Environmental Compensation Factor Influence on Composite Design and Certification

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ABSTRACT

The goals of this research are to document a procedure for applying environmental compensation and scatter factors to account for the static test condition environment and provide data on the effects of temperature and moisture. In addition, this research program investigates the use of probabilistic methods for determining environmental effects and provides guidance material on the application and boundaries of these environmental effects. Environmental factors are developed based upon material performance at the lamina, laminate, coupon, and sub-element levels for the test program. After comparing these over a range of materials, procedures are documented along with examples for a variety of material properties and failure modes.

KEY WORDS: environmental effects, certification, composite

1. INTRODUCTION

Despite their many advantages, such as tailorability, high specific strength and modulus, and fatigue resistance, a common problem encountered with composites is their sensitivity to environmental conditions such as temperature and moisture. During service, composite structures absorb atmospheric moisture, primarily by instantaneous surface contact absorption and subsequent diffusion through the epoxy material. The rate of moisture absorption is accelerated by elevated temperature. Although the mechanisms have not fully been determined, composite absorption of moisture along with water-soluble inclusions results in structural dimension changes (swelling) and degradation of matrix/interfacial-controlled mechanical and thermal properties.

It was demonstrated in reference [1] that fatigue behavior is relatively insensitive to environmental conditions, but that static strength behavior is environmentally dependent. In recognition of this, current practice for static testing is to account for environmental factors in a manner similar to the load-enhancement factor approach. By applying an additional load to the static test article equivalent to the difference produced between the test condition and the maximum operational temperature, the static test could be conducted in conditions other than the maximum operational temperature and moisture. This procedure varies from company to company depending on the application.

2. ENVIRONMENTAL COMPENSATION FACTORS IN COMPOSITE DESIGN STRUCTURAL MARGINS

Analysis alone is generally not considered adequate for substantiation of composite structural design; instead, the "building-block approach" to design development testing is used in conjunction with analysis. This approach is often considered essential to the qualification/certification of composite structures due to the sensitivity of composites to out-of-plane loads, the multiplicity of composite failure modes, and the lack of standardized analytical methods. The building-block approach is also used to establish environmental compensation values applied to full-scale tests at the room-temperature ambient environment, as it is often impractical to conduct these tests at the actual moisture and temperature environment. These environmental compensation factors are typically justified by experiments conducted at lower building-block levels. Similarly, other building-block tests are used for determining truncation approaches for fatigue spectra and compensation for fatigue scatter at the full-scale level.

2.1 Moisture Absorption in Composites

Most polymeric materials, whether in the form of composite matrix or polymeric fiber, are capable of absorbing relatively small, but potentially significant amounts of moisture from the surrounding environment. The physical mechanism for moisture gain, assuming there are no cracks or other wicking paths, is generally assumed to be mass diffusion following Fick's Law (the moisture analog to thermal diffusion). While material surface in direct contact with the environment absorbs or desorbs moisture almost immediately, moisture flows into or out of the interior relatively slow. The moisture diffusion rate is many orders of magnitude slower than heat flow in thermal diffusion. Nevertheless, after a few weeks or months of exposure to a humid environment, a significant amount of water will eventually be absorbed by the material. This absorbed water may produce dimensional changes (swelling), lower the glass transition temperature of the polymer, and reduce the matrix and matrix/fiber interface dependent mechanical properties of the composite (effectively lowering the maximum operational temperature of the material). Because absorbed moisture is a potential design concern for many applications, testing of the airframe materials is usually included in the process of structural substantiation after representative moisture exposure.

These methods for moisture exposure vary from program to program, but are known to be thickness and exposure time-dependent. There are two moisture properties of a Fickian material: moisture diffusivity and moisture equilibrium content (percent-weight moisture). These properties are commonly determined by a gravimetric test method (such as ASTM D5229 Procedure A) that exposes an initially dry specimen to a constant humid environment and documents moisture mass gain versus the square-root of time. During early weight measurements, this mass-time relation is linear, the slope of which is related to the rate of absorption (the moisture diffusivity). As the moisture content in a substantial volume of the exterior of the material begins to approach equilibrium, the mass gain versus square-root time slope becomes increasingly smaller. Eventually, as the interior of the material approaches equilibrium, the difference between subsequent weight reading approaches zero and the slope is nearly parallel to the time axis. The weight percent mass gain at this point is the moisture equilibrium content. Moisture equilibrium content is a function of ambient moisture exposure, such as relative humidity; however, the speed at which this moisture content is achieved is a function of ambient temperature. Figure 1 illustrates this process of total mass gain versus root-time during specimen moisture exposure and the difference in response due to different temperatures. For the 160°F/85% RH condition, Figure 2 shows the moisture profile through the specimen thickness, illustrating the rapid moisture uptake near the surface together with the relatively slow uptake of moisture in the middle of the specimen during early stages of exposure.

