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FATIGUE STRENGTH OF COMPOSITE MATERIALS CONSIDERING HYGROTHERMAL DEGRADATION

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Abstract: Fiber-reinforced polymer composites (FRP) constitute an attractive alternative in the construction industry to conventional materials such as steel and concrete. However, understanding of the influence of environmental conditions in their long-term mechanical behavior is of vital importance to ensure their implementation. The main objective of this project is to assess the effect of hygrothermal exposure on the fatigue performance of glass/vinyl-ester composites. Two types of laminates (uniaxial and biaxial) and vinyl-ester neat resin are investigated. The specimens are immersed in distilled water at 40°C [104°F] for periods of times ranging from 50 days to 500 days. Fatigue tests are performed at a stress ratio (R) of 0.1 and a frequency of 5 Hz. Three stress levels are evaluated: 70%, 50% and 30% of the unaged ultimate tensile strength. Using Epaarachchi and Clausen methodology, a fatigue life prediction model is proposed that incorporates the hygrothermal conditioning effect on the fatigue life. The aging specimens show a decrease in fatigue life compared to the as-received specimens. The higher fatigue life degradation occurred in the uniaxial laminate samples. Fatigue life time predictions of vinyl-ester neat resin samples based on exposure time show a better correlation than the results based on moisture absorption. In the case of laminate specimens, both approaches show good correspondence with experimental results.

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1 INTRODUCTION

Due to the anisotropic nature and flexibility to be tailored to the specific application, composite materials have superior fatigue life than isotropic metal counterparts (Jones, 1999; Barbero 2011). Several authors had evaluated the failure mechanisms and most notable factors of the fatigue behavior of composite materials (Talreja, 1981; Harris, 2003; Zhou et al., 2007; Helmi et al., 2008) among others. The effect of moisture and temperature in the mechanical properties of Glass FRP composites when exposed to environmental influences such as fresh and salt water, UV radiation, etc., has being also well studied (Kajorncheappunngam et al., 2002; Karbhari and Chu, 2005; Helbling and Karbhari, 2005; Vauthier et al., 1995; Roy et al., 2001). However, work regarding the fatigue behavior of composite materials subjected to hygrothermal ageing is limited. Jones et al. (1983) reports results from tensile fatigue and flexural fatigue of glass fiber-reinforced polymers (GFRP), carbon fiber-reinforced polymers (CFRP), and Kevlar-49 reinforced polymers (KFRP) composites under several environmental conditions. Chauteauminois et al. (1993) performed quasistatic and fatigue testing by the three-point bending of uniaxial composites of glass/epoxy material. McBagonluri et al. (1999) studied the short term effects of moisture effect of pultruded GFRP materials. Quaresimin and Guglielmino (2001) tested samples fabricated by the Sheet Molding Compound method. Iqbal (2001) evaluated the fatigue life of two types of GFRP manufactured by pultrusion and hand lay-up. Shan and Liao (2002) tested samples of composite materials reinforced with glass fibers and combination of glass and carbon fibers (hybrids). Ellyin and Rohrbacher (2003) performed testing on several glass/epoxy laminates of several symmetrical lay-ups.

Although the moisture and temperature effect on the fatigue life of composite materials has been studied in certain magnitude, the exposure periods reported were for short time (up to 125 days). This work aims to generate sufficient data on the fatigue behavior of vinyl ester resin, uniaxial GFRP and biaxial GFRP composites exposed to distilled water at 40^{o}C for up to 500 days. The GFRPs were manufactured with the same tested resin. The experimental study includes the preparation and conditioning of the samples previous to testing, evaluation of the moisture level at each ageing time, and the tension-tension fatigue tests at constant amplitude. This work also proposes the use of a modified version of the Epaarachchi-Clausen Model (Epaarachchi and Clausen, 2003) to predict fatigue life in composites calibrating the model with the experimental data as a function of time of exposure or moisture content. The work presented here summarizes the most relevant findings from Román Batista (2009) and is part of a most comprehensive work that studied the degradation of GFRP at the macro and micro scale levels (Godoy et al., 2013; Obando et al, 2009).

2 MATERIAL FOR THE STUDY

The material of this study consisted of vinyl ester resin reinforced with E-Glass fibers. Two schemes were evaluated: uniaxial and biaxial (0/90). The fibers used were Hybon® 2022 Roving in the form of stitched fabrics. Uniaxial fabric (0) weighed 17 oz/yd^2 and the biaxial fabric (0/90) weighed 36 oz/yd^2 distributed 51% in the 0 direction and 44% in the 90 direction. The difference in weight goes to the stitching material. Resin only samples were also tested in the same fashion as the composite samples. The resin was manufactured by Ashland model Derakane 8084. The samples were manufactured using the resin transfer molding technique and post cured in an oven. Detail of the manufacturing and material properties can be found in Obando et al. (2009). Once the specimens were manufactured, their mechanical base properties

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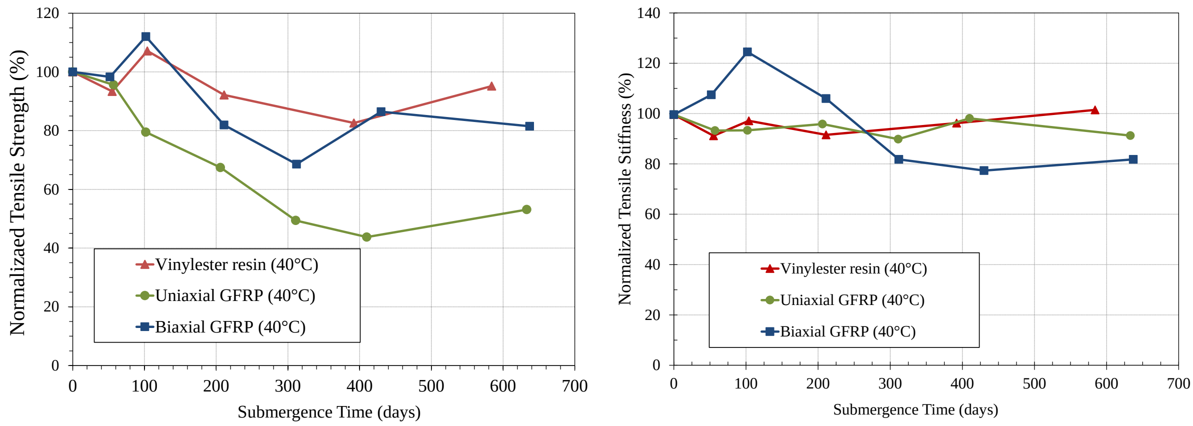
(no degradation) were measured. Tensile test on neat resin and composite samples were performed following the ASTM D638 and ASTM D3039, respectively.

