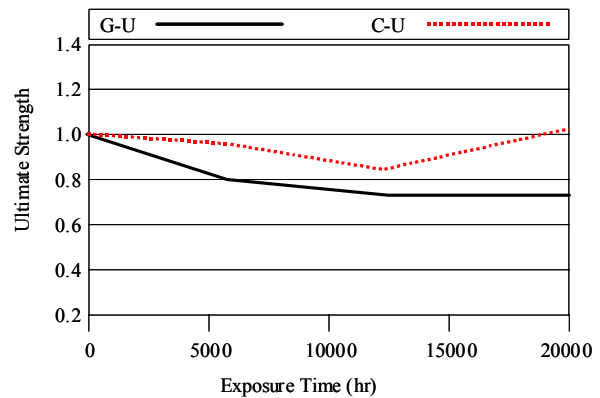


Figure 4: Normalized Values of Ultimate Tensile Strengths vs. Exposure Time for Laminates in Alkaline Solution (pH = 10.0)

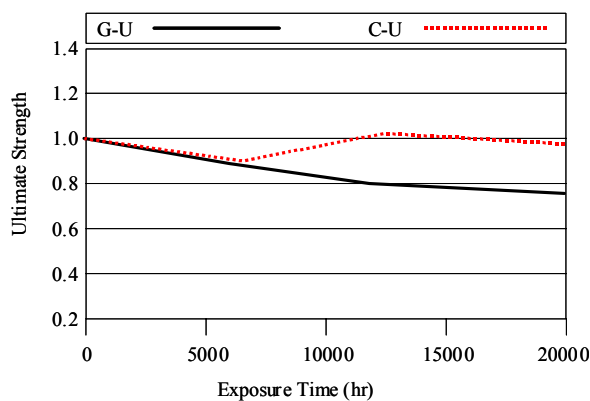


Figure 5: Normalized Values of Ultimate Tensile Strengths vs. Exposure Time for Laminates in Fresh Water Solution (pH = 7.0)

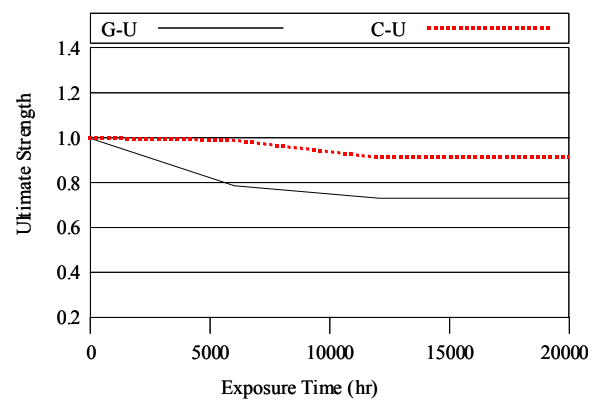


Figure 6: Normalized Values of Ultimate Tensile Strengths vs. Exposure Time for Laminates in Acidic Solution (pH = 2.5)

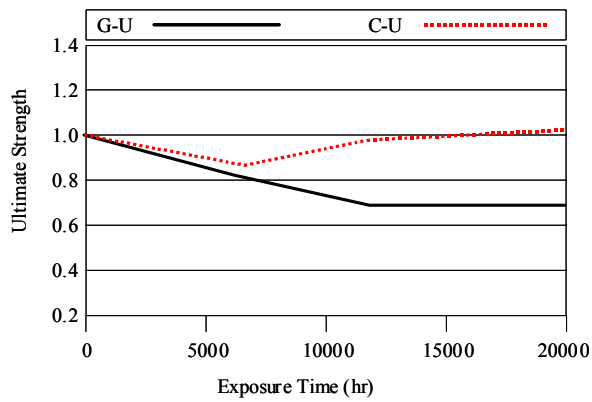


Figure 7: Normalized Values of Ultimate Tensile Strengths vs. Exposure Time for Laminates in Seawater Solution (pH = 7.25)

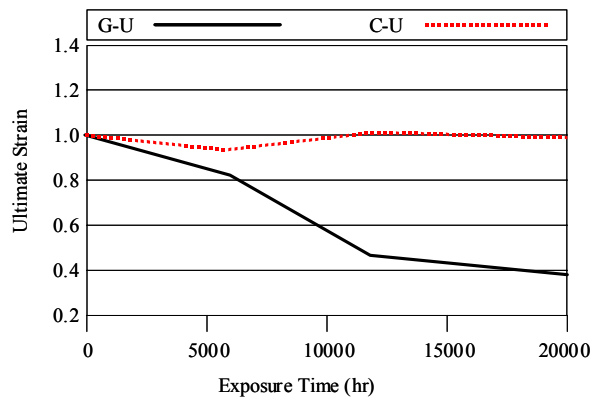


Figure 8: Normalized Values of Strain at Failure vs. Exposure Time for Laminates in Alkaline Solution (pH = 12.5)