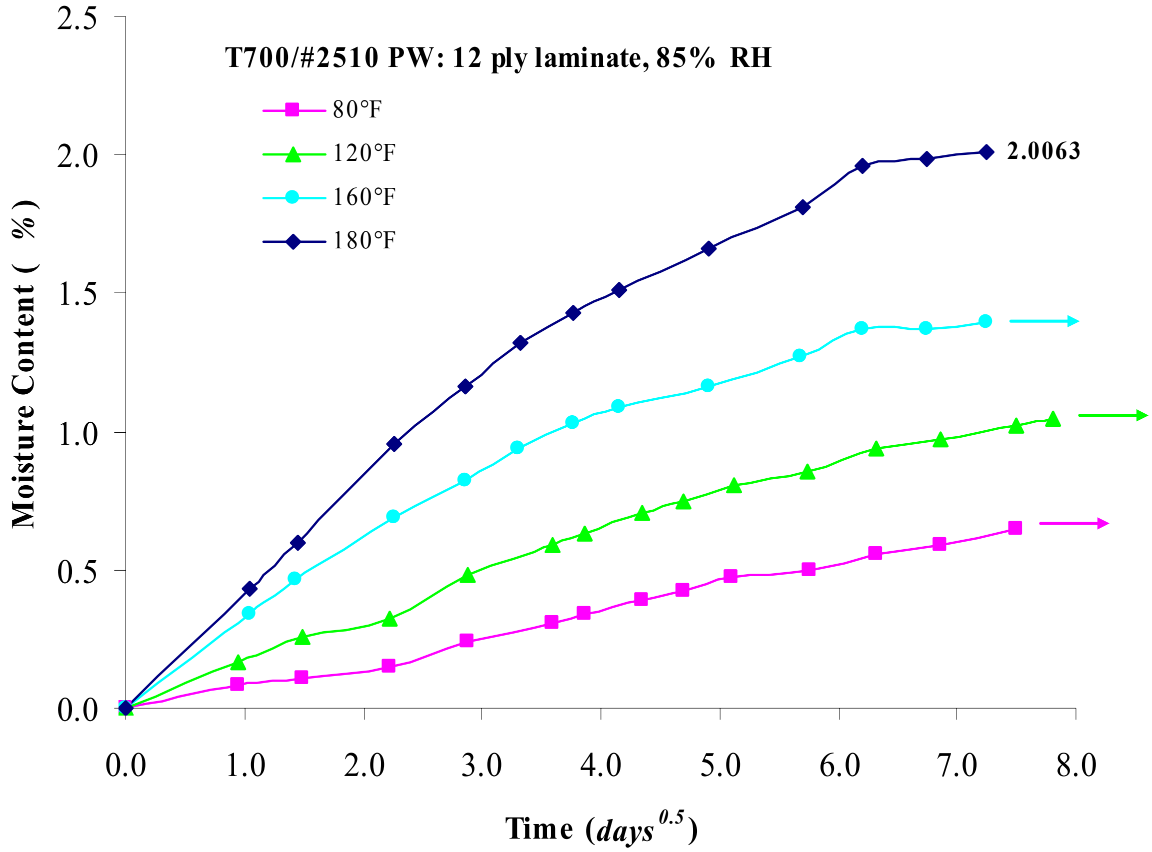

Figure 1 – Typical Moisture Absorption Response

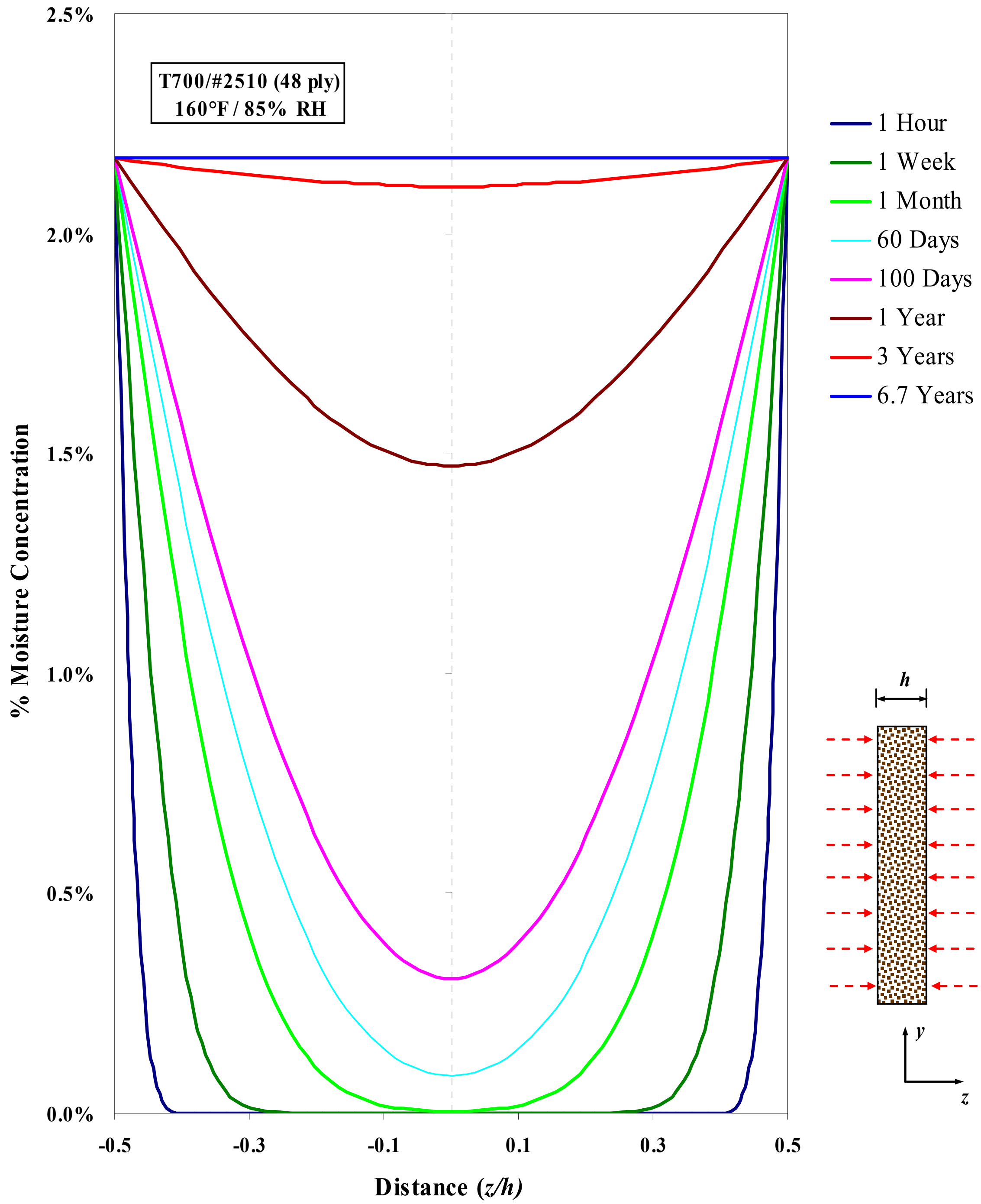

Figure 2 – Typical Through-Thickness Moisture Absorption

2.2 Strain-Based Design and Certification

Composite material components are subjected to a wide range of environments. Environmental factors of major importance include a combination of humidity and temperature. Many studies have been conducted to investigate moisture absorption and the reduction of mechanical properties due to temperature and moisture exposure. The current approach used to account for environmental factors defines extreme exposures and selectively evaluate the effects of such environments on material properties by test. These extremes are then considered to be invariant during