3 HYGROTHERMAL EFFECT ON BASE PROPERTIES

The effect of time of submergence and moisture on the mechanical properties of the Resin and GFRP composite materials was evaluated by performing tension tests on specimens aged in 40^{o} C water for submergence times ranging between 30 and 600 days. Typically, five or more specimens were tested at each submergence period. The tests were carried out using the same procedure used to determine the baseline properties.

Figure 1 shows a summary of the average tensile strength and modulus of the three sets of samples subjected to degradation. These figures present the results in terms of the mechanical property values normalized with respect to the average value obtained for the un-aged specimens (i.e., specimens without hygrothermal exposure). This figures show that the long-term tensile strengths [Figure 1(a)] decreased 17%, 56%, and 28% with respect to the un-aged initial values for the resin, uniaxial GFRP, and biaxial GFRP, respectively. In contrast, the long term elastic modulus values [Figure 1(b)] decreased only 3%, 2%, and 24% with respect to the un-aged values for the resin, uniaxial GFRP, and biaxial GFRP, respectively.



a) Tensile Strength b) Tensile Modulus

Figure 1: Degradation of Macro-scale Properties from Tensile Tests (Adapted from Obando et al., 2009).

4 FATIGUE TESTING PROGRAM

Parallel to the evaluation of the tensile mechanical properties, samples of each group were extracted for fatigue testing. All samples were environmentally conditioned in an oven at 40^{o}C for 24 hours and kept dry in a closed container with desiccant material. The initial weight of each sample was recorded before they were submerged in the water tanks. As mentioned before, the samples were submerged in distilled water bath at 40^{o}C. Samples were extracted and tested in tension-tension fatigue during time intervals starting at 50 days of submersion up to approximately 500 days. Also unaged samples were tested and used as control. From 100 to 500 days, 100 days intervals were specified with a tolerance of ±7 days. Variation of the testing plan occurred due to unexpected events such as failure of the testing frame. The variations are reported together with the experimental results.

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The fatigue testing parameters are the maximum stress (σ_{max}), minimum stress (σ_{min}), mean stress (σ_m), stress amplitude (σ_a), and frequency. Table 1 reports the parameters used for the fatigue testing plan. Tests were run in load control (as opposed to displacement control) to avoid variations in load levels due to changes in the stiffness of the samples during testing. The *R*-ratio, defined as the minimum stress vs maximum stress ratios ($R = \sigma_{min} / \sigma_{max}$), was 0.10. Sinusoidal wave form was used with a frequency of 5Hz. Selection of the frequency was based on typical values found in the literature, that go up to 20Hz (Shan and Liao, 2002). Although a variety of values are found, Jen and Lee (1998) and Zhou et al. (2007) suggested to use 5Hz to prevent sample overheat. From the tests, S-N curves were constructed, thus testing sets of three samples at maximum stress levels of 70%, 50%, and 30% of the control material tensile strength. Table 2 reports specific parameters for each of the tested material sets. These values were determined from the measured unaged material properties.

Tests were conducted using an MTS 810 testing frame with capacity of 245 kN (55,000 lbs). The MTS frame was controlled with an 8500 plus Instron controller. Strain was measured using an Instron extensometer plugged to the controller. The tests were controlled with the Instron software SAX V7.1.

Parameters		Description
Load Classification	Tension-Tension	Load Type
	Constant Amplitude	Load-Time Spectrum
R-ratio	0.10	$\sigma_{min.} / \sigma_{max.}$
Frequency	5 Hz	Cycles per second
Wave Type	Sinusoidal	Load Pattern Form
Load Levels (σ_{max})	0.70	Fraction of the Maximum Tensile Stress ($\sigma_{max} / \sigma_{ult}$)
	0.50	
	0.30	
Mean Stress (σ_m)	See Table 2	$(\sigma_{max.} + \sigma_{min.}) / 2$
Amplitude (σ_a)	See Table 2	$(\sigma_{max.} - \sigma_{min.}) / 2$

Table 1. List of Parameters used for the Fatigue Testing.

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Stress Level ($\sigma_{máx}$ / σ_{ult})	**Maximum Stress MPa (ksi)**	**Mean Stress MPa (ksi)**	**Stress Amplitude MPa (ksi)**
Uniaxial Laminate			
0.70	420.04 (60.92)	231.02 (33.51)	189.02 (27.41)
0.50	300.03 (43.52)	165.01 (23.93)	135.01 (19.58)
0.30	180.02 (26.11)	99.01 (14.36)	81.01 (11.75)
Biaxial Laminate			
0.70	216.51 (31.40)	119.08 (17.27)	97.43 (14.13)
0.50	154.65 (22.43)	85.06 (12.34)	69.59 (10.09)
0.30	92.79 (13.46)	51.03 (7.40)	41.76 (6.06)
Vinyl Ester Resin			
0.70	33.16 (4.81)	18.24 (2.64)	14.92 (2.16)
0.50	23.68 (3.44)	13.03 (1.89)	10.66 (1.55)
0.30	14.21 (2.06)	7.82 (1.13)	6.39 (0.93)

Table 2: Specific Loading Parameters used for each Type of Material.

5 EXPERIMENTAL FATIGUE RESULTS

Load and strain were recorded for each tested sample and the total number of cycles before failure. Plots containing the maximum stress (σ_n) with respect to the maximum number of cycles (N), known as S-N curves, were generated for each set of samples. A regression model was applied to each curve having the axis corresponding to the number of cycles in a logarithmic scale. This well know equation is:

$$\sigma_n = A \log N + B \tag{1}$$

where A is the slope of the curve and B is the intercept with the vertical axis.