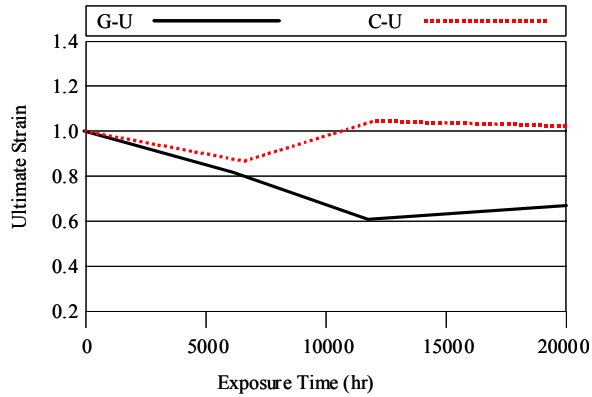


Figure 10: Normalized Values of Strain at Failure vs. Exposure Time for Laminates in Fresh Water Solution (pH = 7.0)

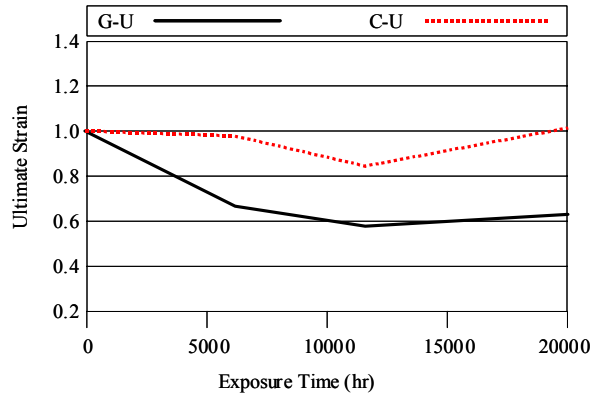


Figure 9: Normalized Values of Strain at Failure vs. Exposure Time for Laminates in Alkaline Solution (pH = 10.0)

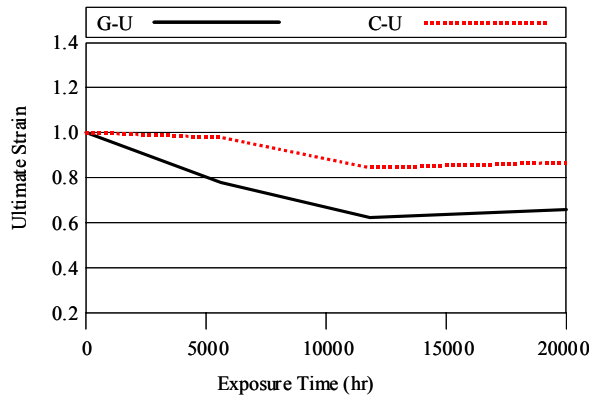


Figure 11: Normalized Values of Strain at Failure vs. Exposure Time for Laminates in Acidic Solution (pH = 2.5)

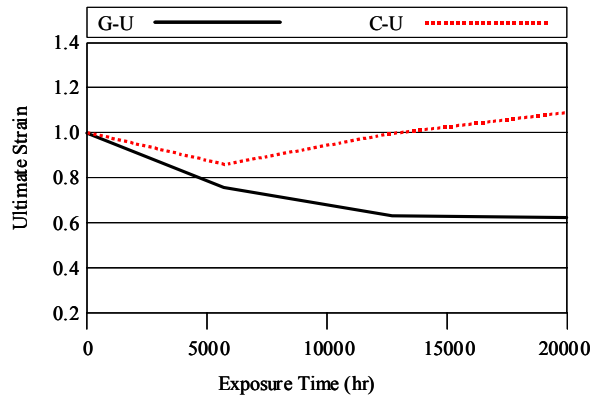


Figure 12: Normalized Values of Strain at Failure vs. Exposure Time for Laminates in Seawater Solution (pH = 7.25)

Acidic Solution (pH of 2.5)

Acidic solution did not affect the modulus of the elasticity of the laminates. The effect of this solution on the other tensile properties of carbon-based laminates was insignificant. Exposed to the pH of 2.50, the strength of G-U laminates reduced by 20%, 27% and 28% while the strain at failure declined by 25%, 38% and 31% after 6000, 12000 and 20000 hours, respectively.

Seawater (pH of 7.25)

Similar to the other solutions, seawater did not alter the modulus of elasticity of the laminates and its influence on the other tensile properties of the laminates containing carbon fibers was not significant. The strength of G-U laminates reduced by 18%, 30% and 30% while the strain at failure declined by 25%, 35% and 39% after 6000, 12000 and 20000 hours, respectively.

Moist Soil with Microorganism

All of the laminates in this environment displayed only minor changes in their tensile properties.