the lifetime of the structure. Strength values are then reduced to coincide with the environmental extremes. Figure 3 is a graphical schematic of strain-based design criteria, which shows the applied loading factors as separate functions of moisture and thermal loading effects. Figure 4 represents a design strain value as a function of temperature in both dry and wet scenarios. The approach employed in this program is to characterize these differences in thermal and moisture factors as typically used in design and certification testing, as well as to include the building-block effect, which shows the scaling effect related to this design criterion.

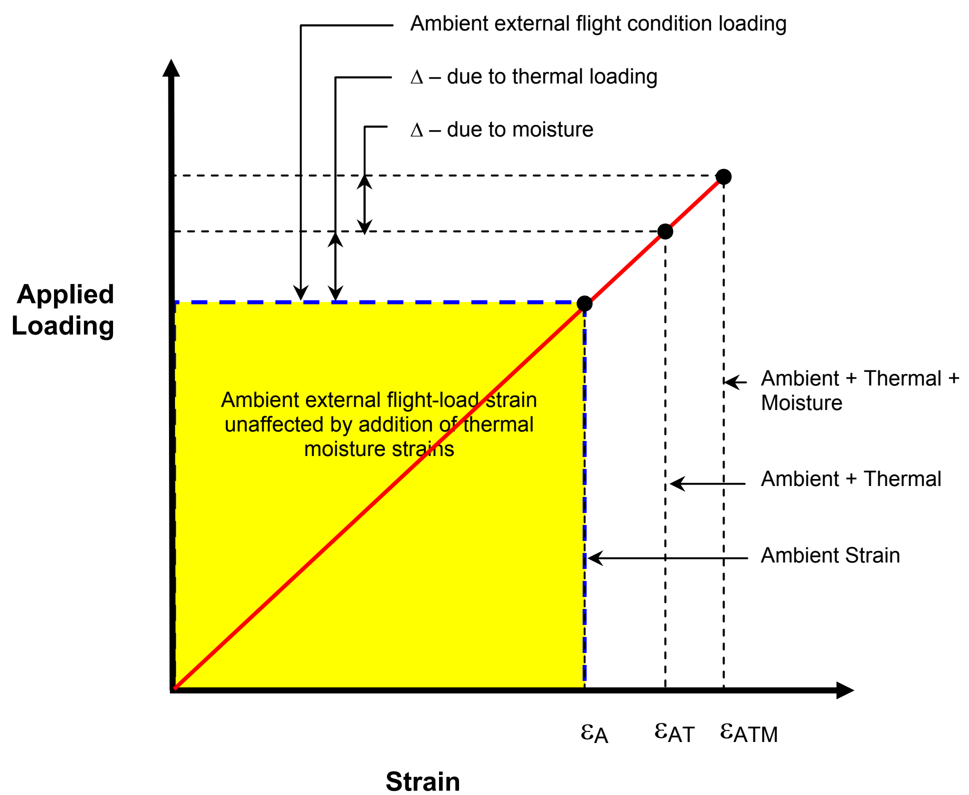

Figure 3 – Schematic of Environmental and Moisture Design Criteria for Composite Structures