Figure 2a, b, and c show examples of failed coupons of all three group of samples. Resin samples (Figure 2a) failed outside the reduced area as shown in the figure. This type of failure is not uncommon as it has been reported by other authors such as Iqbal (2001) and Post (2008). Uniaxial and biaxial samples (Figure 2b,c) failed between the grip area, sometimes originated just below the grip jaws. The dominant failure modes for the biaxial samples (Figure 2b) were delamination and abrupt fiber breakage. Delamination occurred more frequently in samples subjected to higher stresses (50% and 70%). In general, the damage evolution during testing starts with cracking of the matrix between layers. This cracks increase the interlaminar stresses, thus provoking delamination (Harris, 2003; Talreja, 1987). Failure mode for uniaxial samples (Figure 2c) is characterized by a large crack parallel to the fiber direction. In some instances, the crack initiated at the edge of the sample with fiber breakage. Similar failure modes were observed by Iqbal (2001) for uniaxial composites.

Tables 3, 4 and 5 report fatigue test results for the vinyl ester resin samples, uniaxial composites and biaxial composites, respectively. The tables report the actual submersion period in days for each set, the average actual moisture content in percentage, the stress level in percentage, and the average number of cycles for each stress level. The gap in submersion times between samples tested after 200 days and 500 days was due to a malfunction of the testing machine controller. Since the number of samples was limited, a new set to fill the gap

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was not possible. The results from the tests are plotted in S-N charts in Figure 3, were results of each sample as well as a linear regression based on equation 1 is plotted.

From the table and the graphs it is clearly observed that the life cycle of all samples is reduced with moisture content. For the resin samples, the reduction in the fatigue life is at a higher degree for the lowest stress level (30%). In the case of samples tested after 509 days of water submersion, it seems that the number of cycles is slightly higher at 50% and 70% of stress levels compared to the other ages. For the biaxial composite samples, observation of individual stress levels revealed that the samples at 70% stress level have a decreasing tendency in the cycles compared to the other two stress levels (50% and 30%). These stress levels do not present a definite tendency. The curves show a slight reduction in the fatigue live of the samples as the exposure time increases. The larger variation with respect to the control samples was observed for the set tested after 208 days of exposure. Finally, for the uniaxial composite samples, the results show a constant decreasing in the fatigue life for the samples tested at 50% and 70% stress, being 70% the samples showing the largest loss. The graphs clearly show that results of coupons tested at 521 days exhibit a tendency quite different than the rest of the samples.

a) b) c)

Figure 2: Sample of Failed Coupons: a) Vinyl Ester Resin, b) Uniaxial, and c) Biaxial.

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Submersion Time (days)	Average Moisture (%)	σ_{max} / σ_{ult} (%)	Average Number of Cycles
0	0.00	70	864
		50	5,766
		30	117,758
68	0.54	70	265
		50	1,048
		30	9,976
122	0.62	70	223
		50	721
		30	5,927
215	0.72	70	229
		50	828
		30	5,932
509	0.77	70	275
		50	951
		30	4,285

Table 3: Result of the Fatigue Testing of the Vinyl Ester Resin Samples.

Submersion Time (days)	Average Moisture (%)	σ_{max} / σ_{ult} (%)	Average Number of Cycles
0	0.00	70	405
		50	3759
		30	42518
60	0.16	70	213
		50	3247
		30	34837
100	0.17	70	156
		50	1553
		30	44106
208	0.23	70	135
		50	2887
		30	76905
504	0.25	70	126
		50	877
		30	30489

Table 4: Result of the Fatigue Testing of the Biaxial Composite Samples.

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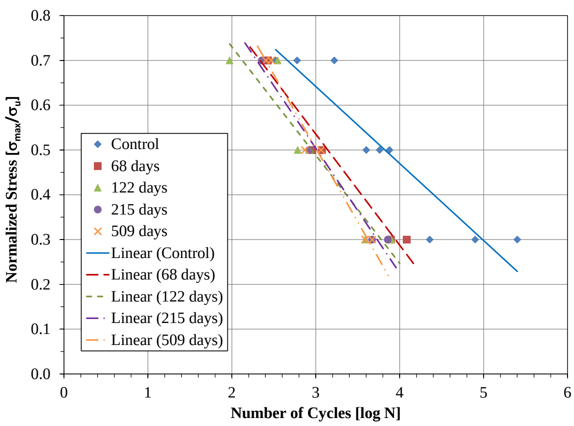
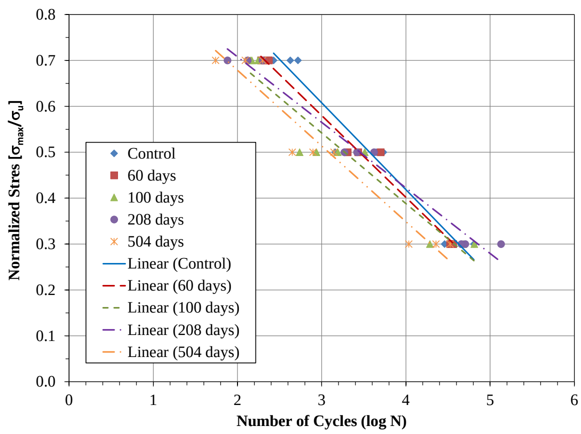
Submission Time (days)	Average Moisture [%]	σ_{max} / σ_{ult} [%]	Average Number of Cycles
0	0.00	70	2033
		50	9876
		30	388259
57	0.16	70	846
		50	8114
		30	537521
110	0.20	70	333
		50	5032
		30	303306
210	0.24	70	214
		50	4533
		30	151050
521	0.25	70	26
		50	2003
		30	99984

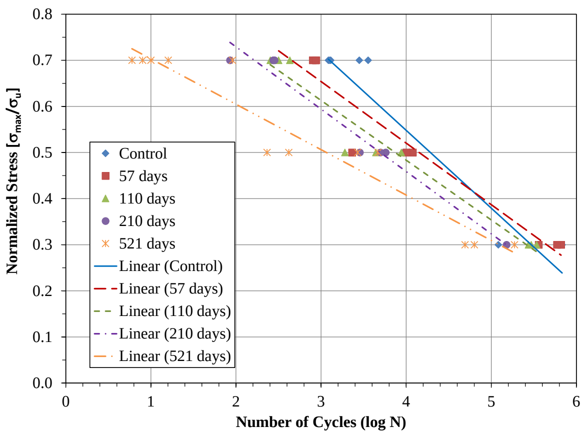
Table 5: Result of the Fatigue Testing of the Uniaxial Composite Samples.



a) Vinyl Ester Resin



b) Biaxial Composite



c) Uniaxial Composite

Figure 3: S-N Curves and their Liner Regressions of the Tested Samples.