Effect of Dry Heat (60°C)

When laminates were exposed to dry heat, their mechanical properties were affected by a smaller percentage compared to the other environments. The ultimate strength of G-U declined by 12% after 12000 hours of exposure. The strain at failure of G-U declined by 18% after 12000 hours of exposure.

Heat and Moisture (50°C and 95%RH)

For the laminates exposed to heat and moisture, G-U laminates displayed the only apparent changes. The ultimate strength of G-U degraded by 16% after 20000 hours of exposure. The strain at failure of G-U fell by 15% after 20000 hours of exposure.

Ultraviolet Radiation

Ultraviolet radiation did not cause any change in the values of the modulus of elasticity of the laminates similar to other environments. With regard to other tensile properties, the laminate did not degraded after exposure. In fact, some showed even a slight increase in their mechanical properties. The UV exposure seemed to help curing of the composites and resulted in improved properties.

Glass FRP

The bundled glass fiber laminates (unidirectional) performed as noted. After 20000 hours of exposure, the ultimate strength and strain at failure, respectively, decreased by 58% and 61% in strong alkaline solution, 30% and 39% in seawater, 29% and 38% in weak alkaline solution, 28% and 31% in acidic solution, and 26% and 32% in freshwater.

Carbon FRP

None of tensile properties of laminates made from carbon fibers were affected significantly even after 20000 hours of exposure in all of the environments. The exposure time did not show any significant effect on the properties. The normalized values of the properties were varying between 0.85 ~ 1.13.

Weight Change for FRP Laminates

The weight change of the laminates in different chambers was analyzed. The specimens exposed to UV radiation displayed an average weight loss of 0.42%, 0.52% and 0.50% after 6000, 12000 and 20000 hours of exposure, respectively. The exposed samples to the dry heat showed continuing weight loss for an average of 1.2%, 1.43% and 1.66% after 6000, 12000 and 20000 hours of exposure, respectively. Samples exposed to the moist heat displayed a lower weight loss of 1.22%, 1.42% and 1.45% after 6000, 12000 and 20000 hours of exposure, respectively due to partial moisture absorption. The samples buried under soil displayed a minimal weight loss of about 0.25%.

The weight changes of the laminate as a result of exposure to different solutions were also analyzed. The exposed specimens were weighted after air-drying in room temperature for 7 days. Specimens submerged in alkaline solution with pH of 12.5 displayed the highest weight loss of 0.26%, 0.76% and 0.78% after 6000, 12000 and 20000 hours of exposure. The alkaline solution with pH of 10.0 produced a weight loss of 0.41%, 0.59% and 0.50% after 6000, 12000 and 20000 hours of exposure, while the specimens in freshwater showed the least weight loss of 0.24%, 0.50% and 0.47% after 6000, 12000 and 20000 hours of exposure. Seawater and acidic solutions, respectively, caused a weight loss of 0.19%, 0.45% and 0.58%, and 0.20%, 0.40% and 0.54% after 6000, 12000 and 20000 hours of exposure.

Table 1: Weight Change of Laminates in Different Environments (%)

Designation	Exposure Time (hr)	W-S-ALK	W-W-ALK	W-NEUT	W-S-ACID	OCIEN	SOIL	HEAT-D	HEAT-M	UV-RAD-D
G-U	20000	-0.40	-0.72	0.28	-0.54	-0.07	0.47	-1.14	-0.97	-0.42
	12000	-0.59	-0.07	0.03	-0.17	-0.18	-0.06	-1.22	-0.70	-0.19
	6000	-0.22	-0.25	-0.09	-0.10	-0.02	0.00	-0.97	-0.76	-0.29
C-U	20000	-0.65	-0.71	-1.32	-0.44	-1.22	-0.64	-2.30	-1.61	-0.39
	12000	-0.97	-0.71	-0.25	-0.62	-0.86	-1.09	-2.04	-2.30	-0.92
	6000	-0.57	-0.39	-0.52	-0.21	-0.50	-0.40	-1.58	-1.61	-0.52

CONCLUSIONS

The effects of different aggressive environments on tensile properties of two different FRP laminates were investigated. FRP coupons were immersed in five different solutions and kept in four different chambers, which simulated typical harsh environments encountered in the field. Following the analysis of the results from the experiments, these conclusions are arrived at:

1. FRP laminates have excellent durability when they are exposed to hot and humid weather, ultraviolet radiation or moist and biologically active alkaline soil. After more than 27 months of exposure, the mechanical properties of most laminates in tension were minimally affected by these environments.
2. Laminates that are made from, or contain carbon fibers have superb durability and remain completely unaffected even after a long period of exposure to solutions with a variety of pHs and ionic compounds.
3. Glass fiber reinforced plastic laminates are most vulnerable to immersion in solutions. High alkaline solution has the most effect on the laminates. Laminates made of glass fibers are not recommended for application exposed to aggressive solutions.

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