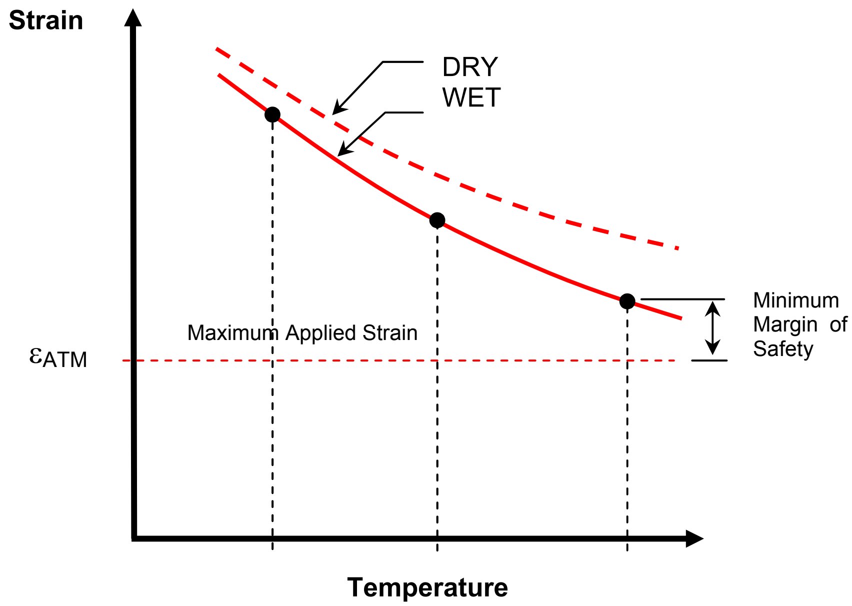

Figure 4 – Schematic of Environmental and Moisture Design Criteria for Composite Structures Related to Strains Used for Application

2.3 Environmental Compensation Factors

In addition to the environmental factors, scatter factors are also usually imposed during static testing and are normally needed when certifying by test. These factors are used to compensate for only testing a small number of replicates (sometimes only one) and account for the test article being non-representative of the worst-case manufacturing article to pass conformity checks. These factors are similar in nature to the load factor increase, but are imposed only on the static test article. In some cases, these factors are eliminated by conforming the test article with pre-imposed manufacturing flaws representative of the worst-case scenario of a production article. The 2001 FAA ACE Policy for Static Strength Substantiation provides a good background and reference regarding this [2].

In order for composite design to satisfy FAA certification requirements, FARs require compliance with CFR 23.573, 23.603, 23.613 and 23.619 (these sections also apply to Part 25 aircraft). General guidelines for composite structure should be considered, which are more stringent than what is normally done for metallic structure certifications (i.e., account for the *difference* between composite and metallic structures in certification). This generates typical "overloads" that are placed on the structure to account for these differences, which may be related to environmental conditions as well as to material factors. An approach which may be used when combined with analytical modeling is to apply these "overloads" within the model to demonstrate compliance after a successful static structural test (may also be applied during the test) indicating positive margins of safety throughout the structure. Another approach is to apply these loads directly to the structure during the static test as an additional factor, which is over and above the traditional factor of safety. This overload may be characterized by a Static Load Factor (SLF) and can be calculated as shown in equation (1):

$$SLF = \frac{C_{\substack{composite \\ variability}} \cdot C_{\substack{composite \\ temperature}} \cdot C_{\substack{composite \\ moisture}}}{F_{\substack{metals \\ variability}} \cdot F_{\substack{metals \\ temperature}} \cdot F_{\substack{metals \\ moisture}}} \tag{1}$$

where

$C_{\substack{composite \\ variability}}$ ≡ composite material variability

$C_{\substack{composite \\ temperature}}$ ≡ composite temperature effects

$C_{\substack{composite \\ moisture}}$ ≡ composite moisture effects

$F_{\substack{metals \\ variability}}$ ≡ metal material variability

$F_{\substack{metals \\ temperature}}$ ≡ metal temperature effects

$F_{\substack{metals \\ moisture}}$ ≡ metal moisture effects

The focus of this task is to develop guidance material for generating these factors as related to composite design and certification and to make rational boundary comparisons between the certification approaches for metallic and nonmetallic structures. This guidance incorporates examples from a variety of available data and characterizes additional parameters as needed in consultation with the FAA working group.

2.4 Moisture Diffusion and Climatic Characterization

Most polymeric materials are capable of absorbing relatively small, but potentially significant amounts of moisture from the surrounding environment. The physical mechanism for moisture mass change, assuming there are no cracks or other wicking paths, is generally assumed to be mass diffusion following Fick's Law. Fickian moisture diffusion into or out of the interior occurs relatively slowly, many orders of magnitude slower than heat flow in thermal diffusion. Nevertheless, given enough exposure time in a moist environment, a significant amount of moisture may be absorbed into the material. This absorbed moisture may cause material swelling, and, particularly at higher temperatures, may soften and weaken the matrix and matrix/fiber interface, which is detrimental to many mechanical properties that are often design drivers for structural applications. Absorbed moisture effectively lowers the maximum operating temperature of the material. The effect is demonstrated by lowering of the glass transition temperature (thus, the particular interest in T_g test results).

A common composite material design practice is to conservatively use the worst-case condition for this exposure, which means saturation until equilibrium (at a recommended relative humidity of 85%) and characterization of the material properties at the maximum operating limit (MOL). Assuming Fickian type behavior and a constant moisture diffusivity at temperature, *T*, the realistic moisture levels and times for composite absorption can be calculated using Fick's second law as shown in equation (2):

$$\frac{\partial c}{\partial t} = D_z(T) \cdot \frac{\partial^2 c}{\partial z^2} \tag{2}$$

where

c	≡ moisture concentration
T	≡ temperature
t	≡ time
z	≡ through-the-thickness direction (position)
$D_z(T)$	≡ moisture diffusivity constant through-the-thickness at temperature T
$\frac{\partial c}{\partial t}$	≡ time rate of change of moisture concentration