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6 PROPOSED FATIGUE LIVE PREDICTION MODEL BASED ON EXPERIMENTAL DATA

This section presents a modification to the model of Epaarachchi-Clausen (2003) following a methodology presented by Helmi (2006) were the parameter of moisture or exposure time is incorporated. This model is calibrated with experimental data developed in this study. In general, the development of a rational model that predicts the fatigue life of a material has several stages: (1) experimental observation of the damage accumulation and the definition of a damage matric, (2) a model formulation and the experimental determination of its parameters, (3) the development of an additional stage that incorporates the additional degradation factor, and (4) the verification of the life predictions of the model (Sendeckyj, 1990). Mayugo (2003) classify the models that estimate the fatigue life of materials in two groups: (a) macroscopic models based in empirical evaluation of the materials behavior, and (b) the mechanical models that consider the different failure mechanisms at the microstructural level of each constituent of the composite material.

6.1 EPAARACHCHI-CLAUSEN MODEL

A close look at the intercept of the S-N curves developed in the previous section revealed that the intercepts of the linear regressions in the semi logarithmic scales gives values of stress ratio larger than one (100%). This is an indication that a nonlinear model is needed.

Epaarachchi and Clausen (2003) implemented an empirical model that describes the fatigue strength degradation of composites subjected to cyclic loads of constant amplitude and frequency. The model starts from a simple formulation of a nonlinear function that represents the entire range of stress ratios ($\sigma_{max}/\sigma_{ult}$). The model uses two principal variables, α and β, that are determined from the experimental data. One advantage of this particular model is that it can be applied with limited amount of experimental data and for a constant *R*-ratio for a range of stress levels. In addition, once the model has been calibrated, it can work for frequencies and *R*-ratios different than the ones used in the calibration data.

The expressions of the model are shown in the following equations:

$$D = \left(\frac{\sigma_{ult}}{\sigma_{max}} - 1\right)\left(\frac{\sigma_{ult}}{\sigma_{max}}\right)^{0.6 - \psi\,|\sin\theta|}\left[\frac{1}{(1-\psi)^{1.6-\psi\,|\sin\theta|}}\right] f^{\beta} \tag{2}$$

$$\frac{D}{\alpha} = \left(N^{\beta} - 1\right) \tag{3}$$

where: σ_{ult} = ultimate tensile stress
σ_{max} = maximum applied stress
$\psi = R \quad for \quad -\infty < R < 1$ (tension-tension or tension-compression)
$\psi = 1/R \quad for \quad 1 < R < \infty$ (compression-compression)
θ = smaller angle between the load direction and the fiber orientation
f = load frequency
N = cycle number
α and β = parameter of the S-N curves (material constants)

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The key factors of the model, α and β, are determined in part by trial and error, adjusting the parameters to obtain the best fit to the data values. For each experimental data set, the values of D and $(N^\beta - 1)$ are determined from Equations (3) and (4) and plotted as shown in Figure 4. Linear regression is used with the intercept set at zero. Then the value of β is adjusted until the best fit is achieved. The parameter from the regression in MS Excel (R^2) is used for this objective. The parameter α is computed as the slope of the linear regression. Once the most suitable parameters are determined, the S-N curves for the entire fatigue life of a given material can be generated.

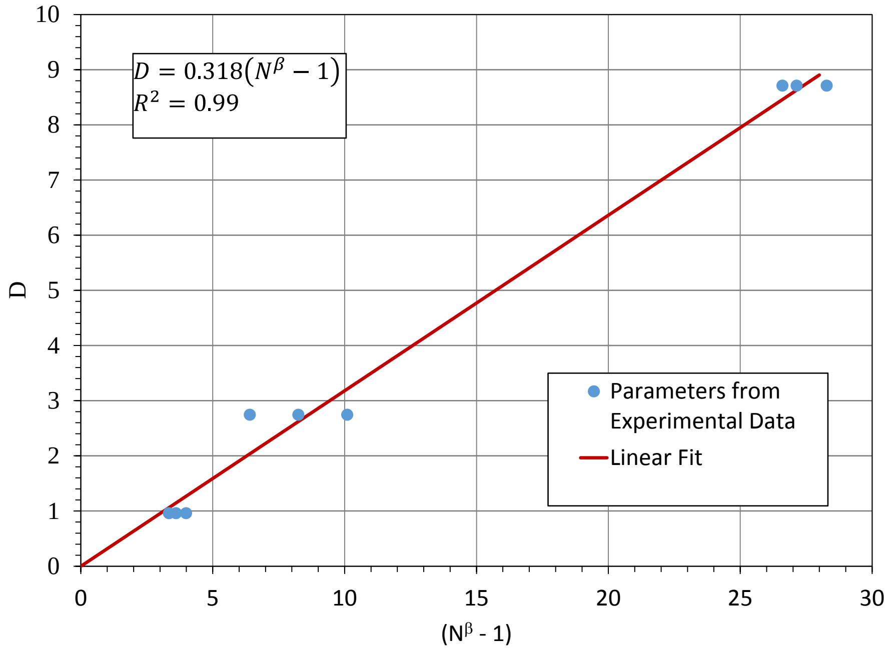

Figure 4: Example of the Estimation of the α and β Parameters for Samples of Uniaxial Composite with 110 Days of Exposure.

6.2 INCORPORATION AND CALIBRATION OF THE MOISTURE EFFECT IN EPAARACHCHI-CLAUSEN MODEL

Results for the parameters α and β for each of the submersion time and moisture content computed for the Epaarachchi-Clausen Model are reported in Table 6. The table also reports the R^2 parameter for the linear regression. Realizing that a family of parameters with respect to submersion time and moisture content are generated, we can then develop expressions for α and β as functions of time or moisture content (α_t, β_t), thus providing a simple way to express a family of S-N curves at different moisture contents or submersion time.

Two types of curves were examined for the curve fitting of the parameters: exponential and quadratic polynomial. Figure 5 shows examples of the propose curves for β_t parameter of the vinyl ester resin coupons (a) as function of submersion time in days and (b) as moisture content. Notice that in Figure 5(a) the best fit is achieved by a polynomial curve while in Figure 5(b), the best fit is for an exponential curve. Table 7 shows a summary of the final expressions of parameters α_t and β_t as function of exposure time and moisture content for each of the tested materials. Notice that only for the resin samples the expressions used for moisture were exponential. For the rest of the samples, their best fit was quadratic polynomials.

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Ageing (days)	**Average Moisture (%)**	α	β	R^2
Vinyl Ester Resin				
0	0.00	0.09	0.41	0.85
68	0.54	0.13	0.50	0.97
122	0.62	0.33	0.40	0.89
215	0.72	0.11	0.56	0.96
509	0.84	0.04	0.75	0.98
Biaxial Laminate				
0	0.00	0.15	0.40	0.93
60	0.16	0.10	0.46	0.99
100	0.17	0.44	0.29	0.93
208	0.23	0.41	0.28	0.94
504	0.25	0.70	0.25	0.90
Uniaxial Laminate				
0	0.00	0.21	0.30	0.90
57	0.16	0.27	0.27	0.98
110	0.20	0.32	0.27	0.99
210	0.24	0.25	0.31	0.99
521	0.25	0.95	0.19	0.92

Table 6: Parameters α and β determined by the Eparachichi-Clausen Model.

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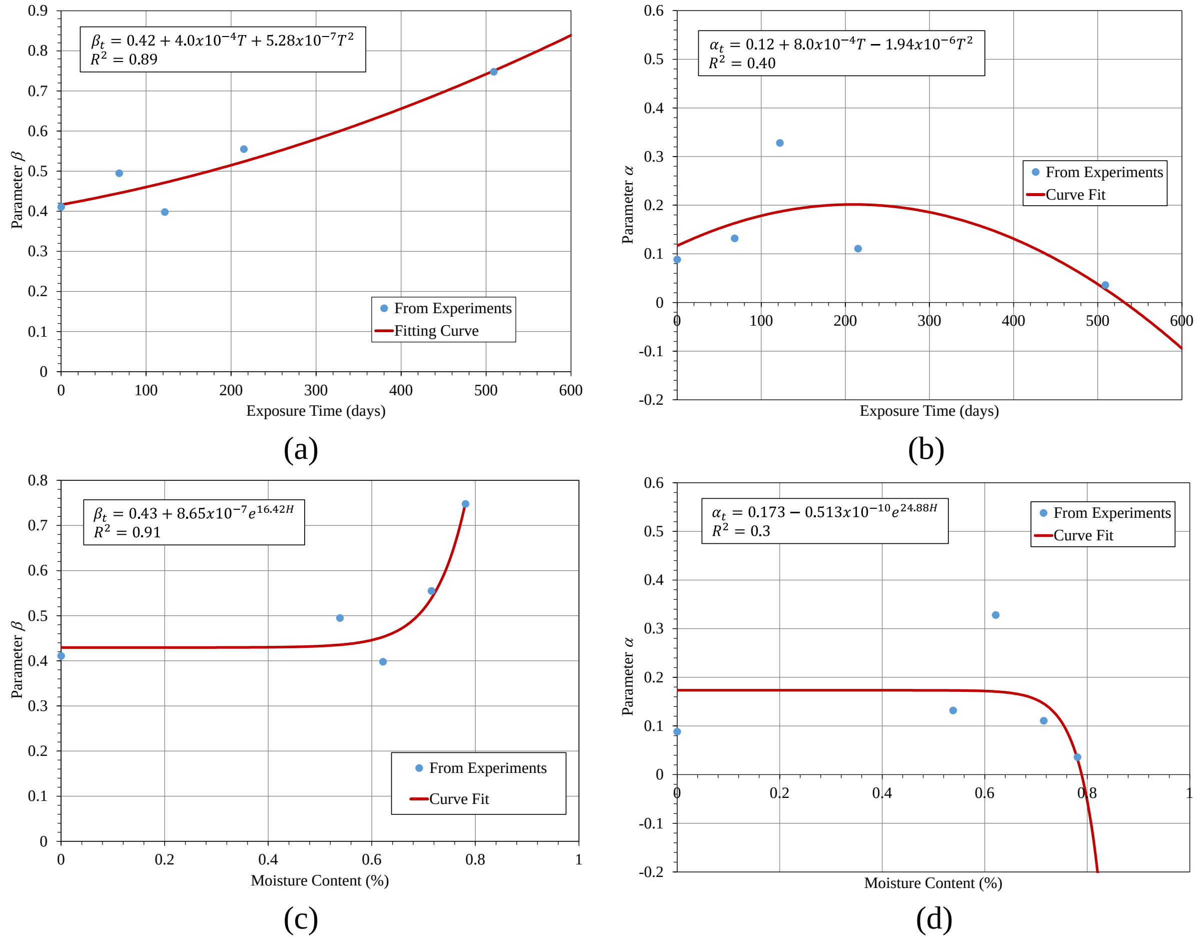

Figure 5: Example of Curve Fitting of the Parameters β [(a) and (c)] and α [(b) and (d)] for the Vinyl Ester Resin Samples as Function of Exposure Time (Days) and as Function of Moisture Content.