The concentration and diffusivity constants shown are highly important to the following discussion. Moisture diffusivity for composite structures is discussed in more detail in CMH-17 [3] and in ASTM "Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials" (D5229). Assuming that the variations in diffusivity through the thickness can be neglected and the article is at steady state, the moisture content simplifies to:

$$M(T,t) = M_b + G(T,t) \cdot (M_m - M_b) \tag{3}$$

where

M_b	≡ baseline moisture content (equal to 0% for oven dried specimens)
M_m	≡ effective moisture equilibrium content (a function of RH only)
$M(T,t)$	≡ moisture content of material as a function of temperature and time
$G(T,t)$	≡ moisture absorption function

M_b, M_m, and $M(T,t)$ are typically given as a % of oven-dry mass. According to ASTM 5229, the moisture absorption function, $G(T,t)$,can be approximated by:

$$G(T,t) = 1 - \exp\left[-7.3 \cdot \left(\frac{D_z(T) \cdot t}{h^2}\right)^{3/4}\right] \tag{4}$$

where

h	≡ thickness of material for double-sided exposure

Thus, from equation (4), with various assumptions to be validated as part of this research investigation, *G(T,t)* is a function of temperature only and does not depend on relative humidity. Figure 5 shows *G(T,t)* plotted as a function of D_z and time for different boundaries of D_z and temperature.

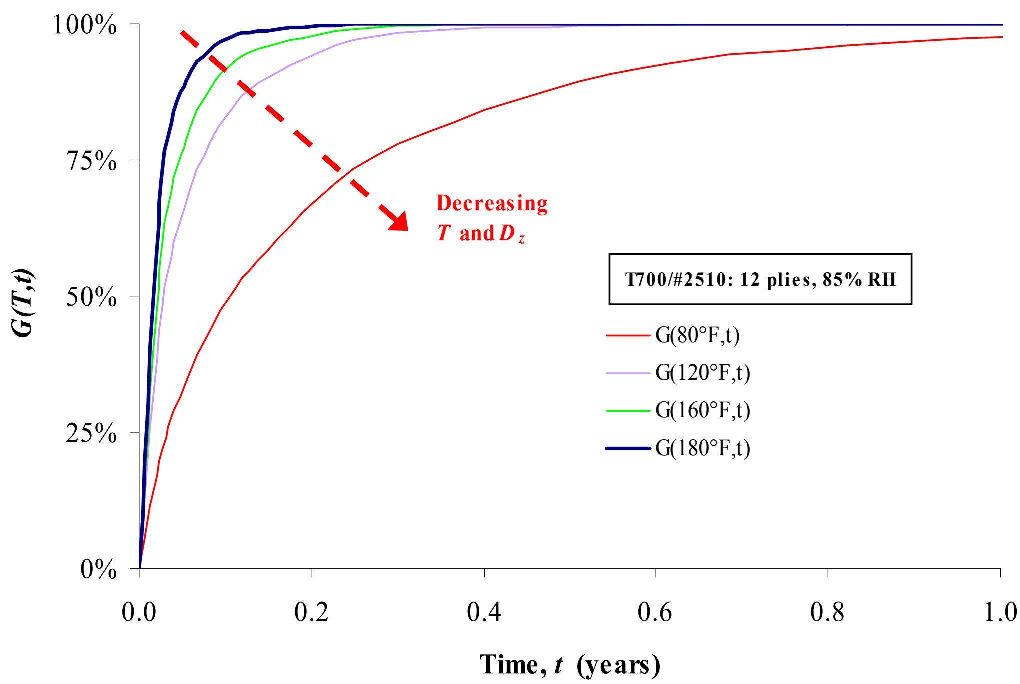

Figure 5 – $G(T,t)$ as a Function of Time for High Temperature, High D_z and Low Temperature, Low *Dz*

Combining equations (3) and (4), the moisture content of the material as a function of temperature and time yields to:

$$M(T,t) = M_b + (M_m - M_b) \cdot \left\{ 1 - \exp\left[-7.3 \cdot \left(\frac{D_z(T) \cdot t}{h^2} \right)^{3/4} \right] \right\} \tag{5}$$

Equation (5) can then be rearranged in terms of time to reach a particular moisture level content as:

$$\tau(T) = \frac{h^2}{D_z(T)} \cdot \left[-\frac{1}{7.3} \cdot \ln\left(1 - \frac{M_\tau(T) - M_b}{M_m - M_b} \right) \right]^{4/3} \tag{6}$$

where

$M_\tau(T)$ ≡ moisture level achieved at time τ , $M(T, t = \tau)$

$\tau(T)$ ≡ time to reach the moisture content of $M_t(T)$ at temperature T

Therefore, the equations for moisture absorption, moisture content and saturation time can all be defined uniquely. Based on the moisture uptake and vs. square root of time data, the diffusivity constant can be calculated from equation (7):

$$D_z(T) = \pi \cdot \left(\frac{h_D}{4 \cdot M_m}\right)^2 \cdot \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \tag{7}$$

where

h_D ≡ average specimen thickness

$\left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)$ ≡ initial linear portion slope of moisture absorption plot at temperature T

Using available data, the diffusion constant (a function of temperature) for T700/#2510 material system is shown in Figure 6. From these curves, it can be seen that the diffusion constant increases with increasing exposure temperature and thus, conditioning specimens or structural components at an unrealistic climatic temperature may induce some over-conservatism into the design. The focus of the proposed research is to provide boundaries for realistic service environments for realistic estimation of the environment to which composite airframe structures are exposed during service.