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Equation		Curve Fit Model
	Vinyl Ester Resin	
(4)	$\beta_t = 0.42 + 4.0\text{x}10^{-4}T + 5.28\text{x}10^{-7}T^2$	Quadratic Polynomial
(5)	$\alpha_t = 0.12 + 8.0\text{x}10^{-4}T - 1.94\text{x}10^{-6}T^2$	Quadratic Polynomial
(6)	$\beta_t = 0.43 + 8.65\text{x}10^{-7}\ e^{16.42H}$	Exponential
(7)	$\alpha_t = 0.17 - 0.51\ e^{24.88H}$	Exponential
	Biaxial Laminate	
(8)	$\beta_t = 0.43 - 1.0\text{x}10^{-3}T + 1.26\text{x}10^{-6}T^2$	Quadratic Polynomial
(9)	$\alpha_t = 0.13 + 1.80\text{x}10^{-3}T - 1.37\text{x}10^{-6}T^2$	Quadratic Polynomial
(10)	$\beta_t = 0.40 + 0.81H - 5.62H^2$	Quadratic Polynomial
(11)	$\alpha_t = 0.16 - 2.29H + 16.40H^2$	Quadratic Polynomial
	Uniaxial Laminate	
(12)	$\beta_t = 0.28 + 2.0\text{x}10^{-4}T - 6.19\text{x}10^{-7}T^2$	Quadratic Polynomial
(13)	$\alpha_t = 0.25 - 4.0\text{x}10^{-4}T + 3.31\text{x}10^{-6}T^2$	Quadratic Polynomial
(14)	$\beta_t = 0.29 - 1.82\text{x}10^{-2}H - 0.71H^2$	Quadratic Polynomial
(15)	$\alpha_t = 0.21 - 2.72H + 17.31H^2$	Quadratic Polynomial
Where:	T = Submersion Time in Days H = Moisture Content (%)	

Table 7: Final Expressions for the Curve Fit of the α_t and β_t for each of the Tested Materials.

6.3 ASSESSMENT OF THE ADEQUACY OF THE PROPOSED MODIFIED MODEL

Theoretical S-N curves were developed from the expressions of α_t and β_t reported in Table 7. The values were compared with the experimental data that was used to calibrate the models. The new curves were generated from the expression in Equation (16).

$$N_t = \left(\frac{D}{\alpha_t} + 1 \right)^{\frac{1}{\beta_t}} \tag{16}$$

where: N_t = Theoretic number of cycles
D = Variable evaluated from equation (2)
α_t and β_t = Parameters previously described adjusted from experimental data.

Figures 6 to 8 show the theoretical S-N curves generated with the parameters in terms of exposure time (red curve), moisture content (green curve), together with the experimental results (dots). In general, there is not a specific tendency regarding weather the formulation based on exposure time vs. moisture content provides the best prediction. In a few cases, both lines were one on top of each other.

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Figure 6 shows comparisons of the empirical prediction curves with experimental values for the vinyl ester resin coupons. The control and 122 days of exposure show better agreement for the time based formulation while the 215 days and 509 days show better agreement based on moisture. For the case of samples exposed for 68 days, both formulations are practically the same.

Figure 7 shows comparison of the empirical predictions curves with experimental values for the biaxial laminate coupons. For this material, the control, 60 days, and 100 days exposures, both predictions based on moisture and exposure time are practically on top of each other. Plots for 208 days of exposure is in better agreement with time of exposure and for 504 days of exposure is in better agreement with moisture content.

Figure 8 shows comparisons of the empirical predictions curves with experimental values for the uniaxial laminate coupons. In this case, the prediction based on time formulation was in better agreement with the experimental results. This was the case for samples of 110 days, 210 days, and 521 days of exposure. The control sample had both curves on top of each other. Finally, for the 57 days exposure samples, moisture based formulation was closer to the experimental data than the exposure time formulation.

Observations of the figures leave us with no definite conclusion regarding whether moisture based formulation or time of exposure base formulation is or not the best to predict the fatigue life of our materials. However, since damage is directly proportional to moisture uptake, it is proposed that the moisture base formulation be the prefer choice to apply for composite materials in general. Fatigue testing has inherent variability as it is seen from the dispersion of the data points reported in Figure 3.The fact that for some cases time formulation agrees better with experiment or moisture can be attributed to this scarcity.

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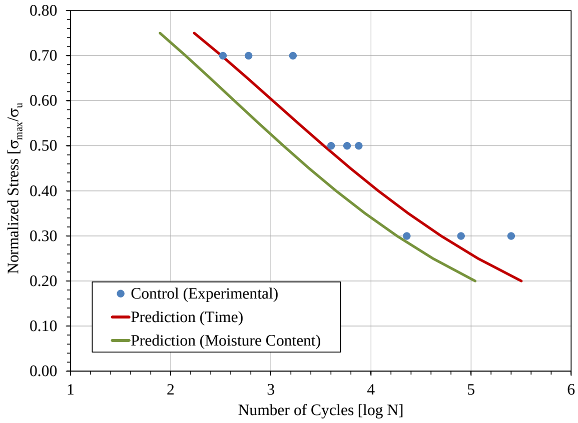
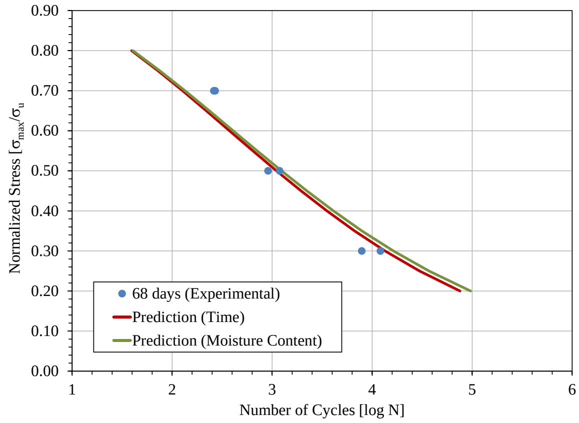
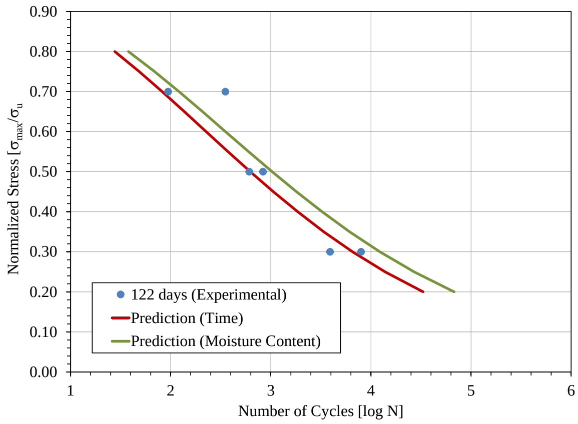