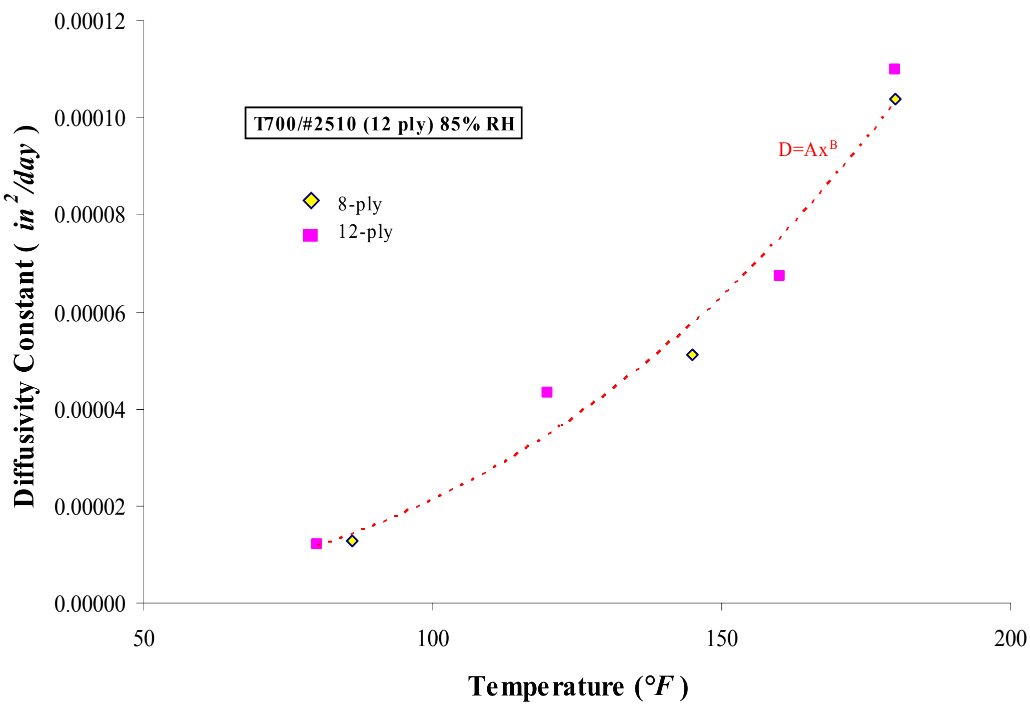

Figure 6 – Diffusion Constant for T700/#2510 as a Function of Exposure Temperature

As shown in Figure 5, the rate of moisture absorbance increases with the conditioing temperature but the equilibrium moisture content is only a function of ambient moisture or relative humidity as shown in Figure 7. An extensive study conducted by Tenney and Unnam [4] based on the flight utilization data for commercial aircraft indicated that the equilibrium moisture level depends primarily on the ground relative humidity during non-flight hours, and the flight service does not have a large effect on equilibrium level. Furthermore, the study showed that a composite panel exposed to solar heating will pick up approximately 30% less moisture than a panel protected from solar exposure. This study was completed for commercial aircraft, which experience longer flight times and a significantly higher service life than general aviation aircraft. Therefore, the flight profile may reasonably be neglected and the aircraft ground environment can be used to characterize the environmental effects.

Using information from Springer [5] and McKague et al. [6], Figure 7 shows that a relative humidity of 77% corresponds to a moisture content of 1.1% in T300/5208. Boeing 737 composite stabilizer was designed with a moisture content of 1.1 ±0.1% [7]. A majority of the studies were completed during the late 1970s and 80s and primarily contained estimated values and analyses on test samples, which resulted in an expected relative humidity of 68% [8]. It should be noted that Figure 7 also indicates that 68% relative humidity corresponds to a moisture content value of 0.95%, which corresponds to end of life teardown inspection results, thus further strengthening the validity of the initial studies when compared to results from the dissected 737 stabilizer.

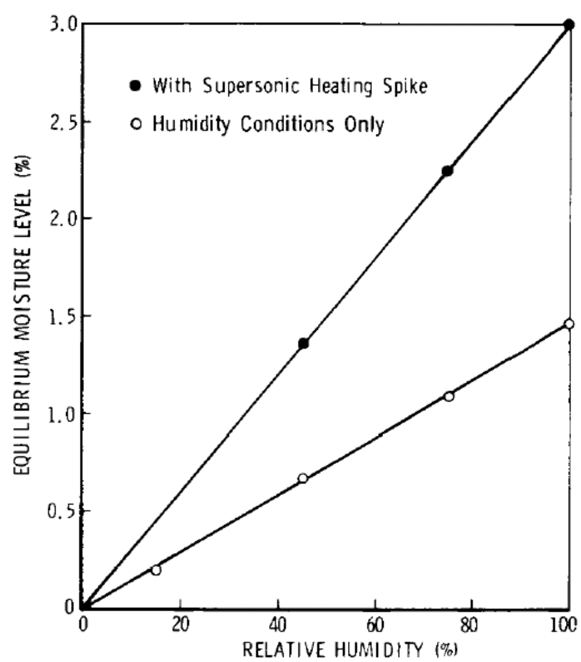

Figure 7 – Maximum Moisture Content vs. Relative Humidity for T300/5208 [6]

This program focuses on establishing guidelines for the incorporation of this type of analysis, coupled with realistic service and efficiency that can be gained from this process versus current design practices. For example, the time required to reach saturation from equation (6) can be used to draw some initial conclusions regarding current practice; at 145°F and 85% RH, the time required to attain 99% saturation for a T700/#2510 specimen of typical thickness is:

- 12 ply saturation time = 113 days
- 48 ply saturation time = 5 years
- 354 ply saturation time = 269 years

Placing this in terms of realistic service environment, a 145°F environment combined with 85% RH appears to be worst case conservative estimate. Based on actual climatic data from MIL-HDBK-310 [9], Figure 8 illustrates a daily cycle of a realistic combination of high humidity and high temperature. Therefore, this program focused on applying more realism to the guideline documentation for the enhancement of new practices in the design and certification which accounts for these environmental factors.