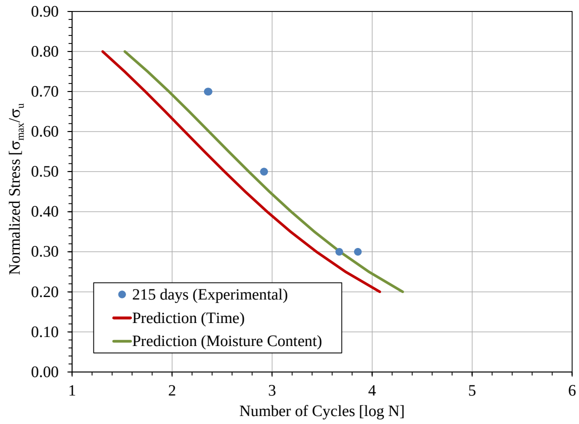
a) Control



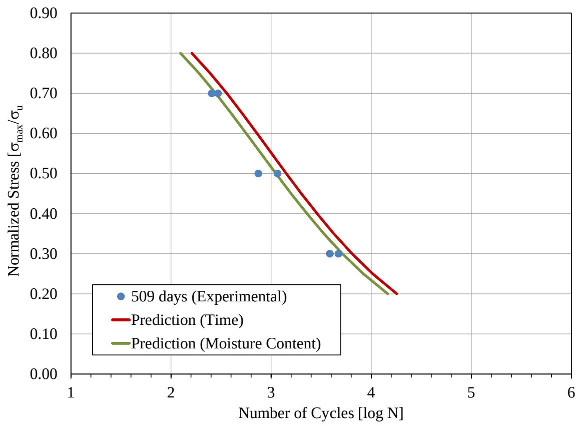
b) 68 Days



c) 122 Days



d) 215 Days



e) 509 Days

Figure 6: Comparison of the Experimental Values with Theoretical Curves for the Vinyl Ester Resin.

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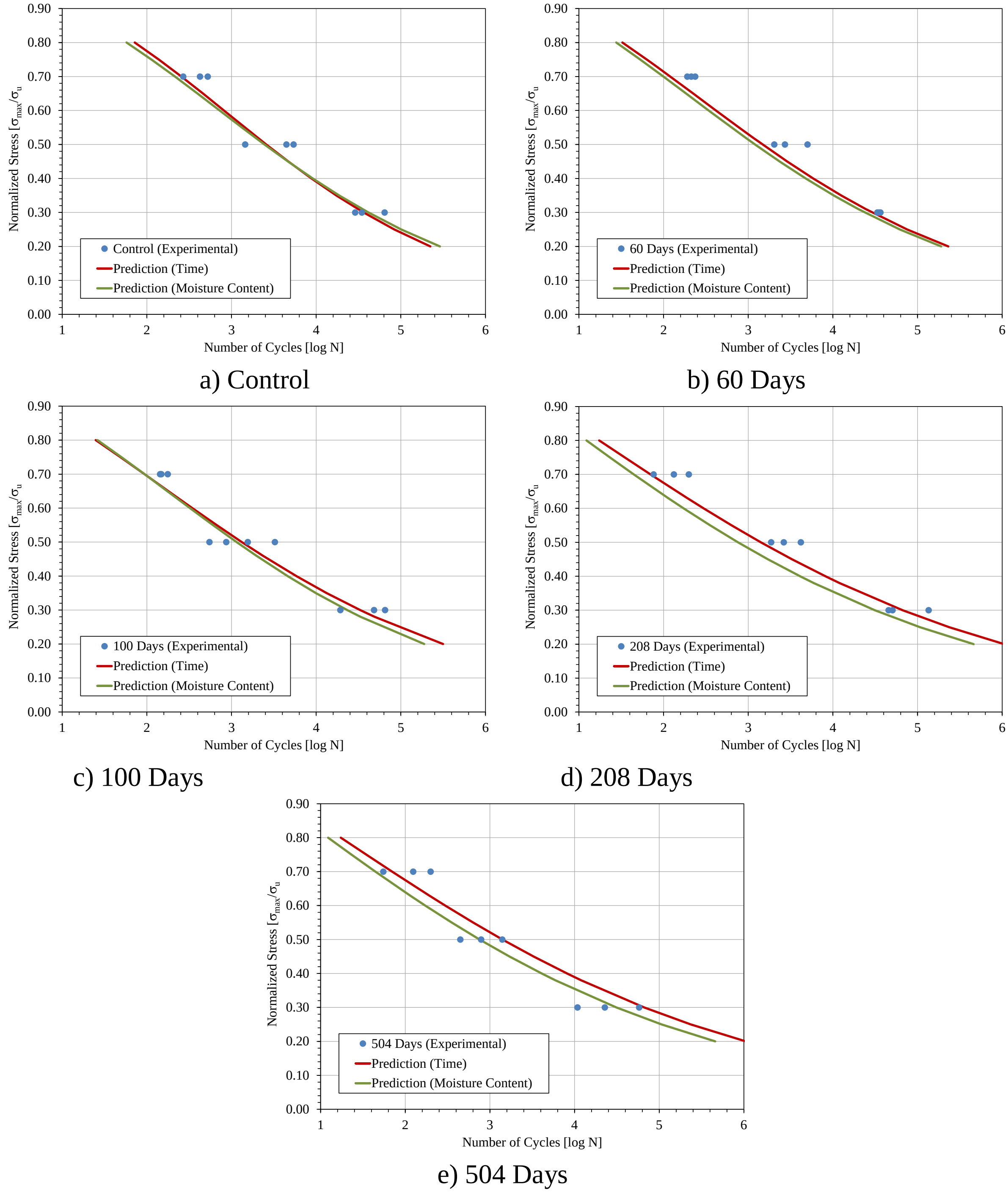

Figure 7: Comparison of the Experimental Values with Theoretical Curves for the Biaxial Laminate.