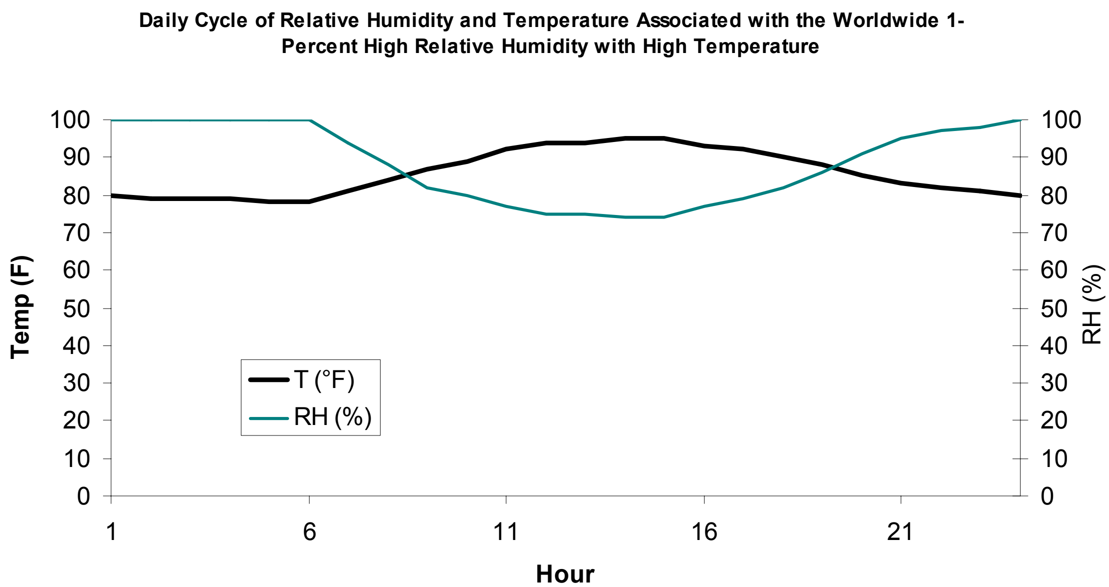

Figure 8 – Climatic Data from MIL-HDBK-310 – Realistic Combination of High Humidity and High Temperature

Based on the worst-case data shown in Figure 8, 90°F and a relative humidity level of 85% was selected as the nominal environmental condition, and the time necessary to reach 99% moisture content was calculated for the T700/#2510 material system and compared with data for 145°F/85% RH environmental exposure for several laminate thicknesses (Figure 9). As can be seen from equation (6), the time increases by the reciprocal of the ratio of diffusivity constants for the two temperatures (2.6 for this case). Data shows that a 12-ply laminate will take approximately 13 years to reach a 99% moisture content, while it will take over 696 years for 354-ply laminate to reach this saturation in a 90°F/85% RH environment. Hence, some realism needs to be taken into account during this analysis, particularly for the thicker laminates. Moisture absorption characteristics of composites, which follow Fick's second law, can be coupled with realistic environmental data to design structurally efficient and economic composite components.

Years for 99% Saturation

Laminate Thickness (in)	**0.1032**	**0.4128**	**3.0444**
90°F/85%RH	0.8	12.8	696.6
145°F/85%RH	0.3	5.0	269.4