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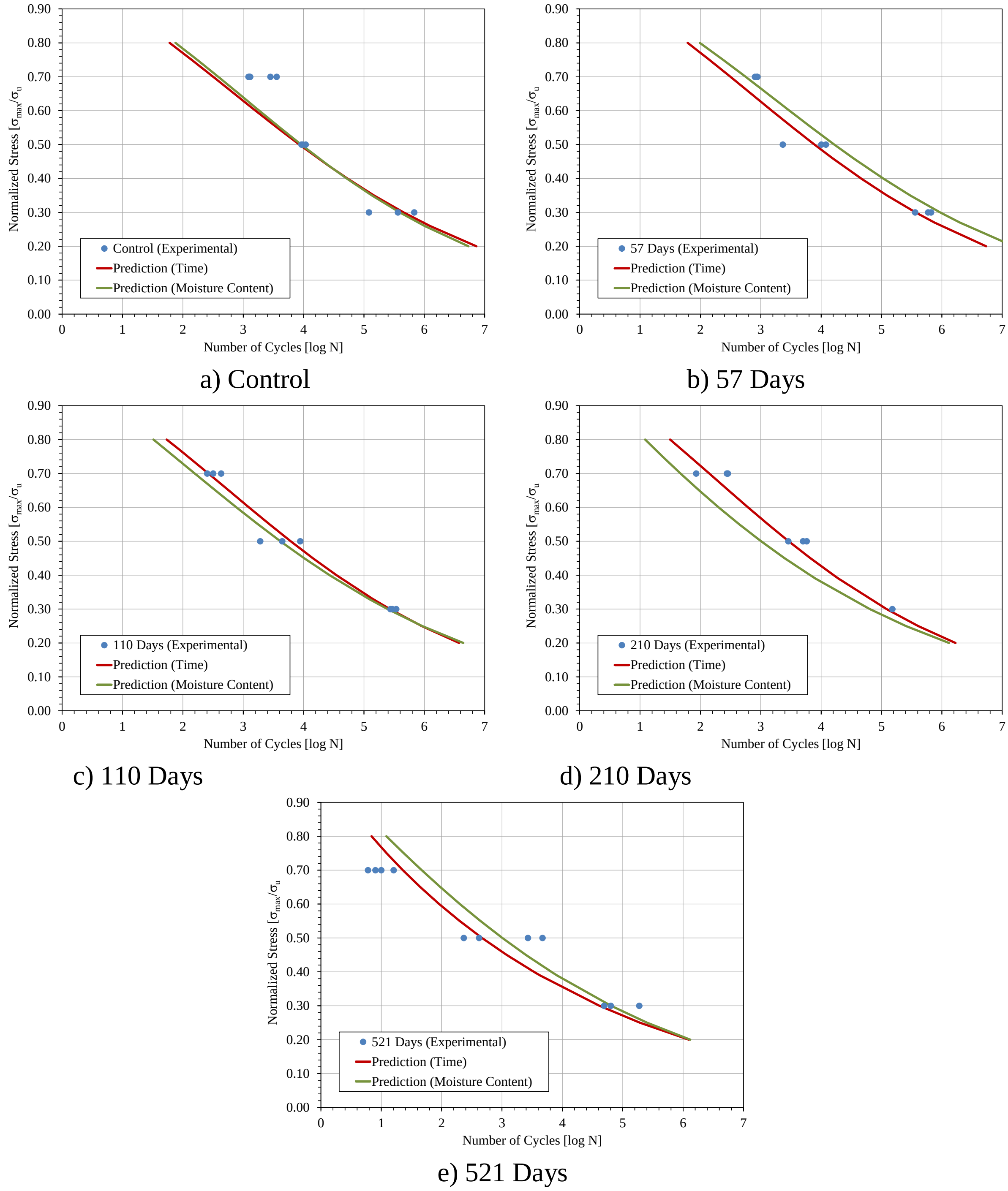

Figure 8: Comparison of the Experimental Values with Theoretical Curves for the Uniaxial Laminate.

7 CONCLUSIONS

This paper presents a study of the evaluation of the fatigue life of composite materials and a constituent (vinyl ester resin) when are exposed hygrothermal ageing for prolonged time (up to 500 days). The fatigue behavior of composite materials has been previously studied. Also various studies have incorporated some source of environmental conditioning for degradation. However, the studies have been limited to exposure conditions for less than 125 days. The test plan was limited to constant frequency and amplitude. Future studies can look into other

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frequencies or variable cycles and into a broader type of materials to be able to reach a more fundamental conclusion. This paper summarized the most relevant findings from the work of Román Batista (2009).

Generally, failure modes of the laminated composites and resin were in agreement with the literature. The results obtained from the vinyl ester resin represent a conservative estimate of their fatigue life because of their failure in the wider section near the grips. It was proven that moisture reduces the fatigue life of composite materials and resins as well compared to unexposed specimens. The vinyl ester resin samples exhibited higher degradation at 30% of the ultimate stress while for the laminates the larger loss in fatigue life was observed for the highest stress levels (70%). The results suggested that the fatigue behavior for composite materials is independent of the moisture content for short exposure times. But for extended exposure, the effect is more noticeable. This is agreement with the report by Zhou *et al*. (2007).

The modified Epaarachchi and Clausen (2003) model represented a reasonable option to incorporate moisture content and exposure time to predict the fatigue life of degraded composites. The principal parameters, α and β, which are determined by trial and error from the experimental data were fitted by quadratic polynomials for composites and exponential and polynomial for the resin. No definite conclusion was found suggesting that the moisture approach or the exposure time is the correct path. However, moisture content is the most logical approach since it is the trigger factor for degradation. Further evaluation is needed for a more precise calibration of the model since in this study, the expressions were obtained and calibrated with the same experimental data.

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