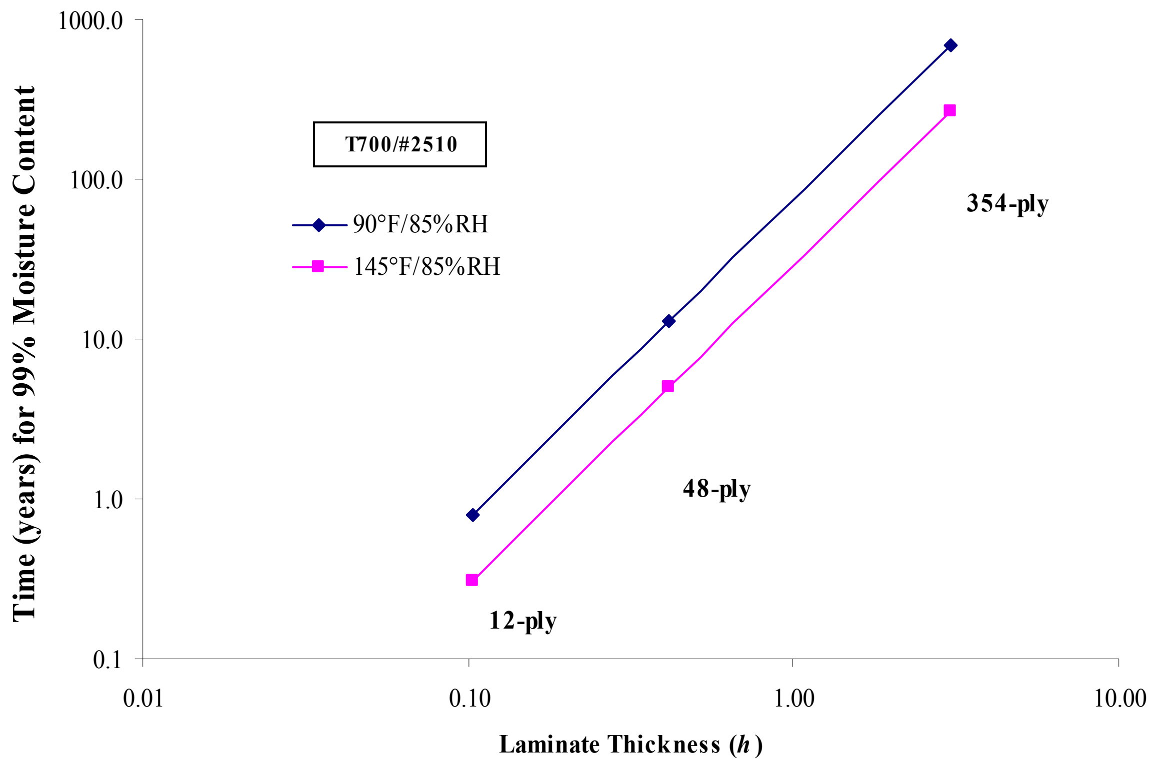

Figure 9 – Time Necessary to Reach 99% Moisture Content for Fixed Temperature and Moisture Exposure

3. CYCLIC MOISTURE ABSORPTION STUDY

In order to support the development of math model for determining the property retention of composite structure under-going humidity and temperature cycling, compression, in-plane shear and Tg properties will be evaluated from a pool of specimen that will undergo moisture absorbance and desorption as shown in Figure 10. This exercise, given the environmental exposure data for a particular composite structure, will be instrumental in incorporating humidity profile into the design to evaluate a design-specific and practical environmental compensation factors (ECF) for composites. In addition, the test data will show any effects of full or partial saturation on the subsequent moisture absorbance. Composite panels are fabricated using Cytec 7714A/M46J unidirectional tape material with a layup of [0/90]8s. The property retention (mechanical and thermal) as well as the effects of the residual damages due to moisture absorption, i.e., swelling, microcracking, on the subsequent moisture absorption following desorption will be evaluated as shown in Figure 10.

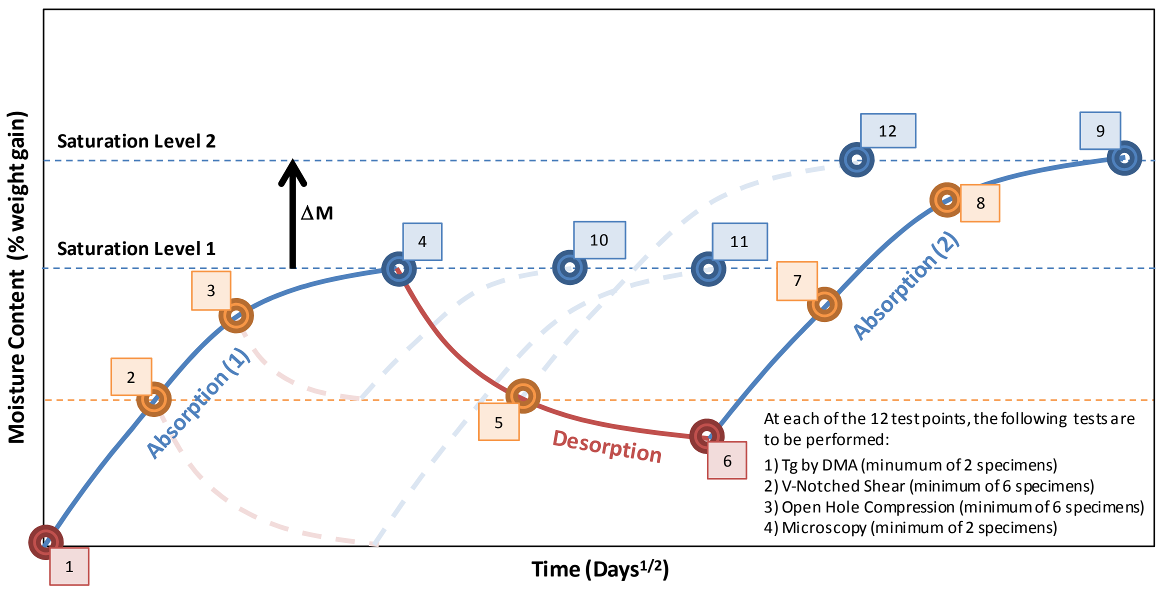

Figure 10 – Cyclic Moisture Absorbance Study

4. CONCLUSIONS

According to the Fick's law for moisture diffusion in composite, thick laminates under service temperatures may take a significantly longer duration depending on the thickness. Hence, some realism needs to be taken into account during this analysis, particularly for the thicker laminates. Moisture absorption characteristics of composites, which follow Fick's second law, can be coupled with realistic environmental data to design structurally efficient and economic composite components. This research will provide guidance to establish practical levels of moisture content and corresponding environmental compensation factors for composite structures.

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